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

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(June 11, 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. The response functions R_{L+TT}, R_T, R_{LT}, and the left-right asymmetry A_{LT} have been extracted for the $1p_{1/2}$ and the $1p_{3/2}$ states. For $P_{miss} < 280$ MeV/c, the data are well described by DWIA calculations. This is in contrast to some previous measurements at lower Q^2. At large P_{miss}, we have observed structure in A_{LT}, which qualitatively indicates the existence of relativistic effects.

Exclusive coincidence electron scattering, (e, e′p), is a powerful probe of the nuclear electromagnetic response [1]. 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 [2] [3], Saclay [4], and Mainz [5] at low four-momentum transfer ($Q^2 < 0.4$ (GeV/c)^2) in various kinematics.[1] Leuschner *et al.* [2] measured the cross section in parallel kinematics as a function of missing momentum and extracted spectroscopic factors of approximately 0.6 using a Distorted Wave Impulse Approximation (DWIA) analysis. This is consistent with valence state spectroscopic factors measured on other nuclei. Blomqvist *et al.* [5] measured the cross section as a function of missing momentum up to $P_{miss} = 700$ MeV/c, however their data is only 50 to 60% of their DWIA calculation. Chinitz *et al.* [4] and Spaltro *et al.* [3] extracted the longitudinal-transverse interference response function R_{LT} in perpendicular kinematics. This response function is much more sensitive to relativistic effects than the total cross section. Their measurements of proton knockout from the $1p_{1/2}$ state agree but their $1p_{3/2}$ measurements disagree dramatically.

The theoretical description of these experiments is typically performed using DWIA, where one proton absorbs the virtual photon and interacts with the rest of the nucleus as it emerges. The final state interaction (FSI) between the knocked-out proton and the residual nucleus is usually described by an optical potential derived from fits to existing proton-nucleus scattering data. Meson exchange currents (MEC) and isobar currents (IC) also contribute to this process. At high Q^2, quasielastic (e, e′p) is expected to be dominated by one-body currents, however, relativistic effects become larger. Calculations show that the longitudinal-transverse response function R_{LT} and the left-right asymmetry A_{LT} are sensitive to relativistic effects [6,7].

This paper reports the results of the first experiment in Jefferson Lab Hall A, Experiment E89-003 [8,9], which measured the cross section and separated the response functions R_{L+TT}, R_T, and R_{LT} for $1p$-state proton knockout at quasielastic kinematics ($\omega = Q^2/2m$) at $Q^2 = 0.8$ (GeV/c)^2 for $P_{miss} < 355$ MeV/c. We used the two Hall A high resolution spectrometers, HRSe and HRSh, to detect electrons and protons respectively. At the focal plane of each spectrometer two Vertical Drift Chambers and two scintillator planes provide the trigger and measure the trajectory and time-of-flight of each particle. In addition, a CO_2 gas Cerenkov detector located on HRSe separates electrons from π^-. The optical properties [10,11] and acceptance [12] of the spectrometers were carefully studied and quantified 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 1.5×10^{-3}. We used a waterfall target with three foils, each about 130 mg/cm^2 thick along the beamline. The typical 100% duty factor beam current was $\sim$70 μA.

We fixed the kinematics of this experiment at $Q^2 = 0.8$ (GeV/c)^2, $\omega = 0.439$ GeV, and $T_p = 0.427$ GeV. Because we chose a H_2O target and kept the electron spectrometer fixed at quasielastic kinematics ($\omega = Q^2/2m$), H(e, e′) was used as a continuous luminosity monitor. Further, H(e, e′p) was used to determine the $\vec{q}$ precisely.

We measured the cross section section as a function of missing momentum by changing θ_{pq}. We measured the cross section at three beam energies ($E_{beam} = 0.843$ GeV, 1.643 GeV, and 2.442 GeV) to redundantly separate the response functions and understand our systematic uncertainties. At $E_{beam} = 2.442$ GeV, data were taken at $\theta_{pq} = 0°, \pm 2.5° \pm 8°, \pm 16°$, and $\pm 20°$; at $E_{beam} = 0.843$ GeV data were taken at $\theta_{pq} = 0°, +8°$ and $+16°$; and at $E_{beam} = 1.643$ GeV data were taken with $\theta_{pq} = 0°, \pm 8°$. The angles $0°, \pm 2.5° \pm 8°, \pm 16°$, and $\pm 20°$ correspond to central missing momenta of 53, 60, 148, 280, and 345 MeV/c. [2] 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 $E_{beam} = 2.442$ GeV agree with those extracted from $E_{beam} = 1.643$ GeV within one standard deviation. The overall systematic error in the extracted response functions was

[1] The kinematical quantities are as follows: the scattered electron transfers momentum $\vec{q}$ and energy ω with $Q^2 = q^2 - \omega^2$. The ejected proton has momentum $\vec{p}_p$ and 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.

[2] Positive θ_{pq} corresponds to $\phi = 180°$ and $\theta_p > \theta_q$. Negative θ_{pq} corresponds to $\phi = 0°$.

estimated to be about 5%. It was dominated by the uncertainty of the H(e, e′) cross section to which the data were normalized [13].

The radiatively corrected ^{16}O(e, e′p) cross section as a function of missing energy for E_{beam} = 2.442 GeV at $P_{miss} \approx 60$ MeV/c is shown in Fig. 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 (FWHM) of 0.9 MeV corresponds to 4×10^{-4} of the beam energy. The broad peak centered at $E_{miss} \approx 42$ MeV is due to proton knockout from the $1s_{1/2}$ state. The spectroscopic factor of the $1s_{1/2}$ state obtained by fitting a DWIA calculation using the energy dependent Lorentzian parametrization [14] is about 88%. The strength of the $(2s_{1/2}, 1d_{5/2})$ doublet located at E_{miss} = 17.4 MeV has been estimated using the spectroscopic factors obtained by Leuschner *et al* [2]. It is small for this kinematical region and has not been subtracted from the $1p_{3/2}$ cross section.

The measured momentum distribution at 2.442 GeV is in good agreement with the relativistic DWIA calculations of Kelly [6,15] and of Van Orden [16–19] for missing momentum less than 280 MeV/c (see Fig. 2). At higher missing momentum, there is some discrepancy between the data and the calculations. The spectroscopic factors for Van Orden's calculations are 0.61 and 0.67 for the $1p_{1/2}$ and $1p_{3/2}$ states respectively. The spectroscopic factors for Kelly's calculations are 0.61 for $1p_{1/2}$ state and 0.62 $1p_{3/2}$ states (see Table I).

We extracted the left-right asymmetry ($A_{LT} = \frac{\sigma(\phi=0°)-\sigma(\phi=180°)}{\sigma(\phi=0°)+\sigma(\phi=180°)}$) from the measured cross sections at $\pm\theta_{pq}$. A_{LT} agree with both relativistic and nonrelativistic DWIA calculations for $P_{miss} < 200$ MeV/c (see Fig. 3). At larger missing momentum, the different calculations diverge: the relativistic DWIA calculations from Kelly [6], Udias [7], and Van Orden [16–19] all predict a slope change in A_{LT} while Kelly's non-relativistic calculations keep decreasing. The data qualitatively agree with the relativistic calculations. In Kelly's model, the relativistic effects at high P_{miss} are mainly due to dynamical enhancement of the lower components of the Dirac spinors in the bound state wave function. The magnitude and shape of the asymmetry at high P_{miss} are very sensitive to FSIs.

We also extracted the the response functions R_{L+TT}, R_{LT}, and R_T. These are reasonably consistent with both DWIA calculations (see Fig. 4).

We used Kelly's DWIA calculations in order to have a single calculation to compute spectroscopic factors for the existing data (see table I). The spectroscopic factors of Blomqvist *et al.* appear to be significantly smaller than those of the other data sets. In addition, since Kelly's calculations describe the $1p_{3/2}$ R_{LT} measured by Chinitz *et al.* [4] but underestimate the $1p_{3/2}$ R_{LT} measured by Spaltro *et al.* [3], the consistency between the calculations of Kelly and the R_{LT} measurement from this experiment indicates that this data set agrees with that of Chinitz *et al.* [4] but disagrees with that of Spaltro *et al.* [3]

In summary, we have measured, in a previously inaccessible region of momentum transfer, cross sections and the response functions R_{L+TT}, R_{LT}, and R_T for ^{16}O(e, e′p) $1p$-state proton knockout. At missing momentum less than 280 MeV/c, the data are in reasonably good agreement with the DWIA calculations. At higher missing momentum, structure in A_{LT} has been observed, which is qualitatively consistent with the prediction of relativistic DWIA calculations. By using the DWIA calculations from Kelly, this data set is consistent with the data of Leuschner *et al.* [2] and Chinitz *et al.* [4] but disagree with those of Spaltro *et al.* [3] and Blomqvist *et al.* [5]

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

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	Kinematics	$1p_{1/2}$	$1p_{3/2}$
Blomqvist [5]	$x \sim 0.66$, $T_p \sim 196$ MeV	0.42	0.36
Chinitz [4]	$x \sim 0.89$, $T_p \sim 160$ MeV	0.55	0.55
Gao [12]	$x \sim 0.97$, $T_p \sim 427$ MeV	0.61	0.62
Leuschner [2]	$0.08 < x < 1.5$, $T_p \sim 96$ MeV	0.55	0.50
Spaltro [3]	$x \sim 1.03$, $T_p \sim 84$ MeV	0.63	0.67

TABLE I. Deduced spectroscopic factors using DWIA from Kelly [6] for the existing data sets. x is the Bjorken scaling variable, approximately unity for quasielastic kinematics.

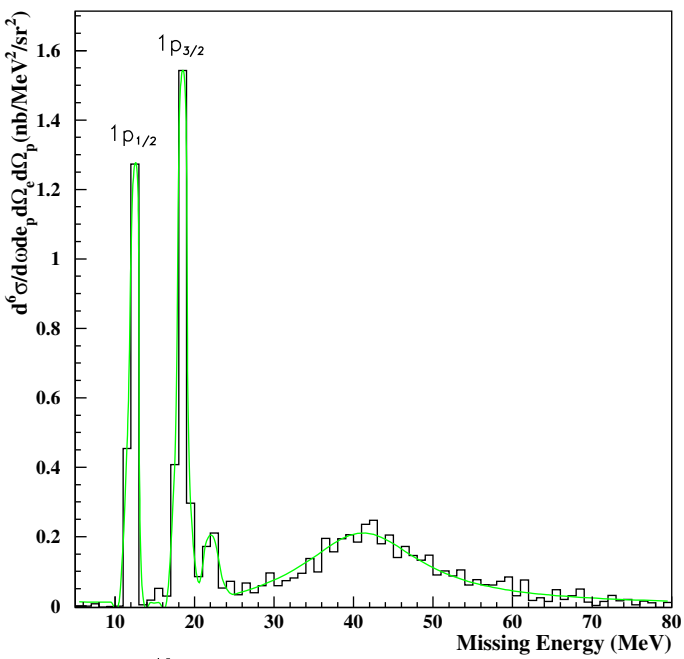

FIG. 1. ^{16}O(e, e′p) missing energy spectrum for E_{beam} = 2.4 GeV at missing momentum 60 MeV/c. The $1p_{1/2}$ and $1p_{3/2}$ states are clearly visible. The FWHM missing energy resolution is ∼0.9 MeV. The spectroscopic factor (88%) for the $1s_{1/2}$-state (broad bump peaked at E_{miss} = 42 MeV) was obtained by fitting a DWIA calculation with an energy-dependent Lorentzian parametrization [14].

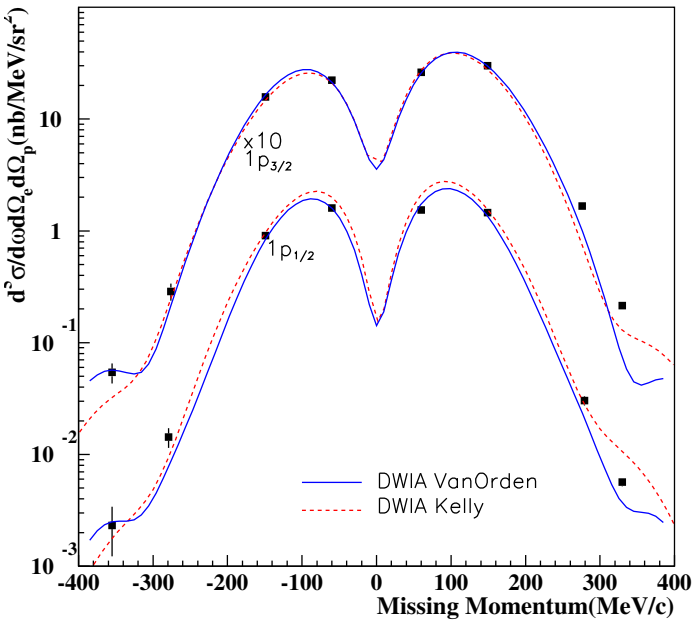

FIG. 2. A comparison between the measured cross sections and DWIA calculations at E_{beam} = 2.442 GeV. The solid line is the Van Orden [16–19] and the dashed line is the Kelly calculation [6]. The $1p_{3/2}$-state cross section and calculation have been multiplied by a factor of 10.

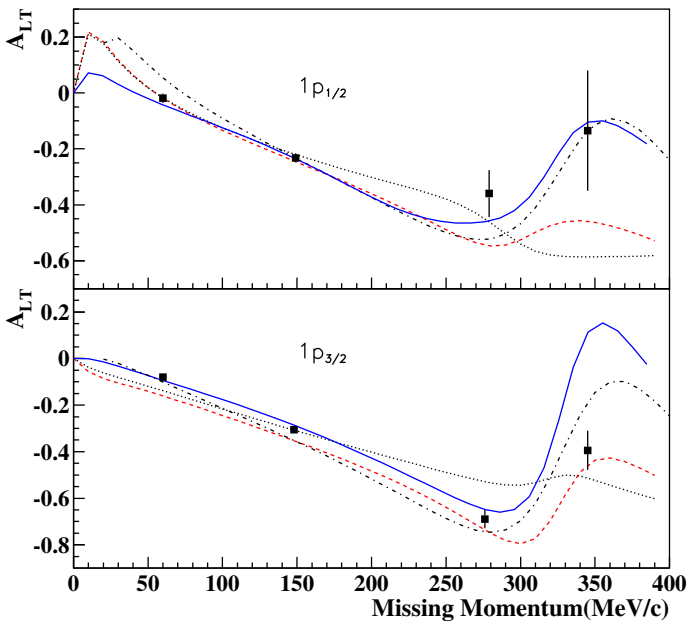

FIG. 3. A comparison between the left-right asymmetry A_{LT} and the DWIA calculations at E_{beam} = 2.442 GeV. The dashed line is from Kelly [6] and includes spinor distortion while the dotted line, also from Kelly, does not. The dash-dotted line is from Udias [7]. The solid line is from Van Orden [16–19].

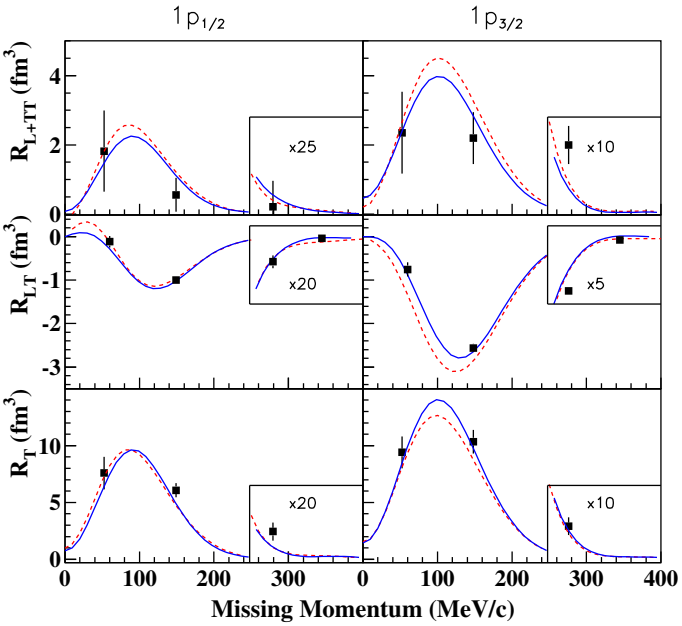

FIG. 4. A comparison between R_{L+TT}, R_{LT} and R_T and the DWIA calculations. The solid line is from Van Orden [16–19] and the dashed line is from Kelly [6]. The data beyond 250 MeV/c missing momentum have been expanded for clarity.