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FUTURE SCIENTIFIC OPPORTUNITIES AT JEFFERSON LAB

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Abstract

Nuclear physics requires at least one major facility world-wide which is capable of fully exploiting the properties of the electro-weak force to investigate precisely the structure of strongly interacting systems. At its current maximum energy of 6 GeV Jefferson Lab has provided a wealth of important information on the structure of nucleons and nuclei. However, the plans to double the energy over the next seven years promise to open new frontiers in nuclear and particle physics. We briefly describe the plans for the 12 GeV Upgrade and the associated physics opportunities.

1 Introduction

The first 10 years of operation of the Continuous Electron Beam Accelerator Facility (CEBAF) at JLab have seen a number of important new results, which have advanced our knowledge of nucleon and nuclear structure as well as our understanding of non-perturbative QCD and the limits on possible physics beyond the Standard Model. The exploitation of parity violating electron scattering has given new meaning to the term precision electroweak measurements. In terms of that precision and its kinematic reach CEBAF is a truly world leading facility. However, the nuclear science community in the United States has realized that by doubling its energy at a relatively modest cost, one can open new frontiers of investigation, from the existence and properties of so-called exotic mesons to three-dimensional imaging of the nucleon to new searches for physics beyond the Standard Model which rival the precision achieved at LEP. Indeed, this 12 GeV Upgrade project has been recognized in the new Long Range Plan as the highest priority for nuclear science in the United States. In what follows we briefly outline what will be done as part of this project as well as the science which it is expected to enable.

2 The 12 GeV Upgrade at Jefferson Lab

CEBAF was designed to permit exploration of the detailed structure of nucleons and nuclei using continuous beams of 4 GeV electrons and nuclear physics research began there in 1995. The accelerator represents the world's first successful large-scale utilization of superconducting radio-frequency (SRF) accelerating structures. Advances in SRF technology have made it possible to increase the beam energy to 6 GeV without installing new equipment. Further developments have led to performance that will permit us to increase the energy to 12 GeV (double the present energy and triple the original) by installing a small number of new accelerating structures but without changing the basic configuration of the facility. Research at 12 GeV is to begin around 2014. We begin by describing the accelerator upgrade plans as well as the experimental equipment planned to exploit the new research opportunities.

2.1 Accelerator upgrade

A new 12 GeV beam to Hall D and beams of up to 11 GeV for Halls A, B, and C are needed for the desired research program. To provide them, the accelerator must be upgraded to 2.2 GeV/pass (1.1 GV/linac) and the beam transport system upgraded and expanded. The following summarizes the planned work:

- 1.1 GV/linac: Increase each linac's voltage by 0.5 GV by adding 5 new high-performance superconducting radio-frequency (SRF) accelerating systems and new RF system for each; the present 5kW@2K cryogenics plant will be roughly doubled to support the increased load;
- Add a tenth recirculation arc, thereby permitting a sixth pass of acceleration through the North Linac and direction of beam toward Hall D;
- Upgrade the capabilities of the present beam transport system to handle the increased beam energies; there will be extensive re-use of existing hardware;
- Add beam transport to Hall D.

2.2 Gluex Experiment in Hall D

Hall D will initially house the equipment for the GlueX experiment and will be situated at the northeast corner of the CEBAF accelerator. The

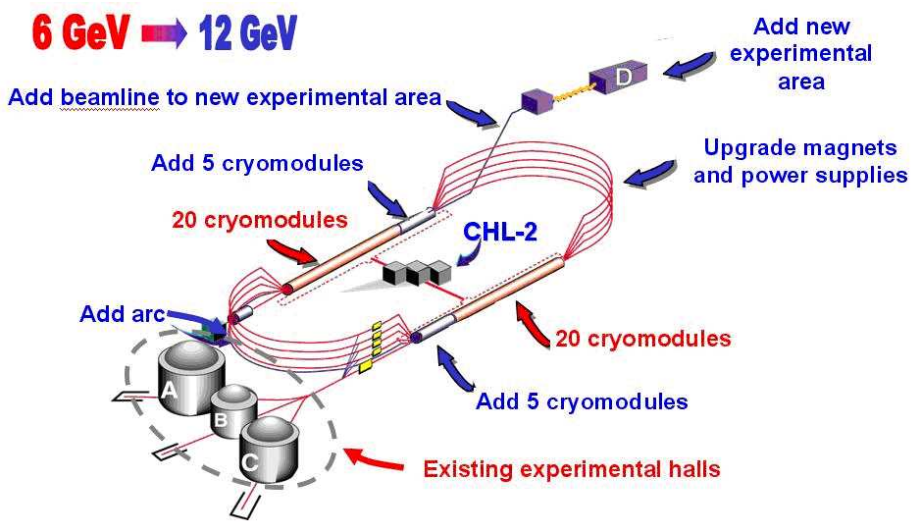

Figure 1: Illustration of the changes to the accelerator facility associated with the Upgrade of CEBAF from 6 to 12 GeV.

design, fabrication and installation of detector components will be performed. System integration and checkout will be performed, including interfacing of detector systems to trigger, data acquisition, slow controls, and monitoring systems. Features of this nearly-hermetic spectrometer include:

- A large solenoid magnet, which in concert with large-area drift chambers provides momentum and vertex measurements for multiple charged particles;
- Reconstruction capability for energy and direction of multiple photons using large-area calorimetry;
- Particle identification for charged particles via time-of-flight, electromagnetic shower calorimeters, Cerenkov detectors, and energy loss;
- A facility for producing a beam of polarized photons of known energies;
- A data acquisition system capable of handling data from a flux of 10^7 photons per second on a hydrogen target, with an architecture which is capable of being upgraded to ten times higher capacity.

2.3 Hall A, B and C Equipment

- In Hall A the beamline will be upgraded to achieve the capability of delivering the maximum energy 5-pass beam to the existing spectrom-

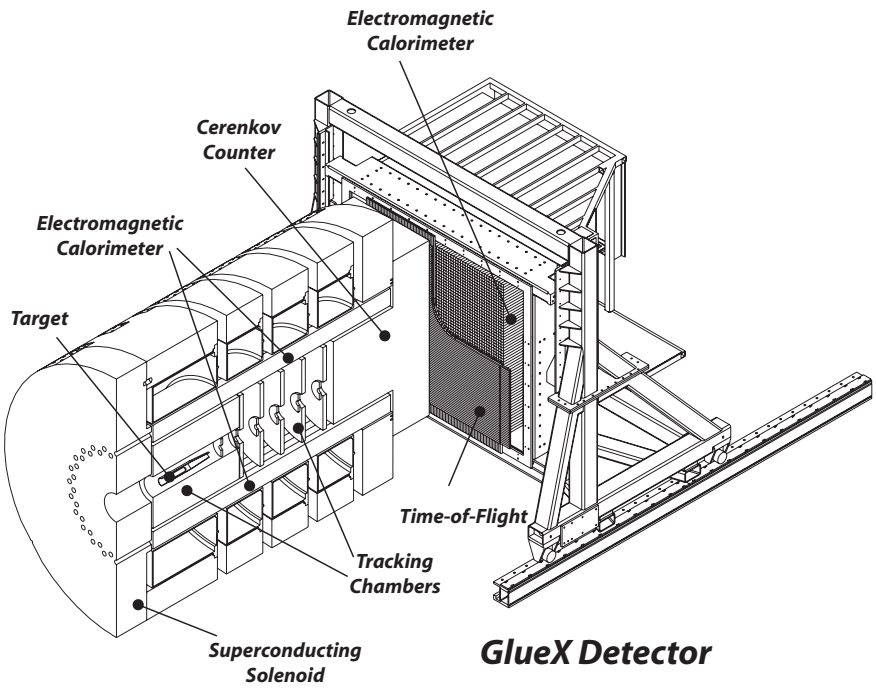

Figure 2: The Gluex detector, specifically optimized to permit reliable partial wave analysis for multi-meson final states, to be installed in Hall D.

eters. Some electronics will also be upgraded to improve data-taking at higher data acquisition rates.

- In Hall B CLAS, the existing large acceptance detector in Hall B will be extensively upgraded with new magnets and detectors to capture the more forward-focused reaction products at the increased luminosity. Features of this upgraded spectrometer include:
  - Toroidal magnetic field, which in concert with large-area drift chambers and silicon vertex detectors provides momentum and vertex measurements for multiple charged particles;
  - Reconstruction of energy and direction of multiple photons in the forward direction using large-area calorimetry;
  - Identification of charged particles via time-of-flight, electromagnetic shower calorimeters, and Cerenkov detectors;
  - Flexibility to accommodate a variety of target types; and
  - Magnetic shielding of Moller electrons adequate to permit measurements with a luminosity of 10^{35} cm^{-2}s^{-1}, and

  - A data acquisition system capable of absorbing the resulting data.

- In Hall C we will install a new focusing spectrometer system, called the Super High Momentum Spectrometer (SHMS) with central momentum up to 11 GeV/c will enable measurements of particles scattered at up to full beam momentum. It will be used together with the existing High Momentum Spectrometer (HMS). Features of the SHMS include:

  - High precision and reproducibility due to a rigid attachment to a central pivot and a robust support and transport structure;
  - Ability to analyze charged particles up to the full 5-pass beam energy;
  - Excellent momentum resolution for charged particles;
  - Particle identification for charged particles via time-of-flight, electromagnetic shower calorimeters, and Cerenkov detectors;
  - Flexibility to accommodate a variety of target types; and
  - Capability to use luminosities of 10^{38} cm^{-2}s^{-1}.

3 Outline of the science to be explored at 12 GeV

In the process of reaching CD-1, we have defined a clear set of physics priorities for the first 5 years of operation after the completion of construction [1,2]. These priorities were judged to be outstanding, with significant discovery potential, by the independent DOE review [3] (in April 2005). This judgement was re-affirmed by the nuclear science community in the United States as part of the Long Range Planning exercise in early 2007. It will, of course, continue to be subject to peer review and re-evaluation. However, there is no known or planned facility which can address those scientific challenges and it is difficult to imagine their importance diminishing in the intervening period.

The major physics aims of the first 5 years of operation are:

- Revolutionize our knowledge of spin and flavor dependence of valence PDFs

- Revolutionize our knowledge of the distribution of charge and current within the nucleon

- Provide a totally new view of hadron (and nuclear) structure through the Generalized Parton Distributions (GPDs).
- Explore QCD in the nonperturbative regime. In particular, establish the existence and properties of exotic mesons and hence explore the mechanism of quark confinement.
- Establish a new paradigm for nuclear physics through the quest to understand nuclear structure in terms of QCD. In particular, the unique features of this new facility will enable us to explore the spin and flavor dependence of the famous EMC effect. We will also be able to study the propagation of quarks through nuclear matter.
- Make precision tests of the Standard Model.

We now briefly outline the main themes associated with each of these topics.

3.1 Exotic mesons and the origin of confinement

Unlike any area of physics hitherto explored, QCD has the property that the force carriers themselves, the gluons, can by themselves form new structures. In combination with quark-anti-quark pairs, gluons can also give rise to new particles whose quantum numbers cannot be made from a quark-anti-quark pair alone. The former are known as glueballs and the challenge to find them has been the lack of any distict quantum numbers, at least in the low mass regime, and the fact that they almost certainly mix strongly with normal mesons. Exotic mesons, on the other hand, are expected to occur at low mass and, precisely because of the signature of their quantum numbers, be readily identifiable. Indeed, the best available theory suggests as many as three nonets of these "exotic mesons" in the mass range 1.5 to 2.5 GeV. The choice of 12 GeV was precisely in order to make this mass region accessible with a proton target. The GlueX detector was specifically designed to have extremely high efficiency for detecting the multi-meson final states resulting from the decay of these exotic mesons. Sophisticated techniques for making the partial wave analysis (PWA) needed to recognize an exotic meson signal have been underway at Indiana University for some years, with recent support at Jefferson Lab.

The physics interest in these states arises because the unique quantum numbers have their origin in excitations of the flux tube or string joining the quark-anti-quark pair. This flux tube is intimately connected with the nature of the QCD vacuum and the origin of confinement itself. Establishing the

existence and properties of these exotics is a crucial step to understanding whether QCD really is the full theory of the strong interaction.

3.2 Spin and flavor dependence of PDFs

It is an astonishing fact that more than 30 years after the discovery of scaling we still do not know the distribution of the momentum of the proton on valence down quarks [4, 5]. For Bjorken x beyond 0.6, the uncertainty in $d(x)$ rapidly grows to 100%. It is crucial to measure the large x behavior of $d(x)$ in order to understand the relative importance of short and long distance di-quark correlations in the valence structure of the proton. It is at least equally important to understand how the spin of the proton is carried by its constituents [6]. With the 12 GeV Upgrade Jefferson Lab will be able to unambiguously map out the distribution of momentum and spin on the valence u and d quarks in the proton. It will also be possible to explore the sea down to Bjorken x of order 0.1.

3.3 Distribution of charge and current in the nucleon

Over the past 8 years, Jefferson Lab has mapped the electromagnetic form factors of the proton and neutron with great precision, out to a momentum transfer of order 4 GeV^2 [6]. The 12 GeV Upgrade will permit the exploration to momentum transfers of order 14 GeV^2, an increase in spatial resolution by a factor of two.

3.4 Generalized parton distributions

The GPDs will yield unique, tomographic information on the three-dimensional structure of nucleons and nuclei [8,9] with particular sensitivity to the orbital angular momentum carried by specific quark flavors [10]. The latter feature is of particular importance in the light of advances made towards resolving the famous proton spin crisis over the past twenty years. We now know that the quarks carry roughly one third of the spin of the proton (rather than the value near zero originally suggested). In addition, it seems likely that the spin carried by polarized gluons in the proton is far too small to play a major role in resolving the discrepancy between modern data and theoretical expectations. Rather, important aspects of the non-perturbative structure of the nucleon, such as the pion cloud and the one-gluon-exchange hyperfine interaction, are sufficient to resolve the remaining problem – see Ref. [11] for a summary. These new mechanisms imply that much of the spin of the proton is actually carried by quarks and anti-quarks in the proton as orbital

angular momentum – most likely in the range of Bjorken-x covered by the 12 GeV Upgrade. This clearly makes the GPD program even more relevant and important.

3.5 The QCD basis of nuclear structure

In more than 20 years since the discovery of the EMC effect (European Muon Collaboration) [12], which showed a dramatic change of the parton distribution functions of nuclei compared with free nucleons, no consensus has been reached as to the underlying physical origin of the effect [13]. It seems clear, however, that standard nuclear binding and kinematic corrections cannot explain the data and one is actually exploring the change in structure of the nucleon-like clusters when imbedded in the nuclear medium [14–16]. These are extremely important questions, going to the heart of how QCD itself yields nuclear matter [17, 18]. It is quite clear that precise data exploring the flavor and spin dependence of this effect [14, 15] will be crucial in choosing amongst the various theoretical models so far proposed to explain it.

There will also be a possibility to explore the interaction of fast quarks with nuclear matter, yielding new insights into the process of hadronization, the nature of confinement and the change of the structure of the QCD vacuum in-medium.

3.6 Beyond the Standard Model

The precise studies of parity violating electron scattering at JLab (as well as Mainz and Bates) have already led to a remarkable increase in the lower bound on the mass scale associated with possible new physics beyond the Standard Model – from roughly 0.4 to 0.9 TeV [19]. This success has also served to emphasize the discovery potential of the Qweak experiment, which will run just before the shutdown, to build the 12 GeV Upgrade [20]. This important experience at the high precision frontier means that the community is ideally placed to exploit the new possibilities opened by the Upgrade. For example, precise measurements of parity violation, in Moller scattering and in hadronic deep inelastic scattering have complementary sensitivities. One can in fact probe new physics, such as supersymmetry, additional gauge bosons and so on, at energy scales far beyond what can be explored directly at high energy facilities. A number of experiments are under consideration and the choice will be made on the highest impact possible with the beam characteristics provided through the Upgrade.

4 Concluding Remarks

At present the project has undergone the reviews necessary to obtain CD-2 before the end of 2007 and we anticipate the award of CD-3, which signals the start of construction, late in 2008.

The science which has already been identified as part of the 12 GeV Upgrade represents a rich program of great breadth and importance for our field. Much of what has been outlined here will be achieved within the first 5 years of operation. We remain completely open to new ideas from anyone, with access to the facility determined by an independent Program Advisory Committee on the basis of scientific feasibility and impact. With an active and growing user base of more than 1,200 scientists we can be certain that many of the best ideas are yet to come!

Acknowledgments

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References

[1] http://www.jlab.org/div_dept/physics_division/GeV/doe_review/

[2] http://www.jlab.org/div_dept/physics_division/GeV/doe_review/CDR_for_Science_Review.pdf

[3] http://www.jlab.org/div_dept/physics_division/GeV/doe_review/science_review.pdf

[4] W. Melnitchouk and A. W. Thomas, Phys. Lett. B **377**, 11 (1996) [arXiv:nucl-th/9602038].

[5] M. Botje, Eur. Phys. J. **C14**, 285 (2000)

[6] X. Zheng *et al.* [Jefferson Lab Hall A Collaboration], Phys. Rev. C **70**, 065207 (2004) [arXiv:nucl-ex/0405006].

[7] C. E. Hyde-Wright and K. de Jager, Ann. Rev. Nucl. Part. Sci. **54**, 217 (2004) [arXiv:nucl-ex/0507001].

[8] X. Ji, Ann. Rev. Nucl. Part. Sci. **54**, 413 (2004).

[9] A. V. Belitsky and A. V. Radyushkin, Phys. Rept. **418**, 1 (2005) [arXiv:hep-ph/0504030].

[10] P. Hoodbhoy, X. D. Ji and W. Lu, Phys. Rev. D **59**, 014013 (1999) [arXiv:hep-ph/9804337].

[11] F. Myhrer and A. W. Thomas, "Resolution of the Proton Spin Problem," arXiv:0709.4067 [hep-ph].

[12] J. J. Aubert *et al.* [European Muon Collaboration], Phys. Lett. B **123**, 275 (1983).

[13] D. F. Geesaman, K. Saito and A. W. Thomas, Ann. Rev. Nucl. Part. Sci. **45**, 337 (1995).

[14] I. C. Cloët, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **95**, 052302 (2005) [arXiv:nucl-th/0504019].

[15] I. C. Cloet, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006) [arXiv:nucl-th/0605061].

[16] J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203 (2005) [arXiv:nucl-th/0505048].

[17] W. Bentz and A. W. Thomas, Nucl. Phys. A **696**, 138 (2001) [arXiv:nucl-th/0105022].

[18] P. A. M. Guichon and A. W. Thomas, Phys. Rev. Lett. **93**, 132502 (2004) [arXiv:nucl-th/0402064].

[19] R. D. Young, R. D. Carlini, A. W. Thomas and J. Roche, Phys. Rev. Lett. **99**, 122003 (2007) [arXiv:0704.2618 [hep-ph]].

[20] W. T. H. van Oers [Qweak Collaboration], "The Qweak Experiment – A search for new physics at the TeV Scale," arXiv:0708.1972 [nucl-ex].

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