The Future of Mr. Jefferson’s Laboratory (née CEBAF)*

Carl E. Carlson

Physics Department, The College of William and Mary, Williamsburg, VA 23187, USA

Abstract

We present one viewpoint plus some general information on the plans for energy upgrades and physics research at the Jefferson Laboratory.

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1 Introduction

This talk reports one viewpoint plus some general information on the plans for energy upgrades and physics research at the Jefferson Laboratory.

The first thing to report is that the name of the place has changed: on 24 May 1996 the former Continuous Electron Beam Accelerator Facility (CEBAF) became the Thomas Jefferson National Accelerator Facility (TJNAF), or the Jefferson Laboratory or JLAB colloquially. Thomas Jefferson lived from 1743 to 1826, wrote the Virginia Statute of Religious Freedom and the American Declaration of Independence, was the second Governor of Virginia under independence, and the third President of the United States under the present constitution. In Virginia he is still referred to as “Mr.” Jefferson.

The actual subject of the talk is the prospect for higher energy at JLAB and what might be done with higher energy there. Skipping over politics, I will make a few comments about what I will call engineering, meaning plans and hopes and methods for energy upgrades and when they may occur, and then devote the bulk of the talk to physics.

* Written version of an invited talk presented at the Second ELFE Workshop on Hadronic Physics (St. Malo, France, September 1996).
2 Engineering

There are plans to upgrade the accelerator to what I am told should be called $9 \pm 1$ GeV. This can be done by (relatively) inexpensive tuning of existing hardware and by adding to the accelerating sections. Getting energy beyond about 10 GeV would involve redoing the bending arcs and would not be cheap.

The first step in the upgrade takes advantage of the fact that on the average, the accelerating cavities have an accelerating gradient well above specification. Further, there is a factor of about 2 spread in the accelerating gradients, and the reasons for this spread are becoming better understood. Thus there is the possibility and the plan that, using the existing maintenance budget, the low gradient cavities can be removed, refurbished, and then reinstalled as high accelerating gradient cavities.

The tentative time frame is to have 6 GeV in 1997 and “7+” GeV in 1999. (By the way, as of the time of this talk, TJNAF has already run at 1 GeV/pass for one pass (the machine usually uses 5 passes or 5 circulations).) If we talk of extra cost rather than absolute cost, the extra cost of step one is zero, since the money is already in the maintenance budget. The likelihood of step one is quoted as at the “90% confidence level.”

Step two involves increasing the number of accelerating cavities by 25%, and put them in existing empty spaces in the straight section. This, incidentally, is possible because of a 1987 decision to have 5 passes instead of 4, reducing the number of accelerating cavities needed. But the concrete had already been poured, so that these empty spaces exist.

The time frame for this step is to submit an accelerator upgrade proposal in 1999, and then maybe in 2001 to have an energy of $9 \pm 1$ GeV. The ballpark cost of this upgrade is $20$ million, and the likelihood can only be guessed.

3 Physics

A useful, albeit two years old, source of information about experiments at a higher energy CEBAF is the proceedings of the “Workshop on CEBAF at Higher Energies” that was held in April, 1994 [1]. The purpose of the workshop was to assess what could be done at CEBAF with an 8 or 10 GeV electron beam.

The proceedings is organized into four headings, which I will also use as my next four headings. I will give some idea of the topics under each heading, and
study (from a 1996 perspective when updating is relevant) in more detail a few examples of potential experiments. I will also add one heading on a possible exotic use of TJNAF.

3.1 Hadron spectroscopy and production

There are a number of things to do with higher energy; some are “more of the same” but better and others are new initiatives not possible at lower energy. Let us start with some numbers to illustrate with gains follows from an energy upgrade. We can work out that a 4 GeV electron beam allows producing

- baryons up to 2.9 GeV mass,
- mesons up to 2.0 GeV mass,
- strange mesons up to 1.8 GeV mass.

This seems fine for baryon spectroscopy studies, but a number of interesting strange quark $s\bar{s}$ mesons states are predicted around 2 GeV, and these cannot be reached without more initial energy. For producing mesons $M$ of mass $\mu$ in $\gamma^* + p \rightarrow M + B$, we get a limit

$$\mu \leq \sqrt{m_N (m_N + 2E_\gamma) - Q^2 - m_B}$$  \hspace{1cm} (1)

(with $Q^2$ positive for spacelike photons). Maximizing $E_\gamma$ and minimizing $Q^2$, we with 8 (or 10) GeV incoming electrons can produce

- baryons up to 4.0 (4.4) GeV mass,
- mesons up to 3.0 (3.5) GeV mass,
- strange mesons up to 2.9 (3.3) GeV mass,

enough to produce the $s\bar{s}$ we mentioned.

So it seems that even 8 GeV is enough to do the hidden-strange meson spectroscopy we want to do. In addition, one will want to undertake hunts for glueballs ($gg$ or $ggg$ states), hybrids ($q\bar{q}g$, in the meson version), oddballs ($J^{PC} = 1^{++}$ states, which are guaranteed not $q\bar{q}$), study possibilities for a $\phi$ factory for $CP$ violation and rare $\phi$ decay studies [2], and glueballinos.

The last are bound states of gluons and gluinos, with the latter being the supersymmetric partner of the gluon and is clearly an interesting particle to find. The usual reason given for not having found the gluino is that it is very heavy,
but in fact there is a window open for the possibility that the gluino is light, under 2 GeV, if it is long lived, with a mean life of over 100 picoseconds [3]. TJ-NAF has a good energy for producing light gluinos—they will not be moving too fast in the final state—and a good intensity. Calculations of gluino production are relatively easy since the vertices are just supersymmetric partner of well known vertices, and the Feynman diagrams involve only propagators of discovered (i.e., known quarks and gluons) particles. Fig. 1 shows a plot of cross section vs. incoming photon energy for gluino photoproduction [4], for different guesses for the glueballino mass, and showing not much sensitivity to what one puts in for the up or down quark mass.

Searching for glueballinos requires observing multiparticle final states, hence is a Hall B experiment. The luminosity in Hall B is anticipated as $10 \text{ nb}^{-1} \text{sec}^{-1}$, so that there will be quite a bit of glueballino production if the mass is 1 GeV. The value of extra energy is, however, clear. The signatures for glueballinos is like that for a weakly decaying meson: copious production, slow decay (a significant gap between decay and production point), and two much mass to be confused with a kaon. One possibility is to find $\pi^+\pi^-$ pairs with a mass above the kaons, corresponding to the decay glueballino into $\pi^+\pi^-\tilde{\gamma}$ with $\tilde{\gamma}$ representing the unobserved photino. Finding the gluino is not necessarily to be expected, but is not impossible, and would be a great confirmation of an important hypothesis in particle physics and a great coup for the machine that finds it.
3.2 Exclusive reactions at high $Q^2$

Possibilities under this heading begin with extensions of things that have been begun at lower energies, particularly including measurements of form factors of various hadronic systems. Meson form factors could be measured to $Q^2$ of $\text{GeV}^2$ if the beam is 8–10 GeV incoming electron energy. Separated measurements of baryon form factors, both elastic and transition, could be done for $Q^2$ up to 10 $\text{GeV}^2$ if the beam is 8 GeV. (Incidentally, they can be done up to 7 $\text{GeV}^2$ even with a 4 GeV beam, according to the Proceedings of the Higher Energy workshop.) Few nucleon systems could also be studied. The $A$ and $B$ form factors of the deuteron could be measured to $Q^2$ of 9 $\text{GeV}^2$ if the beam energy is 8 GeV, compared to 6 $\text{GeV}^2$ for a beam energy of 4 GeV. And the deuteron photodisintegration reaction, $\gamma + d \rightarrow p + n$, could be measured to whatever energy what available. Remarkable measurements have already been made up to $E_\gamma = 4$ GeV.

Further exclusive and semi-exclusive reactions can also be studied. The goal always is to learn something about the structure of hadrons. Take as an example the photoproduction of high transverse momentum pions, both from the viewpoint of learning something about the pions and something about the targets they are produced off.

Taking here the question of what we can learn about pions, recall that exclusive reactions at sufficiently high momentum transfers generally depend upon the distribution amplitude $\phi$ of the particles involved, which in turn is the valence quark wave function $\psi$ integrated over the momenta transverse to the direction of the parent hadron. For a pion,

$$\phi_{\pi}(x) = \int d^2k_T \psi_{\pi}(x, k_T).$$

(2)

A logarithmic scale dependence is tacit, and some factors of 2 and $\pi$ have been ignored; $x$ is the (light-front) momentum fraction carried by one of the quarks. It happens that both the pion electromagnetic form factor and the $\pi^0 \gamma \gamma$ form factor depend on the same integral,

$$I_\pi = \int dx \frac{\phi_{\pi}(x)}{x}.$$  

(3)

One would like another way to measure this integral, and a way may be provided by pion photoproduction. The direct process, Fig. 2 left, has the pion produced in a short range process before the relevant particles leave the immediate reaction region. It is interesting here because the amplitude is proportional to precisely the same integral, $I_\pi$. 

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Fig. 2. Two ways to photoproduce pions. The direct process on the left dominates the fragmentation process at high transverse momentum, if the overall energy is not too large.

Fig. 3. Cross section for $\gamma + p \rightarrow \pi^+ + X$, integrated over longitudinal momentum. (The calculation for the direct process used the asymptotic pion distribution amplitude.)

There is however a serious theoretical background, which is production of high transverse momentum pions by producing quarks or gluons moving fast in a particular direction, and having those partons fragment into hadrons, one of which becomes the observed pion, as in Fig. 2 right. At low transverse momentum, fragmentation is indeed the dominant process. However, as the momentum gets higher, the likelihood that a single pion can carry a large fraction of the partons momentum decreases sufficiently that the direct process can be seen. A typical plot is shown in Fig. 3, for $\pi^+$ production with $E_\gamma = 20$ GeV and integrated over longitudinal momentum [5].

If data can be gotten at the higher transverse momenta, it will be a direct measure of $I_\pi$ (modulo higher twist corrections). The calculations that went into Fig. 3 did assume that we knew the proton quark distributions, but these we think are in fact decently well known now. On the other hand, observations of how the pion production rate depends upon polarization of the beam and target depends on polarized quark distributions, which are not well determined. Such observations may well be a flavor sensitive way to learn something about the target’s polarized quark distributions.
3.3 Inclusive and semi-exclusive scattering

This section will be brief. The proceedings of the Higher Energy Workshop reports several good talks and interesting experiments. An example is the measurement of the spin dependent structure function $g_1$ at higher $x$. However, one particular general problem for semi-exclusive processes was that at the energies under discussion, it would be hard to make a clear distinction between the target and current fragmentation regions. The summarizers of this topic reached the overall conclusion that 8–10 GeV was too little energy [7].

3.4 Hadrons in the nuclear medium

Good experiments to learn things from the behavior of hadrons in the nuclear medium include color transparency, vector meson electroproduction off nuclei, and virtual Compton scattering off nuclei. One of the serious questions about the nucleus is what are the right degrees of freedom to describe baryonic matter when the baryons get very close together. It may be that nuclei can always be described as a collection of neutrons and protons, and that repulsions in the nuclear force keep the nucleons far enough apart so that the nucleons themselves keep more or less the same character that they have in isolation. On the other hand, there may be changes in the matter, and one possibility is that quarks in groups of six, in the simplest cluster, reorganize into a new state. If each quark is in the lowest spatial state, the color-spin-flavor part of the wave function is fixed by antisymmetry and the overall spin-isospin quantum numbers. We shall refer to this as the 6q model, and one problem is how to tell 2N and 6q nuclear configurations apart experimentally. For many experiments, things like the wave functions in the 2N model may be adjusted to give the same results as one would expect from the 6q model. For example, Hanlon, Lassila, and I [8] looked at the spectrum of backward moving protons, $p_B$, in $\ell + d \rightarrow \ell' + p_B + X$, where $\ell$ and $\ell'$ are leptons, and found that pure 2N with any of a collection of standard wave functions gave calculated results that were below the data above 400 MeV backward hemisphere momentum. Adding one or a few percent, by normalization, 6q state allowed matching the data well. However, this is not a proof that the 6q state must be present because it is easy to see how a modest (by the standards of the trade) increase in the tail of the wave function in the 2N calculation would allow a fit to the data.

We need a different type of suggestion to differentiate 2N and 6q contributions to the cross sections, for example, one that takes advantage of how the cross section factorizes differently in the two calculations. For backward proton production in a 2N calculation, the process proceeds with the neutron being
struck, with its pieces going forward, and the proton emerging with whatever fermi momentum it had when the neutron was struck—backward in the cases of interest. The cross section is

$$\frac{d\sigma_{2N}}{dx \, dy \, d\alpha \, dp_T} \equiv \sigma_{2N} = K F_{2n}(\xi)(2 - \alpha)|\psi(\alpha, p_T)|^2. \quad (4)$$

Here, $x$ and $y$ are lepton variables, $Q^2/2m_N\nu$ and dimensionless lepton energy loss (in the lab, lepton energy loss divided by incoming lepton energy), respectively. Variables $\alpha$ and $p_T$ give the momentum of the backward proton, with $p_T$ being the momentum transverse to the incoming lepton momentum and

$$\alpha \equiv \frac{E_p + p^z}{m_N}. \quad (5)$$

$K$ is a known kinematic factor, $\psi$ is the 2N wave function of the deuteron, and the argument of the neutron structure function $F_{2n}$ is the momentum fraction of the struck quark relative to the momentum of the neutron. If the neutron were stationary, it would precisely $x$, but since the neutron is moving,

$$\xi = \frac{x}{2 - \alpha}. \quad (6)$$

Now we can make a suggestion to distinguish the 2N and 6q predictions by studying the two-nucleon test ratio [9],

$$R \equiv \frac{\sigma_{meas}}{KF_{2n}}. \quad (7)$$

If the measured cross section is due to a 2N configuration, $\sigma_{meas} = \sigma_{2N}$, then the ratio $R$ is independent of the lepton variables $x$ and $y$. One could, for fixed $p_T$ and $\alpha$ and integrating over $y$ (both numerator and denominator, before taking the ratio), simply plot $R$ versus $x$. The result should be a flat line, as illustrated by the dashed line in Fig. 4.

In advance of enough data to make such a plot the question for a theorist is, how different is the 6q prediction? The answer, based on some reasonable modeling for the quark distributions in the 6q cluster and some use of counting rules to get the backward proton spectrum, is also shown in Fig. 4. Of course, the deuteron is not 100% 6q cluster, but if we look only at high backward momentum protons, we enhance the fraction of events that come from when the nuclear matter is all close together at the outset, and hence could expect a large fraction of the observed protons to come from a 6q cluster. Hence, if a 6q cluster is present even with small overall normalization, many of the fast
Fig. 4. The two nucleon test ratio $R$ for $p_T = 0$ and $\alpha = 1.4$, or 322 MeV backward protons. The flat dashed line is for 2N, the curves are for three related implementations of a 6q cluster model.

backward protons could come from it, leading to a result close to the curves in the Figure.

How does energy help? Our analysis has used scaling for the neutron structure function. This requires that, at least, $Q^2 > 1 \text{ GeV}^2$ and $W$ (the total hadronic mass of the material coming from the stuck neutron) $> 2 \text{ GeV}$. One of these requirements sets a lower limit on $x$, the other sets an upper limit. The allowed values of $x$ are between the two curves in Fig 5 [9]. For incoming electron energy 4 GeV, the allowed range of $x$ is tiny, but for 8 or 10 GeV the range of $x$ is quite enough to see a distinction between the curves and the flat line in the previous Figure.
A difficult to observe but interesting CP violating decay is

\[ K_L \rightarrow \pi^0 \nu \bar{\nu}. \]  

(8)

The final state is all neutral and two of the particles are essentially impossible to see, but the motivation of testing extensions of the standard model and of finding direct CP violation is strong.

By way of reminder, the long lived neutral kaon is

\[ K_L = K_2 + \varepsilon K_1 \]  

(9)

where \( K_2 \) is the CP odd combination of \( K^0 \) and \( \bar{K}^0 \)—which cannot decay into two pions by a CP conserving force—and \( K_1 \) is CP even. CP violation has been seen only in the two pion and semileptonic decays of the \( K_L \) (i.e., the \( \pi^0 \pi^0, \pi^+ \pi^−, \) and \( \pi^± e^± \nu \) modes) and what is seen is compatible with indirect CP violation, meaning that the CP violation occurs only through the \( K_1 \) admixture, follow by a normal CP conserving decay.

The decay \( K_L \rightarrow \pi^0 \nu \bar{\nu} \) is 100\% CP violating, and is rare [10]. The decay requires flavor changing neutral currents, and it can occur in the standard model only by second order weak interactions such as illustrated in Fig. 6. The calculated branching ratio in the standard model is a few times \( 10^{-11} \) [11].

Different extensions of the standard model give different results for the \( K_L \rightarrow \pi^0 \nu \bar{\nu} \), and the calculated results known to me are summarized in Fig. 7 [12]. All are below the present experimental limit. One, which involves supersymmetry with R-parity violation [13], may be reachable under the design goals of presently running experiments.

Could Jefferson Lab actually measure the decay at the level predicted by the standard model? The question is under discussion [14]. (It is also under discussion at Brookhaven National Lab.) The signal that will be seen is just two photons, from the decay of the \( \pi^0 \) and which together have the mass of the \( \pi^0 \), with the neutrinos unseen. The dineutrino mass, if it can be inferred,
Fig. 7. Various calculated results for branching ratios of $K_L \rightarrow \pi^0 \nu \bar{\nu}$; (a) standard model, (b) supersymmetry with R-parity conserved, (c) extra Higgs doublets with CP violation still in the CKM matrix, (d) extra Higgs doublets with CP violation only spontaneous, (e) Weinberg model, and (f) supersymmetry with R-parity violation.

will sometimes also have the mass of a $\pi^0$, but generally not. High efficiency detectors are clearly needed, so that things are not unseen merely because of falling through cracks in the detector. Dangerous backgrounds come from the decays $K_L \rightarrow \pi^0 \gamma \gamma$ (which occurs at a part in $10^6$) and $K_L \rightarrow \pi^0 \pi^0$ (one in $10^3$ decays), with the detectors only picking up two of the four possible photons.

The time structure of the CEBAF beam may help. The first word of the lab's old name is not correct if one can examine the beam with sufficient time resolution. There are sharp pulses every 2/3 nanosecond, and there is good control over the pulses, so that it is possible to leave spaces empty and deliver a sharp pulse once every (say) 20 ns. Then we know when the $K_L$ was formed, and since it has roughly 50 ns lifetime, one can measure its time of flight and hence its velocity and momentum, allowing the missing mass to be determined. If the missing mass is the mass of a $\pi^0$, cast the event aside. What remains will be (one may hope) mainly $\pi^0 \nu \bar{\nu}$.

This is not an easy experiment, but it interesting just to think that it may be possible.

4 The End

A $9 \pm 1$ GeV electron beam allows some exciting results to be obtained, and may happen at the Jefferson Laboratory. One category of experiments is of the “more of the same” variety, but the extra reach in, for example, $Q^2$ makes them greatly more interesting. In addition a number of new initiatives become
possible.

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