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

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We have measured cross sections 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 $P_{miss} \leq 355$ MeV/c. This was the first experiment performed in Jefferson Lab Hall A. We have extracted the response functions R_{L+TT}, R_T, R_{LT}, and the left-right asymmetry A_{LT} for the $1p_{1/2}$ and the $1p_{3/2}$ states. The data are well described by relativistic DWIA calculations. At large P_{miss}, structure 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 semi-exclusive 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 large four-momentum transfer squared [1], 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 [3–6] indicate that in ^{16}O(e, e′p) the longitudinal-transverse interference response function [2], R_{LT}, and the left-right asymmetry, A_{LT}, are sensitive to dynamical relativistic effects. We report structure in A_{LT} at large P_{miss} that show for the first time clear evidence of the existence of dynamical relativistic effects.

^{16}O(e, e′p) $1p-$shell proton knockout experiments have been performed at Saclay [7,8], NIKHEF [9,10], and Mainz [11] at low Q^2 (less than 0.4 (GeV/c)^2) in various kinematics. Chinitz *et al.* [7], Bernheim *et al.* [8], Leuschner *et al.* [9], Spaltro *et al.* [10], and Blomqvist *et al.* [11] have measured the cross section as a function of missing momentum and have fit spectroscopic factors by comparing data to DWIA calculations. The published spectroscopic factors were between 0.5 and 0.7 except for those obtained by Blomqvist *et al.* [11], which were significantly lower. Chinitz *et al.* [7] and Spaltro *et al.* [10] 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 $1p_{3/2}$ measurements disagree dramatically. DWIA calculations [6] are consistent with the data of Chinitz *et al.* [7]

This paper reports the results [12] of the first experiment [13] in Jefferson Lab Hall A [14]. In this experiment we measured the ^{16}O(e, e′p) reaction cross section in quasielastic kinematics ($\omega = Q^2/2m_p$) at $Q^2 = 0.8$ (GeV/c)^2 and $\omega = 0.439$ GeV for $P_{miss} < 355$ 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 μA was incident on a waterfall target with three foils, each about 130 mg/cm^2 thick along the beamline [15]. We used the two Hall A High Resolution Spectrometers (further details can be found in Ref. [14]) to detect the outgoing particles. We studied the spectrometer optical properties and acceptances both before and during the experiment. The angle of the particle was determined to 0.3 mrad and its absolute momentum was measured with an accuracy $\frac{\delta p}{p} = 1.5 \times 10^{-3}$ [16–19].

The hydrogen in the H_2O target greatly simplified our normalizations and calibrations. We monitored the luminosity by continuously measuring the elastic H(e,e) cross section. We used H(e,ep) to determine the momentum transfer $|\vec{q}|$ absolutely to an accuracy of 1.5×10^{-3} and to reproduce this momentum transfer at each beam energy to a fractional accuracy of 1.5×10^{-4}.

We measured the cross section at fixed $|\vec{q}| = 992$ 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 $\theta_{pq} = 0°, \pm 2.5°, \pm 8°, \pm 16°$, and $\pm 20°$ correspond to central missing momenta of 53, 60, 148, 280, and 345 MeV/c, respectively. Note that at $\theta_{pq} = 0°$, we had to remove events with $P_{miss} < 45$ MeV/c to eliminate contamination from H(e, ep).

For $\theta_{pq} = \pm 8°$, the values of R_{LT} and A_{LT} extracted at $E_{\rm beam} = 2.4$ GeV agree with those extracted at $E_{\rm beam} = 1.6$ GeV within one standard deviation. The overall systematic uncertainty in the response functions is about 5%. This uncertainty is dominated by the uncertainty in the H(e, e) cross section to which the data were normalized [20].

We radiatively corrected the cross section using a modified version of the code RADCOR [21]. The missing energy resolution is 0.9 MeV FWHM, which does not allow us to resolve the $(2s_{1/2}, 1d_{5/2})$ doublet from the $1p_{3/2}$ state. The strength of this doublet was estimated using

[1] The kinematical quantities are as follows: the scattered electron transfers momentum $\vec{q}$ and energy ω 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 θ_{pq} and the azimuthal angle is ϕ. $\theta_{pq} > 0$ corresponds to $\phi = 180°, P_{miss} > 0$ and $\theta_p > \theta_q$. $\theta_{pq} < 0$ corresponds to $\phi = 0°$.

[2] The cross section for (e, e′p) can be written as $\frac{d^6\sigma}{d\Omega_e\, d\omega d\Omega_p\, dE_{miss}} = \frac{E_p p_p}{(2\pi)^3}\sigma_{\rm Mott}(V_L R_L + V_T R_T + V_{LT} R_{LT}\cos\phi + V_{TT} R_{TT}\cos 2\phi)$ 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, ω, and θ_{pq} while varying the electron scattering angle (which changes V_T) and ϕ. One can also extract the left-right asymmetry by measuring the cross section at $\phi = 0, 180°$: $A_{LT} = \frac{\sigma(\phi=0°) - \sigma(\phi=180°)}{\sigma(\phi=0°) + \sigma(\phi=180°)}$.

the spectroscopic factors obtained by Leuschner *et al.* [9] to be approximately 5% of the $1p_{3/2}$ strength for this kinematical region. It was not subtracted from the $1p_{3/2}$ cross section.

The first relativistic calculations for (e, e′p) were performed by Picklesimer and Van Orden [3,4]. We compared our data to more recent calculations by Udias *et al.* [5,22–24] and by Kelly [6]. Both calculations use the Coulomb gauge, the NLSH bound-state wavefunction [25], the EDAIO optical potential of Cooper *et al.* [26], the cc2 prescription of the off-shell e-p cross section [27] (the use of cc1 yielded slightly poorer agreement with the data), and include the effects of electron distortion. The results for the $1p_{3/2}$ state from both calculations include an incoherent contribution from the positive-parity contaminants as parametrized by Leuschner *et al.* [9]. Udias *et al.* solved the Dirac equation in configuration space, while 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.* [28]. The primary difference between these two calculations is that Kelly used an EMA approximation for the lower components of the Dirac spinors while Udias *et al.* solved the Dirac equation directly.

Figure 1 shows the cross section as a function of missing momentum at $E_{\rm beam} = 2.4$ GeV. The calculations of Udias *et al.* and of Kelly are in excellent agreement with the data. This agreement is attributed to the quality of the bound-state wave function used. We note that the NLSH [25] wave function yields values of binding and single-particle energies, as well as the charge radius for ^{16}O, which are in good agreement with data. 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 Figure 2). Note the large change in the slope of A_{LT} at $P_{miss} \approx 300$ MeV/c. This change in slope is reproduced, at least qualitatively, by both calculations, although only when they include distortions of the lower components of the Dirac spinors. As can be seen in the calculations of Udias *et al.* in Figure 2, distortion of the bound-state spinors is more important than that of the ejectile spinors, although both are needed. Kelly also sees an effect due to distortion of the bound-state spinors, but due to approximations he makes, his calculations are not as accurate for $P_{miss} > 275$ MeV/c [6].

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 $R_{L+TT} = R_L + \frac{V_{TT}}{V_L} R_{TT}$. Both Kelly and Udias calculate that R_{TT} is small ($< 10\%$) for these kinematics. Figure 3 shows the response functions and calculations. Again, the calculations are in excellent agreement with the data. Moreover, neither calculation includes any two-body currents.

In summary, we have measured ^{16}O(e, e′p) $1p-$shell proton knockout in a previously inaccessible region of momentum transfer. These measurements included cross sections, the left-right asymmetry A_{LT}, and the response functions R_{L+TT}, R_{LT}, and R_T for missing momentum up to approximately 350 MeV/c. Our cross sections, asymmetries, and response functions are in very good agreement with modern relativistic DWIA calculations without the addition of any two-body currents. We see structure in A_{LT} at higher missing momentum which is due to dynamic enhancement of the lower components of Dirac spinors.

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$E_{\rm beam}$ (GeV)	θ_e (°)	θ_{pq} (°)
0.843	100.7	0, 8, 16
1.643	37.2	0, 8
2.442	23.4	0, ±2.5, ±8, ±16, ±20

TABLE I. Experimental Kinematics

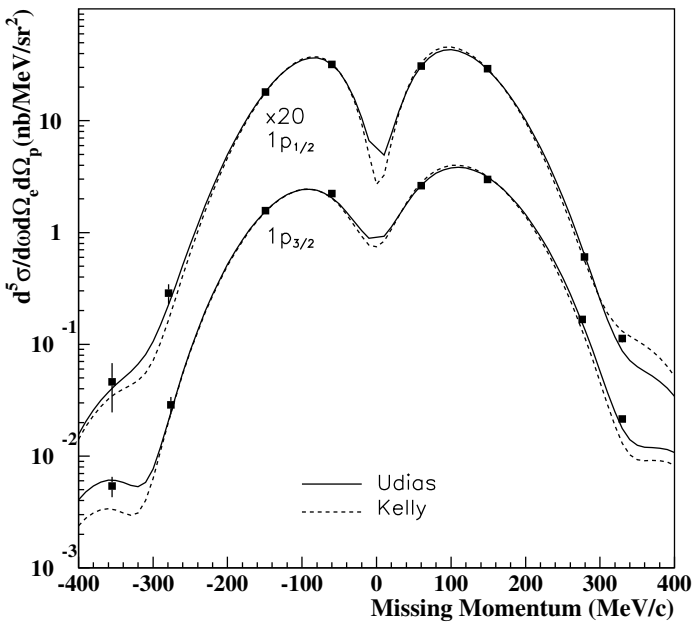

FIG. 1. Measured cross sections and DWIA calculations at $E_{\rm beam} = 2.4$ GeV. The solid line is the Udias *et al.* calculation [5,24], and the dashed line is the Kelly calculation [6]. The $1p_{1/2}$ state cross section and calculations have been multiplied by a factor of 20.

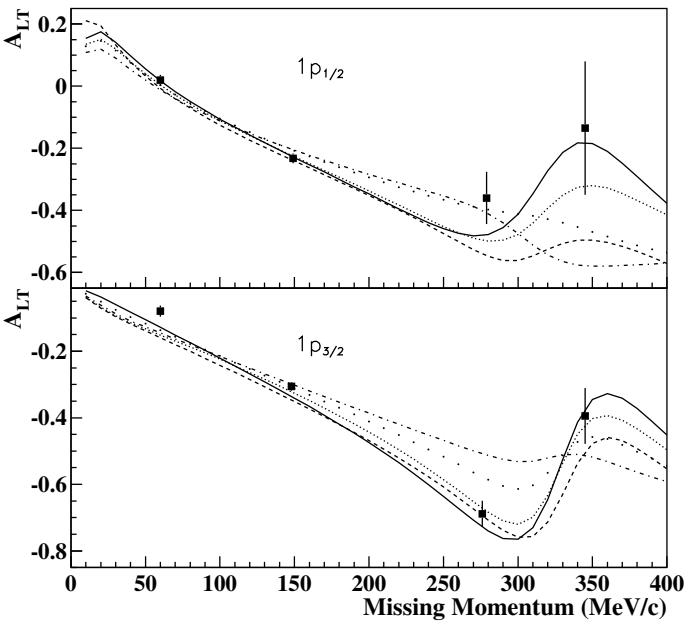

FIG. 2. Measured left-right asymmetry A_{LT} and DWIA calculations at $E_{\rm beam} = 2.4$ GeV. The dashed line is the Kelly calculation [6]. The rest of the curves are from Udias *et al.* [5,24]. The solid line is the fully relativistic calculation, the close dotted line is the calculation with only the bound-state spinor distortion included, the wide dotted line is the calculation with only the scattered-state spinor distortion included, and the dot-dashed line is the calculation without spinor distortion included.

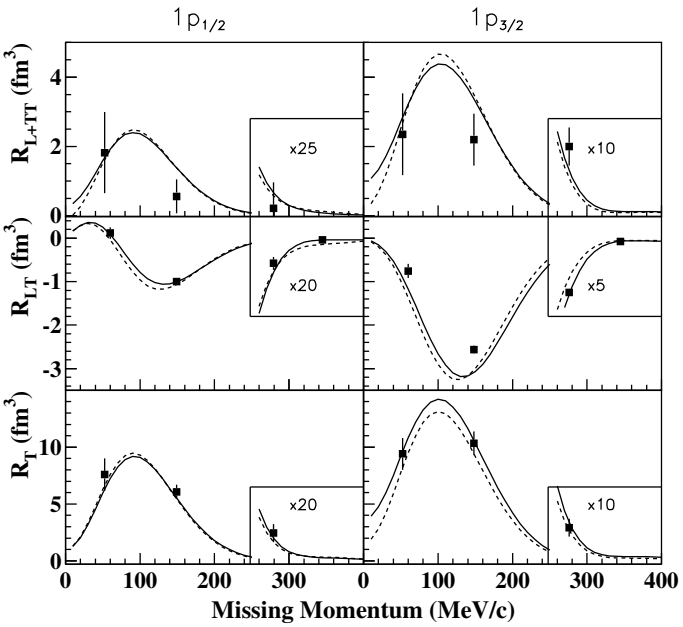

FIG. 3. Measured R_{L+TT}, R_{LT}, R_T and DWIA calculations. The solid line is the Udias *et al.* calculation [5,24] and the dashed line is the Kelly calculation [6]. The data beyond 250 MeV/c missing momentum are expanded for clarity.