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Measurement of R_{LT} and A_{TL} in the $^4He(e, e'p)^3H$ reaction at p_{miss} of 130–300 MeV/c

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Abstract. We have measured the $^4He(e, e'p)^3H$ reaction at missing momenta of 130–300 MeV/c using the three-spectrometer facility at the Mainz microtron MAMI. Data were taken in perpendicular kinematics to allow us to determine the response function R_{LT} and the asymmetry term A_{TL}. The data are compared to both relativistic and non-relativistic calculations.

PACS. 25.10.+s Nuclear reactions involving few-nucleon systems – 25.30.Rw Electroproduction reactions – 21.45.+v Few-body systems – 27.10.+h $A \leq 5$

1 Introduction

There have been many studies of the (e,e′p) reaction with the overall objective of learning more about the detailed single-nucleon distributions in nuclei. Of special interest are investigations of few-body systems and light nuclei since they are more amenable to more complete and detailed theoretical calculations. Interpretation of the experimental results in terms of single-nucleon properties is most readily done in the simple non-relativistic Plane-Wave Impulse Approximation (PWIA). However, it has been clear for sometime now that the simple non-relativistic PWIA is not able to account for the observed cross-sections. One has to understand the nature of the competing processes, particularly in the more interesting kinematic regions of high missing momenta. An important experimental tool in this regard is the response function decomposition of the cross-sections. In the one-photon

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exchange approximation the cross-section can be written as [1]

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_\mathrm{p}\mathrm{d}E_\mathrm{e}} = K\sigma_\mathrm{Mott}\Big[\nu_\mathrm{L}R_\mathrm{L} + \nu_\mathrm{T}R_\mathrm{T} + \nu_\mathrm{LT}R_\mathrm{LT}\cos\phi + \nu_\mathrm{TT}R_\mathrm{TT}\cos 2\phi\Big], \quad (1)$$

where ϕ is the angle between the electron scattering plane and the plane containing the momentum transfer $\vec{q}$ and the detected proton, K is a kinematic factor $\frac{mp_p}{(2\pi)^3}$ (where p_p is the momentum of the ejected proton), σ_Mott is the Mott cross-section, the ν_i are additional kinematic factors and the R_i and R_{ij} are the response functions. The response functions describe the interaction of the longitudinal, L, and transverse, T, polarization states of the virtual photon with the nuclear charge and current. Theoretical calculations suggest that each of these response functions can exhibit selective sensitivity to particular reaction mechanisms in the (e,e′p) process. For example, past measurements of the R_LT interference response function have indicated that it is sensitive to relativistic effects and meson exchange currents (MEC). Measurements of the $^2H(e,e'p)n$ reaction [2] have shown that it is sensitive to inclusion of relativistic terms in the nucleon current while a previous study [3] of the $^4\mathrm{He}(\mathrm{e},\mathrm{e'p})^3\mathrm{H}$ reaction indicated the need to include meson exchange terms in order to reproduce both the cross-sections and the R_LT response function measured for missing momentum $p_\mathrm{miss} = 265$ MeV/c. Studies of the $^{16}\mathrm{O}(\mathrm{e},\mathrm{e'p})^{15}\mathrm{N}$ reaction have suggested that the R_LT response function is sensitive to both MEC [4] and a fully relativistic treatment [5] of the reaction.

The ^{4}He system is of particular interest since it is a tightly bound system for which one can obtain the nuclear wave function from microscopic calculations based on realistic NN interactions. In this paper we report on a measurement of the R_LT interference response function in the $^4\mathrm{He}(\mathrm{e},\mathrm{e'p})^3\mathrm{H}$ reaction. These particular measurements were motivated in part by the measurement of R_LT, performed at the MIT-Bates Laboratory, for the $^4\mathrm{He}(\mathrm{e},\mathrm{e'p})^3\mathrm{H}$ reaction at missing momentum $p_\mathrm{miss} =$ 265 MeV/c, incident electron energy, $E_0 = 572.5$ MeV, momentum transfer, $|\vec{q}| = 360$ MeV/c, and energy transfer, $\omega = 200$ MeV [3]. The present experiment was designed to provide measurements of R_LT under similar kinematic conditions but over a wider range of p_miss.

2 The experiment

The research reported here was done with the three-spectrometer facility at the Mainz microtron, MAMI, by the A1 collaboration. Data were taken at incident beam energies of 675 and 855 MeV and cover a range of p_miss from 131 MeV/c to 300 MeV/c. As was the case for the data of ref. [3] ω was set at approximately 200 MeV and kept relatively constant in an attempt to keep final-state interaction (FSI) effects constant for all measurements and also to minimize FSI effects since proton-nucleus energies of around 200 MeV are near the minimum of the p-^{4}He optical model potential derived by van Oers *et al.* [6].

The experimental setup was almost identical to that described in ref. [7] and ref. [8] except that for the present measurements the electron and proton spectrometers were interchanged, *i.e.* spectrometer A was used to detect protons and spectrometer B was used to detect electrons. (Details of the MAMI three spectrometer facility are described in ref. [9].) Spectrometer C was used as a luminosity monitor. The angular acceptance of spectrometer B, as defined by the data analysis cuts, was 2.29° in the horizontal direction and 7.45° in the vertical direction. The large angular acceptance of the proton spectrometer, spectrometer A, allowed us to break each angular setting into three data points of angular acceptance of 4.30° (vertical acceptance is 11.46°). The target consisted of cold ^{4}He gas (T = 20–23 K and P = 5–10 atm) encapsulated in an 8 cm diameter stainless steel quasi-spherical cell whose walls were 82 μm thick [10].

The target density was determined [8] by measuring elastic scattering from ^{4}He in spectrometer B and normalizing the measured counts to the elastic scattering data and form factor parametrization of ref. [11]. Spectrometer C was configured to detect negatively charged particles and data were taken in spectrometer C during the elastic scattering runs. For each beam energy the angle and momentum settings for spectrometer C were kept fixed. Thus, with appropriate cuts to eliminate background, the recorded counts in spectrometer C, along with the measured beam current, provided a measurement of the target density for any particular data run relative to what was determined from the elastic scattering data runs. The effective target length, as defined by the data analysis cuts, varied depending on the particular kinematic settings between 5.2 to 6.0 cm. The combined effective solid angles and target length of the two-spectrometer extended-target system was determined using the Monte Carlo code AEEXB [12].

Beam energies of 855 and 675 MeV were used with average beam currents of 40 μA. Due to constraints imposed by the available beam energies and the geometry of the experimental hall we were not able to keep $\vec{q}$ constant and $|\vec{q}|$ varied from 404.6 to 639.5 MeV/c. These changes in $|\vec{q}|$ are responsible for the discontinuities that are seen when the data are plotted as a function of p_miss.

To determine the asymmetry term, A_TL, and the interference response function, R_LT, data were taken in perpendicular kinematics.

$$A_\mathrm{TL} = \frac{\sigma_\mathrm{f} - \sigma_\mathrm{b}}{\sigma_\mathrm{b} + \sigma_\mathrm{f}}, \quad (2)$$

R_LT is defined in eq. (1). For each value of p_miss two measurements were made, the first with the proton spectrometer set at an angle forward of $\vec{q}$ (closer to the beam direction) to measure σ_f, and the second with the proton spectrometer set at an equal angle backward of $\vec{q}$ (further away from the beam direction) to measure σ_b. Under these conditions the central value of p_miss is the same for both measurements.

Table 1. Kinematics (central angles and momenta) and cross-sections.

E_0 (MeV)	θ_e (deg.)	q (MeV/c)	θ_p (deg.)	ω (MeV)	p_p (MeV/c)	p_{miss} (MeV/c)	$d^5\sigma/d\Omega^2 dE$ (cm^2/MeV/sr^2)	% error stat.
855.11	47.70	639	22.86	185.11	549.95	300.3	6.34 x 10^{-36}	7
855.11	47.70	639	25.01	185.11	554.19	279.3	9.31 x 10^{-36}	6
855.11	47.70	639	27.16	185.11	558.14	258.2	1.76 x 10^{-35}	4
855.11	47.70	639	78.85	185.11	549.76	301.2	3.33 x 10^{-35}	4
855.11	47.70	639	76.70	185.11	554.01	280.3	5.65 x 10^{-35}	3
855.11	47.70	639	74.55	185.11	557.97	259.1	9.72 x 10^{-35}	2
675.11	55.00	559	27.50	208.11	614.26	169.5	3.55 x 10^{-34}	2
675.11	55.00	559	29.65	208.11	616.28	150.0	5.77 x 10^{-34}	2
675.11	55.00	559	31.80	208.11	618.02	131.0	9.12 x 10^{-34}	1
675.11	55.00	559	58.93	208.11	614.28	169.4	8.93 x 10^{-34}	1
675.11	55.00	559	56.78	208.11	616.30	149.9	1.31 x 10^{-33}	1
675.11	55.00	559	54.63	208.11	618.03	130.8	1.80 x 10^{-33}	1
675.11	36.00	404	22.86	208.11	601.55	260.2	1.04 x 10^{-34}	3
675.11	36.00	404	25.01	208.11	603.24	250.1	1.50 x 10^{-34}	3
675.11	36.00	404	27.16	208.11	604.75	240.7	2.27 x 10^{-34}	2
675.11	36.00	404	62.56	208.11	601.60	259.9	5.52 x 10^{-34}	2
675.11	36.00	404	60.41	208.11	603.28	249.8	6.82 x 10^{-34}	2
675.11	36.00	404	58.26	208.11	604.79	240.4	8.01 x 10^{-34}	2
675.11	50.00	518	22.86	208.11	607.65	221.5	9.74 x 10^{-35}	4
675.11	50.00	518	25.01	208.11	610.07	204.1	1.67 x 10^{-34}	3
675.11	50.00	518	27.16	208.11	612.24	187.0	2.65 x 10^{-34}	3
675.11	50.00	518	64.41	208.11	607.74	220.9	4.02 x 10^{-34}	2
675.11	50.00	518	62.26	208.11	610.15	203.4	5.90 x 10^{-34}	2
675.11	50.00	518	60.11	208.11	612.32	186.4	8.50 x 10^{-34}	2

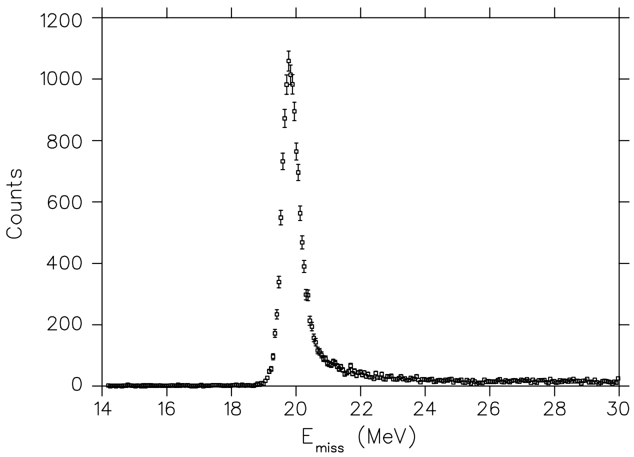

Fig. 1. ^{4}He(e, e′p)^{3}H. $E_{\rm miss}$ spectrum for $p_{\rm miss} = 150$ MeV/c. The three-body breakup threshold is at $E_{\rm miss} = 26.1$ MeV.

Data were taken at one set of angles at the 855 MeV beam energy and three different sets of angles at the 675 MeV beam energy. After breaking up the horizontal angular acceptance of the proton spectrometer into three angular regions, each angular setting yielded three data points, with each data point spanning a total width in $p_{\rm miss}$ between 25 to 58 MeV/c. The kinematics for these data are shown in table 1. To determine $A_{\rm TL}$ and $R_{\rm LT}$ the same cuts were put on $|\vec{q}|$, ω, and $p_{\rm miss}$ for each data point of the pair of angular settings used.

The combined energy resolution of spectrometers A and B along with the approximately 100 keV spread in the beam energy resulted in an $E_{\rm miss}$ spectrum in which the two-body breakup peak had a FWHM of approximately 700 keV. (See fig. 1.) This was more than sufficient to provide clean separation between the two-body breakup peak and the threshold for the three-body continuum. Total combined systematic errors for individual cross-section measurements were approximately 6%. Data are presented here only for the ^{4}He(e, e′p)^{3}H reaction, that is only for the two-body final state $E_{\rm miss}$ peak. The data were corrected for radiative losses due to internal and external bremsstrahlung processes [13,14].

3 Results

The cross-section data for proton angles forward of $\vec{q}$ ($\sigma_{\rm f}$) are shown in fig. 2 and those for angles back of $\vec{q}$ ($\sigma_{\rm b}$) are shown in fig. 3. Only statistical errors, which range between 1% to 7%, are plotted and these are almost always smaller than the size of the data points. The cross-section data are tabulated in table 1. Also shown in figs. 2 and 3 are four different theoretical predictions. We show two PWIA calculations, one using a ^{4}He wave function derived from the Argonne V14 nucleon-nucleon potential [15] and the other using a ^{4}He wave function derived from the Argonne V18 nucleon-nucleon potential and the Urbana IX three nucleon potential [16]. The calculations labeled Schiavilla incorporate the orthonormal-correlated

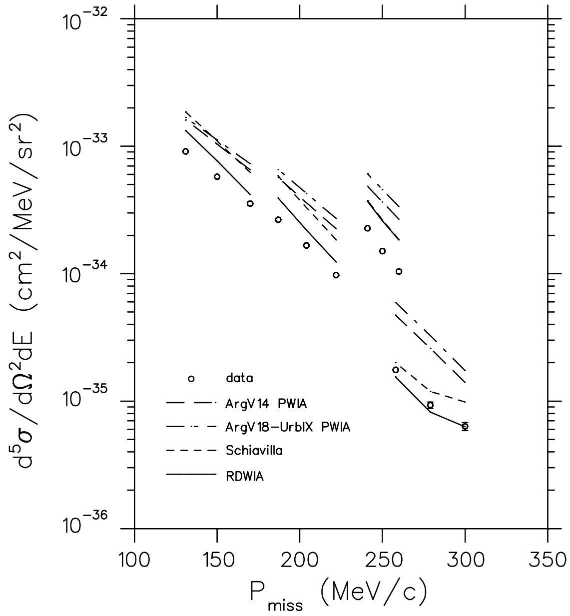

Fig. 2. ^{4}He(e, e′p)^{3}H. Cross-sections for proton angles forward of q.

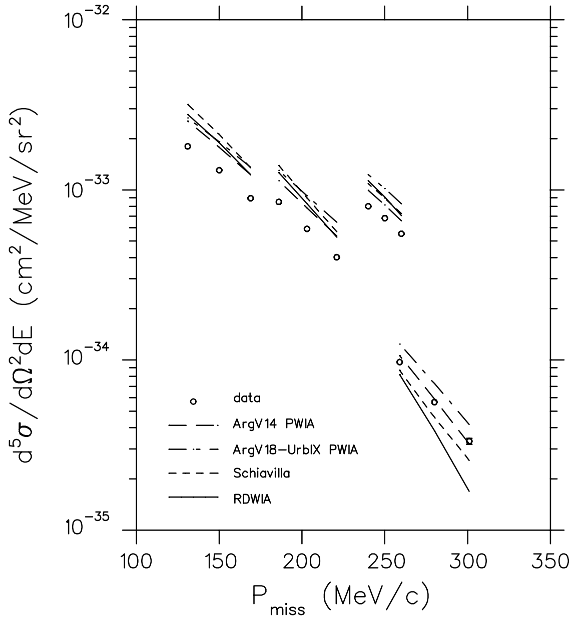

Fig. 3. ^{4}He(e, e′p)^{3}H. Cross-sections for proton angles backward of q.

states method described by Schiavilla [17] and include the effects of short-range correlations, orthogonality corrections, final-state interactions, and two-body charge and current operators.

The curves labeled RDWIA are fully relativistic distorted-wave impulse approximation (RDWIA) calculations by Udias using the Madrid code [18]. This calculation uses the same ingredients as in the corresponding ones in ref. [19] that were compared to the transferred polarization ratio data at similar energies of the ejected proton as in this experiment. Namely: a) a relativistic mean-field

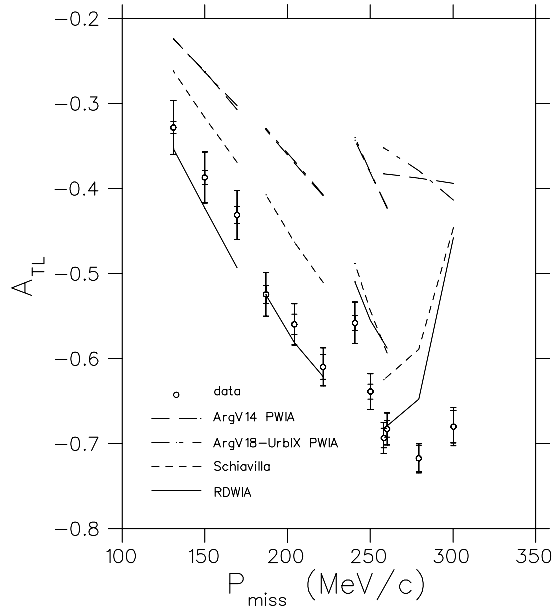

Fig. 4. ^{4}He(e, e′p)^{3}H. The transverse-longitudinal asymmetry A_{TL}.

wave function fit to reproduce the rms radius and binding energy of ^{4}He which reproduces the momentum distributions from the ^{4}He data in ref. [8]; b) an optical potential obtained by folding a density-dependent empirical effective p-N interaction (EEI) [20] with the measured charge density for tritium. Here we use the same potential as in ref. [19], derived from parameters that were adjusted by Kelly to fit proton scattering data from ^{4}He, obtaining a better fit to the proton elastic scattering data in this nucleus than any previous optical potential; c) the CC1 current operator.

The PWIA calculations were averaged over the finite acceptances of the spectrometers while the full Schiavilla and the RDWIA calculations of Udias were done only at the central point of these acceptances. Using the Argonne V14 PWIA calculation we compared the effects of acceptance averaging these calculations. The difference between the point and acceptance averaged calculations were typically less than 8%.

Figure 4 shows the asymmetry term A_{TL} and fig. 5 shows R_{LT}. In these figures the two sets of error bars represent the statistical and systematic errors separately. Except for A_{TL} at $p_{\mathrm{miss}} = 300\,\mathrm{MeV}/c$ the systematic errors are always larger than the random errors. The theoretical predictions shown in figs. 4 and 5 are derived from the cross-section calculations shown in figs. 2 and 3. To investigate the effects of MEC on R_{LT} and A_{TL} the Schiavilla calculations were also run without the MEC term but with everything else included. Figures 6 and 7 show these results.

In comparing theory with the cross-section, R_{LT}, and A_{TL} data it is difficult to draw any firm conclusions. There is some indication from A_{TL} that the RDWIA calculations of Udias or the full calculation of Schiavilla is necessary to produce the qualitative shape of the data. The inclusion

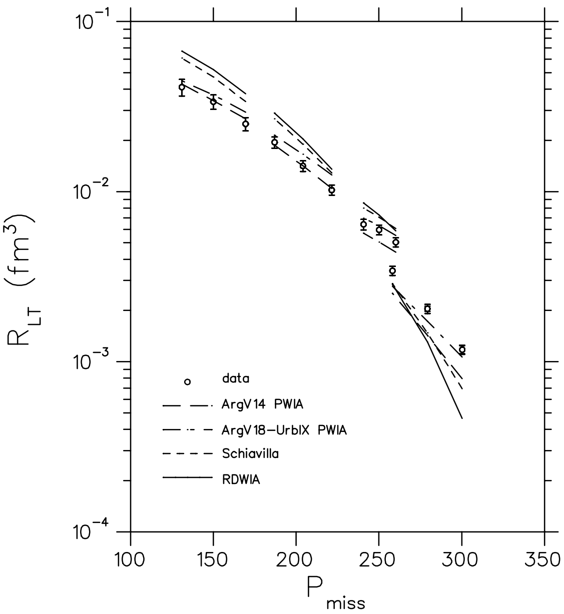

Fig. 5. ^{4}He(e, e′p)^{3}H. The longitudinal-transverse response function R_{LT}.

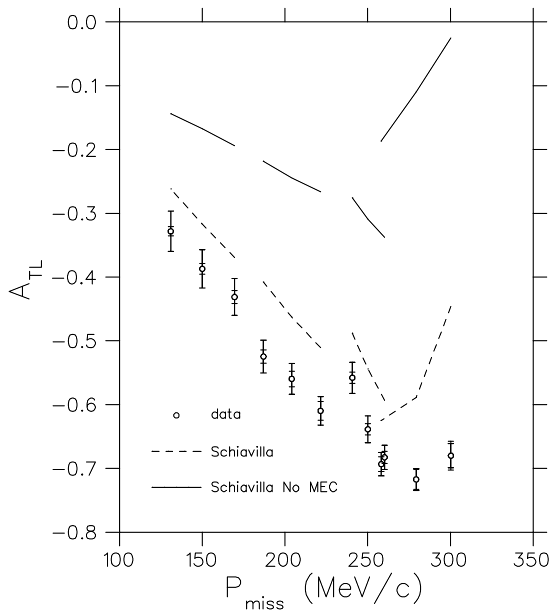

Fig. 6. ^{4}He(e, e′p)^{3}H. A_{TL} Schiavilla calculations with and without MEC terms.

of MEC terms in the Schiavilla calculation also substantially improves agreement with the R_{LT} data as was seen in the earlier MIT-Bates results [3]. However, it is less clear which predictions produce the best fits to the cross-section data. The full calculation of Schiavilla or the RDWIA calculations of Udias agree best with the forward-angle cross-section data while the simple PWIA calculation seems to do better for the back angle cross-sections.

We note that the data measured at 855 MeV have Bjorken $x = 1.08$ and the largest value of Q^2. From the point of view of the electron kinematics the 855 MeV data should have been the best case for quasi-elastic scattering

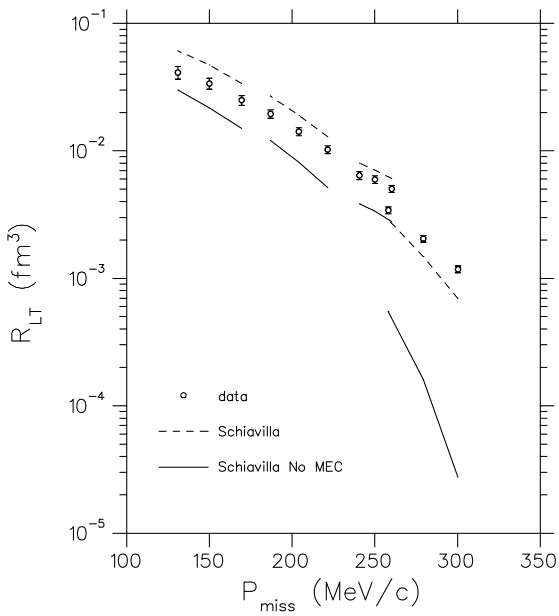

Fig. 7. ^{4}He(e, e′p)^{3}H. R_{LT} Schiavilla calculations with and without MEC terms.

(x near 1) with the smallest contribution from meson exchange currents. In contrast, at 675 MeV and $\theta = 50°$, $x = 0.58$ which should imply a greater role for meson exchange currents. However figs. 6 and 7 indicate that, at least in the context of the Schiavilla calculation, meson exchange currents are more important for the 855 MeV data than for the 675 MeV data. Overall these data suggest that the inclusion of MEC terms and/or a fully relativistic calculation is necessary but at this time we are unable to conclude which effect is dominant.

4 Summary

We have taken data for the ^{4}He(e, e′p)^{3}H reaction in perpendicular kinematics that allowed us to determine R_{LT} and A_{TL} for p_{miss} from 130 to 300 MeV/c. Reasonable agreement with theory appears to require inclusion of final-state interaction effects and the addition of meson exchange reaction terms and/or a fully relativistic treatment of the entire reaction. Additional data might clarify this situation. In this regard there is a proposal under review for a new series of measurements of the ^{4}He(e, e′p)^{3}H reaction to be done at Jefferson Lab.

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