REPORT TO THE NUCLEAR SCIENCE ADVISORY COMMITTEE

Submitted by the

SUBCOMMITTEE ON PERFORMANCE MEASURES

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1. Executive Summary

The United States Federal Government has a legal mandate for stewardship of basic research in nuclear physics, mainly through the Office of Science in the Department of Energy and through the National Science Foundation. It also has a clear interest in ensuring the Nation that all of its programs are effective and efficient. The Government Performance and Results Act of 1993 (GRPA) and *The President's Management Agenda,* dated Fiscal Year 2002 and issued by the Executive Office of the President, Office of Management and Budget (OMB), require the setting of goals for each program and the measurement of program performance against these goals to assess and monitor its effectiveness. This report is an assessment of the effectiveness of the nation's nuclear physics program by reviewing progress towards the goals and Milestones established in 2003.

These goals, described in a report which can be found on the Office of Science website at http://www.sc.doe.gov/np/nsac/docs/nsac_report_performance_measures.pdf, include detailed Performance Measures in the four major subject areas of Nuclear Physics and some 41 Milestones that address specific areas of the overall program. These goals and Milestones were recommended by NSAC in 2003, following their development by the 2003 Subcommittee on Performance Measures. Assessments of progress towards meeting the goals established by this report were to be made every five years. NSAC was subsequently charged July 17, 2006, as part of a broader charge to produce a new Long Range Plan, to review progress towards the above Performance Measures. This Subcommittee was established for that purpose.

The Performance Measures were developed to gauge performance by the field in addressing opportunities and open questions in the major areas of nuclear physics. They were developed in the context of the then-existing state of knowledge, the state of the art in theoretical and experimental practice, and existing facilities. The measures took into account those facilities under preparation or planned for implementation within the 12-year time window considered. The Performance Measures represent attainment of new knowledge, advances in understanding or interpretation of existing data and theory, and realization of new capabilities for the field. Risk is implied in their very definition. Definite efforts must be made; appropriate experiments must be conceived, designed, executed and analyzed. Results must be interpreted in the context of existing theory and the theoretical framework must itself be extended via new concepts, models, and mathematical and/or numerical tools. Additional risk is inherent from the uncertainties of funding support for this research. The original Milestones and Performance Measures were developed in the context of the funding levels anticipated at the time of the 2002 NSAC Long Range Plan. However, funding for the program must be managed by the agencies in the context of actual Congressional appropriations, which have been less than levels anticipated in 2002. Therefore not all goals will be possible to achieve due to the constraints arising from the enacted levels of funding.

We started with a detailed evaluation of work done in the specific areas of the Milestones, since each of these can be tied to specific experiments, theoretical efforts, and publications. We then used the results of this evaluation to analyze progress towards the more broadly defined Performance Measures and to establish an overall grade for progress on each Measure. Each of the 41 Milestones set forth by the 2003 subcommittee were reviewed to identify documented achievements, key work still in progress, and any issues that have developed since 2003, with particular attention to referencing work published in the peer-reviewed scientific literature. We established a grading scale for evaluation of progress towards the broad Performance Measures and another for the more specific Milestones.

This report is the first examination of the original set of Milestones, whose due dates range from 2005 to 2014. It was expected, and indeed found, that most are still works in progress, but a number of them are complete. Where appropriate, we propose revised Milestones and the reasons for them, in some cases changing the scientific focus and in others changing only the date. A number of new Milestones are recommended to reflect progress made and knowledge gained as well as new opportunities that have arisen. Many of these are taken from the 2007 Long Range Plan. Due dates for these new and revised Milestones are proposed. We extend these in some cases to 2020 to reflect the expected timeline for realizing new opportunities and bringing online new facilities described in the 2007 Long Range Plan. The very fact that new Milestones make sense reflects positively on the health and dynamic nature of the field. Details of the Milestone evaluations are given in Appendices 3-9.

We then analyzed progress towards the Performance Measures themselves using the Milestone analysis as key input. A second grading scale was established for this evaluation; it is described in Section 5. Given the dynamic nature of scientific research, new opportunities have arisen that expand the reach of the program supported by DOE SC Nuclear Physics. These are to a significant extent captured in the new and revised Milestones as noted above, but in a few cases warranted revisions to the broader Performance Measures themselves.

Each of the Performance Measures for Nuclear Physics that were set down by the 2003 NSAC Subcommittee on Performance Measures has a completion date of 2015. Not surprisingly, only a fraction of the research that must be carried out to achieve these Performance Measures fully has been completed. Therefore, we took our main task to be the evaluation of progress toward the achievement of the Performance Measures, using the expectations and Milestones established by the 2003 Subcommittee report as the yardstick.

The Performance Measures were laid out in such a way that sustained high effort would be required to achieve them by 2015. Both the goals and pace for achieving them were meant to be demanding. This effort has many aspects, including: focused research addressing specific experimental and theoretical questions, thoughtful deployment of resources, sustained research funding support, a planned program of investments in new capabilities, and pursuit of new scientific opportunities revealed by ongoing research. The assumption of a constant level of effort that formed the basis for the 2002 NSAC Long Range Plan was used by the 2003 Subcommittee to establish the goals, the Milestones, and the timeline for achieving them. In view of the actual budgets in the intervening period, it would be truly remarkable if we were to have achieved excellent progress. Indeed, delays in progress toward a number of the Milestones are directly attributable to the reduced levels of funding actually received.

We determine that progress towards accomplishing the goals in the Performance Measure for Hadronic Physics is Good, meaning that if support of activities underway can be maintained at FY07 levels or better, these activities could reach their planned conclusions to the Good level by

2015. However, the timescale will be a challenge, and the sub-field is not likely to accomplish the goals under the Performance Measure to the Excellent level. The Good rating must be understood in the context of the actual funding levels over the period being evaluated (2003-2007). If expectations for progress are recalibrated to what would have been reasonable with the actual level of funding received (rather than the constant effort budget that was the basis for the expectations), then the timescale for the Performance Measures and Milestones would have been stretched, and the progress achieved likely would have been evaluated as Excellent, rather than Good. Sustained funding and effort at recent (FY07) levels should allow the rating of Good progress to be preserved through 2015.

We determine that progress towards accomplishing the goals in the Performance Measure for Physics of High Temperature and High Density Hadronic Matter is Excellent, with significant additional, related research on the topic completed. This research has led to the conclusion that a true surprise has been found: a new type of strongly-coupled matter with a ratio of viscosity to entropy density lower than any heretofore known. Attempts to understand this property have led to completely unanticipated connections to theories of quantum gravity and to a postulated fundamental quantum limit on the ratio of viscosity to entropy density. Progress in this field has benefited from operation of RHIC, the first ever heavy-ion collider, which has the advantage of exploring a completely new area with the attendant possibility of unexpected new behavior, which was indeed found. Despite these accomplishments, recent funding has meant markedly reduced RHIC running time in the past three years. The result is that data needed to achieve upcoming Milestones are only partly in hand and that only preliminary studies have been carried out preparatory to taking data needed for later Milestones. The result is that several near-term deadlines are in jeopardy, and future progress towards the Performance Measures may only be possible at the Good level.

We determine that progress towards accomplishing the goals in the Performance Measure for Nuclear Structure and Astrophysics is Good or somewhat better. We note that sustained Good or better progress in this area does require access to new beams and improved beam intensities, because much of the pressing new subject matter involves studies of nuclei located well away from the valley of stability and, ultimately, reaching nuclei at the limits of particle stability. Sustained funding and effort at present levels should allow the rating of Good progress to be preserved when a final evaluation in the target year of 2015 is performed, with an Excellent rating remaining a strong possibility.

We determine that progress towards accomplishing the goals in the Performance Measure for Neutrinos, Neutrino Astrophysics and Fundamental Interactions is Good. In contrast to the situation for the three other major subfields, progress here towards the Performance Measures has been uneven, with significantly more progress in some areas than others. This area of Nuclear Physics depends on purpose-built experiments more so than other areas, with a potential large payoff on focused questions. Much of the physics depends on weak interactions with their associated quite small probabilities and attendant need for large-volume detectors and/or very long experiment durations. This means that the pace of capital investment more directly affects whether a given area can make progress. In this area targeted new support, as described in the 2007 Long Range Plan, will enable Good (or better) progress in the future on the Performance Measures for this subfield that have lagged.

We stress that sustained funding is key to being able to pursue the range of activities yet to be accomplished in the specific Milestone areas. If funding can be increased to the growth path of the ACI and America COMPETES act (the scenario that provided the planning basis for the 2007 NSAC Long Range Plan), and sustained as envisioned therein, then one could reasonably expect that an Excellent rating by 2015 is possible for most Performance Measures. We remain concerned that continued stringencies in funding will lead in particular to reduced operation of experimental and computational facilities, making the achievement of Good performance by 2015 difficult; it simply would not be possible to do the work in time if the funding patterns of the past 5 years are continued. The potential for loss to the field from missed scientific opportunities is significant.

In the areas of Performance Measures for Hadronic Physics and for Nuclear Structure and Astrophysics, we find that the current Performance Measures still serve to capture the present and near future focus of these efforts. For High Temperature and High Density Hadronic Matter a new research direction stems from the discovery that a strongly-coupled fluid with a remarkably low ratio of viscosity to entropy density is formed in relativistic heavy-ion collisions at RHIC. Understanding this has led to conjectured links to theories of gravity, a remarkable deduction if proven. The new scope of the needed experimental and theoretical work can be captured by one added Performance Measure, which addresses the low shear viscosity of this fluid. For Neutrinos, Neutrino Astrophysics and Fundamental Interactions major new opportunities have developed since the last report on Performance Measures to NSAC. We propose to return the setting of improved limits on the neutron EDM to the Performance Measure set now that a definite plan for that effort is established (thus addressing a specific concern of the previous report). We further propose two new Performance Measures in this area to capture the effort on precision electroweak measurements by the field.

The revised Performance Measures and the updated table of Milestones should again be reviewed at an appropriate interval, for example five years hence. This future evaluation will be in a different situation: inasmuch as this was the first evaluation against a new set of Performance Measures and Milestones, the next review will need to evaluate progress against a set of Performance Measures whose due dates will be arriving soon. It would be appropriate then to establish a new set of Performance Measures, building on the current set, to encapsulate what will undoubtedly be a new set of program goals that reflect progress to date and new opportunities yet to be defined. We would expect this next review to propose modified Performance Measures and associated Milestones. Their execution will then depend on facilities that will be by the time of this next review being readied for operation, but are at the present time in early project stages. The FRIB recommended in the 2007 Long Range Plan with completion late in the next decade, and the 12 GeV Upgrade of CEBAF at Jefferson Lab (now approaching CD-3), are examples. These several steps will ensure that the Performance Measures remain fresh and continue to set demanding goals.

In a step toward this evolution we have proposed several new Milestones, with due dates out to 2020. They capture current concrete plans and anticipate in part the expected change in focus of those future Performance Measures. We would expect the next evaluation also to reflect progress towards the plan set forth in the 2007 Long Range Plan, which is the most recent in a series which have served Nuclear Physics well these past 30 years.

2. Introduction

The United States Federal Government has a legal mandate for stewardship of basic research in nuclear physics, mainly through the Office of Science in the Department of Energy and through the National Science Foundation. It also has a clear interest in ensuring the Nation that all of its programs are effective and efficient. The Government Performance and Results Act of 1993 (GRPA) and *The President's Management Agenda,* dated Fiscal Year 2002 and issued by the Executive Office of the President, Office of Management and Budget (OMB), require the setting of goals for each program and the measurement of program performance against these goals to assess and monitor its effectiveness. This report is an assessment of the effectiveness of the nation's nuclear physics program by reviewing progress toward the goals and Milestones established in 2003.

On September 13, 2003, the Nuclear Science Advisory Committee (NSAC) was charged by the Department of Energy (DOE) and the National Science Foundation (NSF) to recommend Performance Measures for the Nuclear Physics program to the DOE Office of Science. OMB guidance and proposed Nuclear Physics Performance Measures were provided to NSAC. OMB also requested appropriate Milestones that could be used to judge the quality of the progress that had been made towards the Performance Measures. NSAC was requested to submit a report on the appropriateness of the proposed measures, herein referred to as "Performance Measures", to comment on whether the Performance Measures were suitably ambitious and encompassed the DOE Nuclear Physics program, and to make recommendations for appropriate Milestones for each of the Performance Measures.

A subcommittee was formed to report on this activity and it returned its report on November 18, 2003 to NSAC, which accepted it and transmitted it to the DOE and NSF. This report, which can be found on the Office of Science website at http://www.sc.doe.gov/np/nsac/docs/nsac_report_performance_measures.pdf, established more detailed Performance Measures in four major subject areas of Nuclear Physics, and some 41 Milestones were set down as a means of judging quality of progress by examining quite specific areas of the overall program. The 2003 Report forms the starting point for this report. The process for periodic assessment of progress in the Nuclear Physics program towards these goals was identified as part of the charge to NSAC in 2003; assessments of progress towards meeting the goals established by that report were to be made every five years. NSAC was subsequently charged July 17, 2006, as part of a broader charge to produce a new Long Range Plan, to review progress towards the above Performance Measures. The specific paragraph from that charge letter reads:

> *"Activities across the federal government are being evaluated against established performance goals. In FY2003, utilizing input from NSAC, the long-term goals for the DOE SC Nuclear Physics program and the metrics for evaluations of the program activities were established. It is timely during this long range planning exercise to gauge the progress towards these goals, and to recommend revised*

long-term goals and metrics for the DOE SC Nuclear Physics program, in the context of the new LRP, if appropriate, The findings and recommendations of this evaluation should be a separate report."

The current subcommittee was given this charge; the charge letter and subcommittee membership are given in Appendices 1 and 2. At the time we began our work, a revised version of the Performance Measures had been submitted by DOE SC Nuclear Physics that left the basic Performance Measures intact but changed the scoring from the original two-level scheme established by OMB in 2003 to a more nuanced four-level scoring scheme.

The methodology used to carry out the evaluation is detailed in Section 3 below. The four Performance Measures, together with the recently modified assessment scoring scheme and the reasoning underlying their choice by the 2003 Subcommittee, are given in the Section 4. Much of our task was to assess progress towards these Measures using an analysis of work done in the specific areas covered by the Milestones associated with each of the Performance Measures. The methodology used to carry out that assessment is presented in Section 5. The Milestone results are summarized in our evaluation of the Performance Measures in Section 6. This Milestone summary is also given in Appendix 3, before a description of new and continuing Milestones in Appendix 4 and the detailed Milestone evaluations in Appendices 5-9. Our analysis determines that these Performance Measures do still capture essential elements of the program, but that new opportunities noted in the recently-completed 2007 Long Range Plan coupled with scientific progress since 2003 require that these Milestones be supplemented with over a dozen new ones to capture the full breadth of the program, and that four additions be made to the broader Performance Measures themselves to reflect evolving program focus. The new Performance Measures are presented in Section 7 and a revised set of Milestones, including both new and continuing ones, that is appropriate for the next assessment is given in Appendix 4. We make some concluding remarks in Section 8.

3. Methodology

We started with a detailed evaluation of work done in the specific areas of the Milestones, since each of these can be tied to specific experiments, theoretical efforts, and publications. We then used the results of this evaluation to analyze progress towards the more broadly defined Performance Measures per se and establish an overall grade for progress on each Measure. Each of the 41 Milestones set forth by the 2003 subcommittee were reviewed to identify documented achievements, key work still in progress, and any issues that have developed since 2003, with particular attention to referencing work published in the peer-reviewed scientific literature. We established a grading scale for evaluation, which is given below in Section 5 on Milestones, and used it to evaluate progress for each Milestone. The detailed results of the Milestone evaluations are given in Appendix 3 in summary tables and Appendices 5-9 in detail. The summary together with the evaluations of progress towards the Performance Measures are given in Section 6. Milestone status was noted as complete or not.

This report is the first examination of the original set of Milestones, whose due dates range from 2005 to 2014. It was expected, and indeed found, that most are still works in progress, but a number of them are complete. Where appropriate, we propose revised Milestones and the reasons for them, in some cases changing the scientific focus and in others changing only the date. A number of new Milestones are recommended to reflect progress made and knowledge gained as well as new opportunities that have arisen. Many of these are taken from the 2007 Long Range Plan. Due dates for these new and revised Milestones are proposed. We extend these in some cases to 2020 to reflect the expected timeline for realizing new opportunities and bringing online new facilities described in the 2007 Long Range Plan. The very fact that new Milestones make sense reflects positively on the health and dynamic nature of the field. The Milestone status and evaluation plus the revised list of Milestones including new and revised ones, are given in summary tabular form in Appendices 3 and 4. The detailed evaluations of individual Milestones and supporting references from the scientific literature are given in Appendices 5 through 9.

We then analyzed progress towards the Performance Measures themselves using the Milestone analysis as key input. Another grading scale was established for this evaluation, which is given in Section 5. Given the dynamic nature of scientific research, new opportunities have arisen which expand the reach of the program supported by DOE SC Nuclear Physics. These are to a significant extent captured in the new and revised Milestones as noted above, but in a few cases warranted revisions to the broader Performance Measures themselves. These proposed additions are given after the discussion and summary of progress towards the Measures in Section 7.

These evaluations and proposed new Milestones and Performance measures were discussed with representative members of the field. This resulted in valuable feedback on how well the state of the field was captured, on the feasibility of new Milestones and/or due dates, on the importance of capturing work in certain areas that have benefitted in recent years from investments made by DOE, both in DOE SC Nuclear Physics facilities as well as in, e.g., large-scale computing facilities. We have benefitted from this feedback in preparing this report.

Before proceeding to the evaluations, we comment on the funding of the field, in particular on the assumptions made in the 2002 and 2007 Long Range Plans and in the 2003 Performance Measures report. Unfortunately recent funding history differs significantly from those planning assumptions. We believe this approach is useful to provide context for some of the evaluations in the following. The 2002 LRP, which formed the basis for budget assumptions in the 2003 report on Performance Measures, included a constant level of effort budget based on the FY03 appropriation, i.e., a budget that would follow inflation, as one of a limited number of budget assumptions. This constant level of effort budget was taken as the assumption for the 2003 Performance Measures report. The 2002 LRP advocated that small projects, and even medium sized projects such as the 12 GeV Upgrade Project at TJNAF, be pursued from the base program if possible, but recognized in the section on Resources and Funding that a funding increase targeted to support facility operations across the field was likely needed to accommodate this. The recommendation for a new facility for rare isotope beams was deemed to require an addition of funds outside this level of effort. The recent DOE budget history of the field is FY02: \$359.0M, FY03: \$379.6M, FY04: \$389.6M, FY05: \$404.8M, FY06 \$367.0M, FY07 \$422.8M, and FY08: \$432.7M. All amounts are in at-year dollars. There have been Omnibus Appropriations and budget rescissions in several years and a particular sharp reduction in funding, by 9.3% in FY06. This has necessarily reduced operating time at all four accelerator-based user facilities operated by DOE SC Nuclear Physics, and at the National Superconducting Cyclotron Laboratory, operated by the NSF. It has also necessitated adjusting timelines if not the scope of new projects, and has meant that not all efforts foreseen in 2002-2003 could be undertaken on the timelines envisioned at that time.

The current FY08 funding supports operations at all accelerator-based user facilities, at levels well short of full utilization. It also supports a broad program of investments in new capabilities at current facilities: construction of both the 12-GeV upgrade at TJNAF and the ion source upgrade at RHIC, and certain new efforts particularly in the area of neutrino science and fundamental interactions. The 2007 LRP was written with the assumption of the growth budgets foreseen in the American Competitiveness Initiative and the America COMPETES Act. This level of funding would provide for near full utilization of existing accelerator-based user facilities and further new initiatives, similar to the 12-GeV upgrade at TJNAF, a new capability in low-energy Nuclear Physics called the Facility for Rare Ion Beams (FRIB), a new suite of targeted experiments searching for anticipated physics beyond the Standard Model, and the RHIC luminosity upgrade. There are cases noted below where progress towards goals could have been improved with the benefit of more stable or predictable funding levels, and others where it is noted that the funding levels envisioned under COMPETES would be needed to reach an excellent level of performance.

4. Performance Measures

The Performance Measures listed later in this section were developed to gauge performance by the field in addressing opportunities and open questions in the major areas of nuclear physics. They were developed in the context of the then-existing state of knowledge, the state of the art in theoretical and experimental practice, and existing facilities. The measures took into account those facilities under preparation or planned for implementation within the 12-year time window considered. The Performance Measures represent attainment of new knowledge, advances in understanding or interpretation of existing data and theory, and realization of new capabilities for the field. Risk is implied in their very definition. Definite efforts must be made; appropriate experiments must be conceived, designed, executed and analyzed. Results must be interpreted in the context of existing theory and the theoretical framework must itself be extended via new concepts, models, and mathematical and/or numerical tools. Some risk is inherent to the probability of funding support; the agencies have managed to program in the context of Congressional appropriations, but not all goals may be possible due to the constraints arising from the enacted levels of funding.

The Performance Measures for DOE SC Nuclear Physics and proposed rating scale, as established by DOE, are given here. The Measures are organized into four groups corresponding to major program areas.

4.A Performance Measures for Hadronic Physics

- By 2015, make precision measurements of fundamental properties of the proton, neutron and simple nuclei for comparison with theoretical calculations to provide a quantitative understanding of their quark substructure.
    - What does this measure mean? **-** The broad goals of research in hadronic physics include linking the physics of nuclei to the fundamental theory of strong interactions, namely, Quantum Chromodynamics (QCD), understanding the structure of protons and neutrons that make up nuclei in terms of quarks and gluons because the latter are the fundamental ingredients of QCD, and understanding the structure of light nuclei both in terms of nucleons at low energy and in terms of quarks and gluons at high energy.
    - Why is this measure important? **-** These goals require probing nuclei and their constituents with electron and photon beams that are capable of high spatial resolution and high energy so as to be able to produce the excited mesonic and baryonic states of QCD. Form factors determine how the particles are distributed inside nucleons and light nuclei. Structure functions and generalized parton distributions, the latter being a new tool in the field, determine how the quarks and gluons are distributed in nucleons and how the spin of the proton is built up from the quarks and gluons. High-energy proton-proton collisions provide a complementary window into how the quarks and gluons build up the nucleons. Lattice QCD calculations are expected to provide the best theoretical means to compare experiments directly with QCD, however, a variety of theoretical tools are used to model and understand the observed phenomena. Ab initio many-body calculations based on two-nucleon interactions with the addition of modest three-nucleon interactions provide the best theoretical means to understand the low-energy aspects of the structure and interactions of nuclei. The Milestones for Hadronic Physics include representative examples of progress in each of these aspects without being inclusive of all relevant work.
    - Definition of "Excellent" – 1) Research leads to quark flavor dependence of nucleon form factors and structure functions being measured; 2) hadron states described with QCD over wide ranges of distance and energy; 3) ab-initio calculations of light nuclei performed using two- and three- nucleon interactions determined from an effective field theory linked to QCD; 4) precision measurements of composition of nucleon spin performed.
    - Definition of "Good" – 1) Research leads to quark and gluon contributions to the nucleon's spatial structure and spin being measured; 2) theoretical tools for hadron structure being developed and tested; 3) data show how simple nuclei can be described at a nucleon or quark-substructure level for different spatial resolution of the data.
    - Definition of "Fair" – Supported research leads to modest outputs in only two of the three goals described in the "Good" rating.
    - Definition of "Poor" – Supported research leads to modest outputs in only one of the three goals described in the "Good" rating.
    - How will progress be measured? – *Expert Review every five years will rate progress as "Excellent", "Good", "Fair" or "Poor".*

4.B Performance Measures for High Temperature, High Density Hadronic Matter

- By 2015, create brief, tiny samples of hot, dense nuclear matter to search for the quark-gluon plasma and characterize its properties.
  - What does this measure mean? - The goal is to create for the first time in the laboratory hot (2 x 10^{12} K), dense (≥ 30 times normal nuclear density) matter that is predicted to have existed a few microseconds after the beginning of the Universe by colliding heavy nuclei at center of mass energies up to 200 GeV per nucleon pair. This matter would have features not encountered before in the laboratory, including color deconfinement and chiral symmetry restoration. Its discovery would signal the ability to study in the laboratory one of the major phase changes in the behavior of matter itself at very high temperature, indeed the only such phase change that may be currently accessible. These studies will seek to establish properties of this new state (such as initial temperature, pressure, and entropy) and the time evolution of the collision process.
  - Why is this measure important? - These studies will measure collective phenomena (such as the flow of specific particles) and establish theoretically the dynamics of the process creating these phenomena. The study of penetrating probes such as fast quarks and gluons will provide information on the processes of color and energy transport. Perturbative QCD (pQCD) gives a description of such processes and together with experimental results will shed light on the nature of this strongly interacting matter. We seek to establish whether the temperatures are sufficiently high that the matter consists of weakly interacting quarks and gluons (deconfinement) rather than strongly interacting hadrons, to the extent that the strong color force is sufficiently screened so as to suppress production of bound states of charm and anti-charm quarks (known as the J/ψ family). This research will either verify or nullify the prediction by the Standard Model using QCD on the lattice that a deconfined state of matter, the quark-gluon plasma, exists at high temperatures and densities.
  - Definition of "Excellent" – 1) The existence of a deconfined, thermalized medium is determined; 2) its properties such as temperature history, equation of state, energy and color transport (via jets), and screening (via heavy quarkonium production) are characterized.
  - Definition of "Good" – 1) The existence of hot, high-density matter is established; 2) some of its properties (e.g., its initial temperature via the photon spectrum) measured; 3) confinement properties, and energy transport (via jets) are explored.
  - Definition of "Fair" – Supported research leads to modest outputs in only two of the three goals described in the "Good" rating.
  - Definition of "Poor" – Supported research leads to modest outputs in only one of the three goals described in the "Good" rating.
  - How will progress be measured? – *Expert Review every five years will rate progress as "Excellent", "Good", "Fair" or "Poor".*

4.C Performance Measures for Nuclear Structure and Nuclear Astrophysics

- By 2015, investigate new regions of nuclear structure, study interactions in nuclear matter like those occurring in neutron stars, and determine the reactions that created the nuclei of atomic elements inside stars and supernovae.
  - What does this measure mean? - Our understanding of nuclear structure is poised at a new threshold. Detailed studies of rare isotopes will dramatically expand our understanding of the nucleus and nuclear matter and will provide new insights into the nuclear forces by allowing study of particular nuclei and reactions that isolate and amplify specific nucleonic interactions.

    Nuclear processes play a central role in understanding the evolution of the stars, their violent explosions and the synthesis of the elements in these explosions. This chain of events produces the elements of life itself. A rich and multi-faceted research program in nuclear astrophysics is required to decipher the universe in which we live.

  - Why is this measure important? - In the area of nuclear structure, we will study the limits of nuclear existence and the evolution of structure between these limits. An ultimate goal is a unified microscopic understanding of the nuclear many-body system in all its manifestations, as well as of the remarkable simplicities and collective behaviors that these nucleonic systems display. Complementary studies near stability and the quest to make the heaviest elements form a coherent long-term research program. To achieve these goals across the broad expanse of the nuclear landscape, the program carries out research at a number of smaller facilities, typically in short-term experiments (one to few weeks in nature), whose outcome influences follow-up studies. The character of this research makes it especially difficult for a few, short Milestones to broadly capture what is needed to achieve the performance measures. The Milestones represent important examples of the significant progress that will be made. The foci of this work are to identify the evolution of nuclear structure with mass and charge and improve theoretical models to gain a more complete understanding of the nucleus, and to explore nuclei at the limits of existence to establish their properties and test the models of nuclear structure and reactions in currently unmeasured regimes of nucleonic matter.

    In the area of nuclear astrophysics, we will study the physics of core collapse supernovae, hypernovae, and their connection with gamma-ray bursts. These are the most energetic explosions in our universe and factories for formation of a significant fraction of the elements. We will also study the properties of neutron star remnants left behind by these explosions, which serve as cosmic laboratories for high-density nuclear physics inaccessible in terrestrial experiments. We will investigate type Ia supernovae, the standard candles through which extraordinary facts about our universe and its fate have been illuminated. We will also investigate the evolution of stars and other cataclysmic stellar explosions including novae and X-ray bursts. A unifying theme for these focus areas is to precisely understand how a variety of microscopic nuclear physics phenomena come together to guide spectacular macroscopic phenomena such as the evolution and explosion of stars and their production of the elements.

- Definition of “Excellent” - 1) Extensive measurements on stable and exotic nuclei and the drip lines are performed; 2) their structure is established and the isospin dependence of effective interactions studied; 3) new nuclei with neutron skins are observed and studied; 4) reactions for several astrophysical processes, including some r-process nuclei, are measured and their implications for nucleosynthesis determined.
- Definition of “Good” - 1) Properties of nuclei and reactions near and far from stability are measured allowing study of effective interactions, collective behavior, and structural evolution; 2) new weakly bound nuclei are observed and the limits of binding explored; 3) some reactions of stellar interest are measured.
- Definition of “Fair” – Supported research leads to modest outputs in only two of the three goals described in the “Good” rating.
- Definition of “Poor” – Supported research leads to modest outputs in only one of the three goals described in the “Good” rating.
- How will progress be measured? – *Expert Review every five years will rate progress as “Excellent”, “Good”, “Fair” or “Poor”.*

4.D Performance Measures for Neutrinos, Neutrino Astrophysics, and Fundamental Interactions

- By 2015, measure fundamental properties of neutrinos and fundamental symmetries by using neutrinos from the sun and nuclear reactors and by using radioactive decay measurements.
  - <u>What does this measure mean?</u> The goals of neutrino physics include a complete characterization of the properties of neutrinos and an improved understanding of solar neutrinos. Direct observation of charged- and neutral-current channels is essential to determine the solar neutrino flux of all active flavors. Precise determination of various components of this flux provides stringent limits on neutrino properties (masses and mixings) as well as the theory of the main-sequence stellar evolution. Direct neutrino mass measurements are sensitive to the absolute neutrino mass scale with few, if any, assumptions about neutrino properties.

    The goal of investigating fundamental interactions at low energies is to provide an independent window on new physics beyond our current understanding of the interactions of elementary particles. Precision measurements of the beta decays can give strong signatures of new physics beyond the Standard Model (e.g. supersymmetry).

  - <u>Why is this measure important?</u> Research in neutrino physics will address key issues in understanding the scale of the new physics beyond the Standard Model, provide potential insight into the origin of fermion masses, impact cosmology (hot dark matter, large scale structure formation and anisotropies of cosmic microwave background radiation) and astrophysics (core-collapse supernovae, r-process nucleosynthesis, and the origin of elements). Direct neutrino mass measurements, combined with observables from oscillation and neutrinoless double beta decay experiments, can potentially measure the CP-violating phases in the lepton sector and yield understanding of hierarchy and ordering of neutrino masses.

The neutrino mass scale that is inferred from the solar and atmospheric neutrino experiments implies the possibility of seeing neutrinoless double beta decay with experiments sensitive to masses of about 50 meV. Observation of the zero neutrino mode would establish the Majorana nature of neutrinos (i.e. that neutrinos are their own antiparticles) and may provide clues to the existence of the CP-violating phases.

When the next Galactic supernova occurs a significant number of neutrino events can be detected at neutrino observatories such as the SuperKamiokande, SNOLAB, or KamLAND experiments. Such a measurement will provide important clues to the astrophysics of supernovae as well as to neutrino properties.

In the area of fundamental interactions, the precise predictions of the standard model at the level of quarks and leptons take on additional, still poorly understood, aspects when the weak interactions between nucleons are considered. There is reason to expect that these aspects may be explained in the framework of a more complete theoretical treatment based on the symmetries of QCD.

The violation of CP (Charge-Conjugation times Parity) symmetry for elementary particles during the Big Bang is believed to be responsible for the apparent excess of matter compared to anti-matter that we observe in the universe. While new sources of CP violation are possible in the neutrino sector there could also be larger violations for nucleons due to new physics beyond the standard model. New precise searches for both the neutron and atomic electric dipole moment measurements (EDM) coupled with improvements in the theory could signal a new source of CP violation and better quantify the role of nucleon CP violation in understanding the matter-antimatter asymmetry.

Precise investigation of fundamental symmetries for the neutron can be performed with new sources of Cold and Ultra-Cold neutrons (Cold neutrons have wavelengths of 0.5 - 10 nm and Ultra-Cold neutrons have wavelengths > 50 nm). A cold neutron beamline for fundamental physics studies is under development at the Spallation Neutron Source (SNS), operated by Basic Energy Sciences in DOE. Additional funding (beyond constant effort) would likely be needed to develop and complete measurements of the neutron electric dipole moment with Ultra-Cold neutrons to improve the sensitivity by at least an order of magnitude.

- Definition of "Excellent" - 1) Double beta-decay lifetime limits are extended 10-fold or more; 2) R&D completed demonstrating if precision pp solar experiment is possible; 3) played key roles in low-energy neutrino experiments and beta-decay probing cosmologically interesting neutrino masses.

- Definition of "Good" - 1) Double beta-decay lifetime limits extended; 2) participated in low-energy neutrino experiments and beta-decay probing cosmologically relevant neutrino masses; 3) parameters for quark mixing for nuclear beta-decay quantified.
- Definition of "Fair" – Supported research leads to modest outputs in only two of the three goals described in the "Good" rating.
- Definition of "Poor" – Supported research leads to modest outputs in only one of the three goals described in the "Good" rating.
- How will progress be measured? – *Expert Review every three years will rate progress as "Excellent", "Good", "Fair" or "Poor".*

5. Performance Measure Evaluation Approach

Each of the Performance Measures for Nuclear Physics that were set down by the 2003 NSAC Subcommittee on Performance Measures has a completion date of 2015. Not surprisingly, only a fraction of the research that must be carried out to achieve these Performance Measures fully has been completed. Therefore, we took our main task to be the evaluation of progress toward the achievement of the Performance Measures, using the expectations and Milestones established by the 2003 Subcommittee report as the yardstick.

The Performance Measures were laid out in such a way that sustained high effort would be required to achieve them by 2015. Both the goals and pace for them were meant to be demanding. This effort has many aspects, including: focused research addressing specific experimental and theoretical questions, thoughtful deployment of resources, sustained research funding support, a planned program of investments in new capabilities, and pursuit of new scientific opportunities revealed by ongoing research. The assumption of a constant level of effort that formed the basis for the 2002 NSAC Long Range Plan was used by the 2003 Subcommittee to establish the goals, the Milestones, and the timeline for achieving them. In view of the actual budgets in the intervening period, it would be truly remarkable if we were to have achieved excellent progress. Indeed, delays in progress toward a number of the Milestones are directly attributable to the reduced levels of funding actually received.

Our overall evaluation of progress as defined by the Performance Measures was done using the grading scale defined here. The top grade is reserved to performance in that major area that goes beyond mere achievement of certain pre-defined goals and instead represents a qualitative advance in understanding of that area, the type of advancement that can point to new avenues of study:

Table 1: Performance Measure Grading Scale

Excellent: On track to achieve the Performance Measure fully, either earlier than anticipated or with additional, related research on the topic completed, or with progress (and/or incremental

studies planned that can be completed in time) such that we are confident that the issues will be regarded as definitively settled.
Good: On track to achieve Performance Measure as anticipated.
Fair: Achieving the Performance Measure to the "good" level on the timescale planned is at risk without an increased effort (Note: if the scientific results themselves rule out achieving a Milestone – e.g. new examples of X were not found because Nature does not have any, then we consider the Performance Measure 'achieved', assuming the experiments/calculations were done.)
Poor: Achieving the Performance Measure to the "good" level on the timescale planned is not likely without substantially increased effort.

The Performance Measures, as established, were foreseen to cover a dozen years, i.e., to 2015 and to address what could be accomplished in that time frame. In a sense therefore our report is a mid-term report card, noting what is accomplished, what is underway, what remains, and proposing a few mid-course corrections or added ports of call as science reveals nature and new opportunities are noted.

In order to provide a framework for evaluating progress toward the Performance Measures, the 2003 Subcommittee identified a series of Milestones (forty one in all) that are representative of broader efforts in the whole of Nuclear Physics. These Milestones each connect to one or more of the focus areas identified in the Performance Measures. It was anticipated in 2003 that seven of the forty one Milestones would have been completed by the start of 2008, and that substantial progress would have been made on the other thirty four. These Milestones permit connection to specific research projects, which can be expected to lead to published research results in the peer-reviewed literature and/or to completed specific projects.

Our evaluation of progress began with a detailed evaluation of the status of these Milestones (see Appendices 5-9). In cases where the Milestone date has passed, we asked if the results had been obtained on the timescale (and with the information content) anticipated. For Milestones due in the future, we evaluated actual progress against the anticipated progress that should have been made toward the Milestones. We also asked, in particular, if adequate progress has been made developing the tools, techniques, data, and/or calculations needed for the next steps. New Milestones and revised Milestones are proposed, in particular to capture new directions indicated by recent results and new opportunities for the field noted in the 2007 Long Range Plan.

In evaluating the individual Milestones, we used a grading system directly analogous to the one used for the Performance Measures. For Milestones whose due date had already passed, the grading scale was as follows:

Table 2: Milestone Grading Scale

Exceeded: the Milestone was fully achieved, either earlier than anticipated or with additional, related research on the topic

completed, and the issues are regarded as definitively settled.
Achieved: the Milestone was completed as anticipated.
Not Fully Achieved: the Milestone was not completed on the timescale planned, but significant progress was made. (Note: if the scientific results themselves rule out achieving a Milestone – e.g. new examples of X were not found because Nature does not have any, then we consider the Milestone as 'achieved', assuming the experiments/calculations were done.)
Unlikely: the Milestone was not completed on the timescale planned and is not likely to be achieved soon without substantially increased effort.

For Milestones that are not yet formally due, our evaluation focused on progress toward the Milestones. The grading scale used was:

Table 3: Milestone Grading Scale for Milestones not yet Due

Expect to Exceed: On track to achieve Milestone fully, either earlier than anticipated or with additional, related research on the topic completed, or with progress (and/or incremental studies planned that can be completed in time) such that we are confident that the issues will be regarded as definitively settled.
Expect to Achieve: On track to achieve Milestone as anticipated.
Expect to Not Achieve Fully: Achieving the Milestone on the timescale planned is at risk without an increased effort (Note: if the scientific results themselves rule out achieving a Milestone – e.g. new examples of X were not found because Nature does not have any, then we consider the Milestone as 'achieved', assuming the experiments/calculations were done.)
Unlikely: Achieving the Milestone on the timescale planned is not likely without substantially increased effort.

We note here that while no Milestone was rated Unlikely, some were rated Not Fully Achieved/Expect to Not Achieve Fully due to the actual rate of funding, arising in turn from limitations imposed from outside Nuclear Physics and indeed outside the Department of Energy and NSF.

Our evaluation of each of these Milestones was then mapped, or sorted onto the specific topics in the Performance Measures, both to evaluate the status of each Performance Measure as of today and to evaluate its expected status in 2015. Some of the Milestones map on to more than one Performance Measure. Our evaluations were shared with knowledgeable members of the community active in the relevant sub-field, both to provide a peer review of our process and to solicit the thoughts of the larger community on both the overall health of the sub-field and on possible revisions and additions to the Milestones relevant for future activities.

A rough measure of the health and activity in each of the subfields represented by the Performance Measures can be obtained by averaging over the relevant Milestones and equating the grading scales for the Milestones and the Performance Measures in the order listed. A more thoughtful evaluation of each subfield, which included a review of progress in areas not explicitly identified in the (representative) Milestones, was also carried out; it yielded overall evaluations consistent with the averages over the Milestones.

In the next section, we present our evaluation of the Performance Measures for the four main areas of activity in Nuclear physics, as set down in the 2003 report. We identify the mapping of the Milestones to Performance Measures, and provide an evaluation of progress to date and prospects for further progress.

The status of the Milestones and our proposed revisions and additions, which take note of progress in the subfields, important developments, and new directions identified by the 2007 NSAC Long Range Plan, are then discussed. It is important to note that these new Milestones reflect the assumptions made in the 2007 Long Range Plan about targeted increases in funding. They also serve to reflect the health and dynamic aspects of the field; several new specific opportunities have presented themselves in the last five years. The new Milestones vary in due dates between 2015 and 2020.

In Section 7 we present an updated version of two of the four Performance Measures, those for High Temperature, High Density Hadronic Matter and those for Neutrinos, Neutrino Astrophysics and Fundamental Interactions. We found that in two of the sub-fields the present Performance Measures are still appropriate as summaries of their goals, and that new directions for the research effort are adequately captured within updated sets of Milestones. However, the level of change in the other two sub-fields is such that an updated overall Performance Measure is appropriate as well. The revised set of Performance Measures would be expected to be achieved after the current ones, with a reasonable due date being 2020.

6. Evaluation of the Performance Measures for Nuclear Physics

In this section we identify the mapping of the Milestones to Performance measures, provide an evaluation of progress to date and prospects for the future, and offer summary comments. (For compactness in quoting ratings assigned, we refer e.g. to both "Achieved" for past Milestones and "Expect to Achieve" for future ones as "Achieved".)

6.A Hadronic Physics

The Performance Measure for Hadronic Physics is stated in Section 4.A. The summary ratings for the associated Milestones are given here.

Table 4: Milestone Progress in Hadronic Physics

Year	Milestone	Complete?	Status Assessment
2008 HP1	Make measurements of spin carried by the glue in the proton with polarized proton-proton collisions at center of mass energy, $\sqrt{s}$ = 200 GeV.	Yes	Achieved
2008 HP2	Extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 - 0.4 , and squared momentum change, –t, less than 0.5 GeV^2 in measurements of deeply virtual Compton scattering.	No	Not Fully Achieved
2009 HP3	Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.	No	Expect to Not Achieve Fully
2010 HP4	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .	No	Expect to Exceed
2010 HP5	Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the $^4He(\vec{e}, e\vec{p})$ reaction.	No	Expect to Achieve
2011 HP6	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$ for x=0.2-0.6, and $1 < Q^2 <$ 5 GeV^2 for both protons and neutrons.	No	Expect to Exceed
2012 HP7	Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range Q^2 = 0.1 – 7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.	No	Expect to Achieve
2013 HP8	Measure flavor-identified q and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.	No	Expect to Achieve

2014 HP9	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.	No	Expect to Exceed
2014 HP10	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.	No	Expect to Achieve

To evaluate progress toward this Performance Measure we began by mapping the four goals given in the Performance Measures' definition of Excellent performance in this area to the individual Milestones in Hadronic Physics as follows:

1. Quark flavor dependence of the nucleon form factors and structure functions measured; see Milestones HP2, HP4, HP8, HP9. No Milestone is yet past, nor is any yet complete. HP4 and HP9 were both rated as 'exceeding' the Milestone goals, with HP8 rated as 'achieved'.
2. Hadron states described with QCD over wide ranges of distance and energy; see Milestones HP5, HP6, HP7, HP10. No Milestone is yet past nor is any yet complete. HP6 was rated as 'exceeding' with the other three rated 'achieved'.
3. The nucleon-nucleon interaction mechanisms determined from QCD; see Milestones HP3, HP7, HP9, HP10. No Milestone is yet past nor is any yet complete. HP9 was rated 'exceeding' and HP7 and HP10 were rated as 'achieved'.
4. Precise measurements of quark and gluon contributions to nucleon spin performed; see Milestones HP1, HP8. No Milestone is yet past; HP1 is complete. Both Milestones were rated as 'achieved'.

We note that there have been no roadblocks uncovered to completing the work in any area, no focus areas that have been neglected, and no efforts that failed to produce scientific results. There have been some setbacks arising from budgets below what was anticipated in 2003 (notably in FY2006), and there have been some schedule delays due to external factors, such as Hurricane Isabel, which required rescheduling some planned experiments relevant to HP2, 5, and 6. In the two cases where ratings of 'not fully achieved' were given, only a delay in schedule for completion is foreseen; the anticipated scientific results should still be obtained, and indeed substantial progress has been made, with the required experiments either taking data or anticipating doing so in the immediate future, and the relevant theoretical efforts fully underway and publishing key results.

We determine that the progress towards accomplishing the goals in the Performance Measure for Hadronic Physics is Good, meaning that if support of activities underway can be maintained at FY07 levels or better, these activities could reach their planned conclusions to the Good level by 2015. However, the timescale will be a challenge, and the sub-field is not likely to accomplish the goals under the Performance Measure to the Excellent level. This rating is supported by a calculation of the average for the evaluations of the Milestones, which is somewhat better than

Achieved, reflecting Good progress on a broad range of activities in Hadronic Physics. This summary was also found to be consistent with our overall evaluation of the progress in hadronic physics when other major efforts that are not specifically attached to Milestones are included. The details of the Milestone evaluation are presented in the section below.

The Good rating must be understood in the context of the actual funding levels over the period being evaluated (2003-2007). If expectations for progress are recalibrated to what would have been reasonable with the actual level of funding received (rather than the constant effort budget that was the basis for the expectations), then the timescale for the Performance Measures and Milestones would have been stretched, and the progress achieved would have been evaluated as Excellent, rather than Good. Sustained funding and effort at recent (FY07) levels should allow the rating of Good progress to be preserved through 2015. Future surprises may lead to a re-evaluation, but none are yet apparent. We stress that sustained funding is key to being able to pursue the range of activities yet to be accomplished in the specific Milestone areas. If funding can be increased to the growth path of the ACI and America COMPETES act (the scenario that provided the planning basis for the 2007 NSAC Long Range Plan), then one could expect to achieve a rating of Excellent for this Performance Measure, including new Milestones proposed specifically for early experiments from the JLab 12 GeV Upgrade, by 2020. We remain concerned that continued stringencies in funding will in particular lead to reduced operation of experimental and computational facilities, making the achievement of Good performance by 2015 difficult and the achievement of Excellent performance by 2020 improbable: it simply would not be possible to do the work in time if the funding patterns of the past 5 years are continued. The potential for loss to the field from missed scientific opportunities is significant.

6.B High Temperature and High Density Hadronic Matter

The Performance Measure for Physics of High Temperature and High Density Hadronic Matter is stated in Section 4.B. The summary ratings for the associated Milestones are given here.

Table 5: Milestone Progress in High Temperature/High Density Hadronic Matter

Year	Milestone	Complete?	Status Assessment
2005 DM1	Measure J/Ψ production in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV.	Yes	Achieved
2005 DM2	Measure flow and spectra of multiply-strange baryons in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV.	Yes	Exceeded
2007 DM3	Measure high transverse momentum jet systematics vs. $\sqrt{s_{NN}}$ up to 200 GeV and vs. system size up to Au + Au.	Yes	Exceeded

2009 DM4	Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC.	No	Expect to Achieve
2010 DM5	Measure the energy and system size dependence of J/Ψ production over the range of ions and energies available at RHIC.	No	Expect to Achieve
2010 DM6	Measure e^+e^- production in the mass range $500 \leq m_{e+e-} \leq 1000$ MeV/c^2 in $\sqrt{s_{NN}} = 200$ GeV collisions.	No	Expect to Achieve
2010 DM7	Complete realistic calculations of jet production in a high density medium for comparison with experiment.	No	Expect to Achieve
2012 DM8	Determine gluon densities at low x in cold nuclei via p + Au or d + Au collisions.	No	Expect to Achieve

To evaluate progress toward this Performance Measure we began by mapping the goals given in the Performance Measures' definition of Excellent performance in this area to the individual Milestones in Physics of High Temperature and High Density Hadronic Matter as follows:

1. The existence of a deconfined, thermalized medium is determined; see Milestones DM1, DM2, DM4, DM5. Two Milestones are past; both are complete. DM2 was rated as 'exceeding' the Milestone goals, with DM1, DM4 and DM5 rated as 'achieved'.
2. Its properties such as temperature history, equation of state, energy and color transport (via jets), and screening (via heavy quark production) are characterized; see Milestones DM3, DM6, DM7, DM8. We note the four proposed new Milestones, DM10, DM11, DM12 and DM13, also bear on this aspect of the evaluation. Results from these areas would have to be considered in a future evaluation of progress. One Milestone is past and is complete. DM3 was rated as 'exceeding' with the other three rated 'achieved'.

We note that there have been no roadblocks uncovered to completing the work in any area, no focus areas that have been neglected, and there were no efforts that failed to produce scientific results. Indeed, there have been significant scientific discoveries, notably that the system produced is strongly and not weakly coupled as had been assumed for many years. This does not invalidate scientifically any existing Performance Measure, but does present new opportunities captured in the proposed new Milestones for this area. It may well pose a challenge to demonstrating the Performance Measure on deconfinement, but this is the sort of challenge that inspires scientists to new understanding.

We determine that the current progress towards accomplishing the goals in the Performance Measure for Physics of High Temperature and High Density Hadronic Matter is Excellent, with significant additional, related research on the topic completed. Indeed, as noted in the Milestone evaluations in Appendix 3, results extending the effort laid out in Milestones DM2 and DM3 have already been reported, and the theoretical effort for DM4 has led to the conclusion that a true surprise has been found, a new type of strongly-coupled matter with a ratio of viscosity to entropy density lower than any heretofore known. Attempts to understand this property have led to completely unanticipated connections to theories of quantum gravity and to a postulated fundamental quantum limit on the ratio of viscosity to entropy density. This unforeseen development implies that "viscosity" should be added as a particularly important property to be quantified. In the following we propose both a specific new Milestone as well as an extension of the "Excellent" Performance Measure for this subfield.

We remark that progress in this field has benefitted from operation of RHIC, the first ever heavy-ion collider, which has the advantage of exploring a completely new area with the attendant possibility of unexpected new behavior. Unanticipated behavior has indeed been found, despite the less than optimal facility utilization allowed by funding levels below those anticipated in the 2002 Long Range Plan.

The rating of Excellent is supported by a calculation of the average for the evaluations of the Milestones, which is midway between Achieved and Exceeded, reflecting progress between Good and Excellent on a broad range of activity in Physics of High Temperature and High Density Hadronic Matter. This summary was found to be consistent with our overall evaluation of the progress in high temperature and high density hadronic matter physics when other major efforts that are not specifically attached to Milestones are also included. The details of the Milestone evaluation are presented in the Appendix below.

The field is now in its eighth year meaning base questions are mature and more detailed ones are needed; this is reflected in the proposed new Milestones. However, despite these accomplishments, recent funding has meant markedly reduced RHIC running time in the past three years. The result is that data needed to achieve upcoming Milestones are only partly in hand and that only preliminary studies have been carried out preparatory to taking data needed for DM5. The experiments for DM6 will only be done next year, leaving little time for analysis. New investments for detection capability for DM8 are only now being made. The result is that several near-term deadlines are in jeopardy, and near-term progress towards the Performance Measures may only be possible at the Good level. Future surprises may lead to a re-evaluation, but none are yet apparent. We stress that sustained funding is key to being able to pursue the range of activities yet to be accomplished in the specific Milestone areas.

6.C Nuclear Structure and Astrophysics

The Performance Measure for Nuclear Structure and Astrophysics is stated in Section 4.C. The summary ratings for the two sets of associated Milestones are given here.

Table 6: Milestone Progress in Nuclear Structure

Year	Milestone	Complete?	Status Assessment
2006 NS1	Measure changes in shell structure and collective modes as a function of neutron and proton number from the proton drip line to moderately neutron-rich nuclei.	Yes	Exceeded
2007 NS2	Measure properties of the heaviest elements above Z=100 to constrain and improve theoretical predictions for superheavy elements	Yes	Achieved
2009 NS3	Extend spectroscopic information to regions of crucial doubly magic nuclei such as Ni-78	No	Expect to Exceed
2009 NS4	Extend the determination of the neutron drip line up to Z of 11.	No	Expect to Achieve
2010 NS5	Complete initial measurements with the high resolving power tracking array, GRETINA, for sensitive studies of structural evolution and collective modes in nuclei (Modified due date proposed)	No	Expect to Not Achieve Fully
2013 NS6	Carry out microscopic calculations of medium mass nuclei with realistic interactions, develop a realistic nuclear energy density functional for heavy nuclei, and explore the description of many-body symmetries and collective modes, and their relationship to effective forces	No	Expect to Exceed

Table 7: Milestone Progress in Nuclear Astrophysics

Year	Milestone	Complete?	Status Assessment

2007 NA1	Measure transfer reactions on r-process nuclei near the N=50 and N=82 closed shells	Yes	Achieved
2009 NA2	Measure properties of and reactions on selected proton-rich nuclei in the rp-process to determine radionuclide production in novae and the light output and neutron star crust composition synthesized in X-ray bursts	Yes	Exceeded
2009 NA3	Perform three-dimensional studies of flame propagation in white dwarfs during Type Ia supernova	No	Expect to Exceed
2010 NA4	Reduce uncertainties of the most crucial stellar evolution nuclear reactions (e.g. $^{12}C(\alpha,\gamma)^{16}O$) by a factor of two, and others (e.g. the MgAl cycle) to limits imposed by accelerators and detectors	No	Expect to Achieve
2011 NA5	Measure neutron capture reactions, including radioactive s-process branch-point nuclei, to constrain s-process isotopic abundances	No	Expect to Achieve
2012 NA6	Measure masses, lifetimes, spectroscopic strengths, and decay properties of selected neutron-rich nuclei in the supernova r-process, and reactions to predict radionuclide production in supernovae	No	Expect to Exceed
2013 NA7	Perform realistic multidimensional simulations of core collapse supernovae	No	Expect to Achieve
2013 NA8	Perform simulations of neutron star structure and evolution using benchmark microphysical calculations of the composition, equation of state, and bulk properties of dense matter	No	Expect to Achieve

To evaluate progress toward this Performance Measure we began by mapping the four goals given in the Performance Measures' definition of Excellent performance in this area to the individual Milestones in Nuclear Structure and Astrophysics as follows:

1. Extensive measurements on stable and exotic nuclei and the drip lines are performed; see Milestones NS1, NS2, NS3, NS4, NS5, NA1, NA2, NA5 and NA6. Four Milestones are past and all of these are complete. NS1, NS3, NA2 and NA6 were rated as 'exceeding' the Milestone goals, with NS2, NS4, NA1, and NA5 rated as 'achieved'. NS5 was rated as 'not fully achieved'.
2. Their structure is established and the isospin dependence of effective interactions studied; see Milestones NS1, NS3, NS5, NS6, NA1 and NA6. Two Milestones are past and both are complete. NS1, NS3, NS6, and NA6 were rated as 'exceeding' with NA1 rated as 'achieved'.
3. New nuclei with neutron skins are observed and studied - Milestone NS4. This Milestone is not yet past and is not complete. Substantial progress towards realizing the Milestone has been made and NS4 was rated as 'achieved'.
4. Reactions for several astrophysical processes, including some r-process nuclei, are measured; see Milestones NS3, NA1, NA2, NA4, NA5 and NA6. Two Milestones are past and both are complete. NS3, NA2, and NA6 were rated as 'exceeded', and the others were rated as 'achieved'.

There are three other Milestones listed in the original set, all under Nuclear Astrophysics, NA3, NA7 and NA8, which do not map simply to the four Performance Measures under Nuclear Structure and Astrophysics. These all deal with application of our knowledge of nuclear physics to describe the physics of exploding stars, specifically Type 1a supernovae (NA3, rated Expect to Exceed) and Type II core collapse supernovae (NA7, rated Expect to Achieve) , and the structure of neutron stars (NA8, rated Expect to Achieve). Work on these Milestones makes extensive use also of large-scale computing facilities provided elsewhere in the Department of Energy. Although not directly tied to specific Performance Measures here, we find them useful indicators of the overall health and progress of the field as well as indicators of the links between nuclear physics and astrophysics on the one hand and large-scale computing on the other.

We note that there have been no roadblocks uncovered to prevent completion of the work in any area, although experiments to meet the Milestone on determining the neutron drip line up to Z=11 (NS4) have shown that the drip line is farther from stability than previously anticipated, and the computational complexity of modeling supernovae in three dimensions may require additional time (NA7). There have been additional, unexpected setbacks arising from funding levels below what was anticipated in 2003, with the principal impact on the Milestones being for NS5. Indeed, the timeline associated with the funding profile for the relevant new hardware device, GRETINA, extends beyond what was anticipated in 2003 and the original completion date of 2010 is out of reach. In total, no focus areas have been neglected, and there were no efforts that failed to produce scientific results. Further progress on the Milestones and achievement of the performance measures will benefit from new and upgraded accelerator facilities, both inside and outside of the US that will provide access to key new rare isotopes. These new rare isotope capabilities in the US are the HRIBF high power target upgrade, the CARIBU project at ATLAS, and the reacceleration project at the NSCL. With these new capabilities and the progress achieved so far, we do not at this time advocate any change in this Performance Measure.

We determine that the current progress towards accomplishing the goals in the Performance Measure for Nuclear Structure and Astrophysics is Good or somewhat better. The rating of Good is supported by a calculation of the average for the evaluations of the Milestones, which is somewhat better than Achieved, reflecting Good progress on a broad range of activities in Nuclear Structure and Astrophysics. As was the case for the other subfields above, progress was hampered by funding lower that envisioned at the time the original Milestones and Performance Measures were written. This rating of Good was found to be consistent with our overall evaluation of the progress in Nuclear Structure and Astrophysics when other major efforts that are not specifically attached to Milestones are also included. The details of the Milestone evaluation are presented in the section below.

We note that sustained Good or better progress in this area does require access to new beams and improved beam intensities, because much of the pressing new subject matter involves studies of nuclei located well away from the valley of stability and requires progressing to the limits of particle stability. This is particularly the case for Milestone NA7 on the stellar r-process. The 'exhaustive studies' noted in the first Performance Measure in particular require examining a large range of different nuclei in order that patterns may be established to contrast with and challenge prevailing theoretical predictions. This in turn requires extensive experimentation at several different accelerator facilities and the sustained support for operations and new beam development this implies. Sustained funding and effort at present levels should allow the rating of Good progress to be preserved when a final evaluation in the target year of 2015 is performed, with an Excellent rating remaining a strong possibility. Future surprises may lead to a re-evaluation, but none are yet apparent. We stress that sustained adequate funding is key to being able to pursue the full range of activities yet to be accomplished in the specific Milestone areas.

6.D Neutrinos, Neutrino Astrophysics and Fundamental Interactions

The Performance Measure for Neutrinos, Neutrino Astrophysics and Fundamental Interactions is stated in Section 4.D. The summary ratings for the associated Milestones are given here.

Table 8: Milestone Progress in Neutrinos, Neutrino Astrophysics and Fundamental Interactions

Year	Milestone	Complete?	Status Assessment
2007 FI1	Measure solar boron-8 neutrinos with neutral current detectors	Yes	Exceeded
2008 FI2	Collect first data in an experiment which has the potential to observe beryllium-7 solar neutrinos	Yes	Exceeded

2008 FI3	Initiate an experimental program at the SNS fundamental physics beam line	No	Expect to Achieve
2010 FI4	Make factor of 5 improvements in measurements of neutron and nuclear beta-decay to constrain physics beyond the standard model	No	Expect to Not Achieve Fully
2010 FI5	Make factor of 5 improvement in theoretical uncertainties for testing the Standard Model via low energy electroweak observables	No	Expect to Exceed
2011 FI6	Improve the sensitivity of the direct neutrino mass measurements to 0.35 eV	No	Expect to Achieve
2012 FI7	Extend the sensitivity of searches for neutrinoless double-beta decay in selected nuclei by a factor of ten in lifetime	No	Expect to Not Achieve Fully
2012 FI8	Perform independent measurements of parity violation in few-body systems to constrain the non-leptonic weak interaction	No	Expect to Achieve
2012 FI9	Obtain results from new high-sensitivity searches for atomic electric dipole moments	No	Expect to Achieve

To evaluate progress toward this Performance Measure we began by mapping the three goals given in the Performance Measures' definition of Excellent performance in this area to the individual Milestones in Neutrinos, Neutrino Astrophysics and Fundamental Interactions. The fourth goal is the third from the Performance Measures' definition of Good and is qualitatively different from those listed under Excellent, thus is included specifically in what follows:

1. Double beta-decay lifetime limits are extended 10-fold or more; see Milestone FI7. This Milestone is not yet past, nor is it complete. FI7 was rated 'Not Fully Achieved'. An experiment is in preparation and R&D has started, but the improved precision by the stated deadline is not likely.
2. R&D completed demonstrating if precision pp solar experiment is possible; Milestones FI1 and FI2 bear on the Measure, but not directly. R&D efforts are started for a variety of approaches as noted below, but the effort as yet lacks continuing support and an explicit plan.

3. Played key roles in low-energy neutrino experiments and beta-decay probing cosmologically interesting neutrino masses; see Milestone FI1, FI2 and FI6, with aspects of FI5. Two of these Milestones are past and both are complete. FI1,FI2 and FI5 were rated ‘exceeding’ and FI6 was rated as ‘ achieved’.
4. Parameters for quark mixing for nuclear beta-decay quantified; see Milestones FI3, FI4, FI5, and FI8. No Milestone is yet past, nor is any yet complete. FI5 was rated as ‘exceeded’, and FI3 and FI8 were rated as 'achieved'.

There have been some slower starts arising from budgets below what was anticipated in 2003, with the principal effect on Milestones being for FI7, since the requirements for a successful program in double-beta-decay are more demanding than what was anticipated in 2003. This required careful consideration by a joint HEPAP-NSAC sub-committee, the Neutrino Science Assessment Group (NuSAG), to determine the appropriate technical direction and investment goal for a program that could actually address the Performance Measure. In the case of the Performance Measure on R&D for a precision solar pp experiment, to date only institutional R&D efforts have been pursued on a variety of techniques, both for experiments based on neutral-current and charged-current neutrino interaction approaches. A formal program in this area was recommended by the APS Multi-Divisional Study on Neutrino Physics. Actual funding levels for this area of Nuclear Physics have meant that to date, however, only R&D efforts using institutional funds could be pursued. The results of these initial R&D programs are promising, with the elapsed time required to reach the current state of the art suggesting that a focused program could indeed be carried out by the overall deadline of 2015 for the Performance Measure. Thus, we do not at this time advocate any change in this Performance Measure.

We determine that the current progress towards accomplishing the goals in the Performance Measure for Neutrinos, Neutrino Astrophysics and Fundamental Interactions is Good. This rating is supported by a calculation of the average for the evaluations of the Milestones, which is somewhat better than Achieved, reflecting Good progress on a broad range of activities in Neutrinos, Neutrino Astrophysics and Fundamental Interactions. This summary was found to be consistent with our overall evaluation of the progress in the fields of Neutrinos, Neutrino Astrophysics and Fundamental Interactions when other major efforts that are not specifically attached to Milestones are also included. The details of the Milestone evaluation are presented in the section below.

In contrast to the situation for the three other major subfields, progress here towards the Performance Measures has been uneven, with significantly more progress on the third and fourth Performance Measures compared to that on the first two. A new apparatus to enable efforts in the fourth area will come online soon, and initial construction in support of the first has begun. This area of Nuclear Physics depends on purpose-built experiments more so than other areas, with a potential large payoff on focused questions. Much of the physics depends on weak interactions with their associated quite small probabilities and attendant need for large-volume detectors and/or very long experiment durations. This means that the pace of capital investment more directly affects whether a given area can make progress. In this area targeted new support, as described in the 2007 Long Range Plan, will enable Good (or better) progress in the future on the first two Performance Measures. In the absence of focused new investment, real scientific opportunities with important discovery potential may be missed.

The first Performance Measure, on double-beta-decay, will be very challenging to meet in time, and the second, on R&D for a precision pp solar experiment, still requires a definite plan for its execution. An increased level of funding beyond immediate past levels should allow the progress rating of Good progress to be preserved when a final evaluation in the target year of 2015 is performed. Future surprises may lead to a re-evaluation, but none are yet apparent.

7. New Performance Measures

In the areas of Performance Measures for Hadronic Physics and for Nuclear Structure and Astrophysics, we find that the current Performance Measures still serve to capture the present and near future focus of these efforts.

For High Temperature and High Density Hadronic Matter a new research direction stems from the discovery that a strongly-coupled fluid with a remarkably low ratio of viscosity to entropy density is formed in relativistic heavy-ion collisions at RHIC. Understanding this has led to conjectured links to theories of gravity, a remarkable deduction if proven. The new scope of the needed experimental and theoretical work can be captured by one added Performance Measure, which addresses the low shear viscosity of this fluid. The revised set of Performance Measures for High Temperature, High Density Hadronic Matter is:

Table 9: Revised Performance Measures for High Temperature, High Density Hadronic Matter

Create brief, tiny samples of hot, dense nuclear matter to search for the quark-gluon plasma and characterize its properties • Timeframe – By 2015 • Expert Review every five years rates progress as “Excellent”, “Good”, Fair” or “Poor” • Excellent - 1) The existence of a deconfined, thermalized medium is determined; 2) its properties such as temperature history, equation of state, energy and color transport (via jets), and screening (via heavy quarkonium production) are characterized; 3) viscosity of this medium is determined. • Good – 1) The existence of hot, high-density matter is established; 2) some of its properties (e.g., its initial temperature via the photon spectrum) are measured; 3) confinement properties, and energy transport (via jets) are explored and limits are placed on viscosity of the medium. • Fair – Supported research leads to modest outputs in only two of the three goals described in the “Good” rating. • Poor - Supported research leads to modest outputs in only one of the three goals described in the “Good” rating.

We note that the revised Measure, together with several new Milestones in this area proposed below, requires an intense source of high energy heavy-ion collisions at a luminosity as much as an order of magnitude greater than presently available at RHIC, as will be provided by the RHIC luminosity upgrade discussed in the 2007 Long Range Plan. We note here recent developments in stochastic cooling of bunched beams at RHIC make it highly likely the overall timescale for the RHIC luminosity upgrade will be substantially shortened from that foreseen in the 2007 Long Range Plan, in time to meet the 2015 timeframe for the Performance Measure above.

For Neutrinos, Neutrino Astrophysics and Fundamental Interactions major new opportunities have developed since the last report on Performance Measures to NSAC. We propose to return the setting of improved limits on the neutron EDM to the Performance Measure set now that a definite plan for that effort is established (thus addressing a specific concern of the previous report). We further propose two new Performance Measures in this area to capture the effort on precision electroweak measurements by the field. These will now capture the scope of this subfield. The revised set of Performance Measures is given here.

Table 10: Revised Performance Measures for Neutrinos, Neutrino Astrophysics and Fundamental Interactions

- Measure fundamental properties of neutrinos and fundamental symmetries by using neutrinos from the sun and nuclear reactors and by using radioactive decay measurements
- Timeframe – By 2015
- Expert Review every five years rates progress as "Excellent", "Good", "Fair", or "Poor"
- Excellent – 1) Double beta-decay lifetime limits are extended 10-fold or more; 2) R&D completed demonstrating if a direct, precision measurement of the rate of solar p-p fusion is possible; 3) played key roles in low-energy neutrino experiments and beta-decay probing cosmologically interesting neutrino masses; 4) precision experiments probing electroweak model parameters are completed, for example in beta-decay correlations of the neutron, parity-violating electron scattering, and g-factor measurements of elementary particles; 5) limits improved a factor of ten for the electric dipole moment of the neutron.
- Good – 1) Double beta-decay lifetime limits extended; 2) participated in low-energy neutrino experiments and beta-decay probing cosmologically relevant neutrino masses; 3) parameters for quark mixing for nuclear beta-decay quantified and the limit on neutron electric dipole moment improved.
- Fair – Supported research leads to modest outputs in only two of the three goals described in the "Good" rating.
- Poor – Supported research leads to modest outputs in only one of the three goals described in the "Good" rating.

8. Closing Remarks

The Performance Measures progress evaluations and associated Milestone status assessments reported here show that the field of Nuclear Physics has sustained considerable progress over the past 5 years since the original Performance Measures and Milestones were set down. In addition numerous new opportunities have been identified. Pursuit of these new opportunities together with those addressed by the Milestones still in progress and with related research opportunities will ensure a healthy and dynamic field that exhibits continued good progress. We caution that this generally positive outlook must be tempered by concern about funding outlook. In a sense this is positive – many good ideas are competing for available funds. Yet sustained good or excellent progress requires sustained program support to perform the needed research. The program roadmap laid out in the 2007 Long Range Plan shows the potential for further broad advances on scientific questions.

The revised Performance Measures and the updated table of Milestones should be reviewed again at an appropriate interval, about five years hence. This future evaluation will be in a different situation. This was the first evaluation against the initially formulated set of Performance Measures and Milestones, with the timescale for the reseach to be carried out and evaluated being twelve years. The next review will be evaluating progress against a set of Performance Measures whose due date will be only a few years away. It would seem appropriate to establish at that time a new set of Performance Measures, building on the current set, to encapsulate what will undoubtedly be a new set of program goals that reflect progress to date and new opportunities yet to be defined. We would expect this next review to propose modified Performance Measures and associated Milestones. Their execution will then depend on facilities that will be by the time of this next review being readied for operation, but are at the present time in early project stages. The FRIB recommended in the 2007 Long Range Plan with completion late in the next decade, and the 12 GeV CEBAF Upgrade Project at Jefferson Lab (now approaching CD-3) are examples. These several steps will ensure that the Performance Measures remain fresh and continue to set demanding goals.

To anticipate this situation we have proposed here several new Milestones, with due dates out to 2020. They capture current concrete plans and anticipate in part the expected change in focus of those future Performance Measures. We would expect the next evaluation also to reflect progress towards the plan set forth in the 2007 Long Range Plan, which is the most recent in a series which have served Nuclear Physics well these past 30 years.

Appendix 1: Subcommittee Charge

(see third paragraph from the end of the following letter)

July 17, 2006

Professor Robert E. Tribble
Chair, DOE/NSF Nuclear Science Advisory Committee
Cyclotron Institute
Texas A&M University
College Station, TX 77843

Dear Professor Tribble:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a new study of the opportunities and priorities for United States nuclear physics research and recommend a long range plan that will provide a framework for coordinated advancement of the Nation's nuclear science research programs over the next decade.

The new NSAC Long Range Plan (LRP) should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP and the impacts of these accomplishments both within and outside of the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. program to pursue over the next decade and articulate their scientific impact. A national coordinated strategy for the use of existing and planned capabilities, both domestic and international, and the rationale for new investments should be articulated. To be most helpful, the plan should indicate what resources and funding levels would be required (including construction of new facilities) to maintain a world-leadership position in nuclear physics research, and what the impacts are and priorities should be, if the funding available provides constant level of effort (FY 2007 President's Budget Request) into the out-years (FY 2008-2017).

The recommendations and guidance in the NSAC 2002 LRP and subsequent reports have been utilized by the agencies as important input to their planning and programmatic decisions. Resources have been made available to the programs' major facilities and experiments that have allowed the U.S. program to be successful in delivering significant discoveries and advancements in nuclear physics over the last five years. This has occurred in the context of constrained funding that has resulted in a reduction in the number of DOE National User Facilities and limited the ability to pursue identified scientific opportunities. However, projected funding levels in the out-years would allow the agencies to begin to address the major project recommendations in the NSAC 2002 LRP. The projected funding for DOE is compatible with implementing the 12 GeV Upgrade of the Continuous Electron Beam Accelerator Facility, (CEBAF), and starting construction of a rare isotope beam facility that is less costly than the proposed Rare Isotope Accelerator (RIA) facility early in the next decade. At NSF the process has been put in place for developing a deep underground laboratory project and bringing this project forward for a funding decision.

Since the submission of the NSAC 2002 LRP, increased emphasis has been placed within the federal government on international and interagency coordination of efforts in the fundamental sciences. The extent, benefits, impacts and opportunities of international coordination and collaborations afforded by current and planned major facilities and experiments in the U.S. and other countries, and of interagency coordination and collaboration in cross-cutting scientific opportunities identified in studies involving different scientific disciplines should be specifically addressed and articulated in the report. The scientific impacts of synergies with neighboring research disciplines and further opportunities for mutually beneficial interactions with outside disciplines, such as astrophysics, should be discussed.

An important dimension of your plan should be the role of nuclear physics in advancing the broad interests of society and ensuring the Nation's competitiveness in the physical sciences and technology. Education of young scientists is central to the mission of both agencies and integral to any vision of the future of the field. We ask NSAC to discuss the contribution of education in nuclear science to academia, medicine, security, industry, and government, and strategies to strengthen and improve the education process and to build a more diverse research community. Basic research plays a very important role in the economic competitiveness and security of our Nation. We ask that NSAC identify areas where nuclear physics is playing a role in meeting society's needs and how the program might enhance its contributions in maintaining the Nation's competitiveness in science and technology.

Activities across the federal government are being evaluated against established performance goals. In FY 2003, utilizing input from NSAC, the long-term goals for the DOE SC Nuclear Physics program and the metrics for evaluations of the program activities were established. It is timely during this long range planning exercise to gauge the progress towards these goals, and to recommend revised long-term goals and metrics for the DOE SC Nuclear Physics program, in the context of the new LRP, if appropriate. The findings and recommendations of this evaluation should be a separate report.

In the development of previous LRP's, the Division of Nuclear Physics of the American Physical Society (DNP/APS) was instrumental in obtaining broad community input by organizing town meetings of different nuclear physics sub-disciplines. The Division of Nuclear Chemistry and Technology of the American Chemical Society (DNC&T/ACS) was also involved. We encourage NSAC to exploit this method of obtaining widespread input again, and to further engage both the DNP/APS and DNC&T/ACS in laying out the broader issues of contributions of nuclear science research to society.

Please submit an interim report containing the essential components of NSAC's recommendations to the DOE and the NSF by October 2007, and the final report by the end of calendar year 2007. The agencies very much appreciate NSAC's willingness to undertake this task. NSAC's previous long range plans have played a critical role in shaping the Nation's nuclear science research effort. Based on NSAC's laudable efforts in the past, we look forward to a new plan that can be used to chart a vital and forefront scientific program into the next decade.

Sincerely,

Dennis Kovar
Associate Director of the Office of Science
for Nuclear Physics
Department of Energy

Judith S. Sunley
Acting Assistant Director
Mathematical and Physical Sciences
National Science Foundation

Appendix 2: Subcommittee Membership

Lawrence Cardman, Thomas Jefferson National Accelerator Facility
Robert Janssens, Argonne National Laboratory
Curtis Meyer, Carnegie Mellon University
Hamish Robertson, University of Washington
Brad Sherrill, Michigan State University
Bira van Kolck, University of Arizona
Steve Vigdor, Brookhaven National Laboratory
Glenn Young, Oak Ridge National Laboratory

Appendix 3: Milestone Evaluation Summary

We present here in tabular form our summary assessment of progress towards the Milestones for each of the five subject areas. The areas of Nuclear Structure and Nuclear Astrophysics are kept separate for Milestones but were joined above in the Performance Measure. In evaluating the individual Milestones we used a grading system directly analogous to the one used for the Performance Measures, but focused on progress toward the Milestones, as most are not yet due. It is presented in Section 5 of this report. (Note: these tables were presented earlier in Section 6 of the main report and are repeated here for reference.) This summary is followed in Appendix 4 by a rationale for and list of proposed new Milestones to be added for each of the five areas, immediately followed with the proposed new table of Milestones for that area. These new tables, which include a mix of continuing and proposed new Milestones, would form the Milestones which would be evaluated at the next review.

Hadronic Physics Milestones Evaluation Summary

Our evaluation of the ten Milestones for Hadronic Physics is presented in detail in Appendix 5. The table below summarizes that evaluation.

Table 4: Milestone Progress in Hadronic Physics

Year	Milestone	Complete?	Status Assessment
2008 HP1	Make measurements of spin carried by the glue in the proton with polarized proton-proton collisions at center of mass energy, $\sqrt{s}$ = 200 GeV.	Yes	Achieved
2008 HP2	Extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 - 0.4 , and squared momentum change, –t, less than 0.5 GeV^2 in measurements of deeply virtual Compton scattering.	No	Not Fully Achieved
2009 HP3	Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.	No	Expect to Not Achieve Fully
2010 HP4	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .	No	Expect to Exceed

2010 HP5	Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the $^4He(\vec{e}, e\vec{p})$ reaction.	No	Expect to Achieve
2011 HP6	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$ for x=0.2-0.6, and $1 < Q^2 <$ 5 GeV^2 for both protons and neutrons.	No	Expect to Exceed
2012 HP7	Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range $Q^2 = 0.1 – 7$ GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.	No	Expect to Achieve
2013 HP8	Measure flavor-identified q and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.	No	Expect to Achieve
2014 HP9	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.	No	Expect to Exceed
2014 HP10	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.	No	Expect to Achieve

High Temperature/High Density Hadronic Matter Milestones Evaluation Summary

Our evaluation of the eight Milestones for High Temperature/High Density Hadronic Matter is presented in detail in Appendix 6. The table below summarizes that evaluation.

Table 5: Milestone Progress in High Temperature/High Density Hadronic Matter

Year	Milestone	Complete?	Status Assessment

2005 DM1	Measure J/Ψ production in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV.	Yes	Achieved
2005 DM2	Measure flow and spectra of multiply-strange baryons in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV.	Yes	Exceeded
2007 DM3	Measure high transverse momentum jet systematics vs. $\sqrt{s_{NN}}$ up to 200 GeV and vs. system size up to Au + Au.	Yes	Exceeded
2009 DM4	Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC.	No	Expect to Achieve
2010 DM5	Measure the energy and system size dependence of J/Ψ production over the range of ions and energies available at RHIC.	No	Expect to Achieve
2010 DM6	Measure e^+e^- production in the mass range $500 \leq m_{e+e-} \leq 1000$ MeV/c^2 in $\sqrt{s_{NN}}$ = 200 GeV collisions.	No	Expect to Achieve
2010 DM7	Complete realistic calculations of jet production in a high density medium for comparison with experiment.	No	Expect to Achieve
2012 DM8	Determine gluon densities at low x in cold nuclei via p + Au or d + Au collisions.	No	Expect to Achieve

Nuclear Structure Milestones Evaluation Summary

Our evaluation of the six Milestones for Nuclear Structure is presented in detail in Appendix 7. The table below summarizes that evaluation.

Table 6: Milestone Progress in Nuclear Structure

Year	Milestone	Complete?	Status Assessment

2006 NS1	Measure changes in shell structure and collective modes as a function of neutron and proton number from the proton drip line to moderately neutron-rich nuclei.	Yes	Exceeded
2007 NS2	Measure properties of the heaviest elements above Z=100 to constrain and improve theoretical predictions for superheavy elements	Yes	Achieved
2009 NS3	Extend spectroscopic information to regions of crucial doubly magic nuclei such as Ni-78	No	Expect to Exceed
2009 NS4	Extend the determination of the neutron drip line up to Z of 11.	No	Expect to Achieve
2010 NS5	Complete initial measurements with the high resolving power tracking array, GRETINA, for sensitive studies of structural evolution and collective modes in nuclei (Modified due date proposed)	No	Expect to Not Fully Achieve
2013 NS6	Carry out microscopic calculations of medium mass nuclei with realistic interactions, develop a realistic nuclear energy density functional for heavy nuclei, and explore the description of many-body symmetries and collective modes, and their relationship to effective forces	No	Expect to Exceed

Nuclear Astrophysics Milestones Evaluation Summary

Our evaluation of the eight Milestones for Nuclear Astrophysics is presented in detail in Appendix 8. The table below summarizes that evaluation.

Table 7: Milestone Progress in Nuclear Astrophysics

Year	Milestone	Complete?	Status Assessment
2007 NA1	Measure transfer reactions on r-process nuclei near the N=50 and N=82 closed shells	Yes	Achieved

2009 NA2	Measure properties of and reactions on selected proton-rich nuclei in the rp-process to determine radionuclide production in novae and the light output and neutron star crust composition synthesized in X-ray bursts	Yes	Exceeded
2009 NA3	Perform three-dimensional studies of flame propagation in white dwarfs during Type Ia supernova	No	Expect to Exceed
2010 NA4	Reduce uncertainties of the most crucial stellar evolution nuclear reactions (e.g. $^{12}C(\alpha,\gamma)^{16}O$) by a factor of two, and others (e.g. the MgAl cycle) to limits imposed by accelerators and detectors	No	Expect to Achieve
2011 NA5	Measure neutron capture reactions, including radioactive s-process branch-point nuclei, to constrain s-process isotopic abundances	No	Expect to Achieve
2012 NA6	Measure masses, lifetimes, spectroscopic strengths, and decay properties of selected neutron-rich nuclei in the supernova r-process, and reactions to predict radionuclide production in supernovae	No	Expect to Exceed
2013 NA7	Perform realistic multidimensional simulations of core collapse supernovae	No	Expect to Achieve
2013 NA8	Perform simulations of neutron star structure and evolution using benchmark microphysical calculations of the composition, equation of state, and bulk properties of dense matter	No	Expect to Achieve

Neutrinos, Neutrino Astrophysics and Fundamental Interactions Milestones Evaluation Summary

Our evaluation of the eight Milestones for Neutrinos, Neutrino Astrophysics and Fundamental Interactions is presented in detail in Appendix 9. The table below summarizes that evaluation.

Table 8: Milestone Progress in Neutrinos, Neutrino Astrophysics and Fundamental Interactions

Year	Milestone	Complete?	Status Assessment
2007 FI1	Measure solar boron-8 neutrinos with neutral current detectors	Yes	Exceeded
2008 FI2	Collect first data in an experiment which has the potential to observe beryllium-7 solar neutrinos	Yes	Exceeded
2008 FI3	Initiate an experimental program at the SNS fundamental physics beam line	No	Expect to Achieve
2010 FI4	Make factor of 5 improvements in measurements of neutron and nuclear beta-decay to constrain physics beyond the standard model	No	Expect to Not Fully Achieve
2010 FI5	Make factor of 5 improvement in theoretical uncertainties for testing the Standard Model via low energy electroweak observables	No	Expect to Exceed
2011 FI6	Improve the sensitivity of the direct neutrino mass measurements to 0.35 eV	No	Expect to Achieve
2012 FI7	Extend the sensitivity of searches for neutrinoless double-beta decay in selected nuclei by a factor of ten in lifetime	No	Expect to Not Achieve Fully
2012 FI8	Perform independent measurements of parity violation in few-body systems to constrain the non-leptonic weak interaction	No	Expect to Achieve
2012 FI9	Obtain results from new high-sensitivity searches for atomic electric dipole moments	No	Expect to Achieve

Appendix 4: New, Updated, and Continuing Milestones

New and updated Milestones are needed to reflect progress to date, new discoveries, and the redirection of effort that is necessary as we learn what Nature actually does and adapt our science program to reflect this. They also serve to keep the field "on point". The programmatic direction laid out in the 2007 Long Range Plan makes the case for targeted new investments in all four subfields. New Milestones serve also to capture this, with the proviso that their achievement in many cases depends on the underlying budgetary assumptions.

We give for each of the five subject areas the proposed new table of Milestones. Existing ones that continue are kept with their present number. Revised ones are listed with their new dates and number. Discussion of the revised Milestones depends on the details of the evaluation of the existing Milestone and is given in the corresponding Appendix. Proposed new ones with due dates are given, together with a short explanation after the table stating why they reflect appropriate goals for this subject area.

Table 11: New, Updated and Continuing Milestones for Hadronic Physics

Year	#	Milestone
2009	HP3	Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.
2010	HP4	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .
2010	HP5	Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the $^4He(\vec{e},e\vec{p})$ reaction.
2011	HP6	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$ for x=0.2-0.6, and $1 < Q^2 < 5$ GeV^2 for both protons and neutrons.
2012	HP7	Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range $Q^2 = 0.1$ – 7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.

2012	HP11 (update of HP2)	Measure the helicity-dependent and target-polarization-dependent cross-section differences for Deeply Virtual Compton Scattering (DVCS) off the proton and the neutron in order to extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 – 0.4, and squared momentum transfer, t, less than 0.5 GeV^2.
2013	HP8	Measure flavor-identified q and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
2013	HP12 (update of HP1)	Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.
2014	HP9	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.
2014	HP10	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.
2015	HP13 (new)	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering
2018	HP14 (new)	Extract accurate information on spin-dependent and spin-averaged valence quark distributions to momentum fractions x above 60% of the full nucleon momentum
2018	HP15 (new)	The first results on the search for exotic mesons using photon beams will be completed.

New Milestone HP13 reflects the intense activity and theoretical breakthroughs of recent years in understanding the parton distribution functions accessed in spin asymmetries for hard-scattering reactions involving a transversely polarized proton. This leads to new experimental opportunities to test all our concepts for analyzing hard scattering with perturbative QCD. New Milestone HP14 and HP15 reflect improved opportunities which will become available upon completion of the 12-GeV upgrade at Jefferson Lab. New Milestone HP14 reflects work with upgraded high-resolution spectrometers in the existing complex, while HP15 reflects the first of many new opportunities in the new Hall D with a specially prepared beam of multi-GeV photons, which is a new capability provided by the 12-GeV upgrade.

Table 12: New, Updated and Continuing Milestones for High Temperature/High Density Hadronic Matter

Year	#	Milestone
2009	DM4	Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC.
2010	DM5	Measure the energy and system size dependence of J/Ψ production over the range of ions and energies available at RHIC.
2010	DM6	Measure e^+e^- production in the mass range $500 \leq m_{e+e-} \leq 1000$ MeV/c^2 in $\sqrt{s_{NN}}$ = 200 GeV collisions.
2010	DM7	Complete realistic calculations of jet production in a high density medium for comparison with experiment.
2012	DM8	Determine gluon densities at low x in cold nuclei via p + Au or d + Au collisions.
2014	DM9 (new)	Perform calculations including viscous hydrodynamics to quantify, or place an upper limit on, the viscosity of the nearly perfect fluid discovered at RHIC.
2014	DM10 (new)	Measure jet and photon production and their correlations in A≈200 ion+ion collisions at energies from medium RHIC energies to the highest achievable energies at LHC.
2015	DM11 (new)	Measure bulk properties, particle spectra, correlations and fluctuations in Au + Au collisions at $\sqrt{s_{NN}}$ between 5 and 60 GeV to search for evidence of a critical point in the QCD matter phase diagram.
2016	DM12 (new)	Measure production rates, high p_T spectra, and correlations in heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma.
2018	DM13 (new)	Measure real and virtual thermal photon production in p + p, d + Au and Au + Au collisions at energies up to $\sqrt{s_{NN}}$ = 200 GeV.

Five new milestones are proposed. DM9 notes the effort to develop a theory of viscous hydrodynamics useful for describing observed flow at RHIC. DM10 captures efforts to measure jet correlations over a span of energies at RHIC and a new program using the CERN Large Hadron Collider and its ALICE, ATLAS and CMS detectors. DM11 reflects the commencing intensive search for an expected critical point in the QCD phase diagram and will require operating RHIC at low energies and possibly a new effort at the CERN SPS. DM12 uses the increase in RHIC luminosity that is part of the RHIC luminosity upgrade and associated detector upgrades to study rare particles with charm quarks, and possibly particles with bottom quarks, as a demanding way to learn how matter flow and energy loss are established in the partonic phase at RHIC. DM13 spans real and virtual photons and captures work with both low-mass lepton pairs and photons emitted as blackbody radiation from the collisions at RHIC.

Table 13: New, Updated and Continuing Milestones for Nuclear Structure

Year	#	Milestone
2009	NS3	Extend spectroscopic information to regions of crucial doubly magic nuclei such as Ni-78
2009	NS4	Extend the determination of the neutron drip line up to Z of 11.
2013	NS6	Carry out microscopic calculations of medium mass nuclei with realistic interactions, develop a realistic nuclear energy density functional for heavy nuclei, and explore the description of many-body symmetries and collective modes, and their relationship to effective forces
2013	NS7 (Update of NS5)	Complete initial measurements with the high resolving power tracking array, GRETINA, for sensitive studies of structural evolution and collective modes in nuclei
2015	NS8 (new)	Measure properties and production mechanisms of the elements above Z~102 to understand the nature and behavior of these nuclei, and to assist theoretical predictions for the stability, structure and production of superheavy elements.
2018	NS9 (new)	Measure changes in shell structure and collective modes, from the most proton-rich to the most neutron-rich nuclei accessible, in order to improve our understanding of the nucleus, and to guide theory in every region of the theoretical roadmap (i.e., the light-element region where ab-initio calculations can be performed, the medium-mass region where effective interactions are used, and the region of heavy nuclei, the domain of density functional theory).

New milestone NS9 is proposed to replace the completed original Milestone NS1 from the 2003 set to reflect in particular recent progress in formulating and adapting theory to the various regions of nuclear masses and for the extremes of neutron-to-proton ratio. New Milestone NS8 is proposed to replace the completed original Milestone NS2 from the 2003 set; to capture future progress in this area, with a due date of 2015. The following activities would be expected in pursuing this Milestone: (1) provide further constraints on the location of the single-particle orbitals thought to play a decisive role in the stability of superheavy elements; (2) improve experimental knowledge about the various reaction mechanisms proposed for the production of superheavy nuclei (such as cold and hot fusion, fusion with neutron-rich beams, and collisions between very heavy nuclei); and (3) improve theoretical predictions for structure and production of superheavy elements. Revised Milestone NS7 changes the delivery date of original 2003 Milestone NS5 to take into account actual funding profiles for the GRETINA project.

Table 14: New, Updated and Continuing Milestones for Nuclear Astrophysics

Year	#	Milestone
2009	NA3	Perform three-dimensional studies of flame propagation in white dwarfs during Type Ia supernova
2010	NA4	Reduce uncertainties of the most crucial stellar evolution nuclear reactions (e.g. $^{12}C(\alpha,\gamma)^{16}O$) by a factor of two, and others (e.g. the MgAl cycle) to limits imposed by accelerators and detectors
2011	NA5	Measure neutron capture reactions, including radioactive s-process branch-point nuclei, to constrain s-process isotopic abundances
2012	NA6	Measure masses, lifetimes, spectroscopic strengths, and decay properties of selected neutron-rich nuclei in the supernova r-process, and reactions to predict radionuclide production in supernovae
2013	NA7	Perform realistic multidimensional simulations of core collapse supernovae
2013	NA8	Perform simulations of neutron star structure and evolution using benchmark microphysical calculations of the composition, equation of state, and bulk properties of dense matter
2014	NA9 (new)	Perform mass measurements and nuclear reaction studies to infer weak interaction rates in nuclei in order to constrain models of supernovae and stellar evolution.
2014	NA10 (new)	Measure or constrain key nuclear reaction rates to improve accuracy of astrophysical models of novae and X-ray bursts and allow astronomical data to be used to infer novae and neutron star properties

New Milestone NA9 is proposed to replace the completed original Milestone NA1 from the 2003 set to recognize the importance of weak interactions in astrophysical environments. The results of such measurements of masses and weak decay rates enter dominant terms in determining the isotope abundances created in stellar nucleosynthesis. New Milestone NA10 is proposed to replace the completed original Milestone NA2 from the 2003 set to reflect expected future work in the area of proton-rich nuclei in the rp-process of nucleosynthesis. The accumulated data would be used together with current theoretical models to determine in particular information on the astrophysical site of this nucleosynthesis.

Table 15: New, Updated and Continuing Milestones for Neutrinos, Neutrino Astrophysics, and Fundamental Interactions

Year	#	Milestone
2008	FI3	Initiate an experimental program at the SNS fundamental physics beam line
2010	FI4	Make factor of 5 improvements in measurements of neutron and nuclear beta-decay to constrain physics beyond the standard model
2010	FI5	Make factor of 5 improvement in theoretical uncertainties for testing the Standard Model via low energy electroweak observables
2011	FI6	Improve the sensitivity of the direct neutrino mass measurements to 0.35 eV
2012	FI8 (expanded scope)	Perform independent measurements and key computations of parity violation in few-body systems to constrain the non-leptonic weak interaction
2013	FI9	Obtain results from new high-sensitivity searches for atomic electric dipole moments
2013	FI10 (new)	Determine the implications of improved dipole moment searches for the cosmic baryon asymmetry by carrying out new computations of EDMs and quantum transport calculations for electroweak baryogenesis.
2014	FI11 (new)	Perform measurements of parity violating electron scattering asymmetries using the highest energies available at Jefferson Lab program.

2015	FI12 (new)	Analyze the implications, for possible new fundamental interactions, of precise measurements of parity-violating electron scattering asymmetries, weak decays of nuclei, light hadrons and leptons, and the muon g-factor.
2015	FI13 (new)	Complete R&D demonstrating if a direct, precision measurement of the solar p-p fusion rate is possible
2017	FI14 (Revised FI7)	Extend the sensitivity of searches for neutrinoless double-beta decay in selected nuclei by a factor of ten in lifetime
2020	FI15 (new)	Obtain initial results from an experiment to extend the limit on the electric dipole moment of the neutron by two orders of magnitude

New Milestone FI15 captures an effort just being established to use the ultra-cold neutron beamline being built at the SNS (see FI3) to improve the limit on the neutron's electric dipole moment by two orders of magnitude or better using a novel experimental technique. This project is still obtaining needed Critical Decisions but is projected to have significant results by 2020. The revised deadline for Milestone FI14 reflects the pace at which it has been possible to identify funding to carry out needed R&D as well as commence building the first of the two experiments recommended by NuSAG in this area. R&D results have been most encouraging, with efforts now moving to full system tests. New Milestone FI13 addresses the rate of the primary reaction powering the Sun, p-p fusion. One may look for either the p-p or p-e-p neutrinos, which require distinct experimental techniques. The neutrinos may be detected by charged or neutral current scattering, which place different demands on an experiment. New Milestone FI12 examines implications for physics beyond the Standard Model that can be drawn from precise measurements of scattering by and decays of subatomic particles, processes that can be treated in detail in the Standard Model. New Milestone FI11 takes note of a new effort in parity-violating electron scattering. New Milestone FI10 ties the new results from FI9 to our understanding of the origins of the large asymmetry between the number of baryons and of anti-baryons in the universe.

Appendix 5: Hadronic Physics Milestone Status Summary

Milestone HP1 (2008): Make measurements of spin carried by the glue in the proton with polarized proton collisions at center of mass energy, $\sqrt{s}$ = 200 GeV.

What has been accomplished toward Milestone HP1 and what has been learned from the information gathered?

RHIC has been commissioned as the world's only polarized proton collider. Polarized proton collision experiments have so far been carried out at 200 GeV in 2002-8, with luminosity and beam polarization increasing year by year. The best constraints on the gluon contribution to the proton's spin come from helicity correlations measured for the abundant channels leading to inclusive neutral pion and jet production (with the PHENIX collaboration providing the best measurements for the former, and the STAR collaboration for the latter, channel). Already published results [1] from the 2003-5 RHIC runs, rule out gluon contributions larger than the proton's spin, which were speculated in the 1990's to be responsible for the rather small net spin carried by quarks. Much tighter constraints come from the so far preliminary analysis of 2006 results by PHENIX and STAR, both interpreted within the context of a given model for the dependence of gluon polarization on the fraction of the proton's momentum carried by the gluon. The results are consistent with zero gluon polarization, but still allow for small positive or substantial negative (opposite the proton spin) contributions to the proton spin. They do not rule out gluon helicity preferences that change sign as a function of the gluon's momentum fraction.

What remains to be done to complete the original Milestone as written?

The experiments measure helicity correlations. Information on gluon polarization is extracted from these and other measurements within the context of a perturbative QCD analysis. Robust results on the gluon contribution to the proton spin, with proper accounting for systematic errors associated with the theoretical treatment, await global analyses (now being launched) of the full relevant nucleon spin structure database, including the RHIC spin results. In addition, coincidence measurements (jet-jet and photon-jet) at RHIC are needed to probe the dependence of gluon polarization on momentum fraction more sensitively than is possible with the inclusive data acquired to date. These techniques are under intensive development.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

The measurements to date at 200 GeV are primarily sensitive to gluons carrying between a few and 30% of the proton's momentum. Gluons carrying even lower momentum fractions are highly abundant and, if even slightly polarized, could contribute substantially to the proton's spin. Sensitivity to such softer gluons requires additional coincidence measurements at 500 GeV proton-proton collision energy and/or at more forward production angles. Data for other production channels (e.g., heavy flavor production) can also serve as crosschecks on the robustness of the pQCD interpretation.

Is the Milestone complete? Yes

We anticipate that a first pass at a global pQCD analysis incorporating the RHIC data will be completed during 2008, and we thus judge the milestone to be completed on schedule. In light of what has been learned to date, a more focused update of the Milestone is as follows, extending the goals to build on knowledge gained (proposed new Milestone HP12):

> **Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.**

It should be feasible to complete the new Milestone by 2013.

Bottom line status assessment: Expect to Achieve.

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Milestone HP2 (2008): Extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 – 0.4, and squared momentum transfer, t, less than 0.5 GeV^2 in measurements of deeply virtual Compton scattering.

What has been accomplished toward Milestone HP2 and what has been learned from the information gathered?

Helicity-dependent and helicity-independent cross sections have been measured [1] with high precision over the x_{Bj} and t range specified in the Milestone. A highly accurate measurement of the Q^2 dependence over a limited range demonstrated the dominance of the so-called "handbag" mechanism. This is a prerequisite for using DVCS to probe the structure of the proton that is parameterized by GPDs. Another result of this measurement is the evidence in the helicity-independent cross section of a large contribution from the (DVCS) [1] term. Both absolute cross-section and relative asymmetry measurements are essential for separating the real and imaginary parts of the BH and DVCS interference terms. Available GPD parameterizations are reasonably successful in describing the cross-section differences, but fail significantly for the absolute cross-section data.

A DVCS experiment on deuterium has obtained preliminary results [2] for both the coherent D(e,e'γ)D and quasi-free D(e,e'γ)pn channels. The quasi-free neutron cross-section data, obtained after subtracting the contribution from quasi-free DVCS on the proton, are sensitive to the d-quark contribution to the "Pauli" GPD E. Future experiments on deuterium are under development to further constrain this important element of the Ji angular momentum sum rule.

Beam spin asymmetries and DVCS cross sections have been measured [3] with the CLAS detector. Beam asymmetries largely reflect the interference of the DVCS process with the Bethe-Heitler process. Cross section measurements have also been performed in a range of x_{Bj} = 0.15 - 0.5, Q^2 = 1.5 – 4 GeV^2, and -t = 0.17- 1.5 GeV^2. These measurements cover the full deep inelastic kinematics at reduced statistical accuracy for individual kinematics bin. A first comparison of the measured beam spin asymmetries with current GPD parameterizations shows qualitative agreement for the leading twist components.

What remains to be done to complete the original Milestone as written?

The full statistics of the CLAS beam-spin-asymmetry experiment (only about 1/3 has been completed to date) will be collected in a run scheduled for FY08/FY09. Improvements to the experimental setup should allow higher luminosity, providing high statistics data even for rather high values of Q^2. This was delayed by a combination of the impact of hurricane Isabel on the energy reach of the CEBAF accelerator and budget limitations that delayed restoration of high-energy capability and reduced the total operations of the facility.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

A clarification of the relative importance of the interference and DVCS [1] terms is important for the extraction of GPDs from DVCS data, as current analyses have used the assumption that at JLab energies the dominant contributions to the cross section are from the Bethe-Heitler process modulated by the BH and DVCS interference. A subsequent experiment has been approved to explicitly separate those contributions by taking advantage of the different dependencies of the BH and DVCS amplitudes on the incident beam energy.

Another "follow-on" DVCS experiment with CLAS will use a longitudinally polarized NH_3 target to measure the single target spin asymmetry A_{UL}, which contains a combination of GPDs that is different from the combination in the beam helicity dependent measurements. While the beam asymmetry on the proton is dominated by the vector GPD H, the target asymmetry is more sensitive to the axial GPD. This is not part of the original Milestone, but rather an obvious next step for progress in the field. A first measurement [4] with longitudinally polarized target shows the sensitivity to the axial GPD.

Both Hall A and CLAS experiments will also measure deeply virtual π^0 and η production, which will test the applicability of the handbag mechanism for the more complex DVMP processes, that are needed for a flavor separation of the GPDs.

Is the Milestone complete? No

Not only does the CLAS beam-helicity experiment need to be completed, but the results obtained so far have shown the need for additional experiments (see above). Thus, the Milestone should be reformulated and extended as follows (proposed new Milestone HP11):

> **Measure the helicity-dependent and target-polarization-dependent cross-section differences for deeply virtual Compton scattering off the proton and the neutron in order to extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 – 0.4, and squared momentum transfer, t, less than 0.5 GeV^2.**

It should be feasible to complete the updated Milestone by 2012.

Bottom Line Status Assessment: Expect to Not Achieve Fully

The data obtained and analyzed has allowed substantial progress on the physics goals of the Milestone. In addition, substantial incremental data has been obtained (on the neutron), and a major theory effort has advanced our understanding. However, the full statistics for one of the two data sets planned for the original Milestone will not have been taken by the end of 2008 (the run is planned in early 2009).

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Milestone HP3 (2009): Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.

What has been accomplished toward Milestone HP3, and what has been learned from the information gathered?

The Excited Baryon Analysis Center (EBAC) was established at Jefferson Laboratory during the Spring of 2006, and a collaboration was formed in June 2006 to develop a reaction model [1]for performing the dynamical coupled-channel analysis of meson production data from JLab and other electron facilities. The coupled channel analysis code, EBAC-CC, was developed during the second half of 2006 and its basic hadronic parameters were determined [2] in the spring of 2007 by fitting the Nπ scattering data in the nucleon resonance region. Methods for extracting the resonance poles have been developed and applied to the predicted Nπ amplitudes.

The EBAC-CC was applied during the summer of 2007 to perform [3,4] a first dynamical coupled-channel analysis of pion photoproduction data up to W=1.65 GeV and predict the meson cloud effects for all low-lying nucleon resonances [5] as a first necessary step toward performing a comprehensive analysis of the world data of photoproduction and electroproduction in the πN, ηN, and ππN final states. In parallel, two projects are being developed to extend the EBAC-CC package to analyze ωp and KY production.

The analysis of the predicted πN scattering amplitudes has verified the existence of all low-lying nucleon resonances and identified the regions where the information on the higher mass nucleon resonances can be discovered and extracted from the photo-production and electro-production data. The Q^2-dependence of the γN→Δ(1232) transition form factor has been quantitatively determined [6] and found to be only in very qualitative agreement with the predictions from the relativistic constituent quark models and with quenched Lattice QCD calculations. The predicted meson cloud effects on all low-lying nucleon resonances have verified to a very large extent the finding [7] by the CLAS collaboration that the Roper resonance N(1440) is mainly due to the excitation of the quark substructure of the nucleon, not a meson-baryon molecular state.

What remains to be done to complete the original Milestone as written?

The dynamical coupled-channel analysis of the unpolarized πN, ηN, and ωN cross section data must be completed by the summer of 2008, and the Nππ production data by the spring of 2009. The analysis of the KΛ and KΣ production data must start by the summer of 2008 and be completed by the end of 2009.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

The CLAS collaboration and groups at ELSA and (to a lesser degree) Spring8 are preparing to collect data on single and double meson final states using linearly and circularly polarized photon beams, longitudinally and transverse polarized hydrogen and deuterium targets, and measurement of recoil polarization for hyperons in the final state. These data must be analyzed in a coupled channel frame work that incorporates all channels and all polarization observables in a combined fit, and interpret the resulting amplitudes in terms of the underlying degrees of freedom.

Is the Milestone complete? No.

See comments above on the work remaining. A follow-on, longer-range Milestone that should be considered in the future (once this one has been completed) is to set a goal that by 2014 a comprehensive dynamical coupled-channel analysis is completed for the world data on πN, ηN, ππN, ωN, and KY, and the extracted N* parameters be interpreted in terms of hadron structure calculations. In particular it will be important to have accurate LQCD calculations of the masses of relevant baryon excited states.

Bottom Line Status Assessment: Expect to Not Fully Achieve

Budget driven difficulties, in particular the late start of the project and the shortage of full-time manpower, slowed the ramp-up of EBAC and the analysis and interpretation effort. However, rapid progress is being made through the extensive use of international collaborations. We are close to being on track for the completion of the Milestone by the end of 2009 assuming the continuing availability of the required resources.

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Milestone HP4 (2010): Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .

What has been accomplished toward Milestone HP4, and what has been learned from the information gathered?

Nucleon form factors are related to the spatial distributions of charge and magnetization within protons and neutrons. The electric (G_E^p) and magnetic (G_M^p) form factors of the proton and the magnetic form factor of the neutron (G_M^n) are now known [1] well beyond 3.5 GeV^2.

The observation that the ratio G_E^p/G_M^p decreases with Q^2 is a manifestation of relativistic effects in the proton, while data on all four form factors at $Q^2 < 0.5$ GeV^2 are sensitive to the pion cloud surrounding the core of the nucleon. Data on G_E^p taken by polarization transfer differed significantly from data taken by the traditional Rosenbluth separation technique. Careful measurements have confirmed that both data sets are correct. Theoretical studies [2] of the differences indicate that they are mainly due to the presence of two-photon (dispersive) effects, which are much more important in the Rosenbluth data; experimental tests of this understanding are supportive of the conclusion, but further experiments will be desirable to answer the question definitively.

Measurements of the neutron electric form factor (G_E^n) are more difficult, both because an unbound neutron target is not feasible and because the neutral charge of the neutron implies a small value for the form factor. However, techniques have been developed to extract G_E^n using deuterium and polarized ^3He targets. Recently completed measurements [3] using scattering of polarized electrons on polarized ^3He will extend knowledge of the neutron electric form factor (G_E^n) from 1.5 to 3.5 GeV^2, and analysis is well underway. In addition, analysis is proceeding on an experiment [4] that will improve the precision of G_M^n up to 5 GeV^2.

In addition to the electromagnetic form factors, an ambitious program of measurements aimed at determining the neutral weak form factors of the proton is nearing completion. In order to decompose these form factors, measurements of parity violating electron scattering (PVES) are needed on the proton at both forward and backward scattering angles or additionally on ^4He at forward angles. Quasi-free PVES on the deuteron must be measured at backward angles in order to extract information on the axial form factor. Forward angle measurements over a range of a Q^2 range 0.1 to 1.0 GeV^2 have been made by the HAPPEX [5] and the G0 experiments [6] and higher precision measurements at 0.6 GeV^2 will be obtained by the HAPPEX-III experiment within the next two years. Backward angle measurements of PVES on the proton and deuteron have been made by the G0 experiment [7] and are currently being analyzed. These measurements, combined with the electromagnetic form factors will allow a decomposition of the form factors into contributions from u, d and s quarks. Presently, the measurements indicate that strange quarks may contribute to G_E^p and G_M^p at low Q^2, but only at the level of a few percent.

What remains to be done to complete the original Milestone as written?
Analysis must be completed for data from a number of major experiments: G_M^n (from CLAS), PVES (G0 backward angle), and on the polarized ^{3}He measurement of G_E^n. Then a global analysis must be carried out to complete the flavor separation of the form factors.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
The extension of the G_E^p data to higher Q^2, now underway, will be a valuable supplement to the originally planned measurements, and significant further extensions will be feasible with the 12 GeV Upgrade of CEBAF. Data elucidating the scale and kinematic dependence of dispersive effects in electron scattering, through both the analysis and interpretation of new data on Rosenbluth separation and a planned comparison of positron and electron scattering will put our understanding of these results on a firmer foundation. In addition, theoretical work is needed to understand the size of possible charge symmetry violation (CSV) corrections at higher Q^2.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Exceed
All planned data will have been taken and analyzed, and additional data will be available extending our understanding of the physics relative to the goals of the Milestone

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Milestone HP5 (2010): Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the $^4He(\vec{e},e\vec{p})$ reaction.

What has been accomplished toward Milestone HP5, and what has been learned from the information gathered?

The existence of short-range N-N (and 3N) correlations has been quantitatively established through the observation [1] of steps in the scaling behavior as a function of x_{Bj} of the ratio of inclusive electron scattering off medium and light nuclei. The observation of nucleons with high internal momenta in a nucleus is interpreted as a clean signature for violent nucleon-nucleon collisions (short-range correlations) not described by the standard mean field theory. These nucleon-nucleon correlation effects have been studied in single- and two-nucleon knock-out reactions, mostly off light nuclei where the theoretical description is reliable. A systematic study [2] of the (e,e'p) reaction on ^{12}C directly measured the contribution from short-range correlations at large values of the missing energy E_m and momentum p_m. The quasi-elastic ^3He(e,e'p) reaction was studied [3] up to a very high p_m value of 1 GeV/c. At p_m values larger than 300 MeV/c the cross section is dominated by Final State Interactions. However, the large increase in cross section from the two-body to the three-body breakup channel is interpreted as a strong indication of NN correlations. These measurements have recently been extended to heavier nuclei, such as ^{208}Pb, to explore systems with properties close to those of nuclear matter. A study of the ^3He(e,e'pp)n reaction in CLAS [4] measured the relative and total momenta of pp and pn pairs by hitting the third nucleon and measuring the spectator correlated pairs. A followup measurement, currently under analysis review, will provide more information on the momentum transfer dependence and on the ratio of (pn) to (pp) pairs as a function of relative and total pair momentum. In a recent experiment [5] the number of (pn)-pairs knocked out from ^{12}C was observed to be nearly twenty times as large as the number of (pp)-pairs. This observation was attributed by a recent calculation [6] to the dominance of tensor correlations in the high missing-momentum range studied in the experiment. In a future experiment the ratio of (pn)-pairs to (pp)-pairs knocked out from ^4He will be studied over a large range of missing momentum to investigate the validity of the tensor-correlation dominance.

Possible modifications of the properties of a bound proton in the nuclear medium have been studied [7] via a precision measurement of polarization transfer in the $^4He(\vec{e},e\vec{p})$ reaction, in which a precise comparison is made of the ratio of electric and magnetic form factors for free and bound protons. Changes observed in that ratio in a first experiment supported novel theoretical approaches to nuclear structure starting from the level of quarks and gluons, within which such changes are a natural precursor to the transition to a quark-gluon phase at higher densities. In 2006 a follow-up experiment measured that ratio to a much higher precision. Preliminary results [8] confirm the findings of the first experiment.

What remains to be done to complete the original Milestone as written?

Final analysis, interpretation and publication of available results.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
In a precision experiment planned for the fall of 2007 the longitudinal response for quasi-elastic scattering in a range of nuclei will be determined accurately through a Rosenbluth separation. By integrating this response function over the energy loss one extracts the Coulomb Sum, which will provide sensitive information on N-N short-range correlations and in-medium modifications.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Achieve
On track to have not only met the goals of the Milestone as written but to have added significant supplementary data addressing the underlying physics issues. However, the interpretation of the $^4He(\vec{e},e\vec{p})$ data in terms of the bound proton properties is proving more difficult than was anticipated at the time the Milestone was originally written.

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Milestone HP6 (2011): Measure the lowest moments of the unpolarized structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$ for x =0.2-0.6, and $1 < Q^2 < 5$ GeV^2 for both protons and neutrons.

What has been accomplished toward Milestone HP6, and what has been learned from the information gathered?

The lowest moments for the proton F_2 structure function, *assuming the longitudinal/transverse character is known*, have been published [1]. The fully separated longitudinal (F_L) and transverse (F_1) structure function moments have been determined [2], but not yet published. In general, these data show a remarkably small signature of quark-quark and quark-gluon correlations up to larger distance scales than anticipated, either because the correlations are *small on average*, or there are large cancellations in limited energy regions. These studies provide vital clues to the long-standing challenge of QCD to describe the forces at large distances, comparable with the size of hadrons (~ 1 fm).

The lowest moments for the neutron F_2 structure function are forthcoming from a combination of three input experiments, all completed. The spin-averaged deuteron structure functions have been measured [3,4] and an experiment to fully separate their longitudinal and transverse behavior is under analysis [5]. A third experiment has been completed [6] to validate the extraction of neutron data from deuterium targets, and is under analysis with final results expected within one year. The results would render the best measurements to date of the down quark momentum distribution at moderate quark momentum fractions, important to understand the QCD behavior of valence quarks in the nucleon. The lowest moments representing the *difference* between proton and neutron are being calculated with lattice QCD, and accurate data at $Q^2 = 4$ GeV^2 to benchmark these calculations are expected soon. The results for low-Q^2 spin-averaged and longitudinal/transverse separated structure functions for proton and neutron, augmented with a modest amount of nuclear data, are eagerly awaited as input for the neutrino community in their effort to minimize the associated uncertainties in measurements of the neutrino masses and mixings.

The polarized g_1 structure functions have been determined for both proton and neutron. All proton results have been published [7]. The neutron results as extracted from a polarized deuterium target have also been published [8], whereas those as extracted from a polarized ^3He target are final, but only data up to $Q^2 = 1$ GeV^2 have been published [9]. The results have been analyzed [10] to quantify our knowledge on quark-quark and quark-gluon correlations, and again show these to be small, albeit slightly larger than in the spin-averaged case. The polarized g_2 structure functions have been well mapped [11] up to $Q^2 \sim 1$ GeV^2.

What remains to be done to complete the original Milestone as written?

Complete the analysis of the experiments to determine the neutron structure functions and their moments. Measurements up to $Q^2 \sim 4$ GeV^2 using both polarized proton and polarized neutron (from ^3He) targets are planned to run in 2008. These measurements will determine the ability of the nucleon's constituents to generate a color magnetic field along the direction of its spin, a quantity that can also directly be compared with lattice QCD calculations.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question? None

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Exceed

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Milestone HP7 (2012): Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range Q^2 = 0.1 – 7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.

What has been accomplished toward Milestone HP7 and what has been learned from the information gathered?

Resonance transition form factors and their Q^2 dependence encode information about the internal structure of the excited state and carry information about the confining forces of the 3-quark system. Very significant progress has been made during the past few years, with the newly established Excited Baryon Analysis Center (EBAC) at Jefferson Lab a key factor in this progress. The transition form factors for the lowest mass excited nucleon I=3/2 state, the Δ(1232), have now been determined [1] for Q^2 up to 6 GeV^2 in exclusive π^0 production off protons, and data for Q^2=7 GeV^2 are currently under analysis. Accurate polarization data were also gathered in more limited phase space. The N-Δ transition form factors are now considered along with the nucleon form factors as the benchmark data challenging the theoretical community. The N-Δ transition form factors result allowed the exploration of the meson contributions to the structure of the Δ(1232) to short distances. They were found to be large at low Q^2, and still significant up to Q^2 = 5 GeV^2. These data had strong impact on the development of LQCD calculations and significant progress has been made towards understanding them with quenched Lattice QCD (QLQCD). The data at low Q^2 (large distances) suggest that the Δ(1232) has a slightly oblate shape.

Accurate cross section and beam polarization asymmetries have been measured [2] in experiments that cover nearly the complete phase space of the $n\pi^+$ system. This channel is particularly sensitive to I=1/2 nucleon excitations such as the Roper N(1440)P_{11}.Results for the transition form factors of this state have been published [3], or are in preparation [4]. The unexpected zero-crossing of the transverse Roper amplitude was discovered in these measurements. This represents the first sign change ever seen for a nucleon form factor. The high Q^2 behavior of the Roper amplitudes is qualitatively consistent with what is expected from relativistic quark models for a radial excitation of the 3-quark system. The data have already ruled out the interpretation of the Roper as a gluonic excitation of the nucleon (hybrid baryon) and are challenging other theoretical interpretation models such as the interpretation as a dynamically generated (π-N) system, or as a σ-N molecular state.

The transition from the ground state proton to the N(1535)S_{11} has been mapped out in the pη channel [5]. This state shows a very hard transition form factor even at low Q^2, which may be indicative of a lack of meson contributions even at large distances. This result is in qualitative agreement with constituent quark model calculations.

What remains to be done to complete the original Milestone as written?

The transition form factors for other resonances need to be determined, particularly the N(1520)D_{13} and N(1680)F_{15} as constituent quark models predict a very rapid change of the helicity structure of this state from helicity 3/2 dominance at the photon point to helicity 1/2 dominance at high Q^2. This is in accordance with predictions from helicity conservation and asymptotic QCD. The two states allow access to the orbital and radial wave functions of the 3-quark system. To separately determine the influence of meson contributions it is essential to measure transition form factors for states that have strong coupling to different final states, e.g. the $N(1535)S_{11}$ should be measured in both the $p\eta$ and the $N\pi$ channel to obtain a better understanding of the role of mesons for this state. To determine the transition form factors of many of the higher mass states, e.g., $\Delta(1620)S_{31}$, $\Delta(1700)D_{33}$, and $N(1720)P_{13}$, data in the 2-pion channel, e.g., $p\pi^+\pi^-$ are needed. For some of these states, e.g. $N(1535)S_{11}$ models of this state being not a 3-quark state, but a $K\Sigma$ molecule have been put forward. As has been demonstrated with the Roper resonance, transition form factors are crucial in discriminating between these different interpretations.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

Completion of the EBAC effort for the coupled channel analysis of πN, ηp, and $N\pi\pi$ final states is needed, which is expected for CY2009.

Is the Milestone complete? No

All data needed to complete the original Milestone have been taken. Main tasks are experimental data analysis and phenomenological support for extraction of the underlying physics.

Bottom Line Status Assessment: Expect to Achieve

The Milestone is on track for completion by 2011 assuming a continuation of the present level of resources both to support the completion of the experimental data analyses and to support the phenomenological analysis effort at EBAC.

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Milestone HP8 (2013): Measure flavor-identified q and $\overline{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.

What has been accomplished toward Milestone HP8 and what has been learned from the information gathered?
Beam polarization survival under acceleration to 250 GeV at RHIC has been demonstrated, as essential for the W production measurements. A needed upgrade of the PHENIX detector muon trigger system is under way, and one to STAR's forward tracking resolution is expected to be launched in 2008. Measurements of semi-inclusive deep inelastic scattering of polarized electrons from polarized protons in the HERMES experiment at DESY have suggested small sea quark and antiquark polarizations, but with so far limited precision in comparison to model predictions.

What remains to be done to complete the original Milestone?
Adequate pp collision luminosity and polarization at 500-GeV center-of-mass energy at RHIC must be achieved. This requires sufficient accelerator development time, which has been difficult under recent operating budget history. The relevant PHENIX and STAR detector upgrades must be completed. More realistic simulations must be made to demonstrate the needed suppression of backgrounds under the W production signal in both RHIC detectors. It is anticipated that 500-GeV proton-proton collision running will begin at RHIC in earnest in 2009 or 2010.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
None of the W production data needed to address the Milestone have yet been taken. They are still needed. This requires first operation of the RHIC collider at 500-GeV proton-proton center-of-mass energy.

Is the Milestone complete? No.

The Milestone should remain as originally worded. Technical developments at RHIC are on track to accomplish the Milestone on the projected time scale.

Bottom line status assessment: Expect to Achieve

Milestone HP9 (2014): Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.

What has been accomplished toward the Milestone HP9, and what has been learned from the information gathered?

Lattice QCD has emerged as a powerful tool for *ab initio* calculation of hadron structure. Nucleon properties are calculated by solving lattice QCD for a range of quark masses corresponding to pions in the chiral regime, and using chiral effective theory to determine observables at the physical pion mass. Calculations have performed [1] for the nucleon in full QCD at pion masses at 360 MeV and above for low moments of the quark distribution, quark spin distribution, and quark transversity distribution; for electromagnetic form factors; and for generalized form factors specifying low moments of unpolarized and polarized generalized parton distributions. Agreement with experiment within experimental and statistical errors has been obtained for the isovector nucleon momentum fraction and contribution of the quark spin to the nucleon spin, g_A, the next two higher isovector moments of the spin distribution, and the isovector charge radius of the nucleon form factor. Predictions have also been made for low moments of the transversity.

The measurement of the total angular momentum carried by the quarks, together with measurements of the spin carried by the quarks, neglecting the so-called disconnected diagrams, has shown that the total orbital angular momentum carried by the quarks in the nucleon is negligible, but that the orbital angular momentum carried by the individual quark flavors is substantial. Calculation of the transverse radii of moments of the GPDs has shown the narrowing of the transverse size of the nucleon in impact-parameter space with increasing momentum fraction (Bjorken x), and a comparison of the Generalized Form Factors with phenomenological models has demonstrated the utility of lattice computations is constraining the parametrizations of GPDs [2].

What remains to be done to complete the original Milestone as written?

The national effort in hadron structure, which has been articulated in detail in white papers for the NSAC long range plan and the USQCD project, includes four further steps. The first is to extend full QCD lattice calculations to lighter pion masses and larger volumes, both of which increase the accuracy of chiral effective theory extrapolations to the physical nucleon. This is already under way in approved projects using dedicated USQCD lattice facilities. The second is to use the same lattice action with chiral symmetry that is currently used for valence quarks for dynamical sea quarks as well, which will decrease systematic uncertainties and eliminate operator mixing. Recent algorithmic advances have now made these calculations feasible, and calculations are now underway on dedicated USQCD facilities and additional calculations have been approved for early use time on the DOE Leadership Class Blue Gene at ANL. Third, it is essential to calculate the so-called disconnected diagrams, enabling the calculations to be extended to flavor-singlet quantities, and facilitating reliable confrontation with experiment. Although indirect techniques [3] have produced agreement with the strangeness form factors at low Q^2 for the full set of operators addressed by this Milestone, disconnected diagrams must be calculated directly even though they are much more computationally demanding than the dominant connected diagram contributions that are presently included. Fortunately, a number of powerful new techniques are presently being developed, including multigrid, low mode deflation, hopping parameter expansion, truncated solver, and background field methods. Alone or in combination, these methods are already showing impressive results, and several approved projects on USQCD facilities are aggressively pursuing them. Finally, in addition to quark parton distributions, it is crucial to calculate directly the contributions of gluons to hadron structure. Through the use of improved gluon operators, the contribution of gluons to the momentum of the pion was calculated for the first time [4], and the methodology is directly applicable to the gluon momentum fraction in the nucleon and the gluon contribution to the nucleon spin.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
As explained above, the lattice methodology is at hand to address all the components of this Milestone. With the computational resources provided for the national lattice QCD community to date, lattice theorists have clearly demonstrated the power of lattice QCD in understanding hadron structure from first principles. Continued investment in lattice computational resources at the current level will provide the computer resources to meet the 2014 Milestone. We note it is critical for reaching this Milestone to provide operating time for large computer facilities and for this community to continue to compete successfully for access to that time, which implies continued support of the several personnel key to that project.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Exceed
Lattice calculations have already succeeded in calculating the most computationally accessible components of the Milestone, in agreement with experiment, and with the current rate of growth of computer power for lattice QCD, this project is very well on track to meet this Milestone.

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Milestone HP10 (2014): Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.

What has been accomplished toward Milestone HP10, and what has been learned from the information gathered?

Realistic two- and three-nucleon potentials and associated electroweak currents have been constructed [1] that reproduce well the spectra of light nuclei (up to mass A=12) and a variety of electromagnetic and weak transitions in these light systems, both at the low energies (keV regime) of relevance in nuclear astrophysics [2] as well as at the high energies (GeV regime) probing the short range structure of nuclei. Developments in chiral perturbation theory and power-counting rules have provided a QCD underpinning for these interactions [3] and currents, while a methodology for relating the effective field theory description of the NN interaction with calculations in lattice QCD is being developed [4]. Lastly, the development of new calculational methods, such as quantum Monte Carlo (QMC) techniques and techniques for extracting two-body scattering properties from Euclidean-time lattice QCD (LQCD) computations, as well as the surge in available computer power, have led to significant progress in computing nuclear properties with the realistic potentials and currents mentioned above and, in the context of LQCD, to an *ab initio* determination of the scattering lengths for the π-π and π-K systems [5]. An example, drawn from nuclear physics, is the recent prediction that, on account of the tensor force, the np momentum distribution is one-to-several orders of magnitude larger than that of the pp for relative pair momenta in the range 300-500 MeV/c and vanishing total pair momentum. This feature has a universal character, and beautifully exemplifies the crucial role that the tensor force plays in shaping the short-range structure of nuclei [6]. There are initial indications from a Jefferson Lab experiment involving np- and pp-pair knockout from ^{12}C that the predicted enhancement of the np to pp cross sections is observed in the data.

What remains to be done to complete the original Milestone as written?

While the progress outlined above has been substantial, much remains to be done both in the conventional framework as well as in the effective field theory approach, particularly in the modeling of three-nucleon (and, possibly, four-nucleon) interactions and many-body components in the nuclear electroweak current. For example, current Hamiltonian models, based on conventional and/or effective field theory potentials, fail to provide a quantitatively successful account of all available three- and four-nucleon scattering observables, notable among these discrepancies is the "A_y puzzle," while the measured thermal neutron captures in A=3 and 4 systems and, in a higher energy context, the magnetic form factors of the trinucleons are still not well reproduced by theory. Such models also fail to explain the famous EMC effect on nuclear structure functions, which can only be understood in terms of some modification in the internal structure of the bound nucleons. There has also been remarkable progress within such models in deriving realistic, density dependent effective NN forces, and there are also indications of the origins of key features of these models within LQCD.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

The amalgam of chiral effective theory and LQCD has demonstrated that LQCD can be used to compute the parameters of a chiral effective description of nuclei in a rigorous manner, and the applicability of the approach established in both the NN and meson-meson systems. However, the lattice studies of the nucleon-nucleon interaction need to be extended to quark masses closer to the physical quark masses in order to facilitate an ab initio calculation of the scattering lengths in the chiral limit. The lattice studies of nucleon-nucleon scattering should be extended to the hyperon-nucleon sector, which could provide additional insight important for our understanding of astrophysics, and in particular the time-evolution of supernova.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

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Appendix 6: High Temperature, High Density Hadronic Matter Milestones

Milestone DM1 (2005): Measure J/Ψ production in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV.

What has been accomplished toward milestone DM1 and what has been learned from the information gathered?
The theoretical idea behind these measurements is the conjecture [1] that a c-cbar quark pair would be screened, in the Debye sense, from one another as they separated from their point of production to the asymptotic distance which characterizes a J/ψ (1S). In a dense colored medium the presence of other partons could screen their interaction, thus preventing biding. The initial estimates of the relevant Debye length showed a system with quark-gluon degrees of freedom and of energy density about 2 GeV/fm^3, which is in the expected range for quark deconfinement, would also effectively screen at distances shorter then the characteristic radius of a J/ψ. This would hinder, or "suppress", the formation of J/y at the rate which might be inferred from cross-sections measured in p-p reactions. Calculated sizes of c-cbar and b-bbar quarkonia family members sshowed a pattern of suppression as a function of system energy density for different family members might be observed.

Data has been collected by PHENIX for two decay channels of the J/ψ, the e^+e^- decay channel at central rapidity y=0 and the $\mu^+\mu^-$ channel at forward rapidity y=1.1-2.2. Analysis results were in hand for 200 GeV/nucleon Au+Au [2], d+Au and p+p [3] collisions by the milestone deadline. New data have since been collected for 200 GeV/nucleon Cu+Cu (2005) and for 62 GeV/nucleon Au+Au, Cu+Cu, and p+p, as well as much higher statistics data recorded for Au+Au, d+Au and p+p. All of these raw data are under final analysis and preparation for publication. Transverse momentum spectra of the J/ψ out to 5 GeV/c have been determined, and yields as a function of centrality of the parent collision and reaction plane orientation are in hand. It was realized early on that it would prove important to have a good baseline measurement of open charm production, and one such [4] was published by the milestone deadline to provide proof of principle. Later work is discussed under milestone DM5.

What remains to be done to complete the original milestone as written?
The original goals have been met. The analysis shows recombination of uncorrelated charm-anti-charm quark pairs is important for the total yield. The rapidity dependence of the yield was expected to be important and was thus a principle reason for adding the muon arms to the PHENIX detector, and has since emerged as an area of interest due to theoretical work on color-glass condensates (see Milestone DM8). The transverse momentum dependence is important for separating various models, such as color-screening from those inspired by theories of gravity, requiring measurements out close to 10 GeV/c; some early results were reported at the Quark Matter 2008 conference, and further RHIC runs, notably with upgraded RHIC luminosities, will pursue this. A robust p-p measurement baseline is important, given the lack of ISR data at the correct center-of-mass energy, to sort out scales due to parton distribution functions vs. dynamical effects. Further measurements are again noted under Milestone DM5. Analysis to date

of the d+Au baseline results remains inconclusive as to what fraction of suppression observed is due to the effects of cold matter, e.g. on the parton distribution functions in a heavy nucleus vs. a nucleon. In part to address this, a just-concluded d+Au data run with 30 times statistics as the original 2003 data set will will be analyzed to resolve this key issue.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

One needs energy $\sqrt{s_{NN}}$ dependence and species dependences (see Milestone DM5 for subsequent work). In the future one needs ψ'(2S) and Υ(1S, 2S, 3S) yields, which will require upgraded RHIC luminosities. The suppression pattern predicted is definite – the ψ'(2S) and the Υ(2S, 3S) will be suppressed first, i.e. at lower energy densities than the other family members, due to their relatively large radii, and the J/ψ will be next, at higher energy densities. Measurements at the LHC will yield sizable numbers of upsilon family members, in quantities expected to be larger than those expected to result from operations with the upgraded RHIC luminosity. The Υ(1S) is not expected to be suppressed at RHIC energies due to its very small radius, which is below the range of screening radii probed at energy densities attainable at RHIC, meaning the Υ(1S) therefore acts as a control measurement. The recombination models put forward depend on the square of the number density of c quarks for the psi family and of b quarks for the upsilon family, which should result in a different relative weight of suppression vs. recombination for the two families.

Finally one needs more development of the theory for recombination [5], an improved description of cold-nuclear matter effects once they are quantified from d+Au data, and further theoretical work on the persistence of e.g. c-cbar correlations above the critical temperature in a partonic phase.

Is the Milestone Complete? Yes

Bottom Line Status Assessment: Achieved

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Milestone DM2 (2007): Measure flow and spectra of multiply-strange baryons in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV.

What has been accomplished toward milestone DM2 and what has been learned from the information gathered?

Strange valence quarks are absent in the entrance channel of a collision, which suggests measurement of final-state hadrons with multiple strange quarks (or multiple anti-strange quarks) would yield information on the number density of created particles. The ratio of these yields with those for particles with up and down (anti-)quarks, with reference to a baseline taken from p-p collisions, would then be expected to depend on whether a deconfined system is created. [1] Azimuthal-angle anisotropy of the resultant yields relative to the reaction plane, as defined by the plane containing the two incident colliding nuclei's incoming trajectories, yields information on whether collective motion, or "flow" is established [2],[3], which in turn can given information on whether motion describable in the hydrodynamic limit is observed, and by inference whether and how quickly the matter involved approaches energy equipartition, i.e. how fast it thermalizes. Multi-strange hyperons are an especially fruitful probe of this because they contain more than one quark which must be created in the collision and are not created by simple associated production in a single partonic collision. Their measurement however is made difficult by their relative scarcity coupled with their short proper decay length, requiring careful final-state reconstruction in the high-multiplicity environment of a RHIC collision.

Yields, spectra and azimuthal-angle asymmetry of yield relative to reaction plane has been established for the Λ (s=1), Ξ (s=2) and Ω^- (s=3). [4] A non-zero value of the second Fourier coefficient of the azimuthal anisotropy, v_2, signals an elliptical flow pattern, as would be expected for non-central collisions if the strong pressure gradient developed in the initial stage of the collisions results in collective motion of the matter in the final state. Indeed, strong elliptical flow is observed, saturating the predicted hydrodynamic limit for transverse momenta below 2 GeV/c. The variation of this flow pattern with centrality has been established. [5] Reference p-p data has also been obtained. [6] The value of v_2 for the hyperons is found to follow the pattern as a function of transverse momentum established for earlier π, K, and p, with a "fine structure" observed that depends upon the mass of the specific particle. This pattern is expected from full hydrodynamic calculations and is evidence that the system producing the observed particles not only equilibrates quickly but is most likely in a partonic phase (See Milestone DM4 for a discussion.) This flow pattern is also established for the omega meson, several other hyperons and certain long-lived resonances, and is also observed over a large range of pseudorapidity. [7] Experiments have subsequently studied the scaling of v_2 vs. transverse momentum by the number of valence quarks, n, of the observed hadron. This question was driven in part by the observation that the transverse momentum at which v_2 reaches its peak value depends principally on whether the particle observed is a meson or baryon. The results demonstrate that transverse energy $\sqrt{(m^2+pt^2)} - m$ scaled by n is the best scaling variable for v_2/n, resulting in a universal curve below 2 GeV/c in $(\sqrt{(m^2+pt^2)} - m)/n$, a remarkable result. [8] This suggests recombination of quarks from the system into the final observed hadrons can reproduce the observed results. [9] This is taken as evidence that the collective flow is established very early, at the partonic phase of the collision. This in turn is evidence for very early establishment of thermalization in the partonic phase, leading to a puzzle as to how this is established so quickly.

Further analysis of the measured yields for hyperons relative to those for protons (or anti-protons for anti-hyperons) shows that the chemical potential approaches zero for increasing strangeness. [10] It is also established that all yields expressed as a function of transverse momentum follow the observed split into meson vs baryon families noted previously for pions, kaons and protons. This is discussed further under Milestone DM3. The observation provides further evidence that the relevant degrees of freedom are partonic, not hadronic. This may also be interpreted as a further argument for recombination of free partons into the observed hadrons.

Going beyond the basic measurement, the yields and yield ratios for hyperons and several other species have been established [11] and shown to be similar for those calculated in a model assuming chemical equilibrium, suggesting such equilibrium is well-established in the hadronic final state and that this chemical freeze-out occurs prior to kinetic freeze-out.

What remains to be done to complete the original milestone as written?
The milestone is complete.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
Theoretical efforts to make calculations using viscous hydrodynamics (new Milestone DM9) are needed to establish limits on the viscosity present in the expansion. Measurements with improved counting statistics and improved reaction plane resolution (new detectors installed already for this) are needed to improve uncertainties.

An interesting extension of this work is to charmed particles because the latter offer a more demanding test of the timescale assumed in theoretical models for establishing flow and thermalization. Initial results have been reported. [12] This is addressed in proposed new Milestone DM12.

Is the Milestone complete? Yes

Bottom line status assessment: Exceeded

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Milestone DM3 (2007): Measure high transverse momentum jet systematics vs. $\sqrt{s_{NN}}$ up to 200 GeV and vs. system size up to Au + Au.

What has been accomplished toward milestone DM3 and what has been learned from the information gathered?

Jet emission in high-energy collisions results from the infrequent hard-scattering of the partons. The cross sections for jet production are such that scattering of entrance channel partons is expected to dominate the yield of jets. This generates in-situ high-momentum probes, carrying a color charge, of the matter produced. This means the response of the medium to a color-charged probe can be studied by measuring yields of jets as a function of various kinematical variables. A deconfined system comprised of color-charged quarks and gluons would be expected to modify strongly the final state yields of jets relative to those for p-p collisions, possibly by causing enhanced energy loss of the scattered parton to other partons present before it fragments, or by modifying the fragmentation function of the parton, or both. The expected decrease, or suppression, in yields for high-transverse-momentum single particles, which in turn are predominantly emitted in the fragmentation of the scattered partons as they hadronize, is commonly referred to as "jet quenching" and was predicted, well in advance of first operation of RHIC, as a signature of strong interaction between an energetic scattered parton and an opaque, created color-charged medium [1].

Experimental results have been published for both identified and inclusive leading particles over a remarkably broad range, out to a transverse momentum of 20 GeV/c. [2] Measurements have been made for Au+Au [3], p+p [4], d+Au [5] and Cu+Cu [6]collisions. The center-of-mass-energy dependence of jet yields has been measured from 62 to 200 GeV/c. [7] Correlations of jet yields with the reaction plane and with reaction centrality have been established [8] as well as dependence on rapidity [9]. A useful variable to summarize the results is $R_{AA,}$ which would be unity if jet production in heavy-ion collisions resulted from just a superposition of uncorrelated nucleon-nucleon collisions. Measurements instead established a marked difference of R_{AA} for Au+Au relative to p+p. The latter exhibits the Cronin-effect expected from multiple scattering of entrance channel partons, giving an increase in yield at transverse momenta above 2-3 GeV/c, relative to that expected for a single-scattering of entrance-channel partons. In contrast, the yields for Au+Au exhibit a strong decrease relative to a simple scaling-up of p-p yields to account for the large number of binary nucleon-nucleon collisions in a heavy-ion collision; R_{AA} values as low as 0.2 are found, suggesting the matter formed is highly opaque to probes carrying color-charge. This is known as jet suppression and is observed for single final-state particles at transverse momenta above 2 GeV/c, persisting out to as high as pt= 20 GeV/c, the limit to which integrated luminosity allows measurements to be made. Theoretical interpretation favors gluon density in excess of 1000/unit rapidity. [10]

A distinctive split between suppression behavior of mesons and baryons as a function of transverse momentum is observed, with mesons exhibiting turn-on of suppression at lower transverse momenta than baryons. [11] This is again suggestive of recombination picture noted in the discussion of milestone DM2, wherein the behavior of valence quarks is the determining factor. Comparison measurements of jet suppression for d+Au shows an opposite behavior to Au+Au as function of centrality, with in fact increasing R_{AA} for more central d+Au events, similar to p+p behavior extrapolated to an extended nucleus. This rules out a dense assemblage, e.g. of gluons in a cold Au nucleus, as an explanation of jet suppression seen in Au+Au, and instead requires the origin of the jet suppression to be in the properties of the medium created in the Au+Au collision. It is very difficult for a colored object to penetrate this medium without large fractional energy loss, if indeed such an object can penetrate at all.

What was not expected was where attempts to answer the question "where does the 'lost' energy go" would lead, i.e. does it result in increased transverse momentum for all the fragmentation products of the parton, or creation of several more particles with transverse momentum near the average, or a general response of the bulk medium itself. Early observations of the recoiling jet in Au-Au collisions by looking just at high transverse momentum particles, as familiar from earlier studies of jet fragmentation, showed an apparent complete loss of the recoiling partner jet [12]. Selecting only particles above 4 GeV/c indicates a loss of the expected correlated jet partner at 180 degrees opposite in azimuth. This does not signal non-conservation of momentum, which would be a shock, but something else that should help understand what is occurring. One does see this recoiling partner jet in p+p collisions, as expected for an interpretation of the jets as elastic hard-scattering of entrance-channel partons; both partons will fragment independently to the observed hadrons, thus one can detect both jets by tagging high-momentum particles. The recoiling jet is broader then the triggered one, already in p-p collisions, which can be understood from intrinsic parton transverse momentum in a proton coupled with transverse momentum generated as the scattered parton fragments into the observed hadrons. One also sees a similar pattern of trigger jet and recoiling jet for d+Au collisions, as expected if this reaction just probes cold nuclear matter. The disappearance of energetic particles opposite a trigger particle, which has been measured for Au+Au collisions and now also Cu+Cu ones, instead is signaling that the recoiling jet is broadened much more in heavy-ion than in p+p collisions and apparently is composed only of particles with very low transverse momentum, with mean transverse momenta characteristic of that seen for the bulk of the particles produced in the collision final state. [13] This is quite different from the behavior in p-p collisions and again suggests the recoiling jet interacts very strongly with the bulk medium. A careful removal of the collective flow from the correlation is an essential step in such analyses.

What remains to be done to complete the original milestone as written?
The Milestone is complete.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
Among the many questions following the discovery of jet quenching is whether the medium's opacity saturates in the densest regions and whether the hadrons observed are descended from jets originating at the outer surface of the reaction zone, also known as "surface bias". Hadron pairs can provide more information, but their modification and detection is still intertwined with the location of their parent partons' origin in the medium. For this reason a long-sought measurement is the detection of high transverse momentum hadrons correlated with high transverse momentum direct photons. [14] Because the photon's interaction with the medium is relatively weak, if such pairs are triggered on the photon they could be nearly free of surface bias and provide a direct measure of parton-medium interactions and energy loss due to this improved control of kinematics. Very recent work is studying whether the recoiling jet "shocks" the medium, resulting in a pattern similar to the Mach cone familiar from supersonic travel in a gas, or whether

some other pattern is manifest. [15] Study of propagation of heavy quarks will help tie together jet production, energy transfer, and thermalization. [16] (See also the discussion under DM7.) Other efforts study for example correlations in quark flavor of the hadrons and correlations in the rapidity coordinate. These studies require performing double and triple correlation measurements in- and out-of-plane. Many such studies are underway and captured in new Milestone DM10.

Is the milestone complete? Yes

Bottom Line Status Assessment: Exceeded

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Milestone DM4 (2009): Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC.

What has been accomplished toward milestone DM4 and what has been learned from the information gathered?

A summary of the first 5 years running of RHIC is given in the set of jointly-published papers from the four experiments [1] where the experimental and theoretical arguments are collected for, among other observations, the conclusion that a nearly-perfect fluid is formed in relativistic collisions of heavy nuclei. The large elliptic flow observed in non-central collisions is a chief part of the evidence [2]. Elliptic flow, characterized by the second Fourier coefficient v_2 of the azimuthal angular distribution of detected particles [3], measures the final state momentum anisotropy that is generated by anisotropic pressure gradients in the spatially deformed nuclear collision zone. Various calculations suggest that the elliptic flow is generated early in the collision (see [2] and references therein) and present before the partons coalesce or fragment into hadrons [4]. An efficient conversion of spatial anisotropies into elliptic flow requires strong interactions among the constituents of the fireball medium. Two-body interactions between partons with perturbative QCD cross sections fail to generate enough elliptic flow to reproduce the data [5]. So far the best overall description of the RHIC data is obtained with models that couple a relativistic hydrodynamic stage, which treats the quark-gluon plasma (QGP) phase as an ideal fluid [2], to a realistic hadron cascade to describe the dissipative dynamics in the late hadronic stage [6,7,8].

This leads to the surprising conclusion that the QGP is strongly coupled and not weakly interacting as had long been expected. The success of thehydrodynamic models requires a very low ratio between shear viscosity and entropy density [9], corresponding to extremely short mean free paths. With initial conditions for the spatial eccentricity taken from the Glauber model [10], the elliptic flow data leave practically no room for any appreciable shear viscosity in the QGP phase [7,11]. An alternateapproach based on the Color Glass Condensate model gives larger initial fireball eccentricities [7,12]; in this case, calculations that treat the QGP as an ideal fluid overshoot the measured elliptic flow, opening a window for non-zero QGP shear viscosity to suppress v_2 to its measured value [7,11]. Various proposals to experimentally distinguish between such different initial conditions have been made [13,14,15] but are still under discussion.

Theoretical work on strongly coupled conformal quantum field theories, using techniques developed by superstring theory, suggests that for any real fluid the shear viscosity to entropy density ratio has a lower limit of $1/4\pi$ in natural units [16]. This is well below the previously calculated values for a hadron resonance gas below the quark-hadron transition [17] and for a weakly coupled QGP [18]. The accurate determination of QGP transport coefficients using lattice QCD is within reach [19], with first results suggesting values relatively close to the theoretically conjectured lower limit. Recent success in developing numerical algorithms to solve the equations for dissipative relativistic hydrodynamics [11,20,21] promises that we should soon be able to extract the QGP shear viscosity from measured elliptic flow data. First results from this phenomenological approach also suggest very small viscosity/entropy ratios, with values larger than about 5 times the conjectured lower limit almost certainly excluded [11].This is consistent with models that describe the dynamics of the long-wavelength modes of QCD at and just above the critical temperature as a classical, non-relativistic gas of color-charged quasi-particles [22],and makes the QGP the most perfect real fluid ever observed in the laboratory [23].

Whereas codes for viscous relativistic hydrodynamics are presently only available in 2+1 dimensions, describing the transverse expansion of longitudinally boost-invariant systems, ideal fluid dynamical codes in 3+1 dimensions have now been available for several years [8,23]. They have recently been used to perform calculations of jet quenching, parton energy loss and direct photon production in expanding fireballs with realistic collision geometry and temperature history[25,26,27]. The ideal fluid dynamical model in 2+1 [28] and 3+1 dimensions [29] has also been used to study the response of the medium in the collision zone to energy-momentum lost by fast partons traversing the fireball at supersonic speeds and the possible formation of Mach cones; more work is needed, however, to improve the coupling between the jets and the fireball medium [30].

What remains to be done to complete the original milestone as written? What additional/new data should be taken or theoretical efforts modified or added to address the underlying scientific question?

Realistic modeling of the collective dynamics in heavy ion collisions requires a combination of hydrodynamic methods for the early collision stage with a realistic kinetic theory of the late hadronic stage [6,7,8] Further studies on viscous hydrodynamics are needed; for a complete description of the expansion dynamics it needs to be generalized to 3+1 dimensions. Further work on the conjecture from supersymmetric Yang-Mills theories [16,23] and its implementation in realistic 3-dimensional simulations is needed to see where else these can make contact to observation in heavy-ion collisions and address conceptual issues such as lack of a running coupling constant, no evident thermodynamic phase transition and no asymptotic freedom, all properties of the more-familiar QCD. A new Milestone DM9 (2012) addresses these issues.

Is the milestone complete? No

With over a year to go on this milestone, good progress is reported and a program to do the calculations is in place, but the timeline is still demanding.

Bottom Line Status Assessment: Expect to Achieve

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Milestone DM5 (2010): Measure the energy and system size dependence of J/Ψ production over the range of ions and energies available at RHIC.

What has been accomplished toward milestone DM5 and what has been learned from the information gathered?

This Milestone addresses a continuation of the physics noted under Milestone DM1 above.

Measurements have been performed on p-p [1], d-Au [2], Cu-Cu [3] and Au-Au [4] collisions, at various energies, although most data of adequate statistics for J/ψ has been recorded for $\sqrt{s_{NN}}$=200 GeV. Some data have been recorded at $\sqrt{s_{NN}}$=62 GeV for p-p, Cu-Cu, and Au-Au collisions. A very recent d-Au data set was recorded with a factor 30 higher events than the original 2003 dataset, which is the source of results published to date. The J/ψ cross section has been determined at y=0 and y=1.2-2.4 forward rapidity. Transverse momentum spectra are measured out to 6 GeV/c and yields vs number of participant nucleons have been extracted for d-Au, Cu-Cu and Au-Au collision systems at $\sqrt{s_{NN}}$=200 GeV. These results show that the suppression and mean-squared transverse momentum observed for central rapidity in Au-Au persists in Cu-Cu at a similar level when expressed as a function of the number of nucleon participants in the collision. The suppression observed at RHIC at mid-rapidity is similar in magnitude to that observed at the CERN SPS. Suppression is found to be larger at forward rapidity y=.2-2.4. These results are not consistent with a simple prediction that increasing suppression only depends on increasing local energy density. They remain consistent with theoretical models positing recombination of uncorrelated charm-anti-charm quark pairs. [5] The theoretical models tuned to reproduce the CERN SPS Pb-Pb J/ψ data at $\sqrt{s_{NN}}$=17.6 GeV over predict the expected suppression for the RHIC data. Models positing recombination of initially-uncorrelated c-cbar pairs can be tuned to match the RHIC results, although rapidity dependence and transverse momentum spectra remain a challenge. A measurement of the charm quark cross section is needed to test input assumptions for such models; some initial results have been reported [6]. The d-Au results suggest some of the observed suppression may be due to cold matter effects but these constraints have been shown not to be definitive.

What remains to be done to complete the original milestone as written?

Further analysis and data running are in the RHIC near-term run plan for $\sqrt{s_{NN}}$ of 30 and 62 GeV. Runs at lower center of mass energy are planned for searches for critical point (see proposed new Milestone DM11), but collider luminosity drops as the square of center of mass energy above transition energy in RHIC, which is 26 GeV. Below that the luminosity drops more quickly and the interaction diamond also grows in size, making runs below 20 GeV or thereabouts quite difficult. Because the CERN SPS program took data for systems up to Pb-Pb at $\sqrt{s_{NN}}$=17.6 GeV, this is not an overwhelming problem, but the CERN datasets do not always have p-p and p-A reference data, which are required to establish baseline J/ψ cross sections and isolate cold-nuclear-matter effects.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

More data for lower energy running, $\sqrt{s_{NN}}$=62 GeV and lower, is needed, both to improve statistical accuracy of the results and establish new data points. Reference data from p-p and d-Cu and d-Au collisions is needed to set the baseline and quantify cold nuclear matter effects on the yield, rapidity and transverse momentum spectra. Running at RHIC energies below transition energy ($\sqrt{s_{NN}}$=26 GeV in RHIC) may prove difficult to obtain needed statistics; fixed target runs at the CERN SPS address this energy region but need p-p and p-A runs to establish the same baselines. Measurements of charm and bottom quark production in p-p, d-Au and Au-Au collisions over a wider kinematical range than the presently-covered mid-rapidity are needed both to test predictions of recombination models and establish contact with pQCD calculations. Calculations do exist for fixed-order next-to-leading-log (FONLL) in pQCD. [7] A better understanding of why these underpredict experimental cross sections by a factor of 2 or m ore is needed, however. Theoretical work on analysis of gluon distribution modifications in nuclei, on improving predictions of pQCD for example by improved treatment of next to leading order calculations, and on production cross sections and recombination probabilities for open charm is needed. To tie the last to measurement, calculation of bottom quark production cross sections is also needed.

Is the milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

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Milestone DM6 (2010): Measure e^+e^- production in the mass range $500 \leq m_{e+e-} \leq 1000$ MeV/c2 in $\sqrt{s_{NN}}$ = 200 GeV collisions.

What has been accomplished toward milestone DM6 and what has been learned from the information gathered?

Initial experimental results have been presented for p-p and Au-Au at $\sqrt{s_{NN}}$=200 GeV from RHIC. [1] New results have also been presented for $\sqrt{s_{NN}}$=17 GeV In-In collisions in fixed-target kinematics at the CERN SPS. [2] Results are in hand for central rapidity out to a transverse momentum range above 1 GeV/c. The mass range has been covered from down to 100 MeV/c^2, where Dalitz decays from neutral pions overwhelm any signal, to above the φ meson, with cross sections for the ω and φ mesons decaying to e^+e^- also extracted. The mean transverse momentum of pairs is found to increase with increasing pair mass out to the φ mass, a trend expected for objects experiencing hydrodynamic flow. A calculation of expected yields from hadronic sources, including Dalitz and combinatorial yields, arising from electromagnetic and semi-leptonic decays of in particular hadrons produced in the reaction, has been prepared and compared to the measured yields. This is seen to reproduce results from p-p and peripheral Au-Au collisions, while the yield for central Au-Au collisions shows a factor of 5 excess over this calculated yield.

New measurements of the yield of real photons, using the technique of converting the photons in matter and measuring the resulting e^+e^- pairs, have also yielded data on this spectrum.

What remains to be done to complete the original milestone as written?

Despite these successes, a better means to identify and reject Dalitz decays of π^0 and η mesons and pairs due to converted photons is needed. A proximity-focused Cerenkov counter tuned for the relevant momentum region and largely insensitive to atomic ionization due to passing charged particles, known as a hadron-blind detector (HBD), has been developed and will be deployed at RHIC starting in FY2009. This will enable improved rejection of background and false pairs, resulting in better signal/noise of the primary signal. Operation of RHIC with p-p and Au-Au beams at $\sqrt{s_{NN}}$=200 GeV is then needed to collect the required datasets, whose analysis needs then to be completed.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

The above datasets will complete the base measurement program. Parallel work at the CERN SPS will better establish yields for $\sqrt{s_{NN}}$ around 20 GeV and lighter systems. [2] Theoretical work describing likely sources of continuum low-mass lepton pairs has focused in one case on in-medium modifications of the ρ-meson, resulting in a prediction of a decrease in its mass in-medium and a broadening of its line-shape, and in another on scattering of $\pi^+\pi^-$ pairs resulting in e^+e^- pair creation. An understanding of whether the reported yield enhancement in central Au-Au collisions and central In-In collisions at lower center-of-mass energies results from a deconfined phase or arises in the hadronization stage (e.g. modification of the ρ line-shape) or from final-state interactions leading to chemical and kinetic freezeout ($\pi^+\pi^-$ scattering) remains unsettled. [3], [4])

Is the milestone complete? No

Overall, substantial progress towards this milestone has been made and the significant investments in HBD development, construction and testing are resulting in deployment at this time. A focused effort will be needed to acquire final datasets and analyze them by the 2010 deadline.

Bottom Line Status Assessment: Expect to Achieve

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Milestone DM7 (2010): Complete realistic calculations of jet production in a high density medium for comparison with experiment.

What has been accomplished toward milestone DM7 and what has been learned from the information gathered?

Insertion of a high-momentum probe into the medium created in a relativistic heavy-ion collision and observation of the resulting modification of that probe's space-time history due to the presence of the medium is a promising method to diagnose the properties of the medium. Initial theoretical suggestions included study of jet-quenching [1] and search for suppression of yields of high-p_T particles [2]. Studies of jet production utilize the partons produced via hard-scattering collisions at the outset of the overall nuclear collision to insert such a probe in the early stages of the collision and then have a method of separating it out from all the other products of the collision by selecting final-state particles of large transverse momenta of several GeV/c. The primary rate and spectra of such probes can be calculated in pQCD for p-p collisions, and an ansatz for the initial production in a heavy-ion collision can be made as a superposition of such nucleon-nucleon collisions in order to account for the number of primary nucleon-nucleon binary collisions. First observations of the spectra of such jets were noted earlier under Milestone DM3.

A deconfined system comprised of color-charged quarks and gluons would be expected to modify strongly the final state yields of high p_T hadrons fragmented from jets relative to those for p-p collisions, possibly by causing enhanced energy loss of the scattered parton to other partons present before it fragments, or effectively by modifying the fragmentation function of the parton. To interpret the experimental observations requires an understanding of the propagation of the scattered partons in the medium produced. A color-charged object traversing a dense color-charged medium, for example an initially produced quark or gluon propagating through the dense medium created in a high-energy heavy-ion collision at RHIC, can exchange energy with its environs in a number of ways, including radiation of gluons, elastic scattering from other quarks or gluons present, creation of a quark-antiquark pair or radiation of photons. The first two mechanisms are evident candidates for rapid exchange of energy with the surrounding medium. Calculations of energy loss followed by fragmentation in vacuum is more developed than those of modification of hadronization in-medium. Early theoretical work concentrated on parton propagation in medium and induced radiative energy loss. [3][4][5] Using perturbative QCD and taking into account the Landau-Pomeranchuk-Migdal interference effect [6] the radiative energy loss can be calculated. Major current jet modification schemes include those of Gyulassy, Levai and Vitev (GLV), of Armesto, Salgado and Wiedemann (ASW), of Arnold, Moore and Yaffe (AMY), and the higher twist method of Majumder and Wang. A definite dependence on the path length traversed and the local gluon density of the medium results. Such energy loss is manifest as a modification of the effective parton fragementation functions, which appears as a suppression of yields of high-pT final state hadrons in experiment. [7] For non-central collisions the path-length dependence results in a azimuthal-angle dependence of the spectra. [8] One can study multiple-hadron correlations inside jets that arise from multiple-scattering of the parton in the medium. [9]

Initial analysis of experimental results (see discussion under DM3 for references to these) suggests the qualitative features are indeed due to parton energy loss [10] with an extracted initial gluon density some 30 times than in a cold Au nucleus. [10][11][12] This very high density of scattering centers would be also consistent with rapid thermalization needed to understand the magnitude of collective flow observed, discussed under DM2.

The experimental data suggest that a highly opaque medium is created, possibly causing so much energy loss, or interaction with the medium, that no parton from the center can penetrate. The interpretation of results may well be complicated by the fact that the observed fragmentation of partons to final hadrons does not follow directly from that well-studied for p-p collisions, because for example the ratio of meson/baryon content is notably different at intermediate transverse momenta of a few GeV/c. This has been attributed to quark recombination just before hadronization of the quark gluon plasma. [13][14][15]. Extensive current work examines modification of fragmentation functions from quark recombination, This is done in finite temperature field theory and includes effects from recombination of shower and thermal constituent quarks. [16] This work also derives QCD evolution equations for the quark distribution functions that in turn determine the evolution of the effective jet fragmentation functions in a thermal medium, which one needs to tie to experiment. Very recent work performs jet quenching calculations in a three-dimensional hydrodynamical medium. [17]

The "tomographic" results for light quarks are however expected to be fragile, in that there is a significant reduction in sensitivity of the attenuation to the density of the matter traversed when gluon jets originating from the interior are too strongly quenched. [18] One method to address this is to study mesons containing heavy quarks, such as D or B mesons, since there is negligible probability that a gluon will fragment into such a meson. An early model for heavy (i.e. charm or bottom) quark propagation in a hot dense color-charged medium assumed that the large mass of the heavy quark greatly reduced bremsstrahlung of gluons in the forward direction ("dead-cone effect") compared to the case for light (up, down, strange) quarks. [19] The high mass of charm and bottom quarks changes the sensitivity of elastic and inelastic energy loss in a well-defined way. [20][21][22][23][24]. Intensive current work has established now expectations for bottom quark jet quenching and its influence on the single-electron spectra observed. [25]

This led to an expectation for less energy loss by heavy quarks, an expectation evidently not borne out by experiment. Indeed the suppression for heavy quarks, as determined via their semileptonic decays to e or μ, [26] [27] is similar to that seen for particles comprised solely of light valence quarks. It is also seen that the v_2 of particles containing charm quarks is similar for those having only light quarks. Very recent work, that may well hold the key to this issue, has emphasized that there are medium modifications to the gluon dispersion relations which induce collisional energy loss, a mechanism for energy loss which does not exist in the vacuum. [28]

A new area of focus is the response of the medium to a traversing swift parton (see also DM3). Very recent work is studying whether the recoiling jet "shocks" the medium, resulting in a pattern similar to the Mach cone familiar from supersonic travel in a gas, or whether some other pattern is manifest. [29] A structure in longitudinal space, the "ridge" has also been seen and intensively studied. [30]

What remains to be done to complete the original milestone as written?

Values of key model parameters for energy loss such as the average p_T broadening per unit distance, qhat, which also controls both elastic and radiative parton energy loss, extracted from the experimental data have not converged among various phenomenological studies. [31] A coherent effort among theorists and experimentalists to extract such medium properties is needed. This requires a consistent implementation of the dynamical nature of the expanding collision fireball. The magnitude of radiative vs. elastic energy loss needs to be established. The fragmentation of partons in-medium requires continued theoretical study and improved experimental data especially on back-to-back dihadron correlations and photon-hadron correlations. [32]The studies of charm need to be extended to forward rapidity, and ability to reconstruct D and B mesons directly is needed to separate the behaviors of charm and bottom quarks.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
A coherent accepted picture of the relevant mechanisms for energy loss relevant for a dense colored-charged and dynamically expanding medium is needed.

Is the milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

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Milestone DM8 (2012): Determine gluon densities at low x in cold nuclei via p + Au or d + Au collisions.

What has been accomplished toward milestone DM8 and what has been learned from the information gathered?

The physics question is whether there is evidence for large density of gluons at low momentum fraction in the nucleon. We know from H1 and ZEUS data taken at HERA that the density of gluons increases sharply at low momentum fraction. [1][2] A nuclear environment may increase this; the question is by how much. The result bears on a number of issues, including the structure of nuclei for very soft quanta, the existence of a novel phase of nuclear matter, the color-glass condensate, and the production rate from nuclei of photons and heavy quarks, such as charm and bottom quarks.

Results from the first d-Au runs at RHIC, in 2003, are published. [3] The just-completed d-Au RHIC run in 2007-8 had 30 times the integrated luminosity as the earlier one in 2003. New detectors have been added to cover forward kinematics, such as the forward EMCal in STAR and the MPC in PHENIX. Measurements can be made, at forward rapidities, of photons, of J/ψ, and of continuum lepton pairs. [4] The photon production has a tree-level quark-gluon scattering term. The production of J/ψ depends on gluon-gluon fusion, although whether in the singlet or octet channel is under debate. One can tie to fixed-target results such as from FNAL E866. Lepton pairs depend at tree-level on the number of quarks and antiquarks present. All these thus serve as direct probes of parton densities, with the lepton pairs serving as a check on the other two. There are two routes to access the required low Bjorken-x, i.e. low momentum fraction, of order 10^{-3}. This means at RHIC one needs to go to forward angles to achieve low x_2 as well as an invariant mass or Q^2 large enough that pQCD is thought to describe the situation; several measurements are published. [5] The other option is to increase $\sqrt{s_{NN}}$ in order to be able to measure at mid-rapidity with large enough mass or Q^2 for pQCD to be applicable. This requires $\sqrt{s_{NN}}$=2 TeV, meaning measurements at the LHC in central rapidity are needed.

What remains to be done to complete the original milestone as written?

Currently obtained results must be analyzed. Runs for p-p reference with new detectors in place are needed. The new vertex detectors foreseen for STAR and PHENIX and forward calorimetry for both enable detailed measurements at forward angles, thus requiring further d-Au and p-p runs when they are installed in the next few years.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

Development of the theory of high-gluon density, direct-photon production and heavy flavor production in nuclei will help. [6] RHIC is not a precision machine in the sense of an e-A collider where one can see scaling violations and from these extract gluon densities. One does have a Born-term production diagram, however, in the form of the gluon-quark Compton term. Thus one needs theoretical study of possible modifications of gluon densities in cold matter and prediction of the level of precision needed in measurement and the relevant kinematic ranges where experimental data are needed. [6], [7]

Is the milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

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Appendix 7: Nuclear Structure Milestones

Milestone NS1 (2006): Measure changes in shell structure and collective modes as a function of neutron and proton number from the proton drip line to moderately neutron-rich nuclei.

What has been accomplished toward Milestone NS1 and what has been learned from the information gathered?

For decades the cornerstone of nuclear structure has been the concept of single-particle motion in a well-defined potential leading to shell structure and magic numbers. Shell structure impacts fundamental properties of the nucleus such as its mass, its shape, and its possible modes of excitation. This Milestone reflects the perception taking shape early in the decade that the magic numbers are not immutable: their presence (or absence) depends on the neutron-to-proton asymmetry and the binding energy, and this has consequences for every nuclear property, including collective modes.

There has been substantial recent progress in elucidating both the shell structure and collective aspects of nuclei. By expanding our perspectives, this research has opened new avenues of study and raised new questions. The quest for a coherent description of the entire nuclear landscape has led to a closer integration of theory and experiment, and future goals are emerging.

Perhaps the most dramatic recent achievement reflects a key aspect of the Milestone NS1; e.g., the deepening of our understanding of single-particle nucleonic motion. It is now recognized that the traditional magic numbers, 8, 20, 28 and 50 found along the valley of stability are evanescent in neutron-rich nuclei and that new magic numbers [1-3], such as 14, 16 and 32, appear for certain combinations of proton (Z) and neutron (N) number. Knockout reactions [4] are revealing how the purity of single-particle motion is sensitive to the binding of nuclear systems. Studies [5,6] near ^{100}Sn and ^{132}Sn are mapping shell gaps in heavy doubly-magic nuclei far from stability. Studies of Sn isotopes between these two extremes in mass have uncovered unexpected, drastic changes with neutron excess of the relative energy between specific single-particle orbits [7]. The discovery [8,9] of new superheavy nuclei, possibly up to Z = 118, and new spectroscopic studies [10,11] of nuclei near Z=100, have contributed significantly to advancing our understanding of the shell-stabilized binding of the heaviest systems which are dominated by hugely disruptive Coulomb forces. A new paradigm for determining the superheavy shell gaps has emerged from this spectroscopy (see Milestone NS2).

Sensitive studies [12,13] of collective behavior have focused on nuclei in shape/phase transitional regions, and have led to the development of new descriptions of phase structure and coexistence at the critical point, and to a revised understanding [14] of how structure evolves in regions of emergent collectivity. New regions of low-lying shape coexistence [15,16] have provided stringent tests of our ability to understand the dependence of nuclear binding energy on shape [17]. At the highest nuclear spins, the discovery [18] of rotational states beyond the band termination point has challenged our understanding of the interplay of single-particle and collective degrees of freedom. New modes of excitation (wobbling mode of a triaxial nucleus [19], chiral rotation [20]) have been proposed and their properties are being explored.

Nuclear theory has witnessed significant advances. These follow the themes of the 2007 Long Range Plan in understanding how complex many-body objects arise from their constituent ingredients, and identifying and understanding the remarkably simple patterns that are found in nuclei. A well-defined theory strategy has been developed to incorporate techniques ranging from ab-initio calculations to density functional theory, and to collective and algebraic models (see Milestone NS6). Successes include the precise prediction [21] of the recently measured charge radii of ^{6}He and ^{8}He, and density functional theory predictions of quadrupole collectivity [22] and valence proton-neutron interactions [23].

What remains to be done to complete the original Milestone as written?
The original goals have been met, and in several mass regions the objectives have been far exceeded and unanticipated phenomena have been uncovered.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
To pursue these scientific questions further requires extensive new data, especially on neutron-rich nuclei far from stability, on nuclei with N~Z, on very heavy systems, and on key nuclei near stability. At the same time, development of a variety of theoretical techniques to address structural behavior in marginally-bound nuclei, in nuclei with competing many-body degrees of freedom, and in the heaviest nuclei are urgently needed.

Is the Milestone Complete? Yes
The recent progress in elucidating both the shell structure and collective aspects of nuclei illustrated above satisfies and, in fact, far exceeds the objectives of the Milestone.

Bottom Line Status Assessment: Exceeded
To capture further progress in this area after the date of this Milestone, a new Milestone NS9 with due date of 2018 is proposed:

> **Measure changes in shell structure and collective modes, from the most proton-rich to the most neutron-rich nuclei accessible, in order to improve our understanding of the nucleus, and to guide theory in every region of the theoretical roadmap (i.e., the light-element region where ab-initio calculations can be performed, the medium-mass region where effective interactions are used, and the region of heavy nuclei, the domain of density functional theory).**

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Milestone NS2 (2007): Measure properties of the heaviest elements above Z~100 to constrain and improve theoretical predictions for superheavy elements.

What has been accomplished toward Milestone NS2 and what has been learned from the information gathered?

Superheavy nuclei; e.g., nuclei with proton number beyond Z = 100, represent a frontier of nuclear science. The average attraction between nucleons is offset by the Coulomb repulsion between protons, and this balance is especially sensitive to the properties of nucleon-nucleon interactions; hence, it impacts the ordering and spacing of the quantum states near the Fermi surface. Areas of low-level density cause a quantum shell-stabilization effect, which lowers the ground-state energy, and creates a barrier against fission, where none would otherwise exist. Locating the states near the Fermi surface, and probing the production of nuclei with ever higher Z is central for understanding this heavy frontier and predicting the border of the nuclear landscape at the limit of nuclear mass and charge.

Significant steps have been made in the measurement of the properties of the Z~100 nuclei that severely constrain present theoretical understanding. Among these figure: (a) the discovery of K isomeric states in ^{254}No [1,2] and other Z=100-103 nuclei [3] which determine the energies of single-particle levels responsible for shell gaps in the heaviest nuclei; (b) the study of high spin states in ^{253,254}No [4,5] which test the energy location and the evolution as a function of frequency and deformation of so-called high-j orbitals; and, most importantly, (c) the alpha decay energies of elements 112, and the recently reported elements 113-116 and 118 [6-8]. Because the cross sections involved are very small, each of these measurements represents a real "tour de force", pushing accelerators and detection systems to the very limits of their capabilities. Nuclear theorists now face significant challenges to insure that modern descriptions of nuclear structure correctly describe the structure of the nuclei near Z~100 before they can be relied upon to describe the structure of superheavy elements. While macroscopic/microscopic model calculations [9] predict a proton shell gap at Z = 114, self-consistent mean field calculations yield shell gaps at Z=120 [10] and/or Z=126 [11]. The new data provide stringent constraints on those theoretical models. To summarize, basic questions remain about the structure of the heaviest nuclei, in particular about the interplay between the Coulomb and strong forces in these systems [12].

What remains to be done to complete the original Milestone as written?

Several experiments have been done, studying a range of elements from Z~100, to the current limits of production (Z~118) which arise from the available integrated luminosities and the small production cross sections associated with the synthesizing reactions. This work has pointed to the new pathways noted below. Current efforts include production, nuclear spectroscopy and chemistry of several elements. Other challenges have arisen as a result of the recent data which will require future experimentation to extend the area as noted below.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

The synthesis of elements 112 and 114 by hot fusion reactions has been confirmed by physical [13] and chemical measurements [14,15]. Since the syntheses and decay properties of elements 112, 114-116 and 118 form a self-consistent body of work [6], the validation of the syntheses of elements 116 and 118 will, hopefully, soon follow and the discovery of element 117 will be achieved as well. The data from this large body of work [6] not only constrain nuclear theory, but also present a challenge to reaction theory in that the reported production cross sections with hot fusion reactions are surprisingly large and essentially constant. Furthermore, recent work with neutron-rich radioactive beams [16] appears to indicate another possible route towards the synthesis of superheavy nuclei with larger neutron excess, i.e., closer to the predicted N=184 neutron closed shell where long-lived superheavy elements are predicted by theory. The potential of collisions of massive nuclei for the production of superheavy nuclei remains to be explored as well. Also, the first chemistry of elements 112 and 114 has been reported [14,15]. While element 112 has been shown to be Hg-like but more volatile, in good agreement with Periodic Table trends, element 114 has been shown to be a volatile metal that is most likely gaseous at ambient temperatures. This property is completely unexpected and challenges current quantum chemical calculations.

Is the Milestone complete? Yes
In view of the results above, it is clear that the aim of this Milestone has been met. Despite the challenging nature of the measurements, an exceptional number of new data has been provided and this now represents a complete set of severe new constraints for theory as intended by the Milestone.

Bottom line status assessment: Achieved
To capture future progress in this area, a new Milestone is proposed for 2015. The following activities would be expected in pursuing this Milestone: (1) provide further constraints on the location of the single-particle orbitals thought to play a decisive role in the stability of superheavy elements; (2) improve experimental knowledge about the various reaction mechanisms proposed for the production of superheavy nuclei (such as cold and hot fusion, fusion with neutron-rich beams, and collisions between very heavy nuclei); and (3) improve theoretical predictions for structure and production of superheavy elements.

The new proposed Milestone NS8 with due date 2015 is:

> **Measure properties and production mechanisms of the elements above Z~102 to understand the nature and behavior of these nuclei, and to assist theoretical predictions for the stability, structure and production of superheavy elements.**

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Milestone NS3 (2009): Extend spectroscopic information to regions of crucial doubly magic nuclei such as Ni-78.

What has been accomplished toward Milestone NS3 and what has been learned from the information gathered?

As already stated in Milestone NS1, the cornerstone of nuclear structure is the concept of single-particle motion in a well-defined potential leading to shell structure and magic numbers. Recent experimental evidence indicates that magic numbers are not as immutable as once thought: they appear to depend on the neutron-to-proton asymmetry and the binding energy. Hence, the question arises whether nuclei originally postulated to be doubly magic truly are. Among those figure prominently nuclei playing an important role in the astrophysical rp- and r-processes, i.e., ^{56}Ni (Z=N=28), ^{78}Ni (Z=28, N=50), ^{100}Sn (Z=N=50) and ^{132}Sn (Z=50, N=82).

Pioneering experiments have now been performed in the vicinity of each of these four key doubly-magic nuclei to determine the fate of the "classic" magic numbers 28, 50, and 82. An exciting picture emerges from this first round of measurements:

- There is now evidence that the N=50 shell gap remains intact in the vicinity of ^{78}Ni and there are indications for strong Z=28 proton core polarization as neutrons occupy the $g_{9/2}$ orbit. These conclusions arise from recent data such as (a) the half-life of ^{78}Ni [1], (b) the established low-energy structure of ^{72,74,76}Ni [2], (c) the quadrupole excitation strength in ^{70}Ni [3], (d) low-energy Coulomb excitation and transfer data on Zn and Ge nuclei in the vicinity of ^{78}Ni [4-6];
- First information is now available on the single-particle structure outside ^{100}Sn and, in addition, there is increasing evidence for the important role of excitations across the Z=50 shell gap as ^{100}Sn is approached. The information is based on (a) the discovery of an excited state in ^{101}Sn [7], (b) the superallowed character of the ^{105}Te α decay [8], and (c) transition probabilities to the first excited states of the even $^{106\text{-}112}$Sn [9];
- The persistence of the N=82 shell gap in the A=130 region has now been established and knowledge of single-particle structure in the vicinity of ^{132}Sn has considerably improved. In this case, the evidence is based on new data on ^{132}Sn itself; i.e., the dipole strength distribution [10], the transition strength to the first 2^+ state in ^{132}Sn [11] and the transfer reaction d(^{132}Sn,^{133}Sn)p [12], as well as measurements of magnetic moments [13], of transition strengths [14] , and of beta- and isomer-decays [15] in nuclei in the direct vicinity of Z=50, N=82;
- The doubly-magic character of ^{56}Ni remains in doubt. While the first excited state has an high excitation energy, it is also characterized by a surprisingly large B(E2) transition probability [16,17]. Furthermore, recent new information on neighboring nuclei such as, for example, the magnetic moment of the ^{57}Cu ground state [18] or the B(E2) transition rates in the Ni isotopic chain [17] cannot be reproduced with shell-model calculations utilizing the most modern effective interactions.

What remains to be done to complete the original Milestone as written?

From the above it is clear that significant spectroscopic information has been obtained around these key doubly-magic nuclei, even though the experiments are at the very limits of what is achievable today. Further experiments to map out neighboring nuclei and learn more of single particle energies are needed. Doing this depends in part on the capabilities of the experimental apparatus and critically on the availability of the required unstable nuclei themselves, i.e., on the production rates possible at existing facilities.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

While the first results show the promise intended by the Milestone, more information is required (i) to confirm the present understanding of the observations, (ii) to track the evolution of structure with excitation energy, proton and neutron number in the direct vicinity of these key systems and (iii) to identify the driving forces behind structural changes. For example, the proton and neutron single-particle/hole spectra have to be mapped out and the location of excitations in ^{78}Ni and ^{132}Sn needs to be determined to provide theory with the input necessary to construct an effective shell-model interaction with predictive power or to test the applicability of other approaches that go beyond mean field.

The key doubly-magic nuclei ^{56}Ni, ^{78}Ni, ^{100}Sn and ^{132}Sn have been reached and valuable spectroscopic information has been obtained on these nuclei and their immediate neighbors. In view of the pace of progress over the last few years, there is reason to believe that additional information will be obtained within the next two years and the objectives of the Milestone will not only be met, but exceeded.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to exceed

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Milestone NS4 (2009): Extend the determination of the neutron drip line up to Z of 11.

What has been accomplished toward Milestone NS4 and what has been learned from the information gathered?

The location of the drip line is the point where nuclear binding is not sufficient for a given value of proton (Z) and neutron (N) numbers; i.e., it establishes the very limits of nuclear existence. While the proton drip line is relatively well established experimentally, yet not exactly for most even Z elements and not at all for the heaviest nuclei, the neutron drip line is poorly known due to the fact that the production of neutron-rich nuclei represents an almost insurmountable challenge. Yet, the importance of the most neutron-rich nuclei for nuclear structure cannot be understated as the exotic quantal systems expected to inhabit these boundary regions are predicted to exhibit new phenomena, new types of nucleonic aggregations. They are also likely to be the place where many key aspects of nuclear interactions will be isolated and amplified.

At the beginning of the decade, the location of the neutron drip line was known only up to oxygen with ^{24}O being the last bound isotope with Z=8. More recently, considerable progress in identifying systems with higher Z values has been made at the fragmentation facilities, most notably at the NSCL. For example, in 2007 the production of ^{44}Si (Z=14, N=30), ^{42}Al (Z=13, N=29) and ^{40}Mg (Z=12, N=28) were reported in Refs. [1,2]. The existence of other rare isotopes such as ^{34}Ne (Z=10, N=24) and ^{37}Na (Z=11, N=26) that had only been identified once previously [3,4] was confirmed as well. As part of this work, a new framework for describing the yields of the most exotic nuclei was established in Ref. [1], which was subsequently found to be in good agreement with the production yield of ^{40}Mg [2].

The observation of the stability of odd-odd ^{42}Al is somewhat of a surprise and indicates that a determination of the drip line for Z=11 maybe be more difficult than anticipated. In fact, the neutron drip line is only established with certainty if it can be demonstrated that an isotope with higher neutron number is unbound. This is a non trivial task as the production of the isotopes of interest by fragmentation reactions decreases drastically with increasing neutron excess, raising the possibility that low production cross sections rather than the lack of binding is the reason for non-observation. To address the issue, new techniques for studies of the properties of resonances in nuclei beyond the drip line, that can be applied to nuclei such as ^{25}O, have been developed [5].

What remains to be done to complete the original Milestone as written?

Specifically for Z=9-11, the present experimental situation is as follows. ^{31}F has been shown to be bound [6], as have ^{34}Ne and ^{37}Na [2,3]. However, these results do not necessarily define the location of the drip line. For example, ^{37}Na is the heaviest observed sodium isotope and a limit for the production of the odd-odd nucleus ^{38}Na can be established from the work of Refs [1,2], but the drip line should be considered as firmly established only once the even-odd nucleus ^{39}Na is shown to be unbound. A search for ^{39}Na or ^{35}Ne and/or ^{33}F might well be beyond the capabilities of current facilities, and is likely to require access to an exotic beam facility of the next generation, such as the FRIB described in the 2007 Long Range Plan.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

Improvements in the theory of nuclear binding energies coupled with the new results in this region may provide improved predictions about the location of the drip line. Considerable work is still necessary in this regard and the new results obtained thus far represent significant challenges to theory. For example, calculations with a number of models predicted ^{40}Mg to be unbound [2] although it is not.

Is the Milestone complete? No

With two years to go on this Milestone, one cannot state with certainty that the neutron drip line is established up to Z=11. Indeed, the surprising stability of some of the new isotopes discovered may indicate that the task is harder than expected. There is significant evidence that the drip line is quite close, as ^{38}Na is most likely unbound, but a conclusive search for ^{39}Na has not yet been completed. There is hope, however, that increased primary beam intensities will allow further progress within the next two years. In additions, based on the new data in this region, further insight on the location of the drip line may also come from improved theories. There is a dependence on improved beam intensity and accelerator running time worldwide to meet this Milestone. One must optimistically assume the search for ^{39}Na will be definitive.

Bottom Line Status Assessment: Expect to Achieve

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Milestone NS5 (2010): Complete initial measurements with the high resolving power tracking array, GRETINA, for sensitive studies of structural evolution and collective modes in nuclei.

What has been accomplished toward Milestone NS5 and what has been learned from the information gathered?

Construction has begun on GRETINA, an array of germanium detectors covering a quarter of a sphere around a target. The germanium detectors are of a novel design and are intended to provide the new capability of tracking the origin of the gamma rays by locating to within 2 mm the various interactions of the photons with the crystals.

The project is funded by the DOE Office of Nuclear Physics and received CD0 approval in October 2003, CD1 approval in February 2004, and CD3 approval in November 2007. To date, one prototype cluster of three germanium crystals and the first of seven production clusters of four crystals have been delivered, tested, and characterized. Each of these crystals is highly segmented, with 36 contacts on the outer surface. The mechanical design, including an optimized detector packing geometry and the support structure, is complete, and a prototype computer system has been purchased.

Gamma-ray tracking relies on knowledge of the positions and energies of gamma-ray interactions, determined from the digital analysis of the signal waveforms in the various detector segments. Fast digitizer boards for the many signals have been designed, and several prototype versions tested. An intelligent trigger system has also been designed; both digitizers and trigger operate properly in conjunction and meet all requirements. "Signal decomposition", the determination of interaction positions from the waveforms using real-time processing, represented a serious challenge; however, a signal decomposition algorithm for GRETINA that meets the stringent speed and accuracy requirements has been successfully developed and thoroughly tested.

In-beam tests using the prototype detectors, and preliminary versions of the signal decomposition and tracking algorithms, clearly indicate that the 2 mm position sensitivity required for gamma-ray tracking has been achieved. Moreover, a recent test using a collimated gamma-ray beam demonstrated a position resolution of 1.5 to 1.7 mm. These results demonstrate not only that gamma-ray tracking is technically feasible, but also that GRETINA will have the superb efficiency and resolution advertised. The array will be especially suited to the demands of gamma-ray detection at exotic beam facilities. Moreover, work on gamma-ray tracking has also spurred developments in gamma-ray imaging, with applications in homeland security and medical imaging. The impressive technical progress of the GRETINA project and of techniques related to gamma-ray tracking can be found in Refs. [1-10].

What remains to be done to complete the original Milestone as written?

Construction of GRETINA must be completed by February 2011, the time for which CD4 (project completion) is scheduled. Experiments utilizing GRETINA will begin upon completion. Based on the accomplishments of the last few years, it is clear that all challenges have been met and that the timely completion of the project rests solely with the availability of the appropriate funding and the ability of the detector manufacturer to deliver the crystals on time.

An initial deployment plan for GRETINA has been developed and presented to the funding agencies. This plan addresses an initial set of commissioning tests, and initial tests with beam followed by a subsequent program of first measurements. This program includes a timeline for moving among low-energy accelerator facilities in order to exploit the unique capabilities each of these offers in a timely manner. A possible initial suite of experiments at each facility is described as well. This approach will insure rapid production of first physics results, once the GRETINA array reaches CD4.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

The Milestone is evidently not yet complete and will not be completed by 2010. Although all technical challenges have been addressed and there are no showstoppers left, the project has experienced delays because of the situation regarding funding in the last decade and the scheduling and funding possibilities for initiating new MIEs. When this Milestone was written following the 2002 NSAC Long Range Plan, it was dated two years after the projected 2008 GRETINA completion date. However, at that time, GRETINA was not yet an official DOE project. GRETINA has since been funded, but with a DOE-approved CD4 date in 2011, and with physics operation expected to begin later that same year. Therefore, at best, this Milestone, which marks the completion of the first set of physics runs, will be likewise delayed by two years following the actual project completion date, to 2013.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Not Fully Achieve

We propose to add a revised Milestone NS7 by changing the date of the present Milestone to reflect the planned completion date of GRETINA in 2013.

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Milestone NS6 (2013): Carry out microscopic calculations of medium mass nuclei with realistic interactions, develop a realistic nuclear energy density functional for heavy nuclei, and explore the description of many-body symmetries and collective modes, and their relationship to effective forces.

What has been accomplished toward Milestone NS6 and what has been learned from the information gathered?

The ultimate goal of nuclear structure research is a unified microscopic understanding of the nuclear many-body system in all its manifestations, as well as of the remarkable simplicities and collective behaviors that these nucleonic systems display. This Milestone represents a significant step towards this challenging goal, and the fact that this Milestone was proposed for 2013 is commensurate with the challenge that it represents.

Considerable progress has already made towards meeting the Milestone. An important step in this context is the fact that the low-energy nuclear theory community has effectively organized itself in order to address the issue and has created a roadmap for theoretical progress [1] as well as embarked in collaborations such as SciDAC-2 [2]. Within this framework, new information regarding the fundamental interaction between nucleons is now available from fully dynamic lattice QCD calculations and chiral effective-field theory [3], and a universal low-momentum interaction has been proposed [4]. Benchmark ab-initio calculations for light nuclei and nuclear matter [5] have demonstrated that nuclear theory can be very quantitative in the description of complex many-body systems and their reactions. These calculations provide necessary input and constraints for more phenomenological theories of heavier nuclei. Building on past successes of shell-model methods, realistic calculations for mid-mass nuclei are now viable, and have led to a new, empirically derived, Hamiltonian applicable to nuclei in the mass range $40 \leq A \leq 70$ [6]. In addition, substantial work has also gone into providing a consistent description in the shell-model of both bound and unbound nuclear states [7]. Significant theoretical effort towards development of the universal nuclear density functional include, for example, the study of constraints on the form of the functional from effective field theory [8], global description of proton-neutron valence correlations [9], applications of density functional theory (DFT) to the description of the heaviest nuclei [10], and spectroscopic properties of first excited states [11], etc. Progress has also been made towards the development of a microscopic theory of large-amplitude nuclear collective motion necessary to describe fission and fusion processes [12]. Finally, the algebraic description of shape phase transitions in nuclei continues to progress, and new spectroscopic signatures have been proposed [13].

What remains to be done to complete the original Milestone as written?

Despite these successes, further progress is required to meet the objectives of the Milestone. Just to name a few, among these figure: development of a realistic nuclear energy density functional that is constrained by effective field theory and by the lessons learned from ab-initio approaches and a firm analysis of the associated uncertainties; expanding the bridge between descriptions of nuclear structure and nuclear reactions to provide a description of weakly-bound systems; bridging the gap between macroscopic and microscopic descriptions by providing a microscopic foundation for symmetry-dictated approaches.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

The above efforts may also be extended in related directions to improve connections to other aspects of nuclear physics. These would include: fully dynamical lattice QCD calculations with pion masses approaching the physical value to create a bridge between the physics of hadrons and nuclei; and developing a stringent framework for understanding in medium effects and renormalization of inter-nucleon interactions to remove the "model" from the shell model.

Is the Milestone complete? No

Overall, substantial progress towards this Milestone has been made and the significant investments in low-energy nuclear theory from the DOE are beginning to pay off. There is substantial optimism in the nuclear theory community that many of the critical theoretical methods and computational tools will be in place by 2013 to permit fully realistic calculations of medium-mass nuclei. That said, it is likely that fully reliable calculations of nuclei approaching the neutron drip line will, however, require data on nuclei off the line of stability that may not be available until the FRIB facility described in the 2007 Long Range Plan is operating.

Bottom Line Status Assessment: Expect to Exceed

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Appendix 8: Nuclear Astrophysics Milestones

Milestone NA1 (2007): Measure transfer reactions on r-process nuclei near the N=50 and N=82 closed shells.

What has been accomplished toward Milestone NA1 and what has been learned from the information gathered?
The synthesis of many of the heaviest elements in nature requires an astrophysical site where multiple, fast captures of neutrons is possible. This rapid process, r-process involves nuclei very far from stability, which have in the past been impossible to study. The most important nuclei to study are those near magic numbers where the process slows down. Measurements have been completed on N=50 nuclei ^{82}Ge and ^{84}Se [1,2]. These studies have allowed the determination of the mass of the r-process nucleus ^{83}Ge [1] for the first time, as well as the energy of the first excited state, which is important for understanding the structure of nuclei in this region. Angular distributions for the ground and first excited state were measured from which l-values for these two states were deduced and spectroscopic factors extracted. In the N=82 region, the excitation energies of the four bound low-l neutron single-particle states have been measured [3]. The $1/2^-$ state in ^{133}Sn has found to be significantly lower than previously published. Analytical work continues to extract the relevant astrophysical information from these data. Important information for calculating neutron capture cross-sections has been extracted from the data and compared to shell model predictions [4].

What remains to be done to complete the original Milestone as written?
Given the work in this area we consider the Milestone has been completed. There will be follow-up work to determine the implications of the work for astrophysical environments. In particular further analysis of the data on N=82 is needed. Final values for the single-particle $p_{1/2}$ state in both ^{133}Sn and ^{135}Te will be available soon. In addition, the work on this Milestone has raised additional, interesting questions. The energy of the 1^{st} excited state in ^{83}Ge is not well reproduced in shell model calculations[4]. This indicates that the $0f_{7/2}$ orbital needs to be included in shell model calculations of this region. This may be important for modeling what happens for the more neutron-rich N=51 isotones which are presently out of reach for direct reaction studies.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
A new Milestone to replace this completed one recognizes the importance of weak interactions in astrophysical environments. The proposed new Milestone NA9, with due date 2014, is:

Perform mass measurements and nuclear reaction studies to infer weak interaction rates in nuclei in order to constrain models of supernovae and stellar evolution.

Is the Milestone complete? Yes

Bottom Line Status Assessment: Achieved

The Milestone has been completed on time with the full scope covered; hence, we assign a rating of Achieved.

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Milestone NA2 (2009): Measure properties of and reactions on selected proton-rich nuclei in the rp-process to determine radionuclide production in novae and the light output and neutron star crust composition synthesized in X-ray bursts.

What has been accomplished toward Milestone NA2 and what has been learned from the information gathered?

A wealth of new observational data from space and earth-based observatories is now available on novae and X-ray burst sources. However, accurate modeling is not possible given the large uncertainties in key nuclear reaction rates. The past few years have seen substantial progress by measurement of selected reactions and the demonstration that the necessary nuclear information can be obtained. Measurements using both radioactive and stable ion beams have substantially reduced the uncertainties in key reaction rates that influence the production of γ-rays from the decay of ^{18}F, ^{22}Na and ^{26}Al in novae. Measurements using radioactive ^{18}F beams at the HRIBF have reduced the uncertainty in the $^{18}F(p,\alpha)^{15}O$ reaction rate (the largest uncertainty in the production of 511 keV gamma rays from novae at early times) by more than a factor of 10 [1,2,3]. Measurements of the $^{21}Na(p,\gamma)^{22}Mg$ reaction at TRIUMF-ISAC have reduced the uncertainties in that reaction rate (the most important for the production of gamma rays from the decay of ^{22}Na in novae) from a level of 5 orders of magnitude to only about 20% [4,5]. The most important resonance in the $^{26}Al(p,\gamma)^{27}Si$ reaction which influences the production of ^{26}Al in novae was measured at TRIUMF-ISAC, reducing uncertainties and increasing the expected contribution of novae to Galactic ^{26}Al by about 20% [6].

Stable beam measurements have continue to play an important role in helping to reduce the uncertainties in key reaction rates. Notable examples results from measurements at Yale [7], at Ohio University [8] and at the HRIBF [9] which greatly improved our understanding of the level structure of ^{26}Si and the $^{25}Al(p,\gamma)^{26}Si$ reaction rate, which contributes the largest uncertainty to ^{26}Al production in novae. Measurements at Orsay [10], at TUNL [11] and at the HRIBF [12] reduced the uncertainty in the $^{17}O(p,\alpha)^{14}N$ reaction rate (one of the largest uncertainties affecting ^{18}F production in novae) by more than 2 orders of magnitude to a precision of better than 20%.

Significant progress has also been made in determination of parameters for rp-process simulations. Precision mass measurements have led to big improvement in X-ray burst modeling and significantly reduced the uncertainties in the shape of the light curves near the end of the bursts [13,14,15]. In cases where direct measurements are not possible, new techniques have been developed to make indirect determination of the resonance parameters needed to calculate key reaction rates [16]. Near the termination of the rp-process a puzzling issue in the proton decay puzzle of ^{105}Sb has been solved clarifying branching in the Sn-Sb-Te cycle [17], and the details of the termination of the process are more clear.

What remains to be done to complete the original Milestone as written?

The Milestone as written is complete.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

A new Milestone is proposed to reflect expected future work in this area. A new Milestone should reflect the next step in this area, which is use nuclear data and improved models to infer information on the astrophysical sites. The proposed new Milestone NA10, with due date 2014, is:

> **Measure or constrain key nuclear reaction rates to improve accuracy of astrophysical models of novae and X-ray bursts and allow astronomical data to be used to infer novae and neutron star properties.**

Is the Milestone complete? Yes

Bottom Line Status Assessment: Exceeded

Given the tremendous progress in this field and the large body of relevant measurements this Milestone can be considered complete. Because it is completed two years early we consider the appropriate rating to be Exceeded.

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Milestone NA3 (2009): Perform three-dimensional studies of flame propagation in white dwarfs during type Ia supernovae.

What has been accomplished toward Milestone NA3 and what has been learned from the information gathered?

While not complete, significant progress has been made on this Milestone based on work at the DOE ASCI Center for Astrophysics and Thermonuclear Flashes. A key component has been the development of realistic components to the burning process. Calder and co-workers have developed and calibrated a realistic model flame for hydrodynamic simulations of deflagrations in white dwarf (Type Ia) supernovae [1]. The flame model builds on the advection-diffusion-reaction model of Khokhlov and includes electron screening and Coulomb corrections to the equation of state in a self-consistent way. The model was calibrated - energetics and timescales for energy release and neutronization - with self-heating reaction network calculations that include both these Coulomb effects and up-to-date weak interactions. The burned material evolves postflame due to both weak interactions and hydrodynamic changes in density and temperature. The model includes a scheme to follow the evolution, including neutronization, of the NSE state subsequent to the passage of the flame front. As a result, the model flame is suitable for deflagration simulations over a wide range of initial central densities and can track the temperature and electron fraction of the burned material through the explosion and into the expansion of the ejecta.

The first three-dimensional modeling based on this model is now complete [2]. Related work is also underway by groups in Europe. They have produced the first full-star three-dimensional explosion simulations of thermonuclear supernovae, but based on parameterized deflagration-to-detonation transitions [3,4]. The group has also performed detailed three-dimension studies of the dependences to various parameters [5]. They find that the luminosity and production of ^{56}Ni is critically related to the metalillicity and central density of the white dwarf, indicating the importance of determination of nuclear physics input.

What remains to be done to complete the original Milestone as written?
What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

Based on the work of these two groups, it might be argued that the general goal of this Milestone for 2009 has been reached. This does not, however, tell the whole story. The characteristics of the resulting Type Ia events differ for the two cases - largely due to the different assumptions incorporated into their respective treatments of the flame energetics and evolution. Future work, to fully complete the Milestone, will address the impact of many three-dimensional flow characteristics such as flame front curvature, acoustic behavior, flame front stability, and the effects of finite resolution. It will also define areas were additional input, such as nuclear physics data, is needed.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Exceed

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Milestone NA4 (2010): Reduce uncertainties of the most crucial stellar evolution nuclear reactions (e.g., $^{12}C(\alpha,\gamma)^{16}O$) by a factor of two, and others (e.g., MgAl cycle) to limits imposed by accelerators and detectors.

What has been accomplished toward Milestone NA4 and what has been learned from the information gathered?

The main uncertainty in the $^{12}C(\alpha,\gamma)^{16}O$ reaction is the extrapolation of the S-factor to lower energies. Several approaches have been taken by the community to reduce the present uncertainties and provide better structure and reaction data. This includes sub-Coulomb barrier alpha transfer reaction studies [1], measurement of ^{16}N beta-delayed alpha emission [2], and low energy direct capture measurements in forward [3] and inverse kinematics techniques [4,5]. R-matrix model simulations have been performed to improve the theoretical extrapolation of the reaction data [6]. The results have led to a significant reduction in the uncertainties of the reaction rate, and new simulations have been performed to study the effect on nucleosynthesis in massive stars [7].

Direct measurements of the $^{12}C(\alpha,\gamma)^{16}O$ reaction have reached the limits of sensitivity that are possible with today's detector arrays. For indirect measurements considerable progress has been made in better understanding the systematic uncertainties (which sometimes are of the same order of magnitude as the statistical errors). New information about phase shifts has been obtained and found to affect the values for S(E1).

The crucial nuclear reactions to the MgAl cycle were identified by Jose et al [8]. Of these, two of the most important $^{21}Na(p,\gamma)^{22}Mg$ [9] and $^{26}Alg(p,\gamma)^{27}Si$ [10] have been measured using the ISAC rare isotope beam facility at TRIUMF. The uncertainties in these reaction rates have been reduced by an order of magnitude from previous values.

What remains to be done to complete the original Milestone as written?

The results so far are significant, however, in part due to the availability of better observational data and improved stellar models, further improvements and data are necessary. Considerable progress has been made in many details of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, and taking all new data together they have reduced the uncertainty of one of the components (S(E1)) by up to a factor of two as required in the Milestone.

Other reactions important to novae and the MgAl cycle remain to be measured. Of particular importance is $^{25}Al(p,\gamma)$. A number of rare isotope beam facilities including ORNL and ANL in addition to ISAC may be able to determine this reaction rate in time for the Milestone.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

In order to complete the $^{12}C(\alpha,\gamma)^{16}O$ part of the Milestone, the E2 component of the cross section must be determined with similarly improved accuracies. All these measurements require time-consuming experiments using high beam currents, low backgrounds and well understood systematic uncertainties. The $^{12}C + \alpha$ phase shift data which are available in the literature need to be carefully compared and analyzed. The breakup of ^{16}O induced by gammas planned at the HIGS facility is an interesting new approach for measurements of S(E1) and S(E2), although so far the calculated sensitivities are too low by many orders of magnitude. Other progress will come from inverse kinematics techniques with high acceptance recoil separators being planned at TRIUMF (Canada), U. Naples-Caserta (Italy), and U. Notre Dame. Underground accelerator proposals are being considered at LUNA, Gran Sasso, ALNA, DUSEL that will contribute in the far future beyond the timescale of the Milestone. Photo-dissociation with real and virtual photons are being pursued and planned at HIX-TUNL and GSI, respectively. Improved beta-delayed alpha spectroscopy studies are being planned at ANL and U. Notre Dame.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

At the present time, considerable improvement has been made and an experimental program is in place to make additional progress. It is reasonable to expect that sufficient additional progress will be made that by 2010 the Milestone can be completed.

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Milestone NA5 (2011): Measure neutron capture reactions, including radioactive s-process branch-point nuclei, to constrain s-process isotopic abundances.

What has been accomplished toward Milestone NA5 and what has been learned from the information gathered?

An active program in this area is underway at US facilities to measure key neutron capture rates that will allow precise modeling of the heavy elements produced in older stars during their helium burning phases by a process of neutron captures over millions of years, the s-process. This work complements a broader program of the international community, in which the US participates, centered on measurements in Germany and more recently at the nTOF facility at CERN. Most important are measurements at s-process branch points. Each branch point gives a constraint on the stellar evolution models of different neutron densities, stellar temperatures and time scales. The timeliness of these measurements is driven by observational data from meteoritic inclusions and stellar spectra that are improving greatly in quantity and specificity. Concurrently, theoretical models of stellar evolution are also advancing very quickly.

Experiments on s-process branch-point nuclei have been conducted and are underway at the Oak Ridge Electron Linear Accelerator (ORELA) facility at ORNL and the Los Alamos Neutron Science Center (LANSCE) facility at LANL that will allow this Milestone to be met. Measurements of neutron-capture and total cross sections for isotopes of Pt at ORELA have resulted in the first determination of the neutron-capture reaction rate for ^{192}Pt - the heaviest isotope produced solely by s-process nucleosynthesis, for which the reaction rate had not previously been measured. Classical s-process calculations of the branching at ^{192}Ir, using these data, indicate that the neutron density during the s process is much lower than extracted from analyses of other branching points. This is the first time that the long-predicted freeze-out effect in the classical s process was "observed" [1].

At the Los Alamos Neutron Science Center (LANSCE), the Detector for Advanced Neutron Capture Experiments (DANCE) has been constructed and implemented to measure neutron capture cross sections on very small samples including radioactive s-process branch-point nuclei. Multiplicities of the gamma-ray cascades are determined by this highly segmented array of 160 detectors, and these data can be used to determine spins and parities of resonances [2,3,4]. Understanding the performance of this facility including the output of its 320 waveform digitizers and various sources of backgrounds has taken some time, but now the facility is quite well understood. Measurements have been made of capture cross sections on several nuclei of interest to astrophysics including ^{62}Ni, ^{102}Pd, ^{147}Sm, ^{151}Sm, ^{203}Tl and ^{205}Tl [5,6,7].

Measurements on ^{147}Sm using the new DANCE detector at LANSCE demonstrated a new technique for measuring the spins of neutron resonances in odd-A nuclides [8]. Analyses of these data revealed that the neutron-width distribution for resonances in ^{147}Sm changes shape, from being consistent with the expected Porter-Thomas (PT) distribution below a neutron energy of 350 eV, to being inconsistent with PT for the next 350 eV. This result reinforces an earlier non-statistical effect in this nuclide observed in measurements of the ^{147}Sm(n,γ) cross section at ORELA. No explanation of these effects is known, but because the nuclear statistical model routinely is used to calculate astrophysical rates for nuclides that are beyond current measurement techniques, their impact may be important [9].

Measurements on ^{95}Mo are underway at ORELA. These data are important to the understanding of isotopically anomalous Mo found in primitive meteorites. Current s-process models cannot reproduce these observations, and it has been predicted that the currently recommend ^{95}Mo neutron-capture reaction rate is in error.

What remains to be done to complete the original Milestone as written?
What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
Progress is steady on achieving this Milestone. Many more neutron-capture reaction rates on both radioactive and stable nuclides still need to be measured. In particular many more measurements on radioactive samples must be completed [10]. Further work, e.g. using DANCE with radioactive targets and to measure spins needs to be done. The improved understanding of DANCE and other detectors' response and reactivation of earlier techniques to establish spins will allow continued progress.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

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Milestone NA6 (2012): Measure masses, lifetimes, spectroscopic strengths, and decay properties of selected neutron-rich nuclei in the supernova r-process, and reactions to predict radionuclide production in supernovae.

What has been accomplished toward Milestone NA6 and what has been learned from the information gathered?

One of the main goals of nuclear astrophysics is to understand the origin and distribution in space and time of elements in the universe. One of the keys is achieving a sufficient understanding of nuclear physics to allow prediction of nucleosynthesis from supernovae models (or wherever it turns out the r-process takes place). By the time this Milestone is due, the goal is to have begun a program of study of nuclei relevant to the r-process and progress in refining nuclear models so that predictions can be made with quantifiable errors. Progress on the related question of the actual site of the r-process is also critical.

Considerable work continues on modeling and quantifying the conditions that may lead to an r-process. For example, recent studies indicate that conditions may be favorable in the shocked surface layers of O-Ne-Mg core collapse [1]. Other sites including the stranded neutrino driven winds in iron core collapse supernova continue to be studied.

At ISOLDE at CERN, half lives for ^{137,138,139}Sb have been measured as 470-, 313-, and 107 ms, respectively. [2] Half lives for ^{135,136,137}Sn have been measured as 530, 250, 190 ms, respectively as reported by Shergur et al.[3]. Half lives of 97 and 68 ms have been measured for ^{131,132}Cd, respectively, by Hannawald et al. [4]. These nuclei lie directly in the path of the r-process at neutron densities needed to produce elements beyond A = 130.

The half-life of the doubly-magic nucleus ^{78}Ni [5] has now been measured. In addition several new β-decay half-lives and branchings have been determined for β-delayed neutron emission for a range of neutron rich isotopes in the Fe-Zn range by taking advantage of event-by-event particle identification using fast rare isotope beams. Since this first experiment, a series of additional measurements have been conducted covering the element range from Co to Ru. In particular for the refractory elements in the Zr-Pd range the border of known β-decay half-lives could be extended considerably taking advantage of the chemistry independent production mechanism for fast rare isotope beams [6,7]. A surprise was the low branching for β-delayed neutron emission of ^{120}Rh, which directly affects the ^{120}Sn/^{119}Sn production ratio in the r-process as the decay chains following the r-process freezeout pass through this nuclide.

Significant progress on the application of Penning Trap mass spectroscopy to the measurement of neutron-rich nuclei has been achieved [8]. A series of measurements on nuclei approaching the r-process has been performed, and the results indicate that nuclei are systematically less bound than predicted. If this trend continues in more neutron-rich isotopes in the r-process region, it could have significant consequences for the r-process path.

What remains to be done to complete the original Milestone as written?

Whatever the site, understanding of nuclear structure will play a critical role in determining the final elemental abundances from any r-process. The solar system abundance pattern for the r-process indicates that the normal shell structure must be modified away from stability, so one of the goals of the Milestone is to determine to what extent this is true. Interestingly, some of the first in-beam experiments on N = 50 Ge–Se isotopes [9] and isomer studies following fragmentation [10,11] give evidence for the persistence of the N = 50 shell near one of the key r-process regions. Further experiments on the measurement of decay properties, masses, spectroscopic strengths, and deformation will be needed to resolve the issues raised so far.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?

There are many more decay and in-beam experiments necessary to elucidate the structure of r-process nuclei and improve models for those nuclei that cannot be measured. With current facilities such as the NSCL, HRIBF and CARIBU key r-process nuclei relevant to the N=82 abundance peak will be studied by the time of the Milestone. It may also be possible to begin first experiments on the critical N=126 region.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Exceed

Given the outstanding progress so far and the future measurements possible with existing facilities and equipment on neutron-rich nuclei at N=50, 82 and 132 we rate progress as Expect to Exceed.

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Milestone NA7 (2013): Perform realistic multidimensional simulations of core collapse supernovae.

What has been accomplished toward Milestone NA7 and what has been learned from the information gathered?

One of the biggest remaining mysteries in nuclear astrophysics is the mechanism responsible for the explosion of massive stars in a supernova. Achievement of this Milestone may be necessary to finally answer this question and determine if hydrodynamics, neutrinos, nuclear physics, magnetic phenomena, or other physics is responsible.

Multi-group, multi-angle Newtonian and General Relativistic (GR) calculations of core collapse have been performed in 1D. In one dimension, modeling of supernovae is pretty much a solved problem. However, no model with all the known physics (GR, multi-angle, multi-energy-group, etc.) has been completed in two or three dimensions.

Sophisticated 2D multi-physics simulations have been performed - in particular, with multi-frequency neutrino transport, though the latter are either "ray-by-ray" and not in 2D or use flux-limiting. These simulations have already led to possible insights into core collapse supernova theory. Explosions have been obtained for a range of stellar progenitors between 10 and 20 Solar masses. The explosions result from a confluence of neutrino heating, acoustic heating [1,2] convection, the standing accretion-shock instability, and nuclear burning. Some of these models included improvements/additions to the neutrino interactions (e.g., the inclusion of nucleon recoil in neutrino scattering on nucleons and the inclusion of nucleon-nucleon bremsstrahlung for the production of neutrino-antineutrino pairs). [3,4,5].

What remains to be done to complete the original Milestone as written?

Burrows et al. [6,7] have performed 2D multi-group radiation-hydro simulations. In these calculations, both the transport and the hydro are 2D, but though they multi-group, they are flux-limited, and not multi-angle. In addition, sophisticated 2D simulations that also include magnetic fields, albeit in the case of rapidly rotating progenitors, have begun to illuminate the role of magnetic fields in core collapse supernovae when other important physics is included in the models (e.g., multi-frequency neutrino transport). [8]. Though there are good GR-Magnetohydrodynamic simulations in 2D for supernovae and hypernovae [9] and good GR-Hydrodynamic simulations in 3D, these are not done with realistic microphysics and have not been done with any neutrino transport.

Three-dimensional hydrodynamics studies have been performed that have led to new insights and have demonstrated the need to perform multi-physics core collapse supernova simulations in 3D. Fundamentally new degrees of freedom are allowed in 3D, which in turn may lead to substantially different outcomes. For example, the simulations of Blondin and Mezzacappa suggest the possible existence of significant differential rotation in collapsed stellar cores in 3D, which are capable of reproducing the observed spin periods of young pulsars, even beginning with nonrotating progenitors. [10]. However, Iwakami et al. [11], doing slightly more sophisticated 3D simulations (that still do not include real transport), reach different conclusions about spin.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
Ongoing 2D simulations must be performed again in 3D. Moreover, the approximations made in these 2D studies (e.g., the ray-by-ray-plus approximation to the neutrino transport) must be replaced by more complete treatments of the important physical components. In particular, definitive studies will require 3D neutrino transport using a Boltzmann kinetic description (and perhaps even a quantum kinetic description to account for the impact of the recently discovered neutrino mixing on the mechanism, the element synthesis, and the terrestrial neutrino signatures) and a more realistic treatment of the general relativistic gravitational field [e.g., the conformally flat approximation (CFA)]. Ideally, a full Einstein equation solution would be coupled to the stellar core neutrino magnetohydrodynamics with 3D Boltzmann neutrino transport or quantum kinetics.

We can expect 3D simulations that extend the current 2D simulations within the next 3-5 years. These simulations will be fairly realistic. However, definitive simulations with CFA (or a full Einstein equation solve) coupled to Boltzmann neutrino transport or quantum kinetics will not be performed efficiently prior to the availability of exascale computing platforms, which are expected within the next decade.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Achieve
The full realization of this Milestone may require an additional 5 to 10 years. However, at this early stage, progress is rapid and no change in the Milestone delivery date is proposed at this time. We note that progress is good and thus rate the Milestone as Expect to Achieve. This evaluation should be revisited at the next review, particularly in light of the progress by then in creating the needed exascale computing centers. It is not clear without them that this Milestone can be met, absent significant improvement in computational approach or discovery of an allowed essential simplification in the computational treatment.

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Milestone NA8 (2013): Perform simulations of neutron star structure and evolution using benchmark microphysical calculations of the composition, equation of state, and bulk properties of dense matter.

What has been accomplished toward Milestone NA8 and what has been learned from the information gathered?

An excellent start has been made on completion of this Milestone. Theoretical studies performed on the global aspects of neutron star structure and its connection to the dense matter equation of state have established radius-pressure correlations, limits to rotation rate, and moments of inertia and binding energy relations [1,2]. Studies of crustal properties and their connection to global properties have set the stage for the interpretation of new neutron star oscillation data in terms of crustal thickness and the resulting mass-radius constraints [1,2,3]. New models for the crust of accreting neutron stars have provided much improved predictions for the nuclear processes and the associated distribution and strength of heat sources [4]. Simulations of neutron stars evolving from their birth to old age with up-to-date microphysical inputs have taught us how the presence of exotica (hyperons, quarks, condensates, etc.,), can lead to a star's subsidence into a black hole during its infancy and enhanced cooling during old age [5]. Simulations of binary star mergers have revealed how the dense matter equation of state affects gravity wave emission [6].

Fortunately hand in hand with the theoretical developments, for the first time, observations of accreting neutron stars have affirmed the predicted existence of crusts in neutron stars [6]. Many observational hints are emerging to suggest the existence of the predicted enhanced cooling through either the direct Urca process involving nucleons or one or more forms of exotica (hyperons, quarks, Bose condensates etc.,) [5,7]. These studies have collectively stressed the need to have precise data on masses and radii, preferably of the same stars, so that the equation of state of cold dense matter can be firmly pinned down [3]. For a review of recent progress in neutron star observations and theory see Ref.[8].

What remains to be done to complete the original Milestone as written?

Generally, theory is driven by new observations and experiments. However, in some sense, neutron star theory is ahead of the observational data at this point (in contrast to other fields like supernovae and gamma-ray bursters). Further nuclear data constraints related to the nuclear matter equation of state and weak interaction rates are critical for neutron star models. Experiments to address this missing information include precise measurements of neutron-skin thicknesses in neutron-rich nuclei through electroweak probes (at JLAB [10]), of strangeness couplings in hadronic matter (JLAB, GSI, RIKEN, etc.) and heavy-ion collisions (at NSCL, GSI, etc., [3,9]), and future studies of very neutron rich systems at FRIB. Concomitantly, improved theoretical models of nuclear properties are needed to make precise predictions for experimentally accessible quantities[11].

A critical issue for understanding neutron star crusts is study of low density neutron matter and pairing gaps. Ab initio calculations of low-density neutron matter using Quantum Monte Carlo (QMC) methods have been performed [12,13,14] to provide a quantitative description which can be validated using cold atom experiments. These experiments probe the equation of state and pairing gaps in the strongly interacting Fermi system of ^{6}Li atoms. Diagrammatic many-body methods using soft potentials derived by renormalization group evolution have been shown to provide a useful description of low-density neutron matter [15].

Although the long-term thermal evolution of neutron stars has been extensively developed [1,2], microphysical explorations of superfluidity are not converging [16,17]. This calls for new methods to describe superfluidity and superconductivity in dense strongly interacting systems in addition to explorations of their manifestation (their effects, for example, on Cooper pair emission are still debated) in the neutron star context. The time is ripe to exploit fully the connection between cold atom experiments to validate and constrain theoretical models.

What additional/new data should be taken (or theoretical efforts modified or added) to address the underlying scientific question?
Key nuclear physics inputs for supernova modeling and neutron star evolution from birth to old age have been calculated using improved theoretical methods [16,17]. However, significant additional information is needed on the nuclear equation of state (EoS) and neutrino rates for supernova and neutron star thermal evolution. With these inputs, predictions of neutrino spectra from protoneutron stars have been made [for a summary, see (5)]. The EoS and neutrino response in the hot and dense phases at sub-nuclear density have been calculated using virial expansion directly from the nucleon-nucleon phase shifts and molecular dynamics methods [18]. At higher density, role of nuclear correlations on the EoS and neutrino rates have been studied using QMC methods and finite temperature field-theoretic methods [19,20].

Finally, information on the possible forms of cores of neutron stars will be probed by study of the phases of cold and dense QCD. The role of pairing correlations and superconductivity in dense quark matter have been elucidated in detail [21,22,23].

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

References:

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Appendix 9: Milestones for Neutrinos, Neutrino Astrophysics and Fundamental Interactions

Milestone FI1 (2007): Measure solar boron-8 neutrinos with neutral current detectors

What has been accomplished toward the Milestone FI1, and what has been learned from the information gathered?
The Sudbury Neutrino Observatory concluded its data-taking on November 28, 2006, and is returning the heavy water to the owners. There were three distinct configurations for SNO, one with pure heavy water, the second with NaCl added to the heavy water to enhance capture of neutrons from the neutral-current disintegration of deuterium by solar neutrinos, and the third with strings of discrete ^{3}He-filled proportional counters deployed to detect those neutrons. Each phase lasted about 2 calendar years. Because the ratio of the neutral-current to charged-current rates directly determines the amount of flavor mixing between two neutrino mass eigenstates, it was important to devise systematically different techniques to measure these key reaction rates. The last phase, with ^{3}He counters, produced a neutron signal completely independent of the Cherenkov light signal used to extract the neutral-current rate in the first two phases [for accounts of those measurements. [1][2].

There is a clear neutron signal of approximately the right magnitude in the data from the ^{3}He array; a complete analysis is being carried out under blindness protocols. The statistical precision of the result can be anticipated to be about 3%. Systematic uncertainties are still being evaluated, but there is reason for optimism that the new result will have a lower uncertainty than the 9% total uncertainty of the previous phases, and will be, moreover, largely independent.

What remains to be done to complete the original Milestone as written?
The analysis formalism must be frozen, the “box opened”, and the result published.

What additional/new data should be taken to address the underlying scientific question?
All data-taking is complete.

Is the Milestone complete? Yes

The Milestone is complete except for the publication. Data-taking has been successfully finished and a suite of analysis tools completed, ready for selection and final use once it has been decided to open the box. It is expected that the first results from the final phase of SNO, with the ^{3}He detectors installed, will be published within the first few months of 2008.

Bottom Line Status Assessment: Exceeded

References:

1. Q.R. Ahmad et al. (SNO Collaboration) Phys. Rev. Lett. **89**, 011301 (2002).
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Milestone FI2 (2008): Collect first data in an experiment that has the potential to observe beryllium-7 solar neutrinos.

What has been accomplished toward Milestone FI2, and what has been learned from the information gathered?

The Borexino experiment has this past year not only collected the data but reported its first measurement of the ^{7}Be neutrino flux from the sun [1]. The flux is in agreement with the predictions of the standard solar model and the presently determined neutrino mixing parameters that account for the transformation of electron neutrinos into other active flavors. The first flux measurement, while still far from the ultimate accuracy of which the experiment is capable, is already a substantial improvement over the present experimental value deduced from a combined analysis of the Cl-Ar, SAGE, Gallex, GNO, SNO, and Super-Kamiokande experiments. The result immediately improves (twofold) the precision with which the neutrino luminosity can be compared to the electromagnetic luminosity. Good agreement is seen at this new level.

The success of Borexino has been hard-won, with new frontiers reached in the levels of radioactivity achieved, and with a difficult interlude surpassed during which the spill-containment infrastructure of the Gran Sasso Laboratory had to be improved.

What remains to be done to complete the original Milestone as written?

The Milestone as written is complete.

What additional/new data should be taken to address the underlying scientific question?

Phenomenological analysis of the data will address the role of solar variability, the consistency with new values of metallicity, the existence of sterile states admixed, and the existence of non-standard interactions.

Is the Milestone complete? Yes

Bottom Line Status Assessment: Exceeded

References:

1. G. Arpesella et al., Phys. Lett. **B658**,101 (2008).

Milestone FI3 (2008): Initiate an experimental program at the SNS fundamental physics beam line.

What has been accomplished toward Milestone FI3, and what has been learned from the information gathered?

The Fundamental Neutron Physics Beamline (FPNB) at the SNS consists of a pulsed cold beam and monochromatic 8.9-Å beam for the production of ultracold neutrons. In April 2005 a first call for proposals was issued. An initial suite of 9 proposals was followed by a tenth in December 2007. Three address decay asymmetry following neutron capture in p, d, and ^{3}He, respectively; three make improved measurements of neutron beta-decay and improved determination of the ratio of the axial vector to vector weak coupling constant; one offers an improved value of the neutron lifetime, which is important to Big Bang nucleosynthesis; one measures the spin rotation for polarized neutrons on ^{4}He; and one proposes to improve current limits on the electric dipole moment of the neutron by at least a factor of one hundred. Over 100 scientists are participating. Following the recommendation of the FNPB Proposal Review and Advisory Committee (meeting in Sept. 2005 and Jan. 2008), five of these proposals have been approved and one has been allocated beamtime.

The first experiment to be installed on the cold beamline will be the “npdgamma” experiment. This apparatus is currently under modification at ORNL to incorporate changes following trials at LANSCE and necessary safety reviews to adapt to the SNS environment. Commissioning is planned for the end of 2008. If the budget permits, data collection would begin in early 2009. The first experiment to be installed on the UCN beamline will be the nEDM experiment which received CD1 in Dec 2006. Design work as well as substantive R&D has been underway on the EDM and continues.

These experiments as well as the remaining 3 approved experiments have been incorporated into a provisional 5-year plan for the use of the FNPB.

What remains to be done to complete the original Milestone as written?

The cold beamline is available for use and the first experiment is nearing readiness. The Milestone can be completed this year (2008) and experimental work begun given appropriate funding.

What additional/new data should be taken or theoretical effort modified or added to address the underlying scientific question?

A theory effort to clearly elucidate the connection between all experiments associated with the hadronic weak interaction and Effective Field Theory and/or Lattice QCD is a key program element.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

Milestone FI4 (2010): Make factor of 5 improvements in measurements of neutron and nuclear beta-decay to constrain physics beyond the Standard Model

What has been accomplished toward Milestone FI4, and what has been learned from the information gathered?

A suite of experiments with cold neutrons at NIST and SNS and with ultracold neutrons (UCNs) at LANL is aimed at the measurement of various observables in beta decay. One of the goals is the extraction of the quark-mass matrix parameter V_{ud}. A precise determination of this quantity is marred by poor agreement among experiments on the central values for the neutron lifetime and the beta-decay correlation parameter A.

An absolute neutron flux measurement is in progress at NIST, which will improve accuracy of the existing neutron lifetime measurement by a factor of about 2. Similar improvement might result from magnetically trapped UCNs at NIST. A factor-of-3 improvement is expected perhaps by 2010 from a measurement at LANL that begins to take data in 2008. The eventual goal of this experiment, an extra factor of 10, is beyond 2010. Work in progress on achieving factors of 2 or 3 will help resolve existing discrepancies in the lifetime measurements, but an improvement by a factor 5 by 2010 seems unlikely.

The UCN-A experiment at LANL achieved good polarization and took first data in Dec 07 on the parameter A. A factor 3-5 improvement in A might be achieved by 2010 after a run in 2009 if the experiment continues to run at LANL with good DOE support. An improvement of factor 2-3 might be more realistic.

The aCORN experiment to improve the measurement of the correlation parameter “a” by a factor 5 is currently under construction. The initial physics run at NIST is expected to be completed in the winter 2010 with a factor 2-3 improvement in sensitivity. A factor-of-5 improvement is expected at the end of second physics run in 2013. Other experiments (abBA, Nab, PANDA) have been proposed but results are beyond 2010.

Significant improvement has been achieved in the measurement of Q_{EC} values for nuclear transitions [1][2], which together with theoretical improvements have led not only to an improvement in the precision of the extraction of the CKM matrix element V_{ud} by a factor of 2, but also to a shift in the central value, which coupled with improvements in V_{us} results in the CKM matrix satisfying unitarity (see also discussion under FI5).

What remains to be done to complete the original Milestone as written?

Further factor-of-2 improvements in existing experiments will be needed to achieve Milestone. Proposed experiments that could achieve additional precision await the SNS neutron beam line. The schedule for this line is being determined, but installation of a beta-decay experiment before late 2010 is unlikely. Results are expected 1-2 years after that.

What additional/new data should be taken to address the underlying scientific question?

New experiments at SNS will address further beta-decay parameters with higher accuracy. Operation of the cold neutron beam line at SNS and continuing DOE support are essential.

Is the Milestone complete? No
Various experimental efforts are fully underway, but achievement by the deadline is difficult. Next generation experiments are under design and are likely to have first results within 1-2 years of the date set for this Milestone.

Bottom Line Status Assessment: Expect to Not Achieve Fully

References:

1. G. Savard et al, Phys. Rev. Lett. **95** (2005) 102501.
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Milestone FI5 (2010): Make factor of 5 improvements in theoretical uncertainties for testing the Standard Model via low-energy electroweak observables

What has been accomplished toward Milestone FI5, and what has been learned from the information gathered?

There has been significant progress on several fronts, which improve theoretical uncertainties over the older results of Marciano and Sirlin.

The theoretical, hadronic physics uncertainty in the running of the weak mixing angle has now been reduced by a factor of about 8 [1]. This new theoretical error is small compared to experimental errors in parity-violating electron scattering. The improvement is beyond the Milestone of a factor of 5.

The ratio $R^{\pi}_{e/\mu}$ of the decay widths of the pion into the e-$\nu_e$bar channel vs the μ-$\nu_\mu$bar channel provides constraints on universality-violating new physics.. By use of chiral perturbation theory at two-loop level, the theoretical, hadronic physics uncertainty in radiative corrections has been reduced by a factor of 5 [2], achieving a level comparable to the experimental uncertainties expected from ongoing experimental searches at TRIUMF and PSI.

Theoretical uncertainties in neutron and nuclear beta decay have also been reduced. Using high-order perturbative QCD results and a large-N QCD-motivated interpolation between long and short distances, a reduction by a factor of 2 has been achieved in the hadronic physics uncertainty in radiative terms [3]. A new shell-model calculation of isospin-breaking and nuclear-structure corrections to superallowed nuclear beta decay leads to consistency in corrected Ft values, a lower average of Ft, and a higher value of the CKM matrix element Vud = 0.97418 +/- 0.00026 [4]. This is a reduction of a factor of 4 in the uncertainty relative to the 2003 Particle Data Book value, 0.9740 +/- 0.0010. Although the reduction stated in the milestone has not yet been achieved in this quantity, coupled with the recent new value of V_{us} from semileptonic K^+ decay [5] and neutral K branching ratios [6], unitarity is now satisfied with a precision of 0.1%, a major new result in and of itself. This tightens the limits on new physics by an even larger factor. There is not a very recent analysis of this result in terms of setting limits on specific types of new physics, but one was done in 2005 [7], and certainly an update will be completed within the time frame of the Milestone.

What remains to be done to complete the original Milestone as written?

Improvements can be made on other theoretical uncertainties that affect the interpretation of experiments where discrepancies with the Standard Model exist. For example, improvements in parton distribution functions allowing for small effects such as NLO QCD corrections, departures from isospin symmetry, and an asymmetric strange sea would improve the analysis of neutrino-nuclei deep inelastic scattering data. And a reduction in the hadronic uncertainty in the light-by-light scattering contribution to the muon anomalous magnetic moment would clarify the importance the existing 3 sigma discrepancy.

What theoretical efforts should be modified or added to address the underlying scientific question?

In certain cases, precise limits on new physics can only be extracted once theoretical uncertainties are better quantified. For example, one should have a decrease in the spread of calculations of nuclear matrix elements in neutrinoless double beta decay, in particular by better understanding two-nucleon short-range correlations and effects of deformation. One would also like more calculations of hadronic matrix elements using lattice QCD, for example of the relation between the neutron electric dipole moment and the theta term and other possible time-reversal violating sources. Further progress would be desirable in pushing lattice-QCD simulations to smaller quark masses and larger lattices, and in microscopic nuclear structure calculations rooted in few-nucleon input.

Is the Milestone complete? No
This is a good example where the work done addresses the intent of the Milestone and makes possible further work to go beyond the goal by the assigned deadline.

Bottom Line Status Assessment: Expect to Exceed

References:

1. J. Erler and M.J. Ramsey-Musolf, Phys. Rev. **D72** (2005) 073003.
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Milestone FI6 (2011): Improve the sensitivity of the direct neutrino mass measurements to 0.35 eV.

What has been accomplished toward Milestone FI6, and what has been learned from the information gathered?

"Direct" neutrino mass measurements are taken to include mass determinations from the shapes of beta spectra near the endpoint, but neither double beta-decay nor cosmological methods, which have model dependences. The beta emitter of choice for 60 years has been tritium because of its low 18.6-keV energy, simple molecular structure, and convenient half life. Another nucleus, ^{187}Re, is now also receiving attention because of its very low decay energy, 2.5 keV. Reaching the 0.35 eV level and below is the goal of the KATRIN tritium experiment being built in Karlsruhe, Germany, with US participation. [1] KATRIN is funded in Germany by two agencies and in the US by DOE.

KATRIN makes use of the tritium facility constructed for the ITER project. Construction of KATRIN is well advanced, with the prespectrometer and main spectrometer on the floor already, and the gaseous tritium source, differential pumping systems, and detector system in progress. Delays of approximately one year have been experienced in completing the gaseous source and the Ar frost pumping section. The current schedule calls for initial data taking in 2010. Reaching the 0.35-eV level can be achieved with a year's good data, and the ultimate sensitivity of 0.2 eV takes 5 years at design performance.

What remains to be done to complete the original Milestone as written?

The apparatus must be completed and data taken and analyzed.

What additional/new data should be taken to address the underlying scientific question?

The average neutrino mass is now known to lie within the range 0.02 to 2.3 eV. KATRIN will explore the upper decade of this range, and will largely address whether neutrino mass plays a major role in the large-scale structure of the universe. If the mass is not found there, new methods will need to be discovered to explore the remaining decade. R&D should be in progress now for this eventuality.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Achieve

References:

1. J. Bonn, Acta Phys. Polonica **B37**, 2039 (2007).

Milestone FI7 (2012): Extend the sensitivity of searches for neutrinoless double beta decay in selected nuclei by a factor of ten in lifetime.

What has been accomplished toward Milestone FI7, and what has been learned from the information gathered?

Neutrinoless double beta decay provides the only known means to determine if the neutrino is its own antiparticle, tests the conservation of lepton number, and also can provide information about neutrino mass. Neutrino oscillations have defined the lifetime ranges in which to search. Present limits come from 10-kg scale experiments. In the quasi-degenerate mass regime above 100 meV, 100-kg sources are needed, for the inverted hierarchy around 30 meV, 1000-kg sources are needed, and for the normal hierarchy with light masses, the source mass must be many tons. [1] Three promising candidate isotopes are receiving intensive attention in the US, ^{76}Ge (MAJORANA project), ^{130}Te (CUORE), and ^{136}Xe (EXO). MAJORANA is beginning a Demonstrator phase with a 60-kg array of enriched and natural detectors, to quantify the feasibility of a 1000-kg array. CUORE is presently "CUORICINO", a 41-kg natural Te prototype. EXO is preparing a 200-kg enriched prototype.

What remains to be done to complete the original Milestone as written?

A factor of 10 in lifetime will require fielding a detector of order 100 kg active mass. The present R&D must be completed satisfactorily, showing that backgrounds will be under control at the necessary level. Following commissioning, several years of counting will be needed. Even with strong and immediate funding (thus far absent), there is little chance of meeting the Milestone as written. The originally-anticipated timescale will be unavoidably lengthened by at least 3-5 years. The sensitivity goal remains within reach. Strict adherence to background levels required to accomplish this necessitates both an extensive R&D effort as well as the current search experiments, at the scale of several tens of kilograms, to demonstrate needed and scalable performance. MAJORANA has received $250k in the DOE-SC-ONP-Division funding in FY07, CUORE is funded as a MIE (Major Item of Equipment) beginning in FY08, and EXO is supported for R&D through the DOE-SC-OHEP Division.

What additional/new data should be taken to address the underlying scientific question?

If no signal is seen at the quasi-degenerate or inverted hierarchy scales, very massive detectors will be required to address this fundamental question of whether neutrinos and antineutrinos are the same particle.

Is the Milestone complete? No

Bottom Line Status Assessment: Expect to Not Achieve Fully

References:

1. S.R. Elliott and J. Engel, J. Phys. **G30**,R183 (2004).

Milestone FI8 (2012): Perform independent measurements of parity violation in few-body systems to constrain the non-leptonic weak interaction.

What has been accomplished toward Milestone FI8, and what has been learned from the information gathered?

A vigorous program exists for measurement of parity violation (PV) in few-body systems. At present not all data can be fitted with the simplest models. Recent theoretical progress includes the development both of a model-independent framework for the analysis of PV in few-nucleon systems [1][2] and of accurate few-body calculations [3].

The NPDGamma experiment measuring the PV gamma asymmetry in cold neutron capture on protons has just completed its first phase at LANSCE, providing a precision of 10^{-7}. Under present funding plans, the second phase should take data in 2009 when the SNS cold neutron beam line is ready. A further improvement of 10 in precision is expected and will test predictions for the PV pion-nucleon coupling.

An experiment is in progress at NIST to measure the PV neutron-spin rotation in neutron-alpha scattering. Systematics and background reduction are being studied in order to achieve the goal of 3×10^{-7} rad/m sensitivity, a factor-of-4 improvement over the existing precision. An extra factor of 3 from higher statistics should be achieved within the Milestone timeframe after a move to SNS, reaching then the level of theoretical predictions.

Other PV measurements have been proposed for SNS: the gamma asymmetry in neutron capture on the deuteron aiming at an improvement by a factor 10 in sensitivity, which would constrain models; the longitudinal asymmetry in neutron capture on ^{3}He, for which no real prediction yet exists; and neutron-spin rotation in neutron-deuteron scattering, whose feasibility is based on measurements that indicate a sufficiently low depolarization of cold neutrons passing through solid ortho-deuterium.

What remains to be done to complete the original Milestone as written?

Operation of the neutron beam line at SNS will provide higher neutron flux than at existing facilities, use of polarized neutrons, and a pulsed beam for control of systematic uncertainties related to polarization, thus allowing improved precision in the NPDGamma and n+^{4}He spin rotation experiments, and enable new measurements such as n+d gamma asymmetry, n+^{3}He longitudinal asymmetry, and n+d spin rotation.

What additional/new data should be taken or theoretical efforts modified or added to address the underlying scientific question?

A theoretical framework exists to carry out the analysis of PV in few-nucleon scattering, but calculations are demanding and exist only in a few cases. More investment in theoretical effort will be necessary to fully extract constraints on the non-leptonic weak interaction from the forthcoming data.

Is the Milestone complete? No

A goodly number of different theoretical and experimental efforts are being pursued, however.

Bottom Line Status Assessment: Expect to Achieve

References:

1. S.-L. Zhu et al., Nucl. Phys. **A748** (2005) 435
2. C.-P. Liu, Phys. Rev. **C75** (2007) 065501.
3. R. Schiavilla, J. Carlson, and M.W. Paris, Phys. Rev. **C70** (2004) 044007.

Milestone FI9 (2012): Obtain results from new high-sensitivity searches for atomic electric dipole moments

What has been accomplished toward Milestone FI9, and what has been learned from the information gathered?

Electric dipole moments (EDMs) in atoms or molecules are a signature of time(T)- and parity(P)-violation and represent an important window onto physics beyond the Standard Model. Numerous experiments have been proposed and are in progress in this area.

Diamagnetic atoms are sensitive to a number of sources of T violation, in particular to hadronic T violation inside the nucleus. The most stringent limits on the nuclear sector were set by a 2001 measurement in ^{199}Hg by the Seattle group. Since then they have accumulated data with 10-times better statistical uncertainty, but the systematic uncertainty is still under study. A new limit on the ^{199}Hg EDM should appear by the end of 2008. A further improvement by a factor 2 or 3 is expected before 2012. [1]

Liquid ^{129}Xe has a high electric field breakdown strength, large number density, and a long transverse relaxation time, which make noise limits better than any current experimental limit on EDMs. High nuclear polarization is required. This approach is being pursued by a Princeton group.

A next-generation EDM search is being developed around certain atoms that are predicted to be more sensitive to T-violating interactions than ^{199}Hg by two to three orders of magnitude, due to octupole deformation of the nucleus. An Argonne experiment involves laser-cooled and trapped ^{225}Ra atoms. Laser-cooling and trapping of the radium has been demonstrated, precision spectroscopy performed, and isotope shifts and hyperfine structures of the relevant transitions measured [2]. The EDM measurement is expected in 2010-2012, starting with sensitivity of 1×10^{-26} e cm (already competitive with the existing best limit set by the ^{199}Hg experiment) and having as ultimate goal reaching 1×10^{-28} e cm.

A TRIUMF experiment aims at measuring the atomic EDM of ^{223}Rn with a precision of 10^{-26} to 10^{-27} e cm, thus extending sensitivity to T violation by one or two orders of magnitude over current bounds. Steady progress toward establishing the experiment has been achieved. For example, the polarization and relaxation of ^{209}Rn by spin exchange with laser-polarized alkali metals was investigated [3]. The experiment is expected to begin in 2011, and first results should appear by 2012.

In addition, there exist other efforts to constrain the electron EDM from the atomic data. A measurement in a metastable state of PbO has been suggested for which a proof-of-principle exists, and data on initial-state preparation was taken already in 2006 [4]. A new method has been proposed for the detection of the electron EDM using a gadolinium-iron garnet [5], and sensitivity has improved since by a factor of 5. An Indiana-Yale collaboration is using a solid gadolinium-gallium garnet at sub-Kelvin temperatures and high electric fields, with state-of-the-art SQUID magnetometry, the goal being an improvement of the electron-EDM sensitivity by three orders of magnitude [6].

While challenging, these experiments should be competitive with the present world limit by 2012.

What remains to be done to complete the original Milestone as written?
All experiments are in early stages. Results are needed before the direction of further work is clear.

What additional/new data should be taken to address the underlying scientific question?
See previous comment.

Is the Milestone complete? No.

Bottom Line Status Assessment: Expect to Achieve

References:

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