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Quasi-free ($e,e'p$) reactions: the first look from CEBAF

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Coincidence cross sections for ($e,e'p$) quasi-elastic scattering were measured at CEBAF with high statistical precision for C, Fe, and Au targets for $0.6 < Q^2 < 3.3 \text{ GeV}^2$. E_m and P_m distributions obtained from a preliminary analysis are in reasonable agreement with prior data from SLAC. The preliminary results are compared with a PWIA calculation to determine the nuclear transparency as a function of Q^2 and A . A Rosenbluth analysis to extract the longitudinal and transverse cross sections from these data is anticipated.

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1 Introduction

The elastic scattering of electrons by a free proton is a well understood process, characterized by two electromagnetic form factors in the absence of polarization. When the scattering occurs from a nucleus, the process is more complex. The dominant reaction mechanism at modest Q^2 for kinematics near that of elastic proton scattering is quasi-elastic scattering, in which the electron scatters elastically from a moving, off-shell proton¹. In the PWIA approximation, the cross section for this mechanism may be written as:

$$\frac{d^6\sigma}{dk' dE'_p d\Omega_{k'} d\Omega_{P'}} = P' E'_p \sigma_{ep} S(E, \vec{P}) \quad (1)$$

in which the scattered electron has momentum k' , the scattered proton momentum P' and energy E'_p , σ_{ep} is the elementary electron-proton cross section, and $S(E, \vec{P})$ is the probability density for striking a proton with initial energy E and momentum $\vec{P}$. The spectral function S is directly related to the nuclear wave function, and has normalization:

$$\int S(E, \vec{P}) d^3\vec{P} dE = Z. \quad (2)$$

An exclusive cross section measurement, in which E and P can be determined from the final-state kinematics, may therefore probe nuclear structure through the spectral function. Complicating this simple picture are other effects, such as soft photon radiation, re-interaction of the emerging proton with the $A - 1$ nucleons, and meson exchange currents. Exclusive measurements thus offer an opportunity to study these effects as well.

Previous work at SLAC² and BATES³ has focused on studying the transparency of the residual nucleons to the emerging proton. The authors used a spectral function derived from an independent particle shell model (IPSM) to calculate a theoretical cross section, including radiative effects and some corrections for short-range correlations in the nuclear wave-function⁴. The ratio of the measured cross section to this calculation is plotted in figure 1.

Absorption of the scattered protons results in $T < 1$. The ratio decreases with increasing A as one would expect. For $0.3 < Q^2 < 1.0 \text{ GeV}^2$, T falls with increasing Q^2 . This is consistent with the strong energy-dependence of the total proton-nucleon cross section for proton momenta below 1.5 GeV/c. Various authors^{5,6,7,8,9,10,11} have attempted to calculate the Q^2 and A dependence of these data using a Glauber model of the proton absorption alone, or including more speculative effects such as color transparency—a temporary reduction in the proton's cross section after a hard scattering. The SLAC data

Figure 1: $T = \sigma_{\text{exp}}/\sigma_{\text{pwia}}$ for $(e, e'p)$ quasi-elastic scattering from C, Fe, and Au targets. The solid data points are from ref², and the open points from ref³. Statistical errors are indicated by horizontal ticks on the total error bars.

are consistent with some Glauber calculations, but cannot rule out the color transparency effect if its onset is slow enough in this kinematic range.

The present experiment studies proton propagation through nuclei with $0.6 < Q^2 < 3.3$ (GeV/c) 2 , in the interesting region where the transparency is changing rapidly with Q^2 , and exotic effects like color transparency are small. By measuring high statistics data, including forward and backward angle data at the same Q^2 to separate the longitudinal and transverse response, we hope to improve our understanding of proton-nucleon interactions and to test the validity of the quasi-elastic reaction mechanism.

2 Experiment

This experiment (E91-013) was performed at CEBAF^a in hall C, using the HMS and SOS spectrometers. A 20 μ A continuous (CW) beam of electrons was incident on solid targets of C, Fe, and Au, as well as a target of CH₂ plastic and an extended target of liquid hydrogen for normalization to the well-known

^aNow the Thomas Jefferson National Accelerator Facility.

Table 1: Summary of measurements. The conjugate proton angles for elastic (e, p) scattering are shown in boldface.

Proton Kinetic Energy (MeV)	Electron Energy (MeV)	Electron Angle (degrees)	Proton Angles (degrees)	Q^2 (GeV/c) ²
350	845	78.5	27.8, 31.8 , 35.8, 39.8 43.8, 47.8	0.643
350	2445	20.5	35.4, 39.4, 43.4, 47.4 51.4, 55.4 , 59.4, 63.4 67.4, 71.4, 75.4	0.643
700	2445	32.0	31.0, 35.0, 39.0, 43.0 47.0, 51.0, 55.0	1.283
970*	1645	80.0	22.8 , 26.8, 30.8, 34.8	1.781
970	3245	28.6	33.5, 37.5, 40.5 , 44.5, 48.5, 52.5	1.784
1800	3245	50.0	25.1 , 27.6, 30.1	3.305

* Only C and Fe data for these kinematics.

(e, p) elastic cross section. Table 1 summarizes the measurements made. For each electron angle, cross sections were measured for a range of proton angles spanning the quasi-elastic peak. For all but the highest proton energy, the HMS was used to detect the scattered electrons, and the SOS was used to detect the scattered protons in coincidence. The data for a proton kinetic energy of 1.8 GeV were taken with the spectrometer roles reversed. Typically, enough data were taken to ensure statistical uncertainties in the cross section of 1% or better.

The SOS (Short Orbit Spectrometer) consists of a quadrupole magnet followed by two dipoles in a configuration very similar to the MRS spectrometer of LAMPF. It features a short flight path (7.3 m) with large angular acceptance (7.7 msr) and momentum bite (40%), good momentum resolution (0.1%), and a maximum central momentum of 1.7 GeV. The HMS (High Momentum Spectrometer) consists of three quadrupoles followed by a dipole, all superconducting with cold iron poles. It has a long flight path (23.2 m), comparable solid angle (6.8 msr), smaller momentum bite (18%), but better momentum resolution (0.05-0.1%), with a maximum central momentum of 7 GeV.

Each spectrometer was outfitted with a similar detector package. Four

Figure 2: E_m and P_m distributions, not corrected for spectrometer acceptance.

segmented planes of plastic scintillator were used to form a trigger and to provide time-of-flight particle identification. Two 6-plane drift chambers were used to measure the particle trajectories from which the scattering angle and momentum of the particle were calculated. Additional particle identification was provided by a gas threshold Cerenkov detector, a segmented lead glass shower array, and in the case of the SOS, an aerogel Cerenkov detector.

The solid angle of each spectrometer was defined by a 2 inch thick tungsten collimator with a large octagonal hole. These could be remotely exchanged for collimators with a rectangular array of small holes. Extensive optics data were taken with these 'sieve-slit' collimators to calibrate the trajectory reconstruction coefficients for the scattering angles. Momentum reconstruction coefficients were determined by observing electrons elastically scattered from C and H nuclei at several spectrometer excitations.

Coincidence triggers were readout through fastbus hardware by the CODA data acquisition system¹². After time-of-flight corrections, the coincidence

Figure 3: $T = \sigma_{\text{exp}}/\sigma_{\text{PWIA}}$ for $(e, e'p)$ quasi-elastic scattering from C, Fe, and Au targets at $Q^2 = 0.6 \text{ GeV}^2$, and the yield versus proton angle. The PWIA-based monte-carlo results are shown as the dotted lines.

timing resolution was typically 0.5 ns (fwhm), with a real to random ratio greater than 200.

3 Preliminary results

The missing energy (E_m) and missing momentum (P_m) are defined as the difference between initial state and observed final-state quantities:

$$\begin{aligned} P_m &= |\vec{P}' - \vec{Q}| \\ E_m &= \omega - E_p' + m_p - T_{A-1} \end{aligned} \quad (3)$$

in which $\vec{Q}$ is the 3-momentum transfer, ω is the energy transfer, and T_{A-1} is the kinetic energy of the A-1 nucleons. These may be calculated from the observed electron and proton momenta and angles. In figure 2 we plot the E_m and P_m distributions for the forward electron-angle C data at $Q^2 = 0.6 \text{ GeV}^2$ as a solid line. The scattering from P-shell and S-shell nucleons is clearly resolved into two peaks in E_m .

Figure 4: $T = \sigma_{\text{exp}}/\sigma_{\text{PWIA}}$ for $(e, e'p)$ quasi-elastic scattering from C, Fe, and Au targets. Prior data^{2,3} is shown as open symbols, and this experiment as solid symbols.

The dashed lines are the distributions calculated from a realistic monte-carlo model¹³ which includes radiative corrections, normalized to the same number of total events. The agreement is reasonable, especially in the tail region at large E_m . The P-shell peak at $E_m \sim 20$ MeV appears to be slightly shifted and broadened relative to the monte-carlo. Similar effects exist in the analysis of (e, p) elastic scattering from the hydrogen target, and is thought to originate in incorrect momentum and scattering angle reconstruction. The analysis of the spectrometer optics is still ongoing, and should improve the agreement with the monte-carlo.

In figure 3, we show a comparison of experimental and monte-carlo cross-sections for all the forward electron-angle, $Q^2 = 0.6$ GeV² data, as a function of proton angle. In the top panel we plot the ratio of the cross sections, and in the bottom panel we plot the yields, with the monte-carlo normalized to the average T of the corresponding data. All statistical uncertainties are smaller than the plotting symbols. One can see that there is essentially complete coverage of the proton angular distribution. The ratio of cross sections is fairly flat in the center, but rises at small and large proton angles. These angles correspond to large initial-state proton momenta that are underrepresented in

the monte-carlo (since the IPSM lacks the correlations from which they arise), leading to an increase in the ratio.

A 'central' value for the ratio of experimental to PWIA cross sections at each Q^2 is plotted versus Q in figure 4 for the partial data set analyzed as of May 1996. A correction for the wave-function correlations has been included. These preliminary results contain a 10% systematic uncertainty, which is dominated by the uncertainty with which we understand the spectrometer acceptances. The systematic uncertainties should decrease substantially after all the optics data have been analyzed. We can see that there is fair agreement with the previous data. A full analysis of the entire data-set, including a Rosenbluth separation of the longitudinal and transverse cross sections, is in progress.

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