

PHYSICS AT CEBAF WITH HIGH RESOLUTION SPECTROMETERS

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Abstract. We present here the physics program planned for Hall A at CEBAF. It encompasses exclusive as well as inclusive electromagnetic measurements requiring both high precision and accuracy. The program includes measurements of the elementary form factors of the nucleon, systematic studies of the few nucleon systems (d , $^3,^4\text{He}$), high momentum structure of nuclei, their structure at high Q^2 to look for hadronization and quark effects, spin response of nuclei via $(\bar{e}, e' \bar{p})$ reactions and the study of nuclear pion fields.

1. Introduction

It has been the goal of intermediate energy physics for some time to advance beyond the standard meson nucleon description of nuclear phenomena inferred from observations with present day electron accelerators to the quark gluon description i.e. span the transition between perturbative and non-perturbative QCD in a smooth way. With this in mind a facility with the characteristics of CEBAF was proposed: a 4 GeV continuous beam electron accelerator with very good beam properties extendable to higher energies in the future. At present CEBAF is designed to deliver independent beams to three end stations with intensities up to $200 \mu\text{A}$ and with correlated energies up to 4 GeV. The initial equipment designed for Hall A consists of two 4 GeV/c high resolution spectrometers^[1] which will provide, in conjunction with the high quality CEBAF beam, an unprecedented opportunity to perform exclusive as well as inclusive electromagnetic experiments with both high precision and accuracy. Figure 1 shows a layout of one of the two identical QQDQ spectrometers with some of its basic characteristics. In addition there are plans to build a high resolution 1.3 GeV/c Multi Purpose Spectrometer^[2] (MPS) which will have a short flight path and be able to go out of plane. The MPS will therefore be ideally suited for hypernuclear and $(e, e' \pi)$ studies and can serve also as a third arm in the study of triple coincidence measurements.

Momentum Acceptance $\pm 5\%$
Momentum Resolution $\leq 10^{-4}$
Solid Angle 7 msr
Target Length Acceptance $\pm 5 \text{ cm}$

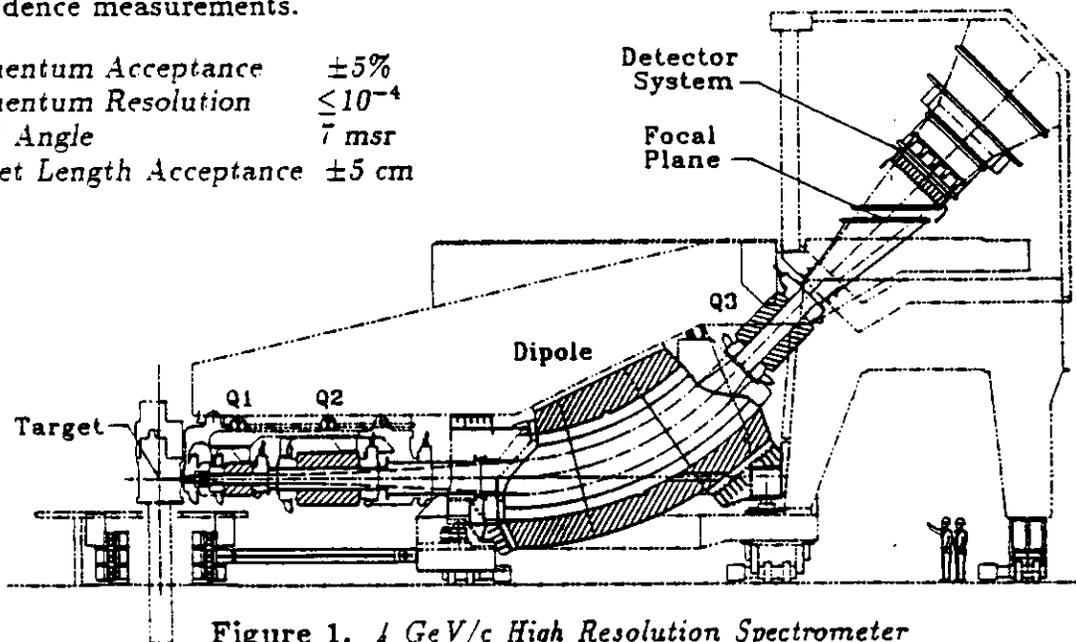


Figure 1. 4 GeV/c High Resolution Spectrometer

2. Structure of the Nucleon

The electric G_E and magnetic G_M form factors of the nucleon are of fundamental importance in understanding both the nucleon and nuclear structure. They are an essential ingredient of the electromagnetic response function of nuclei and their Q^2 dependence is a critical testing ground for QCD based models.

Experimental information on G_E^n is very poor except for the slope at $Q^2 = 0$. Various models predict different behaviour at large Q^2 . Experimentally G_E^n has been extracted from elastic e-d scattering or inclusive quasielastic e-d scattering using Rosenbluth separation techniques, both of which require the knowledge of the structure of the deuteron in order to correct for coherent effects and the dominant proton contribution. This introduces large uncertainties, as at high \bar{q} the cross section is mainly dominated by G_M^p - the transverse component. Dombey^[3] and Arnold, Carlson and Gross^[4] have shown that G_E^n can be determined more accurately if one scatters longitudinally polarized electrons off a polarized target or measure instead the polarization of the recoiling neutron. Two proposals^[C1, C3] apply these techniques using the coincidence $(\bar{e}, e' n)$ reaction to determine G_E^n . In the first proposal^[C3], polarized electrons are scattered off solid ND₃ target polarized in the scattering plane perpendicular to \bar{q} . Target polarizations between 50% and 70% can be achieved at 0.25 K in a 5 T magnetic field. In the second proposal^[C1], a recoil neutron polarimeter is used to measure the transverse in-plane polarization of the recoiling neutron. In both cases G_E^n is extracted from the interference product $G_E^n G_M^n$. The uncertainties in G_E^n obtainable in Proposal C1 for Q^2 of up to 1.5 (GeV/c)² is shown in Figure 2. Proposal C3 proposes to measure G_E^n up to 2 (GeV/c)² with nearly similar uncertainties.

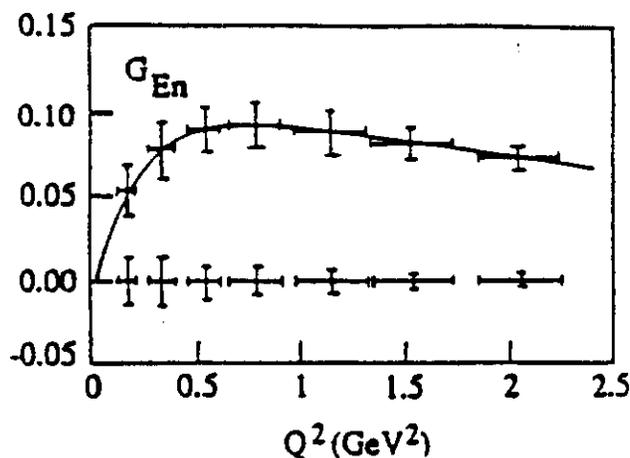


Figure 2. Projected statistical uncertainties in G_E^n from the proposed experiment $^2H(\bar{e}, e' \bar{n})$ ^[C1] permit distinguishing between $G_E^n = 0$ and $G_E^n = -\tau G_M^n$.

Even though the e-p cross section has been measured precisely up to $Q^2 \approx 31$ (GeV/c)², G_E^p is poorly known up to only 4 (GeV/c)². A recent SLAC experiment NE11^[5] plans to determine it to 6 (GeV/c)² with uncertainties of up to 21%. As described for the neutron case, G_E^p can be determined also by performing a coincidence $(\bar{e}, e' p)$ experiment on either a polarized target^[C3] or measuring the transverse in-plane polarization of the recoiling proton^[C2]. Proposal [C2] plans to measure G_E^p to 4.5 (GeV/c)² with errors of less than 4.6% using a focal plane polarimeter. Measuring the $\bar{d}(\bar{e}, e' p)$ reaction in quasifree kinematics on a polarized deuteron target^[C3] or measuring the outgoing recoiling proton^[C12] provides information on the model for deuteron (which is necessary for the proper extraction of G_E^n) and also gives us a measure of G_E^p in the Impulse Approximation where it

has been shown^[6] that the results are remarkably insensitive to the details of the nuclear model including the choice of wavefunctions, FSI and MEC.

3. The Nucleon in the Nucleus

Coincidence experiments have been very useful tools to study specific aspects of the nucleus^[7]. The five proposals [C4-C8] make use of the $(e,e'p)$ reaction on various targets (^2H , $^3,^4\text{He}$, ^{16}O , ^{12}C , ^{63}Cu , ^{208}Pb) to explore not only the single nucleon structure of nuclei, but also to study the behaviour of nucleons embedded in the nuclear medium. The high energy and high duty factor CEBAF beam will extend the kinematical domain of these studies. In particular the various proposals will address one or more of the following issues:

- The Q^2 dependence of the separated longitudinal and transverse parts of the $(e,e'p)$ cross section.

These experiments will extend the domain of momentum transfers where short range effects and possibly the internal structure of the nucleons are manifested. In the Impulse Approximation, the electromagnetic response gives direct access to single nucleon densities and this description seems to provide a reasonable description for quasielastic inclusive as well as coincidence $(e,e'p)$ results. However, when the cross sections are separated into longitudinal(L) and transverse(T) responses, this simple model seems to break down. The transverse response agrees reasonably well with traditional nuclear theory calculations once meson exchange and short range correlations are taken into account. For the longitudinal response, the models always overpredict the experimental results and this is also reflected in the longitudinal sum rule results (see figure 9). This is also evident in the recent ^4He $(e,e'p)$ experiment at SACLAY^[8] where an L/T separation was performed up to $q = 0.7$ GeV/c. The L/T ratio of the response functions shows a reduction of about 30% even after FSI and MEC are applied (see figure 3). When these results are combined with those of the EMC effect^[9], there is question of a possible modification of the nucleon structure within the nuclear medium. Proposal [C7] will extend these studies to $q = 3$ GeV/c in ^3He and ^4He and Proposal [C5] to $q = 2.6$ GeV/c in ^2H .

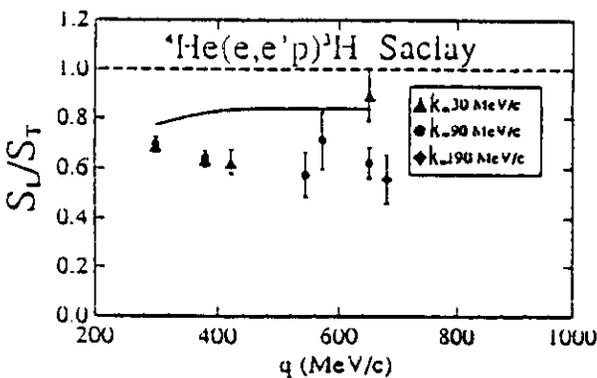


Figure 3. Ratio of longitudinal to transverse response functions for the $^4\text{He}(e,e'p)^3\text{H}$ reaction. The dashed line at unity is the PWIA prediction whereas the solid line is a calculation which includes FSI and MEC.

- Study the high momentum components of the nuclear wavefunction and separation of the various response functions.

The study of high momentum components in nuclei is of special interest in nuclear physics as it is sensitive to correlations arising from the short range part of the NN interaction. Self-consistent mean field descriptions of nuclei fail to describe these components

show that the high momentum strength is completely dominated by correlations and that it is spread over a large continuum in missing energy. This has been clearly demonstrated in ${}^3\text{He}(e,e'p)np$ ^[12] and ${}^4\text{He}(e,e'p)np$ ^[15]. The broad structure observed in both nuclei has the kinematic signature expected from an interaction with a two-nucleon pair, moving to higher values of E_m as the recoil momentum p_R is increased. Excess of strength at high missing energy in ${}^{12}\text{C}(e,e'p)$ experiments at Bates in the quasielastic^[16], dip^[17] and quasifree delta region^[18] also indicate important contributions from two-nucleon processes. Proposal [C7] will vastly extend the kinematic range of these studies on ${}^3,4\text{He}$ and will moreover make an in-plane separation of the response functions in perpendicular kinematics at $Q^2 = 1.0$ $(\text{GeV}/c)^2$ and recoil momenta up to 1 GeV/c .

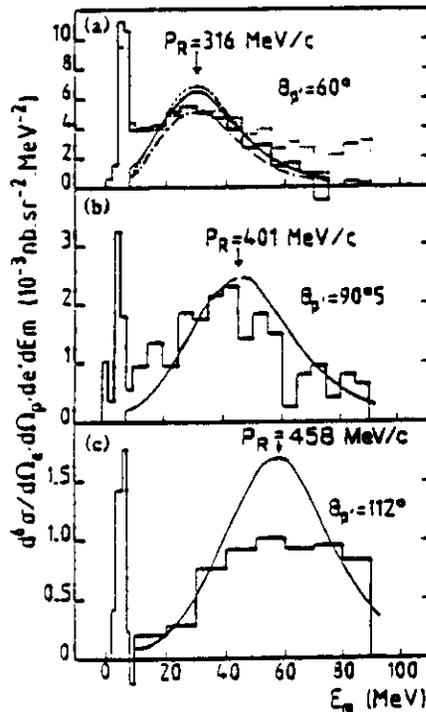


Figure 5. Cross sections for the reaction ${}^3\text{He}(e,e'p)$ vs missing energy E_m ^[12]. Dashed line: PWIA; dot-dash line: DWIA; solid line: DWIA+MEC^[19]. Arrows locate values of $(E_m)_c$ which correspond to the indicated p_R .

- Study of quasi-particle orbits in closed shell nuclei

In nuclear many body theory the mean field description is only the leading contribution in a series expansion in terms of multi-particle correlations. High resolution ${}^{208}\text{Pb}(e,e'p)$ experiment at NIKHEF^[20] has shown a definite binding energy dependence of the occupation of single particle orbitals near the Fermi surface, but the lack of kinematical flexibility has restricted such study of these discrete states to internal momenta of less than 300 MeV/c . Proposal [C8] will investigate the limitations of the mean field theories by determining the momentum distribution of discrete hole states in ${}^{208}\text{Pb}$ at high values of momentum transfer (≈ 500 MeV/c). Separation of response functions in various kinematics will also be performed to help isolate nuclear structure information from reaction mechanism effects.

4. Photodisintegration of the Deuteron

Threshold electrodisintegration of the deuteron $d(e,e')np$ has provided one of the most direct evidence of non-nucleonic degrees of freedom^[21]. A recent SLAC measurement

(NE4)^[22] has extended the SACLAY results to $Q^2 \approx 2.8 \text{ (GeV/c)}^2$ (see figure 6) although with a lower resolution which necessitated averaging over 10 MeV, thus precluding any separation from the elastic scattering process. The proposal [C10] plans to measure the threshold deuteron disintegration with resolution comparable to that obtained at SACLAY ($\approx 1 \text{ MeV}$) and with a cross section sensitivity limit of about $5 \times 10^{-42} \text{ cm}^2/\text{sr}$. The experiment will provide a measurement of the ${}^3S_1 + {}^3D_1 \rightarrow {}^1S_0$ transition and the nearby threshold region of higher excitations. The results will place severe constraints on the diverging theoretical predictions at large momentum transfers and will lead to a better understanding of non-nucleonic and in particular quark-gluon degrees of freedom in the deuteron.

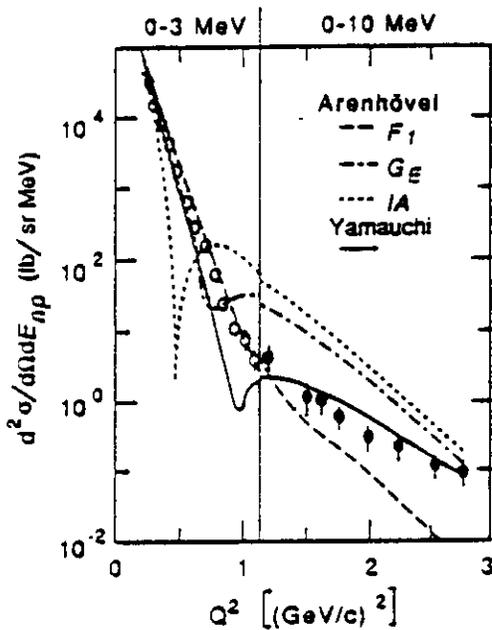


Figure 6. Threshold electrodisintegration cross sections at 180° vs Q^2 . All predictions and SLAC data^[22] above $Q^2 = 1.1 \text{ (GeV/c)}^2$ are averaged over a 10 MeV excitation energy range. Below $Q^2 = 1.1 \text{ (GeV/c)}^2$, the Saclay data^[21] (open circles) and Ahrenhovel's meson-nucleon predictions are averaged over 0-3 MeV, while the hybrid quark-hadron model of Yamauchi is at $E_{np} = 1.5 \text{ MeV}$.

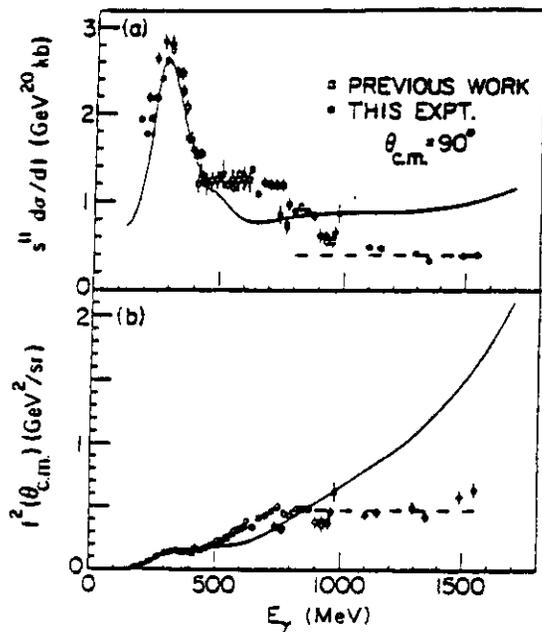


Figure 7. Cross sections for $d(\gamma,p)n$ ^[23] at $\theta_{cm} = 90 \text{ deg}$. The top panel shows $S^{11} d\sigma/dt$ to exhibit scaling. In the bottom panel, the reduced nuclear amplitude is plotted. In either case, scaling would cause an energy independent behaviour given by the dashed lines. The solid lines are based on meson exchange calculations.

The $d(\gamma, p)n$ reaction is a simple test case for nuclear theories. As the incident γ energy is increased, new degrees of freedom become important and can be investigated. Recently, it has been suggested^[23] that dimensional scaling has been observed at photon energies above 1.4 GeV, which indicates that the reaction is sensitive to the quark substructure of the nucleons. Proposal [C9] plans to measure angular distributions of outgoing polarized protons for incident energies from 0.5 to 1.8 GeV for this reaction. This will provide a more sensitive test as spin measurements are typically more sensitive to interference of reaction mechanisms than differential cross section measurements. The results of this experiment will therefore provide a test of the capabilities of conventional nuclear theories and also a sensitive check on the existence of various exotic phenomena such as dibaryons and the onset of dimensional scaling.

5. Pions in the Nucleus

The exchange of pions by bound nucleons creates a population of constituent pions, which has been calculated to be one pion for every eight nucleons for a medium weight nuclei. The proposal [C11] plans to measure the spectral function of this population in an $(e, e'\pi)$ experiment using quasifree kinematics with excitation above the nucleon resonance region. A longitudinal-transverse separation at low four-momentum transfer helps distinguish pion creation on the nucleon (which is mainly a transverse process) from knockout of the constituent pions. The proposed $(e, e'\pi)$ measurement will enable one to connect theoretically the pion spectral function to the two-nucleon potential and the low energy pion-nucleus optical potential.

6. Polarization transfer in Nuclei

Polarization measurements provide additional tests of nuclear wavefunctions and currents and are sensitive to many features of the reaction mechanism. They have been proposed in the determination of the form factors of the nucleon^[C1-C3] and also in the $(\bar{e}, e'\bar{p})$ reactions on ${}^2\text{H}$ ^[C12] and ${}^{16}\text{O}$ ^[C13] where both a polarized beam and a focal plane polarimeter for the protons will be required. All three components of the proton polarization vector (longitudinal, transverse and normal) will be measured. The present plans are to make an in-plane (coplanar) measurement, where only 12 of the full set of 18 response functions contribute: R_L , R_T , R_{TT} and R_{LT} which contribute to the unpolarized cross section, the normal polarization component contributions from R_L^n , R_T^n , R_{TT}^n and R_{LT}^n , the longitudinal from R_{TT}^l and R_{LT}^l , and the transverse from R_{TT}^t and R_{LT}^t . The normal polarization component is beam helicity independent and hence can be separated from the other two components which are helicity dependent. The normal component vanishes in-plane in PWIA, hence its measurement is a sensitive indicator of final state interactions (FSI).

Fabian and Ahrenhovel^[24] have made non-relativistic calculations on the deuteron and have shown that there is large sensitivity (50-100%) to the non-nucleonic degrees of freedom (MEC and IC) along with FSI, especially in the polarization observables. These effects are much weaker in the usual (unpolarized) R_L and R_T responses. The proposal [C12] will attempt to measure the recoil proton polarizations in ${}^2\text{H}(\bar{e}, e'\bar{p})$ over a broad range of kinematics. In the first part all three polarization observables will be extracted in perpendicular kinematics at $\bar{q} = 1.26$ GeV/c reaching a recoil momentum of 300 MeV/c. The polarization asymmetries about \bar{q} will also be extracted. In the next part, a Q^2 dependence (0.23 to 3.24 (GeV/c)²) of the reaction will be studied at zero recoil momentum.

In analogy with the ${}^2\text{H}(\bar{e},e'\bar{n})$ reaction to measure G_E^n (assuming nuclear correlations can be handled), the ${}^2\text{H}(\bar{e},e'\bar{p})$ reaction, in conjunction with the $p(\bar{e},e'\bar{p})$ reaction to measure G_E^p , will test the validity of reaction models for the deuteron.

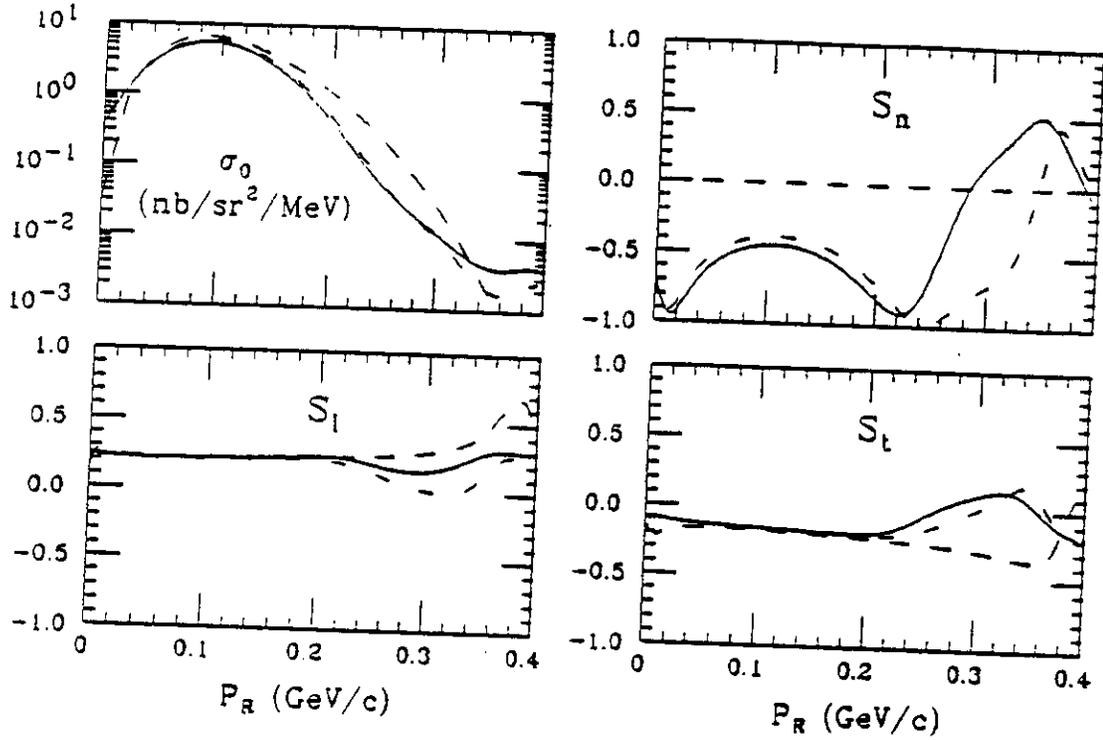


Figure 8. Cross sections and polarization vector for the ejection of 500 MeV protons from the $1p_{1/2}$ shell of ${}^{16}\text{O}$ in constant- q kinematics at an incident electron energy of 4 GeV. Calculations^[25] are shown for Dirac DWIA (solid line), for nonrelativistic DWIA (dot-dashed line) and for relativistic PWIA (dashed line).

The ${}^{16}\text{O}(\bar{e},e'\bar{p})$ reaction will be investigated^[C13] in perpendicular kinematics at $\bar{q} = 1.09$ GeV/c and the proton recoil momenta p_R ranging from 50 to 300 MeV/c for the $p_{1/2}$ state. The object is to look for possible signatures of relativistic dynamics. Relativistic DWIA calculations by Picklesimer and Van Orden^[25] show that each polarized component of the cross section is dominated by a single response function (at the 80% level), the unpolarized by R_T , the normal by R_{TT}^n , the longitudinal by R_{TT}^l , and the transverse by R_{LT}^t . The normal polarization component, S_n , which vanishes in PWIA, is of the order of 50% or more over most of the recoil momentum (p_R) range and shows large differences between the relativistic and non-relativistic DWIA calculations for p_R above 0.25 GeV/c. The longitudinal S_l and transverse S_t components also show considerable sensitivity to the choice of calculation for large p_R .

7. Inclusive Electron Scattering

Quasielastic electron scattering probes the nucleon Fermi momentum distribution in the nucleus (analogous to deep inelastic lepton scattering which probes the quark momentum distribution in the nucleon) and is explained by the Fermi gas model using the free electromagnetic form factors of the nucleons. This simple picture breaks down when

the total response function is separated into its longitudinal and transverse components, especially for medium weight and heavy nuclei, and is an indication that processes beyond the simplistic single particle description of nuclei are necessary. This is similar to the complementary exclusive ($e, e'p$) results which also shows a reduction in R_L and is reflected in the Coulomb sum rule results (see figure 9). Proposal [C14] will make a precision measurement of the inclusive electron scattering cross sections on various nuclei ranging from ${}^2\text{H}$ to ${}^{208}\text{Pb}$ and will extract the longitudinal and transverse response functions at momentum transfers between 0.3 and 1.5 $(\text{GeV}/c)^2$ with a precision between 1% and 12% for R_L over the whole momentum transfer range.

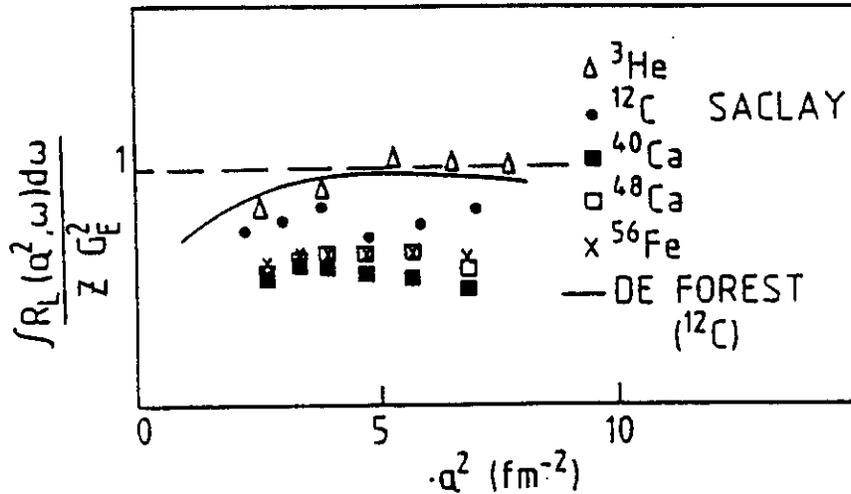


Figure 9. Coulomb sum rule for ${}^3\text{He}$, ${}^{12}\text{C}$, ${}^{40,48}\text{Ca}$ and ${}^{56}\text{Fe}$. The solid line is a calculation by deForest for ${}^{12}\text{C}$ [29].

The form factors of ${}^3\text{He}$, ${}^3\text{H}$ and ${}^4\text{He}$ have been thoroughly investigated both experimentally and theoretically. Recent measurements [26,27,28] have separated the charge and magnetic form-factors of both trinucleon systems up to $\sim 30 \text{ fm}^{-2}$. The charge form factor of ${}^4\text{He}$ has also been measured [26] up to $Q^2=45 \text{ fm}^{-2}$. It is evident that the impulse approximation (IA) alone cannot describe the data correctly and, as in the case of the deuteron, explicit introduction of non-nucleonic degrees of freedom is necessary. The inclusion of MEC and IC as well as three-body forces provides a reasonable description of the data. Data at higher momentum transfers will determine if explicit sub-nucleonic degrees of freedom are also necessary. Proposal [C15] will attempt to measure these form-factors to the highest momentum transfer possible at CEBAF, limited only by a cross section sensitivity of $\sim 2 \times 10^{-42} \text{ cm}^2/\text{sr}/\text{MeV}$, thereby possibly extending the existing Q^2 range in both ${}^3\text{He}$ and ${}^4\text{He}$ by a factor of two.

8. Multihadron Emission in Electron Scattering

A full investigation of two-nucleon currents and correlations in nuclei requires ($e, e'2N$) triple coincidence experiments. Proposal [C17] plans to measure e - p - p and e - p - n angular correlation cross sections in ${}^3,4\text{He}$ in geometries which permit simplified interpretation of the data and selectively emphasize various components of the knockout mechanism. Such experiments will provide important and fundamental information on the elusive short range two nucleon correlations, two-body meson exchange currents and associated final state interactions between the ejected nucleons and the nucleus. Proposal [C16] offers an efficient way to study two nucleon correlations in nuclei by performing the ($e, e'd$) reaction instead. By projecting these correlations onto a deuteron in the final state some details

are lost since effectively an integral is taken over certain correlations. On the other hand the $(e,e'd)$ reaction can be used as an isospin filter and performed with a resolution similar to that of $(e,e'p)$ reactions.

9. Summary Remarks

We have presented here most of the physics programs which have been submitted to the CEBAF Program Advisory Committee to be performed in Hall A. Among the other physics programs which can also be investigated with the facilities planned for Hall A are the study of nucleon resonances in nuclei, hadronization and color transparency and the study of strangeness in nucleons and nuclei. High resolution (200-500 keV missing mass resolutions and ~ 1 MeV for few nucleon systems) and high accuracy (absolute cross section to $\sim 1\%$ accuracy) coincidence experiments in the few GeV region will be the primary goal of Hall A. In essence, it will fully match the unique characteristics of the CEBAF beam — 4 GeV incident energy, 100% duty factor, 200 μ A beam intensity and a momentum resolution of 10^{-4} — to perform exclusive as well as inclusive electromagnetic measurements with both high precision and accuracy.

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