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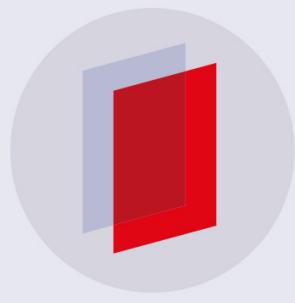
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Making the Case for Jefferson Lab

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Abstract. This chapter is a personal account of the initial planning and competition for a new laboratory, which eventually became known as the Thomas Jefferson National Accelerator Facility, with the official nickname “Jefferson Lab.” The period covered starts as far back as 1964, with the introduction of quarks, and extends up to the late 1980s after the initial team was assembled, the superconducting design was in place, and construction was well underway. I describe some of the major experiments that were proposed to justify the laboratory, reflect on the present status of those initially proposed experiments, and very briefly outline some of the new ideas that emerged after the laboratory was constructed. The science is presented in a simple manner intended for a lay audience, with some of the ideas illustrated by cartoons that were often used in popular lectures given during this period.

1. Washington shoot-out

It was the morning of February 17, 1983, and the auditorium in Washington, DC was filled with so many people it was hard to see who was there. Everyone was tense; five proposals for new electron accelerators, each with a different design, were to be presented and discussed over the next two days. The evaluation panel, chaired by D. Allan Bromley of Yale University, would listen, ask questions, and ultimately make recommendations to the Nuclear Science Advisory Committee (NSAC), which advised the Department of Energy (DOE) and the National Science Foundation (NSF).

The proposal from the newly formed Southeastern Universities Research Association (SURA) was to be presented first, followed by the presentations from the University of Illinois and the National Bureau of Standards (now NIST). Neither Illinois nor NIST wanted to build a high energy accelerator; they were there to present proposals for a new low energy accelerator should the nation decide to go in that direction. The front runners in the competition, scheduled to make their presentations on the second day, were the Massachusetts Institute of Technology (MIT) and the Argonne National Laboratory (ANL).

The performance of the five teams over these two days would largely determine who would be awarded the most important scientific project in a decade, and set the direction for research in nuclear physics for many years. Because all could hear and comment on each of the proposals in an open and unpredictable atmosphere, the participants came to call this the “Washington shoot-out.”

SURA believed that the accelerator could not accomplish its mission unless its energy was at least 4 GeV, while MIT favored a less expensive accelerator with a lower energy of 2 GeV. Since this was controversial, SURA had devoted a considerable fraction of its allotted time explaining why the higher energy was necessary. When SURA had completed its presentation, Bromley began the discussion of the SURA proposal by asking the audience if “anyone” could tell him

why a 4 GeV accelerator was needed. Would the spokesmen for MIT begin the argument for 2 GeV at this time? Should SURA answer the question again?

2. Hadronic physics from 1960 to 1980

In order to appreciate the excitement at the “shoot-out,” it is necessary to go back to the early 1960s. A revolution in physics was underway. In 1964 Murray Gell-Mann (1969 Nobel Prize) [1] and independently George Zweig [2] proposed that many properties of hadronic matter (matter that interacts through the so-called strong forces) could be understood if the world were made of “quarks.” Later it was realized that these quarks come in three identical copies, now called “colors.” The forces between quarks are a consequence of this property of color, but the physical world cannot distinguish *individual* colors – it is “color-blind” (in mathematical language, an exact symmetry of nature). Initially it was unclear whether or not the quarks were real or just mathematical objects helpful to understand the many observed states of hadronic matter. But experiments completed at the Stanford Linear Accelerator (SLAC) by the team headed by Friedman, Kendall and Taylor (1990 Nobel Prize) [3, 4, 5] gave direct evidence for the physical existence of quarks, and then, in the early 1970s, the theory of the strong (colored) interactions, called Quantum Chromodynamics or QCD, was developed [6]. It was later shown that the forces between quarks become very small at large energies, a property of QCD referred to as “asymptotic freedom” (2004 Nobel Prize) [7, 8, 9]. This lead indirectly to a mathematical understanding of why quarks are confined – why they can never be completely separated from one another. By the late 1970s physicists had both the experimental evidence and a theory of quarks that explained why they could not be observed in isolation, so that even the skeptics began to believe quarks were real.

Because of these major discoveries, nuclear physics faced a crisis in the late 1970s. It had initially been believed that the nuclear force might eventually be understood in terms of the exchange of mesons between neutrons and protons (referred to collectively as “nucleons”), and that the size and shape of the nucleon was likely a result of a meson cloud surrounding a bare nucleon core. But now nucleons and mesons were known to be composite systems of quarks. Why weren’t the effects of the underlying quark structure immediately visible? Could new phenomena be discovered that were a direct consequence of QCD and our new understanding of nuclear theory?

To provide an experimental answer to these questions, the Friedlander panel (1976) [10] and the Livingston panel (1977) [11] both recommended that a new high energy, continuous beam, electron accelerator be built for nuclear physics research. Soon after (1979) the first Nuclear Science Advisory Committee (NSAC) [12] included such an accelerator in its first Long Range Plan. The scientific community was on record urging the government to invest in a new accelerator, and these recommendations led directly to the five proposals under consideration at the Washington shoot-out.

3. Specifications for the new accelerator

These advisory panels recommended an electron accelerator (instead of a proton accelerator) because it was believed that electrons were a “clean” well-understood probe that could penetrate deep inside the atomic nucleus and directly feel the presence of the quarks. Figure 1 shows a slide that was often presented at colloquia to explain this property of electrons. It illustrates how electrons interact by exchanging a single photon (represented by the wavy line connecting the electron to one of the three quarks inside a nucleon). The photon exchange mechanism is so weak that most of the electrons pass through matter without interacting at all, and if an electron does interact, the probability that a second photon will be exchanged at the same time is less than 1/100. This simplicity makes it comparatively easy to calculate the interaction theoretically, one of the great advantages of the electron as a probe. James McCarthy, from the

University of Virginia (UVA) and leader of the SURA team, was fond of saying that electrons were like a “sharp knife” that could cut cleanly through hadronic matter revealing its inner structure.

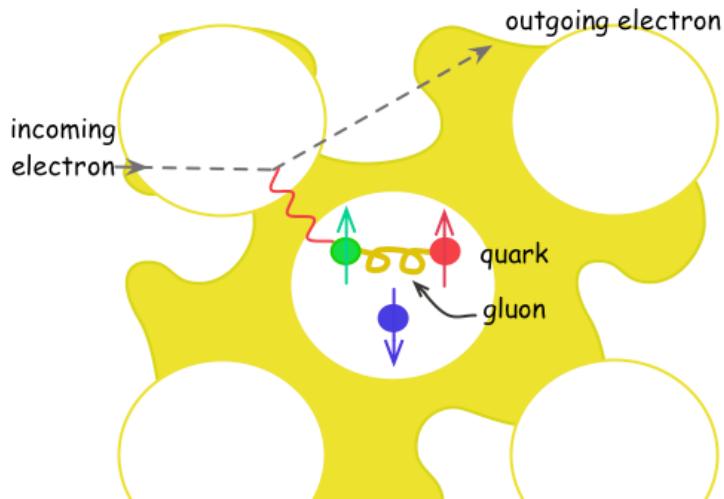


Figure 1. The electron shown as a “clean” probe of the partonic nature of hadronic matter.

High energy electron accelerators, like SLAC, had already played a crucial role in the *discovery* of quarks, but these accelerators could not make the new measurements required for a detailed study of the *behavior* of quarks in nuclei. Currents required to make the magnetic fields needed to accelerate and control high energy electrons are so large that even the best copper conductors and cavities would melt if they were operated continuously. To get around this limitation, the accelerators at the time were powered for very short time intervals so that the accelerator could cool between pulses. The time between pulses for the SLAC accelerator was usually about 8/1000 of a second and the length of the pulse was only about a microsecond. A convenient term which describes the operation of a pulsed accelerator is the *duty factor*, the ratio of the pulse time to the time between pulses. For SLAC the duty factor was less than 1/10,000, or 10^{-4} [13]. Other accelerators had larger duty factors, but did not have either sufficient energy or beam current. To perform the needed measurements an accelerator with a high beam current and a *continuous* beam (or a duty factor close to 1) was needed, and hence a completely new accelerator had to be constructed.

To understand why a continuous beam is needed, it is first necessary to realize that any new phenomena related to the underlying quark structure of matter would most likely be observed only through a *coincidence* measurement (in which the scattered electron is observed in coincidence with one of the nuclear fragments emitted at the same time), and then to understand why coincidence measurements require a high duty factor.

The first point is illustrated in Fig. 2. The figure shows a simple nucleus (the helium nucleus, ${}^4\text{He}$, sometimes called the alpha particle) containing four nucleons: two neutrons and two protons. It is known that most of the time the motion of the quarks is confined into four spherical clusters (the nucleons), but there is a small probability that they might arrange themselves into unusual configurations, and the figure shows an example of such a (very rare) configuration. If only the scattered electron is observed, the cross section is proportional to the *sum* of all possibilities, so rare events cannot be distinguished from common ones. However, when the quarks fluctuate into some rare configuration, the result of the scattering will probably lead to some unusual configuration of hadrons in the final state, which will serve as a “fingerprint” of

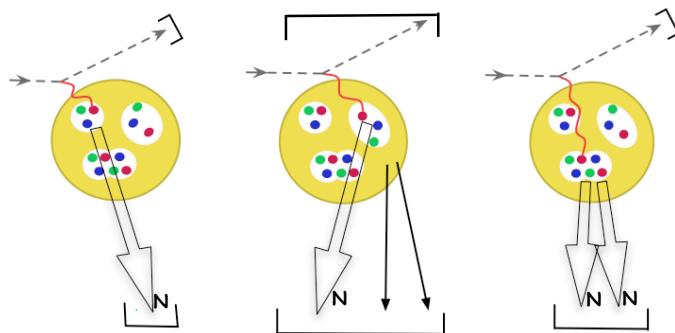


Figure 2. Measurement of hadronic fragments in *coincidence* with the scattered electron can reveal rare structures inside of hadronic matter.

the initial configuration. For example, if a nucleon changes its size in the nuclear medium, as suggested in the leftmost panel of Fig. 2, detection of the single nucleons in coincidence with the scattered electron can reveal this change. If the nucleon is excited inside the nucleus (as illustrated by the elongated nucleon depicted in the center panel, a very rare event) it is most likely that many hadronic fragments will accompany the collision, and if two nucleons overlap and form the unique 6-quark state predicted by QCD (also a rare event illustrated in the right panel) features of this state might be revealed in the signature of two-nucleon emissions.

The second point, that a continuous beam is required in order to do coincidence experiments, is illustrated in Fig. 3. Any detector has a resolution time $\Delta\tau$ within which individual events cannot be distinguished. This time can be converted into a resolution *length*, $c\Delta\tau$, by multiplying by the velocity of light, c . With a pulsed beam (upper panels of Fig. 3) so many electrons arrive at the target in the time interval $\Delta\tau$ that it is impossible to distinguish real coincidences from accidental coincidences. If the beam is continuous (lower panels), the electrons are spread out in time, and any coincidence is unlikely to be “accidental.” In brief, a continuous beam accelerator

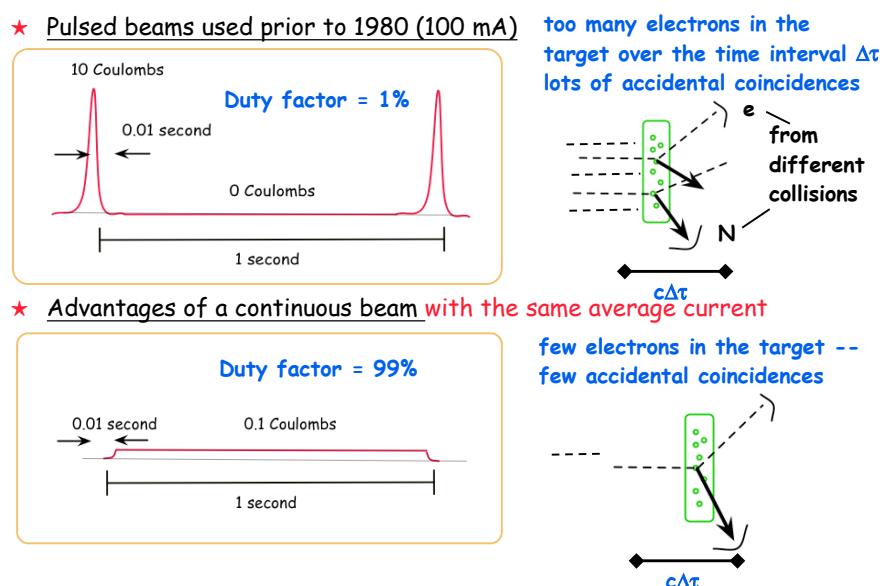


Figure 3. A continuous beam is needed in order to make coincidence measurements.

delivers its electrons spread out evenly over time, so that very few are in the target region at the same time, and accidental coincidences are very rare (they still happen, but can be separated from the real ones using experimental techniques).

4. Building on scientific recommendations (1979 – 1982)

The early recommendations of the Friedlander and Livingston panels which led to the NSAC report of 1979 were only a start. In order to justify the expenditure of \$500 million of public money, a detailed scientific justification with practical accelerator designs was needed. McCarthy, well known for his experimental research in electron scattering and a member of the Livingston panel, wanted to build the next accelerator. He organized a conference at the University of Virginia (UVA) in January, 1979 [14], which examined various design possibilities. Although SURA would not be organized until mid 1980, this conference marks the beginning of the involvement of the Southeastern Universities. McCarthy assembled his team of young designers, including Blaine Norum (who became professor of physics at UVA) and Richard York (who became Associate Director for Accelerators, NSCL, Michigan State University), and John Sheppard (who became head of the Facility for Advanced Accelerator Experimental Tests at the Stanford Linear Accelerator Center).

On the national scene, the Users Group for the Bates Accelerator (run by MIT) invited participants to attend a planning meeting at MIT on January 1980, and both McCarthy and I attended. The Bates Users Group prepared a book (known as the “Blue Book”), released in the summer of 1981 [15], that described the new science, outlined the design specification for an accelerator capable of carrying out the necessary studies, and presented 26 short but detailed descriptions of specific experiments of very high scientific merit that could only be done with the new accelerator. These short “mini-proposals” were an important part of the scientific justification, filling in many details with estimates of the time required for each experiment and the errors expected.

Meanwhile, in the spring of 1980 McCarthy visited The College of William and Mary (W&M) and enlisted the support of physicists Hans von Baeyer (who later became the Secretary of SURA), Robert Siegel (Director of the Space Radiation Effects Laboratory, destined to become the site of Jefferson Lab), Robert Welsh (member of the Livingston panel), and me. Siegel suggested that other universities should be asked to join UVA and W&M, and this idea lead to the formation of SURA. Harry Holmgren (University of Maryland) and Tom Clegg (University of North Carolina) became the President and Treasurer of SURA, respectively, with McCarthy as Vice President. McCarthy and I became SURA scientific spokesmen, and to strengthen the project proposal being prepared by the SURA team, I convened meetings of SURA physicists that produced several new “mini-proposals” not previously included in the Blue Book.

The SURA team did not know when the project would be awarded and, fearing that they might not be ready in time, rushed to prepare their first proposal at the end of 1980. This was too early, but was very helpful in getting off to a quick start and helping SURA establish a national reputation. When DOE called for submissions by the end of 1982, SURA was well prepared with a second proposal [16].

5. The great energy debate

By early 1982, a year before the Washington “shoot-out,” it was clear that the scientific community was in disagreement about whether the energy of the new accelerator should be 2 GeV or 4 GeV. Most of the MIT scientists favored the lower energy because (they argued) (i) it would be better for the study of complex nuclei, (ii) 4 GeV was too low to study the emergence of quark degrees of freedom anyway (some argued that 10 GeV would be necessary – too high for a practical high duty factor, high current machine at the time but, as the 12 GeV upgrade currently under construction has taught us, necessary for a more complete study), and

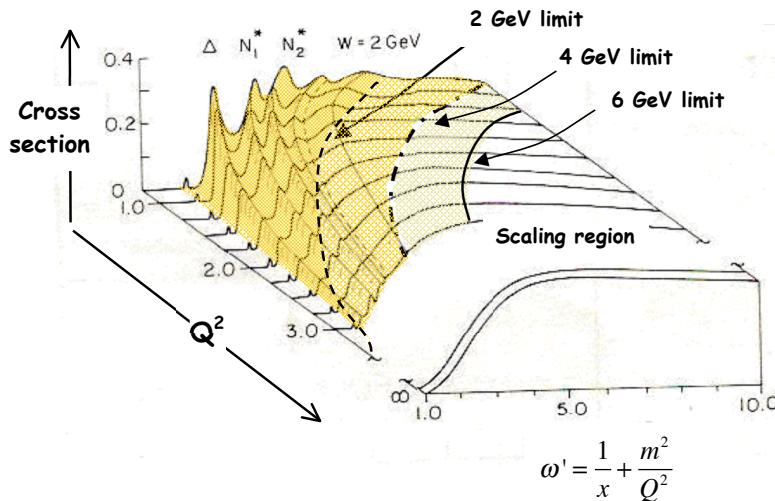


Figure 4. (Adapted from the Barnes panel report [17].) The total cross section for inelastic electron scattering from a free proton depends on two variables: Q^2 and ω' (or x).

(iii) a 4 GeV accelerator was so expensive that the funding might not be forthcoming. They also wanted to use their Bates accelerator as a first stage, and this would not be possible if the energy was as high as 4 GeV. SURA physicists and several physicists from SLAC, including Stan Brodsky, a leader in the application of QCD to nuclear physics, believed that 4 GeV was necessary because it was just high enough to reach the scaling region where quarks had already been “seen.”

A panel of distinguished physicists was convened by NSAC to study the energy issue. It was chaired by Peter Barnes (Carnegie Mellon University and later to become the director of the proton accelerator at Los Alamos) and included Brodsky among its members. After many contentious meetings the Barnes panel finally recommended that the energy be 4 GeV [17]. While no simple argument can adequately summarize all of the discussion, the graph in Fig. 4 gives a rough picture of the committee’s reason for selecting the higher energy. The figure shows how the cross section depends on Q^2 (the negative of the square of the four-momentum transferred by the scattered electron), and the dimensionless scaling variable x ,

$$x = \frac{Q^2}{2m\nu}, \quad (1)$$

where m is the nucleon mass and ν the energy of the virtual photon in the rest system of the nucleon. When Q^2 is large, and x is not too close to unity, the cross section for inelastic electron scattering from a proton flattens out into a broad plateau (referred to as the “scaling region”) where it is (approximately) independent of Q^2 and depends only on the scaling variable x . The existence of the scaling region is strong evidence that the electrons are scattering from point-like quarks inside the proton. The shaded regions in the upper left half of the surface show the parts of the surface that can be studied with 2 GeV, 4 GeV, and 6 GeV accelerators. This shows that 4 GeV provides just enough energy to barely reach the scaling region, and that this region *cannot be reached* with only 2 GeV.

The decision to go to 4 GeV seemed to be a significant victory for SURA, but in early 1983 the SURA team was dismayed to learn that the charge to the Bromley review panel included a reconsideration of the energy of the accelerator. The issue was still open and the SURA team had to prepare to justify the choice of 4 GeV once again.

6. The Washington shoot-out and its aftermath (1983-1985)

So Bromley's question on the morning of February 17 was expected, but the way it was raised seemed to ignore the previous recommendations of the Barnes panel and the presentation SURA had just given. Bromley asked this question several times during the first day, but no one came forward to justify the choice of 2 GeV. The spokesmen for the MIT proposal did not attend the Washington meeting until the *second* day, and by then their arguments for 2 GeV were late and seemed unconvincing. Later, during questioning by Hermann Grunder, the chair of Bromley's technical subpanel (and later to become the first Jefferson Lab director), MIT conceded that it did not have a credible proposal for a 4 GeV accelerator.

In the weeks that followed the Bromley panel decided to support the recommendations of the Barnes panel, and in this way the final choice was between the SURA and Argonne proposals. In its final recommendations to NSAC [18], which were accepted and forwarded to DOE and NSF on April 29, 1983, the SURA proposal was selected for three significant reasons:

- SURA had promised to create at least 35 new faculty positions in nuclear physics to support the science being studied by the new accelerator. (By 1996, 127 such positions had been created.)
- The SURA design could readily be extended to 6 GeV, while the Argonne design was frozen at 4 GeV.
- The SURA design was more conservative (if downgraded to half of the design current) while there were significant concerns about "potential beam loss" if the Argonne design did not meet specifications. In short, the Argonne design could fail completely and produce no beam (the "hard" failure mode) while the SURA design, even if it failed, would always produce a beam (the "soft" failure mode).

The Bromley panel voiced some concern about the relative inexperience of the SURA team, and urged them to hire an experienced management and construction team.

Unfortunately, Argonne protested, and DOE's decision became embroiled in some controversy, which reached as far as the halls of Congress where Senators Mark Hatfield (Oregon) and Bennett Johnston (Louisiana) asked [19] "is there a scientific need for such a machine? Is it the most cost-effective facility for nuclear science?" They went on to ask "Is its justification to satisfy a political or geographical constituency, because so many states and universities are involved and the Southeast is without a major accelerator?" It looked like the 7 years of careful scientific review and preparation would be undone, and it was certainly an irony that the efforts of SURA to generate enthusiasm among the Southeastern universities might turn from an advantage (35 promised faculty positions) into a disadvantage.

In partial response to this criticism, DOE asked for another review, and in Sep. 1984 an NSAC subcommittee chaired by Eric Vogt (director of TRIUMF) reported that it "reaffirms a 4 GeV CW electron accelerator as the first major construction project for nuclear physics" [20]. Soon after, funding became available and the SURA team was able to hire Hermann Grunder as its first director. Grunder arrived in Virginia in May 1985, and brought an experienced team with him, including Christoph Leeman as Associate Director for Accelerator Physics. A year later Grunder hired J. Dirk Walecka, a member of the original Friedlander panel and a distinguished professor of physics from Stanford University, to be the laboratory's first Scientific Director. Leeman later became Deputy Director in 2000 and served as Director from 2002 until his retirement in 2008.

7. Decision to build a superconducting accelerator (1985)

The original design for the SURA machine used a pulse storage ring, as shown in Fig. 5 [21]. Here the linear accelerator (linac) produces a pulse of electrons which is then injected into the

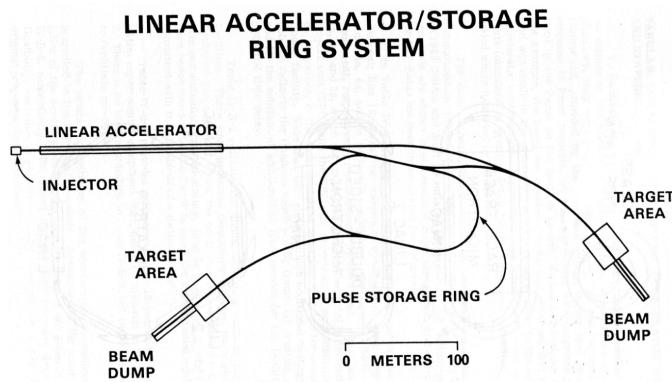


Figure 5. Sketch of the original pulse stretcher ring design for the SURA accelerator.

pulse storage ring. The ring is designed so that the length of the pulse matches the length of the ring; each injected pulse just fills the ring. Then, between successive pulses, the electrons are slowly drained out of the ring, converting the pulse into a continuous current. All of these components operated at room temperature and used conventional copper cavities.

While there were many technical problems to be solved in order to achieve the goals of the SURA design, the pulse storage ring was considered a comparatively “safe” design because it was based on extensions of known technology and, if it did not achieve its goals, it would still produce a high energy beam [18]. Its principal disadvantages were that it could not produce an extremely sharp, well collimated beam and, if it produced multiple beams, they must all have the same energy.

Grunder believed that superconducting technology might be used to build a better accelerator. With this technology the accelerator could be constructed of metal cavities (niobium as it turned out) that become superconducting when cooled to liquid helium temperatures (*i.e.* its resistance to the flow of current drops to almost zero, allowing a large current to flow through the accelerator without heating its components) [22]. Under these conditions the linear accelerator could be operated continuously without overheating, and because the beam in the accelerator would deliver its electrons continuously, the number of electrons in the accelerator at any give time would always be much less than the large number crammed into the pulses of a conventional accelerator, reducing the repulsive forces between them and giving an extremely well focused beam.

While superconducting cavities had already been developed and used for lower energy accelerators, in 1985 no one had designed radio-frequency (RF) accelerator cavities with the high field gradients needed for a 4 GeV machine. Furthermore, RF cavities with high gradients had been promised and expected for many years, so it was easy to overlook the steady progress being made. Grunder asked and received permission from DOE for the new laboratory to review the state of superconducting technology. The review led to a new conceptual design for the accelerator, with many advantages, and in December of 1985, less than eight months after Grunder had taken over leadership of the project, DOE approved the concept of a superconducting linac for CEBAF. This was a remarkable development, clearing the way for Jefferson Lab to eventually become a leading world-wide center for superconducting RF cavity design.

The actual design adopted is illustrated in Fig. 6. The accelerator is basically a linear accelerator (linac), wrapped around five times. As long as the recirculation arcs have a large radius so that the radiation of photons by electrons traveling in a circle is negligible, and

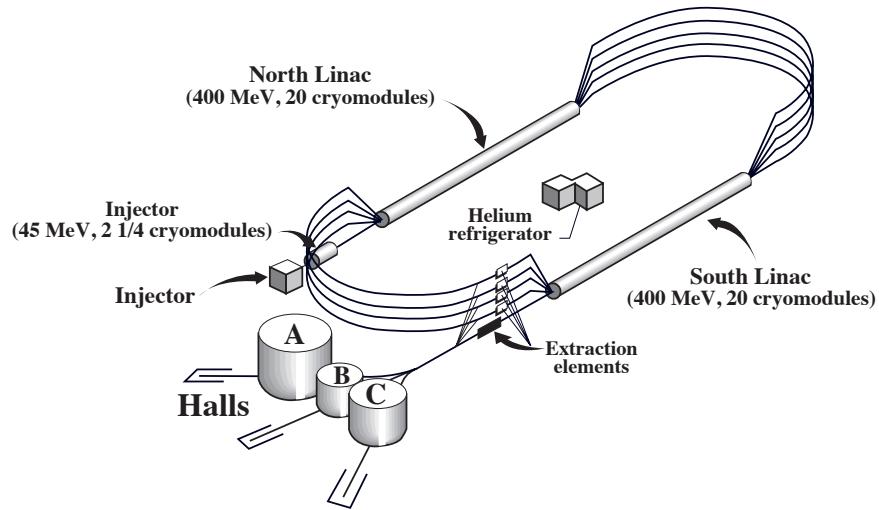


Figure 6. Sketch of the final design for the CEBAF accelerator. The beam travels once through the North and South linacs with each recirculation, when part of it may be extracted and injected to any of the three Halls. The linac energies shown are for operation at 4 GeV; at 6 GeV each linac operates at 600 MeV.

because the electrons are ultrarelativistic and travel with essentially the same speed through their journey, the multiple linacs along each side (not shown in the figure) can be combined into a single linac, saving money and real estate. The number of recirculations is a balance between the lower costs of fewer (or shorter) sections of linac and the higher costs and greater complexity of the arcs with more recirculations. The initial design called for 4 recirculations. It was eventually decided that a 5th recirculation would save money without significantly increasing the risk.

It was recognized from the beginning [23] that the experimental program needed three experimental halls (or “end stations”) with different capabilities, as illustrated in Fig. 6. Hall A houses two high resolution spectrometers well matched to the excellent quality of the CEBAF beam, and is ideal for making accurate measurements of two particle final states. Hall B has the CEBAF Large Acceptance Spectrometer (CLAS) that can detect and identify the several particles expected from the multi-particle reactions illustrated in the middle panel of Fig. 2. Hall C has a medium resolution spectrometer and space for experiments requiring special equipment.

The superconducting design insured several advantages for the scientific program with the simultaneous use of multiple end stations:

- Beam quality was very high; all of the electrons travel in nearly the same direction with a very small angular spread and their momentum spread is also very small. This makes it possible to do very high resolution experiments.
- Beams injected into the three end stations could each have different energies, as long as they were a multiple of the energy of each recirculation. For example, at the full energy of 6 GeV, the beams directed to each hall could be any multiple of 1.2 GeV up to 6 GeV.
- The microstructure of the main beam made it possible to send beams with very different currents into each hall. For example, the detectors in the CLAS spectrometer are exposed and will be blinded unless the current on target is very low (the large acceptance of CLAS compensates for the low current required), while the spectrometers in Hall A have a very small acceptance and require high current in order to give reasonable counting rates. The ability to independently adjust the currents in each of these halls makes it possible to do

experiments in all of them simultaneously.

- If the electron injector produces a polarized beam, this polarization will not be seriously compromised by the comparatively smooth trip around the recirculating linac. Today beams at Jefferson Lab are produced with very high polarization.

8. The overall Jefferson Lab 6 GeV nuclear physics program: then and now

The remaining sections are an introduction to the overall 6 GeV physics program being concluded in 2012, and described in more detail in the rest of this volume. For information about the new 12 GeV physics program now being developed, see the Jefferson Lab web site at www.jlab.org/12GeV/.

The discussion of the overall 6 GeV program is organized into two parts, each consisting of smaller programs focused on specific issues:

- **programs featured in the 1985 Preconceptual Design Report (PCDR)**

- charge distribution in the neutron and deuteron
- coincidence measurements of single particle emission
- two-body correlations in nuclei
- production of excited nucleons
- strangeness in nuclei

- **programs that emerged after 1985**

- numerical solutions of QCD
- parity-violating asymmetries
- structure functions for deep inelastic scattering
- generalized parton distributions (GPDs).

The five experimental programs featured in the PCDR [23] were extracted and distilled from the 26 short mini-proposals included in the proposal submitted by SURA in 1982. The last four programs describe exciting new developments unanticipated (or not emphasized) in 1985.

Recall that colored quarks are the fundamental particles of QCD. Because quarks are confined, states of free quarks do not exist; the only states that can exist in nature are colorless states which can be built out of combinations of two different types of “building blocks”: either (i) three-quarks with one quark of each color (there are only three) combined into a colorless state, or (ii) quark-antiquark pairs (where the “anticolor” of the antiquark renders the pair “colorless”). A nucleon is made of one three-quark system and a “sea” of quark-antiquark pairs. A nucleus with mass number A is therefore a complex color neutral composite of A three-quark systems and a sea of quark-antiquark pairs, somehow clustered into A nucleons. The extent to which the nucleons retain their identity in an environment of other nucleons in close proximity is one of the puzzles to be unraveled, and the existence of the quark substructure opens up many possibilities: are there unique structures of quarks, such as 6-quark bags, present in a nucleus?

9. Programs featured in 1985

Five programs featured in 1985 address these questions in two different ways. Some of them study the structure of the nucleon itself, in order to unravel the distribution of quarks inside of free nucleons. Others study nuclei, with the goal of understanding how nucleons (and hence quarks) are distributed inside of bound systems with more than one nucleon.

9.1. Charge distribution in the neutron and deuteron

In 1985, the charge distributions inside the neutron and the deuteron were very poorly known, and measurement of these distributions was important for similar reasons.

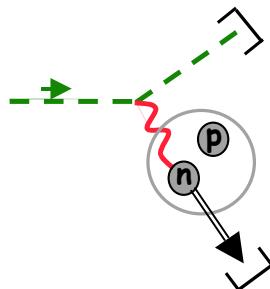


Figure 7. A polarized electron (dashed line with arrow) scatters from the neutron in the deuteron (the simplest nuclear target containing a neutron). Both the scattered electron and the neutron are detected in spectrometers.

The neutron is composed of two *down* quarks with charge $-\frac{1}{3}$ and one *up* quark with charge $+\frac{2}{3}$, making it electrically neutral. If the *up* and *down* quarks had exactly the same spatial distribution within the neutron, the neutron charge would be identically zero everywhere. Measurement of this distribution is therefore an important indicator of how the quarks behave inside the neutron.

This charge distribution can be measured by scattering electrons from a neutron, but unfortunately the neutron is unstable, so the scattering must be done from a deuteron (the *only* stable bound state of one neutron and one proton) or some other simple nucleus (often ^3He). If the recoiling neutron is detected in coincidence with the scattered electron, as shown in Fig. 7, events where the electron scatters from the neutron can be distinguished from those where it scatters from the proton (with a known correction with a small error). A second complication is that the neutron has both a charge and magnetic moment distribution, and the magnetic moment distribution is both less sensitive to the quark distribution and also dominates electron scattering, swamping out the effect of the charge and making it very difficult to “see” how the quarks are distributed inside of the neutron. A good way to separate out the charge from the magnetic moment distribution is to measure the transfer of spin from an electron to the scattered neutron, and this also requires that the neutron be measured in coincidence with the scattered electron. For these two reasons (use of a deuteron target and need to measure the polarization transfer) a coincidence measurement is essential, and requires the new accelerator.

On more than one occasion I was told by someone that he “might support the construction of the accelerator if I could name *one* important experiment” that it could do and that could not be done by another (existing) accelerator. When confronted with such a challenge, I always chose to describe the measurement of the neutron charge distribution; it was hard for anyone to deny the simplicity and importance of this experiment and all could see why it required a new accelerator to measure it.

What happened? The neutron charge measurements produced very accurate results. We now know that the *up* and *down* quarks have different distributions, with a greater density of *up* quarks at the center and *down* quarks at the periphery. This knowledge, important in its own right, also can be used to more reliably interpret the meaning of electron scattering experiments from all nuclei.

Similar measurements were made on the proton and those measurements lead to a big surprise! The proton charge distribution is much easier to measure and had been measured previously by another technique (referred to as a Rosenbluth separation) at SLAC. As part of the Jefferson Lab program, the proton charge distribution was measured again using the new polarization transfer technique, and the *results disagreed with the previous SLAC measurements*. A careful study of the source of this disagreement lead to an interesting discovery: it now seems that the two-photon exchange contribution (illustrated in Fig. 8(b)), previously thought to be very small and never observed, strongly affects the extraction of the charge from a Rosenbluth separation

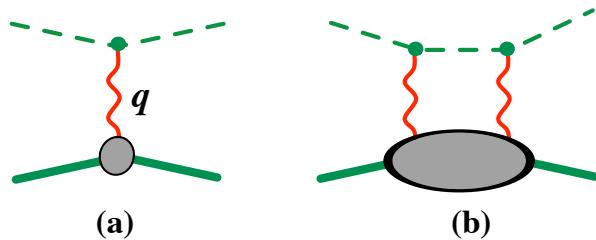


Figure 8. Feynman diagrams showing (a) the usual one-photon exchange approximation to the elastic scattering of electrons from nucleons, and (b) the two-photon exchange contribution.

but has only a little effect on its extraction from a polarization transfer measurement. An extensive program to confirm this picture is currently underway.

The deuteron is the only bound state of two nucleons and is therefore the simplest nucleus. Measurement of its charge distribution gives important information about the nuclear force – in this case the effective force between two nucleon three-quark clusters (labeled the NN force, for short) that accounts for the formation of all nuclei and is responsible for many aspects of the structure of stars.

While this charge distribution can be measured in electron scattering, detailed measurements of the distribution at short distances, where the effects of the NN force might be studied, are masked by effects from charge quadrupole scattering, a large effect insensitive to the details of the NN force. While looking at the deuteron in coincidence with the scattered electron, it is possible to control the scattering so that the (smaller) charge distribution can be disentangled from the larger (and less interesting) quadrupole scattering.

What happened? At Jefferson Lab measurements of the charge distribution of the deuteron were separated from the larger quadrupole contributions and measured to $Q^2 \sim 1.8$ GeV 2 . The charge distribution has a zero around $Q^2 \simeq 0.7$ to 0.8 GeV 2 . One of the surprising things learned from this experiment, completed during first years of the Jefferson Lab program, is that these experimental results can be understood using relativistic state of the art models based on nuclear and meson degrees of freedom, with no need to consider the underlying quark degrees of freedom explicitly.

9.2. Coincidence measurements of single particle emission

The measurement of a single nucleon emitted from a nucleus with A nucleons, in coincidence with a scattered electron, is illustrated in Fig. 9, which shows the two important contributions to the process. In the left diagram, the struck nucleon is emitted without rescattering from any of the remaining $A - 1$ nucleons in the system, while in the right hand diagram the struck nucleon scatters from parts of the $A - 1$ system (it undergoes “final state interactions”). If the rescattering (right figure) is very small (it is never exactly zero), the process depends on the product of (i) the nucleon charge and magnetic distributions, or “form factor” $F(Q)$ (represented by the small grey circle also shown in the one-photon exchange diagram of Fig. 8(a)), and (ii) the momentum distribution $\rho(k)$ of the nucleon just before it scatters from the electron. In this case the momentum, k , of the nucleon in the nucleus *before* it was struck (referred to as the “missing momentum”) can be deduced from the momenta of the outgoing nucleon and the virtual photon, both of which are determined by the measurement.

The rescattering process also depends on the charge distribution of the nucleon in the nuclear medium, but the rest of this amplitude no longer depends simply on $\rho(k)$, but on a more complicated function. Because of this, a good theory is needed to unfold both $\rho(k)$ and $F(Q)$ from this experiment, so neither $\rho(k)$ nor $F(Q)$ are *directly* observable. It is also useful to find situations where the final-state interactions are very small, or at least very well understood. If both $\rho(k)$ and $F(Q)$ can be extracted from this measurement, everything about the shape, size,

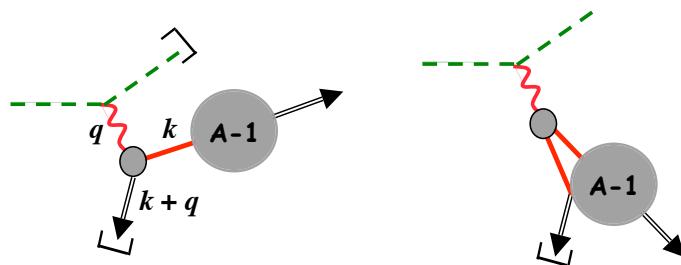


Figure 9. Cartoon showing two of the processes that take place when the emission of a single particle is measured in coincidence with the scattered electron.

and distribution of three-quark clusters in a nucleus will be revealed.

What happened? The question of whether or not the nucleon changes its size in a nuclear medium has been addressed in coincidence experiments where the proton was knocked out of ^4He , leaving the simple ^3H nucleus behind. There is a clear reduction in the ratio of polarization transfers for scattering from ^4He when compared with scattering from the proton, which can be explained by assuming the proton is modified in ^4He , but a firm conclusion is difficult to draw at this time because an alternative calculation of the final state interactions can also explain the results without assuming any modification of the nucleons. Stay tuned for further developments.

Data for proton knockout from ^3He has been separated into two-body (pd) and three-body (ppm) final states, giving clean information about the size of these two processes out to large missing momenta. These data can also be reasonably well explained by models based on nuclear and meson degrees of freedom. Other measurements from few body targets (including the deuteron) and under different kinematic conditions are being analyzed and a more complete picture will emerge soon.

In one particularly interesting study, *real photons* (radiated from electrons) may be absorbed by the deuteron producing a neutron and proton final state. At the high photon energies produced by the accelerator, the total cross sections for this deuteron photodisintegration process exhibit another type of “scaling” (only loosely related to the scaling observed in the inelastic scattering studies sketched in Fig. 4). This scaling prediction, which can be derived from QCD at *very* high energies, referred to as “perturbative QCD” or simply pQCD, is that any differential cross section $d\sigma/dt$ at fixed angle and *very* high energies should behave as

$$\frac{d\sigma}{dt} \sim \left(\frac{1}{s}\right)^{n-2}$$

where s is the square of the c.m. energy and n is the *minimum number of point-like particles* involved in the process. Applied to deuteron photodisintegration, $n = 1 + 6 + 3 + 3 = 13$ (1 photon, 6 quarks in the deuteron, and 3 quarks in each of the nucleons in the final state) leading to the prediction that s^{11} times the differential cross section should go like a constant as $s \rightarrow \infty$. The recent data taken at Jefferson Lab exhibit this behavior (which sets in most rapidly for scattering at 90° c.m.). On the face of it, this would seem to be a brilliant confirmation of the predictive power of pQCD and assurance that this theory can be used to understand deuteron photodisintegration with (comparatively low energy) 4–6 GeV electrons; however, attempts to calculate the *strength* of the s^{-11} behavior have failed, and other predictions (such as polarization observables) do not always agree with the data. We are left with a puzzle: why does pQCD scaling behavior work to such low energies when other pQCD predictions (strength and polarization dependence) fail?

9.3. Two-body correlations in nuclei

The very simplest theoretical picture of a large nucleus treats it as a gas of non-interacting nucleons that move freely through the nuclear volume. Ironically, this overly simple picture is useful because the strong short range repulsion between nucleons keeps them apart, preventing the nucleus from collapsing, guaranteeing that many body forces (involving three or more nucleons) must be small, and clearing the way for the longer range forces to be averaged so that they can be treated as a mean field. From this point of view, any correlations between the nucleons are either a reflection of the strong short range forces, or a signal of the departure from the mean field. In either case, direct observation of correlations is extremely interesting and tells us how the NN force is modified by the nuclear medium, or whether or not there are highly correlated 6-quark states present in nuclei. While this was believed to be an important program, in 1985 it was thought that correlations might show up as the knockout of a pair of nucleons, such as might emerge from a 6-quark bag as suggested by the right-most cartoon in Fig. 2.

What happened? The observations of correlations is one of the most exciting developments to emerge from the Jefferson Lab program but the “best” observation of correlations did not involve a coincidence experiment at all! This was an “inclusive” measurement in which *only* the scattered electron was observed. As shown in Fig. 4, for large Q^2 this cross section depends only on the scaling variable x , and it is easy to show that scattering from a single, free nucleon is possible only if $x \leq 1$. The most direct way to see correlations is therefore to look at processes in which $x > 1$. Under this condition, scattering is *impossible* unless the nucleon is bound in the nucleus. The ratio of the scattering cross section from different nuclei for $x > 1$ will therefore depend in part on the size of the two-body correlations in these nuclei (and, by extension, the ratios for $x > n - 1$ depend on n -body correlations). This fact was predicted before 1985, but sufficiently precise data were unavailable and the accurate observations at Jefferson Lab have opened up this area of study.

As anticipated in 1985, correlations have also been observed in one and two nucleon knockout experiments. The recent observation of the large ratio of np to pp pairs seen in knockout from ^{12}C can be explained by the dominant role of the tensor part of the NN force.

9.4. Study of excited states of the nucleon and search for “missing” states

The nucleon is a complicated system composed of at least three quarks confined in a small volume by the colored forces that interact between quarks. When struck by a pion (the pion, π , is the lowest mass state of quark-antiquark pairs and beams of pions have been used to study the structure of nucleons and nuclei) or a photon, it can be excited into resonance states (most with a very short lifetime). The mass and structure of these baryonic resonance states, together with the way in which their excitation by photon and pion beams differs, give very direct information about the QCD forces that bind the quarks.

In the early 1980s these states had been primarily studied using pion beams (the counting rates for production of these states by pion accelerators is much larger than the rates using electrons and photons) and there was a puzzle: many states predicted by quark models were not seen. Nathan Isgur suggested that a reason for this was that the probability that a pion might excite some of these states was very small, and showed that these “missing states” might be more readily seen in the process $\gamma^* + N \rightarrow N^* \rightarrow N + \pi + \pi$ (where γ^* is a real or virtual photon produced by the electron). These measurements required the large acceptance spectrometer that could measure the momenta of the outgoing nucleon and two pions (and many other multiple particle states) and these requirements eventually lead to the construction of the CLAS detector in Hall B.

What happened? Study of the excited states of the nucleon has been a major part of the Hall B program from the earliest days and is described in this volume. The Hall B CLAS detector

can detect an impressive number of final states, including nucleons, photons, and multiple pions and kaons, and their decay products. It has become increasingly evident that this program must be supported by a major theoretical effort, including the coupled channel calculations being carried out by the Excited Baryon Analysis Center (EBAC), with the goal of isolating resonance states from non-resonant background which must be dynamically calculated at the same time. Form factors of the lowest lying excited states of the nucleon, some very poorly known and others completely unknown in 1985, have now been measured, and while there are intriguing hints of missing states, final conclusions must await further experimental and theoretical analysis of the data.

9.5. Study of strangeness in nuclei

The strange baryons, especially the neutral Λ composed of at least one *up*, one *down*, and one *strange* quark, is unstable but can form stable nuclear states (referred to as hypernuclei), usually by substituting one Λ for one of the nucleons through one of the elementary reactions $\gamma^* + p \rightarrow K^+ + \Lambda$ or $\gamma^* + n \rightarrow K^0 + \Lambda$, where γ^* is a real or virtual photon produced through the (e, e') scattering process, and the K^+ and K^0 are strange mesons containing one *strange* antiquark. The K 's interact weakly with the rest of the nucleus, passing through the nuclear medium and providing a clean “tag” for the conversion of a nucleon to a Λ . These states tell us both about the familiar NN force as well as the new ΛN force between the Λ and the nucleon, related through the underlying quark structure to the NN force. The ability to explain *both* the ΛN and NN forces together is a definitive test of our understanding of how two three-quark clusters interact.

However, to accurately unravel the ΛN force from the energy levels of the hypernuclear states requires that the energies of these states be measured very accurately, and that individual states which sometimes lie very close to each other, be separated and identified. This in turn requires measurements with good energy resolution. In the 1980s, most of the information about these states had been learned from K^- (or π^+) beams, which produce hypernuclei through the reaction $K^- + n \rightarrow \Lambda + \pi^-$ (or $\pi^+ + n \rightarrow K^+ + \Lambda$), and the resolution was limited to about 1.5 MeV. To make important contributions to this study, resolutions below 500 keV were sought.

What happened? The hypernuclear program was supported from the very beginning by a strong group of Japanese and Italian collaborators. Complementary programs in Hall C (which required construction of special spectrometers and has gone through three distinct phases) and Hall A have been established, and resolutions in the range of 500–600 keV have been achieved. Data from a variety of hypernuclei have been obtained and a number of new states identified and studied. Over the next decade Jefferson Lab data will complement and be combined with data from the new facility at J-PARC (the Japan proton accelerator research complex).

10. Programs that emerged after 1985

Several programs featured in this volume emerged after 1985. The theoretical program to solve QCD numerically was anticipated in the first proposal for a Jefferson Lab theory group [24] but not funded until much later. The parity violation program was also anticipated but was not featured. Deep inelastic scattering using *unpolarized* electrons, already advanced in 1985, did not require coincidence measurements, and measurements of the *polarization* dependent structure functions, which require an intense beam with high polarization, only emerged as a strong program later when it was realized that the new CEBAF accelerator had an excellent figure-of-merit for these measurements. Finally, the program to extract generalized parton distributions (GPDs) from deeply virtual Compton scattering, only developed later.

These programs, among the most productive and exciting being undertaken at Jefferson Lab, are examples of the fact that a laboratory will often develop in ways not anticipated during the initial planning.

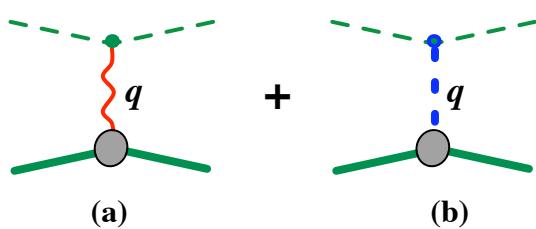


Figure 10. Feynman diagrams showing (a) the exchange of the virtual photon previously discussed in Fig. 8 (denoted M_γ), and (b) the exchange of a neutral Z boson (denoted $M_Z = M_Z^0 + M_Z^P$), which carries the weak force.

10.1. Numerical solutions of QCD (LQCD)

At very high energies, QCD can be solved analytically and the solutions compared with high energy data. The agreement is very impressive, leading to the expectation that QCD is the correct theory of the strong interactions. But very little is known about the solutions at the lower energies involved in normal nuclear reactions or at the scales needed to understand the structure of nucleons and nuclei. Does QCD really explain low energy phenomena as well, or does it break down and is a new theory needed in this region? Solving QCD at lower energy scales and comparing the solutions with experiment is of the highest priority; it is the central question in this field.

At low energies, QCD can be solved numerically on a lattice of space-time points, and the program to obtain such solutions is referred to as lattice QCD, or LQCD. Solutions have given a mass spectrum for mesons and baryons in good agreement with data, giving confidence that QCD also explains low energy phenomena. Numerical results have shown how quarks are confined, confirming what was previously only a conjecture.

To obtain LQCD solutions requires large and very fast clusters of computers, so the accuracy of the solutions we obtain is always limited. For the most part these uncertainties can be controlled and understood (LQCD solutions come with error bars, just like experimental data, and are therefore sometimes called “data”). To solve LQCD for the very small masses of the *up* and *down* quarks is currently near the limits of our computer capability, so many solutions have been obtained for (unrealistically) large quark masses, and are extrapolated to small masses (with associated uncertainties). Furthermore, the lattice used does not have the full rotational symmetry of nature, and certain tricks must be used to extract some quantities correctly.

It turns out that LQCD solutions can only be done in Euclidean space-time (related to the physical space-time by making time an imaginary number). For some quantities, such as particle masses, this is not a restriction. Other quantities cannot be calculated in Euclidean space, so LQCD cannot, in principle, calculate all of the things we want to know. Since LQCD cannot solve all of the problems that interest us, nor give an understanding of all of the physics involved in the solution, it must be supported by theoretical models that can connect numerical solutions to physical pictures and extend our calculations into areas not accessible to LQCD. In this respect LQCD can be an important guide; it can sometimes calculate physical quantities that cannot be directly measured, but which play an important role in the construction of realistic physical models.

This is a rapidly moving field and we expect still better solutions using more and more creative techniques in the years ahead.

10.2. Parity-violating asymmetries

The “Standard Model” is the modest name given to the theory that includes QCD and the combined theory of the electromagnetic and weak interactions (known as the “electroweak” theory). According to the Standard Model, an electron scatters from a nucleon by exchanging not only a virtual photon (the carrier of the electromagnetic force) but also by exchanging a

neutral Z boson, one of the carriers of the weak force. The total scattering is then the sum of these two exchanges, as illustrated in Fig. 10. The strength of the Z boson exchange is about 100,000 times smaller than the photon exchange, so this term can normally be ignored (and, in fact, is more than 1000 times smaller than the two photon exchange mechanism shown in Fig. 8). How can one hope to see such a small effect and why should we care?

The answer to the first part of this question lies in a remarkable property of the weak interactions: they violate parity. Loosely speaking, parity is the symmetry that insures that fundamental laws cannot distinguish left from right. While macroscopic systems often show left-right differences, fundamental laws do not – at least they were not known to until its violation was discovered to be a feature of the weak interactions. The discovery, in the late 1950s, that the weak interactions do not conserve parity came as a great surprise; as far as we know this is not a feature of any of the other fundamental forces of nature.

In the context of electron scattering, a violation of parity will show up as a difference between the scattering of a right-handed electron (one with its spin pointing in the direction of its motion) from that of a left-handed electron (with its spin pointing opposite to its direction of motion) when *no other particles in the reaction are polarized*. The scattering cross section is proportional to the square of the two terms in Fig. 10. The exchange of a neutron Z boson contains a term (M_Z^p) that will change sign when the spin of the electron is switched, giving an *asymmetry* defined to be the difference divided by the sum of the two possible contributions

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{2(M_\gamma + M_Z^0)M_Z^p}{(M_\gamma + M_Z^0)^2 + (M_Z^p)^2} \sim \frac{2M_Z^p}{M_\gamma} \sim 10^{-4}Q^2,$$

where Q^2 is in GeV^2 . Measurement of such small asymmetries is a challenge, and is done by picking the small asymmetry out of the much larger background by flipping the spin from left to right and synchronizing the small variation of the cross section with the spin direction. The excellent beam quality of the CEBAF superconducting accelerator design has helped to make such a program possible.

The study of the weak interactions contains lots of new information that we *cannot* learn from the study of the electromagnetic interaction only. This was recognized in the initial SURA proposal, but it was not featured in the PCDR prepared in 1985. J. Dirk Walecka, Jefferson Lab's first Scientific Director, recognized the importance of this program, and after his arrival in 1986 sought to build a culture that would ensure that these difficult parity-violating measurements would become a regular part of the program.

Study of the weak interaction, Fig. 10(b), is extremely interesting for two, somewhat distinct, reasons. First, a full description of the coupling of the nucleon of either the photon or the Z requires summing the contributions from all three quarks in the nucleon: the u , d , and s . The photon couplings to the proton and the neutron give two observables linearly dependent on all three of these distributions, but only by measuring the coupling of the Z boson to the proton (for example) can we obtain the third linear combination needed to *separately* determine the contribution coming from strange quarks. This search has been a major effort at Jefferson Lab. Early expectations suggested that this contribution might be large, but results obtained so far show that it is very small and this places significant limits on the types of models that can be constructed to explain the structure of the nucleon.

The second direction for the parity-violating program is to use it to test the validity of the Standard Model itself. The Standard Model seems to describe all known phenomena in the realm of nuclear physics; any discovery of a failure would be of very great significance. The primary focus of tests carried out at Jefferson Lab are precision measurements of the strength of the weak interaction. This strength depends on only two parameters, the overall strength of the weak interaction and a mixing angle that can be related to the mass of the Z boson. Once

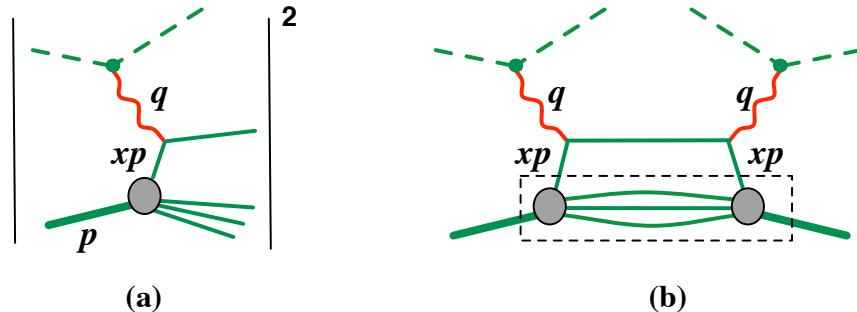


Figure 11. (a) Feynman diagram showing the DIS amplitude at large Q^2 ($Q^2 = -q^2$) where the leading term comes from the virtual photon being absorbed by a single quark, and (b) the cross section, proportional to the absolute value squared of diagram (a).

these parameters have been measured, a number of relations and predictions follow, and any violation in these predictions will signal the breakdown of the theory.

10.3. Structure functions for deep inelastic scattering

As mentioned briefly in the discussion surrounding Fig. 4, the existence of point-like quarks inside the nucleon was inferred first from the study of deep inelastic scattering (DIS) from the proton. At large $Q^2 > 1 \text{ GeV}^2$ and for x not too close to unity, the structure functions that define the DIS cross section begin to scale; they depend primarily on the variable x defined in Eq. (1), with only a weak dependence on Q^2 that can be calculated theoretically. The Feynman diagram that describes DIS is shown in more detail in Fig. 11(a). The DIS cross section is proportional to the square of this diagram, shown in Fig. 11(b). It turns out that the variable x can be interpreted as the fraction of the total momentum p of the nucleon carried by the struck quark, as displayed in the figure.

To fully describe the parity-conserving (electromagnetic) part of the DIS cross section, four structure functions are needed, which are usually denoted $F_1(x)$, $F_2(x)$, $g_1(x)$ and $g_2(x)$. These are extracted from the part of the cross section enclosed in the dashed rectangle shown in Fig. 11(b). The first two (the F 's) are the only ones that contribute when the electron beam is unpolarized; The other two (the g 's) arise when the beam and target are polarized, and have been a particular focus of an intense study at Jefferson Lab. Data for $g_2(x)$, the smallest and most difficult to measure, has been the last to be obtained.

This program of measurements has contributed to efforts to resolve the long standing “spin” puzzle: polarization data show that the spin carried by quarks is only a small fraction of the total proton spin ($\frac{1}{2}$). This is a surprising result; it requires that other contributions to the spin, which must come from the orbital angular momentum of the quarks, possible contributions from strange quark-antiquark pairs, or the spin and angular momentum of the “gluons” (the carriers of the force between the quarks), must be larger than naively expected.

The excellent quality of the CEBAF beam, which can be highly polarized, has made these studies possible. When all of these functions are well known, the distributions in space, spin, and angular momentum of the quarks inside of the nucleon will be tightly constrained. More measurements will be carried out when the Jefferson Lab accelerator reaches 12 GeV.

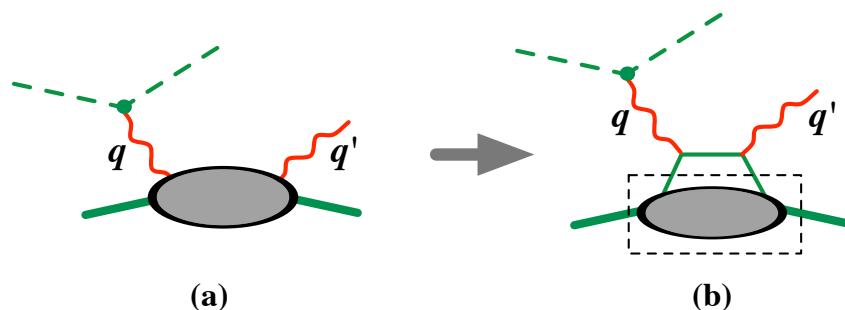


Figure 12. Feynman diagrams showing (a) virtual Compton scattering, and (b) the simplification possible if the virtual photon has a very large Q^2 . The part of the right hand diagram enclosed in the dashed rectangle is the GPD discussed in the text.

10.4. Generalized parton distributions (GPDs)

In the mid 1990s it was realized that measurements of the virtual Compton scattering cross section would open a new window into the study of the structure of the nucleon. Virtual Compton scattering occurs when a virtual photon (produced by the electron) is scattered from a nucleon, producing a final state with a real photon and a nucleon, as shown in Fig. 12. When Q^2 is very large, the full diagram Fig. 12(a) may be “factorized” as shown in Fig. 12(b). In this diagram one of the quarks in the nucleon absorbs the high energy virtual photon and then radiates a real photon which emerges in the final state. Since the energy of the two photons and the interacting quark are all very large, this part of the diagram can be calculated using pQCD. The low energy part of the interaction is confined to the lower part of the diagram (which defines the generalized parton distributions, or GPDs, enclosed in the dashed rectangle).

The GPDs are generalizations of the parton distributions illustrated in Fig. 11. The parton distributions depend only on the scaling variable x , interpreted as the fraction of the target momentum carried by the quark, and therefore give us a picture of the distribution of quark momentum in the direction of motion of the nucleon. The GPDs depend on three variables: x , an asymmetry parameter, ξ , and the momentum transferred to the target, t . Together these additional variables can be analyzed to tell about the structure of the nucleon transverse to its direction of motion, which will ultimately allow us to construct a full three-dimensional image of the proton. They can also give detailed information about the angular momentum carried by the u and d quarks, shedding light on the spin puzzle.

The GPDs can also provide a description of the deeply virtual production of mesons. Here the cross section depends not only on the GPDs, but also on the structure of the meson itself. The 12 GeV upgrade is essential to the development of this program.

11. Conclusions

The Jefferson Lab of today is the end result of a long process of scientific planning, open competition, and scientific peer review, starting in the late 1970s and culminating with first beam on target on July 25, 1994, and the physics program beginning a year later. Without the open competition championed by the DOE, the laboratory would have taken a different form and it is unlikely that more than a hundred new faculty positions would have been created to support its scientific program.

The results obtained so far include some surprises, and have provided us with a detailed picture of the quark structure of the nucleon and a much better understanding of when we can see the quark degrees of freedom hidden in a nucleus. Analysis of data already obtained and

new theoretical work stimulated by these findings continues, so the full impact of this program is yet to be felt. The superconducting accelerator, with its continuous, tightly focused beam, is now being upgraded to 12 GeV. We expect this new facility to provide many new insights, and some surprises, in the coming years.

Acknowledgment

For more complete accounts of the early history of Jefferson Lab, see the excellent articles by Catherine Westfall [25, 26]. Special thanks to Blaine Norum for providing details about the SLAC accelerator.

It was a great privilege to be a part of this unique endeavor and to work with so many fine people. A few (not already mentioned) are Bill Bertozzi, Carl Carlson, Tony Chargin, John Domingo, Bill Donnelly, Bernard Frois, Bernhard Mecking, Ingo Sick, John Tjon, Steve Wallace, Roy Whitney, and Rolf Winter. This work is supported by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.

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