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Few-Body Systems

^{3,4}He(e,e′p) Experiments In Jefferson Lab's Hall A

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Abstract. Coincidence experiments have proven to be very useful tools in studying specific aspects of the nucleus. In particular the (e,e′p) reaction has been used not only to study the single-nucleon structure of nuclei but also to study the behavior of nucleons embedded in the nuclear medium. In this paper, the results of the Jefferson Lab ^{3}He(e,e′p) measurements will be presented along with a discussion of recent and upcoming ^{4}He(e,e′p) measurements.

1 Introduction

The 6 msr, 4 GeV/c high resolution spectrometer pair in Jefferson Lab's Hall A have proven to be an exceptional tool for making cross section and response function separation measurements of the (e,e′p) reaction at high momentum transfers [1, 2]. The first Hall A few-body (e,e′p) experiment was performed on ^{3}He [3]. The range of missing momentum for a fixed (ω, $\mathbf{q}$) is unprecedented and the complete set of data will allow the extraction of the in-plane response functions described below. Data for both the two-body ^{3}He(e,e′p)d reaction and the continuum ^{3}He(e,e′p)pn reaction were taken and preliminary results will be presented herein. In addition to ^{3}He, a focused set of cross section measurements have been performed on ^{4}He [4]. This experiment sought to observe the predicted dip in the ^{4}He(e,e′p)t momentum distribution. It is generally accepted that final state interactions have obscured this dip in previous measurements [5]. These data are presently being analyzed. There are future plans to obtain a set of ^{4}He data in a kinematic range similar to that of the ^{3}He experiment in order to allow the extraction of the in-plane response functions [6]. Taken together, these measurements on ^{3}He and ^{4}He will add to our understanding of relativistic effects in the few-body wave function, ground state short-range correlations, final state interactions, and non-nucleonic degrees of freedom.

2 Kinematics

The kinematics for the (e,e'p) reaction are shown in Fig. 1. The scattering plane is defined by the incoming electron, $e = (E_e, \mathbf{e})$, and the outgoing electron, $e' = (E'_e, \mathbf{e}')$. The four-momentum of the virtual photon is given by $q^\mu=(\omega, \mathbf{q})$ and the four-momentum of the outgoing proton is given by $p'^\mu = (E_p, \mathbf{p}')$. The four-momentum square, $Q^2 = q^2 - \omega^2$, is defined such that for electron scattering Q^2 is always positive. The missing momentum vector is defined as $\mathbf{p}_m = \mathbf{q} - \mathbf{p}'$ and represents the momentum of the recoiling system.

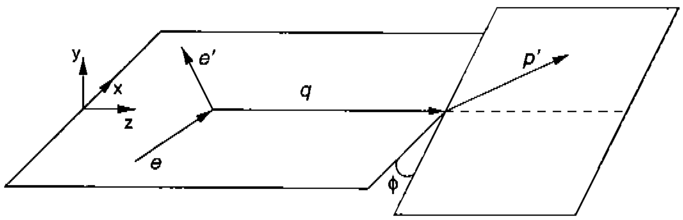

Figure 1. A schematic of the kinematics for the (e,e'p) reaction.

The form of the differential cross section for (e,e'p) reactions in the one-photon exchange approximation without polarization is:

$$\frac{d^6\sigma}{d\Omega_{e'} dE_{e'} d\Omega_{p'} dE_{p'}} = \frac{E_p p'}{(2\pi)^3} \sigma_{Mott} [v_T R_T + v_L R_L + v_{TL} R_{TL} \cos\phi + v_{TT} R_{TT} \cos 2\phi], \quad (1)$$

with ϕ the angle between the plane defined by e and $\mathbf{e}'$ and the plane defined by $\mathbf{p}'$ and $\mathbf{q}$, σ_{Mott} is the Mott cross section,

$$\sigma_{Mott} = \frac{4\alpha^2 E_{e'}^2}{Q^4} \cos^2 \frac{\theta_e}{2}. \quad (2)$$

The kinematics factors v_L, v_T, v_{TL},and v_{TT} are:

$$v_L = \frac{Q^4}{q^4}, \quad (3)$$

$$v_T = \frac{Q^2}{2q^2} + \tan^2(\theta_e/2), \quad (4)$$

$$v_{TL} = \frac{Q^2}{q^2} \left[\frac{Q^2}{q^2} + \tan^2(\theta_e/2) \right]^{1/2}, and \quad (5)$$

$$v_{TT} = \frac{Q^2}{2q^2}. \quad (6)$$

For the two body break-up channel, ^{3}He(e,e'p)d or ^{4}He(e,e'p)t, the proton energy and angle with respect to $\mathbf{q}$ are correlated because the missing energy is fixed. In this case the differential cross is written

$$\frac{d^5\sigma}{d\Omega_{e'}d\Omega_{p'}dE_{e'}} = \frac{E_p p'}{(2\pi)^3}\sigma_{Mott}f_{rec}^{-1}\left[v_T R_T + v_L R_L + v_{TL}R_{TL}\cos\phi + v_{TT}R_{TT}\cos 2\phi\right], \quad (7)$$

where f_{rec} is the recoil factor,

$$f_{rec} = \left[1 - \frac{E_{p'}}{E_t}\frac{\mathbf{p_m}\cdot\mathbf{p}'}{p'^2}\right]. \quad (8)$$

The response functions, R_L, R_T, R_{TL}, R_{TT} can be separated by a suitable choice of the kinematic parameters. In perpendicular in-plane kinematics with a fixed $\mathbf{q}$ and ω, one can separate R_T, R_{TL}, and a combination of the R_L and R_{TT} response functions, denoted as R_{L+TT}. One can also measure the cross section asymmetry A_{TL} for a given $\mathbf{q}$ and ω. This asymmetry is defined as:

$$A_{TL} = \frac{\sigma(\phi = 180) - \sigma(\phi = 0)}{\sigma(\phi = 180) + \sigma(\phi = 0)}. \quad (9)$$

In parallel and anti-parallel kinematics, i.e. when the out-going proton is in the direction of $\mathbf{q}$, one can separate the R_L and R_T response functions. In parallel kinematics p_m points in the opposite direction as $\mathbf{q}$ with $x_B < 1$ while in anti-parallel kinematics p_m points in the same direction as $\mathbf{q}$ with $x_B > 1$ where

$$x_B = \frac{Q^2}{2M\omega} \quad (10)$$

is the Bjorken scaling variable. For $x_B > 1$, the region in ω between the quasi-elastic peak and the elastic peak is being probed; while for $x_B < 1$, the region in ω towards the delta peak is being probed. The region in ω between the quasi-elastic peak and delta peak is often referred to as the dip region.

3 Results

The preliminary cross section results of the ^{3}He(e,e′p)d reaction for a fixed $\mathbf{q}$ = 1500 MeV/c and ω = 840 MeV for a beam energy of 4807 MeV are shown in Fig. 2. The agreement with the theoretical calculations of J.-M. Laget at missing momentum up to 750 MeV/c is striking. The cross section for p_m of up to 300 MeV/c follows the simple plane wave (PW) predictions. For higher p_m, the cross section becomes dominated by final state interactions, as indicated by the full calculations. J.-M. Laget's calculations use the Faddeev Paris two-body potential, the Hannover 18 three-body potential, and final state nucleon-nucleon interactions have been included using the eikonol approximation. There is as yet no clear indication as to what is causing the cross section at the largest missing momentum to be much greater than predicted.

J. Udias is also working on making theoretical calculations on (e,e′p) reactions [9]. Udias has provided the collaboration with a rough A_{TL} calculation [10], shown in Fig. 3. Both the relativistic distorted wave calculation (RDWIA) and the relativistic plane wave calculation (RPWIA) were made using a mean field approximation.

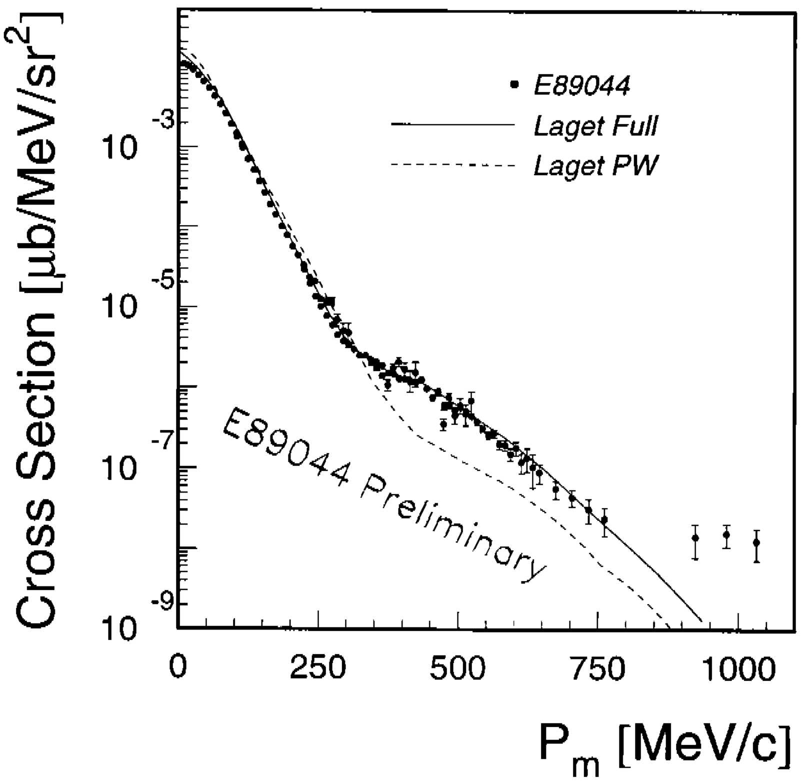

Figure 2. Shown are the preliminary cross section results for the reaction ^{3}He(e,e′p)d as a function of missing momentum with a beam energy of 4807 MeV and with a fixed q = 1500 MeV/c and ω = 840 MeV [1]. The theory curves show a plane wave impulse approximation calculation along with the latest full calculation of J.M. Laget. The enhancement in the cross section near 300 MeV/c and continuing to larger missing momentum is predominately due to final state interactions. There is no clear indication yet from theory what causes the enhancement of the cross section near 1000 MeV/c.

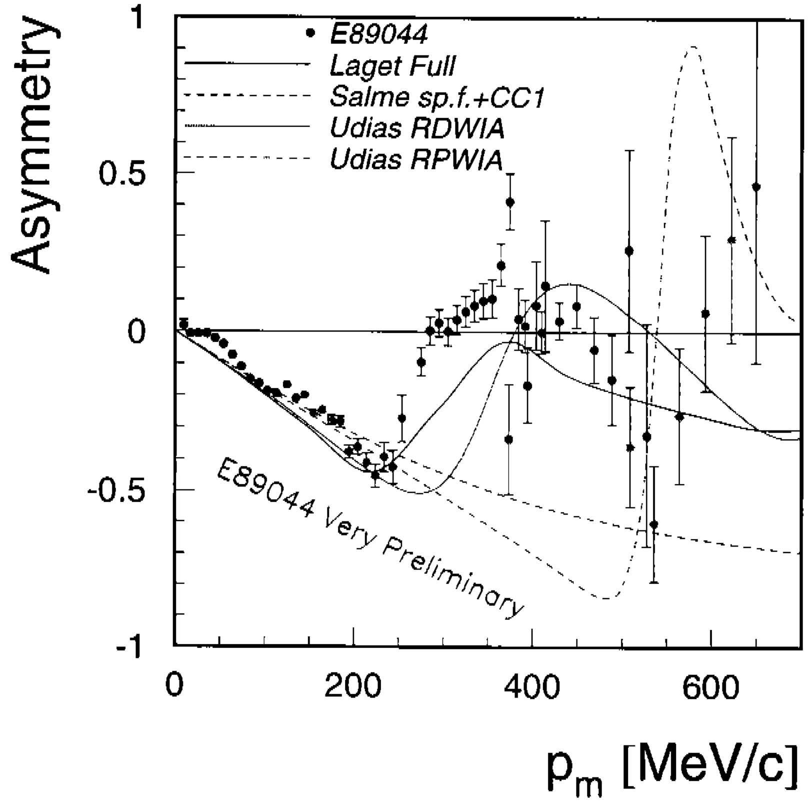

Figure 3. Shown is the preliminary A_{TL} data. The curves show the latest calculation of J.M. Laget along with a preliminary results of J. Udias. At lower missing momentum the theories are most sensitive to relativistic effects, while at the larger missing momentum the theories become sensitive to final state interactions effects.

From the preliminary cross section and A_{TL} asymmetry results, one can already see regions where the theoretical models clearly predicted the experimental results, such as the rise in the cross section at 300 MeV/c in Fig. 2 and the oscillations in Fig. 3. Also seen are the deficiencies in the theories, as indicated by much larger than expected cross section at extremely large missing momentum in Fig. 2 and by the phase and magnitude of the A_{TL} asymmetry.

Presently, the analysis of the separated response function separations is underway. Once these become available, it should become clear what effects are causing the discrepancies between theory and experiment and allow a significant improvement in our understanding of the three-body system. Also in the near future, the Hall A ^{4}He(e,e$'$p) cross section results will become available. In the coming years, the E01-108 ^{4}He(e,e$'$p) experiment will be run in Hall A and will provide a valuable investigation of the four-body system by measuring the in-plane response functions.

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