Missing-Energy Dependence of the Separated Response Functions for the Reaction $^{12}C(e,e'p)$

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A longitudinal-transverse separation of the reaction $^{12}C(e,e'p)$ in the quasielastic region has been performed in parallel kinematics. Above the two-particle emission threshold a broad bump is seen which has been attributed to knockout from the deeply bound s shell. This s-shell region shows a large transverse enhancement compared to distorted-wave impulse-approximation calculations based on free-proton form factors. This enhancement increases with missing energy, indicating that a nonquasielastic reaction mechanism plays a significant role. The p shell is consistent with the free-proton behavior.

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At quasielastic kinematics the nuclear electromagnetic response is expected to be dominated by one-body interactions. Inclusive (e,e') measurements, however, have cast serious doubt on the interpretation of the quasifree scattering process in terms of one-body interactions with free nucleons. In particular, separated inclusive data on $^{12}C(e,e')$ reported by Barreau *et al.*[1] reveal a transverse-to-longitudinal ratio approximately 60% in excess of that predicted from impulse-approximation calculations with unmodified nucleons.[2] In this Letter we report a longitudinal-transverse separation of coincidence $(e,e'p)$ data that attempts to examine this phenomenon by an exclusive measurement.

Below the two-particle emission threshold, the $(e,e'p)$ process in ^{12}C is dominated by p-shell knockout. Above this threshold, the process contains contributions from two-body knockout as well as knockout from the more deeply bound s shell. Examination of the missing-energy distribution in the continuum allows one to isolate various components of the reaction mechanism. Since p- and s-shell protons sample different average nuclear densities, the $(e,e'p)$ process allows one to investigate, assuming a one-body reaction, the density dependence (i.e., medium modifications) of the electron-proton coupling.[3]

In the one-photon-exchange approximation the coincidence cross section can be expressed in terms of four independent structure functions[4] which depend on $\mathbf{q}$ and ω (the momentum and energy transfers), T_p (the proton kinetic energy), and θ_p (the proton angle with respect to $\mathbf{q}$):

$$d^4\sigma/d\Omega_p\, d\Omega_e\, d\omega\, d\epsilon_m = \sigma_M[v_L R_L + v_T R_T + v_{LT} R_{LT}\cos\phi_p + v_{TT} R_{TT}\cos 2\phi_p]. \quad (1)$$

Here, R_L (R_T) is the longitudinal (transverse) response function and R_{LT} (R_{TT}) is the response function generated by interference between the longitudinal and transverse (two transverse) components of the nuclear electromagnetic current. ϕ_p is the angle between the electron-scattering plane and the plane containing $\mathbf{q}$ and the detected proton, σ_M is the Mott cross section, ϵ_m $(=\omega - T_p)$ is the missing energy, and the v's are kinematic factors weighting the various photon polarization states. In parallel kinematics (i.e., the outgoing proton detected in the direction of $\mathbf{q}$) the interference terms vanish and one is left with only two response functions, R_L and R_T. This choice of kinematics was made for this experiment. In the plane-wave impulse approximation (PWIA) the cross section factors into the product of an elementary (e,p) cross section and a quantity which contains only nuclear-structure information, the nuclear spectral function:

$$d^4\sigma/d\Omega_p\, d\Omega_e\, d\omega\, d\epsilon_m = K\sigma_{ep} S(\mathbf{p}_r, \epsilon_m), \quad (2)$$

where K is a kinematic factor and σ_{ep} is an off-shell electron-proton cross section.[5] The spectral function, S, represents the joint probability of finding within the nucleus a proton of momentum $-\mathbf{p}_r = \mathbf{p}_f - \mathbf{q}$ (where $\mathbf{p}_f$ is the momentum of the detected proton) and separation energy ϵ_m. In PWIA the spectral function contains no dependence on the virtual-photon polarization; all such

dependence is contained within the factor σ_{ep}. Thus, if we keep $\mathbf{p}_r$ and ϵ_m fixed, the spectral function remains constant, so that one can determine the longitudinal/transverse (L/T) character of the proton cross section directly. Barring spin-orbit interactions, distortions of the outgoing proton do not destroy the factorization of the cross section, but the distorted spectral function will, in general, have a dependence on the outgoing proton energy.[6]

The cross section for scattering from a free proton can be written as

$$\sigma_{ep}^{\text{free}} = d\sigma/d\Omega = (\sigma_M/\eta)[v_L k_L G_E^2(q_\mu^2) + v_T k_T G_M^2(q_\mu^2)], \quad (3)$$

where G_E (G_M) is the electric (magnetic) proton form factor, $q_\mu^2 = \mathbf{q}^2 - \omega^2$, $k_L = \mathbf{q}^2/q_\mu^2$, $k_T = q_\mu^2/2m_p^2$, $v_L = (q_\mu/\mathbf{q})^4$, $v_T = q_\mu^2/2\mathbf{q}^2 + \tan^2\theta_e/2$, m_p is the proton mass, and θ_e is the electron-scattering angle. $\eta = 1 + 2(E_0/m_p)\times\sin^2\theta_e/2$ is a recoil factor which is present only for scattering to a discrete state. From Eqs. (1)–(3) one can extract longitudinal and transverse spectral functions, S_L and S_T, which, for quasifree knockout of protons exhibiting the free on-shell behavior, are equal:

$$S_L = R_L/Kk_L G_E^2 = R_T/Kk_T G_M^2 = S_T. \quad (4)$$

In reality, one is sampling an off-shell nucleon amplitude. Presently, there is little theoretical guidance on how to extrapolate this off-mass-shell behavior. We will compare our data to a calculation employing the σ_{ep} given by de Forest.[5] This σ_{ep} differs only slightly from the on-shell value in our kinematical region.

The experiment was performed at the Massachusetts Institute of Technology Bates Linear Accelerator Center with use of the spectrometers MEPS and OHIPS to detect electrons and protons, respectively. The properties of the spectrometers are given elsewhere.[7] Both spectrometers were instrumented with a two-plane vertical drift chamber[8] for reconstruction of the particle trajectories and scintillator array for trigger definition. In addition, the electron spectrometer was equipped with an Aerogel ($n = 1.05$) Čerenkov detector for rejection of pions.

Elastic ^{1}H$(e,e)^1$H data, acquired before and after the ^{12}C$(e,e'p)$ data, provided a combined calibration of the solid angle and efficiency of the electron arm. The ratio of the measured to known cross section did not vary by more than 2.2% from the average value of (93.2 $\pm$ 0.6)%. Normalization and calibration of the coincidence setup were achieved through the reaction ^{1}H(e,ep). Together with the ^{1}H$(e,e)^1$H data, this provided a combined calibration of the solid angle and efficiency of the proton spectrometer resulting in a 9.1% correction for the proton arm.

TABLE I. Electron kinematics.

E_0 (MeV)	θ_e (deg)	ω (MeV)	$\mathbf{q}$ (MeV/c)	ϵ
288.1	120	122.3	397.8	0.131
443.1	60	122.7	396.3	0.576

The electron kinematics are given in Table I. For each kinematics the electron angle and final energy and proton angle were kept fixed; the proton energy was the only experimental quantity varied. The range of proton kinetic energies sampled, 60 to 120 MeV, was identical for both kinematics. This resulted in a range for $\mathbf{p}_r$ from -110 to -20 MeV/c for the p shell and from -80 to $+70$ MeV/c for the s-shell region. In order to sample nearly identical ranges of $\mathbf{p}_r$ at both kinematics, software cuts were placed on the electron energy and in-plane and out-of-plane angles. In the one-photon-exchange approximation this means that the only parameter that differs in comparing similar missing-energy bins is the photon polarization,

$$\epsilon = [1 + (2\mathbf{q}^2/q_\mu^2)\tan^2\theta_e/2]^{-1},$$

which was constant at each kinematics.

The separated data with radiative corrections applied are shown in Figs. 1(a) and 1(b). These spectra were

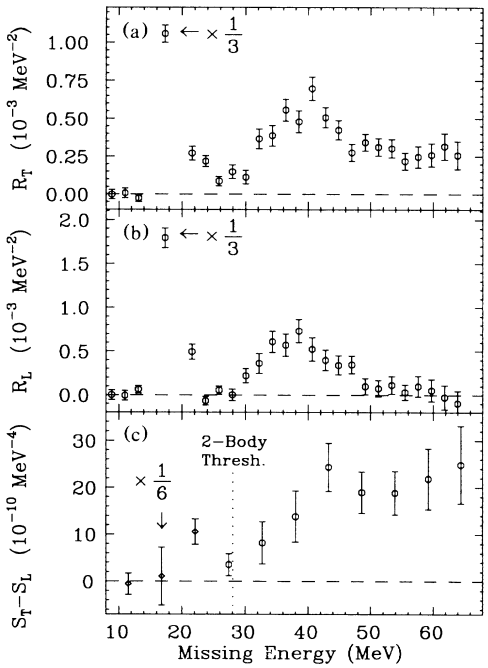

FIG. 1. (a) Transverse and (b) longitudinal response functions and (c) difference of the spectral functions (see text for definitions) vs missing energy (after radiative corrections). For (a) and (b) the bin width is 2.10 MeV and the data have been summed in the missing-energy region from 14 to 20 MeV. This region includes the ground state and first excited state (at 2.12 MeV) of ^{11}B. For (c) the bin width is 5.25 MeV. Only statistical errors are shown.

summed over the ground state and first excited state (at 2.12 MeV) of ^{11}B to avoid artificial oscillations in the response functions which would arise from the different energy resolutions at the two kinematics. The missing-energy resolution was 1.0 (1.5) MeV for the backward (forward) electron angle. The L/T ratio for the p shell includes the weakly excited states at 2.12 and 5.02 MeV and is consistent with the σ_{ep} used,[5] although identical modifications of the proton form factors, G_E and G_M, which cancel in this ratio cannot be excluded. Above $\epsilon_m = 27$ MeV, the shape is different for the two response functions; the transverse is less localized in ϵ_m. For missing energies above 50 MeV, the transverse response shows significant strength and the longitudinal response is essentially zero. This missing-energy behavior indicates the occurrence of a second reaction process. In Fig. 1(c) the difference between the spectral functions, $S_T - S_L$, is plotted versus missing energy. The weakly excited p-shell state at 5.02 MeV does not affect the p-shell ratio appreciably although it shows a significant enhancement of the transverse spectral function relative to the longitudinal. In addition, there is a dramatic rise above the two-body knockout threshold of 28 MeV suggesting the presence of a transverse two-body reaction component in the region of the s shell. For $\epsilon_m > 40$ MeV, this difference is essentially constant and is reminiscent of the uniform continuum strength seen in our earlier measurement in the dip region.[7]

The data for both shells were compared to a PWIA calculation using $1s$ and $1p$ harmonic-oscillator momentum distributions ($b = 1.67$ fm) and de Forest's $\sigma_{\mathrm{cc}}^{\mathrm{cc}}$ prescription[5] for the off-shell (e,p) cross section. Several models for the s-shell missing-energy distribution were investigated, ranging from a δ function to a point-by-point representation of the data. For the p shell, the ratio of the longitudinal to the transverse spectral functions for the radiatively corrected data divided by the same ratio for the PWIA calculation is $0.86 \pm 0.09 \pm 0.12$. The two errors are statistical and systematic, respectively. The same comparison yields $0.56 \pm 0.07 \pm 0.06$ for the s-shell region ($27 \leq \epsilon_m \leq 55$ MeV). The choice of the missing-energy distribution affects this number by less than 1%. The large systematic errors arise mainly from the statistical uncertainty in the normalization data. Also, since the p-shell momentum distribution was sampled in a region where it is rapidly varying (the kinematics were centered on the maximum of the s-shell distribution), uncertainty in the electron incident energy gives rise to a large systematic uncertainty in the calculation used to form the p-shell ratio. The L/T ratio for the s shell is sensitive to the missing-energy integration limits as this ratio decreases with increasing missing energy.

Radiative corrections have been made with use of the prescription of Borie and Drechsel.[9] The model we used assumes the one-body momentum distribution as measured by Mougey *et al.*[10] and was distributed in missing energy and normalized according to the data at each angle. Proton distortion has also been investigated with standard models.[11] It was found that the distorted momentum distributions differed by less than 1% for the two kinematics for the p shell and by 3% for the s shell. Thus, the distortions do not alter the L/T ratios appreciably.

The L/T ratio of the data divided by the same ratio for the distorted-wave impulse-approximation calculations is $0.89 \pm 0.09 \pm 0.12$ for the p shell. A similar measurement was made by van der Steenhoven *et al.*,[12] who reported a transverse enhancement for the p shell. The ratio of spectral functions (S_L/S_T) extracted from their data is 0.67 ± 0.22. This is consistent with our result. The L/T ratio for our data in the s-shell region is $0.61 \pm 0.08 \pm 0.07$. The difference in our measured ratios for the p and s shells is more significant than the individual uncertainties would indicate since, in the double ratio of p- to s-shell L/T [i.e., $(S_L/S_T)_p/(S_L/S_T)_s$], much of the systematic error cancels.

Occupation numbers were obtained by comparison of the data at each angle to the distorted-wave impulse-approximation calculation. This comparison yields $3.96 \pm 0.10 \pm 0.64$ for the p shell and $1.18 \pm 0.03 \pm 0.17$ for the s shell at the forward angle. At the backward angle the same comparison gives $4.13 \pm 0.10 \pm 0.66$ for the p shell and $1.39 \pm 0.04 \pm 0.20$ for the s shell. Most of the systematic uncertainty reflects the sensitivity of the distorted-wave impulse-approximation calculation to the optical potential. In addition, the s-shell occupation number (especially at the backward angle) is sensitive to the range of integration in ϵ_m.

Only under certain assumptions is it possible to make a meaningful comparison to the inclusive (e,e') data; in particular, one must assume a one-body factorized form for the $(e,e'p)$ cross section. The validity of this assumption is questionable since there is evidence of a two-body reaction component in the s-shell missing-energy region. Furthermore, since neutrons also contribute to an inclusive measurement, an assumption about their L/T character must be made as well. Nevertheless, if we assume that the cross section factorizes and that the measured proton L/T ratio stems from a transverse enhancement that is the same for the neutron, the predicted inclusive L/T ratio is 0.77 ± 0.09 compared with the measured value of 0.60 ± 0.04.[2] Our number was obtained by integrating out to $\epsilon_m = 55$ MeV. If we assume that the transverse-longitudinal difference remains constant out to $\epsilon_m \simeq 80$ MeV and that the longitudinal spectral function remains zero above 65 MeV, then the resulting L/T ratio is consistent with the inclusive data of Barreau *et al.*[1]

The average nuclear density sampled by the interior-peaked s shell is roughly 3 times larger than that for the p shell in the range of recoil momenta sampled by the

experiment. In a simple one-body picture of the quasielastic reaction mechanism one might be tempted to attribute the difference seen in the p and s shells to a density dependence of the proton's electromagnetic properties. However, the missing-energy dependence of the transverse-longitudinal difference indicates the presence of a second reaction channel.

In conclusion, the L/T ratio for the p shell is consistent with that expected for quasifree knockout of unmodified protons but the uncertainty in our result does not rule out the modification suggested by van der Steenhoven *et al.*[12] The s shell shows a substantial enhancement of the transverse spectral function relative to the longitudinal. In addition, the transverse component of the s shell exhibits strength at missing energies where the longitudinal response is zero, indicating the presence of a second reaction channel of transverse character. A similar effect was observed in a more pronounced way in our earlier measurement in the dip region.[7] The difference, $S_T - S_L$, rises dramatically above the two-particle emission threshold suggesting that two-body currents are a likely explanation of this excess transverse strength. A quantitative understanding of the dominant reaction processes is required before the relative importance of density-dependent modifications of the intrinsic proton properties and many-body effects can be assessed.

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