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35 YEARS OF ELECTRON SCATTERING

J.D. Walecka
Continuous Electron Beam Accelerator Facility
12070 Jefferson Avenue
Newport News, VA 23606

Symposium - 35 Years of Electron Scattering

J. D. Walecka
The Continuous Electron Beam Accelerator Facility
Newport News, Virginia

Concluding Remarks

When I was coming here on the plane the other night, I did not have the foggiest idea of what I was going to say. I went for a long walk last night, and now I find I can talk for at least an hour. But I am not going too. I enjoyed the symposium. I particularly enjoyed yesterday because it took an historical approach to the subject. We are honoring 35 years of electron scattering, but in fact, Professor Hanson went back to Rutherford. We started with, if I recall one of his slides correctly, something like a 100 KeV gun and detector, and we ended last night with a 100 GeV beam and the L3 detector. And that is all within one lifetime. It is really an impressive history.

Since we are talking about history, let me talk a little bit about history myself. I first got involved in electron scattering through a talk Bob Hofstadter gave when I was a postdoc at CERN in 1958. I was impressed by the quality of the experiments, and particularly by the interaction between theory and experiment. He would present this nice theoretical cross section, the Rosenbluth cross section, the Jankus formula, etc., and from that and the experiments he would then deduce all this marvelous information about what nucleons look like, what the deuteron looks like, what nuclei look like . . . It is a nice field. It really is high-quality information, you know what you measure. I went to Stanford and was associated with Stanford and HEPL for the 20 year period from 1959 to 1979; it was really a very exciting time and a very exciting place. It was built on the klystron, which was developed at Stanford, and on the electron linac. If you stood in the middle of HEPL you could see Hofstadter's spectrometers, and you could see the storage rings. I remember Burt Richter, Gerry O'Neill, Dave Ritson, Bernie Gittleman, and Carl Barber, night-after-night, trying to make those storage rings work. Of course, HEPL led to SLAC, SPEAR, and PEP. The first superconducting cavities were developed there; John Pierce built the first one, if I am not mistaken. Large-scale refrigeration was developed there at Stanford. The first free electron laser was down in the basement of HEPL. it was really a marvelous time and a marvelous place.

I also know bj from Stanford. In fact we overlapped during that period. He and I shared an office for a good fraction of that period. I do not want to embarrass bj, but he has always been my model of a physicist. He can do theoretical physics at the forefront; he can do it with the best of them. But he also realizes physics is an experimental science, and he works closely with experiment. To me, that was one of the things that made Stanford a special place during all that time. It was the close interaction between theory and experiment. After bj's talk about high energy physics, I have nothing to add to that subject. I am therefore going to concentrate on nuclear physics.

Let me go back to the beginning. Why do we do nuclear physics? First the nucleus is a unique form of matter. It consists of many baryons in close proximity. Second, all the forces of nature are present in the nucleus - strong, electromagnetic and weak. The nucleus provides a unique microscopic laboratory to test the structure of the fundamental interactions. Furthermore, the nuclear many-body problem is of intrinsic intellectual interest. In addition, most of the mass and energy in the universe around us comes from nuclei and nuclear reactions. Finally, in sum, nuclear physics is the study of the structure of matter.

Why do we do electron scattering [1]? First, the interaction is known. It is governed by quantum electrodynamics (QED), which is the most accurate physical theory we have. Second, the electron provides a clean probe; we know what we measure. In addition, the interaction is relatively weak, so we can make measurements without greatly disturbing the structure of the target.

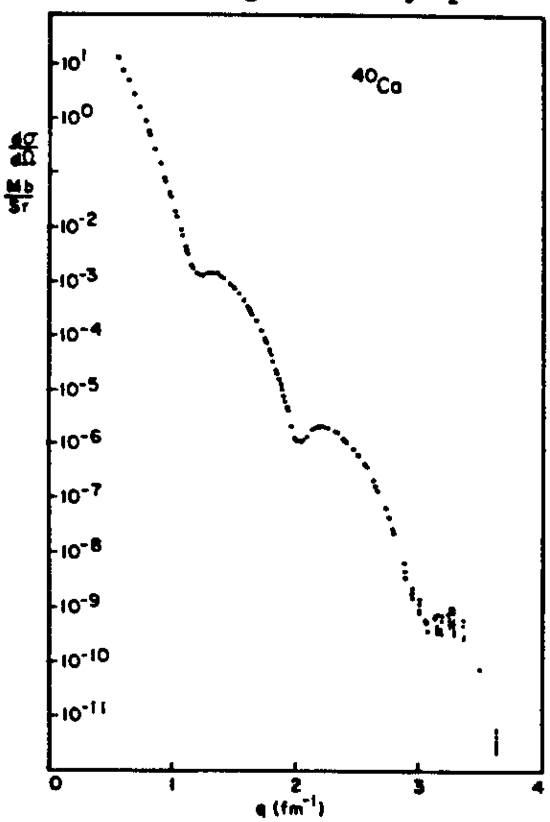

Fig. 1 Elastic (e,e) cross section for ^{48}Ca vs. momentum transfer [2]. The scattering here is from the charge distribution.

What we measure in electron scattering, basically, is a macroscopic diffraction pattern, and I want to show you this once more in Figure 1 [2]. This is the ^{48}Ca diffraction pattern plotted against the momentum transfer q. You set up these huge spectrometers, in the laboratory, and measure this optical diffraction pattern. This one has been measured over 13 decades. You then essentially take the Fourier transform of this diffraction pattern, and determine the microscopic distribution of charge in this nucleus, as shown in Figure 2; the scale here is in Fermis where $1F \equiv 10^{-13}$cm. That little band is the experimental accuracy with which we have determined the charge density in ^{48}Ca from these experiments.

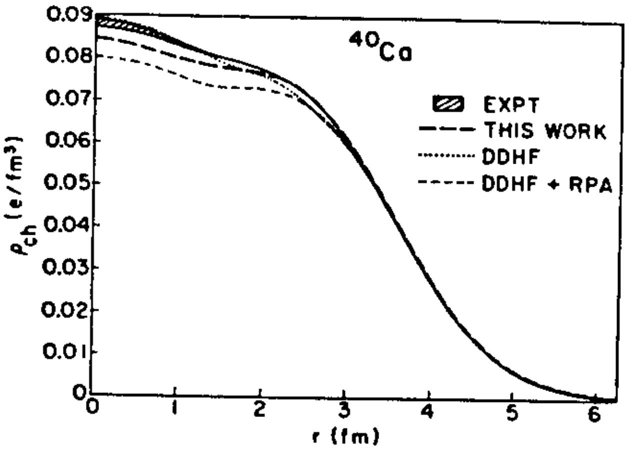

Fig. 2 Experimental charge density of ^{40}Ca with estimated uncertainty from elastic electron scattering (solid lines and shaded area) and relativistic Hartree calculations of this quantity within the framework of QHD (heavy dashed line). Taken from refs. [2, 4].

Furthermore, the electron is a versatile probe for nuclear physics. Not only is there an interaction with the charge density, but there is an interaction with the convection current, and also with the intrinsic magnetization density and corresponding magnetization current coming from the intrinsic magnetic moment of the nucleons.

Let me say a little bit about how we do nuclear physics. I will start with what I call the traditional approach [3]. In this approach you start with a static two-body potential fit to two-nucleon scattering data, you insert that into the non-relativistic many-particle Schrödinger equation, and then you solve that equation within some approximation, or in the two- and three-body problem, you can now essentially solve it exactly. You construct the nuclear currents from the properties of free nucleons, and you use these currents to probe the system. Now although this approach to nuclear physics has had many successes, as you all know, it is clearly inadequate for a more detailed understanding of the nucleus.

A more appropriate set of degrees of freedom for the nuclear system consists of the hadrons, the strongly interacting mesons and baryons. In addition, one of the current goals of nuclear physics is to study nuclear matter under extreme conditions - high temperature, high pressure, high flow velocities. These conditions are relevant to astrophysics, and relativistic heavy-ion reactions. Furthermore, we want to study the response of the nuclear system to high-q^2 probes. In order to have a theoretical framework to describe these phenomena, it is essential that we incorporate general principles of physics such as quantum mechanics, special relativity, and causality, in our theoretical description. The only consistent theoretical framework we have for describing such an interacting, relativistic, many-body system is relativistic quantum field theory based on a local lagrangian density. I like to refer to such theories of the nuclear system as quantum hadrodynamics or QHD [4].

Certainly one of the great intellectual achievements of the last decade has been the unification of the electromagnetic and weak interactions [5-7]. It is essential to continue to put this Standard Model of the electroweak interactions to rigorous tests. Furthermore, we have a theory of the strong interactions binding quarks into the observed hadrons; that theory is quantum chromodynamics or QCD, based on an internal color symmetry [8]. I will discuss how we can use electroweak interactions to probe this structure of the Standard Model of the strong, electromagnetic, and weak interactions, and how we can use nuclei to study the structure of the strong interactions.

I want to say just a couple of words about quantum chromodynamics and remind you of a few key features of this theory [8]. The first is asymptotic freedom. Asymptotic freedom roughly says the following: when the momenta entering into a process are very large, or equivalently at very short distances, the renormalized coupling constant governing that process goes to zero. This means, under these conditions, one can do perturbation theory. The other striking aspect of the theory of QCD is that the underlying degrees of freedom are never seen as asymptotic free scattering states in the laboratory. The quarks and gluons are confined to the interior of the observed hadrons. There are strong indications from lattice gauge theory, which tries to solve QCD in the strong-coupling regime on a finite space-time lattice, that confinement is indeed a dynamical aspect of QCD.

I want to discuss one application of the relativistic aspects of nuclear physics, and Bernard Frois talked about this yesterday. I will go through it again very briefly. Let us take elastic magnetic scattering from ^{3}He, and make the world's simplest model. We will say that ^{3}He is a neutron hole in the ^{4}He core, make an oscillator model, and get the oscillator parameter from elastic charge scattering. The solid line in Figure 3 is the magnetic form factor you then predict for ^{3}He [9]. Now let us add the pion exchange current. This is the current coming from the exchange of charged pions in this nuclear system. In fact, you can calculate the long-range part of

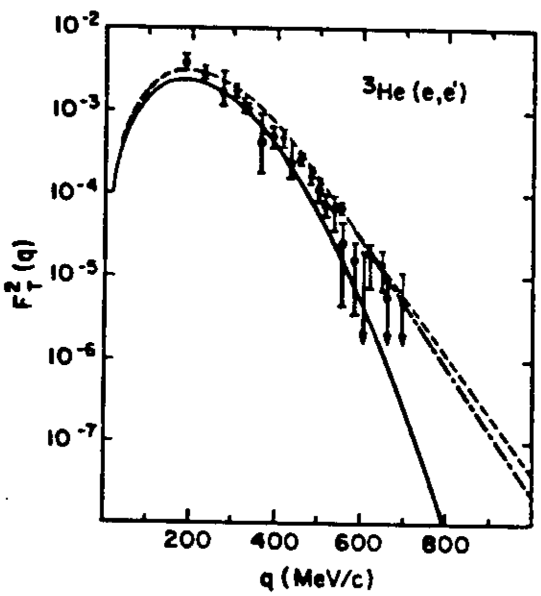

Fig. 3 Elastic transverse form factor for ^{3}He (e,e) with (dashed) and without (solid) one-pion-exchange currents [9].

range part of the pion exchange current from basic low-energy theorems. If you put in that pion exchange current in the calculation, what you get is the dashed curve in Figure 3 [9]. Well, you really are not going to conclude very much from that, right? On the other hand, if you now push and go to high momentum transfer, then you get the data shown in Figure 4 [10]. The data I just showed you is here divided by q^2, that is why the curve goes to one at $q^2=0$. The dashed curve is the best calculation we have based on the solution to the Faddeev equations for this three-body system, and on structureless nucleons. It is clear that what was a small effect before at low q^2 now becomes an order of magnitude effect at larger q^2. This is a clear demonstration of the role of the sub-nucleonic, or hadronic, degrees of freedom in the nuclear system.

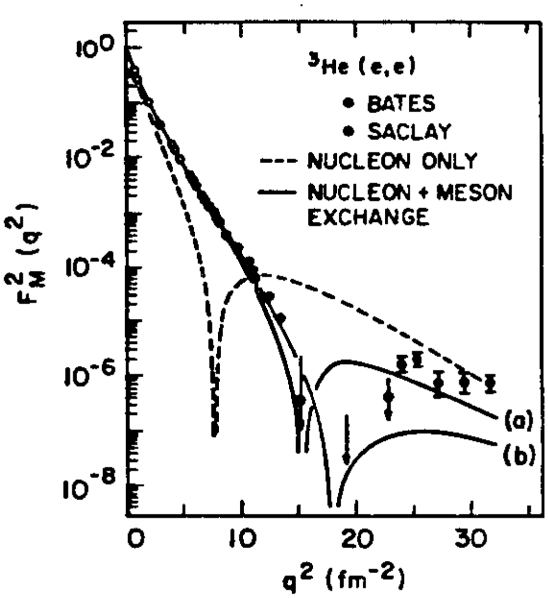

Fig. 4 Elastic magnetic form factor for ^{3}He (e,e) out to high q^2 [10]. Two exchange current theories are shown.

There are several lessons from this story. The first is that the intermediate-q^2 results illustrate the marginal role of exchange currents in the traditional nuclear physics domain. The second moral is that the high-q^2 results illustrate the need for an explicit treatment of the hadronic degrees of freedom in this system, or for QHD. We can summarize that moral in the following way: the appropriate set of degrees of freedom depends on the distance scale at which we probe the system. There is still another lesson in this. The only way we can arrive at this unambiguous identification of exchange currents, or of the role of the sub-nucleonic hadronic degrees of freedom, is to have a very accurate theoretical calculation in which we believe, which is clearly inadequate in some range of kinematics.

Where are we today in nuclear physics? We study the properties of the nuclear system at accelerators such as Bates, Saclay, NIKHEF and others, and we can accurately interpret that data in terms of nucleonic and sub-nucleonic hadronic degrees of freedom. On the other hand, we know from the deep inelastic scattering work done at SLAC that at very high energy transfer and very high momentum transfer, that is in the deep-inelastic region, we see the point-like substructure of these hadrons [11]. Therefore, in the intermediate-range of momentum transfer and energy loss, there is clearly an interesting region of physics. To emphasize this point, I will quote a sentence from the report of the Vogt Subcommittee of NSAC which was the last committee to re-examine the question of constructing a 4 GeV electron accelerator for nuclear physics. It concluded that "The search for new nuclear degrees of freedom and the relationship of nucleon-meson degrees of freedom to quark-gluon degrees of freedom in nuclei is one of the most challenging and fundamental questions of physics."

Let me give you, in Figure 5, a picture of what the nucleus looks like in the Standard Model. This is a cartoon, but underneath that cartoon there is a lagrangian and there are local currents. It is the lagrangian of QCD and the currents are those of the Standard Model. What does the nucleus look like in this Standard Model? First, I want to point out that the structure of confinement in the many-baryon system, as in the single-baryon system, is an unsolved problem. Confinement presumably arises because of the non-linear gluon couplings in the QCD lagrangian. The electroweak interaction, as provided by an electron, or a neutrino, or an e^+e^- annihilation, couples to the quarks; it sees through the gluon structure. The electroweak interaction does not see this confining gluon structure. It is like having a crystal ball, where the quarks are tiny colored objects inside the crystal ball. The electroweak interaction sees that interior quark structure, and the gluons with their non-linear couplings, which are responsible for the confinement, are transparent to this electroweak interaction. Thus the electroweak interaction does indeed directly see the quark structure of nuclei.

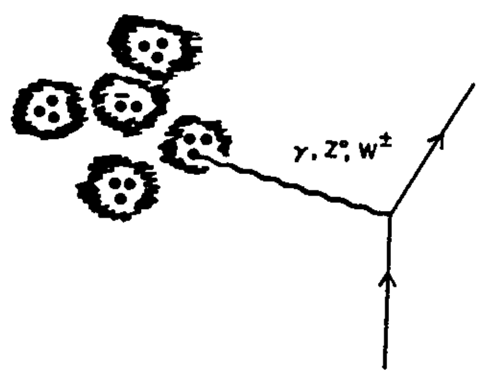

Fig. 5 Picture of the nucleus in the Standard Model.

Now this picture and the underlying lagrangian and the currents have some rather striking consequences. Let me just tell you two of them [1, 12]. Suppose I use the nuclear system to select an isospin-zero to an isospin-zero transition, that is a pure isoscaler transition. Suppose I confine myself to the nuclear domain, where by nuclear domain I mean that part of the Hilbert space made of only up (u) and down (d) quarks, and any number of $\bar{u}$ and d anti-quarks. Within that subspace of the full Hilbert space you can prove the following relation. The neutrino cross section is proportional with a known constant of proportionality to the electron scattering cross section.

$$d\sigma_{\substack{\nu_1 \nu_1' \\ \bar\nu_1 \bar\nu_1'}} = \sin^4\theta_W \frac{G^2 q^4}{2\pi^2\alpha^2}\, d\sigma_{e e'} \qquad ; \; T = 0 \to T = 0$$

Now what does this mean? It means that if I scatter a neutrino from ^{40}Ca, I see that entire diffraction pattern shown before in Figure 1. I can lay those two cross sections (appropriately scaled) on top of each other and they should be the same over those 13 decades! And this holds for all distance scales; it holds at a distance scale where you interpret nuclear structure in terms of gross nuclear properties, down to a distance scale where you interpret it in terms of structureless nucleons, to a distance scale where you must invoke the sub-nucleonic hadronic degrees of freedom, down to the quark-gluon level itself.

As a second example, suppose I look at a $0^+ \to 0^+$ transition, for example elastic scattering from ^{12}C. In that case, the parity-violating asymmetry which arises from an interference of Z° exchange with photon exchange is again a known factor times the ratio of two form factors.

$$\mathcal{A}_{ee'} = \frac{d\sigma_\uparrow - d\sigma_\downarrow}{d\sigma_\uparrow + d\sigma_\downarrow} = -\frac{q^2 G}{2\pi\alpha\sqrt{2}} \left[\frac{F^{(0)}(q^2)}{F^{\gamma}(q^2)}\right] \qquad ; \; 0^+ \to 0^-$$

One is the form factor for the weak neutral current and the other the ordinary electromagnetic form factor. The former measures the distribution of the weak neutral charge over this nucleus, this complicated hadronic system, and the latter the distribution of electromagnetic charge. Within the Standard Model this ratio of form factors is a constant for all q^2, and this asymmetry should be strictly linear in q^2 [13].

$$\mathcal{A}_{ee'} = \frac{q^2 G}{\pi\alpha\sqrt{2}} \sin^2\theta_W \qquad ; \; \begin{matrix} 0^+ \to 0^+ \\ T{=}0 \to T{=}0 \end{matrix}$$

This strict linear dependence, to me, is a true test of the unification of the weak and electromagnetic interactions. An experiment to measure this parity-violating asymmetry for ^{12}C is being carried out at Bates, and the fact that it is a true test of the Standard Model in the nuclear domain, where the strong interactions are strong, is the reason that I personally give it a top priority.

Let me set up a strawman who says, "We have quarks and gluons and the QCD lagrangian, therefore the problem is no longer interesting." Nobody would every say that, right? (I have heard it!) Let me make the same statement, "We have electrons and protons (in nuclei) and the lagrangian of QED. So what?" Well, first we have atoms. Then we have crystals. Then we have semiconductors. And then we have superconductors. And then we have superfluids. (In fact, you would not know about these latter phenomena unless you had the appropriate experimental facilities to study low temperatures, for example, the facilities we heard about in Hermann's talk this morning.) And then of course, you can combine atoms into molecules and you have chemistry, then you have biology, and then you have life. It is not an uninteresting system of consequences following from that lagrangian and these underlying degrees of freedom!

This is just a schematic of where we are today.

NP	↘	Standard Model	→	Structure of Matter
		(Common language)	→	Tests of Standard Model
HEP	↗		↘	Beyond the Standard Mode

One of the things I like is that nuclear physics and high energy physics are, in a certain sense, coming together again through the Standard Model. We now have a framework in which we all operate. It is a new language for nuclear physicists, but it is absolutely essential to learn that language, because it describes the underlying theory of the structure of matter. And now, in fact, we proceed in slightly different directions. Nuclear physics is the study of the structure of the matter that underlying theory describes. High energy physics goes in the direction of probing beyond the Standard Model, as we heard from bj and in the talk yesterday. Both nuclear physics and high energy physics are interested in testing the Standard Model in all of its complexity and all of its richness.

Success generates opportunities. We have talked about 35 years of electron scattering and electron interactions. The success of this field, in studying nuclei and basic interactions, is indicated by where we are today. If you simply look at what is already operating, and what is being contemplated, it is clear that the success of this field is what generates the opportunities ahead of us. We have heard about LEP, we have heard about Mainz, we have heard about HERA, and we have heard about NIKHEF. Let me be chauvinistic and just talk for a moment about the U.S. In nuclear physics, CEBAF is now an approved construction project (as of last weekend!) Bates has an upgrade to 1 GeV with the pulse stretcher ring. Illinois has its microtron which will reach, as we heard, 450 MeV. I think all of these projects will actually go; that is my best estimate at the present time. High energy physics has SLC. As far as nuclear physics is concerned, we have not had the quality beams, the kinematic range, and the coincidence capability before in this country. There is certainly plenty of unexplored physics for everybody. CEBAF, if you like, is pushing on the kinematic frontier. It will stretch our picture of the nucleus to the extreme, test it under extreme kinematic conditions, and work towards asymtopia, or at least asymtopia as demonstrated by the SLAC deep inelastic experiments. Bates has a rich program with high resolution spectroscopy, particularly with internal targets, polarized beams, and exotic polarized jet targets. Illinois has an excellent program of other things, including studying angular correlations of collective levels; we have seen those beautiful angular correlations. This has never been possible before. Certainly from a physics point of view, there is more than a decade of good physics for everybody.

My strongest argument for Bates and Illinois, however, is that they are really the best sources we have for young people for this field, and, in fact, for all of nuclear science. Bright, creative, young people are not only essential to the science, but are also the most valuable resource this country has.

I tried to summarize my own thoughts on CEBAF, and I summarize them this way: CEBAF will provide the most precise, accessible probe of matter. The interaction is known, and one knows what is being measured. It is an interesting time for nuclear physics; we are told there is a whole new underlying set of degrees of freedom and forces in the nuclear system. What we are really building is a tool and a capability for the next generation of nuclear scientists.

The scientific goal of CEBAF is to study the structure of the nuclear many-body system, its quark substructure, and the strong and electroweak interactions that govern the behavior of this fundamental form of matter.

And I would like to close with three quotations and a story. I like these quotes, I use them all the time. The first quote is from Herb Anderson at a talk at Los Alamos. (Actually it was a question he asked Herman Feshbach after Herman's talk.)

> "We have been doing nuclear physics for 50 years
> without quarks. Why do we need them now?"

That is actually a very profound question for nuclear physics and nuclear physicists. I ask you to think about it very carefully.

The second quote is a comment Bob Wilson made to me a couple of years ago.

> "The single most important practical application of the recent advances in particle physics may well be the revolution in our picture of the nucleus."

And finally, Nathan Isgur gave a redefinition of the field for the future which I particularly like.

> "Nuclear physics is the study of the strong-interaction, confinement aspects of QCD."

And now let me close with a story. Some of you may know that I have been pushing a high resolution capability for CEBAF. Two years ago there was a symposium at Stanford to honor Bob Hofstadter's 70th birthday. It was a two-day symposium; I gave a talk there and told this story. Twenty years ago, in about 1968, Bob and I collaborated on the theoretical justification for the proposal of a 2 GeV CW electron accelerator. During that collaboration Bob said that we had to have a high-resolution capability. He said that if you look with high-resolution at high energy, you will certainly discover new phenomena. And I said to myself, "That is nonsense. You are not going to see anything at high energy with high resolution." And now you have to remember the time. In those days high energy physics looked asymptotic. Everything you were doing at that time was smooth, you were already in asymtopia, nothing peculiar was going on. It was actually very dull! And then one night at SPEAR they had a broad bump in their spectrum, and it would have remained just a broad bump forever, but they had the capability of turning a knob and getting the resolution up. And so they sat there that night and kept turning the knob and the resolution kept improving and, of course the ψ was what they saw. They saw the role of a new underlying set of degrees of freedom; they saw it as a very sharp resonance at an energy that nobody had expected. One had never seen such a sharp line before at that energy, and in a certain sense it revolutionized high energy physics. My moral from that story is that I will continue to rely on Bob Hofstadter's intuition.

Thank you for this symposium.

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