Dynamical Relativistic Effects in Quasielastic 1p-Shell Proton Knockout from $^{16}$O


(The Jefferson Lab Hall A Collaboration)

1Université Blaise Pascal/IN2P3, F-63174 Aubière, France
2California State University, Los Angeles, California 90032
3Institut des Sciences Nucléaires, F-38026 Grenoble, France
4Duke University, Durham, North Carolina 27706
5Florida International University, Miami, Florida 33199
6Florida State University, Tallahassee, Florida 32306
7University of Georgia, Athens, Georgia 30602
8Hampton University, Hampton, Virginia 23668
9Harvard University, Cambridge, Massachusetts 02138
10INFN, Sezione di Bari and University of Bari, I-70126 Bari, Italy
11INFN, Sezione di Lecce, I-73100 Lecce, Italy
12INFN, Sezione Sanità and Istituto Superiore di Sanità, Laboratorio di Fisica, I-00161 Rome, Italy
13Kent State University, Kent, Ohio 44242
14University of Kentucky, Lexington, Kentucky 40506
15Kharkov Institute of Physics and Technology, Kharkov 310108, Ukraine
16University of Maryland, College Park, Maryland 20742
17Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
18University of New Hampshire, Durham, New Hampshire 03824
19Norfolk University, Norfolk, Virginia 23504
20North Carolina Central University, Durham, North Carolina 27707
21Old Dominion University, Norfolk, Virginia 23529
22Institut de Physique Nucléaire, F-94106 Orsay, France
23Princeton University, Princeton, New Jersey 08544
24University of Regina, Regina, Saskatchewan, Canada S4S 0A2
25Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854
26CEA Saclay, F-91191 Gif-sur-Yvette, France
27State University of New York at Stony Brook, Stony Brook, New York 11794
28Syracuse University, Syracuse, New York 13244
29Temple University, Philadelphia, Pennsylvania 19122
30Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
31Tohoku University, Sendai 980, Japan
32University of Virginia, Charlottesville, Virginia 22901
33College of William and Mary, Williamsburg, Virginia 23187
34Yamagata University, Yamagata 990, Japan
35Yerevan Physics Institute, Yerevan 375036, Armenia

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We have measured the cross section for quasielastic $1p$-shell proton knockout in the $^{16}$O$(e,e'p)$ reaction at $\omega = 0.439$ GeV and $Q^2 = 0.8$ (GeV/c)$^2$ for missing momentum $P_{\text{miss}} \leq 355$ MeV/c. We have extracted the response functions $R_{L+TT}$, $R_T$, and $R_{LT}$, and the left-right asymmetry, $A_{LT}$, for the $1p_{3/2}$ and the $1p_{1/2}$ states. The data are well described by relativistic distorted wave impulse approximation calculations. At large $P_{\text{miss}}$, the structure observed in $A_{LT}$ indicates the existence of dynamical relativistic effects.

Electron scattering is a powerful probe of the nuclear electromagnetic response [1,2]. Exclusive and semiexclusive proton knockout reactions, $(e,e'p)$, have long been used to study single-nucleon aspects of nuclear structure and to search for non-nucleonic degrees of freedom. At high four-momentum transfer squared [3], $Q^2$, quasielastic $(e,e'p)$ is expected to be dominated by single-body interactions, hence distorted wave impulse approximation (DWIA) calculations should be more accurate than at low $Q^2$. Calculations [4–7] indicate that in $^{16}$O$(e,e'p)$ the longitudinal-transverse interference response function [8], $R_{LT}$, and the left-right asymmetry, $A_{LT}$, are sensitive to dynamical enhancement of the distorted lower components of the Dirac spinors with respect to undistorted (free) spinors. The calculations predict that proper inclusion of these dynamical relativistic effects is needed to reproduce both $A_{LT}$ and $R_{LT}$. We report structure in $A_{LT}$ at large $P_{\text{miss}}$ that shows for the first time clear evidence of the existence of dynamical relativistic effects in electromagnetic reactions. $^{16}$O$(e,e'p)$ $1p$-shell proton knockout experiments have been performed at Saclay [9,10], NIKHEF [11,12], and Mainz [13] at low $Q^2$ [less than 0.4 (GeV/c)$^2$] in various kinematics. These experiments measured the cross section as a function of missing momentum and have extracted spectroscopic factors by comparing data to DWIA calculations. The published spectroscopic factors were between 0.5 and 0.7, but Kelly [2] showed that the data of Blomqvist et al. [13] suggest a significantly smaller normalization factor. Chinitz et al. [9] and Spaltrio et al. [12] also extracted $R_{LT}$, the longitudinal-transverse interference response function, at $Q^2 = 0.3$ (GeV/c)$^2$ and 0.2 (GeV/c)$^2$, respectively. Their measurements of proton knockout from the $1p_{1/2}$ state agree, but their $1p_{3/2}$-state measurements disagree dramatically. DWIA calculations [7] are consistent with the data of Chinitz et al. [9].

This paper reports the results [14] of the first experiment [15] in Jefferson Lab Hall A [16]. In this experiment, we measured the $^{16}$O$(e,e'p)$ reaction cross section in quasielastic kinematics ($\omega = Q^2/2p_0$) at $Q^2 = 0.8$ (GeV/c)$^2$ and $\omega = 0.439$ GeV for $P_{\text{miss}} < 355$ MeV/c. We separated the response functions $R_{L+TT}$, $R_T$, and $R_{LT}$, and extracted $A_{LT}$ for $1p$-shell proton knockout.

The 100% duty factor beam current of typically 70 $\mu$A was incident on a waterfall target with three foils, each about 130 mg/cm$^2$ thick along the beam line [17]. We used the two Hall A High Resolution Spectrometers [16] to detect the outgoing particles. We studied the spectrometer optical properties and acceptances both before and during the experiment. The angle of any tracked particle was determined to 0.3 mrad and its absolute momentum was measured with an accuracy $\delta p / p = 1.5 \times 10^{-3}$ [18–21].

The hydrogen in the H$_2$O target greatly simplified our normalizations and calibrations. We monitored the luminosity by continuously measuring the elastic $^1$H$(e,e')$ cross section. We used $^1$H$(e, ep)$ to determine the momentum transfer $Q^2$ absolutely to an accuracy of $1.5 \times 10^{-3}$ and to reproduce this momentum transfer at each beam energy to a fractional accuracy of $1.5 \times 10^{-4}$.

We measured the cross section at fixed $|Q^2| = 992$ MeV/c at three beam energies (corresponding to three virtual photon polarizations) to separate the response functions and understand our systematic uncertainties (see Table I). The angles $\theta_{pq} = 0^\circ$, $\pm 2.5^\circ$, $\pm 8^\circ$, $\pm 16^\circ$, and $\pm 20^\circ$ correspond to central missing momenta of 53, 60, 148, 280, and 345 MeV/c, respectively. Note that, at $\theta_{pq} = 0^\circ$, we had to remove events with $P_{\text{miss}} < 45$ MeV/c to eliminate contamination from $^1$H$(e, ep)$.

For $\theta_{pq} = \pm 8^\circ$, the values of $R_{LT}$ and $A_{LT}$ extracted at $E_{\text{beam}} = 2.4$ GeV agree with those extracted at $E_{\text{beam}} = 1.6$ GeV within 1 standard deviation. The overall systematic uncertainty in the 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 [22]. We also studied the effect of the finite acceptances of the spectrometers on the cross sections. The difference between the cross sections averaged over the spectrometer acceptances and calculated for a small region of the central kinematics was approximately 1%.

We radiatively corrected the cross section using a modified version of the code RADCOR [23]. The missing energy resolution is 0.9 MeV FWHM, which does not allow us to resolve the $(2s_{1/2}, 1d_{5/2})$ doublet located at $E_{\text{miss}} = 17.4$ MeV from the $1p_{3/2}$ state (at $E_{\text{miss}} = 18.4$ MeV).

### Table I. Experimental kinematics.

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$ (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, 16</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 strength of this doublet was estimated using the spectroscopic factors obtained by Leuschner et al. [11] to be approximately 5% of the $1p_{3/2}$ strength for this kinematical region. It was not subtracted from the cross section for the $1p_{3/2}$ state.

The first relativistic calculations for $(e,e')p$ were performed by Picklesimer and Van Orden [4,5]. We compared our data to more recent calculations by Udias et al. [6,24–26] and by Kelly [7]. Both calculations use the Coulomb gauge, the NLSH bound-state wave function [27], the energy dependent, atomic-mass independent parametrization for oxygen (EDAIO) optical potential of Cooper et al. [28], the cc2 current operator [29] (the use of cc1 yielded slightly poorer agreement with the data), and include the effects of electron distortion. We note that the NLSH wave function [27] yields values of binding and single-particle energies, as well as the charge radius for $^{16}$O, which are in good agreement with data. Udias et al. solved the Dirac equation directly in configuration space, whereas Kelly solved a relativized Schrödinger equation and used the effective momentum approximation (EMA) to incorporate spinor distortion into an effective current operator based on that of Hedayati-Poor et al. [30]. Effectively, the primary difference between these two calculations is that Kelly used the EMA approximation for the lower components of the Dirac spinors while Udias et al. solved the Dirac equation directly. To remain consistent with the experimental data, the $1p_{3/2}$ state in both calculations includes an incoherent contribution from the positive-parity contaminants as parametrized by Leuschner et al. [11].

Figure 1 shows the cross section as a function of missing momentum at $E_{beam} = 2.4$ GeV. The calculations of Udias et al. and Kelly are in very good agreement with the data. This agreement is attributed to the quality of the bound-state wave function used. The spectroscopic factors are 0.73 and 0.72 for the $1p_{1/2}$ state and 0.71 and 0.67 for the $1p_{3/2}$ state for the calculations of Udias et al. and Kelly, respectively.

We extracted $A_{LT}$ from the measured cross sections (see Fig. 2). Note the large change in the slope of $A_{LT}$ at $P_{miss} = 300$ MeV/$c$. The data are compared to calculations by Udias et al. and Kelly. In all of Udias’ calculations, the nucleon current is computed with a fully relativistic operator. The wave functions are four-component spinor solutions of the Dirac equation with scalar and vector potentials. As a result, their lower components are dynamically enhanced with respect to a solution of a Dirac equation without potentials (a free spinor). This dynamical effect of spinor distortions affects the $A_{LT}$ and $R_{LT}$ observables. To illustrate this point, we also present curves by Udias et al. in which this enhancement of the lower components is removed from the relativistic wave functions. Thus, the differences between the four Udias’ curves demonstrate only the effect of spinor distortions. In these curves, all other ingredients are kept the same (in particular, the relativistic structure of the current operator and the upper components of the Dirac spinors). Note that the dotted-dashed curve (no spinor distortions) is essentially identical to one resulting from factorized calculations. As can be seen in the calculations of Udias et al. in Fig. 2, distortion of the bound-state spinors is more important than that of the ejectile spinors, although both are needed. Also presented in Fig. 2 are calculations by Kelly, which include spinor distortions. Kelly also sees an effect due to distortion of the bound-state spinors, but, because of the approximations he makes, his calculations are not as accurate for $P_{miss} > 275$ MeV/$c$ [7].

We also extracted the response functions $R_{L+TT}$, $R_{LT}$, and $R_T$. Since we measured the cross sections in perpendicular kinematics, we could not isolate the longitudinal response function $R_L$. Instead, we extracted the combination $R_{L+TT} = R_L + \frac{\nu_T}{\nu_L} R_{TT}$. Both Kelly and Udias calculate the term $\frac{\nu_T}{\nu_L} R_{TT}$ to be small (<10%) for these kinematics. Figure 3 shows the response functions and calculations. Again, the calculations are in good agreement with the data. We note that spinor distortions are needed to reproduce $R_{LT}$ in the missing momentum range $P_{miss} < 275$ MeV/$c$ as well [6,26]. Hence, these relativistic dynamic effects are required to consistently reproduce both $R_{LT}$ and $A_{LT}$ over the entire measured $P_{miss}$ range. Moreover, neither calculation includes any two-body currents, suggesting that such currents are unimportant at this $Q^2$. This suggestion is further supported by calculations which estimate the contribution of meson exchange and isobar currents in $R_{LT}$ to be significant at lower $Q^2$ [31], but only
FIG. 2. Measured left-right asymmetry \( A_{LT} \) and DWIA calculations at \( E_{beam} = 2.4 \) GeV. The dashed line is the Kelly calculation [7]. The other curves are from Udias et al. [6,26]. The solid line is the fully relativistic calculation. The densely dotted line is the calculation with only the bound-state spinor distortion included. The loosely dotted line is the calculation with only the scattered-state spinor distortion included. The dotted-dashed line is the calculation without spinor distortion included, which is essentially identical to factorized calculations. The error bars shown include both statistical and systematic uncertainties.

FIG. 3. Measured \( R_{LT}, R_{LT}, R_L \), and DWIA calculations. The solid line is the Udias et al. calculation [6,26] and the dashed line is the Kelly calculation [7]. The data beyond 250 MeV/c missing momentum are expanded for clarity. The error bars shown include both statistical and systematic uncertainties.

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[3] The kinematical quantities are as follows: the scattered electron 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 \( E_{miss} = \omega - T_p - T_{recoil} \) and missing momentum \( \vec{P}_{miss} = \vec{q} - \vec{p}_p \). The angle between the ejected proton and virtual photon is \( \theta_{pq} \) and the azimuthal angle is \( \phi \). \( \theta_{pq} > 0 \) corresponds to \( \phi = 180^\circ \), \( E_{miss} > 0 \), and \( \theta_p > \theta_q \). \( \theta_{pq} < 0 \) corresponds to \( \phi = 0^\circ \).
[7] J. J. Kelly, Phys. Rev. C 60, 044609 (1999); the calculations were revised using the NLSH wave functions.
[8] The cross section for \( (e,e'p) \) can be written as \( \frac{d^3\sigma}{d\Omega\, du\, dE_{miss}} = \sum f_{R_i} V_i \times \Phi_{VT} \Phi_{RT} \times \cos\phi + \Phi_{LT} \Phi_{TL} \cos2\phi \) \( \times \), where the kinematic factors \( \{V_i\} \) are known and the response functions \( \{R_i\} \) contain information about the nuclear charge and current densities. One can extract response functions by measuring the cross section at fixed \( Q^2, \omega \), and \( \theta_{pq} \) while varying the electron.
scattering angle (which changes $V_T$) and $\phi$. One can also extract the left-right asymmetry by measuring the cross section at $\phi = 0, 180^\circ$: $A_{LT} = \frac{\sigma(\phi=0^\circ) - \sigma(\phi=180^\circ)}{\sigma(\phi=0^\circ) + \sigma(\phi=180^\circ)}$.

[14] www.jlab.org/~fissum/e89003.html
[16] www.jlab.org/Hall-A/equipment/HRS.html