Quasielastic (e,e'p) Scattering at Large Momentum Transfer.


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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 \(0.6 < Q^2 < 3.3 \text{ GeV}^2\). Missing energy and missing momentum 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 \(A\). At both \(Q^2 = 0.6\) and \(Q^2 = 1.8 \text{ GeV}^2\) data were taken to perform a Rosenbluth separation to extract the longitudinal and transverse cross sections. The preliminary missing-energy distributions of the forward and backward angle measurements do not indicate an obvious excess of transverse strength.

1 Introduction

Quasielastic electron scattering experiments can be used to explore single-particle properties of the nucleus. Until recently, such experiments were performed at relatively moderate four-momentum transfer squared \((Q^2)\), typically \(Q^2 \approx 0.2 \text{ (GeV/c)}^2\). In these experiments single-particle properties can be accessed because inside the nucleus the dominant reaction mechanism for kinematics near that of elastic electron-proton scattering is quasielastic scattering, in which the electron scatters elastically from a moving, off-shell proton.\(^1\) Under these Plane-Wave Impulse Approximation (PWIA) conditions the coincidence cross section for \((e, e'p)\) scattering off a nucleus may be written as:

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

where \(k'\) is the momentum of the scattered electron, \(P'\) and \(E'_p\) are the momentum and energy of the scattered proton, \(\sigma_{ep}\) 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 obeys the sum rule:

\[
\int S(E, \vec{P}) d^3 \vec{P} dE = Z.
\]

An exclusive cross section measurement, in which \(E\) and \(P\) can be (approximately) determined from the final-state kinematics, can thus probe nuclear structure through the spectral function. Inside a complex nucleus investigation of the single-particle properties may be obscured due to the presence of Meson-Exchange Currents or the possibility of Final-State Interactions (FSI) of the outgoing proton with the nuclear medium. The presence of additional reaction mechanism effects next to the dominant quasielastic scattering can be investigated through a so-called Rosenbluth separation, which separates

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Figure 1: Transparency ratios for \((e,e'p)\) quasi-elastic scattering from C, Fe, and Au targets. The solid data points are the ratio of experimental to PWIA cross sections from Ref. 2. The open points are the ratio of exclusive to inclusive cross sections from Ref. 3. Statistical errors are indicated by horizontal ticks on the total error bars.

the longitudinal nuclear response from the transverse nuclear response of the exclusive \((e,e'p)\) reaction. The latter effect, Final-State Interactions of the outgoing proton in the nuclear medium, can absorb or deflect the struck proton, and thus reduce the measured \((e,e'p)\) cross section. This reduction can be expressed in terms of a transparency \(T\), defined as the ratio of the experimental to the theoretical cross sections \(T = \sigma_{\text{exp}} / \sigma_{\text{pwia}}\). This transparency is of fundamental interest too, both as a measure of the corrections to the dominant first-order process and as a source of insight into the nature of proton-nucleus interactions. The transparency has a clear physical interpretation, i.e. the probability that a struck proton escapes the nucleus without significant FSI.

Previous work at SLAC\(^2\) and BATES\(^3\) focused on studying the transparency of the residual nucleons to the emerging proton. The SLAC data were compared with theoretical cross sections based on a spectral function derived from an independent particle shell model (IPSM) and including radiative effects and some corrections for short-range correlations in the nuclear wave function.\(^4\) The ratios of experimental to theoretical cross sections \(T = \sigma_{\text{exp}} / \sigma_{\text{pwia}}\) are plotted in Fig. 1. The BATES data were divided by the inclusive cross section after subtraction of the inelastic contribution; these ratios are also plotted in Fig. 1.
Absorption of the scattered protons results in $T < 1$. The ratio decreases with increasing $A$ as one would expect. For $0.3 < Q^2 < 3.0 \text{ GeV}^2$, $T$ 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 have attempted to calculate the $Q^2$ and $A$ dependence of these data using a Glauber model of the proton absorption, or including more speculative effects such as color transparency—a proposed reduction in the final state interactions after a hard scattering that would cause an enhancement of the nuclear transparency at high $Q^2$. The SLAC data 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 in the $Q^2$ range $0.6 < Q^2 < 3.3 \text{ (GeV/c)}^2$. This is the region where the nuclear transparency is changing rapidly with $Q^2$, and any color transparency effect is expected to be 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 quasielastic reaction mechanism.

2 Experiment

This experiment (E91-013) was performed at CEBAF in Hall C, using the High Momentum (HMS) and Short Orbit (SOS) spectrometers. A continuous (CW) beam of electrons was incident on solid targets of C, Fe, and Au, as well as a target of CH$_2$ plastic and an extended target of liquid hydrogen to check the absolute normalization relative to the well-known ep elastic cross section. Table 1 summarizes the measurements. The first four kinematics of Table 1 were taken in December 1995 with beam currents up to 20 μA, the last two kinematics were taken in May 1996 with beam currents up to 60 μA. We will here mainly report on the analysis of the December 1995 data. For each electron angle, cross sections were measured for a range of proton angles spanning the quasi-elastic peak. The HMS was used to detect the scattered electrons and the SOS was used to detect the scattered protons in coincidence, except for the data at a proton kinetic energy of 1800 MeV, where the spectrometer roles were reversed. Typically, enough data were taken to ensure statistical uncertainties in the cross section of 1% or better.

The SOS consists of a quadrupole magnet followed by two dipoles in a configuration modelled after the MRS spectrometer of LAMPF. It features a

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*Now the Thomas Jefferson National Accelerator Facility.*
Table 1: Summary of measurements. The conjugate proton angles for elastic (e, p) scattering are shown in boldface.

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

* Only C and Fe data for these kinematics.

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/c. The HMS 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 (20%), but better momentum resolution (0.05-0.1%), with a maximum central momentum of 7.3 GeV/c.

In each spectrometer, four 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 and a segmented lead glass shower array. Both the Cerenkov and the lead glass array could be made part of a composite trigger.

The solid angle of each spectrometer was defined by a 2-inch thick tungsten collimator with a large octagonal hole. These could be exchanged remotely with collimators featuring a grid 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 scattered elastically from C and H nuclei at several spectrometer excitations. Coincidence triggers were read out through fastbus hardware by the CODA data acquisition system. After time-of-flight corrections, the coincidence timing resolution was typically 0.5 ns (fwhm), with a real to random ratio greater than 200. The calculation of absolute cross sections included corrections for detector inefficiencies, computer dead-time, and proton losses from secondary scattering in the target and the spectrometer windows. The latter was derived by comparing the inclusive $^1$H(e,e') reaction with the exclusive $^1$H(e,e'p) reaction.

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:

$$|P_m| = |\bar{Q} - \bar{P}|$$
Figure 3: $E_m$ distribution for the forward and backward angle kinematics at $Q^2 = 0.6$ (GeV/c)$^2$, not corrected for spectrometer acceptances.

$$E_m = \omega - E_p' + M_p - T_{A-1}$$

in which $\vec{Q}$ is the 3-momentum transfer, $\omega$ is the energy transfer, $M_p$ is the proton mass, and $T_{A-1}$ is the kinetic energy of the A-1 nucleons, with the convention that $P_m$ is positive (negative) if $P'$ is at a larger (smaller) angle with respect to the incident electron than $\vec{Q}$. $E_m$ and $P_m$ may be calculated from the observed electron and proton momenta and angles. In Fig. 2 we plot the $E_m$ and $P_m$ distributions for the forward electron-angle C data at $Q^2 = 0.6$ GeV$^2$ as a shaded area. The data have been cut with $|P_m| < 300$ MeV/c and $E_m < 80$ MeV. The scattering from p-shell and s-shell nucleons is clearly resolved into two peaks in $E_m$.

The solid lines are the distributions calculated from a realistic Monte Carlo model$^{13,14}$ which includes radiative corrections, normalized to the same number of total events. The normalization equals the experimental transparency found for this kinematics, which will be shown later. The agreement is reasonable, especially in the tail region at large $E_m$, where the cut is placed. 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 originate in incorrect momentum and scattering angle reconstruction. The understanding of the spectrometer optics over the full acceptances is still ongoing.

Fig. 3 shows the comparison of the experimental missing energy distribution for both the forward (shaded area) and backward (solid line) electron scattering angle measurements. The missing energy distributions are normalized to each other. To be less sensitive to differences in phase space between the forward- and backward-angle kinematics, the data have been cut with \(|P_m| < 100\ \text{MeV/c}\) and \(E_m < 80\ \text{MeV}\). A good agreement can be seen between the forward and backward angle kinematics in the tail region, and no obvious excess of additional strength is seen in this tail region. A more definite conclusion on the influence of additional reaction mechanisms to the dominant quasielastic scattering process will have to wait for the final analysis.

In Fig. 4, we show a comparison of experimental and Monte Carlo cross-sections for all the forward electron-angle, \(Q^2 = 0.6\ \text{GeV}^2\) data, as a function
of proton angle. The same $P_m$ and $E_m$ cuts have been applied. 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 missing momenta that are underrepresented in the Monte Carlo (which is based on the Independent Particle Shell Model and thus lacks the correlations from which the large missing-momentum components 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 $\sqrt{Q^2}$ in Fig. 5 for the partial data set analyzed as of June 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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References