The Nuclear Physics Scientific Horizon:

Projects for the Next Twenty Years

Report of the Ad-hoc Facilities Subcommittee of the
Nuclear Science Advisory Committee

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The Charge From Dr. Orbach

A. Consider what new or upgraded facilities in your discipline will be necessary to position the Office of Nuclear Physics at the forefront of scientific discovery. **Please start by reviewing the attached list of facilities,** assembled by Dr. Peter Rosen and his team, subtracting or adding as you feel appropriate, with prudence as to cost and timeframe. For this exercise please **consider only facilities/upgrades requiring a minimum investment of $50 million.**

B. Provide me with a report that discusses each of these facilities in terms of two criteria:

1. The **importance of the science** that the facility would support. Please consider, for example: the extent to which the proposed facility would **answer the most important scientific questions;** whether there are **other ways** or other facilities that would be able to answer these questions; whether the facility would contribute to **many or few areas** of research; whether construction of the facility will create **new synergies** within a field or among fields of research; and what **level of demand** exists within the scientific community for the facility. In your report please **categorize the facilities in three tiers,** such as "absolutely central," "important," and "don't know enough yet," according to the potential importance of their contribution. Please do not rank order the facilities.

2. The **readiness** of the facility for construction. Please think about questions such as: whether the concept of the facility has been **formally studied** in any way; the level of confidence that the **technical challenges** involved in building the facility **can be met**; the **sufficiency of R&D** performed to-date to assure technical feasibility of the facility; and the extent to which the **cost** to build and operate the facility **is understood**. Group the facilities into **three tiers** according to their readiness, using categories such as "ready to initiate construction," "significant scientific/engineering challenges to resolve before initiating construction," and "mission and technical requirements not yet fully defined."

SCIENCE

1 "Absolutely central"

2 "Important"

3 "Don't know enough yet"

READINESS

1 "Ready to initiate construction"

2 "Significant scientific/engineering challenges to resolve before initiating construction"

3 "Mission and technical requirements not yet fully defined"

The subcommittee used these rough definitions, but several comments are important here.

The present review process comes after a recent extensive review of proposed facilities for nuclear science that resulted in the comprehensive report "Opportunities for Nuclear Science: A Long-Range Plan for the Next Decade" in April 2002. The process that led to that report (LRP 2002) involved much of the nuclear science community over many months. **The recommendations and discussion in the LRP 2002 thus carried great weight with the present subcommittee**, and none of the evaluations in the present report should be interpreted as contradicting it.

Those projects in **Science category 1** that were included in one of the four major recommendations of LRP 2002 have a very strong endorsement from the community. Other projects in this category, while clearly very strong, have generally not yet been as thoroughly reviewed.

A number of proposals that might have been put into **Science category 2** "important" were considered during the long range planning process. Because the community considered these projects to be less compelling, we did not consider them here.

Projects included in **Science category 3** have not yet been considered by the community; they are very long term projects. While we expect them to do excellent science, the precise science goals can be expected to develop significantly before they are ready for review in the next decade.

Readiness category 1 "Ready to initiate construction" was interpreted as "ready for Critical Decision 0 (CD-0)" in standard DOE terminology, with no significant scientific/engineering challenges to resolve prior to construction.

Readiness category 2 "Significant scientific/engineering challenges to resolve before initiating construction," was applied to projects that had significant R&D issues to address or whose technical design and goals had not yet been fully vetted by the community. Note that it may be possible for a project in this category to be in a position to request a near-term CD-0 so that it can initiate the required R&D.

Readiness category 3 was interpreted as "mission **and/or** technical requirements not yet fully defined."

Some of the projects have **physics goals** that are at least in part **closely related** to those of other projects. Examples are **eRHIC and ELIC**, and the **Underground Detectors I and II**. The subcommittee has assigned each of these projects to Science category 1—we decided that the science proposed for each of them is absolutely central. The fact that they were assigned to different Readiness categories of course in no way reflects on **their relative merits**, which **must be evaluated in future Long Range Plans**.

PROJECT	SCIENCE	READINESS
Rare Isotope Accelerator (RIA)	1	1
CEBAF 12 GeV Upgrade	1	1
GRETA	1	1
RHIC II/eRHIC	1/1	2
Underground Detector I	1	2/3
CEBAF II/ELIC upgrade	1	3
Upgrade Stable Beam Facility	3	3
RIA II	3	3
Underground Detector II	1	3

PROJECT TITLE: Rare Isotope Accelerator

First Estimate : ☐ $50M -$99M ☐ $100M-499M
☒ $500M-$1B ☐ >$1B

SCIENCE (Category 1)

- What is the structure of atomic nuclei and how do complex systems derive their properties from their individual constituents?
- How are the heavy elements created and how do nuclear properties influence the stars?
- What are the fundamental symmetries of nature?

Addresses one of eleven questions in the NRC Report: "Connecting Quarks with the Cosmos"

Unique?
LRP 2002: "RIA will be the world-leading facility for research in nuclear structure and nuclear astrophysics."
There are other less ambitious projects proposed, but RIA will be the most intense and versatile facility in the world.

Different areas, synergies?
Nuclear structure and Astrophysics, Biomedical research, stockpile stewardship, materials science

Demand?
Nuclear structure and reactions commands perhaps the largest of the nuclear communities; they have been ardent supporters for a decade.

Reviewed?
LRP 2002 highest recommendation for new construction.

READINESS (Category 1)

Formally studied? Reviewed?
1999 ISOL Task Force: Technology "based principally on moderate extrapolations from proven technologies…No technical show stoppers were identified and the community is ready to proceed to the conceptual design stage." Recommended "modest" preconstruction R&D.

Confident that technical challenges can be met? Sufficient R&D?
Expert panel annually assesses R&D plan and guides R&D. Significant progress in each major R&D item, including gas-stopper beam extraction, fragment range compression, ECR sources, multiple charge state acceleration, superconducting RF structures, and high-power targets.

Cost understood?
2001 NSAC subcommittee review: Preliminary cost estimate "reasonable" and 32% contingency "appropriate". "the technical risk on the major components is low with appropriate R&D." Recent updates show that cost is stable.

PROJECT TITLE: CEBAF 12 GeV Upgrade at Thomas Jefferson Laboratory

First Estimate : ☐ $50M -$99M ☒ $100M-499M ☐ $500M-$1B ☐ >$1B

SCIENCE (Category 1)

- The experimental study of gluonic excitations in order to understand the confinement of quarks.
- The determination of the quark and gluon wavefunctions of the nuclear building blocks.
- Exploring the basis of our understanding of nuclei.
- Tests of the Standard Model of electro-weak interactions and the determination of fundamental parameters of QCD.

Unique?

Yes. No existing or proposed accelerator will have CW beams at high intensity in this energy range.

Different areas, synergies?

Large-scale computing, high-energy physics, astrophysics

Demand?

User community for present accelerator is 1100 scientists from 29 countries. Long sought upgrade.

Reviewed?

2002 LRP: one of four major recommendations

READINESS (Category 1)

Formally studied? Reviewed?

Straightforward accelerator upgrade—CEBAF designed with upgrade in mind.
2001 Institutional Plan Review
2002 DOE S&T Review of Jlab: It appeared that the 12 GeV upgrade project is technically ready to proceed."
2002 LRP: "ready to initiate construction"

Confident that technical challenges can be met? Sufficient R&D?

Both key issues in accelerator upgrade addressed successfully: better RF cavities and increased bending power in arcs. All remaining R&D focused on cost reduction and lower contingency.

Cost understood?

Detailed Work Breakout Sheets generated. Cost estimate stable for some years. CD-0 package has been generated.

PROJECT TITLE: Gamma Ray Energy Tracking Array (GRETA)
First Estimate : ☒ $50M -$99M ☐ $100M-499M ☐ $500M-$1B ☐ >$1B

SCIENCE (Category 1)

- understanding interplay of single-particle and collective modes
- exploring (Z, N) limits for bound nuclei
- unraveling properties of exotic nuclei
- investigating density oscillations in nuclear matter

Unique?
Absolutely—this is a much improved version of Gammasphere, itself perhaps without peer.

Different areas, synergies?
Since it is an essential complement of RIA, it ha s applications in nuclear structure and astrophysics, homeland security and medical physics.

Demand
A significant fraction of the expected users of RIA have already organized to develop GRETA. A device like this would be very useful soon, and essential at RIA.

Reviewed?
LRP 2002 noted: "*The physics justification for a [new] 4π tracking array is extremely compelling, spanning a wide range of fundamental questions…*"

READINESS (Category 1)

Formally studied? Reviewed?

Engineering designs have been generated for all critical components of the project. A national gamma-ray tracking coordination committee (GRTCC) has reviewed all aspects of the device including the R&D plan, the mechanical design, the specifications for detectors and electronics, the time line for construction, the cost and contingency estimates, etc.

Confident that technical challenges can be met? Sufficient R&D?

Over the last 5 years, major R&D efforts at several universities and national laboratories have validated the GRETA concept and demonstrated proof of principle. The major upcoming milestone will be the testing of the three-crystal detector module. No high-risk technical challenges were identified in the GRTCC review and GRETA was found to be ready to initiate construction.

Cost understood?

A total cost and cost profile has been generated by Jay Marx, Bill Edwards, Bob Minor and others. The cost depends critically on the price of the germanium crystals, which has increased significantly recently.

PROJECT TITLE: RHIC II/eRHIC

First Estimate : ☐ $50M -$99M ☐ $100M-499M

☒ $500M-$1B ☐ >$1B

SCIENCE (Category 1) RHIC II

The recent NRC "COSMOS" report listed "Are there new states of matter at exceedingly high density and temperature?" RHIC II will explore this new state.

- complete mapping of spectroscopy of heavy flavor bound states
- measurement of the very tightly bound upsilon, an essential control
- nature of chiral symmetry breaking and restoration

Unique?

Entirely, until the LHC arrives. The latter will spend relatively little time with heavy ions, and the physics is expected to be complementary, not competing.

Different areas, synergies?

Large scale computing, particle physics and astrophysics.

Demand?

RHIC has a large and vibrant user community.

Reviewed?

LRP 2002 noted that "significant upgrades of the collider and the experiments will be needed…[to] allow in-depth pursuit of the most promising observables characterizing the deconfined state."

PROJECT TITLE: RHIC II/eRHIC

First Estimate : ☐ $50M -$99M ☐ $100M-499M
☒ $500M-$1B ☐ >$1B

SCIENCE (Category 1) eRHIC

- the complete dynamics of nuclear binding
- meson stucture
- elucidate the role of spin in the proton wavefunction.
- hadronization
- colored glass condensate

Unique?
No existing machine comparable. Some overlap with ELIC physics goals.

Different areas, synergies?
Large scale computing, particle physics and astrophysics.

Demand?
RHIC has a large and vibrant user community, many of whom would be users of this facility.

Reviewed?
LRP 2002 stated that such an *"electron-ion collider initiative…is an extremely exciting initiative for the long term"* and recommended R&D support of this initiative.
Many workshops.

RHIC/eRHIC READINESS (Category 2)

Formally studied? Reviewed?

- Scientific goals well studied
- Accelerator parameters, detector designs studied in workshops at MIT, Yale, BNL
- Conceptual design for 50 MeV electron cooling beam prepared in collaboration with Budker Institute
- Plans for extensive R&D

Confident that technical challenges can be met? Sufficient R&D?

There is a well-defined plan of research and development to allow detailed design and construction for each step. However, significant technical challenges are not yet resolved, and additional R&D is needed before construction can begin. The staged nature of the RHIC II/eRHIC project is designed to take advantage of each R&D step as it is completed and carry out construction in stepwise manner.

Cost understood?

Preliminary cost estimates have been made.

PROJECT TITLE: Underground Detectors I, II

SCIENCE (Category 1)
Cosmos Report question: "What is the mass of the neutrino and how have neutrinos shaped the evolution of the Universe?" Two main approaches:

- Are neutrinos their own antiparticles, or is the antineutrino a different entity? [neutrinoless double beta decay]
- Are there other neutrino states, sterile but slightly admixed with the three active states? [low-energy neutrinos from the sun]

Unique?
A number of different projects have been proposed. Two main areas are double beta decay and low energy solar neutrinos. Future LRP will have to decide.

Different areas, synergies?

- Particle physics, nuclear physics, astrophysics and cosmology.
- Also synergistic connections to industrial technologies and homeland security issues.

Demand?
The user community has been growing rapidly

Reviewed?One of the four primary recommendations of LRP 2002 was *"the immediate construction of the world's deepest underground science laboratory."* Individual projects not yet reviewed.

Detector I (A Double Beta Decay Experiment)

First Estimate : ☐ \$50M -\$99M ☒ \$100M-499M
☐ \$500M-\$1B ☐ >\$1B

Two primary goals of the next-generation double beta decay experiments:

- determine whether or not neutrinos are their own antiparticles
- establish the absolute mass scale.

READINESS (Category 2/3)

Two detector projects were considered in this evaluation. The ^{76}Ge experiment (**MAJORANA**) was viewed to be the most mature, based on tried-and-true Germanium semiconductor technology. The ^{100}Mo-based detector (**MOON**) might be capable of both double beta decay searches and low energy solar neutrino investigations.

Formally studied? Reviewed?

MAJORANA is at the proposal stage; MOON now considering different detector configurations.

Confident that technical challenges can be met? Sufficient R&D?

Considerable R&D needed for MOON; MAJORANA probably close to ready.
Both require well-shielded underground laboratory.

Cost understood?

Preliminary serious cost estimate available for MAJORANA.

Detector II (A Low Energy Solar Neutrino Experiment)

First Estimate : ☐ \$50M -\$99M ☒ \$100M-499M
☐ \$500M-\$1B ☐ >\$1B

Low energy (p-p and ^{7}Be) solar neutrinos needed for:

- Mixing angles and unitarity of mixing matrix
- Existence of sterile neutrinos
- Neutrino magnetic moments

READINESS (Category 3)

Formally studied? Reviewed?

At least four projects are underway, based on different technologies. Pre-engineering designs exist for all.

Confident that technical challenges can be met? Sufficient R&D?

All experiments working on small prototypes. About 100 scientists, about \$2M per year R&D.

All are faced with challenging issues:

- Detector purity and radioactive backgrounds
- Suitable deep underground site
- Safety

Medium to significant technical risks for different projects. Estimate 2-5 years to demonstrate technical feasibility.

Cost understood?

Only very rough cost estimates available.

PROJECT TITLE: CEBAF II Upgrade

First Estimate : ☐ $50M -$99M ☐ $100M-499M
☒ $500M-$1B ☐ >$1B

An upgrade of CEBAF to 24 GeV has been considered for some time; more recently, plans include also a high-luminosity electron-light ion collider (ELIC) facility in the center-of-mass (CM) energy range of 20-65 GeV.

SCIENCE (Category 1)

- Complete our quantitative understanding of how quarks and gluons provide the binding and the spin of the nucleon.
- Help us understand how quarks and gluons evolve into hadrons via the dynamics of confinement.
- Determine how the nucleus affects quarks and gluons.

Unique?
No existing machine comparable. Some overlap with eRHIC physics goals.
Different areas, synergies?
Large-scale computing, high-energy physics, astrophysics
Demand?
User community for present accelerator is 1100 scientists from 29 countries. Long sought upgrade.
Reviewed?
LRP 2002 stated that such an *"electron-ion collider initiative…is an extremely exciting initiative for the long term"* and recommended R&D support of this initiative.
Many workshops.

(CEBAF II UPGRADE) READINESS (Category 3)

Formally studied? Reviewed?

24 GeV Upgrade relatively straightforward, based on 12 GeV cryomodules. ELIC project requires upgrade of Jefferson Lab's CEBAF accelerator to a 5 GeV energy-recovering linac and the realization of a storage ring complex, accelerating and storing light ions of up to 100 GeV. Design studies have indicated many possible parameters of the facilities. No reviews have taken place.

Confident that technical challenges can be met? Sufficient R&D?

R&D underway on, e.g., the "circulator ring" concept, analysis and simulations of electron cooling and short bunches, along with experiments on energy recovery in large scale systems. Significant technical challenges are not yet resolved, and considerable R&D is needed. Decisions about appropriate elements and configuration of upgrade are some years away.

Cost understood?

Preliminary cost estimates have been made for the 24 GeV Facility; only very rough estimates for ELIC available.

PROJECT TITLE: Upgrade of Stable Beam Facility
First Estimate : ☐ $50M -$99M ☒ $100M-499M ☐ $500M-$1B ☐ >$1B

SCIENCE (Category 3)

Formally studied? Reviewed?
In July 2001, an NSAC subcommittee recognized that "*it is essential to maintain sufficient capabilities in the production of stable beams of sufficient intensity, energy and atomic mass range to pursue the high quality physics program that is emerging*". The forefront stable beam envisioned here would be complementary to RIA, which would strongly influence its program. It is thus premature to define goals.
Unique?
This is likely to be one of a few such machines in the world.

READINESS (Category 3)

Technical specifications uncertain.

Likely parameters:
- Ions: All masses up to uranium
- Energy: 50 MeV for protons to 10 MeV/u for uranium
- Intensity: 1 particle μA for uranium, more for lighter ions

It is expected that a state-of-the-art accelerator of this type will benefit greatly from the R&D effort for RIA.

PROJECT TITLE:Rare Isotope Accelerator Upgrade
First Estimate : ☐ $50M -$99M ☒ $100M-499M ☐ $500M-$1B ☐ >$1B

SCIENCE (Category 3)

Formally studied? Reviewed?
RIA's first results will raise new scientific questions that, along with new emerging technologies, will provide the direction for future upgrades. Consideration of a science program will not happen for some years.

Unique?
RIA will possibly compete with other accelerators of rare isotopes on the world scene and upgrade plans may need to be designed to complement future initiatives in other countries.

READINESS (Category 3)

Technical specifications uncertain.

Some plausible upgrade paths:

- Increase the isotope yields from RIA by a combination of factors based on evolving new technologies
- Increase the energy of the primary beams to provide high intensity uranium capability in the GeV range
- Incorporate a storage ring as an experimental tool
- Increasing the energy of the reaccelerated beams to several tens of MeV