A Study of $(e,e'N)$ Reactions from Nuclear Targets
in the Quasi-elastic Region

CONF-840784--1

DE84 015825

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A major goal of a new, high-energy, high duty-factor electron accelerator will be to extend $(e,e'p)$ measurements to a wide range of kinematic conditions with high precision. In the quasi-elastic region, where the dominant reaction mechanism is one-nucleon knockout, the cross section is determined primarily by single-particle properties. As we will see below, the Coulomb-Transverse structure function is sensitive to the convection current and the spin-orbit potential in this energy region.

Since we are considering exclusive reactions, the nucleon-nucleus optical potential will play an important role in predicting cross sections. In particular, the optical potential sets the overall magnitude of the cross section. With polarized incident electrons, i.e. $(\vec{e},e'N)$ reactions, a new structure function exists. This fifth structure function has the feature that it vanishes in the absence of final-state interactions in the hadronic sector; thus providing a sensitive probe of the optical potential. In this paper, we will first consider unpolarized $(e,e'p)$ reactions and discuss our results for ^{12}C and ^{16}O targets. We will then discuss the fifth structure function present in polarized $(\vec{e},e'p)$ reactions.

The kinematic variables for the unpolarized coincidence reaction $A_1(e,e'X)A_2$ are shown in Fig. 1. In general, the cross section can be decomposed into a sum of four structure functions $W_i (i = L, T, CT, TT)$:¹

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$$\frac{d^5\sigma}{d\varepsilon_2 d\Omega_2 d\Omega_x} = \frac{1}{M_1} \sigma_{\text{Mott}} \{ v_L W_L + v_T W_T + v_{CT} W_{CT}^{(+)} \sin\phi_x + v_{TT} W_{TT} \cos 2\phi_x \} . \quad (1)$$

In the above equation, M_1 is the mass of the target nucleus, σ_{Mott} is the Mott cross section, and the v_i are leptonic kinematic factors. The dependence of the cross section in first-order Born approximation on the azimuthal angle ϕ_x of the outgoing coincidence particle is shown explicitly (our convention for this angle is shown in Fig. 1). The form of Eq. (1) then implies that the Coulomb-Transverse structure function can be separated by exploiting the asymmetric angular dependence in the scattering plane, i.e.

$\phi_x = \pi/2$ for $\Theta_x > 0$ and $\phi_x = -\pi/2$ for $\Theta_x < 0$ where Θ_x is the polar angle of the coincidence particle. In order to separate the Transverse-Transverse structure function, it is necessary to go out of the scattering plane.

The structure functions occurring in Eq. (1) can be expressed in terms of products of transition matrix elements of the electromagnetic current operator. As shown in Ref. 1, the structure functions can ultimately be expressed in terms of reduced matrix elements of the standard electromagnetic multipole operators.² In the quasi-elastic region, where the one-body piece of the current dominates, the required matrix elements can be expressed in terms of single-particle matrix elements and one-body densities. The single-particle matrix elements of the multipole operator O_{JK}

$$\langle x_{q,l'j}, {}^0 O_{JK} {}^R R_{nlj} \rangle$$

depend on the bound state wavefunction $R_{nlj}(r)$ and the scattering wavefunction $x_{q,lj}(r)$. In the calculations to be discussed below, we have used Woods-Saxon

wavefunctions (with the potential parameters taken from Elton and Swift³) for the bound states. The continuum wavefunctions have been calculated using the energy-dependent optical potential of Abdul-Jalil and Jackson, which includes a spin-orbit interaction.⁴ The one-body densities have been evaluated assuming that the daughter nucleus is in the hole state $(n\ell j)^{-1}$.

In Fig. 2, we show our result for the spectral function S for the reaction $^{12}\text{C}(e,e'p)$ for knocking out a $1p_{3/2}$ proton. The kinematic conditions are for the data of Bernheim et al. in the perpendicular kinematic configuration.⁵ The spectral function S is defined as the cross section in Eq. (1) divided by an electron-proton cross section and, in the factorization approximation, is simply related to the Fourier transform of the bound state wave function. The overall normalization has been obtained by a fit to the data. The convention of Bernheim et al. is that $p_2 > 0$ for $\phi_x = \pi/2$ and $p_2 < 0$ for $\phi_x = -\pi/2$, where p_2 is the recoil three-momentum of the daughter nucleus. From the discussion following Eq. (1), we see that the asymmetry in the spectral function is due to the Coulomb-Transverse structure function. Our calculations indicate that the Coulomb-Transverse structure function is due primarily to an interference between the Coulomb and convection current matrix elements and is sizeable even in the absence of final-state interactions.

The effect of spin-orbit interactions can be seen by comparing $(e,e'p)$ cross sections for spin-orbit partners. In Figs. 3 and 4, we show our results for the reaction $^{16}\text{O}(e,e'p)$ for knocking out a $1p_{3/2}$ proton and $1p_{1/2}$ proton, respectively. The data is again taken from Bernheim et al.⁵ In the absence of spin-orbit forces, the cross sections for the two cases will be identical, except for an overall scale factor. Therefore, we are led to conclude that for the $1p_{3/2}$ -knockout, the spin-orbit forces act to enhance the

Coulomb-Transverse structure function, whereas for the $1p_{1/2}$ -knockout, they act to decrease the Coulomb-Transverse structure function.

We have also investigated the general behavior of the $(e,e'N)$ cross section and can summarize our results as follows: First, for the case where the target nuclei have $J^\pi = 0^+$, the quantum numbers of the residual hole determine the shape of the nuclear angular distribution. Second, in the Coulomb-Transverse structure function $W_{CT}^{(+)}$, the contribution of the magnetization current tends to average out. This structure function comes predominantly from a Coulomb-convection current interference. Third, the Transverse-Transverse structure function W_{TT} tends to be negligible in the cases we have investigated. We would expect these conclusions to be valid only as long as the reaction mechanism is dominated by one-nucleon knockout (see also Ref. 6 for a discussion of the second and third points above).

We have also considered coincidence reactions with longitudinally polarized incident electrons, i.e. reactions of the type $A_1(\vec{e}, e'X)A_2$. One can define an asymmetry parameter A as the difference in differential cross sections for righthanded and lefthanded polarizations of the incident electrons divided by the sum:

$$A \equiv \frac{d\sigma_{\uparrow} - d\sigma_{\downarrow}}{d\sigma_{\uparrow} + d\sigma_{\downarrow}} \quad (2)$$

The asymmetry A can be expressed in terms of a new structure function $W_{CT}^{(-)}$, which is an interference between transition charge and current matrix elements, as^{7,8}

$$A = \frac{v_{CT}' W_{CT}^{(-)} \cos\phi_X}{\{v_L W_L + v_T W_T + v_{CT}' W_{CT}^{(+)} \sin\phi_X + v_{TT}' W_{TT} \cos 2\phi_X\}} \quad (3)$$

The explicit ϕ_x -dependence implies that the asymmetry will be at a maximum when the coincidence particle is ejected perpendicular to the scattering plane. The new structure function $W_{CT}^{(-)}$ is comparable in size to the structure function $W_{CT}^{(+)}$ which occurs in the unpolarized cross section. The structure function $W_{CT}^{(-)}$ has the feature that it vanishes in the absence of final-state interactions (whereas $W_{CT}^{(+)}$ does not).

In Fig. 5, we show a calculation of the asymmetry versus the proton angle in the center-of-mass system for the reaction $^{12}C(e^+, e'p)$. The kinematics are taken to be: incident electron energy $\epsilon_1 = 300$ MeV, energy transfer $\omega = 60$ MeV, electron scattering angle $\theta_e = \pi/3$, and $\phi_x = 0$ (i.e. perpendicular to the scattering plane). These kinematics correspond to the top of the quasi-elastic peak at this energy. In Fig. 5, the dashed curve is the asymmetry for knocking out a $1s_{1/2}$ proton while the solid curve is for a $1p_{3/2}$ proton. As can be seen, the predicted asymmetry can be reasonably large; typically we find $A \sim 10\text{-}20\%$. In order to judge the sensitivity to the details of the optical potential used, we show in Fig. 6 the result of using a different optical potential. The optical potential chosen was that of Fiedeldey and Engelbrecht⁹ to which the Coulomb potential has been added (note that the optical potential of Ref. 9 is for neutrons). This optical potential was chosen because it does not contain a spin-orbit interaction. A comparison of Figs. 5 and 6 implies that the asymmetry is fairly sensitive to the optical potential used, and in particular to the spin-orbit part. In Fig. 7 we show the predicted asymmetry for the reaction $^{16}O(e^+, e'p)$ for the kinematic conditions of Bernheim et al.⁵ In this case the solid curve is for $1p_{1/2}$ protons and the dashed curve for $1p_{3/2}$ protons. We again see that the asymmetry is fairly sizeable.

We have calculated $(e,e'p)$ cross sections in the quasi-elastic region in an attempt to unravel the contributions of the various structure functions and to study the effect of the optical potential. Our calculations for ^{12}C and ^{16}O indicate that the Coulomb-Transverse structure function $W_{\text{CT}}^{(+)}$ plays an important role in understanding the data. We have also calculated the coincidence cross section with polarized electrons; the asymmetry A due to final-state interactions is predicted to be of order 10-20% for the cases considered and is sensitive to details of the optical potential.

This work supported by the U. S. Department of Energy under contract number W-31-109-ENG-38.

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Figure Captions

- Fig. 1 The kinematic variables for the coincidence reaction $A_1(e,e'X)A_2$ are as shown. The convention used here for the azimuthal angle ϕ_x is shown explicitly (note that this differs from the convention used in Ref. 8).
- Fig. 2 Predicted spectral function S versus recoil three-momentum p_2 of the daughter nucleus for the reaction $^{12}\text{C}(e,e'p)^{11}\text{B}(1p_{3/2})^{-1}$. The data is from Bernheim et al. in perpendicular kinematics (note that the overall normalization is determined by a fit to the data).⁵
- Fig. 3 Predicted spectral function for the reaction $^{16}\text{O}(e,e'p)^{15}\text{N}(1p_{3/2})^{-1}$. See Fig. 2.
- Fig. 4 Predicted spectral function for the reaction $^{16}\text{O}(e,e'p)^{15}\text{N}(1p_{1/2})^{-1}$. See Fig. 2.
- Fig. 5 Predicted asymmetry A versus polar angle θ_x of the outgoing proton in the center-of-mass system for the reaction $^{12}\text{C}(e^+,e'p)^{11}\text{B}$. The solid curve is for $1p_{3/2}$ protons and the dashed curve is for $1s_{1/2}$ protons. The kinematics were chosen to be $\varepsilon_1 = 300$ MeV, $\omega = 60$ MeV, $\theta_e = \pi/3$ and $\phi_x = 0$. Note that harmonic oscillator wavefunctions have been used here for the bound state wavefunctions.
- Fig. 6 Predicted asymmetry for the reaction $^{12}\text{C}(e^+,e'p)^{11}\text{B}$ using the optical potential of Ref. 9. See Fig. 5.
- Fig. 7 Predicted asymmetry for the reaction $^{16}\text{O}(e^+,e'p)^{15}\text{N}$ for the kinematic conditions of Bernheim et al.⁵ with $\phi_x = 0$. The solid curve is for $1p_{1/2}$ protons and the dashed curve for $1p_{3/2}$ protons.

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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