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 $1p_{1/2}$ and $1p_{3/2}$ states. At $P_{miss} < 280$ MeV/c, the data are all well described by the DWIA calculations. This is in contrast to some previous measurements at lower Q^2. At large missing momentum, the data seem to prefer the relativistic DWIA calculation.

Nucleon knockout from nucleus by electron scattering provides a powerful probe of the electromagnetic properties and nucleon momentum distributions in nuclei [1]. In the impulse approximation (IA), the nucleon absorbs the virtual photon mediated by the incident electron and interacts with the rest of the nucleus before it is knocked out. The final state interaction of the knocked-out nucleon and the residual nucleus is usually described by an optical potential which fits to the existing nucleon-nucleus scattering data. Meson exchange currents and isobar currents 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 bind energy is 12.1 MeV for $1p_{1/2}$ state and 18.4 MeV for $1p_{3/2}$ 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 ^{16}O$(e,e'p)$ reaction are well understood. Therefore, one can derive good predictions for both the cross sections and the response functions.

In the one photon exchange approximation, the fivefold cross section for $1p$-shell proton knocout in ^{16}O$(e,e'p)$ reaction 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 $K = E_p p_p/(2\pi)^3$, σ_{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 the kinematic factors, and ϕ is the out-of-plane angle. ω and $\vec{q}$ are the energy and momentum transfer, and $Q^2 = \vec{q}^2 - \omega^2$. Missing energy and missing momentum are defined as $E_{miss} = \omega - T_p - T_R$, $\vec{P}_{miss} = \vec{p}_p - \vec{q}$, 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} have the information of the nuclear electromagnetic current. R_{LT} can be obtained by measuring the cross sections on both sides of $\vec{q}$ ($\phi = 0^\circ$ and $\phi = 180^\circ$) with ω, Q^2, and P_{miss} fixed. By combining the cross section measured at a different beam energy but the same ω, 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, it is expected that $R_{TT} \ll R_L$.

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

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 information, and two Vertical Drift Chambers (VDCs) are paired to precisely locate the trajectories of the charged particles. In addition to that, there is a CO_2 gas Cerenkov detector on HRSE to separate electrons from π^-. A three-foil waterfall target was chosen to study ^{16}O. The thickness of each foil along the beamline was about 130 mg/cm^3, and the typical 100% duty factor beam current was ~ 70 μA. The optical properties [8] and acceptance [10] of the spectrometers were studied carefully. Since the kinematics of E89-003 was in the quasielastic region, H(e,e') can serve as a continuous luminosity monitor, and H$(e,e'p)$ can be used to determine the $\vec{q}$-direction precisely. The kinematics of this experiment was fixed at $\omega = 439$ MeV, $Q^2 = 0.8$ (GeV/c)^2, and T_p =427 MeV. The missing momentum was mapped out by changing the angle between $\vec{q}$ and HRSH, and it was about perpendicular to $\vec{q}$. The 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 $\theta_{pq} = \pm 8^\circ, \pm 16^\circ$, and $\pm 20^\circ$, while for E$_{beam}$=843.2 MeV data were taken at $\theta_{pq} = +8^\circ$ and $+16^\circ$. The data taken at E$_{beam}$=1642.5 MeV with $\theta_{pq} = \pm 8^\circ$ were just redundancy. In fact, for $\theta_{pq} = \pm 8^\circ$, R_{LT} and A_{LT} extracted at E$_{beam}$=2441.6 MeV agree with that from E$_{beam}$=1642.5 MeV within one standard deviation. The overall systematic error in the response functions was estimated to be about 5%, which was dominated by the uncertainty of H(e,e') cross section.

The results have been compared with the non-relativistic DWIA calculation from Kelly [1] [11] and the relativistic DWIA calculation from 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 Plane Wave Impulse Approximation (PWIA) calculation from Kelly was obtained simply by turnning off the final state interaction. The calculation from 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.

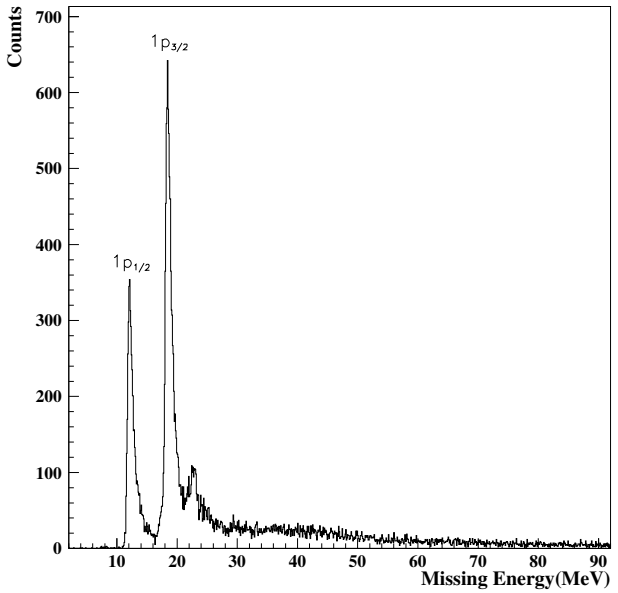

FIG. 1. ^{16}O$(e,e'p)$ missing energy spectrum for 2441.6 MeV beam energy at $\theta_{pq} = +8°$.

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 doublets $(2s, 1d)$ (peaked at missing energy 17.4 MeV) is expected to be small for this kinemats region and is included in the $1p_{3/2}$ state for data analysis.

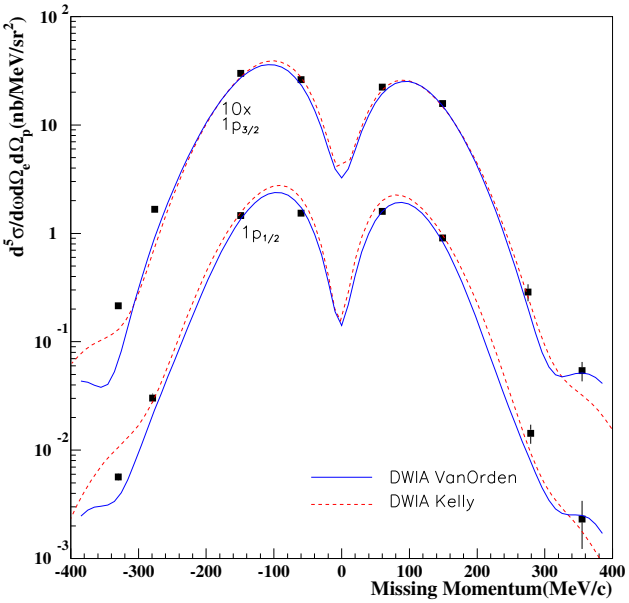

FIG. 2. Comparison of the cross sections with the DWIA calculations. The beam energy is 2441.6 MeV.

Figure 2 shows the comparison of the measured cross section with 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 from Kelly indicates that this data set agrees with the data from Leuschner *et al* [2], but disagrees with the data from Blomqvist *et al* [5].

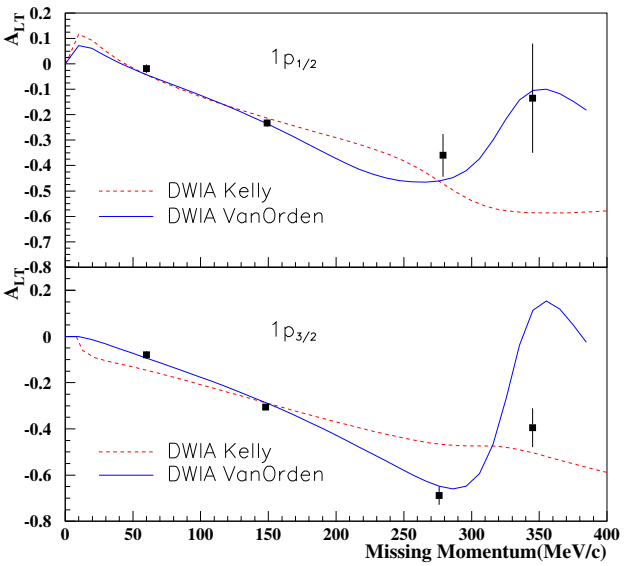

FIG. 3. Comparison of the left-right asymmetry with the DWIA calculations. The beam energy is 2441.6 MeV.

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

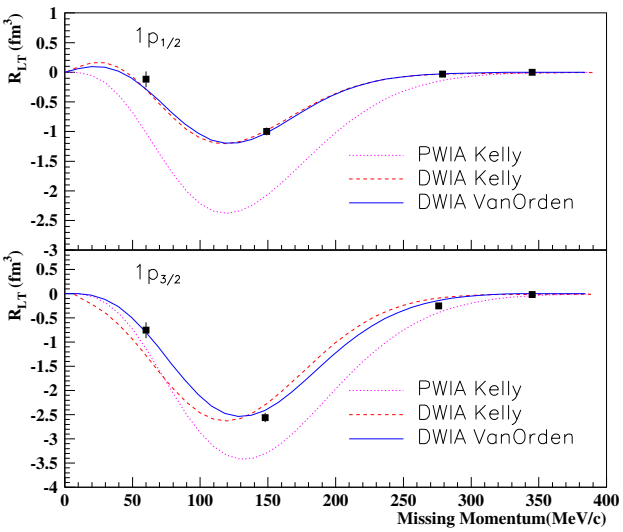

FIG. 4. Comparison of R_{LT} with the calculations. The beam energy is 2441.6 MeV.

Figure 4 shows a comparison of the response function R_{LT} with the calculations. The data are reasonably consistent with both DWIA calculations. This indicates that the R_{LT} measurement for $1p_{3/2}$ state agrees with that from Chinitz *et al* [3] but disagrees with that from Spaltro *et al* [4].

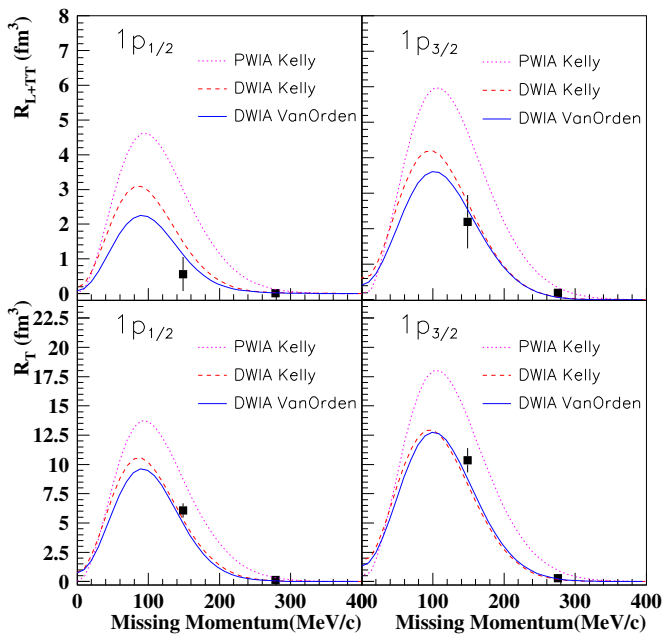

FIG. 5. Comparison of R_{L+TT} and R_T with the calculations. The Coulomb gauge was used.

Figure 5 shows a comparison of separated R_{L+TT} and R_T with the DWIA calculations. At a missing momentum of ~149 MeV/c, the data agree with both DWIA calculations.

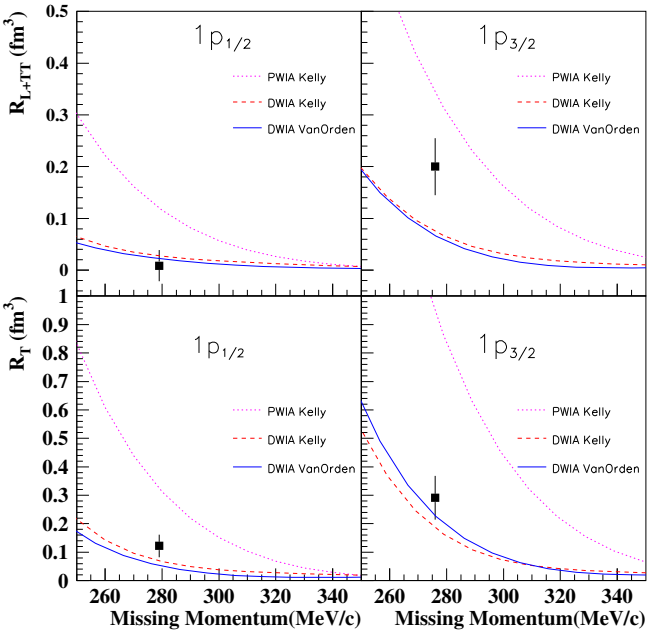

FIG. 6. An enlargement of the high missing momentum region of Figure 5.

Figure 6 is an enlargement of the high missing momentum region of Figure 5. Except the fact that R_{L+TT} lies away from both DWIA calculations for the $1p_{3/2}$ state, the data reasonably agrees with the DWIA calculations.

In summary, the cross sections for ^{16}O$(e,e'p)$ $1p$-shell knockout have been measured at ω = 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 agree with that of Chinitz *et al* [3] for R_{LT} measurement. At large missing momentum, the A_{LT} results favor the relativistic DWIA calculation at large missing momentum.

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