High-precision Studies of the $^3\text{He}(e,e'p)$ Reaction at the Quasielastic Peak

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(March 30, 2022)

Precision studies of the reaction $^3\text{He}(e,e'p)$ using the three-spectrometer facility at the Mainz microtron MAMI are presented. All data are for quasielastic kinematics at $|q^2| = 685$ MeV/c. Absolute cross sections were measured at three electron kinematics. For the measured missing momenta range from 10 to 165 MeV/c, no strength is observed for missing energies higher than 20 MeV. Distorted momentum distributions were extracted for the two-body breakup and the continuum. The longitudinal and transverse behavior was studied by measuring the cross section for three photon polarizations. The longitudinal and transverse nature of the cross sections is well described by a currently accepted and widely used prescription of the off-shell electron-nucleon cross-section. The results are compared to modern three-body calculations and to previous data.

PACS numbers: 21.45.+v, 25.10.+s, 25.30.Dh, 25.30.Fj

The study of few-body nuclear systems has acquired new importance due to recent developments on both theoretical and experimental fronts. Several schemes have been developed to perform microscopic calculations which are based on the NN interaction rather than on a mean-field approach. These include non-relativistic Faddeev-type calculations for three-body systems [1] and Monte-Carlo variational calculations for three- and four-body systems [2]. Fully-relativistic calculations are also being developed for three bodies [3]. New experimental facilities with high-quality continuous-wave (cw) electron beams and high-resolution spectrometers provide the means to rigorously test these modern calculations. In particular, precision measurements of electromagnetic response functions, which are selectively sensitive to the various components of the nuclear currents, are possible.

The first results of a program to study $^3,^4\text{He}(e,e'p)$ at a fixed 3-momentum transfer, $q = |\vec{q}| = 685$ MeV/c, and three energy transfers, $\omega$, corresponding to kinematics on top of the quasielastic peak, well above it (“dip”) and well below it are reported here. By varying the energy transfer, we hope to selectively enhance or suppress various effects contributing to the interaction. In order to further understand these contributing effects, we studied the longitudinal and transverse components of the cross section by measuring it at three electron scattering angles (virtual photon polarizations, $\epsilon$). The ongoing research program was carried out in the three-spectrometer facility [3] at the Mainz microtron MAMI by the A1 collaboration. The results reported here are from measurements performed on $^3\text{He}$ in quasielastic kinematics ($\epsilon_B = 1$; $\omega = 228$ MeV), where the dominant mechanism is expected to be the quasi-free knockout of a single proton. Further experimental details are described in Ref. [4].

Few exclusive and semi-exclusive electron-scattering measurements have been performed on $^3\text{He}$, and the existing data are inconclusive. The $^3\text{He}(e,e'p)$ reaction was measured at Saclay [5] at 3-momentum transfers of 300 and 430 MeV/c. Measurements covered the missing energy range 0–70 MeV and missing momentum range $0 \leq p_m \leq 300$ MeV/c. Momentum distributions were extracted for the two-body breakup channel, $^3\text{He}(e,e'p)^2\text{H}$. Another $^3\text{He}(e,e'p)$ measurement at Saclay [5] in dip kinematics suggested the existence of two-body (short-range) correlations. The latter data exhibit some agreement with calculations by Laget [6]. Both experiments were performed in perpendicular kinematics. The longitudinal and transverse response functions were measured for $^3\text{He}(e,e'p)^2\text{H}$ in quasielastic kinematics at Saclay [10] over the $q$ range of 350–700 MeV/c. At the lower $q$, the longitudinal response is quenched by about 30% relative to the transverse, while at $q > 500$ MeV/c, the experimental spectral functions are consistent with PWIA pre-
dictions. In another L/T measurement in the dip region \([11]\) at missing momentum \(260\,\text{MeV/c}\), the longitudinal spectral function was observed to be strongly quenched for both the two-body breakup and the continuum channels, in agreement with calculations by Laget which include meson-exchange currents and final-state interactions (FSI). A few experiments are planned at the high momentum-transfer range now available at TJNAF. In particular, a measurement of cross sections and response functions at high \(q\) and for high \(p_m\) \([12]\) is scheduled for late 1999.

In this Letter, we report on measurements of the \(^3\text{He}\text(e,e'p)\) reaction at a central 3-momentum transfer \(q = 685\,\text{MeV/c}\) and central energy transfer \(\omega = 228\,\text{MeV}\), corresponding to the center of the quasielastic peak. Three incident beam energies \((E_b = 540, 675, \text{and } 855\,\text{MeV})\) with electron scattering angles \((\theta_e = 103.85^\circ, 72.05^\circ, \text{and } 52.36^\circ)\) were used. This corresponds to three virtual photon polarizations \((\epsilon = 0.214, 0.457, 0.648)\) respectively. Protons with momenta ranging from 393 to \(710\,\text{MeV/c}\) were detected in parallel kinematics \((\Delta\Omega \approx 5.6\,\text{msr})\) to facilitate the study of the longitudinal and transverse components of the cross section. The incident cw beam current was \(40\,\mu\text{A}\), and the beam was rastered on the target by \(\pm 3.5\,\text{mm}\) in both the horizontal and vertical directions. Scattered electrons were detected in Spectrometer A \((\Delta\Omega \approx 21\,\text{msr})\) and time-coincident protons in Spectrometer B \((\Delta\Omega \approx 5.6\,\text{msr})\). Spectrometer C was used as a luminosity monitor by detecting electrons at a fixed setting for each kinematics. The solid angle subtended by the spectrometers for an extended target was extensively studied, and a detailed description can be found in Ref. \([13]\).

The target \([13,14]\) consisted of cold \(^3\text{He}\) gas \((T = 20 - 23\,\text{K} \text{ and } P = 5 - 10\,\text{atm})\) encapsulated in a stainless steel sphere \(8\,\text{cm}\) in diameter and having \(82\,\mu\text{m}\) thick walls. A fan circulated the target gas from the cell through a heat exchanger to dispense the heat deposited by the incident electron beam. The target density was determined at each beam energy by measuring elastic electron scattering at a low beam current \((5\,\mu\text{A})\) and comparing the result to published cross sections \([14]\). The target density (which varied with the incident electron beam current) was then monitored and determined continuously using the singles rate in Spectrometer C. The systematic error on the overall normalization is \(\pm 5\%\) and is dominated by the uncertainties in the \(^3\text{He}\) elastic cross sections and the monitoring of the target density over time.

At each kinematic setting, the \(^3\text{He}\text(e,e'p)\) cross section was measured as a function of both missing momentum \((p_m)\) and missing energy \((E_m)\). The missing momentum range accessed was different for each kinematic setting. Hence, at \(\epsilon = (0.214, 0.457, 0.648)\) the \(p_m\) range was \((10-95, 10-125, 10-165\,\text{MeV/c})\) respectively. Great care was given to the radiative corrections, which were performed by unfolding \([16]\) the radiative tails in a 2-dimensional \((E_m, p_m)\) space. The correction factor proposed by Penner \([17]\) was used for internal (Schwinger) radiation, and the factor proposed by Friedrich \([18]\) for external radiation, which included substantial contributions from the target walls. Additional details about the radiative corrections can be found in Ref. \([4]\).

Fig. 1(a) displays radiatively-corrected missing energy spectra for \(^3\text{He}\text(e,e'p)\) at the three different \(\epsilon's\) and for an arbitrarily chosen missing-momentum bin of 40-50 MeV/c. The high resolution evident in the figure enables accurate definition of the parameters \((E_m, p_m)\) at which the cross sections were extracted. The dominant features are the two-body breakup \((^3\text{He} \rightarrow p + ^2\text{H})\) peak at 5.49 MeV and the threshold for three-body breakup \((^3\text{He} \rightarrow p + p + n)\) at 7.72 MeV. Higher missing energies correspond to the continuum of unbound states of the undetected \(pn\)-pair. The continuum includes the excitation of the unbound singlet S-state of the deuteron at \(E_m = (7.72+0.55)\,\text{MeV}\). There is no strength at \(E_m > 20\,\text{MeV}\) in the radiatively-corrected spectrum. We note that there was no measured strength at \(E_m > 20\,\text{MeV}\) for the entire \(p_m\) range for which these results are reported.

The 2-dimensional experimental spectral function,

\[
S_{\text{exp}}^\epsilon(E_m, p_m) = \frac{1}{p_p^2 \cdot \sigma_{ep}^{CC} \cdot d^6\sigma \cdot d\Omega_e d\Omega_p dE_p d\Omega_p},
\]

where \(\sigma_{ep}^{CC}\) is the electron-nucleon off-shell cross section of de Forest \([19]\) has been determined. Fig. 1(b) displays the measured spectral functions for the three virtual photon polarizations and for an arbitrary missing momentum bin 40 \(\leq p_m \leq 50\,\text{MeV/c}\). The extracted \(^3\text{He}\text(e,e'p)\) spectral functions are found to be independent of \(\epsilon\) within statistical and systematic uncertainties over the entire region \(0 \leq E_m \leq 20\,\text{MeV}\). Also displayed in the figure is a theoretical spectral function from Schulze and Sauer \([20]\) for \(p_m = 45\,\text{MeV/c}\). The theoretical spectral function describes the shape of the experimental one well, but the magnitude is approximately 20% larger. Note that the experimental values were affected by FSI which account for at least part of this difference.

For the two-body breakup channel, \(^3\text{He}\text(e,e'p)^2\text{H}\), the measured cross section as a function of \(p_m\) for the three values of \(\epsilon\) is shown in Fig. 2(a). A strong dependence on \(\epsilon\) is observed.

To gain insight into the \(\epsilon\)-dependence of the cross-section, the measured \(^3\text{He}\) proton momentum distributions \(p_2(p_m)\), obtained by integrating \(S_{\text{exp}}^\epsilon(E_m, p_m)\) over the two-body breakup peak, are plotted in Fig. 2(b). The momentum distribution shows very little dependence on the virtual photon polarization indicating that the longitudinal/transverse behavior of the two-body breakup cross section is explained well by \(\sigma_{ep}^{CC}\). The data also overlap well with published results \([6]\) obtained in non-parallel kinematics and at \(q = 430\) and
300 MeV/c, supporting the (PWIA) hypothesis that $S_{exp}^\rho(E_m, p_m)$ can be factorized in the cross section.

The remaining $\epsilon$ dependence of the cross sections is evaluated by comparing the integrals

$$N(\epsilon) = 4\pi \int_{10}^{100} \rho_2(p_m) \cdot \rho_3^2 dp_m$$

in Fig. 2 (b). The uncertainties quoted for $N(\epsilon)$ are statistical only. The values of $N(\epsilon)$ vary by about 10% for $\epsilon = 0.214 - 0.648$. We note that, to the extent this difference may be significant, the cross sections are slightly more longitudinal than those of $\sigma_{cp}^{CC1}$. Also shown in the figure are three calculations by Schulze and Sauer [20], Salmè et al. [21], and Forest et al. [22]. The Schulze and Sauer momentum distribution was calculated using the Paris potential, and is very similar to that of Salmè. The calculations by Forest et al. use the Argonne v18 NN-potential and the Urbana IX three-nucleon-interaction potential together with variational Monte-Carlo techniques. Note that the theoretically-extracted momentum distributions do not take into account final-state interactions which do affect the measured distributions. Hence, the differences of about 20-25% between the measured and calculated integrals, $N$, in Fig. 3 (b) contain (but are not necessarily restricted to) the effects of FSI.

A similar analysis can be performed at higher excitation energies. The experimentally-extracted momentum distributions for the continuum, $\rho_3(p_m)$, integrated over the range $E_m = 7-20$ MeV, are presented in Fig. 3. They display about a 10% dependence on $\epsilon$, similar to the two-body breakup channel. Also shown in the figure are older data from Saclay [5] and a calculated momentum distribution from Schulze and Sauer [24]. We note that at $p_m < 50$ MeV/c, our data set is well below that of Jans et al. The theoretical values from Schulze and Sauer are again approximately 20% larger than the data which are subject to the effects of FSI.

We have performed precise measurements of the $^3\text{He}(e,e'p)$ reaction in quasielastic kinematics. The data span the missing momentum range up to 95-165 MeV/c, and missing energy range up to 80 MeV. After radiative corrections, there is no observed strength at excitations higher than 20 MeV. The dependence on the virtual-photon polarization of the observed cross section (and hence the longitudinal/transverse behavior) over the entire excitation range is almost entirely due to the off-shell e-N cross section, and is described well by $\sigma_{cp}^{CC1}$. We conjecture that meson exchange and isobar currents, which are predominantly transverse, cannot be very important because the experimental results scale as $\sigma_{cp}^{CC1}$. We note that in a similar region of momentum transfer ($q = 500$ MeV/c and $q = 1050$ MeV/c), the inclusive $^3\text{He}(e,e')$ cross section, which integrates mainly over non-parallel kinematics, exhibits similar behavior [23]. Theoretical calculations of the spectral function and momentum distributions reproduce well the shape of the measured quantities, but are 10-20% larger in magnitude. This difference can be attributed, at least in part, to the effects of FSI. A theoretical study which includes an exact treatment of FSI is now in progress [17].

We would like to thank the MAMI staff for providing excellent support for this experiment. This Work was supported by the Deutsche Forschungsgemeinschaft (SFB 201), by the Bundesministerium für Forschung und Technologie and by the U.S. Department of Energy and the National Science Foundation.

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FIG. 1. \(^3\text{He}(e,e'p)\) cross sections (a) and spectral functions (b) as functions of missing energy for a missing momentum bin \(p_m = 40-50\) MeV/c.

FIG. 2. (a): \(^3\text{He}(e,e'p)^2\text{H}\) cross sections as a function of missing momentum. (b): extracted momentum distribution for the two-body breakup process are compared to various calculations. All uncertainties are statistical only.
FIG. 3. Momentum distribution for the $^3$He(e,e'p)np continuum integrated over the range $E_m = 7$-20 MeV. All uncertainties are statistical only.