JLab 25th Year Anniversary Celebration

NUCLEAR PHYSICS SCENE AT THE TIME OF CREATION OF JEFFERSON LAB

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I. INTRODUCTION

I want to thank the organizers of this 25th Anniversary Celebration of CEBAF, now Jefferson Lab, for asking me to give this talk.

II. SOME HISTORY

I am fond of telling my students that the neutron and I are the same age, as the neutron was discovered in 1932, the year that I was born. Nuclei are made from neutrons and positively charged protons, held together by the strong nuclear force. It is a remarkable fact that all the knowledge we have about the structure of the atomic nucleus has been obtained within one person's lifetime.

The much lighter, negatively-charged electrons have only electromagnetic interactions. In the neutral atom, the electrons form a cloud around the nucleus that determines the chemical properties of the elements and the periodic system. The binding energy of the electron in the deuterium atom is 13.6 eV, while it requires 2.2 million eV, or 2.2 MeV, to separate the deuterium nucleus into a proton and neutron. These energies serve to characterize the strong and electromagnetic interactions.

In the early days, nuclei were studied by looking at the remnants and characteristics of various nuclear reactions.

The theoretical description was based on static nucleon-nucleon potentials and non-relativistic quantum mechanics. The shell model provided a unifying basis for describing nuclear structure and excitations. It indicated that nucleons move relatively independently in a nuclear mean field.

In 1935 Yukawa developed a theory of the strong interaction in analogy to quantum electrodynamics (QED). In QED the interaction of two static charged particles with the electromagnetic field results in the long-range Coulomb potential between two charges. The quanta of the electromagnetic field are photons. Yukawa observed that the interaction of two static nucleons with a neutral, massive scalar field can yield the strong, short-range "Yukawa Potential". He predicted the quanta of this field should appear as mesons. The pion was subsequently discovered in 1948, and it is the pion that provides the long-range part of the force between two nucleons.

How big is the nucleus? A typical nuclear size is a $(few)\times 10^{-15}m$. To help comprehend this number, go in the opposite direction. The distance light travels in one year is $10^{+16}m$. The nearest star is 4 light-years away. Thus the ratio of the size of a nucleus to a meter stick is roughly the same as that of the size of the CEBAF accelerator to the distance to *Proxima Centauri.*

III. ELECTRON SCATTERING

Can one actually see anything this small? An elementary optics experiment provides a key. Put a tiny pinhole in an opaque sheet, and shine a laser through it, with known wavelength matched to the size of the hole. Now observe the resulting pattern on a wall. There will be a central spot surrounded by concentric bright rings. This is a diffraction pattern, characteristic of any type of wave motion. Take a meter stick and measure the distance from the pinhole to the wall, and then the distance from the central spot to the first bright ring. The ratio of these two numbers is the ratio of the size of the pinhole to the wavelength of the light. By making a macroscopic measurement with meter sticks in the laboratory, one can determine the size of a microscopic pinhole!

How does one obtain a wavelength of $10^{-15}m$? It is the starting point of quantum mechanics that particles have an associated wave that determines their trajectory, and the wavelength is Planck's constant over the particle's momentum. What energy must an *electron* have to have a wavelength of $10^{-15}m$? The answer is 1.24 thousand MeV, or 1.24 GeV. This is a good number to remember, since it sets the energy scale for everything we will talk about today.

I want to briefly discuss three electron scattering experiments that formed the physics base for CEBAF.

The first was carried out at HEPL, the High-energy Physics Laboratory at Stanford, in the 50's and 60's. A spectrometer matched to the electron energy was used to measure that diffraction pattern. Furthermore, since the mechanism for the scattering is the electric interaction between the charges, by looking at the details of the diffraction pattern one can determine just how the charge is distributed in the nucleus. In this manner, we could actually *see* what the nucleus looks like, and obtain benchmark data to test theories.

There is, in addition, a magnetic interaction between the electron and nuclear currents, and by measuring the diffraction pattern at all angles, one is able to determine the spatial distribution of the entire nuclear current. A subsequent series of elastic and inelastic scattering experiments at HEPL, Bates Lab at MIT, Saclay in France, NIKHEF in Holland, and Mainz in Germany, convinced the nuclear community of the power of electron scattering.

The second key experiment was carried out at SLAC, the Stanford Linear Accelerator Center, in the early 70's. At very high energy-loss and momentum transfer, the electron appears to scatter *freely* from *tiny bits of charge* within the nucleon. These are the quarks. It was the search for theories of the strong interactions between quarks, where the quarks behave freely at short distances, that led to the concept of asymptotic freedom and the theory of quantum chromodynamics (QCD), with the interaction of quarks mediated by gluon fields.

The nucleon is not unlike a piece of fruit with hard, tiny seeds hidden inside, where the seeds (the quarks) surround themselves with the fruit (the mesons) through the strong interactions of QCD.

The third key experiment was also done at SLAC in the mid-70's. Electrons have another interaction not yet touched on. Neutrons, both free and in the nucleus, can beta-decay into a proton, electron, and neutrino. In the nuclear domain the coupling constant for this process is much smaller than the electric charge, and this is a weak interaction. The Standard Model is a unified theory of the weak and electromagnetic interactions developed in the early 70's, and it is a consequence of this Model that when electrons scatter from the nucleus, they also interact with a new, weak, neutral current. The effects of this current are completely masked by the electromagnetic current, unless one looks for something that is only there because of the presence of the weak interaction. Parity-violation is such an effect. Electrons have spin, and scattering with the spin aligned and anti-aligned with the momentum must give the same result, except for this weak interaction. The tiny difference was measured at SLAC for the nucleon and found to be in agreement with the Standard Model, playing a crucial role in its verification and acceptance.

Parity-violation experiments, though notoriously difficult, double the power of electron scattering, since the spatial distribution of the weak neutral current can now also be determined.

The challenge and opportunity for CEBAF at the outset was to use electron scattering to study just how the traditional picture of the nucleus, involving static potentials, and eventually mesons, evolves with increasing resolution into the quark picture and QCD. In addition, parity-violation experiments could access the weak neutral current.

IV. THE NUCLEAR PHYSICS COMMUNITY

The field of nuclear physics in the U.S. was in disarray in the 60's and 70's. There were many reasons for this, but that is another talk. One reason is that the low-energy, university-based accelerators were coming to the end of their useful life, and many physics departments were using freed-up faculty positions to go in other directions. Although nuclear physics was moving into a user's mode, most, if not all, of the major universities did not have nuclear physics user's groups. Another source of concern was that the number of nuclear physics Ph. D.'s had fallen from 234 in 71/72 to 130 in 73/74, and was projected to continue to decline. The situation was sufficiently serious that in 1975 the National Academy set up an Ad Hoc

Panel on the Future of Nuclear Science, chaired by Gerhardt Friedlander from Brookhaven. After 2 years of intense deliberation, the Panel issued its report in 1977. Two of its recommendations are of prime importance for us here today. The first states

An early start on a feasibility and design study for a high-current cw electron accelerator in the energy region $\geq$ *1 GeV is recommended. If technical feasibility is established, the Panel recommends that early construction of such a national facility be considered.*

The technical feasibility was subsequently established by another agency panel. The second recommendation was

We recommend that a Nuclear Science Advisory Panel be formed to advise the federal funding agencies on a continuing basis

This seemingly innocuous recommendation had a profound impact on the field, for it provided a focus and mechanism for long-range planning.

In the first paragraph of a 1983 NSAC Long-Range Plan, largely formulated internally, it is stated that "*We reaffirm our earlier recommendation for the earliest possible start on the construction of a national electron accelerator laboratory*".

It was the subsequent Long-Range Plan, carried out in conjunction with the Division of Nuclear Physics of the American Physical Society, that involved the whole community. Working groups were set up, white papers were written, town meetings were held, and a sizable body then spent a week in Boulder going over the physics and hashing out priorities. The Plan was presented in 1989 in the document *Nuclei, Nucleons, Quarks: Nuclear Science in the 1990's.* Its first recommendation reads:

The highest priority in U.S. nuclear science at this time is the timely completion of the Continuous Electron Beam Accelerator Facility (CEBAF) and the beginning of its important research program

One cannot overstate the impact it has had to have the entire community argue and set priorities internally, and then stand united in their defense.

The '89 Report also laid out the projected physics issues:

1. *Study of the nucleus as a strongly interacting many-body system, consisting of nucleons and mesons*

2. *Exploration of the fundamental theory of the strong interaction, QCD, in the nuclear medium*

3. *Study of the thermodynamic properties of nuclear matter expressed in the equation of state, and its phase transitions*

4. *Searches for new phenomena at the very limits of nuclear stability*

5. *Exploration of the electroweak force and its connection to quarks, as prescribed by the Standard Model, in the nuclear medium*

V. CONCLUSION

I want to conclude with a piece of poetry that speaks to just why we do nuclear physics. It is not what you might expect. It is the last paragraph of the forward to a book *Theoretical Nuclear Physics,* written by Amos de Shalit and Herman Feshbach some 30 years ago. The forward was written by Viki Weisskopf, my thesis supervisor:

There is a fascination in dealing with nuclear processes, with nuclear matter with its tremendous density; a matter, however, that is inert on earth but is not inert at all in most other accumulations of matter in the universe. The dynamics of nuclear matter are probably much more essential to the life of the universe than are terrestrial atomic and molecular physics. After all, what is that *physics? It deals with the electron shells around nuclei that are only formed at very low temperature on a few outlying planets where the conditions are just right—where the temperature is not too high, low enough to form those electron shells but high enough to have them react with each other. These conditions are possible only because of the nearness of a nuclear fire. Under the influence of that nuclear fire, self-reproducing units were formed here on earth. And after billions of years of benign radiation from the solar furnace, thinking beings evolved who investigate the processes that may lie nearer to the heart of the universe than the daily world in which we live.*