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# Quasielastic 1p-shell proton knockout from $^{16}$O at $Q^2 = 0.8$ (GeV/c)$^2$

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In Hall A, Jefferson Laboratory, we have measured the cross sections for 1p-shell proton knockout in $^{16}$O(e, e$'$p) reaction at $\omega = 439$ and $Q^2 = 0.8$ (GeV/c)$^2$ for $P_{miss} \leq 355$ 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 all well described by DWIA calculations. This is in contrast to some previous measurements at lower $Q^2$. At large missing momentum, the data seem to prefer relativistic DWIA calculations.

Electro-nucleon knockout from the nucleus provides a powerful probe of electromagnetic properties of nuclei and nucleon momentum distributions in them [1]. In the Impulse Approximation (IA), the nucleon absorbs the virtual photon emitted by the incident electron and interacts with the rest of the nucleus as it emerges. The final state interaction (FSI) between the knocked-out nucleon and the residual nucleus is usually described by an optical potential derived from fits to existing nucleon-nucleus scattering data. Meson exchange currents (MEC) and isobar currents (IC) also contribute to this process. The mechanism of nucleon knockout has been widely studied by quasielastic (e, e'p) from discrete states of nuclei. $^{16}$O is a unique candidate for this study. It is a doubly-magic, closed-shell nucleus. The proton configuration of $^{16}$O is $(1s_{1/2})^2(1p_{3/2})^4(1p_{1/2})^2$. The binding energy is 12.1 MeV for the $1p_{1/2}$ state and 18.4 MeV for the $1p_{3/2}$ state. The bound state wavefunctions are relatively easy to calculate. As proton elastic scattering from $^{16}$O has been studied over a wide range of kinematics, the final state interactions for the $^{16}$O(e, e'p) reaction are well-understood. Therefore, good predictions for both the cross sections and the response functions may be derived.

In the one photon exchange approximation, the five-fold cross section for $^{16}$O(e, e'p) 1$p$-shell proton knockout can be written as $d^5\sigma/d\omega d\Omega_e d\Omega_p = K\sigma_{Mott}\ (V_L R_L + V_T R_T + V_{LT} R_{LT}\cos\phi + V_{TT} R_{TT}\cos(2\phi))$, where $K = E_p p_p/(2\pi)^3$, $\sigma_{Mott}$ is the Mott cross section, $V_L = \frac{Q^4}{\vec{q}^{\,4}}$, $V_T = \frac{Q^2}{2\vec{q}^{\,2}} + \tan^2(\theta_e/2)$, $V_{LT} = \frac{Q^2}{\vec{q}^{\,2}}[\frac{Q^2}{\vec{q}^{\,2}} + \tan^2(\theta_e/2)]^{\frac{1}{2}}$, and $V_{TT} = \frac{Q^2}{2\vec{q}^{\,2}}$ are kinematic factors, and $\phi$ is the out-of-plane angle. $\omega$ and $\vec{q}$ are the energy and momentum transfer respectively, and $Q^2 = \vec{q}^{\,2} - \omega^2$. Missing energy and missing momentum are defined as $E_{miss} = \omega - T_p - T_R$ and $\vec{P}_{miss} = \vec{p}_p - \vec{q}$, where $\vec{p}_p$ and $T_p$ are the momentum and kinetic energy of the knocked-out proton, and $T_R$ is the kinetic energy of the recoil nucleus. The response functions $R_L$, $R_T$, $R_{LT}$, and $R_{TT}$ contain all the information about the nuclear electromagnetic current. $R_{LT}$ can be obtained by measuring the cross sections on both sides of $\vec{q}$ ($\phi = 0°$ and $\phi = 180°$) with $\omega$, $Q^2$, and $P_{miss}$ fixed. By combining the cross section measured at a different beam energy but the same $\omega$, $Q^2$, and $P_{miss}$, the response functions $R_L + \frac{V_{TT}}{V_L} R_{TT}$ and $R_T$ can be separated. For the kinematics of this expriment, $R_{TT} \ll R_L$.

Quasielastic $^{16}$O(e, e'p) 1$p$-shell proton knockout experiments have been performed at NIKHEF [2] [3], Saclay [4], and Mainz [5] in various kinematics. Inconsistencies in these data have been found when comparing them to standard Distorted Wave Implse Approximation (DWIA) calculations. The DWIA calculation using the spectroscopic factors and parameters for the bound state wave functions extracted from fits to the data of Leuschner *et al.* [2] at NIKHEF overestimates the distorted momentum distribution measured by Blomqvist *et al.* [5] at Mainz by almost a factor of two even at low missing momentum. Further, the response function $R_{LT}$ measured by Chinitz *et al.* [4] and Spaltro *et al.* [3] agree reasonably for the $1p_{1/2}$ state but disagree dramatically for the $1p_{3/2}$ state. These inconsistencies indicate the deficiencies in standard DWIA calculations. Experiment E89-003 [7], recently performed in Hall A at Jefferson Laboratory measured the cross sections and separated the response functions $R_{L+TT}$, $R_T$, and $R_{LT}$ for 1$p$-shell proton knockout. This data set clarifies some of the discrepancies present in the previous experimental work.

E89-003 used the standard Hall A setup, two high resolution spectrometers (HRSE and HRSH) to detect electrons and protons respectively. At the focal plane of each spectrometer, two scintillator planes provide trigger signal and time-of-flight (TOF) information, and two Vertical Drift Chambers (VDCs) are paired to precisely locate the trajectories of the charged particles. In addition, a $CO_2$ gas Cerenkov detector located on HRSE can separate electrons from $\pi^-$. A three-foil waterfall target was used. The thickness of each foil along the beamline was about 130 mg/cm$^2$, and the typical 100% duty factor beam current was ~70 $\mu$A. The optical properties [8] [9] and acceptance [10] of the spectrometers were studied carefully. Because quasielastic kinematics was chosen, H(e, e') was used as a continuous luminosity monitor, and H(e, e'p) was used to determine the $\vec{q}$-direction precisely. The kinematics of this experiment were fixed at $\omega = 439$ MeV, $Q^2 = 0.8$ (GeV/c)$^2$, and $T_p = 427$ MeV. Missing momentum distributions were investigated by changing the angle between $\vec{q}$ and the HRSH. As $\vec{q}$ and $\vec{p}_p$ had nearly the same magnitude, and the angle between them was small, missing momentum was about perpendicular to $\vec{q}$. Three beam energies (843.2 MeV, 1642.5 MeV, and 2441.6 MeV) were employed to separate the response functions. For $E_{beam} = 2441.6$ MeV, data were taken at $\theta_{pq} = \pm 8°, \pm 16°$, and $\pm 20°$, while for $E_{beam} = 843.2$ MeV data were taken at $\theta_{pq} = +8°$ and $+16°$. The data taken at $E_{beam} = 1642.5$ MeV with $\theta_{pq} = \pm 8°$ were for systematic checking. In fact, for $\theta_{pq} = \pm 8°$, $R_{LT}$ and $A_{LT}$ extracted at $E_{beam} = 2441.6$ MeV agree with those extracted from $E_{beam} = 1642.5$ MeV within one standard deviation. The overall systematic error in the extracted response functions was estimated to be about 5%. It was dominated by the uncertainty of H(e, e') cross section to which the data were normalized.

The results have been compared with the non-relativistic DWIA calculations by Kelly [1] [11] and the relativistic DWIA calculations by Van Orden [13] [14]. Kelly's calculation used the EDAD1 optical potential [12]. The spectroscopic factors obtained by comparing this calculation with the data of Leuschner *et al.* are 0.75 for $1p_{1/2}$ state and 0.64 for $1p_{3/2}$ state. The calculations of Van Orden employed a relativistic quantum field theory for the bound state [15] and a relativistic optical potential formalism [16] to describe the final state interaction. The spectroscopic factors folded in this calculation are 0.61 for both $1p_{1/2}$ and $1p_{3/2}$ states. Since the acceptance of HRSE and HRSH is relatively small (~±4% in relative momentum, and ~5 msr in solid angle), the difference between the calculation averaged over the acceptance and the calculation using the central kinematics values is estimated to be ~1%.

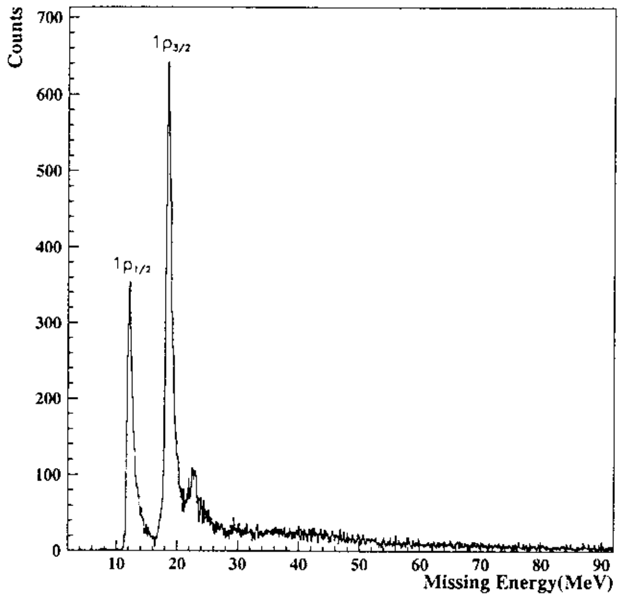

FIG. 1. $^{16}O(e,e'p)$ missing energy spectrum for 2441.6 MeV beam energy at $\theta_{pq} = +8°$. The $1p_{1/2}$ and $1p_{3/2}$ states are clearly visible. The FWHM missing momentum resolution is ~0.9 MeV.

Figure 1 shows the $^{16}O(e,e'p)$ missing energy spectrum with $E_{beam}$ = 2441.6 MeV. The two prominent peaks correspond to proton knocked-out from $1p_{1/2}$ and $1p_{3/2}$ states of $^{16}O$. The missing energy resolution (FWHM) is about 0.9 MeV. The strength of the $(2s_{1/2}, 1d_{5/2})$ doublet (peaked at missing energy 17.4 MeV) is expected to be small for this kinematical region and has not been removed from the $1p_{3/2}$ state data during the analysis.

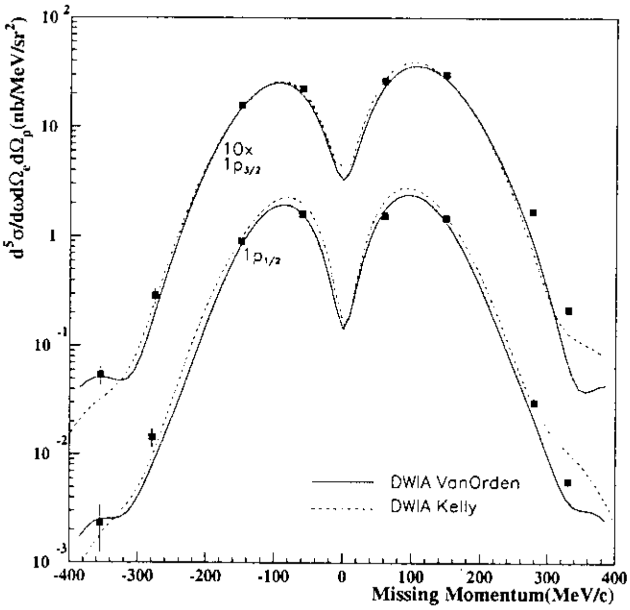

FIG. 2. Comparison of the cross sections with the DWIA calculations. The beam energy is 2441.6 MeV. Both DWIA calculations describe the data very well.

Figure 2 shows a comparison between the measured cross sections and the DWIA calculations. The data is in good agreement with both DWIA calculations for missing momentum less than 280 MeV/c. The consistency between the data and the DWIA calculation of Kelly indicates that this data set agrees with the data of Leuschner *et al.* [2], but disagrees with the data of Blomqvist *et al.* [5]

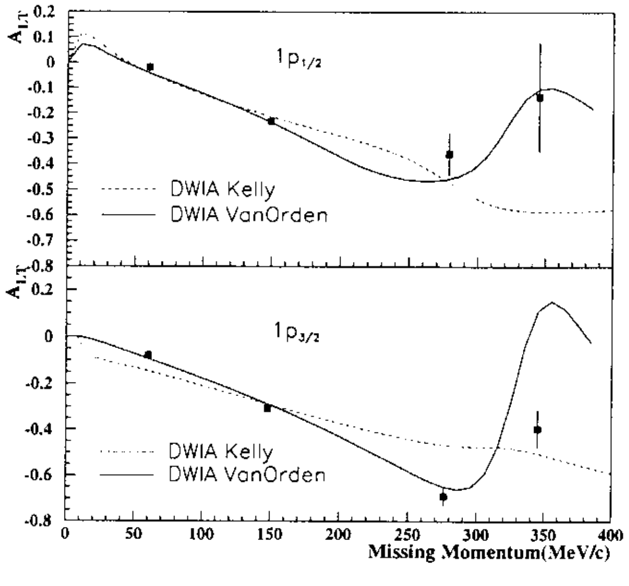

FIG. 3. Comparison of the left-right asymmetry with the DWIA calculations. The beam energy is 2441.6 MeV. The data favor the relativistic DWIA calculation.

Figure 3 shows a comparison between the extracted left-right asymmetry ($A_{LT} = \frac{\sigma(\phi=0^\circ)-\sigma(\phi=180^\circ)}{\sigma(\phi=0^\circ)+\sigma(\phi=180^\circ)}$) and the DWIA calculations of Kelly and Van Orden. The data prefer the relativistic DWIA calculation of Van Orden at large missing momentum (> 250 MeV/c).

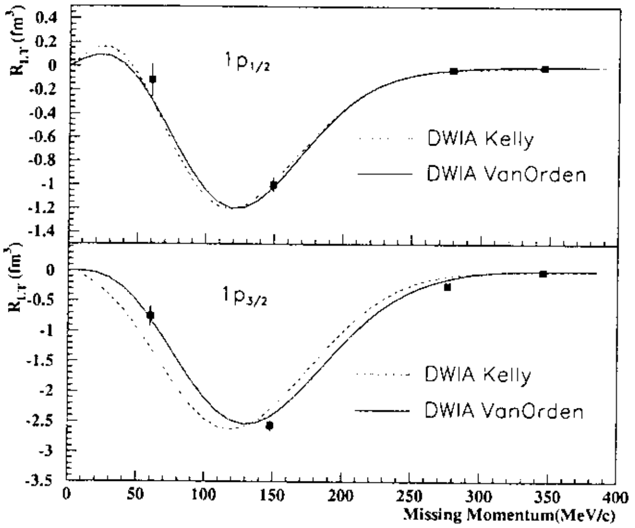

FIG. 4. Comparison of $R_{LT}$ with the calculations. The beam energy is 2441.6 MeV. The data agree with both DWIA calculations.

Figure 4 shows a comparison of the response function $R_{LT}$ with the calculations. The data are reasonably consistent with both DWIA calculations. Since the DWIA calculations of Kelly can describe the $R_{LT}$ for $1p_{3/2}$ state measured by Chinitz *et al.* [4] but underestimate the $R_{LT}$ for $1p_{3/2}$ state 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] It also implies that this data set agrees with that of Leuschner *et al.* [2] and therefore disagrees with that of Blomqvist *et al.* [5]

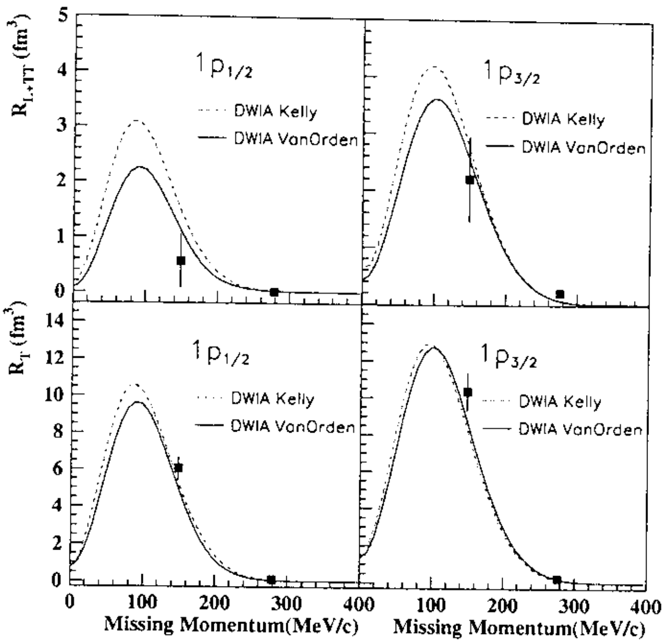

FIG. 5. Comparison of $R_{L+TT}$ and $R_T$ with the calculations. The data agree with both DWIA calculations.

Figure 5 shows a comparison of separated $R_{L+TT}$ and $R_T$ with the DWIA calculations. Both DWIA calculations describe the data set very well. This is another indication that this data set agrees with that of Leuschner *et al.* [2] but disagrees with that of Blomqvist *et al.* [5]

In summary, cross sections for $^{16}$O(e, e$'$p) 1$p$-shell proton knockout have been measured at $\omega$ = 439 MeV/c and $Q^2 = 0.8$ (GeV/c)$^2$ up to 355 MeV/c in missing momentum. The response functions $R_{L+TT}$, $R_T$, and $R_{LT}$ as well as the left-right asymmetry $A_{LT}$ have been obtained. The cross sections are consistent with both DWIA calculations. This implies our data agree with the data of Leuschner *et al.* [2] For missing momentum less than 280 MeV/c, the response functions $R_{L+TT}$, $R_T$, and $R_{LT}$ basically agree with the DWIA calculations. This suggest that our data also agree with those of Chinitz *et al.* [4] but disagree with those of Spaltro *et al.* [3] for $R_{LT}$ measurements. At large missing momentum, the $A_{LT}$ results favor the relativistic DWIA calculation at large missing momentum.

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