The Role of Electromagnetic Interactions in Nuclear Science

A Report of the DOE/NSF Nuclear Science Advisory Committee (NSAC) to the Department of Energy and the National Science Foundation. This Report was prepared by the Subcommittee on Electromagnetic Interactions and was accepted by NSAC at its meeting on April 27, 1982.

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Preface

Acting in its advisory role to the Department of Energy and to the National Science Foundation, the Nuclear Science Advisory Committee (NSAC) organized the Subcommittee on Electromagnetic Interactions in August 1981. Briefly, it was charged with reviewing the current status and future directions for basic nuclear research with electromagnetic probes and with assessing the need for facilities to pursue the highest priority aspects of this research. The full charge to the subcommittee is presented in Appendix A. In accordance with that charge, the Subcommittee sets forth in this document its view of the physics program to be pursued in the coming years together with an analysis of the facility parameters that will be required in order to execute the highest priority components of this program.

Over the past decade a number of studies have analyzed possible directions for the development of nuclear science. In particular, NSAC in 1979 developed a report entitled "A Long Range Plan for Nuclear Science" [1]. In 1977 there was a joint DOE/NSF study on the "Role of Electron Accelerators in U.S. Medium Energy Nuclear Science" [2] and a report from the National Research Council entitled "Future of Nuclear Science" [3] which was preceded by the "Committee to Review U.S. Medium Energy Sciences" [4]. In the intervening years there have been important new observations of physical phenomena, new developments in the theory of nuclear processes and new technological advances in accelerator design. It is in this context that the Subcommittee has made a new assessment of the scientific objectives of the national program for nuclear research with electromagnetic probes and the technical capability required to meet these objectives.

No attempt is made in this report to evaluate the scientific impact of electromagnetic probes relative to other types of nuclear probes currently or potentially available. *In addition* ***no attempt has been made to assess what fiscal and manpower resources of the overall nuclear physics program could be brought to bear on the physics of electromagnetic interactions.*** *These are important considerations that must be studied in the development of any effective national program but they lie outside the charge to this Subcommittee. Finally, in developing its recommendation the Subcommittee has focused on considerations of scientific priority and to some extent on technical feasibility and cost. However, in no way is it an advocate for proposals from specific institutions or for specific accelerator designs.*

The organization of the report is as follows. In Section I a brief introduction to the role of electron accelerators in nuclear science and to the physics program is presented, together with the findings of the Subcommittee. A short summary of recent advances and future prospects for nuclear physics with electromagnetic probes is presented in Section II. A detailed analysis of the specific subfields of nuclear science in terms of those scientific questions that can be attacked through utilization of electromagnetic probes is presented in Section III. Facility related issues are discussed in Section IV where accelerator performance criteria are analyzed and the characteristics of a new facility are discussed. The conclusions and recommendation of the Subcommittee are discussed in Section V. The notation used in this report is summarized in Appendix D.

The deliberations of the Subcommittee extended over three meetings as identified in Appendix B. During the course of the proceedings, members of the Subcommittee wrote position papers on a number of topics which for the most part were incorporated into this report.

The Subcommittee was aided in its work by many scientists. Some individuals met with the Subcommittee and made oral presentations at specific meetings while others were contacted in the process of writing this report. The names of these contributors are presented in Appendix C. The Subcommittee would like to gratefully acknowledge the assistance of these individuals.

The active support and information provided by the liason representatives from the Department of Energy and the National Science Foundation were crucial to the operation of the Subcommittee and their contribution is also greatly appreciated.

The chairman is especially thankful to Carl Dover for his outstanding effort as scientific secretary to the Subcommittee. His broad background and good judgment were of great value in our deliberations. Finally, this document has been prepared with the help and assistance of Maria Markwell and Frances Megahan, to whom the Chairman wishes to express his sincere thanks.

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Section I.
Introduction and Summary

In the past decade we have witnessed dramatic advances in our understanding of the physics of nucleons and nuclei. Developments in topics as varied as the quark substructure of the nucleon, meson exchange currents in nuclear matter, and the excitation of collective multipole modes of nuclei have provided a new perspective in our understanding of nuclear phenomena. The evolution of particle acceleration techniques has been equally dramatic. The recent development of new accelerator designs that achieve both high energy and high duty factor through beam recirculation and beam storage techniques offer dramatic new opportunities for experimental research. In light of these events, this report presents an analysis of the role that **electromagnetic probes** might play in the future development of nuclear science. In this section after a brief review of the development of electron accelerator facilities in this country, we present the highlights of a future program in electromagnetic interaction physics and the **Findings of the Subcommittee**. A more detailed discussion of these topics is presented in the following sections.

I.1. Role of Electron Accelerators in Nuclear Science

The growth of experimental research with electromagnetic probes in nuclear science has extended over a period of more than three decades. Major advances in accelerator capabilities have permitted experimentation that has consistently stimulated or confirmed significant new advances in our understanding of nuclear phenomena. In the early 1950's systematic studies of nuclear sizes were performed at Stanford University and at the University of Illinois. Experiments resulting from the construction of the Stanford Linear Accelerator, SLAC, in the 1960's have provided detailed information on the charge and current distributions in the nucleon. Many facilities contributed to the investigation of nuclear systems at lower energies. The low energy but high current facilities constructed at the National Bureau of Standards, Rensselaer Polytechnic Institute, and Yale University, also during the 1960's, have contributed to our understanding of the electro-disintegration of few body systems, collective excitations in nuclei as well as to neutron induced reactions. These low duty factor accelerators (< 0.1%) have been followed in the past decade by the construction and operation of facilities at both higher duty factor (1-2%) and higher energy (400-600 MeV) at M.I.T. and Saclay. Experiments at these facilities have had significant impact on our understanding of meson production, meson exchange currents, and nuclear spectroscopy.

The search for techniques to achieve full (100%) duty factor and higher energy has generated a number of innovative projects in the last decade. Studies of devices that use both recirculated beam techniques and superconducting R.F. cavities at Stanford University and at the University of Illinois have generated facilities that achieve > 50% duty factor at energies in the region of 100 MeV. Several new projects using similar recirculation techniques are now in progress. The available beam energy at the Bates linear accelerator will be increased to 700 MeV with little or no loss in duty factor (1%) by a single recirculation of the electron beam through the linac. The University of Illinois, which is currently operating a superconducting microtron facility at 100% duty factor, <1 μA and 60 MeV, has proposed a new (room temperature) facility to achieve substantially higher currents and energy. The performance of room temperature microtron devices under very high current conditions is now being studied in a joint R&D project by the National Bureau of Standards and the Los Alamos National Lab. Argonne National Lab has recently considered a microtron design that achieves high energy through utilization of multiple linacs. Related microtron projects are being developed in Europe and are discussed in Section IV of this report.

The application of storage rings to these problems either to achieve very high or very low duty factor is also widely discussed. For example, in designs being developed at the University of Virginia (and at the Los Alamos National Lab), high (low) duty factor is achieved by filling a storage ring with beam from a linac followed by slow (fast) beam extraction. Two rather different examples are the operation of SPEAR at SLAC and the electron storage ring at the University of Bonn. The development of electron beam storage rings for tagged photon experiments is being discussed at several labs.

Because of both the expanding physics program accessible with electron beams and the innovative accelerator designs that have been developed over the past several years, it is an especially opportune time to review the future role that electron accelerator facilities might play in the United States nuclear science program.

I.2. Nuclear Electromagnetic Interaction Physics

Electromagnetic interactions provide a unique probe of hadron and nuclear structure by a (virtual) photon beam of variable energy, tuneable mass, and selectable polarization. Unlike hadron-induced reactions, there is no uncertainty or complications from the structure of the scattered electron. In particular, the absence of initial and final interactions in electron-induced reactions implies that the invariant momentum, Q, transfered to the scattered electron translates directly to resolution of the target at the corresponding length scale $d \sim 1/Q$.

At low momentum transfers, $Q < 1\ \mathrm{fm}^{-1} = 0.2$ GeV/c, in electron nucleus scattering the photon interacts with the nucleon and meson exchange currents within the nucleus. At larger momentum transfers, $Q > 5\ \mathrm{fm}^{-1} = 1$ GeV/c, the photon begins to resolve the point-like quark current within the nucleus. Certainly one of the most important areas of investigation for fundamental nuclear physics is observing this transition to the quark and gluon degrees of freedom believed to be described by quantum chromodynamics (QCD). The focus is not on testing perturbative quantum chromodynamics at high momentum transfers (which is now being extensively carried out by high energy leptonic probes), but rather on exploring phenomena sensitive to the coherent and quark-confining QCD mechanisms underlying the nuclear force.

Thus an ever expanding list of new experiments in which the unique properties of electromagnetic probes can be exploited in nuclear science research is being developed. We identify a few of these opportunities below and discuss them in detail in Sections II and III of this report.

- **Single nucleon structure**

  Precision measurements of the proton and neutron form factors at large momentum transfers ($Q \gtrsim 10\ \mathrm{fm}^{-1}$) will emphasize the spatial extent and quark substructure of the nucleon.

- **Deuteron and few body form factors and inelastic processes**

  Separation of electric and magnetic form factors of all the very light nuclei at high Q^2 together with detailed measurements of both inclusive structure functions and exclusive coincidence measurements of inelastic processes for few body systems will be crucial in studying the interface between conventional nuclear dynamics and the quark-gluon substructure of QCD.

- **Production of vector mesons and baryons**

  Electro- and photoproduction of ρ, ω and ϕ mesons with polarized electron beams can extend our knowledge of the spin properties of vector meson couplings to nucleons; searches for excited baryons and measurements of their properties can provide an interesting test of quark models.

- **Discrete states and giant resonances in complex nuclei**

  Continued studies of not only elastic and inelastic scattering but also (e,e'X) reactions (X = p,n,d,α,f,etc.) are required to map out the quantum numbers and strength distribution of nuclear levels.

- **Δ and N^* production in nuclei**

  This can be studied throughout the nuclear volume via electro- and photoproduction measurements.

- **Single nucleon hole states in complex nuclei**

  Higher energy studies of the (e,e'N) reaction will be less sensitive to final state interactions and permit good separation of transverse and longitudinal response functions.

- **Hypernuclei**

  The (γ,K^+) reaction permits the excitation of unnatural as well as natural parity levels in hypernuclei.

- **Deep inelastic scattering on complex nuclei**

  Such experiments can reveal the quark substructure of a complex nucleus through deviations from single nucleon additivity.

- **Fundamental symmetries**

  Searches for parity violating amplitudes in high q elastic electron scattering on nuclei test modern theories of the weak interaction.

The committee has studied these subjects in detail, examined the scientific feasibility of specific experiments in each area, and identified the type of facilities required for these measurements. Our conclusions are summarized below.

I.3. Subcommittee Findings and Recommendation

Findings: The Subcommittee has examined a rich spectrum of physics accessible to electron beams in the energy range up to about 5 GeV. We conclude that qualitatively new opportunities leading to a more fundamental understanding of nuclear physics will become available through the development of new electron beam facilities of high energy, intensity, and duty factor.

Very rich and illuminating studies of nuclear structure and dynamics are in progress in the momentum range $Q < 5\ \mathrm{fm}^{-1}$. In this region the Subcommittee forsees a new generation of experiments that would become feasible with beams of higher duty factor and energy. The Subcommittee concludes that investigations of complex nuclei with electron beams of 0.1-1.0 GeV, high duty factor, and high intensity would have an important impact on our understanding of nuclear structure and dynamics.

The Subcommittee foresees the opening of a new frontier for the investigation of nuclear phenomena in the momentum transfer range $Q = 5\text{-}15\ fm^{-1}$. Because of the opportunities they offer for **fundamental advances** using electromagnetic probes, the Subcommittee assigned the **highest scientific priority** to investigation of hadron structure and two body interactions, three and four body systems, and fundamental symmetries. This is both because of their intrinsic scientific interest and because of the opportunity they offer to study the largely unexplored transition between nucleon-meson and the quark-gluon descriptions of nuclear systems. It is the Subcommittee's judgment that an electron beam capable of reaching about 4 GeV with high intensity and duty factor would have substantial impact on the analysis of this transition. One Subcommittee member felt that investigation of this transition region could be achieved with a less energetic beam. Other beam parameters required by the physics program have also been analyzed.

Subcommittee Recommendation - The Subcommittee strongly recommends the construction of a variable energy electron beam facility capable of operation at both high intensity and high duty factor, and able to achieve an electron energy of about 4 GeV, for the purpose of making coincidence measurements on nuclear targets at large excitation energy and momentum transfer.

Section II.
Nuclear Science and Electromagnetic Interaction Physics - Summary of Research Program

II.1. General Remarks

The field of nuclear science has made significant advances in the last decade. We exhibit here the role played by electromagnetic probes in achieving this progress. Complementary aspects of nuclear structure are probed by different incident projectiles, which interact either electromagnetically or strongly (or both) with the nucleus. Each probe elicits different aspects of the nuclear response, and none is complete in itself. The electromagnetic probes play a special part, since their reaction mechanism is well understood. For example, inelastic form factors as measured in electron scattering can be used as input to check theories of inelastic scattering of strongly interacting particles such as pions, protons and alphas. This cross-fertilization has led to a greater unity in the field of nuclear structure physics.

In the past, the greatest emphasis in electron scattering experiments has been on measurements of the charge and magnetic multipole distributions for nuclear ground states. Recently, the ^{2}H, ^{3}H and ^{3}He elastic form factors have been extended to the high q region where the quark degrees of freedom start to come into play. The form factors of these simple nuclei show scaling behavior for fairly low four momentum transfer, $Q^2 \approx 1$ (GeV/c)^2. Traditional Hartree-Fock nuclear wave functions based on potential models cannot explain this data at high Q^2, although such models work well at low Q^2 and explain changes in charge radii or magnetic radii in an isotopic series.

In recent years, the mesonic degrees of freedom and meson exchange currents in nuclei have been explored in a variety of processes. Electromagnetic probes have played an important role in this program, via experiments on photo- and electro-disintegration of the deuteron, inelastic electron scattering to unnatural parity final states, and others. New data on electromagnetic excitation of the Δ resonance display modifications of the Δ's energy and width in the nuclear medium. The shortened lifetime of the Δ in the nucleus is evident from the increased width of the Δ peak in the photoabsorption cross section. Interesting effects due to the nuclear medium have also been seen in the electromagnetic production of pions near threshold.

The field of giant resonance physics has made enormous strides in the last decade. In addition to the long-known E1 giant dipole resonance, the systematics of E0, M1 and E2 resonances have also been mapped out. These strongly collective excitations of nuclei have been seen in a number of reactions such as (p,p′), (p,n), (α,α'), (^{3}He,^{3}He′) and (e,e′). Inelastic electron scattering has played a significant role in this development. Recently, the decay modes of giant resonances have been studied following their excitation via inelastic electron scattering. For instance, there is data on the ^{12}C(e,e′p)^{11}B reaction. From the angular correlation between the final state electron and proton, one verifies the dominant E1 character of the excitation, but one also measures the very interesting admixtures of other multipoles, both in magnitude and relative phase. So far the form factors for such reactions have only been extracted over a very limited domain of momentum transfer.

In recent years, particular attention has been paid to high spin states in nuclei. These have been seen as magnetic multipole contributions, M(L), to electron scattering for large L, as "stretched" particle-hole configurations in inelastic medium energy proton scattering, and aligned particle orbits in rapidly rotating nuclei excited in (heavy ion, Xn) reactions, where extremely high values of spin are achieved.

Inelastic electron scattering has been used to excite the nucleus to the intermediate region of 50-150 MeV of excitation energy. The classical interpretation of such data was phrased in terms of the quasi-free electron scattering from the current, charge, and magnetic moments of the individual nucleons in a Fermi sea. Recent experiments have been able to measure separately the charge and magnetic moment pieces of the cross section. This gave the surprising result that the nuclear response for charge and magnetic scattering are of different size and shape, as if all nucleons contributed to the magnetic scattering but not all protons produced charge scattering. This phenomenon has been seen for several targets, suggesting that it may be a general property of nuclei.

II.2. Anticipated Program

We now focus on a brief review of the anticipated program in electromagnetic interactions. There are several principal themes which run through our discussion of the opportunities for future progress. A primary theme is the importance of performing **coincidence measurements**. Such observations, which require high duty factor electron accelerators, allow us to probe finer details of nuclear structure not accessible in single arm experiments. Many body aspects of the nucleus are more vividly revealed by studying the correlations in energy and angle of final state products than by a single particle measurement.

A second theme is the necessity for **higher energies**, in the 2-4 GeV range, to accomplish a significant fraction of the physics program. To date, the region of excitation from 140 MeV (pion production threshold) to several GeV is largely unexplored. It is in this region that one hopes to investigate the transition from nucleon and meson degrees of freedom in the nucleus to a description in terms of the fundamental quark and gluon constituents. Electron beams at GeV energies can productively be brought to bear on numerous aspects of medium and high energy nuclear physics that are now being probed with protons and pions. Experimental techniques and theoretical analyses must both deal with the problem of multiparticle final states in this interesting new energy regime.

A third theme which was repeatedly emphasized in our discussions is the need for measurements at **high momentum transfer** ($Q \approx 10\ fm^{-1}$) for various nuclear excitation energies. This is required to obtain the spatial resolution of the order 0.1 - 0.2 fm necessary to study the very short range part of the nucleon-nucleon interaction, where a meson exchange description is expected to break down.

Thus the essential experimental tools for this program are measurements of electron-nucleon and electron-nucleus scattering and particle production in a kinematic range of momentum transfer Q and photon energy ν which spans the regime between hadron-dominated and single electron-quark dominated dynamics. High duty factor, high intensity, and in some cases, beam polarization are necessary to study and separate specific electroproduction channels and coincidence measurements.

An essential question is the minimum electron beam energy required for bridging the transition region from nuclear to QCD dynamics. The observation of near scale-invariant behavior in the inelastic electron-nucleon cross section at momentum transfers, $Q^2 > 1\ (GeV/c)^2$, and production energies, $W^2 > 4\ GeV^2$, suggests the scale where the electromagnetic interaction is dominated by point-like incoherent electron-quark scattering sub-processes. The power-like scaling of meson and nucleon elastic form factors as predicted by QCD is also observed in this momentum transfer regime.

An electron accelerator with an energy of approximately 4 GeV will be sufficient on one hand, to explore the kinematic regime for inelastic scattering up to $Q^2 \approx 2\ GeV/c^2$ and $W^2 = 6\ GeV^2$ with a scattered electron angular range sufficient to separate longitudinal and transverse currents, see Fig. 19. Such separation is essential for unraveling the contributions of different scattering sub-processes. On the other hand, the nucleon and nuclear form factors can be probed up to $Q^2 \approx 4\ GeV^2/c^2$ and beyond, that is $Q \approx 10\ fm^{-1}$. This energy is also sufficient to study the production of isobars, vector mesons, and strange particles in the nuclear medium, as well as to study effects specific to nuclear dynamics, e.g., deviations from single nucleon activity, and the short distance effects which can reflect the extra hidden color degrees of freedom of nuclei predicted by QCD.

Nucleon Structure

One of the fundamental objectives of the future research program of electromagnetic interactions with one and two nucleon systems will be to investigate the spatial extent and quark substructure of the nucleon. This can be achieved through precision measurements of the proton and neutron form factors for large momentum transfers $Q \geqslant 1$ GeV/c. In this region, nucleon electric form factors G_{Ep} and G_{En} are poorly known; their measurement could be accomplished by a high precision Rosenbluth separation in which the electron and nucleon are detected in coincidence over a range of angles. Another possibility requires that the polarization transferred to the recoiling nucleon by a longitudinally polarized electron beam be observed in an analyzing second scattering.

Deuteron Form Factors

Electron scattering from the deuteron is of fundamental interest as a probe of the nucleon-nucleon interaction. For $Q \leqslant 1\ fm^{-1}$, the virtual photon interacts with the nucleon and meson degrees of freedom, and is sensitive to the long range part of the nucleon-nucleon force. For $Q \gtrsim 5\ fm^{-1}$, one starts to resolve the quark structure of the deuteron. For high Q, Quantum Chromodynamics (QCD) predicts a simple monopole form $(Q^2 + m_0^2)^{-1}$ for the reduced deuteron form factor. Separate measurements of the charge, G_C, magnetic, G_M, and quadrupole, G_Q, form factors of the deuteron will give crucial information about the role of quarks in simple nuclei, and will also test more conventional calculations which include meson exchange currents and relativistic effects. The G_C - G_Q separation could be achieved by measuring the tensor (vector) polarization of recoil deuterons in unpolarized (polarized) electron scattering. Conventional nuclear models predict a minimum in G_C near $Q \approx 4.5\ fm^{-1}$, so a measurement of G_Q in this region is a sensitive test of short range effects such as meson exchange currents and possible hidden color.

Few Body Systems

The charge form factor of ^3H, and the magnetic form factors of both ^3H and ^3He will complete the program of form factor measurements from the simplest nuclei, and will give important new information about the three body system which can be compared to "exact" three body calculations. Comparisons between ^3H and ^3He will help separate isospin one meson exchange currents from nuclear structure effects.

A major program of inelastic measurements from few body systems (particularly ^2H, ^3H, and ^3He) will be crucial in studying the interface between conventional nuclear dynamics and the quark-gluon substructure of QCD, and will also provide decisive tests of conventional calculations based on the Faddeev equation. The explicit emergence of quark degrees of freedom can be inferred from a detailed study of the collective behavior of all the inelastic channels as a function of both Q^2 and W. The various channels can be separated by coincidence measurements of the form (e, e'x), where x = p, n, d and other elementary hadrons like the pion and kaon. Inclusive measurements will be continued, where the focus will be on separation of the longitudinal and transverse components, measurements at large values of the Bjorken scaling variable x, and study of the polarized target - polarized beam structure functions.

Vector Meson Production

The electro- and photoproduction of vector mesons (ρ,ω,ϕ) is another important topic for future experiments. Since vector mesons are short-lived, one must observe their decay products, which requires a high duty factor electron accelerator for coincidence measurements. Future experiments with polarized beams and/or targets can give more detailed information on the properties of vector meson couplings to nucleons. The production of ϕ mesons throws light on the mechanism for strange quark production and the nature of the Zweig rule.

Discrete States and Giant Resonances in Complex Nuclei

An important part of the future program consists in systematic measurements of the charge density ρ(r) and the magnetization density μ(r) to 1% for more than just a few simple nuclei. Electron energies in the range 100 MeV to 1 GeV are suitable for these studies, well below the region of 2-4 GeV required for studies of meson production and quark phenomena. Future research in inelastic electron scattering to discrete states would involve continued systematic studies over a wider range of targets and momentum transfer. Excellent energy resolution and high beam currents are a prerequisite.

For investigations of giant resonance phenomena in the future, coincidence measurements are called for. These experiments are of the type (e,e'X), where X is a proton, neutron, deuteron, alpha, fission fragment, etc. In medium light nuclei angular correlation experiments at fixed momentum and energy transfer may yield the spin-parity and hence enable one to unravel 0^+ and 2^+ giant resonances. Measurements of the angle integrated yield to a particular final state as a function of q give the form factors for the coupling of a giant resonance to specific final states.

Δ and N^* Production in Nuclei

With 3-4 GeV electron beams, one can investigate the production of higher mass nucleon resonances as, for example, the N^* (1688). The future experiments in this field would certainly include Δ and N^* photo- and electroproduction, i.e. (γ,Nπ) and (e,e'Nπ). Nuclear Compton scattering above the pion production threshold is also of interest. For coincidence experiments such as (e,e'Δ) and (e,e'N^*), high duty factor is needed, as well as an incident energy of 2-3 GeV.

Single Nucleon Hole States

Single nucleon hole states in complex nuclei can be well studied with the (e,e'N) reaction and electron beams with energies of a few GeV. Such a beam energy permits the nucleon to emerge easily with a few hundred MeV of kinetic energy, helping to minimize the effect of final state interactions. Future (e,e'N) experiments will emphasize the separation of longitudinal and transverse response functions. In addition to phenomena involving nucleons only, the transverse response contains contributions involving meson degrees of freedom as well. The existing (e,e'p) measurements are severely limited by random coincidences due to the poor duty factor of existing accelerators. By measuring both the energy and angular dependence of the cross section, one can attempt to disentangle one and two-nucleon effects. A natural extension of this work is the study of the (e,e'NN) reaction, in order to observe directly the relative momentum distribution of two nucleons in the nucleus. With 3 GeV electrons, for instance, one can explore the NN system in the region 200-700 MeV/c of relative momentum.

Hypernuclei

The (γ,K^+) or (e,e'K^+) reactions excite both natural and unnatural parity hypernuclear configurations with comparable strength, unlike the (K^-,π^-) process. Electromagnetic reactions may thus provide us with a significant extension of our knowledge of hypernuclear structure. Such experiments would be feasible at a few GeV electron accelerator; 2 GeV is sufficient for most spectroscopic studies of hypernuclei.

Deep Inelastic Scattering and the Quark Structure of Nuclei

Deep inelastic scattering of electrons from **nuclei** is expected to open up a new domain of phenomena, of interest in both nuclear and particle physics. Single arm measurements, A(e,e'), should exhibit interesting deviations from single nucleon additivity. It will be important to separate transverse and longitudinal contributions to the cross section. Coincidence measurements of the type A(e,e'X), where X is a hadron, shed light on different fundamental aspects of nuclear physics. If X is a K^+ meson, we learn about the mechanism of strange quark production.

Fundamental Symmetries

Electron accelerators in the multi-GeV region will also be effective in probing aspects of fundamental symmetries. A high energy electron machine equipped with a polarized source would be a good tool to explore weak interactions in the semi-leptonic (and non-leptonic) sector(s), particularly through parity violating amplitudes. High q is needed for these effects to be measurable. Tests of symmetries in grand unified theories may be carried out at a future electron accelerator, for example, through investigation of the rare decay modes of muons or pions produced by the electron beam. Other tests of symmetries include the search for $\Delta I = 2$ isospin-violating reactions induced by real or virtual photons, and detailed balance checks on time reversal invariance.

Section III.

Research Program - Recent Advances and Scientific Opportunities

III.1. Few Body Systems

III.1.1. Hadron Structure and Two-Nucleon Interactions

The basic building block of nuclear physics is the nucleon-nucleon interaction. This interaction has been considered at different levels for many years, and has been used in many different forms to describe the observed properties of nuclei. In recent years the most successful description has been in terms of boson exchange, although the derived force has rarely been used, in all detail, in structure calculations. Boson exchange models were never able to handle the short-range part of the interaction satisfactorily; ad hoc cutoffs were employed.

A number of measurements, especially deep inelastic scattering, have now shown us that, to a good approximation, the nucleon consists of three quarks. The Yang-Mills equations of QCD are commonly accepted as the underlying equations, describing how quarks couple to colored electromagnetic fields. As one goes to shorter distances, these equations predict that the quarks become asymptotically free, again in agreement with the experiments of deep inelastic scattering. At these very short distances, i.e. within the confinement region, quark interactions can presumably be described perturbatively, in terms of gluon exchange.

We are confronted by a new situation with exciting perspectives. Whereas in the boson exchange model, interactions became stronger and stronger as the distance decreases, QCD suggests that there will be a distance at which they begin to weaken and can probably be described perturbatively. What is that distance? For very large q^2, the running coupling constant in QCD goes as

$$\alpha_s(q^2) \approx \frac{12\pi}{(33 - 2n_f)\, ln\, (q^2/\Lambda^2)}$$

where Λ is a constant which sets the energy scale for the coupling constant, and n_f is the number of quark flavors. Since Λ gives the only scale in the underlying theory, hc/Λ is certainly related to the size of the confinement region. Present determinations of Λ range from 100-500 MeV, depending upon the renormalization procedure. The empirical Λ needed to describe charmonium levels [5] is $\approx$ 400 MeV. Although Λ is the only underlying parameter, the size of the nucleon may be somewhat influenced by mesonic couplings, especially by the pion cloud, since mesonic couplings are large, e.g.

$$\frac{g_{\pi NN}^2}{4\pi} = 14 .$$

Thus, about the only guide we have from the underlying theory is that the radius of the confinement region in the nucleon; i.e., the dimensions of the quark substructure, is $\lesssim$ 1 fm. The success of boson exchange models would suggest that it is less than 1 fm.

One of the fundamental objectives of the future research program in electromagnetic interactions will be to determine the size of the quark substructure of the nucleon. Further objectives will be to determine the dynamical properties of this region. The most definitive experiments to accomplish this are likely to appear only later. It may be useful to recall the recent history of the development of our understanding of mesonic exchange currents. These have been useful in exploring the "meson presence in nuclei".

Whereas since the development of Yukawa's theory, one has believed that nuclear forces came from meson exchange, explicit mesonic degrees of freedom were not needed in the first decades of nuclear structure theory. It seemed clear that mesons mediated nuclear forces, but no experiments pinned down their presence in nuclei. Progress in past years came firstly from the accurate experimental determination of the need for mesonic exchange currents in, e.g., reactions such as $n + p \rightarrow d + \gamma$. This was accompanied theoretically by the realization that chiral invariance, treated for many years as an empirical invariance of the theory, gave strong guidance in how to construct the exchange currents theoretically, especially how to "single count".

These developments lead logically into the search for quark substructure of the nucleon: experimentally, because more detailed and precise experiments continuing along the above lines delineate the region of validity of the boson exchange theory; and theoretically because it is natural to try to exploit chiral invariance, which is an underlying symmetry of QCD, in the quark domain.

The above program has been pushed nearly as far as possible with existing accelerators. One of the best examples is in the electrodisintegration of the deuteron [6] (Figure 1). By selecting only np pairs of low energy E_{np} = 0-3 MeV, this process can be forced far off shell so that the exchange currents give most of the amplitude at large momentum transfers. What is surprising here is that predictions [7, 8] based on chiral invariance, using point vertex functions (no form factors), reproduce the experiments up to momentum transfers of 3-4 fm^{-1}, implying that the description is valid down to internucleon distances of 1/4 to 1/2 fm. The above example indicates that one should be prepared to go to momentum transfers well in excess of 4 fm^{-1} in order to pin down discrepancies.

Although we have worked with the nucleon for decades, much remains to be learned about it. Recent suggestions [9, 10] that the nucleon is highly deformed, with 30-40% D-state admixture, are accompanied by the surprising observation that the introduction of such a large D-state admixture need not damage any of the known points of agreement between theory and experiment. The Δ(1232) isobar, in such models, is also expected to be deformed. Precision experiments on electroproduction of pions should tell us more about the transition E2 moment between nucleon and isobar.

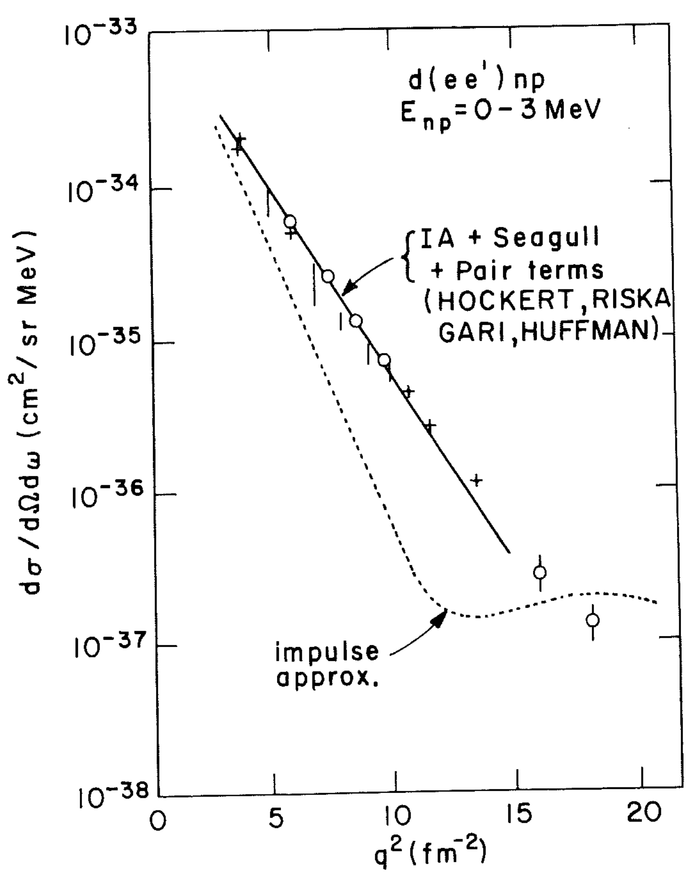

Figure 1 *Cross section for the electrodisintegration of the deuteron, taken from M. Bernheim et al. [6]*

The above outlines longer-term objectives. In the nearer term, there will be experiments delineating the role of virtual Δ(1232)'s, π-mesons, etc. as necessary nuclear constituents. The role of the isobars in exchange currents and in providing high-momentum components in few-nucleon systems has been utilized for some years in electron physics; the necessity of Δ-components has only recently been strikingly confirmed in investigation of Gamow-Teller resonances in complex nuclei [11]. (See [12] for the theoretical discussion.) Thus even if none of the major bonuses from determination of quark substructure were to accrue, we still need high-precision means of determining the character of the nuclear components beyond the nucleon.

We now consider in more detail the classes of electron experiments with one and two-nucleon targets, with particular attention to how measurements at high momentum transfer would shed light on various aspects of QCD. We first note the most remarkable feature of electron scattering reactions, which is that one can probe hadron dynamics with a (virtual) photon beam of variable energy, tuneable mass, and selectable polarization: longitudinal, transverse, linear, and circular. The photon mass $Q = (q^2 - \omega^2)^{1/2}$ is an index of the resolution length. For example, in electron deuteron scattering at low momentum transfers ($Q \lesssim 1$ fm^{-1}) the photon interacts with the constituent nucleons and meson exchange currents within the deuteron. At larger $Q^2 > 1$ $(GeV/c)^2$ the photon resolves the point-like quark current of the nucleus, yielding an essentially scale-invariant inelastic electron-nucleus cross section. In the case of elastic electron-deuteron scattering at $Q^2 > 1$ $(GeV/c)^2$, conventional impulse approximation calculations based on electron-nucleon scattering subprocesses begin to break down since the struck nucleon is far off-shell. At high momentum transfers the deuteron elastic form factor $F_d(Q^2) = [A(Q^2)]^{1/2}$ can be computed in quantum chromodynamics from its six-quark structure. Here $A(Q^2)$ is a linear combination of charge, quadrupole, and magnetic form factors: G_C^2, G_Q^2 and G_M^2. If one defines the "reduced" deuteron form factor

$$f_d(Q^2) \equiv \frac{F_d\,(Q^2)}{[G_{Mp}\,(Q^2/4)\;G_{Mn}\,(Q^2/4)]}$$

which removes the effects of the single nucleon magnetic form factors G_{Mn}, then QCD predicts (up to log factors) a simple monopole form

$$f_d(Q^2) \approx 1/(Q^2+m_0^2).$$

The data from the American University/SLAC experiment [13] are consistent with this prediction for $1 < Q^2 < 4$ $(GeV/c)^2$ (see Figure 2). This gives further confirmation of QCD as the underlying theory of hadron and nuclear dynamics, and evidence for the applicability of perturbative ideas in nuclei at momentum transfers as low as $Q^2 \approx 1$ $(GeV/c)^2$.

It is also important to note that QCD predicts that the traditional nucleon, isobar, and meson degrees of freedom are **not** sufficient to describe the deuteron ground state; "hidden color" six-quark configurations (which are not separable into two 3-quark color singlet clusters) must also exist. In addition, one expects excited hidden color states of the deuteron. Finding these may require very careful searches in experiments such as large-angle elastic Compton scattering $\gamma d \rightarrow \gamma d$ and electrodisintegration $ed \rightarrow epn$.

As mentioned earlier, the key question for nuclear physics in the next decade will undoubtedly be the study of the interface and synthesis of traditional nuclear dynamics with the short-distance quark and gluon substructure of hadronic interactions and wavefunctions. An essential tool will be electron scattering reactions at sufficient energy to span the transition between long-distance and short-distance scale-invariant QCD dynamics. One needs an electron beam of high duty factor and sufficient luminosity to allow coincidence measurements and longitudinal/transverse photon polarization separation to resolve the spin of the interacting constituents. Some of the important experiments will also require polarized electron beams. Many of the electron scattering experiments discussed below, such as the measurement of G_{En}, the neutron form factor, will provide information about hadrons which is essential for understanding nuclear structure. On the other hand, the nuclear target measurements, such as the search for hidden color nuclear states and the determination of the deuteron structure functions in the $x > 1$ domain, are relevant to the fundamental understanding of hadron dynamics. Here, x, the Bjorken scaling variable, is defined as:

$$x = Q^2 / (2M_N \nu),$$

where ν is the energy transfer in the target rest frame.

We now consider specific experiments, starting with form factor measurements. The **deuteron magnetic, charge, and quadrupole form factors** G_M, G_C, and G_Q are fundamental measures of nuclear structure at low momentum transfer and of QCD at high momentum transfer. Only the $A(Q^2)$ structure function has been extensively measured. The magnetic form factor $G_M \approx [B(Q^2)]^{1/2}$ is known only up to $Q^2 \approx 0.5\ (\mathrm{GeV/c})^2$. The traditional nucleon impulse approximation picture predicts that G_M will have a diffractive feature at $Q^2 \approx 1\ (\mathrm{GeV/c})^2$ with a size and shape that is strongly influenced by the possible presence of meson exchange currents.

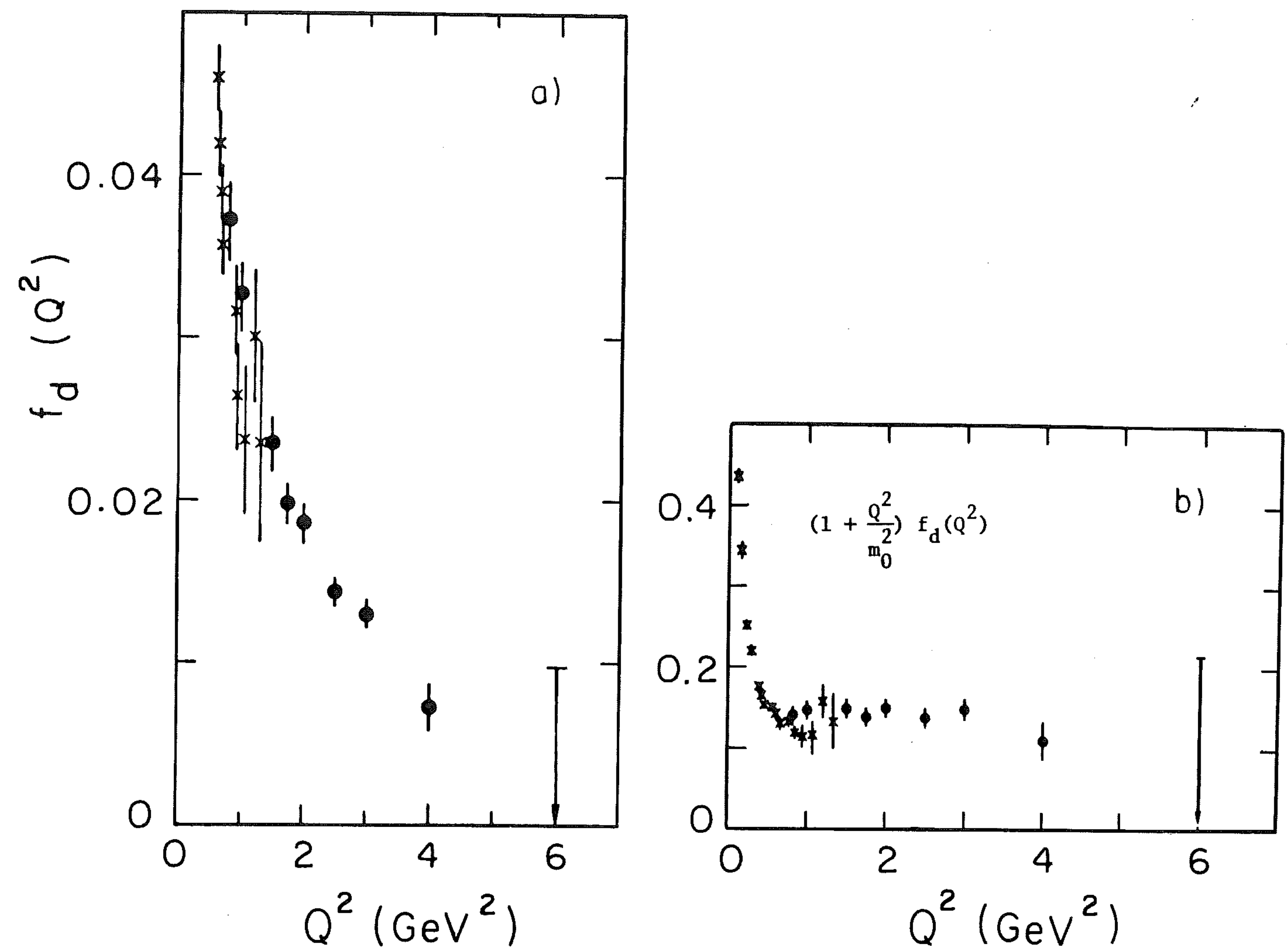

Figure 2 *Scaling behavior of the deuteron reduced form factor $f_d(Q^2)$. The QCD prediction is that the product shown in (b) tends to a constant for large Q^2. The data are taken from Arnold et al. [13]; in (b), $m_0^2 = 0.28$ GeV^2 is assumed.*

Measurements of G_M require backward angle electron scattering (preferably 180°) on the deuteron at beam energies at least up to 2 GeV. High intensity is essential but high duty factor is not. The separation of G_C and G_Q requires that a deuteron polarization quantity be measured. Elastic electron deuteron scattering with polarized deuteron targets does not appear to be feasible at this time. However, measurements of G_C and G_Q using polarization transfer to the deuteron from a polarized electron beam in an analyser-detector using a second scattering should be possible [14].

Since conventional nuclear force models predict a minimum of $G_C(Q^2)$ at $Q^2 = 0.8$ $(GeV/c)^2$, this may provide a particularly sensitive measure of short distance effects such as hidden color and meson exchange contributions. Measurements of polarization transfer to the deuteron in the Q^2 region of the expected diffraction minimum in G_C will require high intensity longitudinally polarized electron beams of at least 2 GeV. High duty factor is helpful but is not essential.

Model-independent measurements of the **neutron electric form factor** $G_{En}(Q^2)$ do not exist (beyond the $Q^2 = 0$ slope measurements), despite its fundamental importance for understanding neutron substructure. In addition, the G_{En} form factor is critical for conventional analyses of the deuteron form factor. It can be measured from the electron to neutron spin transfer in ed → enX, neutron electroproduction on a deuteron at the quasi elastic peak. Measurements of G_{En} at Q^2 below 1 $(GeV/c)^2$ could be made with existing facilities when polarized electrons at E = 0.7 GeV become available. Measurements in the range $Q^2 = 1$ to perhaps 4 $(GeV/c)^2$ appear feasible and will require high intensity polarized beams of at least 4 GeV. High duty factor is not essential.

A similar spin transfer technique could be used to measure the **proton electric form factor**, G_{Ep}. Present data extend only to $Q^2 = 3.8$ $(GeV/c)^2$, and for Q^2 above 2 $(GeV/c)^2$ the errors are large (30% to 50%). Better knowledge of G_{Ep} is essential, not only for understanding the structure of the proton, but also for the interpretation of many nuclear structure problems, especially the nuclear charge form factor at large Q^2. Polarization transfer measurements could significantly improve present results in the region $Q^2 = 2$ to 4 $(GeV/c)^2$ and could extend the data to perhaps $Q^2 = 6$ $(GeV/c)^2$. This would require high intensity polarized beams with energies of 3 to 10 GeV. High duty factor is not essential.

Pion and kaon form factor measurements are fundamental tests of QCD for momentum transfers $Q^2 \gtrsim 2$ $(GeV/c)^2$. There is no data for $F_K(Q^2)$. The meson form factors can be determined from measurements of meson electroproduction ep → $e\pi^+n$, ep → $eK^+\Lambda$ at large momentum transfer. High duty factor, reasonable intensity, and high energy $E \approx 4$ GeV are required to extend measurements of $F_\pi(Q^2)$ in the range $3 < Q^2 < 6$ $(GeV/c)^2$. High duty factor and high intensity are required to separate the much smaller K^+ signal from the large (100:1) pion background.

We now consider **single arm inelastic electron-proton and electron-deuteron scattering**. A representation of the behavior of the proton structure function, νW_2, is shown in Figure 3. The function W_2 is related directly to the momentum distribution of the constituents in the target hadron [15, 16]. Although extensive data for structure functions exist in the deep inelastic scattering region, detailed measurements of many important quantities are still lacking, such as:

(A) the large x behavior of the structure functions, especially neutron/proton comparisons,

(B) the separation of longitudinal and transverse components (especially in the quasi-elastic and nucleon resonance region),

(C) the polarized target/polarized beam structure function.

In general one expects a sum of contributions

$$\sum_a G_a(x_a) \frac{d\sigma}{dQ^2} (ea \rightarrow ea)$$

to the deuteron structure function corresponding to the electron scattering from various clusters or constituents: a = p, n, π, K, qq, $q\bar{q}$, q, etc. Each contribution has a different x, σ_L/σ_T and Q^2 behavior predictable from QCD or nuclear physics, corresponding to the spin and degree of compositeness of each cluster. Measurements of all of the above quantities over a range of Q^2 and x are essential for disentangling the various contributions to the cross section. In particular, the high x, $Q^2 > 1$ $(GeV/c)^2$ behavior of the deuteron structure function is sensitive to the six-quark and hidden-color components of the deuteron wavefunction. QCD also predicts anomalous behavior of σ_L/σ_T in this region.

The single arm measurements at high x and $Q^2 \gtrsim 1$ $(GeV/c)^2$ with σ_L/σ_T separation require a high energy electron beam, $E \approx 4$ GeV, with high intensity.

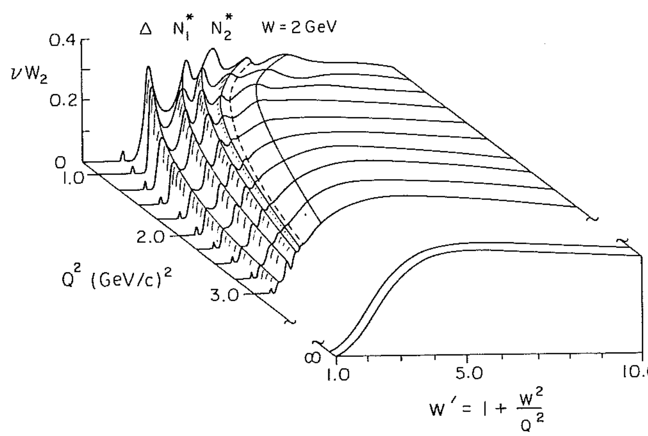

***Figure 3** The proton inelastic structure function νW_2 as a function of Q^2 and the scaling variable w'. The Δ, N^*_1, and N^*_2 peaks are at missing masses W ≈ 1.23, 1.15, and 1.65 GeV, respectively. W = 2 GeV is shown as a dashed line. The figure shows how the peaks fade into the background and νW_2 becomes a function of only w' for large Q^2 and W. (Constructed from data summarized in [16].)*

High duty factor is not essential. The polarized structure function measurements will require moderate intensity, polarized beams plus polarized targets.

While single arm measurements will provide much essential information, it seems almost certain that a full understanding of the transition from nucleon to quark degrees of freedom will require a major new program of **double and triple arm coincidence** measurements from **nucleon and deuteron** targets. By this technique it will be possible to isolate and study directly the Q^2 and x dependence of **each** inelastic channel which contributes to the scattering. For this program a high duty factor electron beam of energy sufficient to study the entire transition region is needed. A rough idea of the extent of this transition region can be obtained [16] by studying Figure 3. At low Q^2 and small missing mass, W, the resonances clearly stand up above the background, the latter is due to scattering from individual quarks. For $W^2 > 4$ GeV^2 and $Q^2 \gtrsim$ 3-4(GeV/c)^2, the resonances have faded away, suggesting that the transition primarily taking place in the region of $W \lesssim 2$ GeV, $Q^2 \lesssim$ 3-4(GeV/c)^2. To cover this entire region with σ_L/σ_T separation requires a beam of at least 4 GeV.

Some channels of special interest are:

(a) ed → epn, ed → epX. The electroproduction of nucleons far away from the quasi-elastic peak on a deuteron target gives essential information on the far off-shell short-distance structure of the deuteron wavefunction and the n-p interactions. A power-law behavior of the nucleon momentum distribution at the edge of phase-space is predicted by QCD perturbation theory. The exclusive channel ed → epn (a triple coincidence measurement), can be used to search for hidden-color resonant states in the six quark system.

(b) ed → enπX. The electroproduction of nucleon pion pairs (Δ's and N*'s) gives information about the pre-existing isobar components in the ground state wave function, and coupling constants and magnetic moments of the isobars [15]. Hidden color components may also make enhanced contributions to such channels.

(c) Comparison of pion, kaon electroproduction on proton and deuteron targets. This is important for understanding specific nuclear effects and meson exchange components in electroproduction.

The electroproduction experiments require the same range of Q^2 and energy as the single arm measurements with the added requirement of high duty factor for the coincidence measurements. The accessible kinematic regions allowed for E_0 = 2 GeV and E_0 = 4 GeV are shown in Figure 4.

Finally, we mention the possibilities for **tagged photon beam experiments**. A low intensity, high duty factor electron beam allows the study of the entire range of photoproduction experiments with a monochromatic photon beam of variable linear polarization. A polarized electron beam yields a circularly polarized photon beam. Studies of Compton scattering on nucleons and deuterons can be especially interesting because of the simplicity of the photon probe. Large angle $\gamma d \rightarrow \gamma d$ scattering is an important place to search for hidden color nuclear states.

III.1.2. Three- and Four-Body Systems

The study of the physics of three- and four-body systems is of considerable importance in the determination of the parameters of a high energy electron accelerator [17].

The A=3,4 nuclei are important for several distinct reasons:

A) The A=3 system is the heaviest nucleus for which the wave function has been calculated "exactly" in terms of a given nucleon-nucleon force and the assumption that only nucleons make up a nucleus. Thus, we can test our ability to understand nuclei in terms of their nucleonic constituents and their interactions. We can therefore also test for the presence of other constituents, such as the Δ(1232).

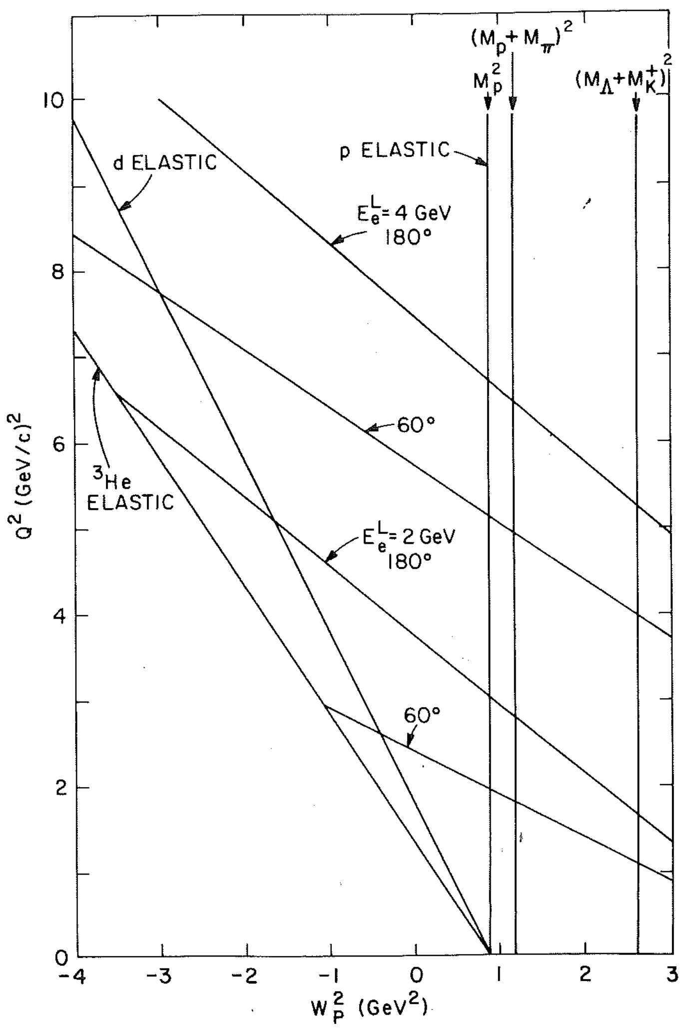

Figure 4 *Kinematics for electron-proton and electron-nucleus scattering. The four momentum transfer is Q, and we define the missing mass,* W_p *as* $W_p^2 = M_p^2 - Q^2 + 2M_p\omega$ *in the proton rest frame. The region* $W_p^2 < M_p^2$ *is kinematically forbidden for nucleons at rest, but becomes accessible with nuclear targets.*

The A=4 and some other more complicated systems approach the above state of affairs. In particular, coupled channel calculations for A=3 nuclei including Δ-components, or the nucleonic wave function for A=4 nuclei are at the verge of becoming quantitative.

B) A=3 is the only system where nature offers us a pair of nearly stable mirror nuclei and it is the one with the smallest Coulomb force. A most significant test of charge symmetry breaking of nuclear (and quark) forces can be expected to come from precise ^{3}H-^{3}He comparisons.

C) The three- and four-body systems offer unusually high densities: the maximum density for A=3 reaches 1.5 times nuclear matter density, and twice nuclear matter density for A=4. These high densities result from the dominant s-state component of the wave functions, so that high spatial overlaps may occur. At these high densities, we can expect to see better than anywhere else the short-range phenomena that we hope to identify in nuclei. In particular, three-body forces, constituents other than nucleons (e.g. N^*, π, quarks) are expected to become more prominent at high densities and short range. The transition from nucleon- to quark-constituents, also can be studied at these high nuclear densities where nucleons have a good chance to overlap, lose their identity and reveal the importance of their interior structure.

These three points make it imperative to study A=3, 4 in detail. Why use electrons for this study?

For a fundamental test of our understanding of nuclei, we need to look at these nuclei with a probe for which the interaction is understood. Most interesting phenomena (such as points B and C above) can be isolated only if the reaction mechanism is understood quantitatively. Thus electrons are most appropriate because

a) The electron-nucleon interaction is known, and described by an exact theory, QED. We therefore can use electrons to probe the nucleus.

b) The electron-nucleus interaction is relatively weak, so that the electron is more likely than any other probe (except for neutrinos) to undergo one-step processes. In this case, the achievement of large momentum transfer implies the study of short-distance phenomena. For strongly interacting probes, large momentum transfers can be achieved with multi-step processes, each of which involves low momentum transfers. However it is at short distances that we expect to be able to observe phenomena due to the presence of Δ's, quarks and other exotic constituents of nuclei.

Finally, the program of inelastic coincidence measurements in the region $W \lesssim 2$ GeV, $Q^2 \lesssim$ 3-4(GeV/c)^2 designed to follow the transition from nucleon to quark degrees of freedom (and discussed in the previous section) should be carried out on A = 3, 4 nuclei as well. Briefly, these nuclei allow one to study such phenomena in a system which has high nuclear density, but is also simple enough to permit a comparison with detailed calculations. Also since the nucleonic wave functions are quite well known it is easier to understand processes like π, Δ, or K-production in three and four body systems. Many of these processes will be discussed in later sections. In the following paragraphs we discuss a few specific experiments [15] of outstanding importance related to the short range, high density aspects of the few-body system.

Elastic **charge scattering** is distinguished by the fact that it is mainly sensitive to the one-body features of the nuclear wave function. Two-body processes and meson exchange currents (MEC) are of lesser importance, and better studied by looking at magnetic form factors. These one-body form factors are a unique source of information on short-range properties of the wave function provided that the momentum transfer q_{max} is high enough to yield the spatial resolution, (given approximately by $1.5/q_{max}$), desired. For a study of short-range correlations between nucleons, a spatial resolution of the size of the repulsive core of the NN interaction, $\approx$ 0.5 fm, is required. For a study of quark structure aspects of nuclei, we need to resolve what happens inside this region of 0.5 fm. To explore this region in detail, a resolving power of order 1/5 to 1/3 of its size, or 0.1 to 0.15 fm, is required. At this scale, the interior structure of nucleons should become apparent and "visible", but the nuclear wave function aspects are not yet lost.

A measurement of the ^{3}H, ^{3}He, and ^{4}He charge form factors up to momentum transfers allowing 0.1 fm resolution thus is a goal of very high priority. At present, measurements extend up to $q \approx 10$ fm^{-1} for the charged form factor of ^{3}He, but errors are large beyond 5 fm^{-1}. For ^{4}He, the data extends only to 6 fm^{-1} [18]. An explanation of the high q behavior of these form factors has been advanced in terms of their quark constituents [19].

Elastic **magnetic scattering** at large momentum transfer emphasizes a different aspect of nuclear wave functions, the presence of meson exchange (MEC) processes. The contribution of exchanged π, ρ, ω, and Δ's in nuclei appears most clearly in magnetic form factors $F_M(q)$, and dominates at large q. This domination results from several factors: For pure M1 form factors the one-body contribution falls off quickly with increasing q, so that the two-body contribution emerges clearly. The D-state component of the A=3 system leads to S-D transitions which are the main contributors to MEC. Multipolarities greater than M1 being absent, a quantitative interpretation of F_M is greatly facilitated [20]. The non-nucleonic components of nuclear wave functions and the short-range structure of MEC (including the exchange of more exotic particles like ρ,ω,...) and quark contributions can be investigated in a unique way by going to momentum transfers $q > 6$ fm^{-1}. In this q-region, the magnetic form factors have passed their first diffraction minimum where the interference of MEC, one-body contributions and D-state effects are largest, as seen in Figure 5 [21].

Measurement of both ^{3}H and ^{3}He magnetic form factors up to $q > 6$ fm^{-1} consequently are an important goal for testing our knowledge of nuclear structure and determining magnetization distributions.

Electrodisintegration of few-body nuclei, a most promising tool, has been hardly explored in the past. The unique advantages of inclusive scattering and the simplifications in the interpretation occurring at high momentum transfers could not be exploited due to lack of data.

Techniques have been developed to investigate the nucleon through inclusive deep inelastic electron scattering [22]. This process was shown to be an excellent tool to analyze the structure of hadrons irrespective of the complexities of the final states produced. For instance, the best evidence for the quark structure of nucleons still comes from the inclusive scattering data and the scaling feature of the inelastic cross section. Application of the same techniques to scattering off nuclei [23] can be expected to provide similar information, and show in a clean way the transition from nucleon physics (near the exclusive limit of the inelastic spectrum) to quark physics (in deep inelastic scattering). The y scaling property of inclusive e-^{3}He scattering [24] is shown in Figure 6 and defined in Section III.2.4.

In order to push this program vigorously, data is required at momentum transfers that are very large compared to the nuclear Fermi momentum (1.3 fm^{-1}); 10 fm^{-1} seems to be a minimum. To make the transition from quasielastic scattering via excitation of discrete nucleon resonances to deep inelastic scattering, electron energy losses of $\omega > 1$ GeV are required.

A measurement of the **spectral function** S(q,ω) and the (e,e'xN) cross section for A=3 nuclei should be vigorously pursued. Predictions are available for the initial state wave function, including an "exact" treatment of short range correlations based on the best NN potentials. A similar treatment of the three-nucleon final state seems quite feasible. For A=3, we are able to measure observables relating to the **entire** wave function in a nucleus of high density.

The (e,e'N) experiments in the domain relevant for conventional nuclear physics should involve nucleon momenta with k < 4 fm^{-1} (where S- and D-state components are reasonably large) and separation energies less than 200 MeV.

Exclusive and semi-inclusive reactions can be studied to yield information on both structure and reaction mechanisms. Examples are e + ^{4}He → e + d + d, → e + p + ^{3}H, → e + ^{4}He + π^0, → e + π^+ + ..., or still other final states. Coincidence studies are required for these experiments and they require theoretical studies of the continuum three body problem.

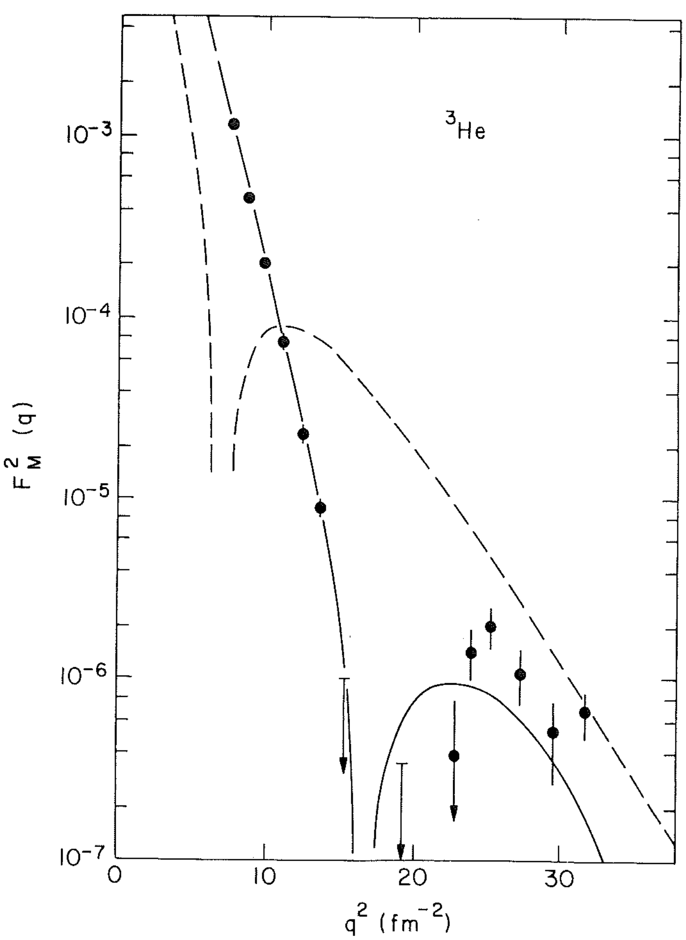

__Figure 5__ Experimental ^{3}He magnetic form factor [21] together with a Faddeev prediction including one-body (dashed) and one-plus-two body (solid line) contributions.

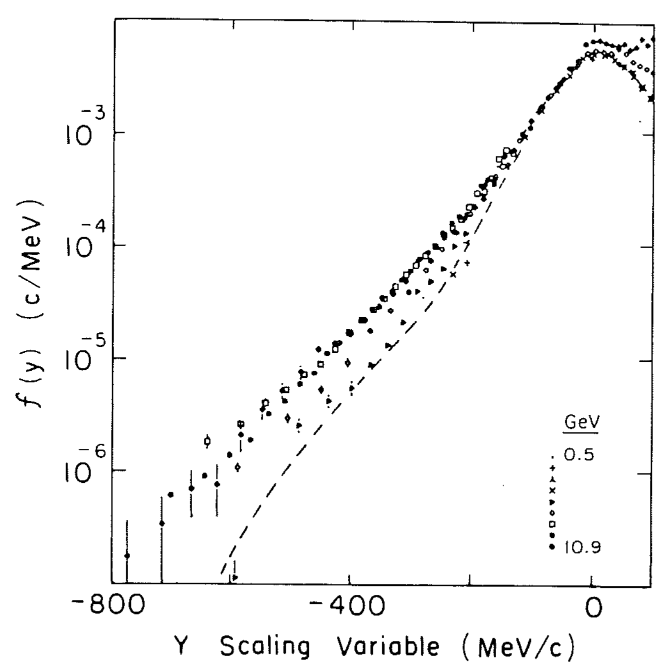

__Figure 6__ The y scaling property [24] of the inclusive e-^{3}He scattering data for energies between 0.5 and 10.9 GeV as defined in Section III.2.4. The dashed curve represents cross sections calculated using a Faddeev spectral function.

III.1.3. Production of Vector Mesons and Baryons

In the vector dominance model [25, 26] the (virtual) photons are direct sources of ρ and ω particles. These mesons interact hadronically with nuclei, and are strongly absorbed. They are of importance for the understanding of the short-range repulsion between nucleons. To understand better the interactions of ρ,ω in nuclei, coherent production experiments are needed. Dense few-body nuclei with well known wave functions are the ideal targets.

A study of the ϕ meson production is also of interest. The ϕ has the quark structure ($s\bar{s}$). Study of its production mechanism and the role of the Zweig rule is needed. Comparative studies of kaon production, which involve a single strange quark, should also be helpful. Again, the lightest nuclei are particularly suitable targets because their structure is better understood.

To produce ρ,ω, and ϕ mesons in nuclei, momentum transfers $q \geqslant 5\ \mathrm{fm}^{-1}$, are required. The energy loss, ω, should be of the order of 1 GeV ($= m_\phi$) plus nucleon recoil energies (several hundred MeV). The comparisons of electron and photon production with hadronically induced production reactions should prove helpful in understanding the latter processes.

The short lived vector mesons (10^{-20}s) must be detected through their decay products

$$\rho(776) \rightarrow \pi^+\pi^-$$
$$\omega(783) \rightarrow \pi^+\pi^-\pi^0$$
$$\phi(1020) \rightarrow K^+K^-$$

Previous measurements at energies above 2 GeV have used bremsstrahlung beams (tagged and untagged) and were limited by poor duty factor. With a continuous duty machine the coincident detection of pions or kaons would be greatly facilitated and allow the photoproduction cross section (especially the coherent part of it) to be traced from 2 GeV down to threshold. In addition photoproduction experiments with polarized beams, targets, and recoil polarization could be performed.

Coherent photoproduction of vector mesons is one area of high energy physics where nuclear targets have been used extensively. The total absorption cross section of photons on nuclei above 2 GeV is less than the sum of A individual nucleons; this phenomenon is called **nuclear shadowing**. It has been explained as the spontaneous conversion of high energy photons into vector mesons which then interact strongly and are attenuated within the nuclear interior. An extensive series of measurements and theoretical calculations [25, 26] have confirmed this hadronic structure of the photon. The effect is seen to disappear as the photon energy drops below some critical value or when the photon becomes virtual.

Shadowing should be a small effect below a few GeV. The interest in photoproduction of vector mesons between threshold (0.8 GeV) and several GeV is to establish the meson-nucleon interaction inside the nucleus to a high level of accuracy. This will allow a more reliable calculation of the influence of vector mesons on the short range repulsion of the effective NN interaction and on calculations of exchange currents.

Electron beam energies up to 2 GeV are required to measure coherent production cross sections. Polarized photon beams will require twice this energy. The use of tagged bremsstrahlung beams requires high duty factor, as does the coincident detection of pion or kaon decay products.

Photoproduction of excited states of baryons could also provide an interesting test of quark models [15]. A number of such states in the mass region from about 1.8 to 2.5 GeV have been predicted but not seen in πN scattering. The quark model predictions also explain why the states are not seen--some of these states are practically decoupled from πN scattering, but couple strongly to $N\pi\pi$ ($\Delta\pi$ or $N\rho$) and to γN, indicating that they should be seen in photoproduction.

III.2. Complex Nuclei

III.2.1. Ground State Properties and Discrete States

Electromagnetic processes provide a particularly powerful probe of the structure of atomic nuclei both because the interaction mechanism between the probe and nuclear systems is well understood, and because the nucleus is disturbed very little during the interaction process. In discussing the physics connected with ground state properties, discrete states and giant resonances of complex nuclei, arguments will be advanced which point to the necessity of low energy electron beams in addition to the multi-GeV beams needed to explore other areas.

In the study of **ground state properties of complex nuclei**, namely charge, matter and magnetization densities, various important advances have been made in the past several years. The radial shape of the nucleus has been investigated experimentally with the help of elastic hadron and electron scattering experiments. Since strongly interacting particles are absorbed in the nucleus, hadron scattering yields information especially on the matter density in the nuclear surface region [27]. Electrons, on the other hand, penetrate the nucleus with virtually no absorption and are therefore extremely well suited to the study the charge distribution in the interior [28] as well as at the surface.

The ground state **charge density distribution**, is derived from a combined analysis of elastic electron scattering form factors (measured for momentum transfers of $q \leqslant 4\ \mathrm{fm}^{-1}$) and muonic x-ray data. The current status is best characterized by two observations: (a) Monopole charge densities of several spin-zero nuclei have been determined to better than 1% at any radius r, and (b) ground state charge density differences [29] between isotones and isotopes, which give extremely valuable information about the spatial distribution of valence protons and the polarization of the core, have been measured very accurately. Indeed, in some instances [30], differences in equivalent radii for adjacent odd-even nuclei have been evaluated with an experimental uncertainty as low as $\approx 3 \times 10^{-4}$ fm.

The experimental observations mentioned above have been subjected to a comparison with extensive theoretical model calculations. Such a comparison is shown in Figure 7 for several nuclei [31]. Self consistent mean field theories, which incorporate an effective nucleon-nucleon interaction, predict for closed shell nuclei rms-radii and charge densities in the surface region accurate to a level of a few percent, but still fail to describe the measured charge density in the nuclear interior [32]. The deviation between experiment and theory in this case reaches the 10% level. The inclusion of configuration mixing or long range correlations improves the results somewhat. At present, for ground-state densities of nuclei between closed shells, in the transition region, no adequate theoretical description exists.

Of equal importance to the ground state charge distribution, is the structure of the ground state **current or magnetization density** distribution [33]. It is clear from the existing experiments that electrons are the best probe to study the distribution of magnetism in the ground state of nuclei. In odd mass nuclei, the valence particle largely determines the ground state magnetic moment and therefore an accurate measurement of the spatial distribution of the unpaired valence nucleon is possible. The current status and outcome of such measurements, of which fewer exist than in charge scattering, might be summarized as follows: For elastic electron scattering from the high-order multipole distribution of the nuclear magnetization density, rms radii for the different valence shell wave functions for both protons and neutrons were derived to within about 1% accuracy,in the following cases ^{49}Ti($1f_{7/2}$ neutron hole), ^{51}V($1f_{7/2}$ proton), ^{87}Sr($1g_{9/2}$ neutron hole) and ^{93}Nb($1g_{9/2}$ proton). As an example, the cross section due to the 2^9-pole contribution to the magnetization density of ^{87}Sr is given in Figure 8. Since neutrons contribute to the magnetic scattering through their intrinsic moments, magnetic electron scattering is a unique tool for looking also at neutrons.

Again, as in charge scattering, theoretical mean field models using density dependent effective forces are not able to reproduce the valence shell radii to better than about 6%, the experimental radii being smaller [31-33]. Furthermore, the measured magnetization distributions are, for low multipole magnetic moments, especially sensitive to meson-exchange currents.

Consider now the **interplay of electromagnetic probes with other projectiles**. For example the results from magnetic electron scattering may be compared to other methods by which wave functions of nucleons in individual shells are determined [33]. Because of their surface nature, nucleon transfer reactions are mainly sensitive to the tail of the nuclear wave function, which can be extracted with a precision of about 10%. The difference between charge densities of isotone pairs, as obtained in elastic electron scattering for nuclei where core polarization is either small or calculable, yields average radii of nucleon orbits which are uncertain to about 4%. The same precision is achieved in (e,e'p) knock-out reactions where the momentum space wave function of the knocked out proton is measured. However, because coincidence experiments are involved,

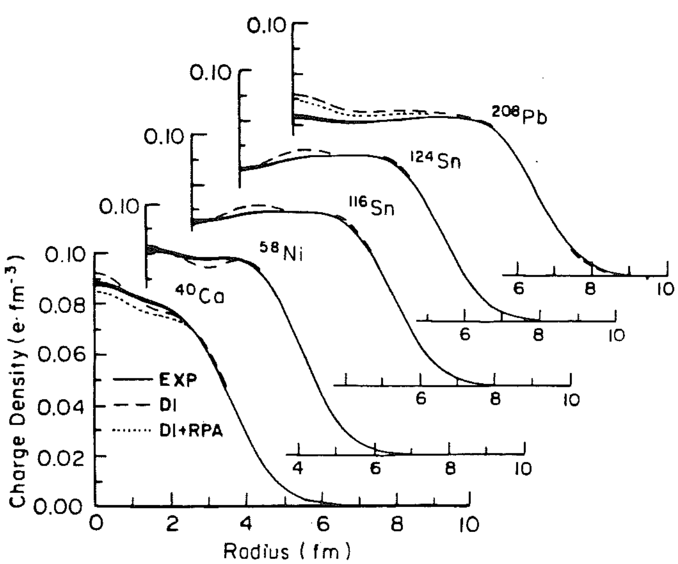

Figure 7 Comparison of experimental and calculated charge densities on various nuclei [31]. The curves are labelled as follows: EXP-experimental results, DI-density dependent Hartree-Fock prediction, and DI-RPA-density dependent Hartree-Fock prediction including RPA long range correlations.

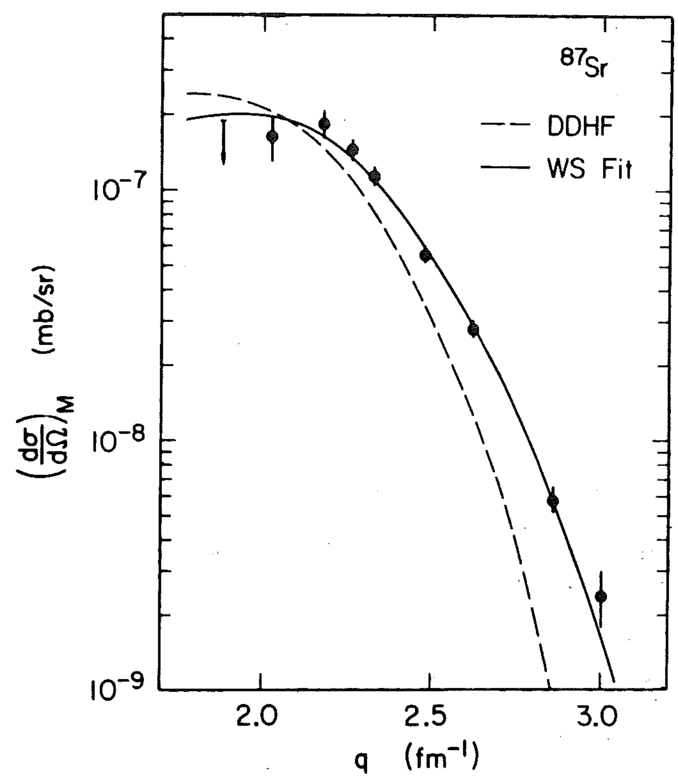

Figure 8 Comparison of the cross section due to the 2^9-pole contribution to the magnetization density of ^{87}Sr to a density dependent Hartree-Fock prediction (DDHF) and a fit using Woods-Saxon (WS) radial wave functions [33].

only a few nuclei have been studied at present. Finally, we mention the major impact that magnetic electron scattering has had on spectroscopic factors [34]. Hitherto, these quantities had been normalized in single nucleon transfer reactions to sum rule strengths. Using radial wave functions from electron scattering, **absolute spectroscopic factors** can now be derived, which show that a large part of the single particle strength is not observed in nucleon transfer reactions.

Recent advances in the investigation of ground state properties are attributable mainly to electrons. The nucleus responds differently, however, when it is bombarded with real photons. While the elastic electron scattering cross section (except in the case of magnetic scattering) is hardly influenced by exchange effects, the photon elastic cross section is increased considerably. Some evidence for this has been seen recently [35] in the measurement of the diffractive nuclear γ-ray form factor with unpolarized photons, incident on ^{208}Pb in the energy region between 40 and 100 MeV.

The direction which the study of ground state properties will take in the future is clearly marked by the need to obtain results on the charge and magnetization density with about 1% accuracy on more than just the few nuclei for which these quantities now exist. This is necessary in order to further stimulate the development of microscopic theoretical models which aim at calculating ground state wave functions self-consistently starting from the bare nucleon-nucleon interaction. It also remains to be seen if any remaining discrepancies might be signatures of mesonic or quark degrees of freedom. The optimum energy for these studies lies between 0.1 and 1 GeV.

The study of **discrete states** in nuclear reaction processes has been traditionally the most fruitful source of information on nuclear structure. Recent advances made in this field are based almost entirely on high resolution nucleon, pion and electron scattering spectroscopy. Due to the use of modern dispersion - matching techniques, energy resolution $\Delta E/E$ as low as 6×10^{-5} has been obtained. Thus spectroscopy studies have been possible not only in light nuclei with large level spacings, but also in heavy nuclei.

Inelastic electron scattering has the advantage that for a fixed energy loss, ω, to the target, the momentum transfer q can be varied, and the Fourier transforms of the one-body **charge, current and magnetization transition densities** from the ground state to the excited state at energy ω can be mapped out. Such transition densities when measured over a large range of momentum transfers, constitute an important test for any nuclear model. They have been determined lately for a number of elementary particle-hole excitations as well as for vibrational and rotational collective modes of excitation. Due to the finite energy resolution and sometimes limited accelerator beam time available, inelastic electron scattering has been performed on only a few nuclei up to $q = 3 - 3.5\ fm^{-1}$. Nevertheless, interesting observations have emerged with remarkable impact on the theory [36].

The current status of results in the field may be summed up as follows: In the realm of elementary particle-hole excitations, a number of form factors have been measured with the explicit aim of providing a stringent test of nuclear many-body wave functions. Often the shape and strength of the second maximum (and of higher maxima) of the form factor have been decisive in solving nuclear structure problems, especially on the nature of the effective particle-hole interaction. Besides electric transitions in closed or near closed shell nuclei, magnetic spin flip transitions, of which the simplest involve stretched particle-hole states, have been studied. A stretched configuration consists of a particle-hole structure $(j_p j_n^{-1})^{J_{max}}$ with $j_p = l_p + 1/2$, $j_n = l_n + 1/2$ and $J_{max} = j_p + j_n$. In Figure 9, is shown the form factor of such a stretched state in ^{24}Mg, a J^π; $T = 6^-$; 1 state of the configuration $(f_{7/2} d_{5/2}^{-1})^{J_{max}=6}$, measured with high resolution inelastic electron scattering [37]. Transitions to discrete states with a multipolarity up to M14 are presently known. The knowledge of the excitation energies of the spin-isospin excitation modes has been important in fixing the effective p-h interaction. Although the nuclear structure involved in these magnetic transitions to isovector giant resonances at first sight appears to be simple, it should be noted that there is to date no satisfactory quantitative explanation why the summed transition strength is at most half of that predicted by 1p - 1h RPA calculations.

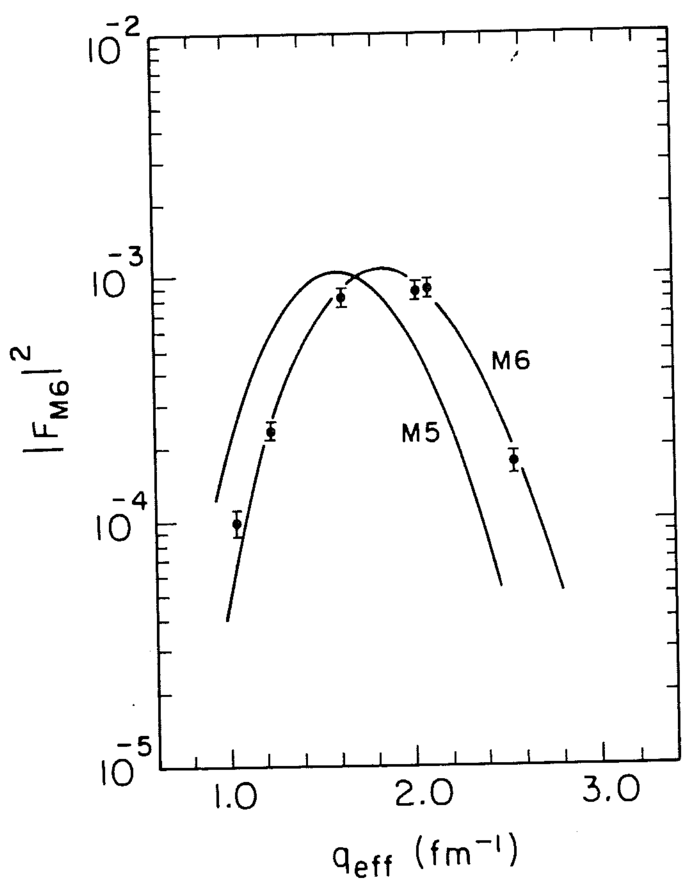

__Figure 9__ The form factor for a stretched particle-hole J^π; $T = 6^-$; 1 state at an excitation energy of 15.045 ± 0.035 MeV in ^{24}Mg displayed together with an open shell RPA prediction. A theoretical form factor for an M5 transition is shown for comparison [37].

The first experiments have been performed in which the same unnatural parity states with stretched configurations were excited in inelastic electron, pion and proton scattering. A unified analysis of the measured cross sections yielded information on the structure of these states, the hadronic reaction mechanism and the effective interaction potential of the π and p probes. A recent example for this is the combined analysis of the form factors into various $J^{\pi} = 4^{-}$ states of stretched configurations in ^{16}O at excitation energies of 17.79, 18.99 and 19.80 MeV measured in pion-, electron and proton scattering. Figure 10 shows the theoretical predictions for the electron and proton data when the wave functions deduced from the pion work were used [38].

Results from measurements of transition densities, especially in light nuclei, yield predictions of the weak interaction rate (with respect to neutral and charge changing currents), since nuclear electromagnetic interactions in a nucleus A(Z,N) are closely related to analogous transitions in nuclei A(Z$\pm$1, N$\mp$1) induced by the weak vector and axial vector interaction operators. Other analogous processes involving the spin operator are, for example, charge exchange reactions and radiative pion capture and pion production. Inelastic electron scattering combined with these processes thereby serves as a tool to obtain the best nuclear wave functions for studying the weak interaction [39-41].

Inelastic electron scattering on a number of heavy nuclei with large permanent deformations has been the testing ground for nuclear mean field theories and the concept of a deformed intrinsic state [32]. The properties of the ground and lowest excited rotational and vibrational states in deformed nuclei have been analyzed successfully in the framework of the interacting boson approximation [42].

The inelastic scattering cross section to the collective 3^{-} state in ^{208}Pb, measured at different momentum transfers in almost every electron accelerator laboratory [36, 43], forms together with the ground-state density a classic test case for theoretical models. The transition density is best described in the RPA, in which the 3^{-} state is built on a density dependent Hartree-Fock ground state. However, the same deficiency is observed as for the ground-state density, in that the transition density in the nuclear interior is not well described.

The subfield of inelastic scattering to discrete nuclear states has made significant progress recently, with advances in experimental conditions at accelerators and with magnetic spectrometers and has been viable only because of the high energy-resolution achieved. The various points which characterize the present status of the field are often based on single experiments or at most on experiments on a few nuclei. In none of the experiments could one speak of systematic studies and nearly all suffer from a limited range in momentum transfer. For some problems, as for example the investigation of deformed nuclei in the transition region, an energy resolution of $\Delta E/E < 10^{-4}$ is a prerequisite as well as a beam current of $\approx 100\mu A$ at an electron accelerator operating at incident energies between E = 0.1-1 GeV. The beam parameters are therefore essentially not different from those required in the future for the measurement of ground-state properties. Because of the multiplicity of the physics problems to be studied, one should consider an **electron accelerator providing multiple beams**.

III.2.2. Giant Resonances

The role of giant resonances in elucidating the structure of the nucleus and establishing the interaction between its

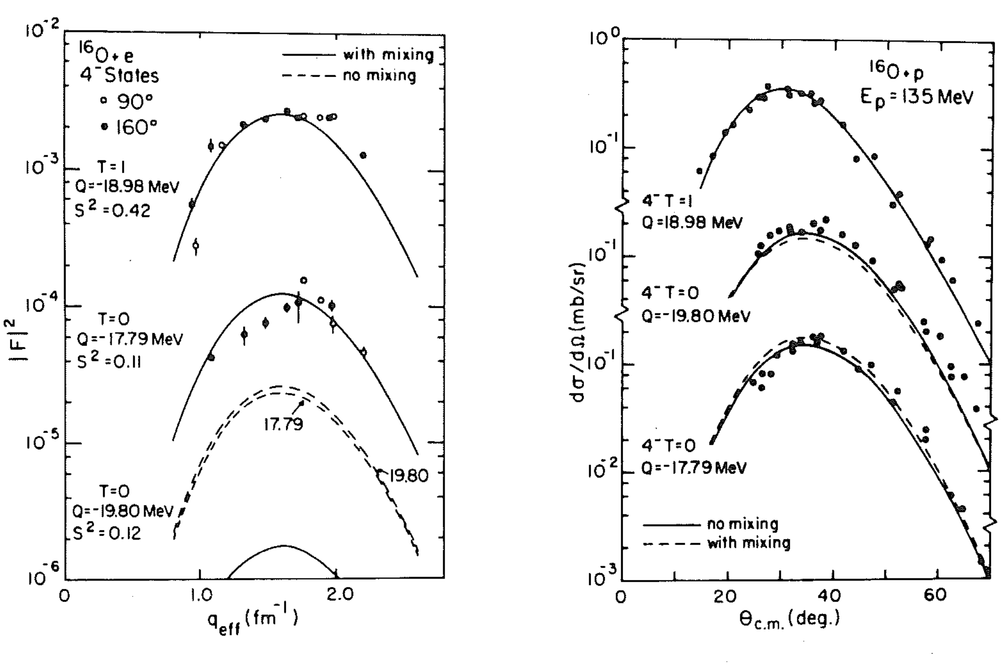

Figure 10 *The excitation of stretched 4^{-} states in ^{16}O measured in (e,e') and (p,p') scattering. The data are compared to theoretical results (with and without isospin mixing) based on wave functions derived from (π, π') scattering [38].*

constituents is well known. Our understanding is not yet complete but due to recent **inelastic hadron and electron scattering experiments**, as well as **charge exchange and photonuclear reactions**, it is at an advanced stage. Here we only list the **main advances** in the last few years:

(A) Photonuclear studies with monoenergetic photons, produced either by positron annihilation or by tagged photon techniques, and experiments involving radiative capture of hadrons, partly with polarized protons, have yielded very high quality data mainly on the giant dipole resonances [44-47].

(B) Inelastic hadron and electron scattering have added to the discovery of giant multipole resonances other than the giant dipole resonance. The drawback of having $q = \omega$ in research with real photons and hence $qR << 1$, with R being the nuclear radius, which leads to the dominance of the electric dipole, is overcome in inelastic electron scattering where the momentum transfer q for all values satisfying $q \geqslant \omega$ can be varied. By adjusting an energy transfer ω to the nucleus appropriate to the excitation energy region of a particular giant resonance, form factors of the giant resonance may thus be obtained. The high selectivity of electron scattering with respect to the excitation of certain electric and magnetic multipoles according to the choice of the momentum transfer is therefore advantageous.

A wealth of data exists on the location and strength of the isoscalar E2 giant resonance. To a lesser extent, the same information is available for isoscalar octupole and hexadecapole giant resonances and for the isovector giant quadrupole resonance [48]. From the few coincidence measurements of the type $(\alpha,\alpha'X)$ and (e,e'X), with X = p,α or n, in some light and medium heavy nuclei and in ^{208}Pb, [49] first results are available on the decay modes of the isoscalar giant quadrupole resonance. An example of the charged particle decay of this resonance in ^{16}O studied in inelastic alpha particle scattering [50] is shown in Figure 11.

(C) In giant resonance studies the discovery of the giant monopole resonance [51] has played an important role, since its properties are intimately connected to the nuclear compressibility.

(D) Some of the most exciting results from giant resonance studies in the past few years have involved nuclear spin degrees of freedom, i.e. from the magnetic dipole giant resonance excited in low q inelastic electron scattering [52, 53] through the $\sigma \cdot \tau$ operator from the nuclear ground state, and from the analogous giant Gamow-Teller resonance observed in (p,n) charge exchange reactions [54, 55], again excited via the $\sigma \cdot \tau$ operator.

Two examples of such elementary spin excitations in nuclei are given in Figure 12. In the upper part high-resolution backward angle inelastic electron scattering spectra [56] on ^{40,42,44,48}Ca with strong magnetic dipole transitions denoted by an arrow are shown. In all four isotopes the same region of excitation energy between $E_x \approx$ 8-12 MeV is covered. Only very few states are excited with noticeable strength despite the fact that the density of nuclear states is quite high at those excitation energies. This is also an example of the statement made above that inelastic electron scattering has the advantage of exciting transitions of a particular multipolarity if the momentum transfer is chosen appropriately. The M1 excitation of the prominent 1^+ state in ^{48}Ca is the strongest one known in a heavy nucleus and this isovector giant resonance has, since its discovery, been investigated in inelastic scattering with other probes than electrons. The lower part of Figure 12 shows a neutron energy spectrum [57] from the ^{48}Ca(p,n)^{48}Sc reaction, in which the isobaric analogue state of the strong 1^+ state in ^{48}Ca is seen at E_x = 16.8 MeV in ^{48}Sc. It carries a significant fraction of the isospin $T_>$ Gamow-Teller strength, the $T_<$ strength being concentrated in states around E_x [dblapprox] 10 MeV. The behavior of the M1 Gamow-Teller strengths and moments in proceeding from light to heavy nuclei, in particular the considerable quenching of those quantities with respect to the most refined shell-model predictions within a large pure nucleon particle-hole space, has provided evidence for Δ(1232) degrees of freedom [58-68]. Besides M1 modes of excitation, properties of M2 and higher modes are known from inelastic electron scattering as well as from hadron induced processes.

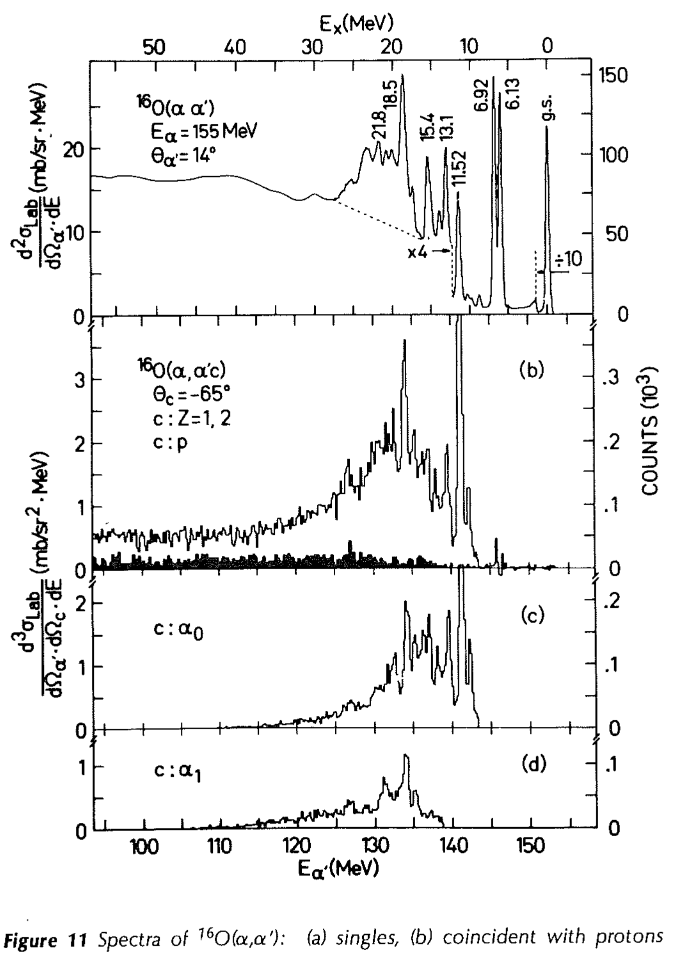

Figure 11 *Spectra of $^{16}O(\alpha,\alpha')$: (a) singles, (b) coincident with protons (black area) and all Z = 1, 2 reaction products, (c) α_0 decay and (d) α_1 decay into the first excited state of ^{12}C, [50].*

The experimental observations (A)-(D) in the field of giant resonances have had an impact on the theoretical description of both high-lying collective states and the response of the nucleus exposed to an external field. The latest giant resonance models address questions like the density dependence of the effective residual force, the self consistent determination of wave functions and single-particle energies, coupling to the continuum, the spreading width, sum rules and nuclear polarizability. This last point has been brought to the forefront by the most elementary of spin excitation modes, the magnetic dipole, and has led to the development of models where virtual Δ(1232) components contribute even at excitation energies small compared to the pion mass. This illuminates the role of the virtual pion field inside nuclei as the generator of the spin-isospin dependent force and calls for the enlargement of the purely nucleon model space. It has been in this area where in recent years low energy nuclear physics has made an important contribution to medium energy physics.

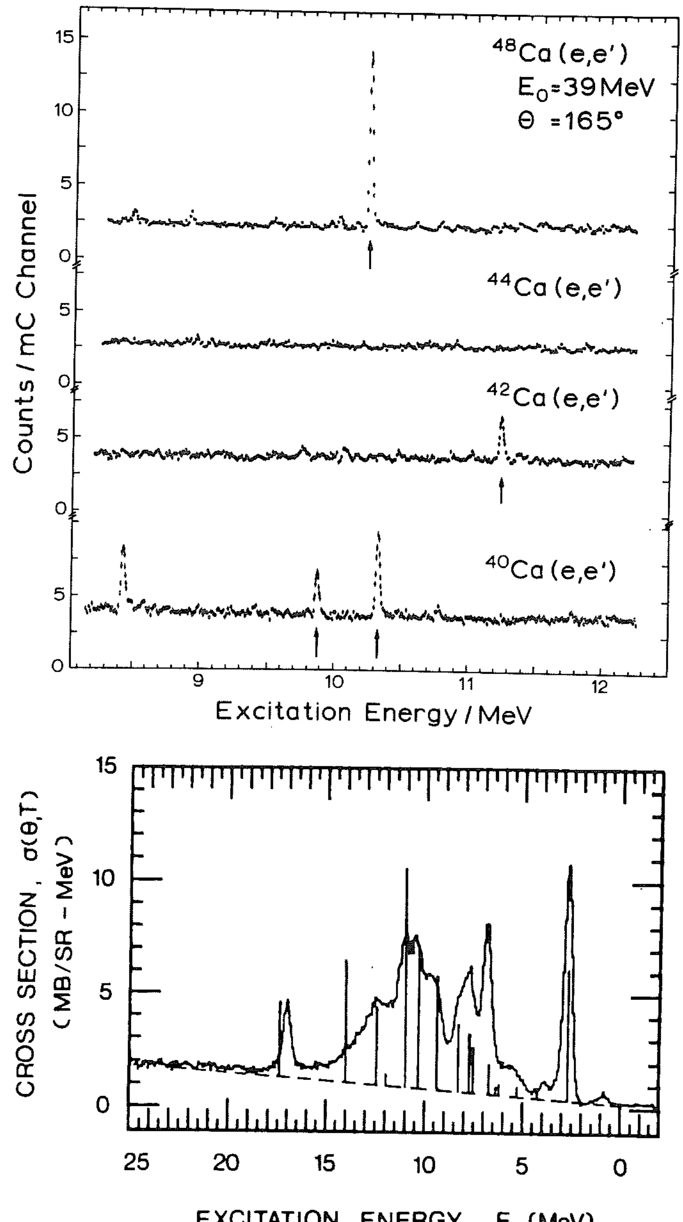

Figure 12 *Upper part: High resolution inelastic electron scattering spectra of ^{40,42,44,48}Ca with magnetic dipole transitions marked by an arrow. Note the prominent 1^+ state in ^{48}Ca at E_x = 10.23 MeV [56]. Lower part: Neutron energy spectrum for ^{48}Ca(p,n)^{48}Sc. The state at E_x = 16.8 MeV in ^{48}Sc is the isobaric analogue state of the strong 1^+ state in ^{48}Ca seen in the upper part of this figure. It carries a significant fraction of the $T_>$ (T=4) Gamow-Teller strength. A theoretical strength function [38] is shown by the vertical lines [57].*

The knowledge which presently exists on the response of the nucleus in the excitation energy region from 0-30 MeV, when it is exposed to an external field, is the result of a number of different experimental approaches involving hadronic and electromagnetic probes. The amount of work remaining to be done, however, before the M1 and E2 giant resonances are properly understood might be estimated from the long time required to understand the E1 resonance after its initial discovery. With respect to the E2 giant resonance, for example, experimental information is available on the widths, and in some nuclei, on its decays. However, due to background and interference with other resonances, determining these quantities experimentally is presently only possible with large uncertainties. This is true for both hadron and inelastic electron scattering experiments, although the former relies heavily on a model for the reaction mechanism (DWBA). The situation is illustrated in Fig 13 where medium- and high-energy resolution inelastic electron scattering spectra [69] in the region of the E2 giant resonance are compared with a (α,α') spectrum [70] and a $(\alpha,\alpha' n\gamma)$ spectrum [71]. There is no resemblance between the (e,e') and the hadron spectra, except perhaps for the case of the coincidence spectrum which exhibits more structure than all hadron scattering singles experiments. In the low momentum transfer (e,e') experiment, no states with multipolarity $\lambda > 2$ are excited. This is not the case in inelastic hadron scattering.

The **objectives of research** in the subfield of giant resonances are the identification of spin, parity, isospin and the location of the multipole strength of the giant

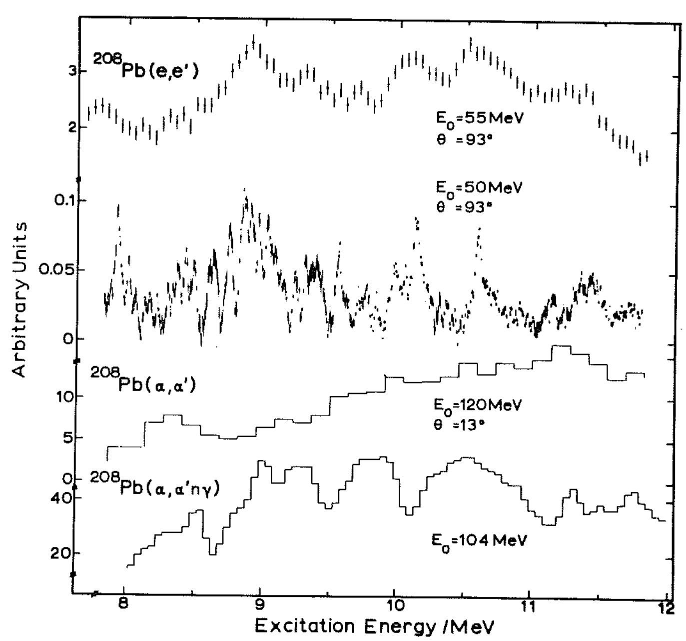

Figure 13 *Comparison of medium- and high-resolution (e,e') spectra with (α,α') and $(\alpha,\alpha' n\gamma)$ spectra in the region of the isoscalar quadrupole giant resonance in ^{208}Pb [69].*

resonances in the nuclear excitation region up to $\omega \approx 50$ MeV. To meet these objectives, (e,e'x) experiments, where the inelastically scattered electron is detected in coincidence with a decay particle x = (p,n,d,α,..., fission fragment), can be helpful. Using electrons instead of hadrons enables one to take advantage of the known reaction mechanism and exploit the selectivity with respect to multipolarity by adjusting the momentum transfer appropriately. Such coincidence experiments are usually more susceptible to direct interpretation than the more complicated hadronic ones, not only because of the simplicity of the reaction mechanism, but also because of the multi-valued momentum transfer in the hadron experiments. Nevertheless, in $A > 40$ the experimental evidence suggests that giant resonances dissolve into the "background states" and decay in a statistical manner which reduces the impact of these coincidence experiments in heavy targets.

Three sorts of coincidence experiments can be carried out. Firstly, angular correlations measured at fixed momentum and energy transfer depend upon the spins and parities J^π of the specific final state as well as the angular momentum of the partial wave of the outgoing particle. This type of experiment will yield the J^π of the giant resonance and will be able to unravel the 0^+ and 2^+ modes. Secondly, the angle integrated yield to a specific final state as a function of q yields the form factor for the coupling of the giant resonance state to that state. Such an experiment registers the overlap of the two wave functions involved, and by using the q dependence of the form factor will again help to determine J^π of the decaying resonance. Thirdly, charge and current transition densities might be separated by measuring the respective longitudinal and transverse form factors. This can be accomplished in exclusive coincidence experiments with non-planar geometry, which are sensitive to the interference between charge and current. Finally, it should be pointed out that a complete set of coincidence cross section measurements made as a function of q and ω will provide a complete two-dimensional map of the giant multipole resonance excitation function.

The **electron beam** needed to execute these experiments most efficiently would be of variable energy between 0.05 and 1 GeV and, in order to achieve reasonable coincidence counting rates, would provide beam currents of up to 100 μA. These parameters are almost the same as for the single arm experiments to measure ground- and excited states properites. The difference, however, is that the accelerator required for (e,e'x) coincidence experiments requires a duty factor of 80 to 100%. A time structure for the chopped beam of 1ns may be necessary for neutron time-of-flight measurements. Because of the width of the states in the continuum region the necessary electron energy resolution might be relaxed to $\Delta E/E \approx 10^{-4}$.

Polarized electron beams are generally not crucial for the type of experiments discussed in this subfield of nuclear physics. Such beams are, however, important for tests of parity as is pointed out elsewhere in this report.

III.2.3. Production and Propagation of Mesons and Baryon Resonances

For a quantitative understanding of the non-nucleonic components of nuclear wave functions, the properties of Δ's and other baryon resonances in nuclei should be explored. At present, the propagation and interaction of Δ's in nuclei is beginning to be studied, particularly in pion scattering experiments [72]. Further studies aimed at understanding the Δ-N interaction in nuclei would be very helpful. New insights can be obtained by producing a Δ in a nucleus by electron or photon scattering and then studying the Δ-N interaction via the final-state interaction. Recent (γ,π) experiments of this type on light nuclei have been performed at Saclay and reviewed by Laget [72].

Electromagnetic production of mesons and baryon resonances from proton and deuteron targets was an important activity in elementary particle physics in the period 1950-1970. Although one would not refer to this activity as a closed field, it has reached a plateau on which the accuracy and completeness of the data and the state of phenomenological analysis are considered adequate. The field is summarized in [73]. As a result, elementary particle physicists using electron accelerators with energies above 1 GeV now devote most of their attention to the physics of electron-positron annihilation.

In contrast, our data base and theoretical arsenal for electromagnetic excitation of nuclei in the energy interval between pion threshold and 2 GeV is very sparse. Above 2 GeV, much work was done on photoproduction of vector mesons and deep inelastic electron scattering as a function of A to study the phenomena of nuclear shadowing and to test the predictions of vector dominance in real and virtual photon absorption. The data gap between 140 MeV and 2 GeV for nuclei occurs in the region of many baryon resonances, for instance the $\Delta(1232)$, $N^*(1688)$ and $Y^*(1520)$.

The rationale to study meson and isobar production, propagation, and decay inside a nucleus is the following:

(A) Mesons and baryon resonances become increasingly important components of the nuclear wave function in governing high momentum or high energy transfer interactions. Thus an understanding of their off-shell behavior is essential for a complete theory of high energy nuclear reactions;

(B) Mesons and isobars are intimately involved in the problem of nuclear forces. For instance, our understanding of three-body (and higher order) forces can be augmented by in-medium studies of these particles;

(C) The eventual realization of the quark-gluon description of nuclear structure and reactions will benefit by the testing of concepts and approximations on data relating to the propagation of more exotic particles in the nucleus. In particular, one would like to look for manifestations of quarks in the electromagnetic transition densities of the Δ.

We now present a generic discussion of proposed measurements in this area, along with some comments on their interpretation and the corresponding electron beam requirements. In general one would carry out these measurements throughout the periodic table to find the A dependence of the relevant nuclear parameters (optical potential, response function, spectral function). To explore pion production and Δ(1232) physics, one studies nuclei in the range 140-500 MeV of excitation energy by electron and photon-induced reactions. Single arm experiments include real photon elastic scattering and total absorption, pion photoproduction (γ,π) and the measurement of form factors in the (e,e') reaction. The interesting coincidence experiments include pion, Δ(1232) and $N^*(1688)$ production via the (e,e'π), (γ,Nπ) and (e,e'Nπ) processes, as well as the production of hyperon resonances. The detailed proposals for this class of experiments are given in [15]. Intense photon beams produced by laser backscattering (from, for example, existing stored electron beams such as the Brookhaven Light Source) could be effectively used to do some exploratory work on the single arm experiments.

As one moves from inclusive measurements such as photon absorption to the highly differential inclusive case (e,e'Nπ), the information content and sensitivity to details of the model increase rapidly. The theoretical quantities of interest are the effect of the nuclear environment on the real or virtual absorption vertex, pion and delta propagation functions, and decay vertex of the delta.

This area of nuclear physics has been developing rapidly under the impetus of pion-nucleus scattering data from the meson factories. The advantage of electromagnetic production lies in the fact that it occurs throughout the nuclear volume.

Our interest in the region of 140-500 MeV nuclear excitation energy places a lower limit on the incident electron energy. The highest electron energy required is set by the highest momentum transfer and the lowest electron scattering angle needed for a Rosenbluth separation (see Figure 4) or for a reasonable electron counting rate.

The free Δ(1232) transverse form factor has been parametrized as

$$F_\Delta(q) = (1 + q^2/\Lambda^2)^{-2}$$

with Λ = 1 GeV/c.Thus choosing q^2(max) as 1 $(GeV/c)^2$ will allow mapping of the nuclear medium form factor to a point where differences from its free space value will be clear. The spatial resolution achieved will be $\Delta r = 1.5/q$ = 0.3 fm. If $\theta_e = 50^o$ is chosen as an acceptable electron angle for Rosenbluth separations, then

$$E_{max} = q/(2\sin 25^o) + 0.5\ \text{GeV} = 1.7\ \text{GeV}.$$

The single arm experiments can be done with any duty factor; the coincidence experiments require high duty factor to reject accidentals. A chopped beam might be useful for time-of-flight neutron energy measurements in a reaction like $A(\gamma,n\pi^-)$.

III.2.4. Quasi-free Electron Scattering and Nucleon Knockout

As one moves up in nuclear excitation energy from the discrete states through the giant multipole resonance region to the continuum region, the structural details of specific nuclear states become less important and the generic properties of nuclear matter become dominant.

In the continuum region the response of the nucleus is dominated by two features: quasi-free scattering in which the energy-momentum of the virtual photon is absorbed by a nucleon which is ejected from the nucleus, and quasi-free pion production in which the energy-momentum of the photon is absorbed by a nucleon which produces real pions. These two features are easily identified in the inclusive electron scattering spectrum at sufficiently high energy loss and momentum transfer. The inclusive cross section is largest at an energy loss, ω, given by Q^2 divided by twice the nucleon mass M

$$\omega \approx \frac{Q^2}{2\ M_p}$$

and for the first πN resonance, Δ(1232 MeV), at

$$\omega \approx 2\ M_\pi + \frac{Q^2}{2\ M_\Delta}.$$

Figure 14 shows these two peaks in the inelastic spectra of 2.0 - 2.7 GeV electrons on two light nuclei [74].

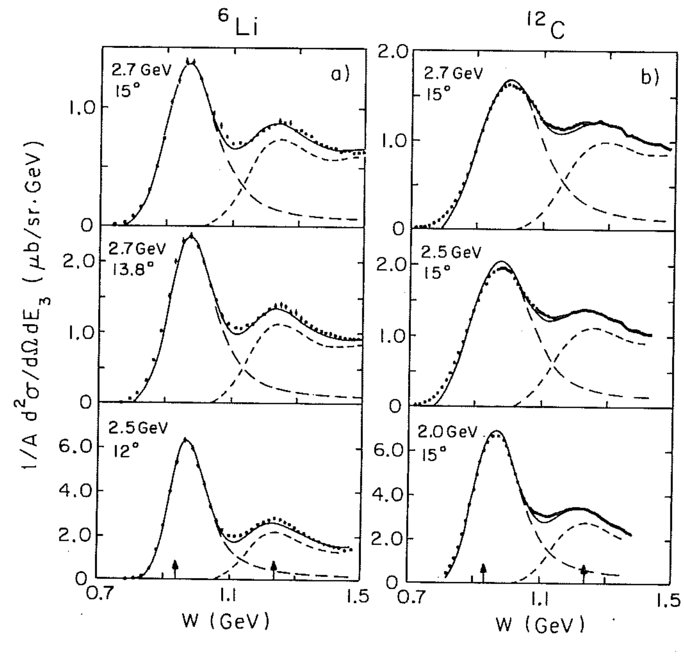

Figure 14 Electron scattering cross section versus the invariant mass W for ^{6}Li and ^{12}C target nuclei. The long- and short-dashed lines represent the calculations for quasi-elastic and N(e,e')Δ scattering, respectively. The solid line is the sum of both. The arrows indicate the masses of the proton and the Δ_{33} resonance. The data are from Glawe et al. [74].

The position of the quasi-free peak and its width have been used to extract the average nucleon binding energy and momentum. The information available from its magnitude and from the details of its shape have been largely controversial. It has been difficult to distinguish nucleon ejection from the onset of meson production for $\omega > Q^2/2M_p$. Only recently have systematic studies been performed to separate the longitudinal from the transverse response in the quasi-free region. Surprisingly, the longitudinal response, thought to be largely independent of mesonic degrees of freedom, is rather poorly reproduced by a Fermi gas calculation, both in magnitude and in shape at momentum transfers as large as 400 MeV/c. In this kinematic region it is also surprising that the transverse response is adequately explained by a simple Fermi gas calculation. If the longitudinal response is integrated over all energy losses, the resultant quantity is known as the Coulomb sum rule. The first experiments in which this sum rule could be seriously evaluated have found only about one-half of the expected strength. These experiments point to greater complexity in the nuclear response than has been anticipated; however, they can benefit from higher energy. It would be useful to repeat these experiments at a momentum transfer greater than two or three times the nuclear Fermi momentum. It is useful to make the longitudinal-transverse separation over as large an energy loss as possible.

A novel feature of the quasi-free excitation region is a phenomenon called y-scaling. A plot of the inelastic form factor

$$f = \frac{d\sigma_A}{d\Omega\, d\omega} \Big/ \frac{d\sigma_N}{d\Omega}$$

versus the variable y defined as

$$y = \frac{\bar{p}\cdot\bar{q}}{M_N|q|} = \frac{\omega - \epsilon}{q} - \frac{q}{2M_N}$$

where p is the nucleon initial momentum and ϵ is an average nucleon separation energy, yields a universal curve over a large range of (q,ω), as shown in Figure 15 [75] (see also Figure 6). The reduction from the expected two independent kinematic variables (q,ω) to one, namely y, is understood as a reflection of the fact that the y is the initial longitudinal velocity of the struck nucleon (nonrelativistically). The breaking of y-scaling (for positive y in the meson production region or for collective excitation) is a signal that the reaction mechanism is not quasi-free. At high momentum transfer this test may uncover two-nucleon knockout and exchange currents. Eventually y-scaling goes over into relativistic x-scaling, well known in high energy ep deep inelastic scattering.

The direct ejection of a proton in the quasi-free region has been measured [76] in the coincidence experiment (e,e'p) with the 2% duty cycle accelerator at Saclay. These are the only experiments that have achieved energy resolution and momentum resolution sufficient to identify nuclear shell structure for systems as heavy as A=40. The process measures the momentum distribution of the struck nucleon after it has left the nucleus. The momentum distribution of 1s and 1p states have in these experiments been measured to about 300 MeV/c. At this point the experiment is overwhelmed by accidental coincidences.

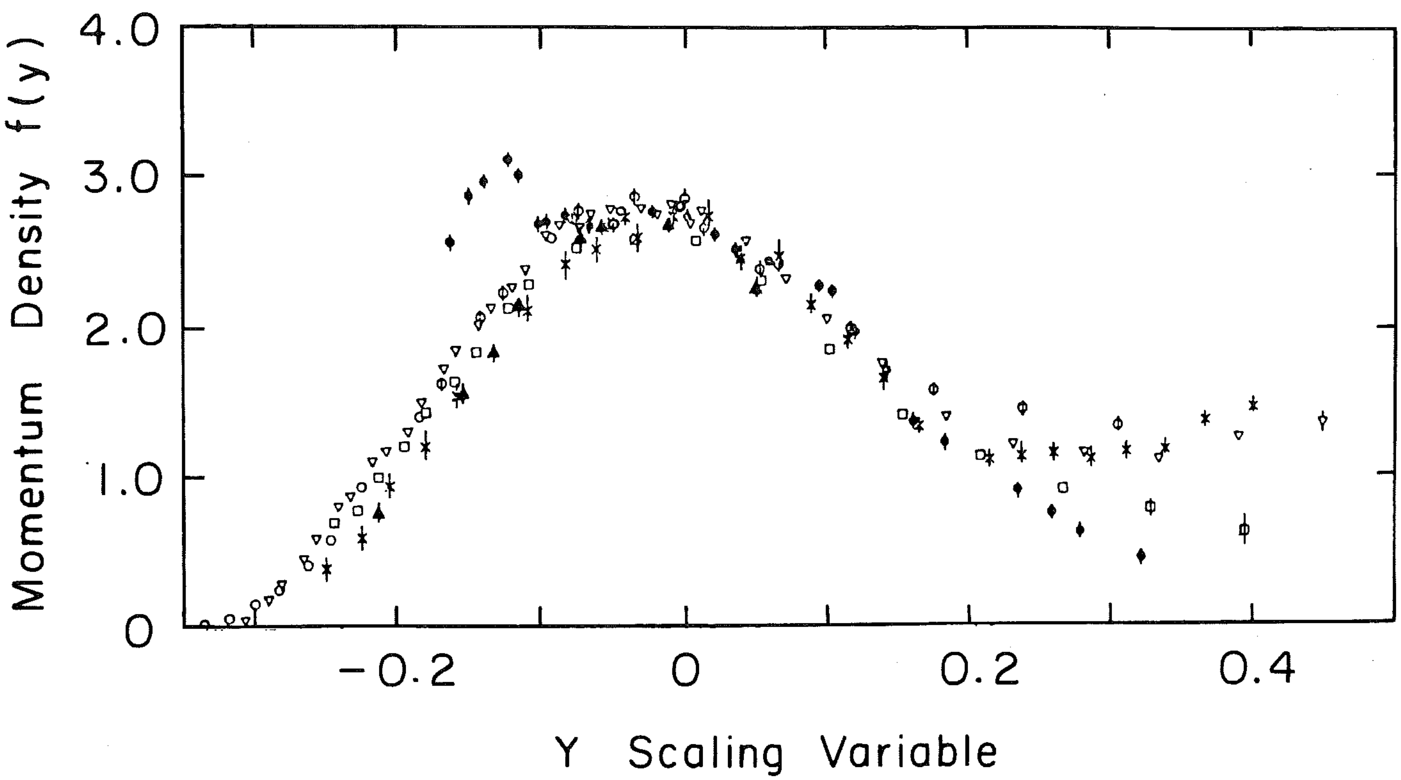

Figure 15 *Values of momentum density f(y) are plotted against the scaling variable y for several quasi-elastic ^{40}Ca spectra obtained at scattering angles from 60° to 160°. Over a wide range of y a scaling curve is obtained indicating that the scattering proceeds primarily via one nucleon knockout. The data are from Zimmerman et al. [75].*

The major portion of these experiments were completed a few years ago and there has been no significant work recently. The Amsterdam accelerator at 500 MeV and a duty cycle of 2.5% will be soon able to verify the Saclay results, but it will be unable to extend these measurements to much higher momentum transfer. As these experiments are the most direct measurement of the momentum distribution of a nucleon in the nucleus, they represent a major program for a new high energy, high duty factor accelerator. The Saclay results have been interpreted in the distorted wave impulse approximation. The momentum distributions up to 300 MeV/c appear rather reasonable, but the occupation numbers extracted are often found to be too small by as much as 30%. At the Saclay energy the ejected nucleon has a kinetic energy of about 80 MeV. A larger energy, perhaps 200 MeV to 400 MeV, would reduce the magnitude of the final proton-nucleus interaction. In this energy region the proton nucleus optical potential is at its minimum. The momentum distribution becomes much more interesting between 450 MeV/c and 600 MeV/c. Here many body theories begin to differ in their predictions of the momentum space wave function. These momenta are 50% to 100% larger than the Fermi momentum. Although the probability of these momentum components is small, 0.1% or less, it depends sensitively on the treatment of the two body interaction.

The validity of the impulse approximation for the virtual photon-proton interaction in the nuclear medium has never been tested. This approximation could be tested by making a longitudinal-transverse separation of the (e,e'p) cross section. The energies available at accelerators of sufficient energy resolution have been too low to permit consideration of this experiment. The bulk of the studies of single nucleon knockout reactions could be performed at incident energies well below 2.0 GeV.

The longitudinal-transverse separation of the (e,e'p) data would give valuable clues about the proton wave function. The detection of the neutron in a quasi-free (e,e'n) measurement would indicate whether our current picture of nearly identical single particle behavior for protons and neutrons is correct.

In high energy photoproton measurements, proton momenta up to 900 MeV/c [77] have been observed; see Figure 16. The interpretation in terms of an initial single-particle momentum distribution is controversial, however, as the photoneutron cross section is roughly of the same magnitude. Direct photon coupling to the neutron is much smaller than to the proton.

The high momentum components of the nucleon wave function presumably arise from the short range part of the nucleon-nucleon interaction, from resonances (e.g., the Δ), and from quark degrees of freedom. It is fair to state that there is no direct experimental determination of the relative momentum distribution of an interacting pair, the theoretical construct of which is known as the two-nucleon correlation function. Some 20 years ago a few experiments were made of the (γ,np) reaction from which a phenomenology based on the interaction with a quasi-deuteron evolved. Little quantitative work has been done with those experiments largely because the data could not motivate a more penetrating analysis.

The average nucleon momentum places a boundary outside of which there can be no dominant contribution to the inclusive electron scattering spectrum from quasi-elastic scattering. These regions are far from the quasi-elastic peak. The optimal region to examine the interacting pair is in the region where single nucleon emission is suppressed. The repulsive core of the nucleon nucleon interaction sets the scale of distance at 0.5 fm. To examine the two nucleon momentum distribution then requires a spatial sensitivity smaller than 0.5 fm, and a momentum transfer to the pair considerably greater than 600 MeV/c. To eject two high energy colinear nucleons would require incident energies in excess of 2 GeV.

III.2.5. Hypernuclei

The structure of Λ and Σ hypernuclei have recently been explored with the low momentum transfer ($K^-,\pi^{\pm}$) reaction [81]. For example, focussing on lambda hypernuclei, it is possible to implant a Λ^0(M_Λ = 1115.6 MeV, $J^\pi = 1/2^+$, T = 0, S = -1) in a nucleus in any configuration that is energetically possible, including its deepest-lying shells, as it is not blocked by the Pauli exclusion principle (contrast this with adding a nucleon to a nucleus). As the lifetimes for lambdas in hypernuclei are long enough ($\approx 10^{-10}$ sec) for a stable system to form, a whole new regime of nuclear structure studies is opened up extending from the lightest systems throughout the periodic table.

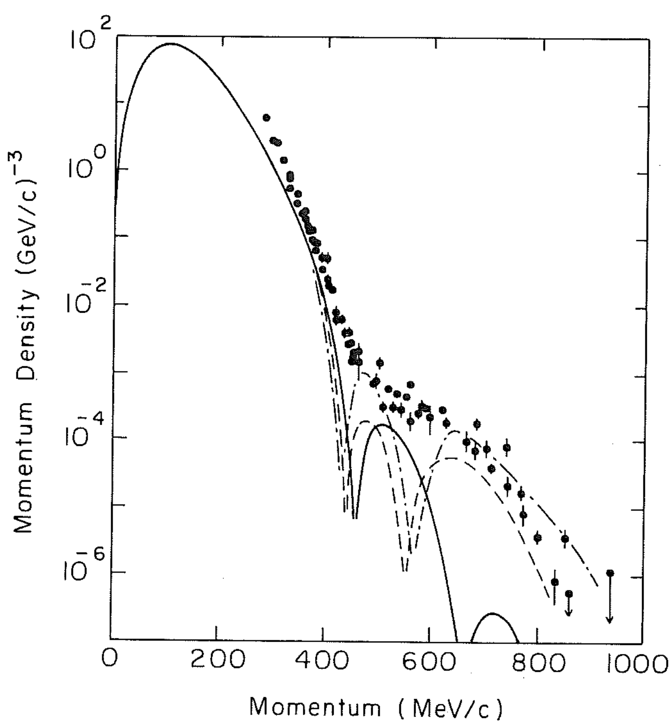

Figure 16 *Comparison [77] of the $^{16}O(\gamma,p)$ momentum distribution (solid circles) with theory. The solid curve is the Elton-Swift distribution [78]. The dashed curve was obtained from the density-dependent Hartree-Fock wavefunctions of Negele [79], the dot-dashed curve represents the momentum distribution based on a model of Ciofi degli Atti [80] using a Jastrow correlation function.*

The $(K^-,\pi^\pm)$ reactions can also be used to produce Σ hypernuclear states, some of which are surprisingly long-lived [82, 83]. The (K^-,π^-) reaction has two main features:

(A) it excites strongly only the natural parity hypernuclear states;

(B) the K^- and π^- are strongly absorbed so that the reaction occurs in the nuclear surface.

The $(\gamma,K^{+,0})$ or $(e,e'K^{+,0})$ reactions on nuclei offer another method of producing Λ and Σ hypernuclei [84]. In contrast to (K^-,π), the photo and electroproduction reactions excite both natural and unnatural parity hypernuclear states with comparable strength. Since γ and $K^{+,0}$ are only weakly absorbed, the reaction is not confined to the nuclear surface and is predominantly a simple one-step process. An exciting prospect for real and virtual kaon photoproduction is that it may offer a method for studying deeply bound Λ (and Σ) hypernuclear states and also high spin states; the latter can also be produced in $(\pi,K^{+,0})$ reactions. The K^+ and K^0 are sufficiently weakly absorbed in the final state that it should be possible to deposit a Λ in its lowest shells with appreciable cross section even in a very heavy nucleus.

It should also be noted that states of Σ hypernuclei may also be observable in (γ,K) reactions. Here one implants a Σ (M_{Σ^+} = 1189.4 MeV, M_{Σ^0} = 1192.5 MeV, M_{Σ^-} = 1197.3 MeV, $J^\pi = 1/2^+$, $T = 1$, $S = -1$) in the nucleus. The cross section for Σ photoproduction on nucleons is comparable to that for kaon photoproduction, and thus yields comparable nuclear cross sections.

The cross section [85] for $p(\gamma,K^+)\Lambda^0$ rises from threshold to a peak at 1.5 GeV and then falls to a low value above 4 GeV. Bremsstrahlung or tagged photons would be used as the photon source. A maximum photon energy of 2 GeV would be sufficient for most spectroscopic studies. Since the hypernuclear levels are observed by measuring the K^+ energy in a magnetic spectrometer, the electron beam producing the bremsstrahlung need only have a moderate step size and uncertainty. A high duty factor is required if event-tagging is to be accomplished. On the other hand the detection of K^0's is much more difficult. One scheme involves the regeneration of $K_L^0 \rightarrow K_S^0$ followed by the coincident detection of the decay pions $K_S^0 \rightarrow \pi^+\pi^-$, although the practicality of this procedure is not obvious.

III.2.6. High Momentum Transfer, Short Distance Studies of Nuclei

One of the most important developments in physics of this decade has been the demonstration from deep inelastic electron-nucleon scattering that the electromagnetic current within hadrons and nuclei is carried by point-like spin 1/2 quarks. For momentum transfers $Q^2 > 1\text{-}2\ \text{GeV}^2$ the inelastic electron-nucleon cross section begins to display a scale-invariant behavior consistent with the simplest type of impulse approximation, where the electron scatters directly against point-like quark constituents of the target. The deep inelastic data also provide a basic confirmation of quantum chromodynamics (QCD), which predicts that the strong interactions of the quarks become asymptotically weak in high momentum transfer reactions. The deviations from point-like behavior which are observed in the whole range of deep inelastic electron, muon and neutrino scattering data are consistent with the color radiative corrections to the quark current predicted by QCD. In addition, at low values of Q^2 there is also evidence for corrections associated with coherent multiquark processes and final state interactions.

The fact that inelastic electron scattering at large momentum transfer resolves the basic quark structure of hadronic matter makes inelastic electron-nucleus reactions a particularly important probe for nuclear physics. The specific nuclear effects, i.e. the deviations from simple nucleon additivity, open up a new range of phenomena which is of interest to both nuclear and particle physics. The fact that Q can be varied gives us the unique capability of examining the electromagnetic structure of the nucleus with a variable resolution scale: at small Q^2 of order of a few fm^{-2} or less, the photon effectively couples to the constituent nucleons and virtual mesons contributing to the nuclear force. However, at low Q^2 but with energies above the ρ^0 production threshold, the photon effectively interacts with the nucleons and mesons at or near the nuclear surface. This is the nuclear "photon shadowing" effect first predicted in vector meson dominance models. At large $Q^2 > 1\ (\text{GeV/c})^2$ ($> 25\ \text{fm}^{-2}$) the shadowing of the photon interactions is negligible and one begins to resolve the underlying quark structure of the nucleus over the entire nuclear volume. In addition, by studying the variation of the inelastic electron-nucleus cross section as a function of electron scattering angle one can separate the interaction of longitudinally and transversely polarized photons. This in turn can be used to determine the spin of the constituent scatterer in the nucleus, whether it is a nucleon, meson, or quark.

The study of the transition between standard nucleon-meson degrees of freedom and the subconstituent quark-gluon QCD degrees of freedom is clearly one of the most important future areas of investigation in nuclear physics. In addition to allowing the spanning of this transition region, a high-duty electron accelerator of moderate energy provides the capability of measuring detailed dynamics properties of the nucleus by measuring the final state particles in coincidence with the scattered electron. The correlation of the final nuclear fragments and produced particles with the electron scattering plane allows measurements corresponding to a linearly polarized virtual photon. Increasing the energy, ω, of the photon allows the unveiling of new dynamics in the nucleus as physical thresholds are passed, such as strange particle production and the possible excitation of "hidden color" nuclear states - new degrees of freedom predicted by QCD.

We review below some specific electron-nucleus inelastic scattering experiments which are relevant to the short distance structure of complex nuclei.

The basic **single-arm eA → e'X measurement** determines the virtual photoabsorption cross sections,

$\sigma^T_{\gamma^* A}(\nu,Q^2)$ and $\sigma^L_{\gamma^* A}(\nu,Q^2)$, as a function of laboratory photon energy, E, and four momentum transfer, Q. The most relevant questions for nuclear physics are the specific nuclear effects which give deviations from simple nucleon additivity:

$$\sigma_{\gamma^* A} = Z\sigma_{\gamma^* p} + (A-Z)\sigma_{\gamma^* n}$$

In particular one is interested in understanding the nuclear photon shadowing from low to high Q^2 through the QCD transition region. The specific nuclear dependence of σ_L/σ_T is of interest because of the sensitivity of this ratio to bosonic currents and coherent effects. At high Q^2 one resolves the quark structure of the nucleus. For example, the nature of charge-symmetry breaking of the quark momentum distributions can be elegantly determined from a detailed comparison of e^3He and e^3H deep inelastic scattering. The region with $x = Q^2/(2M_N\nu) > 1$ is particularly interesting to study, since this determines the quark momentum distributions beyond nucleon target kinematics. At high Q^2 and $x > 1$ the quark degrees of freedom of the nucleus (including hidden color components) are probed. Measurements of the polarized structure functions with polarized electron beam and polarized target could be interesting at $x > 1$ to study the correlations between quark and nuclear spins.

The main requirements for the single arm experiments are a high intensity electron beam with sufficient electron energy to cover the kinematic regions of interest. High duty factor is not necessary.

In order to help disentangle and identify the different processes which contribute to the total cross section, it is essential to separate σ_L and σ_T. Measures of σ_L require electron scattering at moderate forward lab angles $\theta_{e'} \lesssim 60°$. The accessible (nucleon target) kinematic region for E = 2 GeV and E = 4 GeV is shown in Figure 17. The region accessible to σ_L/σ_T separation is

$$Q^2 < 2\ (\mathrm{GeV/c})^2,\ \nu < 1\ \mathrm{GeV\ at\ E = 2\ GeV}$$

and

$$Q^2 < 2.8\ (\mathrm{GeV/c})^2,\ \nu < 1.5\ \mathrm{GeV\ at\ E = 4\ GeV}$$

For measurements with $Q^2 < 1\ \mathrm{GeV}^2$, the kinematic limits are

$$W^2 < 2.5\ \mathrm{GeV}^2,\ \nu < 1.5\ \mathrm{GeV\ at\ E = 2\ GeV}$$

and

$$W^2 < 5\ \mathrm{GeV}^2,\ \nu < 3\ \mathrm{GeV\ at\ E = 4\ GeV}$$

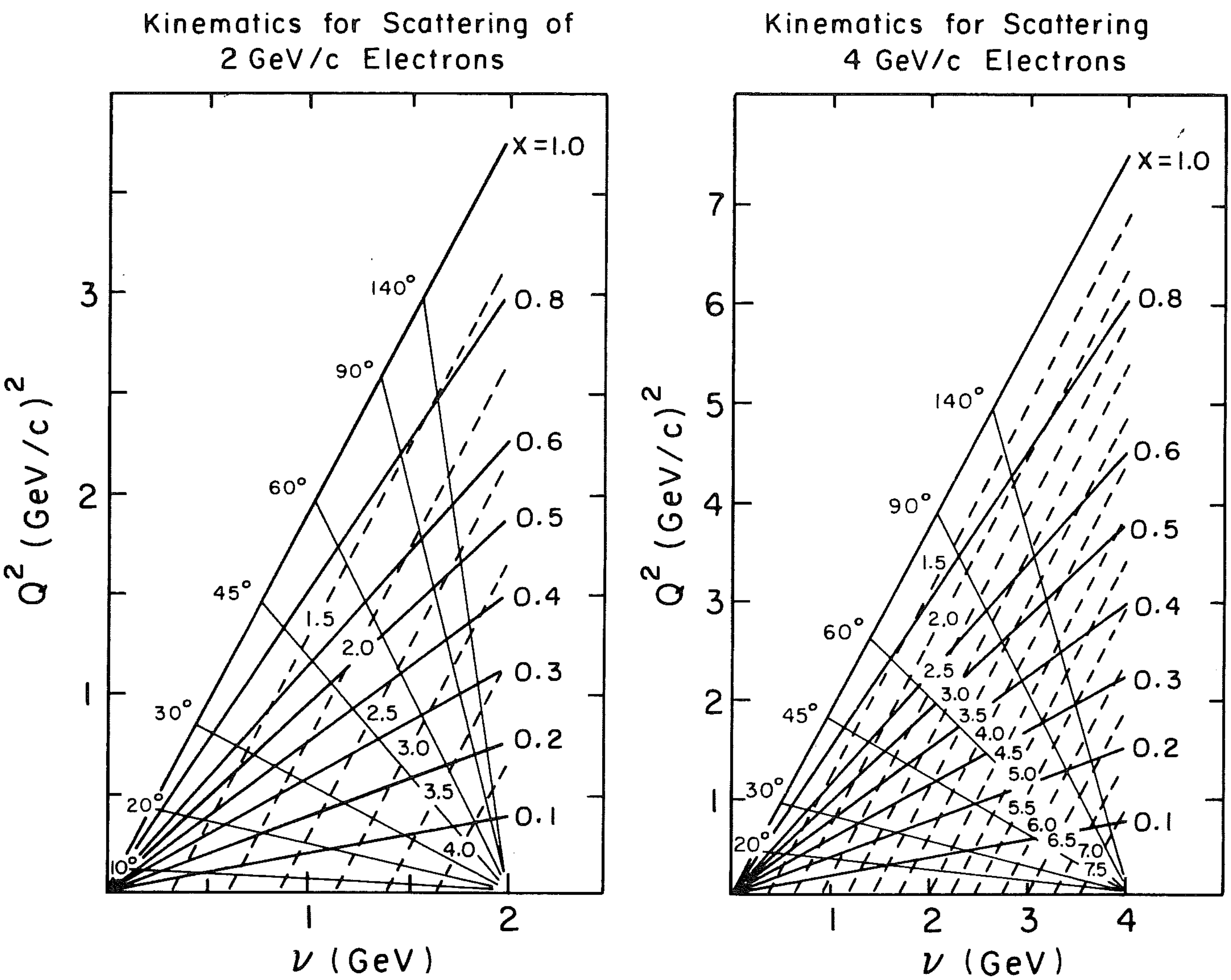

Figure 17 Electron-proton scattering kinematics. The dashed liines correspond to fixed W^2 (in GeV^2). Taken from C.F. Williamson et al. in Future Directions in Electromagnetic Nuclear Physics [15].

where $W^2 = M_T^2 - Q^2 + 2M_T\omega$ in the target rest frame. The QCD scaling regime starts at $Q^2 > 1$ (GeV/c)^2 and $W^2 > 3.5$ GeV/c^2 (above the resonance region). The strange particle threshold is at $W^2 \approx 2.6$ GeV^2. A comprehensive review of present data on electroproduction is given by T. H. Bauer et al. [86]

For a nuclear target the kinematic range in Q^2 and W^2 is extended because of Fermi motion. The accessible kinematic region is essentially controlled by counting rate. For fixed Q^2, higher beam energy can be used to increase the cross section by working at a smaller scattering angle. For example, at a given Q^2, the cross section is proportional to the scattered electron energy squared. The polarized structure function measurements require a polarized electron beam and efficient polarized targets.

Coincidence measurements of specific channels: $eA \rightarrow eHX$ where $H = p, n, \pi, K, \rho, d, \alpha$, etc. in inelastic electron-nucleus scattering can shed light on many different fundamental aspects of nuclear physics. The electroproduction mechanism for each channel can be studied as a function of photon mass and transverse versus longitudinal polarization. In addition, the correlation of the production and electron-scattering plane reflects the linear polarization of the virtual photon. At low Q^2, the production is mainly from the surface of the nucleus because of shadowing. At high Q^2, production can occur anywhere in the nuclear volume, but can be strongly affected by final state collisions and absorption.

In the case of the electroproduction reactions $eA \rightarrow epX$, $eA \rightarrow enX$, one measures the momentum distribution of nucleons in the nucleus far from the quasi-elastic peak where far-off-shell short distance components of the nuclear force are relevant. Studies of baryon production in the backward direction at high Q^2 provide the cleanest possible study of the "cumulative" effect usually studied in hadron-hadron collisions. These measurements of the nucleon Fermi distribution can be compared with the momentum spectrum of baryon fragmentation in fast heavy ion collisions, as well as QCD counting rule predictions. One can also study in an analogous way the electroproduction of nuclear clusters or components such as d, α, etc. in a heavy nucleus. One is particularly interested in studying the importance of these channels for nuclear structure functions at very large x values. In general one wishes to study how the scaling structure functions are built from the contributing channels. Measurements of the A and Q^2 dependence of proton electroproduction is important for understanding the nucleon photon shadowing effect.

Another important goal for electroproduction is to study the meson presence in the nucleus. Comparisons between $ep \rightarrow e\pi X$ and $eA \rightarrow e\pi X$ will teach us about the production and propagation of the mesons and the isobars in the nuclear medium. The A-dependence, Q^2-dependence, angular dependence, and σ_L/σ_T separation should allow a separation of the production mechanisms and specific nuclear effects. Electroproduction of the K^+ may be particularly interesting because of the relatively small final state effects.

These coincidence measurements require high duty factor and high intensity. The kinematics requirements are similar to a single arm measurement. The production of strange particles and other high mass final states with $W^2 > 3$ GeV^2 thus requires high beam energy beyond $E_0 = 3$ GeV.

Measurements of the **properties** of the entire **multiparticle final state** in deep inelastic electron-nucleus scattering could be particularly interesting since, in principle, one can study the evolution and hadronization of the scattered quark in the nuclear volume after it is scattered incoherently by the electron. Measurements of the A-dependence of the hadron multiplicity, the momentum distributions transverse to the virtual photon axis, and the leading particle production all reflect the interaction of the quark jet in the nuclear medium. The machine requirements here are high duty factor and high energy. One must be in the scaling region ($Q^2 > 1$, $W^2 > 2.5$ GeV^2) in order to interpret the results in terms of quark propagation.

Each of the above electroproduction experiments can be studied with **real photons from a tagged photon beam** as a check on the $Q^2 \rightarrow 0$ extrapolation of $\sigma_T^{\gamma^* A}(\nu, Q^2)$ and the shadowing effect for each channel. Compton scattering processes on a complex nucleus, particularly at large momentum transfer can be used as searches for resonance effects, e.g. possible hidden charm nuclear states. One can use Compton scattering to also study the propagation of isobars and collision-broadening of resonances in the nuclear medium.

III.3. Fundamental Symmetries

Of the various symmetries which can be investigated with greater profit with medium energy and particularly higher electron accelerators, parity presently stands out as the most interesting one [87]. The last decade has seen the development and testing of a combined electroweak interaction theory. The simple SU(2) x U(1) theory of Weinberg and Salam, as supplemented by the Glashow-Illiopoulos-Maiani mechanism has, to date, passed all the tests which have been applied to it. For electromagnetic (radiative) corrections to the Weinberg-Salam theory see, e.g. refs. [88, 89, 90].

Semi-leptonic interactions occur due to both charged and neutral weak currents. Beta decay is an example of the former. Detection of neutral currents for the charged leptons, such as electrons, requires the presence of parity violating effects. Such parity violation occurs due to the interference of weak and electromagnetic interactions and can be observed in electron scattering. One of the most dramatic and compelling tests of the Weinberg-Salam theory was carried out at SLAC with very high energy longitudinally polarized electrons scattered from deuterons and protons [91]. Within the errors of the measurements, the parity non-conserving asymmetry measured was found to be in good agreement with the theory [26]. Other tests of the theory, primarily with neutrinos, also agree with it.

The weak interactions can be probed in several sectors, the purely leptonic one, the semi-leptonic, and the nonleptonic ones. A high energy electron accelerator fitted with a polarized source is a particularly appropriate tool to test the semi-leptonic sector. First of all, it should be noted that the weak interactions occur at very short distances, and therefore high momentum transfer experiments allow one to probe the interactions more readily. Indeed, dimensional arguments are sufficient to indicate that the asymmetry in polarized electron-nucleon or electron-nucleus scattering is of the order $GQ^2/(4\pi\alpha)$, where G is the dimensional Fermi weak coupling constant, $GM_p^{\,2} \approx 10^{-5}$, where M_p is the proton mass, $h = c = 1$, Q is the four momentum transfer, and α is the fine structure constant. Thus, for $Q^2 \approx M_p^{\,2}$, the asymmetry is of order 10^{-4}. However, the accuracy of the measurement may not increase with Q^2, since the number of scattered electrons falls off as $1/Q^4$ due to the electromagnetic interaction. Nuclear and nucleon form factors modify the above arguments.

The weak interaction of the electron with a nucleon is described in terms of four independent coupling constants. These refer to the strengths of the weak neutral currents of the electron, and nucleons. It is only the parity violating products of the vector (axial vector) current of the electron coupled to the axial vector (vector) current of the proton and neutron, or alternatively to the isospin zero and isospin one parts of the nucleon currents which enter. Alternatively, quarks can be substituted for nucleons in the above description. It is just this interplay which may make these measurements of parity nonconservation in high (2-4 GeV) energy electron scattering from nucleons of even higher value than merely as probes of the weak interaction. For 10 GeV electrons, the quarks in the nucleons couple incoherently to the electron whereas at energies below a GeV the coupling is to the coherent proton (or neutron) target. Thus, the region of 2-4 GeV is likely to be sensitive to the quark distribution in nucleons and the nucleus, since the scattering from the valence quarks will be neither totally coherent nor incoherent. Such sensitivity is likely to give us considerable insight into quark confinement mechanisms and to test various models (e.g. bags) for describing quark wave functions or distributions in the nucleon and nucleus. Form factors will be required and are measures of quark distribution functions.

Experiments which seek to exploit parity violation will be carried out at medium energies in the near future at Bates ((M.I.T.) and Mainz. At these and at higher energies there are a number of tests [92, 93] of weak interaction theory which can be carried out with proton and deuterium targets:

(A) Determination of the four independent coupling constants and of weak form factors.

(B) The determination of the product of the weak vector coupling of the electron to the Z^0 (which is proportional to $1\text{-}4 \sin^2 \Theta_W$, where Θ_W is the Weinberg angle) and the axial vector isoscalar current of the nucleon [94, 95]. This coupling is doubly small, once because $\sin^2 \Theta_W$ is close to 1/4 and again because in the pure Weinberg-Salam theory without renormalizations the axial current of the nucleons is purely isovector in nature. There are corrections due to strange quark loops and other effects which predict that the isoscalar coupling is of the order of 0.1. The effective coupling is thus of order 1/100 and of the same order as radiative corrections to the theory. Such higher order effects, i.e. G^2 or $G\alpha$, are clearly sensitive to details of the theory and therefore serve as important tests of it. For instance, the presence of further neutral bosons in addition to the Z^0, will affect such results. Measurements of elastic scattering not only from ^{2}H, but also from ^{4}He, ^{12}C, or other isospin zero nuclei allow one to test this aspect of the theory.

(C) Tests of the conserved vector current in weak interactions [96]. For instance, the asymmetry due to the axial electron current and vector nucleon current should be independent of any form factor since it is determined by the ratio of the weak neutral vector to the electromagnetic current of the hadron, and these should be identical to within a constant [92].

(D) Tests of a pure V, A theory by way of searches for scalar, pseudoscalar, and tensor (S,P,T) components of the current.

(E) Parity nonconservation experiments in inelastic scattering and reactions can also serve as tests of the theory [97]. By choosing exclusive reactions to definite final states one can probe particular aspects of the theory. Enhancements may also be sought. For instance, as pointed out by Feinberg [98] and by Borie and Drechsel [99], a transition from the 0^+ ground state of ^{16}O to a 0^- excited state of isospin zero picks out the nuclear axial current of isospin zero. The asymmetry is enhanced because the electromagnetic transition requires two photons. By measuring the electromagnetic transition rate in addition to the asymmetry, some of the nuclear model dependence can be removed. (For a further example, see [100]).

(F) A further class of experiments is inclusive scattering measurements as in deep inelastic processes. These are likely to be particularly sensitive to quark distribution functions.

(G) Parity nonconservation in pion production [101] at the Δ resonance and to other final states with a meson (π,ρ,ω, etc.) will help to determine the nature of the weak currents of the mesons and resonances.

(H) Photon beams can also be used to probe weak interactions. Because of the gauge invariance required, direct Z^0 exchange effects do not occur in this case, and in general, the asymmetry will be reduced relative to electron scattering by order α. However, the use of photon beams may allow one to determine the parity nonconserving couplings of various mesons to nucleons as for example, the pion coupling constant from (γ,π) reactions [102]. In the case of photon absorption in nuclei, it is the non-leptonic weak interaction which is likely to be probed because the weak interaction of a photon is small [92]. PV of the photon may be studied through Compton scattering [103].

Another sector of the weak interactions is the nonleptonic one [97]. Considerable progress has been made during the past decade in studies of this sector through parity violation studies in p-p scattering and in nuclei. The experiments carried out to date, however, are still insufficient to determine the parameters of the weak (parity violating) force between nucleons. Such a force has been described in the past through the exchange of mesons with one hadronic and one weak parity-violating (PV) vertex. It is the strength of the PV vertices of mesons to nucleons which are related to the basic theory via quark models of nucleons. Quark models are beginning to be used to calculate nuclear PV effects directly. Electron scattering at small momentum transfer may also be used for investigations of hadronic or non-leptonic parity violations and weak interactions [92]. As already pointed out, such tests may be carried out in the elastic scattering of electrons from isospin zero targets. In addition, the electroexcitation of states of the same angular momentum as the ground state of a target nucleus but with opposite parity may be sensitive to nuclear parity nonconservation [97]. In particular, if the excited state is close to the ground state as in ^{19}F, such nuclear parity-violating effects may be larger than those from Z^0 exchange, at small momentum transfers. Detailed calculations will be required to check this possibility. Undoubtedly other examples exist, where the effects of nuclear parity violation can compete with those due to Z^0 exchange. This will occur, typically, whenever the isoscalar axial nuclear weak current is involved.

It may become feasible to carry out tests of various grand unified theories through searches for forbidden reactions. Examples are searches for rare decay modes of muons and pions produced by the electron accelerator.

One can also envision tests of quantum-electrodynamics (QED) with electron accelerators. It is doubtful that a 2 GeV accelerator can compete with the very high energy tests of QED, which show that the electron is a point particle and that there is no cutoff larger than $\approx 10^{-16}$ cm. On the other hand, a high intensity several GeV electron accelerator will allow other tests of QED or electromagnetic theory. For instance, 2γ induced reactions can be studied. There are a number of ways of signaling the presence of 2γ intermediate states. In particular, the charge conjugation properties of such states is opposite (+) to those reactions induced by a single photon (-). The interference of such reactions with weak processes may be possible to study. In e^-e^+ annihilation, the forward-backward asymmetry signals the presence of two photon processes or the presence of weak interactions.

Other tests of electromagnetic theory include searching for $\Delta I = 2$ processes [104-107]. For instance, $I = 2$ states cannot be excited by real or virtual photons incident on an $I = 0$ target. In the past, such $\Delta I = 2$ pieces of the electromagnetic current have been sought in the reaction $\gamma p \rightarrow N\pi$ in the region of the $\Delta(1232)$ resonance.

Many tests of time reversal invariance (TRI) which have been carried out to date involve electromagnetic transitions or detailed balance tests in photon induced reactions [97,104-107]. In some cases, experiments give indications that time reversal invariance may be violated in such transitions. An example is the $\gamma\ ^3\mathrm{He} \rightarrow pd$ reaction [108-113] and its inverse $pd \rightarrow \gamma\ ^3\mathrm{He}$ [114-116]. No definitive conclusions should be drawn until further experimental checks of beam normalization, etc. have been made. Photon correlation experiments indicate that TRI holds to better than $\leqslant 10^{-3}$ [117].

With the advent of higher electron energies the above tests or similar ones can be repeated. Further tests with polarized electrons or polarized targets might be carried out with electrons. Examples are:

$$\vec{e}\,d \rightarrow e\,d$$

$$\vec{e}\,p \rightarrow e\,\Delta\ (1232)\ .$$

Correlations of the type $\langle\vec{\sigma}\rangle \cdot (\vec{p}_i \times \vec{p}_f)$, where $\langle\vec{\sigma}\rangle$ is a polarization, and p_i and p_f are initial and final momenta, can be looked for. However, if the source of the time reversal noninvariance has the strength of a milliweak force, no effects will be observed in such studies. It is only if millistrong effects were to be present, which is not expected in QCD, that effects would be observed. Since two photon effects can mimic time reversal noninvariance signals, observed effects at a level of $\leqslant 10^{-3}$ must be interpreted with care [117, 118].

Section IV.
Facility Requirements

In order to define the facilities needed to execute the high priority aspects of a nuclear electromagnetic interactions research program, the Subcommittee considered the following questions:

- *What accelerator capabilities are required by the measurement program outlined in Section III?*
- *What electron accelerators are presently available in the United States and foreign laboratories?*
- *What new facilities are needed and what are the design and cost considerations involved?*

IV.1. Capability Required by the Research Program

A review of proposed measurements of electromagnetic nuclear interactions demonstrates that future requirements on parameters of electron beams will be more stringent than those obtained in the past. These requirements arise because more detailed information must be obtained in reaction studies to test nuclear models and as input for interpreting reactions induced by strong and weak projectiles.

IV.1.1. Beam Energy and Duty Factor

There are four major factors which enter into the determination of electron beam energy, E_0, for a given experiment: **maximum momentum transfer**, q_m, **maximum energy transfer**, ω_m, **angular range** of the scattered electrons, and the effect of beam energy on experimental **counting rates** at fixed q and ω.

An important criterion in choosing the **maximum momentum transfer** is the spatial resolution desired in extracting the nuclear transition density $\rho(r)$ from the measured form factor (here we use the three momentum, q, instead of the more correct four momentum, Q).

$$F(q) = \int_0^\infty \rho(r)\, j_L(qr)\, r^2\, dr.$$

A reasonable quantity characterizing the spatial resolution Δr is the half-wave of the Bessel function, roughly $\pi/(2q) \approx 1.5/q$. Then a given Δr will be achieved for a three-momentum transfer

$$q_m = 1.5/\Delta r\,.$$

Another way to choose q_m is to consider the inverse Fourier-Bessel transform

$$\rho(r,q_m) = r^{-1} \int_0^{q_m} F(q)\, \sin(qr)\, q\, dq$$

The left-hand-side is a damped oscillatory function of q_m that converges, for $q_m \to \infty$, to the charge density. The amplitude of the last observed oscillation represents the uncertainty $\Delta\rho$ with which $\rho(r)$ is determined at finite q_m. To reach a $\Delta\rho/\rho$ of 1% takes $q_m = 8\ fm^{-1}$ for ^3He, 4.5 fm^{-1} for ^{12}C, and 3.5 fm^{-1} for Pb.

Another consideration in choosing q_m is the maximum nucleon (or constituent) momentum k to be studied. A given k requires, roughly, a momentum transfer of q = 4/3 k. This results from the fact that form factors are momentum overlap integrals of the type

$$F(q) = \int \Psi(k)\, \Psi(k+q)\, d^3k.$$

Since the single particle wave function $\Psi(k)$ drops off rapidly at large k, the biggest contribution to the integral occurs at a value of k slightly smaller than the momentum transfer; a realistic compromise is k = (3/4)q. Kinematically one also needs q>k to obtain reasonable freedom in detecting knockout nucleons in an (e,e'N) measurement.

The **maximum energy transfer** ω_m, for example in an (e,e'X) reaction, is determined by three quantities which the electron energy loss must supply:

(A) *the excitation energy of X, (for instance the nucleon resonance energy M_{N^*}-M_N).*

(B) *the recoil energy, $Q^2/2M_X$ (often >200 MeV in order to minimize nucleon-nucleus final state interactions; for light targets at high Q^2, it can be very large).*

(C)*the excitation energy of the residual (A-X) nucleus, typically 0-100 MeV for knockout from an arbitrary shell.*

The sum of energies (A), (B), and (C) should not exceed 2/3 of the incident electron energy because radiative corrections can become very large leading to unacceptable systematic errors.

The third factor, **range of electron scattering angle**, affects the maximum electron energy needed in a measurement because one often needs to separate the cross section into its longitudinal and transverse components by means of a Rosenbluth plot of σ versus $\tan^2 \theta/2$

$$\sigma = \sigma_L(Q,\omega) + (1/2 + \tan^2 \theta/2)\, \sigma_T(Q,\omega)$$

At large Q, σ_T often dominates over σ_L. Therefore to determine σ_L, the factor $(1/2 + \tan^2 \theta/2)$ should be minimized by keeping θ small. At $\theta = 50^o$, $\tan^2 (\theta/2) \cdot \sigma_T$ increases the inevitable contribution, $(1/2)\sigma_T$, by 44%. If this is an acceptable degradation of the ideal experiment, i.e. $\tan^2 \theta/2 = 0$, then θ_{min} and a given Q and ω, fix the beam energy at

$$E_0 = \frac{\omega}{2} + \frac{1}{2}\left[\omega^2 + \frac{Q^2}{\sin^2(\theta_{min}/2)}\right]^{1/2}$$

A $\theta_{max} = 150^o$ is usually sufficient to determine σ_T except in special circumstances where 180^o is essential.

The fourth factor in the choice of beam energy is achieving an acceptable **counting rate** for processes with small form factors. The Mott cross section is:

$$\sigma_{Mott} = \frac{\alpha^2 \cos^2(\theta/2)}{4 E_0^2 \sin^4(\theta/2)} \cdot \left[1 + \frac{(2 E_0 \sin^2 \theta/2)}{M_T}\right]^{-1}$$

Here M_T is the mass of the object (nucleon, cluster, or entire nucleus in the case of elastic scattering) that recoil with the electron energy-momentum transfer. This expression (which enters all counting rate calculations) has a strong energy dependence for fixed Q and ω.

To illustrate this effect, values for this cross section versus electron angle at fixed Q^2 (Q^2 = 2 and 4 $(GeV/c)^2$) are shown in Figure 18. Also shown is the kinematical limit for two choices of electron beam energy, E_0 = 2 GeV, and E_0 = 4 GeV.

The figure suggests that a large increase (a factor of 10 to 20) in cross section is to be gained in experiments requiring a specific momentum transfer, Q, if the maximum electron beam energy, E_0, is increased so forward angles can be used. However, this increase in cross section represents a more modest gain in actual counting rate in a real experiment. In evaluating the impact of this gain in cross section, several factors must be considered which

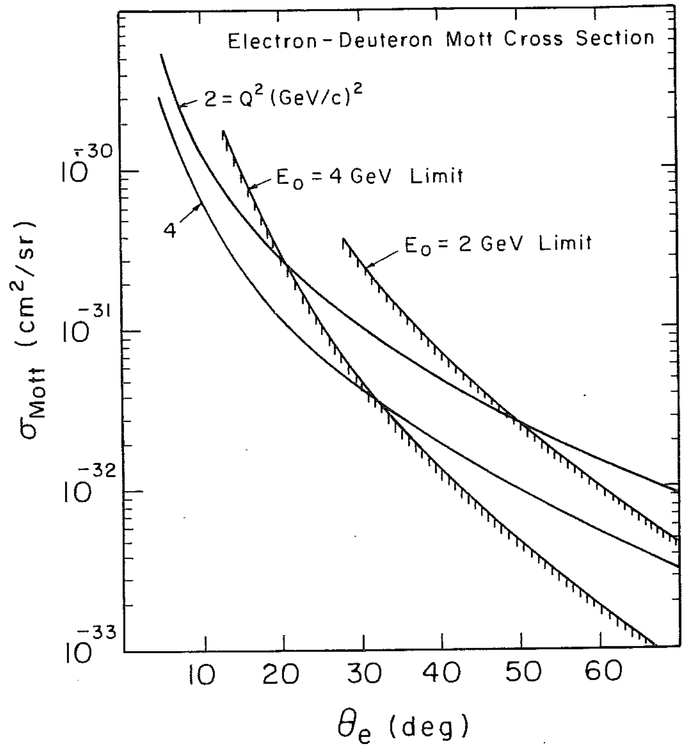

Figure 18 *The Mott cross section at fixed Q^2 versus electron scattering angle for electron-deuteron elastic scattering with recoil corrections. The hatched barriers show the kinematical limits for electron energies of 2 GeV and 4 GeV. The solid lines correspond to Q^2 = 2(GeV/c)^2 and Q^2 = 4(GeV/c)^2.*

depend on the details of the beam line and spectrometer design, as well as on construction and operating costs:

(A)Mass resolution - If a fixed missing mass resolution, ΔW, is required, the increased incident momentum will require better momenquired, the increased incident momentum will require better angular resolution which may also translate into a reduced event rate.

(B)Momentum transfer resolution - if a fixed momentum transfer resolution, ΔQ, is required, the increased incident momentum will require better angular resolution which may also translate into a reduced event rate.

(C)Cost per event - The higher cross section is achieved with a more expensive accelerator but may require fewer hours of operation for a fixed number of events.

While the optimum choice of E_0 for a given Q^2 requires detailed knowledge of the facility involved, it would appear that the factor of 20 increase in cross section in studying Q^2 = 4 $(GeV/c)^2$ with a E_0 = 4 GeV compared to 2 GeV favors the higher energy for that specific class of experiments where high Q^2 is required.

The requirements for the three kinematic parameters: maximum three- **momentum transfer** q_m (or four-momentum Q_m), **energy loss** ω_m, and **angular range**

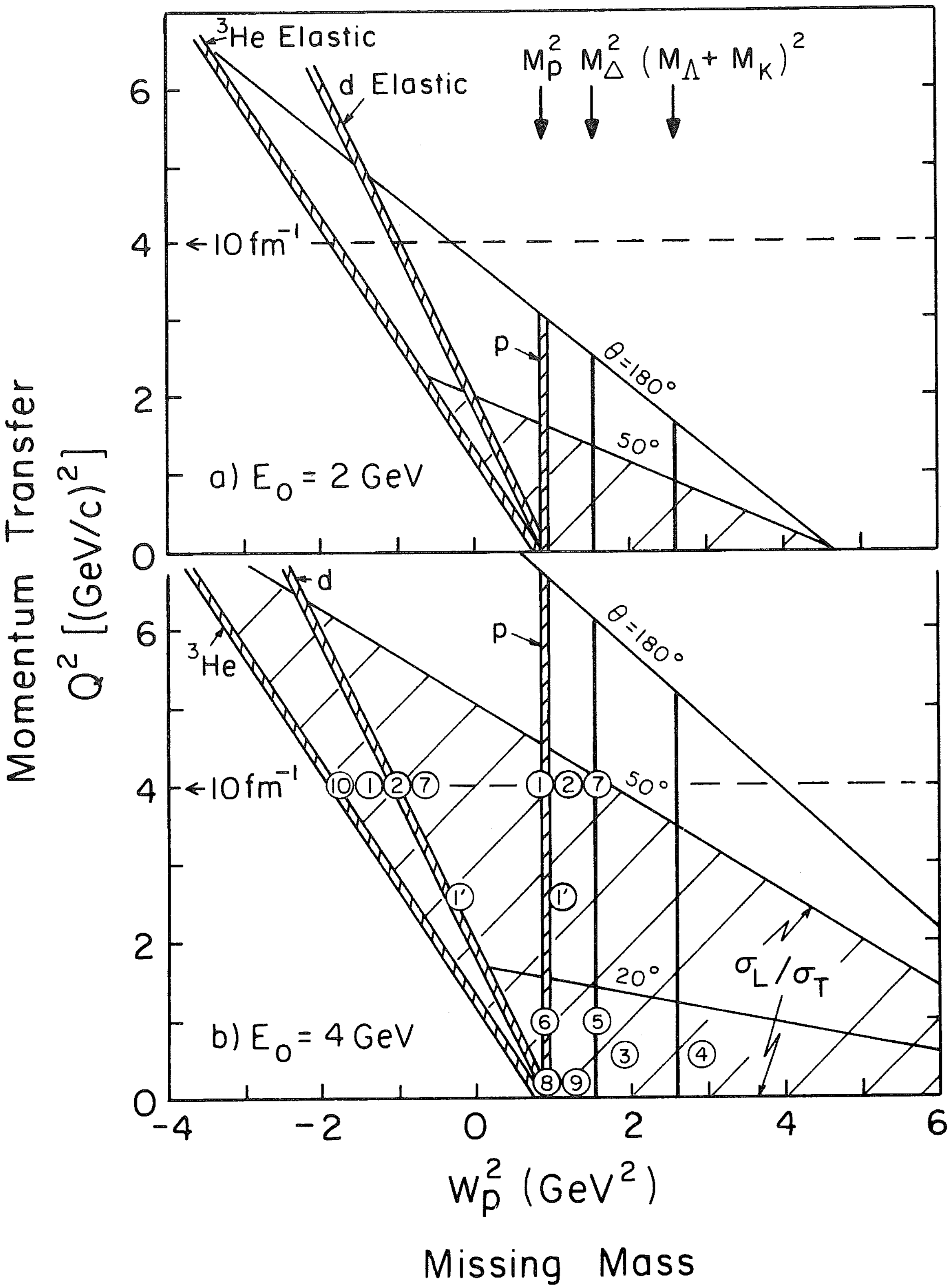

Figure 19 *Kinematic region accessible with (a) 2 GeV and (b) 4 GeV electron energy and targets of p, d, and* ^{3}*He. Here* W_p^2 *is the missing mass squared, treating the proton as the target. The region for* $W_p^2 < M_p^2$ *is kinematically forbidden for nucleons at rest, but becomes accessible with nuclear targets. The circled numbers indicate the location of typical experiments discussed in the text. The shaded regions are accessible for* σ_L/σ_T separation.

needed for Rosenbluth separations will now be discussed together with the appropriate **beam energy** E_0 and **duty factor** DF needed for ten measurement categories:

1. *Few nucleon targets (single arm measurements)*
2. *Few nucleon targets (coincidence measurements)*
3. *Vector mesons*
4. *Kaons and hypernuclei*
5. *Delta resonance*
6. *Nucleon knockout*
7. *Deep inelastic scattering*
8. *Giant resonances*
9. *Discrete states of complex nuclei*
10. *Symmetries*

Items 5 - 9 refer to measurements in complex nuclei ($A > 5$).

The conclusions are summarized in Figures 19 and 20. Figure 19 shows the region of momentum transfer, Q, and missing mass, W_p, accessible with a) E_0 = 2 GeV and b) E_0 = 4 GeV. Here

$$W_p^2 = M_p^2 - Q^2 + 2 M_p\omega$$

As discussed above, the σ_L/σ_T separation is best accomplished for $\theta \leq 50°$ as indicated. Regions of specific physics interest are indicated by category number as discussed below.

With respect to maximum electron energy, E_0, and duty factor, DF, we seek to determine for each physics category a performance **level A** which would permit the execution of a **major fraction** of the identified new measurements. We also give a performance **level B** of maximum energy and duty factor which could produce some significant new physics, but which **precludes** a major fraction of the new measurements. The profile that emerges (see Figure 20) is helpful in clarifying how much new physics accrues at each level of E_0 and DF. The "optimum" combination occurs when any E_0 and DF is available to the experimenter.

1. **Few Nucleon (single arm)**: The elastic form factors $F_{Ch,Mag}$ (Q^2) and inelastic structure functions of A = 1-4 nuclei are essentially single arm measurements, although a coincidence measurement (at low DF) may be used to identify elastic scattering. Rosenbluth separations out to momentum transfers of q = 10 fm^{-1} ($Q^2 \approx 4(\text{GeV/c})^2$) giving a spatial resolution of Δr = 0.15 fm can be obtained with $\theta < 50°$, a 4 GeV beam and target mass of A = 1-4. These considerations place the "adequate" point for these measurements at E = 4 GeV, DF = 10^{-1}% or lower. The "minimum" point at 2 GeV would allow an extension of our present knowledge of few nucleon structure but would not achieve the desired spatial resolution. Note that $Q^2 = 4(\text{GeV/c})^2$ cannot be achieved for A = 1 with a E_0 = 2 GeV facility (Figure 19).

One major type of experiment to advance our knowledge of nucleon and deuteron form factors by separating the electric monopole and quadrupole and the magnetic contributions requires polarization transfer using polarized electrons and can be attempted at 2 GeV/c. Due to the low efficiency of recoil nucleus polarization analyzers, large detectors are required, and these are realistic only for high DF and Q < 7 fm^{-1}. This type of experiment attacks several old, but fundamental problems. Another point (1') at 2 GeV with high DF expresses this in Figure 20.

2. **Few Nucleon (coincidence)**: Coincidence measurements of the scattered electron and the reaction products (deuterons, nucleons, and mesons) require the same range of momentum transfer, Q^2, as category 1., but require measurements out to $W_p^2 \approx 4(\text{GeV/c})^2$ with enough duty factor to keep down the accidental rates and pileup. A DF of 80% for "adequate" and 10% for minimum is a conservative estimate. Figure 19 shows that a beam energy of E_0 = 4 GeV is necessary to cover the entire Q^2, W_p region; about half of this region is kinematically inaccessible with a 2 GeV electron beam. This topic includes Δ and N^* resonances formation, nucleon knockout, and deep inelastic scattering in nuclear systems with $A \leq 4$.

3. **Vector Mesons**: Short-lived vector mesons must be identified through their decay products so coincidence is always required. Coherent photoproduction (with tagged bremsstrahlung) near threshold is probably the most interesting class of measurements. A peak energy of 1.5 GeV is adequate at 80% duty factor; some work could be done at DF = 10%.

4. **Kaons and Hypernuclei**: The spectroscopy of hypernuclei would probably be studied either using the tip of the bremsstrahlung spectrum and detecting K^+ mesons in a single arm measurement or using tagged γ beams. For this experiment E_0 = 1-2 GeV spans the region of feasibility; the tagged gammas require high DF.

Topics 5-9 deal with complex nuclei ($A > 5$).

5. **Delta Resonance**: The reaction (e,e'Nπ) in the nuclear excitation region 140-500 MeV and momentum transfer up to 1 GeV/c can be studied with 2 GeV, high DF incident electrons. Single arm measurements i.e. (γ,π) in this excitation region can be done with 700 MeV low duty factor beams. Tracing these reactions to higher Q and ω is treated in category 7.

6. **Nucleon-Knockout**: The now classic nucleon knockout reaction measurements of (e,e'p) were performed with a 500 MeV, 2% DF beam. To make large improvements in our knowledge of the structure function $S(q,\omega)$ one needs a 2 GeV, high DF beam. Extension of the single arm (e,e') measurements into the quasifree region begins to be profitable above 0.7 GeV, with DF = 10%.

7. **Deep Inelastic Studies on Complex Nuclei**: When one traces electro-nuclear reaction processes to momentum transfers that will reveal quark-gluon processes, i.e.

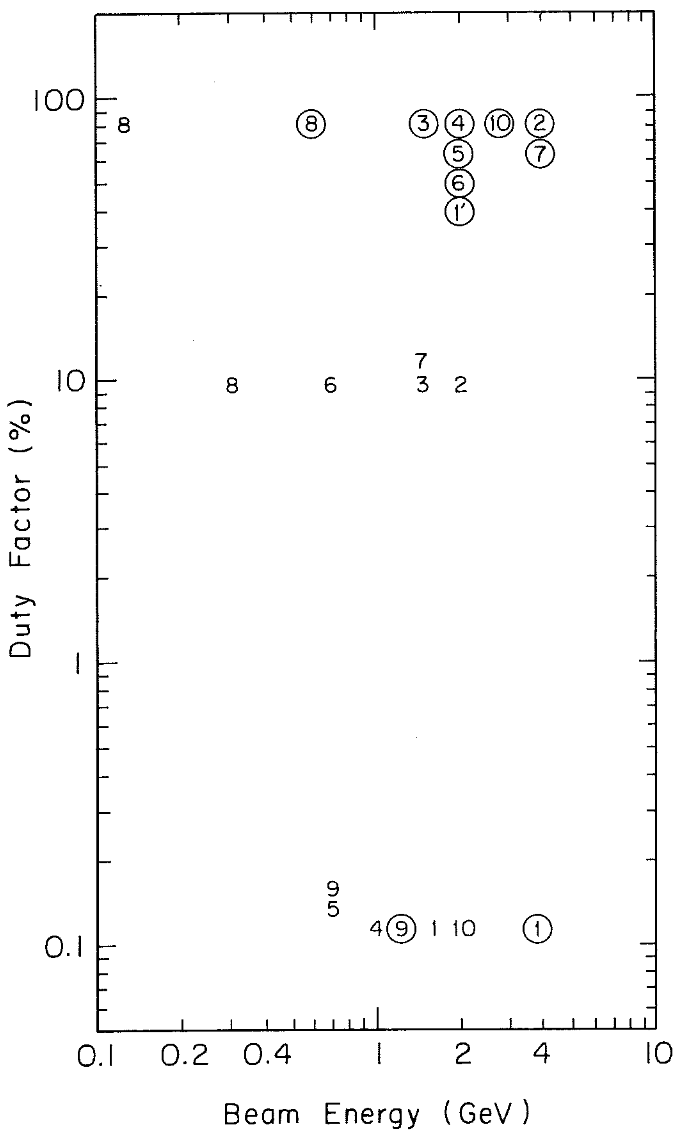

Figure 20 *Display of "adequate", level A (circled numbers) and "minumum", level B (plain numbers) energy and duty factor for ten types of electro-magnetic measurements as listed in the text and Table 1.*

beyond what was assumed in categories 5. and 6., the acceptable beam energy becomes much higher. As in category 2., for few nuclear targets, one needs 4 GeV and CW beams for an adequate measurements program, and 2.0 GeV, 10% DF for a minimum program.

8. **Giant Resonances**: The form factors of giant resonances with excitation energies in the 10-50 MeV range need to be traced to $q = 2.5\ fm^{-1}$ in order to extract their longitudinal and transverse transition densities. This could be done well with 600 MeV, 100% DF and at an acceptable level between 100 MeV, 100% DF to 250 MeV, 10% DF as the endpoints of a tradeoff locus of "minimum".

9. **Discrete States of Complex Nuclei**: Transition densities for charge, current, and spin for discrete states can be defined to $\Delta r = 0.5\ fm^{-1}$ by form factor measurements out to $q \approx 3\ fm^{-1}$ momentum transfer. Counting rates at fixed q rise as the square of the incident electron energy for heavy nuclei so that the time to make a measurement is reduced accordingly. The trend to use high electron energies is countered by the requirement of energy resolution, $\Delta E/E$, to find the state in a high level density environment. Taking $\Delta E = 50$ Kev as an acceptable resolution and 4×10^{-5} as an achievable $\Delta E/E$ for a spectrometer, one concludes that 1.2 GeV is a good compromise and that 0.7 GeV is acceptable for spectroscopic studies.

10. **Symmetries**: Electroweak parity violating studies with polarized electrons becomes most interesting for momentum transfers to the nucleon that reveal its quark structure. The 2 to 4 GeV energy range is judged to be sufficient to make significant tests of the gauge theory and to measure its coupling constants. The asymmetry in polarized electron-nucleon (nucleus) scattering increases with Q^2. Such experiments are practical only if detectors with very large solid angle (order of magnitude larger than conventional magnetic spectrometers) are available. Such detectors are realistic only for DF $\approx$ 100%.

These energy and duty factor requirements are summarized in Table 1 as well as in Figure 20.

Table 1

Energy and Duty Factor needed for ten types of measurements

	Measurement Category)	Level A Maximum Energy (GeV)	Level A Duty Factor (%)	Level B Maximum Energy (GeV)	Level B Duty Factor (%)
1.	Few nucleon targets (single arm measurements)	4.0/2.0	10^{-1}/80	2.0	10^{-1}
2.	Few nucleon targets (coincidence measurements)	4.0	80	2.0	10
3.	Vector mesons	1.5	80	1.5	10
4.	Kaons and hypernuclei	2.0	80	1.0	10^{-1}
5.	Delta resonance*	2.0	80	0.7	10^{-1}
6.	Nucleon knockout*	2.0	80	0.7	10^{-1}
7.	Deep inelastic scattering*	4.0	80	2.0	10
8.	Giant resonances*	0.6	80	0.1	80
9.	Discrete states*	1.2	10^{-1}	0.7	10^{-1}
10.	Symmetries	3.0	80	2.0	10^{-1}

A facility that achieves **Level A** is considered "adequate" in that a major fraction of the identified new measurements could be performed; **Level B** is considered minimal in that some significant new physics could be studied, but a major fraction of the new measurements would be excluded.

* This item refers to measurements in complex nuclei ($A > 5$).

Table 2

Beam parameters required by experiment

Beam Parameter	**"Minimal"**	**"Special"**
Energy	see Table 1	
Step Size ($\Delta E/E$)	2×10^{-2}	3×10^{-4}
Energy Uncertainty ($\Delta E/E$)	1×10^{-3}	5×10^{-4}
Emittance*	---	0.01 π mm-mrad near 1 GeV
Maximum Current	50 μA	150 μA
Current Stability	$\pm$ 20%	$\pm$ 20%
Duty Factor	80%	80%
Micro Structure	10^{-9} s	Chopped or Bunched
Polarization	0	40%

"**Minimal**" means most experiments can be performed if all parameter values are obtained simultaneously. "**Special**" means certain important measurements require one or more specific parameters to meet this specification, at the expense of other parameters. The numbers given in the table are derived from the physics requirements, with some consideration of present technical feasibility.

* The "minimal" value required for the emittance must be assessed in the context of the coincidence spectrometer system design.

IV.1.2. Other Beam Parameters

Energy and duty factor clearly are the most important beam parameters. Other beam properties such as intensity, energy spread, and time structure can be critical for some measurements, but a majority of experiments can be performed with electron beams that satisfy a simultaneous set of "minimal" beam parameters. Table 2 shows these numbers plus a set of "special" beam parameters which are required by certain important experiments. These "special" numbers need not be achieved simultaneously; tradeoffs can be made with other parameters without compromising the final experimental results. These parameters include:

Step Size: Rapid changes in beam energy by small increments are sometimes necessary. A fractional change of 2% sufficies for most cases, but yield curves (particularly near threshold of a reaction) and photon experiments using the tip of the bremsstrahlung spectrum can put a more stringent limit on this quantity.

Energy Uncertainty: Incident beam energy stability, spread, and reproducibility contribute to this overall quality factor. Dispersion matching to a spectrometer or pair of spectrometers improves the effective $\Delta E/E$ of the experiment by a factor 10 beyond that of the accelerator. Good energy resolution in the primary beam of the accelerator reduces the complexity and cost of the beam handling system and spectrometers. The highest resolution requirements come from measurements that attempt to isolate discrete states in a dense spectrum. The signal to noise ratio often limits the highest momentum transfer to which a state can be followed.

Emittance: The energy normalized product of the beam cross section radius and the angular divergence, i.e. the emittance, is set by the accelerator and magnetic optics performance. Modern conventional pulsed linacs produce beams with emittance $\approx 10\pi$ mm-mrad/γ, (where $\gamma = E/m_e$) for instantaneous currents near 1 ma. Synchrotron radiation places a fundamental limit on the emittance that can be achieved at higher energies in circular machines. Since emittance limits the ultimate energy resolution achieved, the most stringent class of experiments for this property is discrete state spectroscopy, of interest mainly for energies below 1 GeV. As with energy uncertainty, the beam transport may place stronger limitations than nuclear physics measurements on emittance. Aside from the area (π $r\theta$) of the phase space plot, the intensity distribution function (particularly the wings of the distribution or halo) is an important consideration for minimizing experimental backgrounds.

Maximum Current: Thermal properties of the target limit the current density and total heat deposited by the electron beam. Degradation of solid targets and nonlinear effects in gas and liquid targets suggest 50μA target as a conservative current. Bremsstrahlung production where the maximum photon flux is desired can profit by the use of higher currents.

Current Stability: Fluctuations in the amplitude of a continuous electron beam affect the true to accidental count rate ratio in a coincidence measurements. Since the maximum current is often limited by the peak counting rate in some detector, any beam intensity below the maximum is equivalent to a loss in duty factor.

Duty Factor: The time required to complete a coincidence measurement to a given level of statistical accuracy is proportional to the duty factor (if limited by accidentals and/or pile up). Although 100% is desirable, a lower value of 80% (averaged over an eight hour period) may be more realistic, and also acceptable.

Micro-Structure: When coincidence circuit resolving time falls below the period between beam bunches of the rf cycle, the effective duty factor falls precipitously. A resolving time of a few nanoseconds is a realistic number for most situations, thus the microstructure must be kept below this number.

Chopping and Bunching: Eliminating the beam for periods of nanoseconds to microseconds (chopping) can give timing information for detectors to determine the type or energy of reaction products. Keeping the average current constant while reducing the duty factor (bunching) is useful in low count rate measurements where cosmic ray background is a limitation.

Polarization: Longitudinal and transverse polarization of the electron beam are needed for measurements of the electroweak force, and (with polarized targets or reaction products) the separation of different multipolarities that normally cannot be distinguished. The degree of electron polarization on-target depends on the gun-source, the depolarizing action of the accelerator, and on polarization rotation in the beam transport system. A polarization of 100% is desirable, but current technology offers high intensity beams with polarization of about 50%.

IV.2. Current and Planned Facilities

Facility planning is carried out not only in the context of scientific needs and opportunities but also in the context of existing facilities and evolving technology. At the present time a number of electron accelerator facilities dedicated to basic nuclear science are in operation or under construction in the U.S. and elsewhere, with active research and development (R&D) in progress toward future facilities. The recent history and present posture of existing facilities as well as work in progress on accelerator R&D are described below and summarized in Table 3 and Figure 21.

The situation in 1977 was summarized in the Livingston report [2]. Only the changes since that time in beams available as electromagnetic probes of nuclear structure are discussed here. The current status of these facilities is discussed below while proposed improvements are presented in Table 3.

The MIT-Bates facility continues as the major U.S. medium energy electron user laboratory. The present configuration has nominal parameters of 400 MeV at 75 microamps and 1.0% macroscopic duty factor. A very high

Table 3

Laboratories with high current electron beams

LABORATORIES	NEAR TERM PLANS	LONG TERM PLANS
UNITED STATES		
Illinois	(proposed) 450 MeV, 100 μA, 100% D.F. 9 + 32 pass recirculator	
MIT-Bates	700 MeV, 75 μA, 1.0% D.F. 2 pass recirculator	
NBS	185 MeV, 550 μA, 100% D.F. 15 pass recirculator	
SLAC	(proposed by American Univ.) 2.9 GeV, 27 μA, 3 x 10^{-4} D.F.	
FOREIGN		
Amsterdam	500 MeV, 500 μA, 2.5% D.F. linac	
Bonn	2.5 GeV, 0.5 μA, 95% D.F. stretcher ring	3.5 GeV, 1 μA, 70% D.F.
Darmstadt	130 MeV, 20 μA, 100% D.F. superconducting linac plus 2 pass recirculator	
Frascati	Back scattered laser beam 5-80 MeV from 1.5 GeV storage ring	500 MeV, 100 μA, stretcher ring
Lund	100 MeV, 10 μA, 100% D.F. 19 pass recirculator plus stretcher ring	500 MeV, 40 μA, 100% D.F. storage ring
Mainz	180 MeV, 100 μA, 100% D.F. 51 pass recirculator	840 MeV, 100 μA, 80 pass recirculator
Montreal	(proposed) 200 MeV, 300 μA, 100% D.F. 17 pass recirculator	1 GeV, 300 μA, 25 pass recirculator
Saclay	600 MeV, 100 μA, 1% D.F. linac	2.0 GeV, $\leqslant$100 μA stretcher ring
Sao Paulo	17 MeV, 100 μA, 100 D.F. linac	185 MeV, 100 μA, 15 pass recirculator
Tohoku	150 MeV, 3 μA, 90% D.F. stretcher ring	1.2 GeV, 90 μA, stretcher ring
Tsukuba	500 MeV, 100 μA, 0.2% D.F. linac	600 MeV storage ring 150 MeV stretcher ring

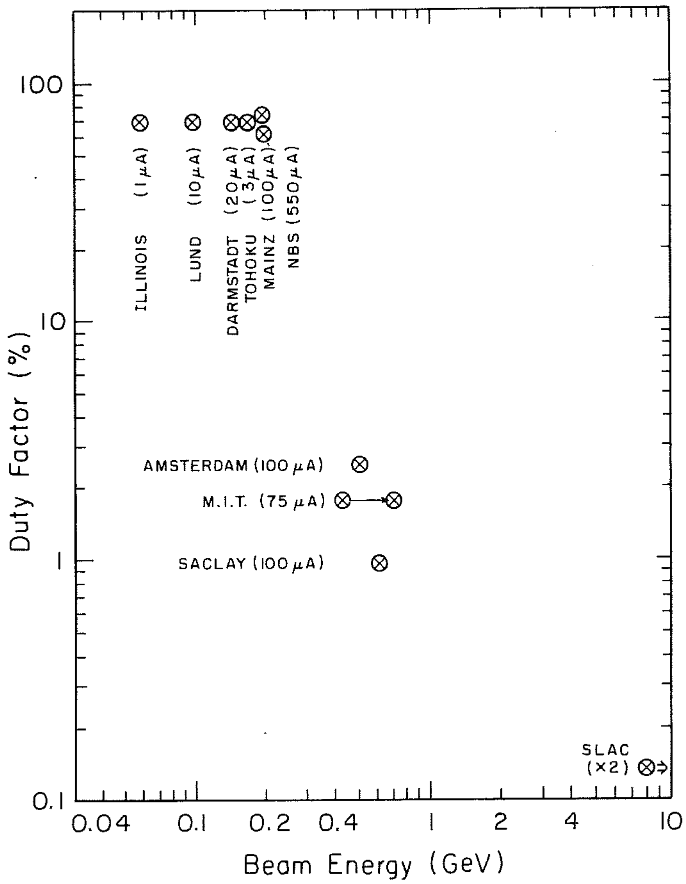

Figure 21 *Duty factor and beam energy for accelerators currently in operation or under construction. Facilities with beam currents less than 1μA are not shown.*

resolution spectrometer is a major element in the research instrumentation. Since 1977 the laboratory has been evolving significantly. An "energy doubler" upgrade was funded in FY 1980 and is being installed in 1981/82. By a single recirculation, the beam energy is to be raised to about 725 MeV with minor degradation in intensity and duty factor. Recent experiments with the magnetic spectrometer have achieved a resolution of 11 keV at 165 MeV. A new experimental hall is in service and three spectrometers are being constructed for use in this area. A polarized source is under construction (50 μA at 40% to 50% polarization is anticipated). Beam sharing operation is planned.

These major improvements to the Bates facility can be expected to maintain it in a competitive posture with respect to other medium-energy, moderate duty factor linear accelerators such as ALS, Saclay (600 MeV, 100 μA, 1% DF) and the newly commissioned IKO, Amsterdam (500 MeV, 50 μA, 2.5% DF).

The SLAC accelerator at Stanford has been used for a few scattering studies on light nuclei at energies mostly above 1 GeV. The intensity and duty factor limit the scope of these studies. A proposal to install a downstream injector to increase the intensity at lower energies has been developed.

The superconducting microtron MUSL 2 at the University of Illinois has been operating at 65 MeV with 6 pass recirculation at intensities below 1 μA. Attempts to control the blow-up modes to reach the design objective of 10 μA are continuing. A proposal to increase the energy of the facility to the 450 MeV range has been developed. The superconducting linac with a three pass recirculated beam at Stanford University is operating at 120 MeV, 20 μA (limited by beam breakup), and 75% DF.

A room temperature 100% DF microtron is under development at NBS. Although funded as an R&D project to test components of a future larger machine, it is possible that after testing this accelerator could continue in service in a research capacity. The new machine is 185 MeV, 550 μA, 100% DF.

There are a number of existing or proposed electron facilities outside of the United States. A 100-180 MeV two stage CW room temperature microtron, MAMI is under construction at Mainz. A third stage to raise the beam energy to 820 MeV is planned. At Tohoku University, Sendai, Japan, a stretcher ring has been added to the electron linac and is now operating at 150 MeV with 100% DF. Plans to develop a 1.2 GeV beam of 100 μA and 100% DF are under discussion.

A 100 MeV, 10μA, pulsed linac and stretcher ring is under construction at Lund, Sweden. The possibility of using the ring to accelerate the stored beam to 500 MeV is being studied. A 130 MeV, 20 μA superconducting recyclotron is under construction at Darmstadt, Germany and a 200 MeV, 100μA, CW room temperature microtron has been proposed by a group at the University of Montreal.

A number of older synchrotrons in the 1 to 10 GeV energy region have been omitted from this discussion. They have beam currents below 1 μA which strictly limits their use for nuclear studies.

There are linacs at Hamburg (0.7 GeV), Frascati (1.6 GeV) and Orsay (2.3 GEV) which are primarily used to fill storage rings, but which should be mentioned as a beam source in the interesting energy region. The Bonn accelerator is currently being expanded to a 2.5 GeV, 1μA, 95% DF stretcher ring facility.

In Figure 21 and Table 3 the energies, duty factor and maximum current of electron accelerator facilities that currently exist or have been funded are summarized. Accelerators with average current below 1μA are not included.

A comparison of the accelerator capability required by the physics program as reviewed in section IV.1 with the facilities currently available or under construction here in the United States and abroad is extremely revealing. **There currently exists no electron accelerator of any type, performing at high duty factor (>10%) with an electron current exceeding 1μA and an energy in excess of 500 MeV.** On the other hand, inspection of Figure 20 indicates that the major part of the physics program lies in the inaccessable 0.5-4.0 GeV energy region. The Subcommittee has studied this situation both from the point of view of scientific priorities and with respect to the technical feasibility and cost of constructing a new high energy, high duty factor, high current facility. Its conclusions and recommendations are treated in section V of this report. The following section deals with feasibility and cost related issues in the context of constructing a new facility. In particular, the case of a 4.0 GeV, 150 μA, 80% DF project is considered.

IV.3. Facility Design Considerations, Storage Rings, and Cost

There are a number of electron accelerator facilities used for basic nuclear science in the United States and abroad which will continue to play an important role in providing electromagnetic probes of the nucleus. However, there is no facility above 500 MeV which can provide the beams of high intensity and high duty factor which have been identified in Section IV.1 as being essential for attacking the most important scientific questions. In this section, general design considerations for an accelerator which can satisfy the scientific requirements are discussed.

It is the Subcommittee's judgment that a new accelerator facility meeting the energy, intensity, and duty factor requirements, as well as other performance criteria necessary for the physics program, could be constructed using existing and currently developing accelerator technology. In order to emphasize the importance of continuing research and development work on a project of this type we mention the following general considerations.

IV.3.1. General Considerations

With our present level of understanding there may be two or more accelerator design concepts which could provide beams with a reasonable match to the scientific requirements. A detailed cost comparison is beyond the scope of this document, but it would appear at this time that in the range up to 4.0 GeV, the total cost of a laboratory based, for example, either on a recirculating CW microtron or a pulsed linac with stretcher ring, is not different enough to rule out either choice on the sole basis of cost. Because of the very large beam currents and beam power required, all of the possible designs must be carefully assessed for the current limit they can achieve and for the practicality of beam extraction with sufficiently small loss to ensure long-term maintainability.

The results of R&D projects on accelerating structures requiring less rf power consumption will be of great value in reducing both capital and operating costs for a new facility. Studies are required of beam breakup limits, such as those carried out at SLAC in connection with improvement of intensity at lower energies, the recent tests on the Mainz CW microtron, and those planned for the NBS microtron R&D project. In combination with theoretical analysis, one can then extrapolate to the operating region of the proposed facility.

Because of the manner in which the cost of beam switchyard components and some research equipment, such as high resolution magnetic spectrometers, is dependent on beam emittance, it would be useful to have a better quantitative understanding of the increase in normalized emittance observed in the initial stages of linac acceleration. In particular there appears to be a paucity of quantitative data on existing electron accelerators in the literature with respect to the tails of both the emittance profile and the corresponding longitudinal phase space profile. This information is needed to establish magnet apertures for an acceptably low spill at high intensity.

Continuing work on extraction designs appears necessary. Other studies related to specific design concepts would help in assessing technical feasibility. For example, stretcher ring beam-wall instabilities, extracted intensity modulations reflecting injection phenomena, depolarization resonances, remote handling access and the question of multiple rings to allow simultaneous operation with high duty factor at more than one energy, need to be considered. Simultaneous multiple-beam extraction schemes using microtrons, magnet designs, and booster feasibility studies, in addition to continuing operational tests of existing microtrons, are relevant to the ultimate choice of technology.

IV.3.2. Applications of Storage Rings

There are at least three applications of storage ring devices that may become important for the nuclear physics facility under discussion.

- *High current pulse stretchers to increase the duty factor, DF.*
- *Recirculating beams with thin (jet) targets for charged particle reactions.*
- *Recirculating beams for production of monochromatic photon beams.*

It is extremely important to evaluate these applications both with respect to technical feasibility and to impact on the accelerator design.

Storage rings used as synchrotron radiation sources and for electron-positron colliding beam experiments have proliferated over the past decade. This technology may have important applications in an electron accelerator facility used for basic nuclear science. The use of a storage ring to increase the duty factor of a pulsed accelerator by intermittent injection and approximately continuous extraction has been proposed by several groups. Accelerators based on this concept and operating in the 100-150 MeV range are under construction in Lund, Sweden and Tohoku, Japan.

Because the total number of electrons stored in a ring is limited by the onset of various instabilities, the throughput required to place on target a large extracted current, imposes a refill cycle on the order of 1 KHz, while spill limitations for long-term maintainability require extremely high injection and extraction efficiencies. A high current stretcher is therefore quite different in technical detail from the storage rings in common use which tend to have long holding times ($>10^3$ sec) and low average refill currents.

Recirculated beams represent a class of ring applications involving storage cycle times of 10^{-1} to 10^{+1} seconds and moderate average refill currents (10^{-6} Amps rather than 10^{-4} Amps). In this time range the synchrotron radiation acts as a damping mechanism (typical cooling time constants are $\approx 10^{-2}$ seconds for energies > 0.5 GeV) which serves to make the emittance and longitudinal spread of the beam independent of the accelerator characteristics. An internal target introduced into such a ring can make highly efficient use of the stored beam for nuclear reaction and scattering studies. If the target is of an appropriate thickness, the incoherent heating of the beam by the target is removed by the synchrotron radiation cooling mechanism. Thermal equilibrium is established and maintained as the stored beam is gradually depleted by nuclear interactions with the target. The high efficiency means very low background and greatly reduced demand for beam from the accelerator.

The extent to which the experiments identified as requiring a new accelerator facility can be adapted to internal target operation is largely an open question. Study has begun of the production of monochromatic photon beams by laser backscattering from a stored beam of electrons, internal tagging, or annihilation of a stored positron beam. Even the high resolution scattering experiments, apparently ruled out by the lower limit to the energy spread of a stored beam induced by quantum fluctuations in the synchrotron radiation, may be possible by using a high dispersion and resolving power straight section for a spectrometer target. Preliminary studies indicate that laser backscattering from stored electron beams could produce intense photon beams in the few hundred MeV region, very appropriate for studies of Δ excitation in nuclei.

Because of the potential savings in accelerator cost associated with the beam use efficiency of these techniques, it is important that a better understanding of their limitations and advantages be obtained.

If a new accelerator must fill several such rings intermittently, the injection problem strongly favors an accelerator that can produce high peak current pulses alternating in energy. Beam quality and transmission efficiency are not particularly important during the refill mode. However, if the accelerator also serves conventional external target experiments between the ring fill bursts, then the usual performance requirements apply along with the additional complication of transient loading phenomena.

It may be worthwhile to study internal target performance by parasitic measurements in an existing ring such as SPEAR or one of the other synchrotron radiation sources. Design studies for a nuclear ring using SLAC or Bates as an injector might be considered. These initiatives should be coupled to a proper orbit dynamical analysis including synchrotron damping, quantum excitation and beam-target interactions in a variety of straight sections tailored for individual experiments. A rough analysis indicates that these internal target techniques may work best in the 0.5 to 5 GeV range which is of high interest for nuclear investigations.

IV.3.3. Facility Costs

It is neither within the charge nor the capability of this Subcommittee to make a detailed cost analysis of any proposed facility. Nevertheless, it is essential in making priority judgments and recommendations to work within some framework of fiscal constraints. The two cost estimates described below for $E_0 = 2.0$ GeV and 4.0 GeV facilities represent our best judgment and are consistent with other estimates recently developed in the community.

For the purpose of arriving at an approximate construction cost for a new high energy, high duty factor electron accelerator without restricting the choice of accelerator technology to be employed, we assume the following minimum configuration based on the scientific requirements. The accelerator proper will be designed to deliver 150 μA at any energy from 0.5 GeV up to its maximum design energy, E_0, at better than 80% microscopic duty factor in continuous research operation while satisfying the basic subsidiary beam parameters described in Table 2. The accelerator will be preceded by both polarized and unpolarized sources, and by a chopper/buncher which can either fill every rf bucket, or can produce maximum instantaneous current in one rf cycle with an adjustable beam off interval between pulses. The accelerator will be optimized for minimum total cost (construction plus operation), assuming 15 years of operation, at 5500 hours/year.

The accelerator will be connected to experiments by a beam distribution system which will deliver simultaneous CW beams of independently variable energy to three target locations. The beam intensity at any target station may have any value from 0 to 100 μA and any energy between 0.5 GeV and E_0. Polariation is to be preserved in transport to any station.

One of the target stations will be equipped, as part of the construction cost, with two or more spectrometers suited to the full range of coincidence experiments. An ultra high resolution magnetic spectrometer of the type discussed for 1 GeV operation is not included in this estimate. Another of the target stations will make available monoenergetic photons. A further target station should be designed to permit a variety of special purpose detector setups. Shielding arrangements must permit access to the general purpose target station for setup, while operating the coincidence spectrometers at full current.

We assume that accelerator and experimental area buildings will be constructed but that office and other personnel support buildings will become available at the host institution. The laboratory must meet applicable safety requirements and should provide a suitable working environment for visitors, as well as the resident scientific and technical staff.

We assume that construction funding begins in FY1986 and is largely completed by FY1989 with funds being available for expeditious progress at each step of the construction schedule.

With this set of assumptions, the total cost for a facility with E_0 = **2.0 GeV** with all appropriate contingency factors (FY1982 dollars) will probably lie in the range **\$80-\$100 million** (total capital cost). The cost would be approximately equally divided between the accelerator and its building on one hand and the beam distribution, target stations, and research equipment on the other hand. If the laboratory were to be designed for an accelerator energy of E_0 = **4.0 GeV** without compromising the other parameters, the **incremental** capital cost for this parameter change would be expected to be **at least \$35 million**.

Laboratories of these types might be expected to operate at a cost of **\$15-20 million per year**.

In conclusion, the cost to construct and operate a facility providing high intensity, high energy, high duty factor beams is substantial. Therefore it is especially important to ensure that a new facility is carefully optimized for maximum performance at minimum **total** cost. It is suggested that realistic operating costs over a 15- to 20-year projected life be included in a total cost assessment, and that both the accelerator and the research area costs be included in the cost assessment and optimization, insofar as the research component can be established at that time. It is not wise to design a low capital cost accelerator if this unduly raises the operating cost or the cost of the research equipment.

Section V.
Conclusions and Recommendation

V.1. Conclusions

Based on its analysis of the current and future role of electromagnetic probes in nuclear science and its review of the present status of electron accelerator facilities together with new developments in accelerator technology, the Subcommittee draws the following conclusions:

(A) *A broad spectrum of physics problems, potentially of very high impact in nuclear science, are highly suited for study with electromagnetic probes.*

(B) *An analysis of the accelerator requirements for executing these experiments reveals the need for high electron energy, intensity and duty factor.*

(C) *Existing electron accelerators in the United States and abroad are not adequate to pursue a major part of the research program outlined here.*

(D) *A new accelerator facility meeting the full energy, intensity and duty factor requirements, as well as other performance criteria necessary for* **the physics program***, could be constructed using existing and currently developing accelerator technology.*

(E) *A major fraction of the coincidence measurements identified as advancing our knowledge of* **nuclear structure and dynamics** *could be carried out with high duty factor electron beams up to* $\approx$ *2 GeV.*

(F) *An exploration of that part of the experimental program which emphasizes the* **quark structure of the nucleus** *requires high duty factor and electron energies in the region of 4 GeV.*

(G) *A significant although not the major portion of this research program could be carried out at accelerators limited to either low energy (*$<$*1 GeV) with high duty factor or at high energy with low duty factor (*$<$*1%).*

V.2. Scientific Priorities and Recommendation

After a review of the various lines of scientific research discussed in Section III, the Subcommittee evaluated each area in terms of the following criteria:

- *Probability for important fundamental advances developing in each area.*
- *Impact of these advances on other areas of physics.*
- *Probability that these fundamental advances will result from experiments requiring an electromagnetic probe.*
- *Technical feasibility for the crucial experiments using electromagnetic probes in this area.*
- *Scientific feasibility for these crucial experiments.*

Here technical feasibility refers to the ability to collect the data under discussion while scientific feasibility deals with the ability to extract answers to the scientific questions from the data. A number of conclusions developed from these considerations.

All the physics areas discussed at both low and high momentum transfer, were found to provide important new opportunities to expand our understanding of nuclear physics phenomena with electromagnetic probes. A broad spectrum of problems in the **low momentum transfer range**, $q < 5\ fm^{-1}$, has been identified. Very rich and illuminating studies are already in progress in this region. If higher duty factor and somewhat higher energy were to become available, we foresee that a new generation of experiments would become feasible. The Subcommittee concluded that the investigations of complex nuclei with electron beams of 0.1-1.0 GeV, high duty factor, and high intensity, would have an important impact on our understanding of **nuclear dynamics and structure**. Investigation of ground state properties, discrete states, and giant resonances, together with studies of quasifree electron scattering and nucleon knockout processes, will provide important new opportunities to establish the role and proper description of the nuclear force in many body systems.

The Subcommittee sees the opening of a new frontier for the investigation of nuclear phenomena in the **higher momentum transfer range**, $q = 5\text{-}15 \text{ fm}^{-1}$. The Subcommittee found that the **major opportunities for fundamental advances** using electromagnetic probes were in the following physics areas:

- *Hadron structure and two nucleon interactions.*
- *Three and four body systems.*
- *Fundamental symmetries.*

There was a clear consensus on the Subcommittee that these topics should receive the highest scientific priority. This is both because of their intrinsic scientific interest and because of the opportunity they offer to study the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of the nuclear force. This transition should also be studied in more complex nuclei (A > 5) through investigation of such processes as deep inelastic scattering. The unique properties of electromagnetic probes are ideally suited for these short distance high momentum transfer studies.

Having identified those areas of highest scientific priority and having developed the conclusions listed in section V.1 the Subcommittee makes the following recommendation:

Subcommittee Recommendation

The Subcommittee strongly recommends the construction of a variable energy electron beam facility capable of operation at both high intensity and high duty factor, and able to achieve an electron energy of about 4 GeV, for the purpose of making coincidence measurements on nuclear targets at large excitation energy and momentum transfer.

This recommendation would provide a research capability over a broad electron energy range and reflects the very high priority the Subcommittee places on investigation of the transition region between the nucleon-meson and quark-gluon degrees of freedom as a description of nuclear structure. The precise electron energy range required to explore this transition is not easy to assess in advance but it is the Subcommittee's judgment that an electron beam capable of reaching about 4 GeV would have substantial impact on the analysis of this transition. One Subcommittee member felt that the investigation of this transition region could be achieved with a less energetic beam. In section IV and table IV.2 other beam parameters required by the physics program are discussed.

An electron facility capable of operation at energies up to 4 GeV could explore a major fraction of the physics opportunities identified in this report. However, the Subcommittee has not evaluated the technical and cost considerations that determine the **dynamic range** of a 4 GeV facility. It may be that a single high energy and high duty factor accelerator facility will not cover the entire range of physics described in chapter III, in particular the important region below 1 GeV. The Subcommittee feels that this issue should be carefully considered when a 4 GeV facility design is evaluated, together with possible schemes for developing a lower energy (< 1 GeV) high intensity and duty factor beam at a separate facility. It is the development of the complementary aspects of the 4 GeV and 1 GeV investigations that will provide the richest electron physics research program.

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APPENDIX A.
The Charge to the NSAC Subcommittee on Electromagnetic Interactions

Over the past decade, a number of studies have identified construction of a high energy, high duty factor, electron accelerator facility as a high priority need of basic nuclear research. The most recent of these studies are the DOE/NSF Nuclear Science Advisory Committee's "A Long Range Plan for Nuclear Science (December 1979)" and the joint DOE/NSF study "Role of Electron Accelerators in U.S. Medium Energy Nuclear Science" (chaired by R. S. Livingston, December 1977).

The Subcommittee shall review the current status and needs of basic nuclear research with electromagnetic probes. Within the international context the Subcommittee shall examine the scientific need for facilities to investigate with electromagnetic probes the fundamental properties of nuclei and nuclear interactions. The Subcommittee shall determine the scientific priorities among the various lines of possible research and determine the accelerator performance criteria necessary for execution of the highest priority lines of research.

In its deliberations, the Subcommittee shall keep in mind questions of technical feasibility and cost of various possible facilities. The Subcommittee will review specific facility proposals for background information only.

APPENDIX B.
Schedule of Subcommittee Meetings

September 27-28, 1981	National Science Foundation Washington, D.C.
November 15-17, 1981	University of Illinois Urbana, Illinois
January 14-15, 1982	National Science Foundation Washington, D.C.

APPENDIX C.
Acknowledgements

The Subcommittee solicited and/or received information, opinions, ideas, and comments from many nuclear scientists. We believe the following is a reasonably complete list of those individuals.

F. Ajzenberg-Selove, Univ. of Pennsylvania
K. Althoff, Bonn, West Germany
R. G. Arnold, SLAC, American Univ.
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APPENDIX D.
Symbols Used in This Report

E	Incident electron beam energy in lab system
E'	Final state energy of electron
E_0	Maximum accelerator energy
ω	Energy transfer E-E′ in rest system of target (also called ν in a general frame)
DF	Beam duty factor
q	Magnitude of three-momentum transfer
q_{max}	Maximum value of q
$Q > 0$, Q_{max}	Four-momentum transfer $(q^2-\omega^2)^{1/2}$
M_p, M_T	Proton or nuclear target mass
W_p	Missing mass for a proton target at rest ($W_p^2 = -Q^2 + 2M_p\omega + M_p^2$)
W	Missing mass for a nuclear target at rest
x	Bjorken relativistic scaling variable
y	Scaling variable for quasifree scattering
Δr	Spatial resolution 1.5/q(fm^{-1}) achievable for momentum transfer q
Δ or Δ(1232)	Non-strange baryon resonance (mass 1232 MeV) in the spin-parity $J^\pi = 3/2^+$, isospin I = 3/2 pion-nucleon system
N^*	An isospin 1/2 non-strange baryon resonance
ρ, ω, ϕ	Vector mesons sharing the quantum numbers of the photon ($J^{\pi C} = 1^{--}$)
$K^\pm, K^0, \bar{K}^0$	Strange mesons
PV	Parity Violating
σ_L, σ_T	Longitudinal and transverse electron scattering cross sections
Λ, Σ	Strange baryons (hyperons)
MEC	Meson exchange currents

$\sigma^{L,T}_{\gamma^*A}$	Longitudinal and transverse parts of the virtual photoabsorption cross section
$\rho(r)$	Monopole charge density of the nucleus
$\mu(r)$	Magnetization density of the nucleus
$F_M(q)$	Magnetic form factor of a nucleus
$S(q,\omega)$	Spectral function of a nucleus
$F_\Delta(q)$	Transverse form factor of the Δ resonance
G_{En}, G_{Ep}	Electric form factors of neutron and proton
G_{Mn}, G_{Mp}	Magnetic form factors of neutron and proton
$A(Q^2), B(Q^2)$	Few-body structure functions related to the electric and magnetic form factors
G_C, G_Q, G_M	Charge quadrupole and magnetic form factors for electron-deuteron elastic scattering
$f_d(Q^2)$	Reduced deuteron form factor
$F_\pi(Q^2), F_K(Q^2)$	Pion and kaon form factors
G	Fermi weak coupling constant
θ_W	Weinberg angle
Z^0	Neutral intermediate vector boson