Quasielastic $1p$ state Proton Knockout from ^{16}O at $Q^2 = 0.8$ (GeV/c)^2

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(July 9, 1999)

In Jefferson Lab Hall A, we have measured cross sections for quasielastic $1p$ state 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. 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. At large P_{miss}, we have observed structure in A_{LT}. In contrast to some previous measurements at lower Q^2, our data are very well described by relativistic DWIA calculations.

Exclusive coincidence electron scattering, (e, e′p), is a powerful probe of the nuclear electromagnetic response [1,2]. It has been used to study single-nucleon aspects of nuclear structure and to search for non-nucleonic degrees of freedom.

^{16}O(e, e′p) $1p$ state proton knockout experiments have been performed at NIKHEF [3,4], Saclay [5,6], and Mainz [7] at low four-momentum transfers ($Q^2 < 0.4$ (GeV/c)^2) in various kinematics.[1] Bernheim *et al.*, Leuschner *et al.*, Chinitz *et al.*, and Blomqvist *et al.* have measured the cross section as a function of missing momentum and have fit spectroscopic factors by comparing data to Distorted Wave Impulse Approximation (DWIA) calculations. The published spectroscopic factors were between 0.5 and 0.7 except for Blomqvist *et al.*'s, which was significantly lower. Chinitz *et al.* and Spaltro *et al.* also extracted the longitudinal-transverse interference response function R_{LT}[2] in perpendicular kinematics. Their measurements of proton knockout from the $1p_{1/2}$ state agree but their $1p_{3/2}$ measurements disagree dramatically.

At high Q^2, quasielastic (e, e′p) is expected to be dominated by one-body currents, hence DWIA calculations should be more accurate. Calculations, as well as data at lower Q^2, show that R_{LT} and the left-right asymmetry A_{LT} are sensitive to dynamical relativistic effects [6,8–10].

This paper reports the results of the first experiment in Jefferson Lab Hall A [16,17]. In this experiment we measured the ^{16}O(e, e′p) reaction cross section at 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 A_{LT} and the response functions R_{L+TT}, R_T, and R_{LT} for $1p$ state proton knockout.

The 100% duty factor beam current was typically 70 μA and was incident on a waterfall target with three foils, each about 130 mg/cm^2 thick along the beamline [18]. We used the two Hall A High Resolution Spectrometers [19] to detect the outgoing particles and carefully studied their optical properties [20,21] and acceptances [19] both before and during the experiment. The angle of the particle was determined to 0.3 mrad and the absolute momentum of the particle was measured to $\frac{\delta p}{p} = 1.5 \times 10^{-3}$. We also surveyed the central angles and offsets of each spectrometer at all locations to an accuracy of 0.02 mr and 0.5 mm [22].

The hydrogen in the H_2O target greatly simplified our normalizations and calibrations. We monitored the luminosity by continuously measuring H(e, e′) and determined $\vec{q}$ by measuring H(e, e′p).

We measured the cross section at fixed $|\vec{q}\,| = 992$ MeV/c at three beam energies (virtual photon polarizations) to redundantly separate the response functions and understand our systematic uncertainties (see Table I). We reproduced this momentum transfer at each beam energy to an accuracy of 1.5×10^{-4} using H(e, e′p). 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 the data at $P_{miss} < 45$ MeV/c to eliminate contamination from H(e, e′p).

For $\theta_{pq} = \pm 8°$, R_{LT} and A_{LT} extracted at $E_{beam} = 2.4$ GeV agree with those extracted at $E_{beam} = 1.6$ GeV within one standard deviation. The overall systematic uncertainty in the response functions is about 5%. This uncertainty is dominated by the uncertainty of the H(e, e′) cross section to which the data were normalized [23].

The radiatively corrected ^{16}O(e, e′p) cross section as a function of missing energy for $E_{beam} = 2.4$ GeV at $P_{miss} \approx 60$ MeV/c is shown in Figure 1. The two prominent peaks at $E_{miss} = 12.1$ and 18.4 MeV correspond to protons knocked-out from the $1p_{1/2}$ and $1p_{3/2}$ states. The missing energy resolution is 0.9 MeV FWHM. This does not allow us to separate the $(2s_{1/2}, 1d_{5/2})$ doublet located at $E_{miss} = 17.4$ MeV. The strength of this doublet has been estimated using the spectroscopic factors obtained by Leuschner *et al.* [3]. It is small for this kinemat-

[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 $\vec{p}_p$, 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 $P_{miss} = |\vec{q} - \vec{p}_p|$. The angle between the ejected proton and virtual photon is θ_{pq} and the out-of-plane angle is ϕ. Positive θ_{pq} corresponds to $\phi = 180°$ and $\theta_p > \theta_q$. Negative θ_{pq} corresponds to $\phi = 0°$.

[2] The cross section for (e, e′p) can be written as $\frac{d^4\sigma}{d\Omega_e\, d\omega\, d\Omega_p\, dE_{miss}} = E_f p_p \sigma_{Mott}(V_L R_L + V_T R_T + V_{LT} R_{LT} \cos\phi_{pq} + V_{TT} R_{TT} \cos 2\phi_p q)$ where E_f is the final electron energy, 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_{pq}. One can also extract the left-right asymmetry by measuring the cross section at $\phi_{pq} = 0, 180°$: $A_{LT} = \frac{\sigma(\phi=0°) - \sigma(\phi=180°)}{\sigma(\phi=0°) + \sigma(\phi=180°)}$.

ical region and has not been subtracted from the $1p_{3/2}$ cross section. The peak at 22 MeV is a complex multi-state cluster that we did not investigate. The broad peak centered at $E_{miss} \approx 42$ MeV is due to proton knockout from the $1s_{1/2}$ state.

We compared our data to three DWIA calculations. The model of Picklesimer and Van Orden [8,24] is based on a Dirac optical model using Horowitz and Serot [25] bound state wave functions, the standard relativistic Dirac-plus-Pauli current operator form, and the Franey-Love Impulse Approximation parameterization of the Dirac optical potential. Kelly [9] solved the relativized Schrödinger equation in an effective momentum approximation in coordinate space to incorporate spinor distortion using an effective current operator based on Hedayati-Poor *et al.* [26] The calculations shown here use the cc2 vertex function with off-shell extrapolation [27], the energy-dependent EDAIO optical potential of Hama *et al.* [28] for ^{16}O, Dirac-Hartree wave functions [25], and include electron distortion. Udias *et al.* [10–12] computed the amplitude for the process in configuration space, solving the Dirac equation for the bound and the scattered state by considering the whole operator structure of the $\vec{\sigma} \cdot \vec{p}$ operator for both the upper and lower components. They also included electron distortion. The main difference between the calculations of Udias and Van Orden is that Udias works in configuration space instead of momentum space and uses more modern bound state wave functions and optical potentials.

Figure 2 shows the measured momentum distribution at $E_{beam} = 2.4$ GeV. The calculations of Udias are in excellent agreement with the data, whereas the calculations of Van Orden and Kelly are in good agreement up to $P_{miss} = 280$ MeV/c. The spectroscopic factors are 0.75, 0.61, and 0.61 for the $1p_{1/2}$ state and 0.75, 0.67, and 0.62 for the $1p_{3/2}$ state for the calculations of Udias, Van Orden, and Kelly, respectively.

We extracted the left-right asymmetry A_{LT} from the measured cross sections (see Figure 3). The Udias calculations describe the data significantly better than the others. Note the large change in slope of A_{LT} at $P_{miss} \approx 300$ MeV/c. The importance of performing unfactorized calculations is shown by the fact that neither the Udias calculations using an asymptotic final-state momentum nor the Van Orden calculations in Plane Wave Impulse Approximation (PWIA) reproduce this feature [13,14]. Fully relativistic calculations are unfactorized as they include both positive and negative energy components of the wave function and do not impose the stringent relationship between the upper and lower components of the wave function such that the single-nucleon amplitudes follow the same behavior as the amplitudes for the free nucleon [15].

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 $R_{L+TT} = R_L + \frac{V_{TT}}{V_L} R_{TT}$. R_{TT} is small ($< 10\%$) for these kinematics. Figure 4 shows the response functions and calculations. The calculations agree with the data.

We used Kelly's DWIA calculations to compute consistent spectroscopic factors for the existing data (see Table II). Most of the experiments are reasonably consistent, although the spectroscopic factors of Blomqvist *et al.* appear to be significantly smaller than those of the other data sets. We also used Kelly's calculations to compare our R_{LT} to those of Chinitz *et al.* and Spaltro *et al.* While our R_{LT} for the $1p_{1/2}$ state agrees with both, our value for $1p_{3/2}$ is consistent with Chinitz *et al.* and inconsistent with Spaltro *et al.*

In summary, we have measured ^{16}O(e, e′p) $1p$ state 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 less than 355 MeV/c. Despite the very large difference in Q^2, this data set is consistent with previous measurements, except for the $1p_{1/2}$ and $1p_{3/2}$ spectroscopic factors of Blomqvist *et al.* and the $1p_{3/2}$ R_{LT} of Spaltro *et al.* We see structure in A_{LT} at higher missing momentum which is consistent with the prediction of relativistic DWIA calculations and is sensitive to the proper inclusion of the negative-energy components within its framework. Our cross sections, asymmetries and response functions are in excellent agreement with the relativistic DWIA calculations of Udias *et al.*

We acknowledge the outstanding support of the staff of the Accelerator and Physics Divisions of Jefferson Laboratory that made this experiment successful. We thank Drs. T.W. Donnelly, J.M. Udias, and J.W. Van Orden for providing their theoretical calculations and for valuable discussions. This work was supported in part by DOE.

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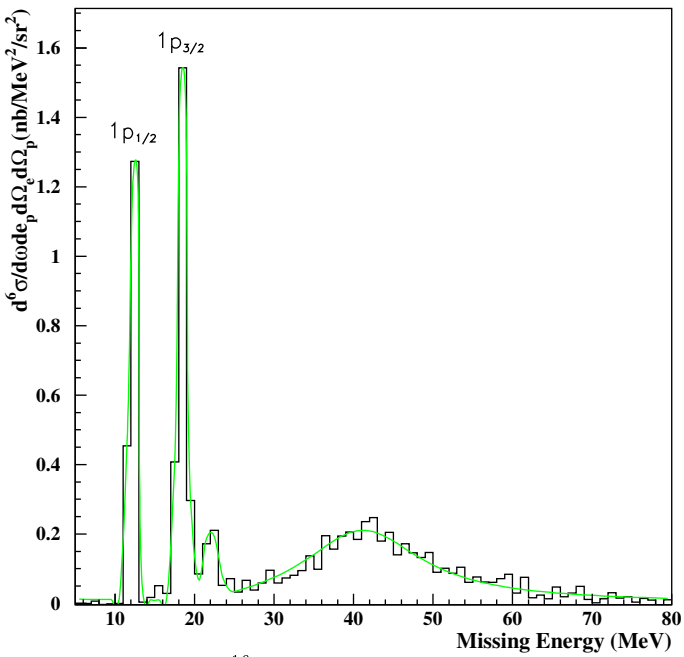

FIG. 1. Measured ^{16}O(e, e′p) missing energy spectrum for $E_{beam} = 2.4$ GeV at $P_{miss} = 60$ MeV/c.

Beam Energy	θ_e	θ_{pq}
0.845 GeV	100.7	$0, 8^\circ, 16^\circ$
1.643 GeV	37.2	$0, \pm 8^\circ$
2.442 GeV	23.4	$0, \pm 2.5^\circ, \pm 8^\circ, \pm 16^\circ, \pm 20^\circ$

TABLE I. Experimental Kinematics

Data	x_B	T_p (MeV)	$1p_{1/2}$	$1p_{3/2}$
Spaltro *et al.* [4]	1.0	84	0.63	0.67
Leuschner *et al.* [3]	$0.04 - 1.7$	96	0.55	0.50
Bernheim *et al.* [5]	0.9	100	0.50	0.50
Chinitz *et al.* [6]	0.9	160	0.55	0.55
Blomqvist *et al.* [7]	$0.1 - 0.6$	196	0.42	0.36
Gao *et al.*	1.0	427	0.61	0.62

TABLE II. Deduced spectroscopic factors using DWIA from Kelly [9]. $x_B = Q^2/2m\omega$ is the Björken scaling variable, approximately unity for quasielastic kinematics.

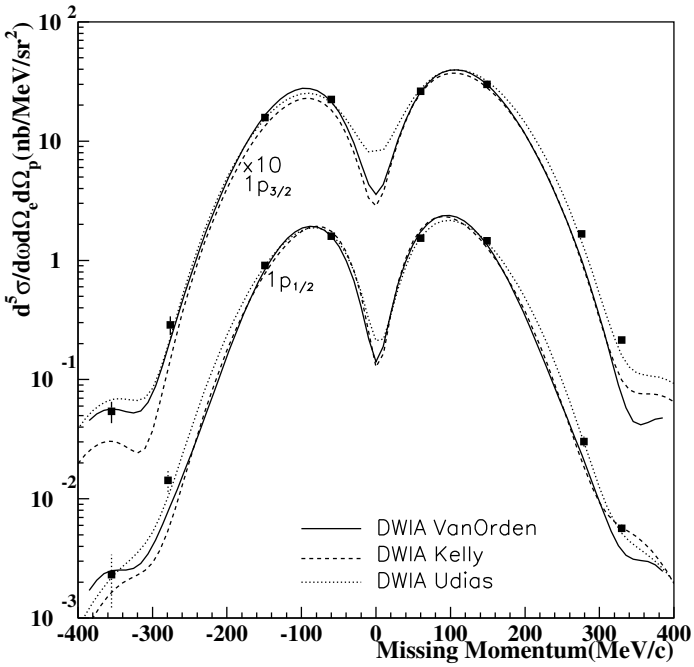

FIG. 2. Measured cross sections and DWIA calculations at $E_{beam} = 2.4$ GeV. The solid line is the Van Orden [8,24], the dashed line is the Kelly [9], and the dotted line is the Udias [10] calculation. The $1p_{3/2}$-state cross section and calculation have been multiplied by a factor of 10.

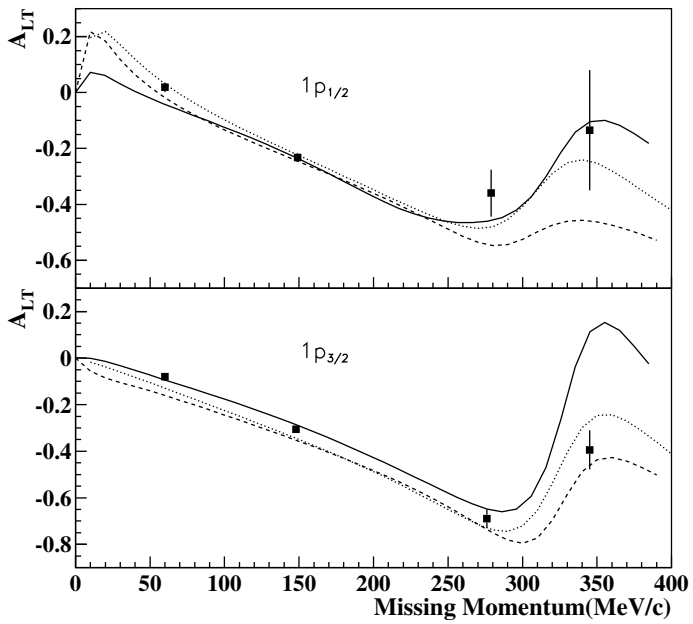

FIG. 3. Measured left-right asymmetry A_{LT} and DWIA calculations at $E_{beam} = 2.4$ GeV. The solid line is the Van Orden [8,24], the dashed line is the Kelly [9], and the dotted line is the Udias [10] calculation.

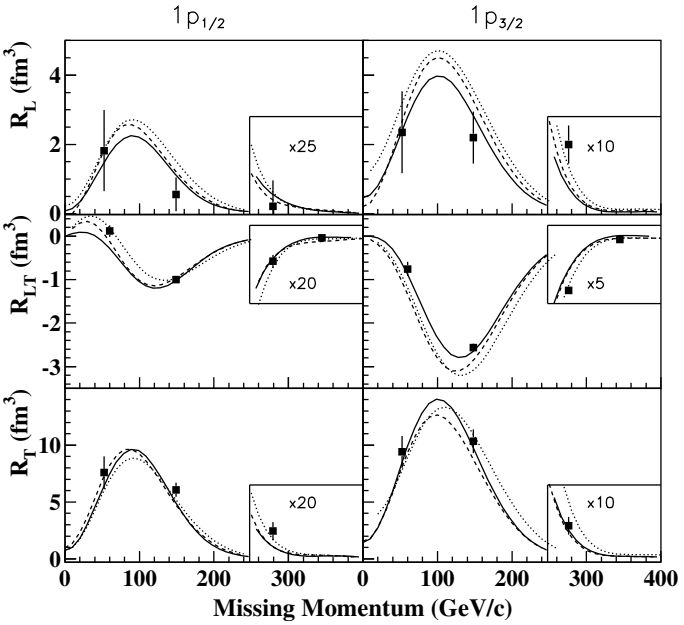

FIG. 4. Measured R_{L+TT}, R_{LT} and R_T and DWIA calculations. The solid line is the Van Orden [8,24], the dashed line is the Kelly [9], and the dotted line is the Udias [10] calculation. The data beyond 250 MeV/c missing momentum have been expanded for clarity.