CEBAF AT JEFFERSON LAB, AN OVERVIEW

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The Continuous Electron Accelerator Facility, CEBAF, is devoted to the investigation of the electromagnetic structure of mesons, nucleons, and nuclei using high energy and high duty-cycle electron and photon beams. The physics program and the experimental equipment at CEBAF will be described. Selected examples for the results obtained will be given. The motivation for upgrading the accelerator to higher energy and the corresponding experimental equipment will be discussed.

1 Introduction

The Southeastern University Research Association, SURA, operates the Thomas Jefferson National Accelerator Facility, also called Jefferson Lab (or JLab), for the U.S. Department of Energy. JLab's main instrument is the Continuous Electron Beam Accelerator Facility, CEBAF, a continuous-wave electron accelerator capable of delivering precise electron beams for experiments in three experimental areas. CEBAF's user community consists of about 1,500 physicists, roughly 800 of them are actively involved in the experimental program. In addition to its main mission, JLab makes contributions to the development of Free Electron Lasers, to medical imaging, and to community outreach programs.

2 The CEBAF Accelerator

CEBAF's central instrument is a superconducting electron accelerator with a maximum design energy of 4 GeV and 100 % duty-cycle. Three electron beams with a maximum total current of 200 μA can be used for simultaneous electron scattering experiments in the three experimental areas, Halls A, B, and C.

The accelerator design is based on two parallel superconducting continuous-wave linear accelerators joined by magnetic recirculation arcs. The accelerating structures are 338 five-cell superconducting niobium cavities operating at a temperature of 2K with an average design energy gain of 5 MeV/m.

The isochronous magnetic arcs allow the electron beam to be recirculated up to five times. After each of the first four passes, a transverse radio frequency

separator can be activated to extract every third bunch, and to deliver an electron beam with an energy of $1/5$, $2/5$, $3/5$, or $4/5$ of $E_{\max}$ to one of the three experimental areas. At the end of the fifth pass, a last separator can split the beam up to three ways; this allows the highest energy beam to be sent to all three halls. Typical beam parameters are $\delta E/E \leq 10^{-4}$ and a beam size of the order of a few hundred μm .

An important component of the accelerator is the polarized electron source. Using three independent pulsed lasers on a strained GaAs photocathode makes it possible to create up to three polarized electron beams that can be varied in intensity by varying the laser beam intensity. The spin precession in the accelerator and the beam lines can be compensated by a Wien filter to give the desired longitudinal polarization on target. All halls monitor the electron polarization with Møller polarimeters; in addition, Hall A uses a Compton backscattering polarimeter.

3 Experimental Halls

Three experimental halls are available for simultaneous experiments. Since the beam intensity can be varied over a large dynamic range, the only important restriction for multi-hall operation is that the beam energies have to be multiples of the single pass energy. The halls contain complementary equipment which covers a wide range of physics problems: Hall A has two high resolution magnetic spectrometers, Hall B houses a large acceptance spectrometer, and Hall C uses a combination of a high momentum and a short orbit spectrometer. The hall equipment will be discussed in detail in the following sections.

3.1 Hall A

The Hall A instrumentation is designed for experiments that require the precise measurement of the mass of the unobserved hadronic final state via missing-mass techniques; a typical example is the excitation energy of the unobserved nucleus A^* in the $A(e, e'p)A^*$ reaction. The instrumentation consists of two high resolution magnetic spectrometers (HRS) that can be rotated around a common pivot. Design requirements are 10^{-4} momentum resolution in a 10% momentum bite, and a solid angle of 7 msr. The spectrometers are based on a QDDQ design with superconducting magnetic elements. The tracking part of the detector systems is identical for both spectrometers; the particle identification part is specialized for electrons in one spectrometer, and for hadrons in the other. The hadron arm also contains a focal plane

polarimeter to measure the transverse polarization components of protons.

3.2 Hall B

Hall B is equipped with a large acceptance detector (CEBAF Large Acceptance Spectrometer, CLAS). Its main mission is to carry out experiments that require the detection of several, only loosely correlated particles in the hadronic final state, and measurements at limited luminosity (e.g. due to the use of a polarized target). For real photon experiments, a bremsstrahlung tagging spectrometer, located at the entrance of the hall, is used to determine photon energy and flux.

CLAS is a toroidal multi-gap spectrometer; its magnetic field is generated by six iron-free superconducting coils. The particle detection system consists of drift chambers to determine the trajectories of charged particles, Cerenkov counters for the identification of electrons, scintillation counters for the trigger and for time-of-flight measurements, and electromagnetic calorimeters to identify electrons and to detect photons and neutrons.

3.3 Hall C

The main instruments in Hall C are two focusing magnetic spectrometers: the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS). Typical values for the momentum resolution are 0.1%. The HMS is a QQQD spectrometer with iron-dominated quadrupoles and a homogeneous field dipole. All HMS magnets use superconducting coils to reach momenta up to 7 GeV/c. The SOS is a normal-conducting QDD spectrometer with a maximum central momentum of 1.5 GeV/c. Its short path length makes it ideal for the detection of decaying particles, such as pions and kaons.

4 Accelerator and Hall Status

Due to the excellent performance of the superconducting cavities, the accelerator has by far exceeded the 4 GeV design goal. Experiments have been conducted at 5.7 GeV, and 6 GeV has been reached in a short test run. Three-hall operation has become routine, with intensity ratios up to $10^5 : 1$ (note that Hall B is typically operating at a few nA , only).

The strained GaAs polarized source has reached a CW current of $140\mu A$ with good lifetime. Helicity correlated changes in beam parameters are small enough to make parity violation experiments routine.

Hall C was the first hall to become operational. Seventeen experiments

have been completed, including several that required specialized setups, e.g. deuteron polarimeter, polarized target, and hypernuclear spectroscopy.

The Hall A HRS spectrometers are fully operational since 1997. Nineteen experiments have been completed. Special efforts were required to measure small asymmetries caused by parity violation effects, and to carry out experiments using a polarized ^3He target.

In Hall B, CLAS has been in routine use since 1998. In electron scattering experiments the design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ has been reached; up to 3,000 events/s can be recorded and stored for later analysis. Special efforts were required to mount experiments with a dynamically polarized hydrogen/deuterium target.

5 Experimental Results (Examples)

Proposals submitted by CEBAF's user community are reviewed by the Program Advisory Committee (PAC) which meets twice a year. As of the summer of 2000, the PAC has recommended approval of a total of 121 experiments proposed by 869 authors from 156 institutions located in 24 countries. Thirty experiments have been completed, partial data has been taken for 47 additional experiments.

In the following sections, some representative examples for completed CEBAF experiments will be given. The experiments have been chosen not only for their physics interest, but also to highlight the capabilities of the accelerator and the halls.

5.1 Parity Violation in $e - p$ Elastic Scattering

The proton is a composite object containing constituent u and d quarks, and potentially a sea of $q\bar{q}$ -pairs. Little is known about the $q\bar{q}$ -contributions, especially the strange quark content of the nucleon. Combining the form factors of proton and neutron, and invoking isospin symmetry, allows the separation of the contributions of u and d quarks. The additional information required to determine the $s\bar{s}$ content can be obtained from measuring parity violation in the scattering of polarized electrons off unpolarized protons. The parity violating asymmetry arises from the interference between the dominant one-photon and the weak Z^0 exchange. The asymmetry in elastic $e - p$ scattering - in combination with the electromagnetic form factors of the proton and the neutron - makes it possible to separate the contributions of u , d , and s quarks.

Measuring parity violating effects is conceptually straightforward; all that is required is to flip the helicity of the incident electrons and look for a change

Figure 1. Parity Violating Asymmetry in Elastic e-p Scattering.

in the reaction cross section. However, due to the smallness of the parity violating effect (a few ppm or less), these experiments have been notoriously difficult in the past. The main reason is that beam parameters like intensity, energy, halo, etc. are not perfectly stable when the helicity is flipped. It had been hoped that these problems would be easier to handle with the new generation of high duty-cycle electron accelerators.

An experiment was carried out in Hall A¹ to measure parity violation in elastic $e-p$ scattering. A $100\mu A$ longitudinally polarized electron beam with an energy of 3.3 GeV hit a high-power liquid hydrogen target. The beam helicity was changed in a pseudo-random fashion with 30 Hz frequency. Both HRS spectrometers were set up at small angles ($\approx 12^\circ$), elastically scattered electrons were detected in lead-lucite sandwich counters. To handle the high counting rates, the electronic output signals of the counters were integrated over 30 Hz periods.

The performance of the accelerator during the experiment exceeded the high expectations: helicity correlated systematic changes in beam position were on the order of a few nm ; changes in the beam energy at the 10^{-8} level. Therefore, the corrections to the raw asymmetry for helicity correlated effects are negligible, a first for parity experiments.

The experimental parity violating asymmetry has been compared to what is expected on the basis of no strange quark contribution. The difference is plotted in Fig. 1 as a function of Q^2 . The measurement does not support a large contribution of strange quarks to the proton.

The Hall A spectrometers will continue to be used for parity experiments. In addition, a specialized toroidal spectrometer with eight gaps is being constructed for Hall C. This device will be able to cover both forward and backward electron scattering (in separate runs), and will allow separation of the strange electric and magnetic form factors.

5.2 Measurement of t_{20} in Elastic $e - d$ Scattering

The electromagnetic properties of the deuteron (a spin-1 nucleus) are described by three independent form factors, characterizing the spatial distribution of charge, magnetization, and quadrupole strength. The standard Rosenbluth technique (varying the electron scattering angle while keeping the momentum transfer constant) determines only two combinations of form factors. An additional polarization measurement is required to isolate all three form factors.

A custom setup² was used in Hall C to determine the tensor polarization, t_{20} , of the recoiling deuteron in elastic $e - d$ scattering. An electron beam with currents up to $120\mu A$ hit a high-power liquid deuterium target resulting in an average luminosity of $3 \cdot 10^{38} cm^{-2} s^{-1}$. Elastically scattered electrons were detected in the HMS. Deuterons were transported from the production target to a secondary scattering target in a specially constructed achromatic magnetic channel. The tensor polarization of the recoiling deuterons was determined from the angular distribution of the protons in the $p(\vec{d}, pp)n$ reaction. The analyzing power of the polarimeter had previously been determined at SATURNE using a deuteron beam of known polarization.

The experiment covered a range in momentum transfer $Q^2 \approx (0.65 - 1.7)(GeV/c)^2$. The results are displayed in Fig. 2. In this Q^2 range there are no indications yet for the onset of the scaling effects predicted by perturbative QCD. In fact, the results are well described by assuming that the deuteron is a conventional bound proton-neutron system (with appropriate corrections for meson-exchange currents and relativistic effects).

5.3 Measurement of the $N \rightarrow \Delta$ Transition

Exploring the electromagnetic structure of the excited states of the nucleon is one of the major experimental programs at CEBAF. These studies are of fundamental importance since they determine charge and current distribution

Figure 2. Tensor Analyzing Power t_{20} in Elastic $e-d$ Scattering.

as well as the transition currents. Measurements of these quantities may be used to test microscopic models, such as QCD based quark models, chiral bag models, and Skyrme models.

Electromagnetic excitation of the nucleon resonances on the free nucleon yields information on the γNN^* vertex. The broad width of the resonances makes it impossible to separate them in inclusive reactions. By determining in coincidence the angular distribution of the N^* decay products, such as πN , ηN , ρN , and $\pi \Delta$, it is possible to separate the contributions of the individual resonances.

There is a broad program in Hall B using the CLAS detector to determine these transition amplitudes from a measurement of differential cross sections and polarization asymmetries for meson photo- and electro-production. A prominent example is the quadrupole strength in the $N \rightarrow \Delta$ transition.

In SU(6) symmetric quark models, this transition is described by a simple quark spin-flip in the $L_{3Q} = 0$ ground state, corresponding to a magnetic dipole transition M_{1+} . The electric and scalar quadrupole transitions are predicted to be vanishing: $E_{1+} = S_{1+} = 0$. In more elaborate QCD based models which include color-magnetic interactions due to one-gluon exchange

at small distances, the $\Delta(1232)$ acquires an $L_{3Q} = 2$ component, leading to small electric and scalar contributions. A deformation of the Δ can also be created by a pion cloud surrounding the three-quark core.

Figure 3. Electric and Scalar Quadrupole Amplitudes for the $N \rightarrow \Delta(1232)$ Transition.

The values of the electric and scalar quadrupole amplitudes can be derived from an analysis of the angular distribution (in both polar and azimuthal angles) of the pion in the $p(e, e'p)\pi^0$ reaction. The CLAS detector in Hall B was used to cover a large range in Q^2 , mass of the hadronic final state, W , and pion angles simultaneously³. Figure 3 shows the electric $Re(E_{1+}M_{1+}^*)/M_{1+}^2$ and the scalar $Re(S_{1+}M_{1+}^*)/M_{1+}^2$ amplitudes at the position of the $\Delta(1232)$ as a function of Q^2 . The results demonstrate the importance of taking the coupling of the photon to the pion cloud explicitly into account.

6 The CEBAF Energy Upgrade

There is a broad class of important physics questions that can not be addressed at the present time due to the lack of an electron accelerator with the combination of high energy, high duty-cycle, and the high beam power required to study rare phenomena. Of particular importance are to study:

- the origin of quark confinement by searching for mesons with exotic quantum numbers. These objects can be formed by exciting the flux tube that binds $q\bar{q}$ -systems.
- the quark-gluon structure of the nucleon by mapping out the longitudinal quark momentum distributions in the valence quark region, and by studying quark-quark correlations via exclusive processes (by exploiting the newly discovered Generalized Parton Distributions).

In addition to these new programs, the present program can be extended to higher momentum transfers.

The optimization of the physics reach and practical considerations have led to the development of the present 12 GeV upgrade proposal⁴. Higher energy than 12 GeV would allow to get to higher momentum transfer, Q^2 , and thus make access to the deep-inelastic regime easier. However, with increasing energy the requirements on detector resolution and luminosity (to get sufficient count rate at the higher Q^2) will become increasingly difficult and costly to meet.

Upgrading the CEBAF accelerator to 12 GeV will require increasing the energy of the linear accelerator from the present 1200 MeV to 2200 MeV. This will be accomplished by adding additional accelerating structures, and by replacing some of the original cavities by newer, higher gradient versions. All of the recirculating arcs will have to be upgraded to higher integral magnetic field.

The highest energy of 12 GeV will be available in a new experimental area at the end of the north linac, Hall D. This area will be devoted to the photoproduction of exotic mesons using a linearly polarized photon beam and a large acceptance detector. The three existing areas will be able to use any multiple of 2200 MeV (or a lower energy), up to 11 GeV.

The hall equipment will be upgraded to take advantage of the higher energy. In Hall A, a broad-range spectrometer (Medium Acceptance Detector, MAD) will be added. The CLAS in Hall B will be upgraded to higher luminosity and improved forward coverage. In Hall C, the SOS will be replaced by a new Super High Momentum Spectrometer, SHMS, to cover very small angles and high momenta.

7 Summary

The physics motivation and the experimental instrumentation of the Continuous Electron Beam Accelerator have been discussed. The unique combination of high energy, high duty-cycle, high intensity and small phase space beams from CEBAF's superconducting accelerator, in combination with complementary equipment in three experimental halls, allows performing experiments that determine the internal structure of mesons, nucleons, and nuclei with unprecedented precision.

Many important physics issues that are addressed in CEBAF experiments require isolating small components of the cross section via the measurement of interference terms. The use of polarized electrons, polarized targets, and polarimeters has become increasingly important.

The energy of the CEBAF accelerator has exceeded the initial design energy, and is now approaching 6 GeV. Exciting new physics questions require the energy of the accelerator to be increased to 12 GeV. An economical plan has been developed to achieve this increase by relatively small changes to the present accelerator. Concurrently, the hall equipment needs to be upgraded to handle the experimental challenges at the higher energy.

References

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