

## Measurement of the Exclusive ${}^3\text{He}(e, e'p)$ Reaction Below the Quasielastic Peak

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New, high-precision measurements of the  ${}^3\text{He}(e, e'p)$  reaction using the A1 Collaboration spectrometers at the Mainz microtron MAMI are presented. These were performed in antiparallel kinematics at energy transfers below the quasielastic peak, and at a central momentum transfer of 685 MeV/c. Cross sections and distorted momentum distributions were extracted and compared to theoretical predictions and existing data. The longitudinal and transverse behavior of the cross section was also studied. Sizable differences in the cross-section behavior from theoretical predictions based on the plane wave impulse approximation were observed in both the two- and three-body breakup channels. Full Faddeev-type calculations account for some of the observed excess cross-section, but significant differences remain.

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Renewed precision studies of few-nucleon systems have been fueled by recent developments on both the theoretical and experimental fronts. Theoretically, progress toward full microscopic calculations based on realistic  $NN$  potentials has been achieved—for example, via nonrelativistic Faddeev-type calculations for three body, [1,2], and via Monte Carlo variational calculations for few-body, systems [3]. Experimentally, new facilities such as the Mainz microtron MAMI and the Thomas Jefferson National Accelerator Facility provide high-quality continuous-wave electron beams, high-resolution magnetic spectrometers and fast data acquisition. These features allow for precision measurements of the nuclear electromagnetic response through coincidence proton-knockout electron scattering, and thus also for detailed studies of unresolved issues related to few-nucleon systems—some of which were first raised in inclusive  $(e, e')$  measurements more than 20 years ago.

The experiment reported in this Letter is part of the systematic program [4] to study nucleon-knockout reactions on  ${}^3,4\text{He}$  nuclei over the quasielastic (QE) peak at a fixed central momentum transfer of  $|\vec{q}| = 685 \text{ MeV}/c$ . The measurements reported here were performed with  ${}^3\text{He}$  on the low-energy-transfer side of the QE peak (fixed central energy transfer,  $\omega \approx 158 \text{ MeV}$ ;  $x_B = (q^2 - \omega^2)/2M_p \omega \approx 1.5$ ), where the contributions from isobars are suppressed, thereby enhancing the possibility of observing the effects of short-range  $NN$  correlations. This low-energy-transfer region was studied extensively in the 1970s and 1980s using inclusive electron scattering at  $|\vec{q}| \gg k_F$  [5–7]. The measured  ${}^3\text{He}(e, e')$  cross sections in this kinematical regime were much higher than the plane wave impulse approximation (PWIA) predictions [7,8], and the discrepancy with prediction increased as  $\omega$  decreased (i.e., as  $x_B$  increased). Since these inclusive cross sections were measured over a wide range of mo-

mentum transfer and exhibited so called “ $y$  scaling” in this regime, it has been argued that the discrepancies cannot be accounted for by nonquasifree mechanisms such as meson-exchange (MEC) or isobars [9]. Further, effects of final-state interactions (FSI) in this region were estimated to be small [10]. It was suggested [7], as a possible solution to this discrepancy, that the high-momentum components in the  $^3\text{He}$  spectral function should be increased. Such an increase would be indicative of short-range  $NN$  correlations not accounted for in the theory. This suggestion came under scrutiny, and it was subsequently suggested [8] that exclusive and semiexclusive  $^3\text{He}(e, e'p)$  measurements were required to test such a modification, and to also examine the missing-energy ( $E_m$ ) dependence of the spectral function. In fact, a later measurement of  $^3\text{He}(e, e'p)$  at high missing momenta [11] ( $p_m$ ) did not support *ad hoc* attempts to increase the spectral function high-momentum components—leading to the conclusion that the observed enhanced strength in the earlier inclusive data (as discussed in Ref. [7]) was more likely due to defects in the PWIA model assumptions. However, it should be noted that these exclusive data of Ref. [11] sampled the kinematical domain with  $x_B < 1$  (“dip” region), and not the low- $\omega$  side at which the inclusive data are discussed in Ref. [7]. In the low- $\omega$  region,  $y$  scaling was observed, indicating that single-nucleon reaction mechanisms dominate. Still, problems did exist with the calculations and assumptions used in Ref. [7], since even at the QE peak ( $x_B \approx 1$ ), the theoretical calculations underpredicted that magnitude of the cross-section data by as much as 20%. It can also be noted that none of the since-reported exclusive  $^3\text{He}(e, e'p)$  measurements [12–15] have been carried out under the kinematical conditions studied by Ref. [7]. In this Letter, we report the first  $^3\text{He}(e, e'p)$  measurements on the low- $\omega$  side of the QE peak. These new exclusive data were taken with the momentum of the detected proton ( $\vec{p}_p$ ) parallel to  $\vec{q}$ , making the initial-proton-momentum  $\vec{p}_m = \vec{q} - \vec{p}_p$  antiparallel to  $\vec{q}$  (“antiparallel kinematics”).

The measurements utilized three incident beam energies  $E_i = 495, 630, \text{ and } 810$  MeV with electron scattering angles  $\Theta_e = 109.3^\circ, 75.3^\circ, \text{ and } 54.6^\circ$ , corresponding to virtual-photon polarizations of  $\epsilon = 0.19, 0.44, \text{ and } 0.64$ , where  $\epsilon = [1 + 2 \frac{|\vec{q}|^2}{w^2 - q^2} \tan^2 \frac{\Theta_e}{2}]^{-1}$ . The total systematic uncertainty of the measured cross sections was estimated to be  $\pm 3\%$ . This uncertainty is dominated by the uncertainty in the density of the  $^3\text{He}$  gas in the cold ( $T = 20$  K), high-pressure ( $P = 1823$  kPa) target. All error bars shown in the figures of this Letter are statistical only. More details on the experimental setup, performance, and data-analysis can be found in Ref.[16,17].

The  $(e, e'p)$  cross section for  $^3\text{He}$  was obtained as a function of missing-energy  $E_m = \omega - T_p - T_{A-1}$  and  $\vec{p}_m$ , where  $T_p$  and  $T_{A-1}$  are kinetic energy of detected proton and recoil  $A - 1$  system, respectively. The contri-

bution from radiative processes were corrected in the 2D ( $E_m, p_m$ ) space using the Mainz version of the RADCOR code [18]; the results agree with those extracted using a second method in which the radiative processes are accounted for in a Monte Carlo simulation code MCEEP [19,20]. It is found that the observed strength beyond  $E_m = 30$  MeV is completely dominated by radiative contributions and that, thus, the nuclear cross section (and therefore the spectral function) becomes too small to be measured beyond  $E_m = 30$  MeV.

The cross-section in (anti)parallel kinematics can be written as  $\sigma = K(\sigma_T + \epsilon\sigma_L)$ , where  $K$  is a kinematical factor,  $\sigma_T$  and  $\sigma_L$  are the contributions to the cross section from longitudinally ( $L$ ) and transversely ( $T$ ) polarized photons which can be separated by measurements at different  $\epsilon$  (with  $\sigma$  here standing for the sixfold differential cross section). Dividing  $\sigma$  by the elementary  $e - p$  cross-section  $\sigma_{ep}$  yields the distorted spectral function:

$$S^{\text{dist}}(E_m, p_m) = \frac{1}{p_p^2 \sigma_{ep}^{cc1}} \frac{d^6\sigma}{d\Omega_e d\Omega_p dp_e dp_p} \quad (1)$$

Division of the cross section by a well-defined form of  $\sigma_{ep}$  removes the predominant kinematic ( $\epsilon$ ) dependence, enabling easier identification of residual nuclear dependencies. Physical interpretation of the data was done by comparison to: (i) simple PWIA based on the de Forest *cc1* prescription [21] for the elementary  $e - p$  cross-section ( $\sigma_{ep}^{cc1}$ ), and (ii) full calculations using the Faddeev technique for the two-body breakup channel only [1]. For the full calculations, the AV18 NN potential was used, and MEC were included; to isolate the effects of including FSI and MEC on a PWIA starting point, comparison is made to the full calculations divided by PWIA—both with MEC included (which we label PWIA+FSI+MEC), and without MEC inclusion (labeled PWIA+FSI).  $\sigma_{ep}^{cc1}$  was selected for convenience in our PWIA description to allow direct comparison to earlier data from Ref.[12] and Ref. [13]

The measured sixfold cross section for the reaction  $^3\text{He}(e, e'p)X$  as a function of  $E_m$ , averaged over one sample  $p_m$  bin of  $150 \pm 10$  MeV/ $c$ , is shown for the three different  $\epsilon$  values in Fig. 1(a). The dependence of the cross section on the virtual-photon polarization is evident. This dependence, however, disappears by dividing out the elementary  $ep$  cross section in the spectral function, as can be seen from Fig. 1(b). The residual  $\epsilon$ -dependence is less than 5% and shows no systematic trend, meaning that the  $L/T$  behavior of the  $(e, e'p)$  cross-section is fully described by the  $\sigma_{ep}$ .

Two-body  $p - d$  (distorted) momentum distributions,  $\rho_2$ , were obtained by integrating the extracted  $S^{\text{dist}}$  over the two-body breakup peak. The extracted  $\rho_2$  distributions are shown in Fig. 2(a) plotted as a ratio with respect to the Kievsky spectral function. Like the spectral func-

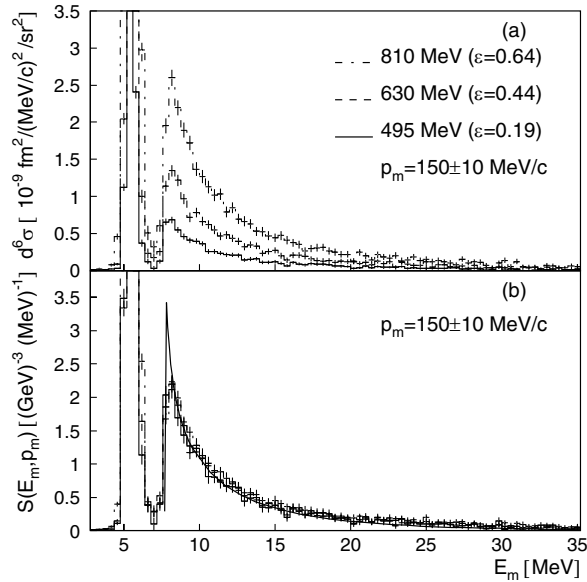


FIG. 1. (a) Radiatively-corrected sixfold  ${}^3\text{He}(e, e'p)X$  cross sections. The two-body breakup peak at 5.49 MeV dominates the spectrum. The three-body breakup continuum starts at 7.72 MeV. (b) The experimental spectral function for the three measured  $\epsilon$  values compared to the theoretical calculations from [22].

tion itself, this ratio is independent of  $\epsilon$  for the entire  $p_m$  range. Also shown in Fig. 2(a) are earlier data [12,13]. Several points are notable on the plot. First, a roughly constant 20% suppression of the data compared to the spectral function is seen for  $p_m$  up to 100 MeV/c. This roughly 20% difference between data and the Kievsky spectral function at low  $p_m$  has been previously observed (e.g., see Ref. [12]) and has been interpreted to be resulting predominantly from the fact that the theoretical spectral function does not account for FSI, and thus needs to be correspondingly renormalized. Second, agreement is seen between the current measurement and the earlier parallel kinematics Mainz data of Ref. [12], which were taken at the top of the QE peak. Third, the data of Ref. [13]—which were taken on top of the QE peak, but is the only data-set taken in transverse kinematics, thus at constant  $\omega$ —display reasonable agreement with those of Ref. [12] for  $p_m$  up to 95 MeV/c, but deviate both from our new data and those of Ref. [12] at higher  $p_m$ .

The notable new feature observed in Fig. 2(a) is the significant relative increase in the measured cross-section compared to the PWIA for  $p_m$  above 100 MeV/c. The beginning of this phenomenon of relative increase can be also seen in the few highest  $p_m$  points of Ref. [12] but not in the data of Ref. [13], which, in contrast to our new data, show a steady decrease with respect to the calculation for increasing  $p_m$ . It should be noted that the parallel kinematics data from Ref. [12] extend from the top of the QE peak to the low- $\omega$  side, and that their  $p_m$  dependence is coupled to the  $\omega$  dependence from kine-

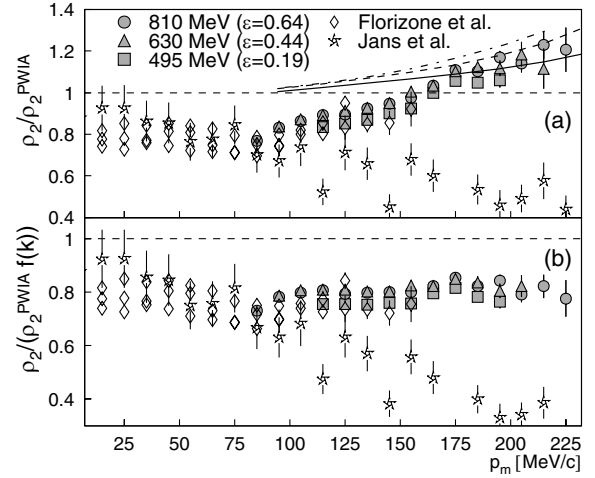


FIG. 2. (a) Ratio of extracted proton-momentum distributions for the  ${}^3\text{He}(e, e'p)d$  two-body breakup channel ( $\rho_2^{\text{exp}}$ ) to the spectral function prediction ( $\rho_2^{\text{th}}$ ) of Kievsky *et al.* [22]. The data extracted from our measurements at the three values of  $\epsilon$  are shown as full symbols. Earlier data from MAMI [12] and Saclay [13] are shown as open symbols. Note the Saclay data of Ref. [13] were taken under different kinematical conditions than the other data, being nonantiparallel and fully centered at  $x_B = 1$ . Theoretical curves ( $\rho_2^{\text{th}}/\rho_2^{\text{PWIA}}$ ) [1] shown are for 810 MeV beam energy PWIA+FSI (solid), PWIA+FSI+MEC (dashed), and for 495 MeV beam PWIA+FSI+MEC (dashed-dotted); (b) Same ratio as in plot (a), except now obtaining  $\rho_2^{\text{th}}$  by multiplying the spectral function of Ref. [22] by the renormalization factor  $f(k)$  as suggested in Ref. [7].

matical correlations, just as for the new data. This suggests that the (relative) increase in the cross section is a phenomenon observed only at the low- $\omega$  side. Moreover, our observed enhancement in strength appears to be consistent with that observed in the earlier inclusive measurements [5–7]. This can be demonstrated by multiplying the spectral function of Kievsky *et al.* by the enhancement factor that was suggested in Ref. [7]:  $f(k) = 1 + (k/\tilde{k})^n$  (where  $n = 2.5$ ,  $\tilde{k} = 285$  MeV/c, and  $k$  is the primordial proton-momentum in the nucleus, using  $k = p_m$  here). When the theory is modified in this way, then the  $\rho_2^{\text{exp}}/\rho_2^{\text{PWIA}}$  ratio for our new data becomes mainly constant at roughly 0.8 over the entire  $p_m$  range up to 225 MeV/c. This is demonstrated in Fig. 2(b).

Finally, the last item to note with regard to Fig. 2(a) is the comparison to the full theory calculations. The calculations including effects of FSI and MEC merge to equal the PWIA calculation at the lowest  $p_m$  values ( $p_m < 100$  MeV/c); however, these full calculations still show a 20% enhancement compared to data, even for the low  $p_m$  region. This overall 20% difference may be due to the lack of consistent relativistic dynamics in the theory, due to the relatively high value of  $q$ . Nevertheless, these calculations provide the best current possibility of evaluating whether the increase in the measured  $\rho_2^{\text{exp}}/\rho_2^{\text{PWIA}}$  ratio, for  $p_m$  above 100 MeV/c, is a manifestation of either FSI or

MEC effects. The full PWIA+FSI curve shows an increasing trend similar to the data (increasing by 11% as  $p_m$  increases from 100 to 200 MeV/c), and proper inclusion of MEC provides even more of a relative increase (with an 17% increase between  $p_m = 100$  and 200 MeV/c)—but the data still exhibit a greater still relative increase: 35% between  $p_m = 100$  and 200 MeV/c. This result suggests that FSI and MEC neglected by Ref. [7] are important and may explain a substantial part of the discrepancy between data and PWIA. Thus, it appears the  $f(k)$  enhancement factor is largely accounting for FSI and MEC—however, it should be noted again that the full calculations still do not show as a rapid an increase (as a function of  $p_m$ ) as do our new data. Finally, the full calculations also suggest that  $\epsilon$  dependence is small (<5%) and comparable with our systematic uncertainty, as shown on Fig. 2(a) for the 495 and 810 MeV beam energies.

Distorted proton-momentum distributions for the three-body breakup channel,  $\rho_3$ , were obtained by integration of the experimental spectral function  $S^{\text{dist}}(E_m, p_m)$  from seven to 20 MeV in  $E_m$ . These extracted  $\rho_3$  distributions are shown in Fig. 3(a), multiplied by  $4\pi p_m^2 \Delta p_m$ . Again, no systematic  $\epsilon$  dependence is observed. The ratio  $\rho_3^{\text{exp}}/\rho_3^{\text{PWIA}}$  is shown as a function of  $p_m$  in Fig. 3(b) using the unaltered theoretical prediction

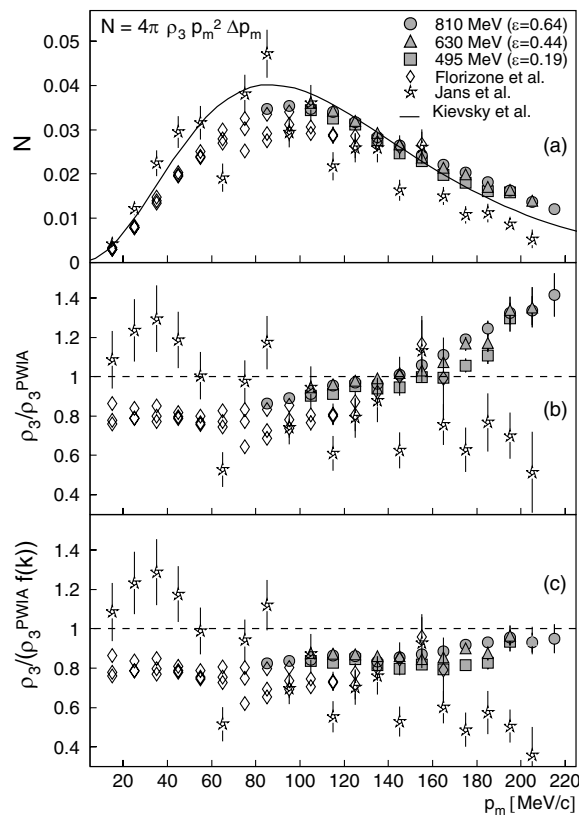


FIG. 3. Distorted proton-momentum distributions,  $\rho_3$ , for the  ${}^3\text{He}(e, e'p)pn$  three-body breakup channel. Plots and symbols follow the identical format used for  $\rho_2$  in Fig. 2.

of Kievsky *et al.* These ratios for the continuum channel show a similar feature as seen in the two-body channel. In Fig. 3(c), the prediction as modified by the enhancement factor  $f(k)$  from Ref. [7] is shown, leading to a better agreement with the data, but not as good as was observed for the two-body breakup channel.

In conclusion, we have performed measurements of the  ${}^3\text{He}(e, e'p)$  reaction on the low- $\omega$  side of the QE peak. Cross sections, distorted spectral functions and distorted proton-momentum distributions were obtained as a function of  $E_m$  and  $p_m$  for both the two-body and continuum breakup channel for three  $\epsilon$  values. The  $(e, e'p)$  cross-section strength falls to near zero for  $E_m > 30$  MeV. The strong  $\epsilon$  dependence of the cross section, both for two- and three-body reaction channels, is due to the  $L/T$  behavior of the elementary  $e-p$  cross-section. The distorted proton-momentum distributions for both the two- and three-body breakup channels significantly deviate in shape from the PWIA predictions of Ref. [22] for  $p_m$  above 100 MeV/c. Full calculations using the Faddeev technique show a roughly 20% over prediction at low  $p_m$ , but also show a functional dependence on  $p_m$ , above 100 MeV/c, that compares to the data significantly better than does PWIA—indicating that the contributions from FSI and MEC neglected in earlier PWIA analyses (e.g. [7]) are not small and should be accounted for. Thus, although the new generation of theoretical calculations have changed the normalization issue, the physics issues surrounding high  $p_m$  remain unresolved—in fact, even the full calculations do not give satisfactory description of the data at  $p_m$  above 100 MeV/c, which could be indicative of relativistic effects in the dynamics. The correction function suggested in Ref. [7] to enhance the high-momentum components of the spectral function, based on inclusive measurements in this same kinematical region ( $\omega < \omega_{QE}$ ) is therefore seen to account for deviations from PWIA in  $p_m$  dependence arising predominantly from FSI and MEC. Additional work is needed, both experimental and theoretical, to identify the source of the remaining discrepancy between our new data and the full calculations.

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