Dynamics of the $^{16}$O($e,e'p$) Reaction at High Missing Energies


(The Jefferson Lab Hall A Collaboration)

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We measured the cross section and response functions for the quasielastic $^{16}$O$(e,e'p)$ reaction for missing energies $25 \leq E_m \leq 120$ MeV at missing momenta $P_m \leq 340$ MeV/c. For $25 < E_m < 50$ MeV and $P_m = 60$ MeV/c, the reaction is dominated by a single $1s_{1/2}$ proton knockout. At larger $P_m$, the single-particle aspects are increasingly masked by more complicated processes. Calculations which include pion exchange currents, isobar currents, and short-range correlations account for the shape and the transversity, but for only half of the magnitude of the measured cross section.

The $(e,e'p)$ reaction in quasielastic kinematics ($\omega = Q^2/2m_p$) [1] has long been a useful tool for the study of nuclear structure. $(e,e'p)$ cross section measurements have provided both a wealth of information on the wave function of protons inside the nucleus and stringent tests of nuclear theories. Response function measurements have provided detailed information about the different reaction mechanisms contributing to the cross section.

In the first Born approximation, the unpolarized $(e,e'p)$ cross section can be separated into four independent response functions, $R_T$ (longitudinal), $R_L$ (transverse), $R_{LT}$ (longitudinal-transverse), and $R_{TT}$ (transverse-transverse) [2,3]. These response functions contain all the information that can be extracted from the hadronic system using the $(e,e'p)$ reaction.

The first $(e,e'p)$ energy and momentum distributions were measured by Amaldi et al. [4]. These results, and the many others that followed them [5,6], were interpreted in terms of single-particle knockout from nuclear valence states despite cross sections that were about 40% lower than expected. A series of $^{12}$C$(e,e'p)$ experiments performed at MIT-Bates [7–11] measured much larger cross sections at high missing energy than expected by single-particle knockout models. Ulmer et al. [7] reported a substantial increase in the transverse-longitudinal difference, $(S_T - S_L)$, above the two-nucleon emission threshold in $^{12}$C$(e,e'p)$. $(S_X = \sigma_{Mot} V_X R_X / \sigma_{Tot}^0$, where $X \in \{T, L\}$, and $\sigma_X^0$ is calculated from the off-shell $ep$ cross section obtained using deForest’s cc1 prescription [12,13].) Similar $R_T/R_L$ enhancement has also been observed by Lanen et al. for $^6$Li [14], by van der Steenhoven et al. for $^{12}$C [15] and, more recently, by Dutta et al. for $^{12}$C, $^{56}$Fe, and $^{197}$Au [16].

There have been several theoretical attempts [17–19] to explain the continuum strength using two-body knockout models and final-state interactions, but no single model has been able to explain all the data.

In this first Jefferson Lab Hall A experiment [20], we studied the $^{16}$O$(e,e'p)$ reaction in the quasielastic region at $Q^2 = 0.8$ (GeV/c)$^2$ and $\omega = 439$ MeV ($|q| = 1$ GeV/c). We extracted the $R_L$, $R_T$, and $R_{LT}$ response functions from cross sections measured at several beam energies, electron angles, and proton angles for $P_m \leq 340$ MeV/c. This paper reports the results for $E_m > 25$ MeV; $p$-shell knockout region ($E_m < 20$ MeV) results from this experiment were reported in [21].

We scattered the $\sim 70$ $\mu$A continuous electron beam from a waterfall target [22] with three foils, each $\sim 130$ mg/cm$^2$ thick. We detected the scattered electrons and knocked-out protons in the two high resolution spectrometers (HRS$e$ and HRS$p$). The details of the Hall A experimental setup are given in [23,24].

We measured the $^{16}$O$(e,e'p)$ cross section at three beam energies, keeping $|q|$ and $\omega$ fixed in order to separate response functions and understand systematic uncertainties. Table I shows the experimental kinematics.

The accuracy of a response-function separation depends on precisely matching the values of $|q|$ and $\omega$ for different kinematic settings. In order to match $|q|$, we measured $^1$H$(e,e'p)$ (also using the waterfall target) with a pion collimator in front of the HRS$e$. The momentum of the detected protons was thus equal to $\vec{q}$. We determined the $^1$H$(e,e'p)$ momentum peak to $\frac{\delta p}{p} = 1.5 \times 10^{-4}$, allowing us to match $\frac{|q|}{|q|}$ to $1.5 \times 10^{-4}$ between the different kinematic settings. Throughout the experiment, $^1$H$(e,e)$ data, measured simultaneously with $^{16}$O$(e,e'p)$, provided a continuous monitor of both luminosity and beam energy.

The radiative corrections to the measured cross sections were performed by two independent methods: using the code RADCOR [24,25] which unfolds the radiative tails in $(E_m,P_m)$ space, and using the code MCEEP [26] which simulates the radiative tail based on the prescription of Borie and Drechsel [27]. The corrected cross sections obtained by the two methods agreed within their mutual statistics. The radiative corrections in the continuum amount to 10%–15% of the cross section.

At $\theta_{pq} = \pm 8^\circ$, $R_{LT}$ extracted independently at beam energies of 1.643 and 2.442 GeV agree well within statistical uncertainties. This indicates that the systematic uncertainties are smaller than the statistical uncertainties.

<table>
<thead>
<tr>
<th>$E_{beam}$ (GeV)</th>
<th>$\theta_{e}$ (°)</th>
<th>$\theta_{pq}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.843</td>
<td>100.7</td>
<td>0, ±8</td>
</tr>
<tr>
<td>1.643</td>
<td>37.2</td>
<td>0, ±8</td>
</tr>
<tr>
<td>2.442</td>
<td>23.4</td>
<td>0, ±2.5, ±8, ±16, ±20</td>
</tr>
</tbody>
</table>
The systematic uncertainty in cross section measurements is about 5%. This uncertainty is dominated by the uncertainty in the $^1$H$(e,e')$ cross section to which the data were normalized [28].

Figure 1 shows the measured cross section as a function of missing energy at $E_{\text{beam}} = 2.4$ GeV for various proton angles, $2.5^\circ \leq \theta_{pq} \leq 20^\circ$. The average missing momentum increases with $\theta_{pq}$ from 50 to 340 MeV/c. The prominent peaks at 12 and 18 MeV are due to protons as a function of missing energy. The cross section

At small $P_m$, where there is a clear peak at 40 MeV, this model describes the cross section (see Fig. 1) and the separated $R_L$ and $R_T$ responses well [24]. The extracted magnitude of $(S_T - S_L)$ [24] is consistent with the decrease in $(S_T - S_L)$ with $Q^2$ seen in the measurements of Ulmer et al. [7] at $Q^2 = 0.14$ (GeV/c)^2 and by Dutta [16] at $Q^2 = 0.6$ and 1.8 (GeV/c)^2. This suggests that, in parallel kinematics, transverse non-single-nucleon knockout processes decrease with $Q^2$. At larger $P_m$, where there is no peak at 40 MeV, the DWIA cross section is much smaller than the data (see Fig. 1). Relativistic DWIA calculations by other authors [32,33] show similar results. This confirms the attribution of the large missing momentum cross section to non-single-nucleon knockout.

Figure 1 also shows $(e,e'pn)$ and $(e,e'pp)$ contributions to the $(e,e'p)$ cross section calculated by Ryckebusch et al. [34] in a Hartree-Fock (HF) framework. The cross section for the two particle knockout has been calculated in the “spectator approximation” assuming that the two nucleons escape from the residual $A - 2$ system without being subject to inelastic collisions with other nucleons. This calculation includes pion exchange currents, intermediate $\Delta$ creation, and central tensor short-range correlations. According to this calculation, in our kinematics, two-body currents (pion-exchange and $\Delta$) account for approximately 85% of the calculated $(e,e'pn)$ and $(e,e'pp)$ cross sections. Short-range tensor correlations contribute approximately 13% while short-range central correlations contribute only about 2%. Since the two-body currents are predominately transverse, the calculated $(e,e'pn)$ and $(e,e'pp)$ cross section is mainly transverse. The flat cross section predicted by this calculation for $E_m > 50$ MeV is consistent with the data, but it accounts for only about half the measured cross section. Hence, additional contributions to the cross section such as heavier meson exchange and processes involving more than two hadrons must be considered.

Figures 2 and 3 present the separated response functions for various proton angles. Because of kinematic constraints, we were able to separate only the responses for $E_m < 60$ MeV. The separated response functions can be used to check the reaction mechanism. If the excess continuum strength at high $P_m$ is dominated by two-body
currents rather than by correlations, then it should be predominantly transverse.

Figure 2 presents the separated response functions \( R_{L+TT}, R_T, \) and \( R_{LT}; \) \( R_{L+TT} \equiv R_L + \frac{V_{LT}}{V_{TT}} R_{TT} \) for \( \theta_{pq} = 8^\circ \left( \langle P_m \rangle \approx 145 \text{ MeV}/c \right) \). The Mahaux parametrization does not reproduce the shape of \( R_L \) or of \( R_T \) as a function of missing energy. For \( E_m > 50 \text{ MeV} \), \( R_{L+TT} \) (which is mainly longitudinal because \( \frac{V_{LT}}{V_{TT}} R_{TT} \) is estimated to be only about 7% of \( R_L \) [29] in these kinematics) is consistent with both zero and with the calculations. \( R_T \), on the other hand, remains nonzero to at least 60 MeV. \( R_T \) is also significantly larger than the DWIA calculation. \( R_{LT} \) is about twice as large as the DWIA calculation over the entire range of \( E_m \). \( R_{LT} \) is nonzero for \( E_m > 50 \text{ MeV} \), indicating that \( R_L \) is also nonzero in that range.

Figure 3 presents the separated response functions for \( \theta_{pq} = 16^\circ \left( \langle P_m \rangle \approx 280 \text{ MeV}/c \right) \). At this missing momentum, none of the measured response functions show a peak at \( E_m \approx 40 \text{ MeV} \) where single-particle knockout from the \( 1s_{1/2} \) state is expected. \( R_{L+TT} \) is close to zero and the DWIA calculation. However, \( R_T \) and \( R_{LT} \) are much larger than the DWIA calculation. \( R_T \) is also much larger than \( R_{LT} \) indicating that the cross section is due in large part to transverse two-body currents. The fact that \( R_{LT} \) is nonzero indicates that \( R_L \), although too small to measure directly, is also nonzero.

To summarize, we have measured the cross section and response functions \( R_L, R_T, \) and \( R_{LT} \) for the \(^{16}\text{O}(e, e'p)\) reaction in quasielastic kinematics at \( Q^2 = 0.8 \text{ (GeV}/c)^2 \) and \( \omega = 439 \text{ MeV} \) for missing energies \( 25 < E_m < 120 \text{ MeV} \) at various missing momenta \( P_m \leq 340 \text{ MeV}/c \). For \( 25 < E_m < 50 \text{ MeV} \) and \( P_m = 60 \text{ MeV}/c \) the reaction is dominated by single-nucleon knockout from the \( 1s_{1/2} \) state and is described well by DWIA calculations.

At increasing missing momenta, the importance of the single-particle aspects is diminished. The cross section and the response functions no longer peak at the maximum of the \( s \) shell (40 MeV). They no longer have the expected \( s \)-shell Lorentzian shape. DWIA calculations [29] underestimate the cross section and response functions at \( P_m > 200 \text{ MeV}/c \) by more than a factor of 10. Hence, we conclude that the single-particle aspect of the \( 1s_{1/2} \) state contributes less than 10% to the cross section at \( P_m > 200 \text{ MeV}/c \). This is in contrast to the \( p \) shell, where DWIA calculations describe the data well up to \( P_m = 340 \text{ MeV}/c \).

At \( 25 < E_m < 120 \) and \( P_m > 200 \text{ MeV}/c \) the cross section is almost constant in missing energy and missing momentum. For \( E_m > 60 \text{ MeV} \) this feature is well reproduced by two-nucleon knockout calculations, \((e, e'pp)\) plus \((e, e'pn)\). These calculations also account for the
predominantly transverse nature of the cross section. The transversity of the cross section and the calculations suggest that two-body currents (such as MEC and IC) contribute significantly to the excess continuum strength at high $P_m$. At least according to this model, these contributions are much larger than those from correlations. To our knowledge, this is the only model which can account for the shape, transversity, and about half of the magnitude of the measured continuum cross section. The unaccounted for strength suggests that additional currents and processes play an important role.

We acknowledge the outstanding support of the staff of the Accelerator and Physics Divisions at Jefferson Laboratory that made this experiment successful. We thank Dr. J. Ryckebusch for theoretical calculations. We also thank Dr. J. M. Udias for providing the NLSH bound-state wave functions. This work was supported in part by the U.S. Department of Energy Contract No. DE-AC05-84ER40150 under which the Southeastern Universities Research Association (SURA) operates the Thomas Jefferson Accelerator and Physics Divisions at Jefferson Laboratory. We thank the Accelerator and Physics Divisions at Jefferson Laboratory for strength suggests that additional currents and processes play an important role.

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[1] The kinematical quantities are as follows: the electron scattered at angle $\theta_e$ transfers momentum $\vec{q}$ and energy $\omega$ with $Q^2 = \vec{q}^2 - \omega^2$. The ejected proton has mass $m_p$, momentum $\vec{p}_p$, energy $E_p$, and kinetic energy $T_p$. The cross section is typically measured as a function of missing energy $E_m = \omega - T_p - T_{\text{recoil}}$ and missing momentum $P_m = [\vec{q} - \vec{p}_p]$. The polar angle between the ejected proton and virtual photon is $\theta_{pq}$, and the azimuthal angle is $\phi$. $\theta_{pq} > 0^\circ$ corresponds to $\phi = 180^\circ$ and $\theta_{pq} > 0^\circ$, $\theta_{pq} < 0^\circ$ corresponds to $\phi = 0^\circ$.


[23] www.jlab.org/Hall-A/equipment/HRS.html


