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The ^{4}He(e,e'p)^{3}H reaction at JLab

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Abstract. In the recent experiment E97-111 at Jefferson Lab the unseparated cross section for the (e,e'p) reaction on ^{4}He was measured at recoil momenta up to 530 MeV/c. In the plane-wave impulse approximation, many calculations predict a sharp minimum in the cross section for recoil momenta around 450 MeV/c and show that its location is sensitive to the short-range part of the internucleon potential. However, reaction dynamic effects such as final-state interactions and meson-exchange currents can obscure such a minimum. To distinguish and study these effects data were taken at several different kinematic points. The preliminary results of the experiment are presented and compared to recent model calculations.

1 Introduction

Studying few-body nuclear targets via the (e,e'p) reaction is a powerful method to investigate specific aspects of the nucleus. The ^{4}He nucleus is an especially interesting target since it already has many of the ingredients of a complex, heavy nucleus, while as an A=4 system, microscopic calculations are still feasible. Measurements of the cross section for the two-body breakup reaction ^{4}He(e,e'p)^{3}H and extracting the spectral function for $^4\text{He} \to t + p$ allow a study of the effective nucleon momentum distributions in this nucleus. Those momentum distributions are sensitive to ground-state short-range correlations, as well as to reaction dynamic effects such as final-state interactions, meson-exchange contributions, Δ-excitations, and relativistic effects.

The higher beam energies available at Jefferson Lab (JLab) as compared to other facilities such as MAMI, Mainz or NIKHEF, Amsterdam, provide more flexibility in the selection of kinematics and allow an extension of the measurements to higher momentum transfers. That way it is possible at JLab to obtain the spectral function at high recoil momentum in parallel kinematics. This gives access to regions where short-range correlations and possibly the internal structure of the nucleons become important. In the classical nuclear-physics literature nuclei are mostly described in terms of the independent-particle model, which itself can be derived from Hartree-Fock type calculations using effective interactions. These effective interactions have to be constructed by a procedure which has to take the short-range part as well as the long-range part of the NN-interaction into account. Whereas the long range part of the interaction is well understood in terms of the exchange of physical mesons, at shorter range only a phenomenological description is available. This presumably reflects a breakdown of the meson-exchange picture at small separations. Measuring the short-range component of the NN-interaction will teach us about the transition from mesonic to chromodynamic degrees of freedom.

An especially promising example for studying short-range correlations is the $^4\text{He} \to t + p$ spectral function, as discussed in [1]. Using an harmonic-oscillator nuclear model, these authors find a spectral function which monotonically drops as the recoil momentum of the struck proton increases. However, if they use realistic NN-interactions which include two-body currents via the ATMS method, the resulting spectral function is shaped like a classic diffraction pattern with a minimum at recoil momenta around 450 MeV/c. Furthermore, the structure of the spectral function at high momenta is sensitive to the short-range part of the NN-interaction. It is fortuitous that it is not possible to couple a proton and a triton in a relative $L = 2$ state to the $J^\pi = 0^+$ ^{4}He ground state. Otherwise the longer-ranged tensor correlations which are strong in the d-wave channel could severely obscure the minimum, as it happens e.g. for the two-body breakup of $^3\text{He} \to d + p$. Therefore, it was concluded in [1], that an observation of a minimum in the $^4\text{He} \to t + p$ spectral function could be directly linked to the s-wave correlation in the ground state. Other calculations of the spectral function for this channel [2,3] yield a similar result. The position of the minimum, as well as the position of the second maximum, again depend on the details of the interaction used.

The spectral function can be determined by measuring the cross section for the (e,e'p) reaction, which is to first order proportional to the spectral function

$$\frac{d^6\sigma}{d\Omega_{e'}dE_{e'}d\Omega_{p'}dE_{p'}} = K\sigma_{eN}\frac{1}{\eta}\alpha_{SF}S\left(\mathbf{p_r}, \epsilon_m\right) \qquad (1)$$

where K is a kinematical factor; η is the recoil factor; α_{SF} a spectroscopic factor; σ_{eN} the elementary off-shell

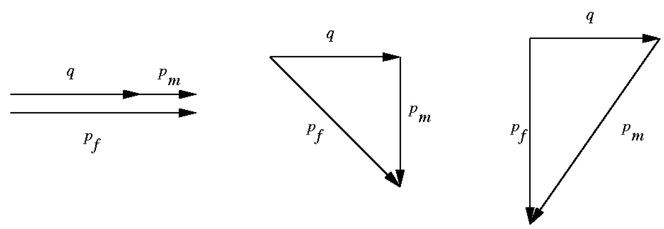

Fig. 1. Various values of p_m for fixed $(\omega, \mathbf{q})$

eN cross section, which includes all the dependence on the polarization of the virtual photon; and S is the spectral function, which gives the joint probability to find a nucleon inside the nucleus with a momentum $-\mathbf{p_r}$ and a separation energy ϵ_m. In this first order approximation for the (e,e'p) reaction the separation energy is given by the missing energy, and the recoil momentum $|\mathbf{p_r}|$ is equal to the missing momentum p_m. Thus a measurement of the (e,e'p) cross section in the appropriate kinematical region is a direct probe of short-range correlations in ^{4}He. However, this first-order approximation is not perfect and the plane-wave impulse approximation (PWIA) does not give a complete description of such experimental data. Reaction dynamic effects such as final-state interactions (FSI), meson-exchange currents (MEC), Δ-excitations (IC), and relativistic effects are relatively enhanced in the region of interest, since the cross section goes through a minimum.

Two experiments[4,5] have previously measured the cross section for ^{4}He(e,e'p)^{3}H at recoil momenta covering the range of interest. Neither of these experiments observed a significant signature of the dip near 450 MeV/c. According to [6,7,8,9], the absence of a minimum is due to the combined effects of FSI and MEC. Figure 1 shows how these measurements were done: the electron kinematics were fixed to an electron energy transfer ω of 215 MeV and to a momentum transfer $|\mathbf{q}|$ of 400 MeV/c. The missing momentum was varied by changing the detection angle for the recoiled proton. At a recoil momentum of 450 MeV the angle θ_{pq} between $\mathbf{q}$ and the outgoing proton was therefore about 50^o.

Many ideas have been formulated about how to suppress contamination from these reaction dynamic processes in experiments. They usually require more kinematical flexibility than previously possible at the facilities in Mainz and at NIKHEF, due to the limited beam energy available there, which puts correlated constraints on ω, q, and p_m. To reach the high missing momenta p_m at NIKHEF it was necessary to detect the knock-out proton at a large angle with respect to $\mathbf{q}$. Final-state interactions can seriously distort measurements in this region, since at the same electron kinematics processes involving FSI are possible, where the primarily knocked out proton had a smaller recoil momentum, but due to FSI scattered to larger angles and therefore is reconstructed at larger p_m. Since the cross section at lower missing momentum can be several orders of magnitude higher, those rescattered events can significantly contribute and even dominate the cross section in the dip region. This effect can be partly avoided or at least minimized utilizing parallel kinematics, where the recoiled proton is detected along the q-axis. In terms of the y parameter, where y is the minimum momentum a struck proton could have originally had while still satisfying the measured (e,e') kinematics, parallel kinematics coincide with $|y| = p_m$. However, there are two possibilities to fulfill this condition, positive and negative y, corresponding to parallel (the struck proton moves in the same direction as the virtual photon) and antiparallel alignment (the struck proton moves in the opposite direction). This parameter also provides a relation between the chosen electron kinematics and the quasi-free peak position. Positive y indicates an excess of energy transfer relative to the momentum transfer (high-energy side of the quasi-elastic peak). Although this would be undesirable for inclusive experiments, it is thought to be advantageous for the special situation of (e,e'p) in parallel kinematics, since both $\mathbf{q}$ and $\mathbf{p}_s$ must line up to the final ejected-proton momentum, suppressing contaminating or multistep processes. Negative y would be favorable for inclusive measurements, since due to the smaller value of the energy transfer MEC and IC effects are smaller. These qualitative arguments for utilizing parallel kinematics are supported by calculations [10,11]. Those calculations also show that although both positive and negative y can help to suppress reaction dynamic effects, the positive y option is superior for (e,e'p).

The higher beam energies available at JLab allow a substantial variation in the four momentum transfer Q^2 for a given ϵ_m, p_m region. Those variations are helpful in two respects: to help discriminate between one- and two-body currents contributing to the cross section and to suppress the contaminant two-body currents. The one-body direct knockout process of interest only depends on Q^2 through the electron-proton cross section σ_{ep}, while MEC and IC contributions are expected to have a very different Q^2 behavior. Higher values of Q^2 will help to suppress MEC and IC contributions due to the additional $1/Q^2$ dependences of the meson propagators $N\pi$ and $N\rho$, and of the $NN\pi$ $(NN\rho)$ form factors.

Close to quasi-elastic kinematics the momentum transfer essentially determines the momentum of the outgoing proton. FSI are a strong function of the proton energy. From proton scattering experiments it is known that they are lowest at proton momenta of about 700 MeV/c. Above this momentum, absorption effects begin to increase, but the elastic rescattering continues to decrease. However, for the case of the two-body breakup the latter effect is more important; therefore higher momentum transfer appears to be favorable in terms of suppressing FSI.

2 The experiment

The E97-111 experiment ran in the fall of 2000 at Jefferson Lab Hall A, using the standard equipment available there: two high resolution spectrometers (HRS) with standard detector packages and the cryo-target system for a high pressure gasous ^{4}He target [12]. All ideas about the suppression of reaction dynamic effects described in the previous section were accommodated in this experiment.

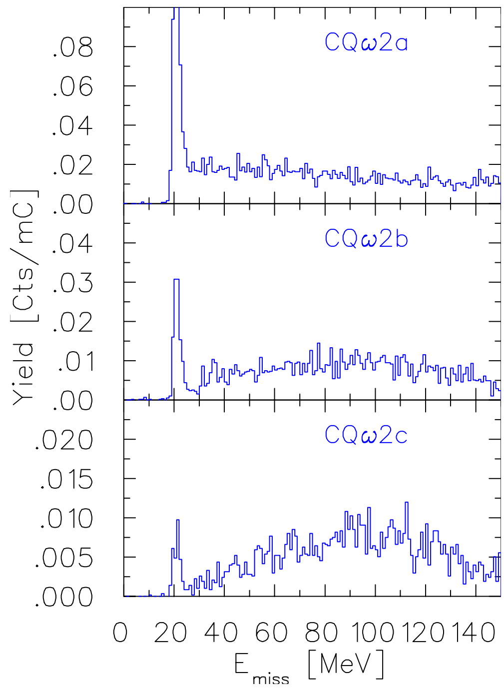

Fig. 2. Missing-energy spectra for the E97-111 experiment. Shown are the spectra for a beam energy of 3952 MeV, an electron scattering angle of 20.90^o, and an average missing momentum of 395 MeV/c (*top*), 446 MeV/c (*middle*), and 495 MeV/c (*bottom*)

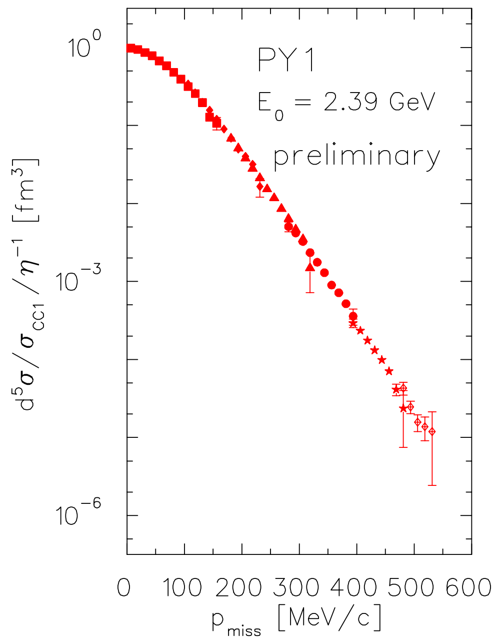

Fig. 3. Preliminary results for the reduced cross section for the six PY1 parallel kinematics at a beam energy of 2390 MeV. The momentum transfer Q^2 ranged from 0.44 (GeV/c)^2 for the lowest missing momenta to 0.28 (GeV/c)^2 for the highest missing momenta. The error bars only show the statistical uncertainty

The main emphasis was on measuring the ^{4}He(e,e'p)^{3}H cross section at recoil momenta up to 530 MeV/c in parallel kinematics at two different beam energies 2.389 GeV and 3.170 GeV/c. Additional data were taken in two quasi-perpendicular kinematics, with ω fixed to 525 and 487 MeV and Q^2 values of 1.78 and 1.82 (GeV/c)^2. Each of these kinematic points required several settings of the two Hall A HRS spectrometers, summarized in Table 1.

The exclusiveness of the two-body breakup channel is guaranteed by means of cuts on the missing energy ϵ_m. Since the residual nucleus is a triton, which has no excited states, the ^{4}He(e,e'p)^{3}H reaction will only occur at $\epsilon_m = 19.81$MeV/c. The continuum is well separated, with a threshold for the three-body breakup of 26.1 MeV and 28.3 MeV for the four-body breakup. Figure 2 shows the missing energy spectra for the three settings in the so-called CQω2 configuration, the peak at roughly 20 MeV corresponds to two-body breakup events.

3 Preliminary results

Preliminary results for the reduced cross sections in the PY1 kinematics are shown in Fig. 3. The error bars show the statistical error only. The cross section is divided by the elementary e-p off-shell cross section σ_{CC1}, using the description of [13] and the recoil factor η, to remove the basic kinematical dependence on the polarization of the virtual photon. At this beam energy recoil momenta from 0 to 530 MeV/c were covered. The reduced cross section falls monotonically within this momenta range. Figure 4 shows a similar plot of the reduced cross section for the PY2 kinematics at a higher beam energy of 3.17 GeV. The experimental data again cover recoil momenta up to 530 MeV/c. Two sets of theoretical predictions are also shown. The first set from J.M. Laget [14] consists of a PWIA calculation (dashed), a calculation including FSI (dotted), and the full calculation (solid), including FSI as well as MEC and IC. For the FSI at lower energies the phase shift description of [6] was used, which describes elastic NN scattering. At higher energies the high energy parameterization of the NN scattering amplitude of [15] was used, its imaginary part representing the absorptive part of the NN interaction.

The second group of calculations is from H. Morita and C. Ciofi degli Atti [16]. The first curve (long dashes) is a Glauber type calculation (labeled G), and the dashed-dotted curve (labeled G+FFT) additionally includes finite formation time (FFT) effects [17]. Although data were taken in parallel kinematics and at high momentum transfers, the reduced cross section still falls monotonically in the investigated region, with no sign of a minimum or a change in the slope. This feature appears in all but the PWIA calculations. Neither of the full calculations preserves the minimum in the spectral function at this kinematical setting. Laget's calculations indicate, that this is mainly due to FSI, whereas the inclusion of MEC and IC has only a small effect on the predicted cross section. These calculations also show that below 280 MeV/c the PWIA cross section is larger than the one of the full calculation, above that value the PWIA cross section is smaller.

Table 1. Overview of the different kinematic settings of E97-111. For the constant **q**-ω settings (CQω2, CQω3) the beam energy E_i was 3952 MeV, and the electron scattering angle θ_e was 20.90^o. The parallel kinematics were performed at $E_i = 2389$ MeV, $\theta_e = 16.9^o$ (PY1) and $E_i = 3170$ MeV, $\theta_e = 18.98^o$ (PY2)

	E_0 (GeV)	Q^2 ((GeV/c)^2)	ω (MeV)	p_m (MeV/c)	p_e (MeV/c)	p_p (MeV/c)
CQω2a	3.952	1.78	525	395	3427	1041
CQω2b	3.952	1.78	525	446	3427	1041
CQω2c	3.952	1.78	525	495	3427	1041
CQω3	3.952	1.82	487	468	3465	960
PY1a	2.389	0.44	284	26	2105	744
PY1b	2.389	0.42	369	126	2020	870
PY1c	2.389	0.40	478	226	1911	1015
PY1d	2.389	0.37	624	325	1765	1193
PY1e	2.389	0.33	830	425	1559	1431
PY1f	2.389	0.28	1035	495	1354	1657
PY2a	3.170	0.89	537	24	2633	1105
PY2b	3.170	0.85	653	124	2517	1250
PY2c	3.170	0.80	798	223	2372	1419
PY2d	3.170	0.73	985	323	2185	1627
PY2e	3.170	0.65	1239	423	1931	1900
PY2f	3.170	0.57	1481	493	1689	2154

This indicates that the FSI tends to shift cross section from low p_m (where the spectral function is high) to the dip region (where the PWIA cross section is tiny). The FFT effects, which are believed to restore the minimum at very high momentum transfers, are in these kinematics not of great importance. At lower recoil momenta the full calculations of both groups give a reasonable description of the data. Starting at around 350 MeV/c they start to differ from the data and among themselves. Whereas the Laget calculation overpredicts the cross section, the Ciofi calculation underpredicts it at high missing momenta.

Figure 5 shows the preliminary results for the reduced cross section in perpendicular kinematics CQω2 at a beam energy E_i of 3952 MeV and a Q^2 value of 1.78 (GeV/c)^2. The experimental data cover missing momenta from 300 to 530 MeV/c. The experimental data are again compared to the calculations from J.M. Laget. In the investigated region of missing momenta, the experimental data fall monotonically, there is no visible minimum around p_m=450 MeV/c and no sign of a second maximum at higher values of p_m, although the data can not exclude the possibility that the reduced cross section flattens out at missing momenta above 500 MeV/c. The calculations from Laget show again that in the framework of PWIA a minimum at 460 MeV/c should appear, but that it is mainly filled due to reaction dynamic effects. In contrast to the PY2 settings, both FSI and MEC/IC effects contribute to the cross section in the dip. However, at this higher momentum transfer it is predicted that although the dip is filled significantly, there is still some structure left in the reduced cross section, with the reduced cross

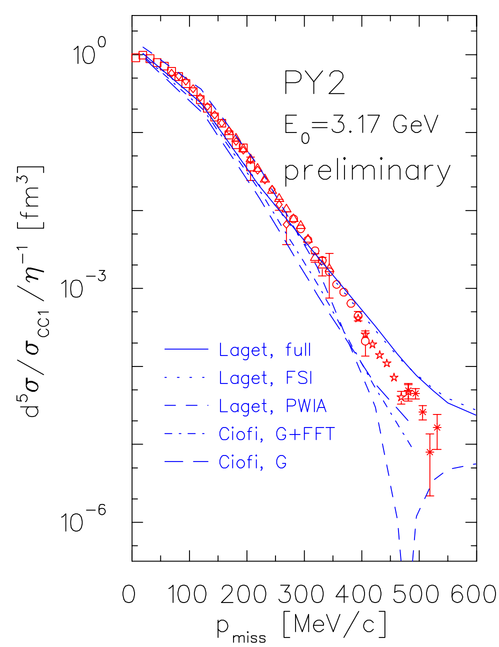

Fig. 4. Preliminary results for the reduced cross sections of the PY2 parallel kinematics at a beam energy of 3170 MeV. The momentum transfer Q^2 ranged between 0.89 (GeV/c)^2 and 0.57 (GeV/c)^2. The error bars on the experimental data points only show the statistical uncertainty. The *dashed line* (*short dashes*) shows the theoretical prediction by Laget in PWIA, the solid line depicts the full calculation, the *dotted line* only includes FSI. The *dashed curve* (*long dashes*) is a Glauber calculation by Ciofi and Morita, the *dash-dotted curve* additionally includes finite formation time effects

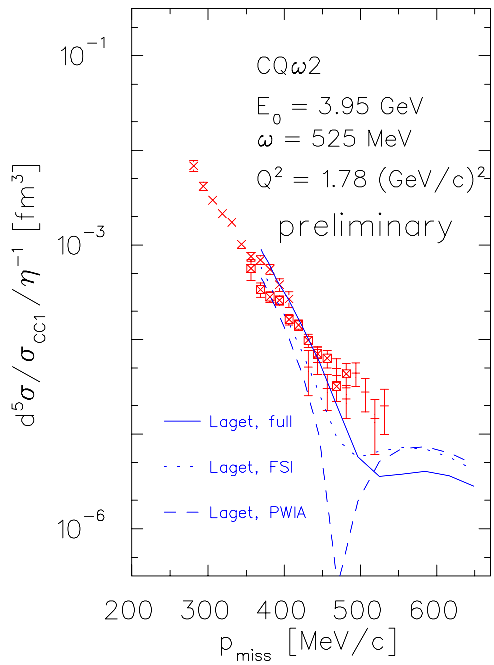

Fig. 5. Preliminary results for the reduced cross section in the CQω2 kinematics. The value of Q^2 was fixed to 1.78 (GeV/c)^2 at a beam energy of 3952 MeV. As in the previous figure, error bars only include the statistical uncertainty. The *dashed line* shows the theoretical prediction by Laget in PWIA, the *solid (dotted) line* is his full (FSI) calculation

section flattening out at missing momenta above 480 MeV At missing momenta above 550 MeV/c, which is outside the scope of the E97-111 experiment, the PWIA and the FSI calculations mainly agree, and only MEC/IC contributions lead to a reduction of the cross section.

4 Conclusions

We have studied the ^{4}He(e,e'p) proton knockout for the two-body breakup at missing momenta up to 530 MeV/c in several different kinematics, two settings utilizing parallel kinematics, and two in perpendicular kinematics. All of these data sets show a monotonically decreasing reduced cross section as the missing momentum increases. The minimum, which is predicted by most of the available PWIA calculations at a recoil momentum around 450 MeV/c, is not observed. However, the preliminary data are in reasonable agreement with the predictions from the latest full calculations, which include FSI, MEC, IC and relativistic effects. To observe the minimum, one would probably have to go to even higher momentum transfers.

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