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Separated spectral functions for the quasifree ^{12}C$(e,e'p)$ reaction

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A separation of the longitudinal and transverse ^{12}C$(e,e'p)$ cross sections in the quasifree region has been performed in parallel kinematics at Q^2 of 0.64 and 1.8 GeV^2 for initial proton momentum $<$80 MeV. The separated transverse and longitudinal spectral functions at $Q^2=0.64$ GeV^2 show significant differences for missing energy between 25 and 60 MeV indicating a breakdown in the single nucleon knockout picture. The transverse spectral functions exhibit definite momentum transfer dependence.

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Quasifree electron scattering from complex nuclei is expected to be dominated by single nucleon processes and is described in terms of the impulse approximation (IA), i.e., the electron-nucleon interaction is described in terms of free-nucleon currents. However, a body of empirical evidence, both from inclusive (e,e') scattering and exclusive $(e,e'p)$ scattering, suggests a breakdown of the interpretation of quasifree scattering as one-body interactions with free nucleons. Most directly, the $^{12}\mathrm{C}(e,e'p)$ experiment of Ulmer *et al.* [1] at four momentum transfer squared, Q^2, of 0.15 GeV^2 reported significant excess in the nuclear response to transverse photons compared to that for longitudinal photons beyond the two-body breakup threshold. Excess transverse strength has been observed in other light nuclei including ^{3}He [2] and ^{6}Li [3], however, no excess transverse strength is observed in recent ^{3,4}He experiments [4]. Similar transverse enhancements have also been invoked to explain the longitudinal-transverse interference terms in unseparated data [5,6]. These results suggest contributions from multinucleon currents and a breakdown of the IA. Difficulties are also evident in describing the momentum transfer dependence of unseparated $(e,e'p)$ cross sections [7], but coincidence data at higher Q^2 $(1-7\ \mathrm{GeV}^2)$ [8] appear consistent with a purely single particle IA picture. In several inclusive (e,e') experiments on diverse nuclei the separated responses in the quasifree region show sizable transverse-to-longitudinal enhancements [9–11] above impulse approximation calculations, while others [12,13] at similar Q^2 find much smaller discrepancies. Thus the interpretation remains controversial. In this Rapid Communication we report the longitudinal-transverse separation of $^{12}\mathrm{C}(e,e'p)$ data at Q^2 of 0.64 and 1.8 GeV^2 to examine the reaction mechanism of quasifree $(e,e'p)$ scattering. Since longitudinal photons couple to the charge density, they are expected to be more directly sensitive to single particle nuclear structure effects while multinucleon meson-exchange currents preferentially influence the nuclear response to transverse photons.

In the one photon-exchange approximation, the $(e,e'p)$ coincidence cross section can be expressed in terms of four structure functions [14] $(W_L, W_T, W_I$ and $W_S)$. In parallel kinematics (where the momentum of the outgoing proton $\mathbf{p}'$ is along the direction of the three-momentum transfer $\mathbf{q}$) only two structure functions W_L and W_T remain [15]:

$$\frac{d^6\sigma}{dE_{e'}d\Omega_{e'}d^3p'}=\sigma_{\mathrm{Mott}}\frac{Q^2}{\mathbf{q}^2\epsilon}\times[\epsilon W_L(\omega,q,p')+W_T(\omega,q,p')], \quad (1)$$

where $\sigma_{\mathrm{Mott}}=[\alpha^2\cos^2(\theta_{e'}/2)/(4E_{e'}^2\sin^4(\theta_{e'}/2))]$ is the Mott cross section, ω is the electron energy loss, $\epsilon=[1+(2\mathbf{q}^2/Q^2)\tan^2(\theta_{e'}/2)]^{-1}$ is the virtual photon polarization parameter, and $\theta_{e'}$ is the electron scattering angle. (The speed of light c is taken to be 1.) The interference structure functions W_I $(\propto\sin\theta_{qp}\cos\phi)$ and W_S $(\propto\sin^2\theta_{qp}\cos 2\phi)$ disappear in parallel kinematics or when integrating over the azimuthal angle (ϕ) and are expected to be small in nonparallel kinematics compared to W_L and W_T for small $\sin(\theta_{qp})$, where θ_{qp} is the angle between $\mathbf{q}$ and the outgoing proton.

For scattering from a bound nucleon, it is more natural to express W_L and W_T in terms of variables more directly related to the nuclear single particle structure, the separation energy, and the initial proton momentum. In the plane wave impulse approximation (PWIA), the cross section factors into a product of an elementary electron-proton cross section σ_{ep} and a nuclear spectral function $S(E_m,\mathbf{p}_m)$, which represents the probability of finding a proton with separation energy $E_m=\omega-E_{p'}+M_p-T_{A-1}$ ($E_{p'}$ is the energy of the outgoing proton, M_p is the proton mass, and T_{A-1} the kinetic energy of the recoiling $A-1$ nucleus) and initial momentum $\mathbf{p}_m=\mathbf{p}'-\mathbf{q}$ inside the nucleus, i.e.,

$$\frac{d^6\sigma}{dE_{e'}d\Omega_{e'}d^3p'}=\sigma_{ep}S(E_m,\mathbf{p}_m). \quad (2)$$

Here σ_{ep} is the off-shell electron-proton scattering cross section which on-shell reduces [15] to

$$\sigma_{ep}=\sigma_{\mathrm{Mott}}\frac{Q^2}{\mathbf{q}^2\epsilon}\left(\epsilon|G_E(Q^2)|^2+\frac{Q^2}{4M_p^2}|G_M(Q^2)|^2\right), \quad (3)$$

where $G_E(Q^2)$ and $G_M(Q^2)$ are the electric and magnetic elastic scattering form factors of the proton. Since the energy conserving delta function is now included in the spectral function this differs by $\delta[\omega-(Q^2/2M_p)]$ from the usual free cross section, $d\sigma/dE_{e'}d\Omega$. Allowing for different single particle responses in the longitudinal and transverse channels, the cross section can be rewritten as

$$\sigma_{ep}S(E_m,\mathbf{p}_m)=\sigma_{ep}^L S_L(E_m,\mathbf{p}_m)+\sigma_{ep}^T S_T(E_m,\mathbf{p}_m). \quad (4)$$

It follows from Eqs. (1)–(4) that one can extract the longitudinal and transverse response functions W_L and W_T or the longitudinal and transverse spectral functions S_L and S_T from measurements in parallel kinematics with different ϵ but the same Q^2 and ω. The spectral functions are the appropriate measures of the nuclear single particle strength and allow the direct comparison of the longitudinal and transverse strengths if the impulse approximation is valid. The sepa-

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rated spectral functions are equal for quasifree knockout of protons exhibiting the free on-shell single particle behavior,

$$S_L = W_L / G_E^2 = W_T / (G_M^2 Q^2 / 4M_p^2) = S_T. \tag{5}$$

Since the nucleons are off-shell in the nucleus the de Forest CC1 prescription [14] was used for σ_{ep}^L and σ_{ep}^T in Eq. (4) to extract S_L and S_T. The separated S_L and S_T are sensitive to the choice of the off-shell cross section and this must be borne in mind when comparing spectral functions extracted with different procedures. In addition the spectral functions extracted from the data are distorted spectral functions $[S_{L,T}^D(E_m, \mathbf{p}_m)]$, since they include the effects of proton final state interactions. DWIA estimates of the distortion effects were made using the EEI interaction of J. Kelly [16] which gave ratios of DWIA to PWIA of 0.72 and 0.51 for p and s single-particle orbitals at Q^2 of 0.64 GeV^2 (0.67 and 0.43 at Q^2 of 1.2 GeV^2) close to the integrated ratios measured [17] at Q^2 of 0.64 and 1.3 GeV^2. Reference [17] saw no evidence of a Q^2 dependence from 1.3 to 3.3 GeV^2 so the values calculated at 1.2 GeV^2 were used at Q^2 of 1.8 GeV^2. It is assumed here that the proton distortion effects are the same in W_L and W_T. Independently of the off-shell cross sections one can determine the response function ratio $R_G = \sqrt{W_T 4M_p^2 / W_L Q^2}$. For free nucleons this reduces to $R_G = G_M / G_E$.

The experiment, E91013, was carried out at the Thomas Jefferson National Accelerator Facility. The 100% duty factor electron beam, with incident energies of 0.845 – 3.245 GeV and currents of 10 to 50 μAmps, was used on a solid carbon target (230 mg/cm^2). The spectrometers and detections systems are described in Ref. [17] along with the kinematics for the forward angle measurements. Backward angle data were taken at E_e of 0.845 GeV (1.645 GeV) and $\theta_{e'}$ of 78.5 (80.0) degrees for the Q^2 of 0.64 (1.82) GeV^2 measurements leading to $\Delta\epsilon$ ranges of ≈ 0.5. At each momentum transfer the absolute cross sections for e-p elastic scattering were extracted with electron singles and electron-proton coincidence measurements using a liquid hydrogen target. The absolute normalization of the hydrogen cross sections agreed with Monte Carlo simulations of the detector acceptance to $\pm 1.5\%$ using the dipole parameterization for the electric and the Gari-Krümpelmann parameterization [18] of the magnetic form factors, consistent with the experimental results of [19]. These results test the acceptance and the simulation of the smearing and redistribution of events due to radiative effects.

In addition to the electron-proton coincidence $(e,e'p)$ events, the electron singles (e,e') events were also recorded for every run to monitor the product of beam current, target thickness, and electron reconstruction efficiency. The run-to-run variations in the normalization were less than 2%. The experimental cross sections are assigned a systematic correlated point-to-point uncertainty of 1.8–3.1 % which is dominated by the uncertainty of the measured kinematic quantities such as momentum and scattering angle. The cross sections are also assigned a multiplicative (to the entire data set) uncertainty of 2.7% which is dominated by the stability of the results to variation in the applied analysis procedure.

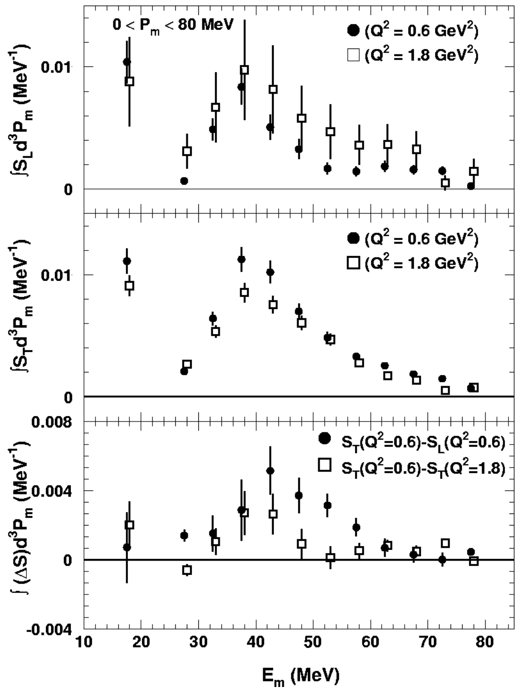

FIG. 1. The integrals of S_L (top panel) and S_T (middle panel) from $0 < p_m < 80$ MeV are shown at Q^2 of 0.64 (circles) and 1.8 GeV^2 (squares). In the bottom panel the differences, $S_T - S_L$ at 0.64 GeV^2 (circles) and $S_T(Q^2 = 0.6) - S_T(Q^2 = 1.8)$ (open squares), are shown. The errors are the sum in quadrature of the statistical and systematic uncertainties. The lowest E_m point is an average over $10 < E_m < 25$ MeV. The response functions at 1.8 GeV^2 are corrected for differences in the energy dependence of the proton attenuation [16] by factors of 1.075 for $E_m < 25$ MeV and 1.18 for $E_m > 25$ MeV.

Coulomb scattering of the electrons was taken into account using the effective momentum approximation following the prescription of Ref. [20]. The data were analyzed and sorted into small bins in E_m and p_m. Events in each bin were divided by the corresponding σ_{ep}^{CC1} and weighted by the individual detection volume (phase space) as determined by a Monte Carlo simulation [17] of the experiment. This gives us an experimental distorted spectral function, still affected by proton final state interactions and the smearing and redistribution of events due to radiative effects. The deradiation procedure involved correcting the model spectral function for each bin using a factor obtained from the ratio of a Monte Carlo simulation [17] with radiative losses to one without radiative losses. The process is then iterated until the integrated deradiated spectral function strength converges. The dependence of the procedure on the E_m and p_m distribution of the initial model spectral functions is estimated to be $< 5\%$ and 1% on the integrated yield. The 5% uncertainty is the largest systematic uncertainty in the measured distorted spectral functions but it is correlated at forward and backward angles and leads to a similar contribution to the error in the L-T separation.

To avoid the effect of the interference terms W_I and W_S, only the central proton angle (which constrains $|\theta_{qp}| < 5.5°$) with $|p_m| < 80$ MeV was utilized for the L-T sepa-

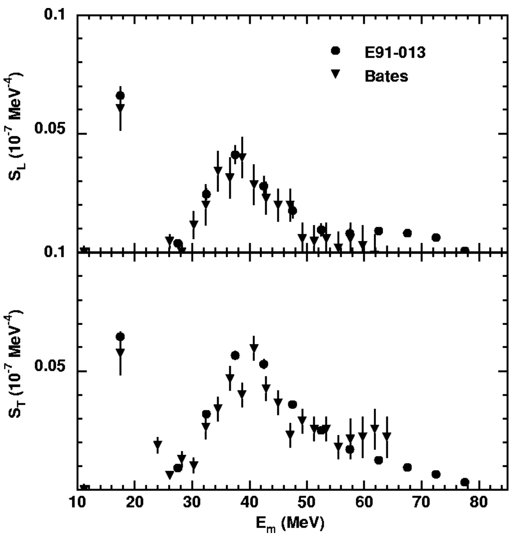

FIG. 2. S_L (top panel) at Q^2 of 0.64 GeV^2 and S_T (bottom panel) at Q^2 of 0.64 (circles) compared to the results of Ref. [1] at Q^2 of 0.15 GeV^2 (triangles). The statistical uncertainties only have been shown. No attempt has been made to correct for different final state proton attenuation effects, but estimates [16,24] suggest they are similar at the two proton energies.

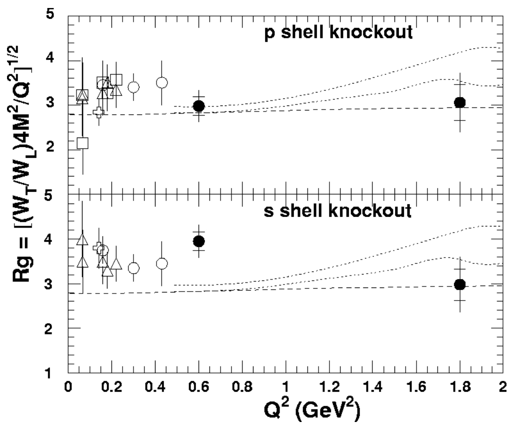

FIG. 3. $R_G = \sqrt{W_T 4M_p^2/W_L Q^2}$ for ^{12}C (solid) from the measurements of this experiment with ^{6}Li (p shell: open squares [3], open circles [25], and s shell: open triangles [3], open circles [25]) and ^{12}C (p shell: open cross [1], open triangles [15], and s shell: open cross [1]). The top panel is for the p shell region and bottom panel is for the s shell region. The inner error bar represents that statistical error and the outer error bar includes the systematic error. The dashed line represents R_G for the free proton with the dipole electric and Ref. [18] magnetic form factor while the dotted lines represent the one sigma error band of the recent proton results of Ref. [27].

ration. Using Eq. (4) at the different ϵ values the longitudinal and transverse spectral functions were separated and integrated over $0<p_m<80$ MeV with appropriate $4\pi p_m^2$ weight for each p_m bin. Figure 1 shows the separated longitudinal (upper panel) and the separated transverse (middle panel) spectral functions at $Q^2=0.64$ and 1.8 GeV^2. No distortion corrections were applied to the lower Q^2 data and the higher Q^2 data are corrected by the ratios of the distortion corrections for the two Q^2, a factor of 1.075 for the p shell ($E_m<25$ MeV) and 1.18 for the s shell ($25<E_m<80$ MeV). The strength in the p shell region has been averaged over $10<E_m<25$ MeV in order to avoid oscillations due to small differences in the E_m resolution for the data and Monte Carlo simulations. The sizable errors on the longitudinal spectral function at the higher Q^2 reflect that $\sigma_{ep}^T/\sigma_{ep}^L \approx \mu_p^2 Q^2/(4M_p^2) \approx 4$, where μ_p is the proton magnetic moment.

The transverse spectral function is significantly higher than the longitudinal spectral function at the lower Q^2 (bottom panel of Fig. 1), and most of this excess strength occurs for $25<E_m<60$ MeV, the region traditionally associated with s shell knockout. At the higher Q^2 the transverse spectral function is reduced by about 20%. The dominant error on S_L is correlated point-to-point, so the observation that $S_L(Q^2=1.8)$ appears to be one σ larger than $S_L(Q^2=0.6)$ cannot be considered significant. The difference $S_T(Q^2=0.6)-S_T(Q^2=1.8)$ is also shown in the lower panel of Fig. 1. The significant excess in the transverse strength beyond the two body breakup threshold of ^{11}B ($E_m>27.4$ MeV) at low Q^2 is similar to observations of Ulmer *et al.* [1] (Fig. 2). However this excess transverse strength is reduced at $Q^2=1.8$ GeV^2. The results suggest a breakdown of the impulse approximation. One possible mechanism for this breakdown is multinucleon or meson exchange currents (MEC) [21] which are primarily transverse in nature. The results also show that the impulse approximation improves at higher Q^2 which is consistent with the picture that as the momentum transfer increases the wavelength of the virtual photons exchanged gets smaller and the photon couples more readily to a single nucleon [22].

Figure 2 compares the separated spectral functions of this experiment with those of Ref. [1]. The separated response functions obtained from Ref. [1] over a similar p_m range were converted to spectral functions and compared to the spectral functions obtained in the present experiment (without integrating over p_m) [23]. The longitudinal spectral functions are consistent with each other; however, the results of the present experiment show that the longitudinal strength definitely extends to higher E_m than suggested in the discussion of Ref. [1]. While no attempt has been made to correct for the differing proton distortion effects at the two different proton energies the calculations of Ref. [24] suggest that the magnitude of the attenuation corrections appropriate for Ref. [1] are similar to those of Ref. [16] for the present data.

The ratios R_G ($=\sqrt{W_T 4M_p^2/W_L Q^2}$) for the p shell ($2.98\pm0.21\pm0.22$, $3.06\pm0.40\pm0.52$ for Q^2 of 0.6 and 1.8 GeV^2; the first error is statistical and the second systematic) and s shell ($3.95\pm0.21\pm0.29$, $2.98\pm0.35\pm0.51$) regions of ^{12}C are shown in Fig. 3. Results from previous measurements at lower Q^2 on ^{12}C and ^{6}Li nuclei [1,3,15,25] are also shown. The dotted line represents the free nucleon value of the ratio R_G (using the nucleon form factors described above). The results of this experiment are consistent within errors with previous experiments for both the p and the s shell region, but the ratio of the R_G's for the s and p regions at $Q^2=0.64$ GeV^2 are consistent with Ref. [1] but larger than the trend of the other measurements. For the p shell region the results of this experiment are also consistent with the free proton value of R_G, at both high and low Q^2. However for the s shell region, at $Q^2=0.64$ GeV^2 we see a significant difference in R_G from the free proton value.

The deviation of the ratio R_G from the free nucleon value is another way of illustrating a breakdown of the impulse approximation. This has been interpreted as a possible medium modification of the e-p coupling. Such effects would naturally be larger for the s state orbital [26] but the missing energy dependence shown in the lower panel of Fig. 1 is not consistent with a uniform modification throughout the s shell region.

The p shell spectroscopic factors were calculated from the longitudinal spectral functions to be 2.83 ± 0.30 at Q^2 of 0.64 GeV^2 and 2.76 ± 0.46 at Q^2 of 1.8 GeV^2 using the distortion corrections discussed above. These spectroscopic factors are about $1-2\sigma$ higher than the more precise spectroscopic factors obtained from higher resolution, lower Q^2 experiments at NIKHEF [5]. While the present separated results only cover a limited range of p_m, unseparated perpendicular kinematics measurements from the forward angle 0.64 GeV^2 data with $-300<p_m<300$ gave a spectroscopic factor of $2.98\pm0.15\pm0.15$. Consistent unseparated spectroscopic factors are observed at all the higher momentum transfers where data on both sides of **q** were available.

A recent report [27] of polarization transfer measurements of the ratio of G_E^p/G_M^p, while consistent with the values used in the present work at Q^2 of 0.64 GeV^2, measures a value of G_E^p/G_M^p at the higher Q^2, 25% smaller than was used in this analysis. The effect on the separated transverse spectral function is within the quoted systematic errors but this result implies that the $Q^2=1.8$ GeV^2 S_L extracted here is too small by a multiplicative factor of roughly 1.5. The R_G measurement is unaffected but the free proton curve rises from Q^2 of 0.6 to 1.8 GeV^2 as shown by the dotted curves in Fig. 3 which displays the error band of Ref. [27]. Given the large systematic errors on our longitudinal measurement at $Q^2=1.8$ GeV^2, we have chosen to focus on the Q^2 dependence of the transverse response and the comparison with the lower Q^2 longitudinal response.

In conclusion, the longitudinal-transverse ratio in the p shell region for $|p_m|<80$ MeV is consistent with a quasifree knockout picture at both Q^2 of 0.64 and 1.8 GeV^2. At higher missing energies a significant excess transverse strength is seen at Q^2 of 0.64 GeV^2 and the transverse strength is reduced at Q^2 of 1.8 GeV^2. The differing E_m dependence of the transverse strength at the two Q^2 does not seem consistent with an explanation based on a change of the average nucleon structure for an s shell nucleon. This suggests that the excess transverse strength is likely due to multinucleon processes and that these effects become less important at higher momentum transfer. The results of this experiment also show that the longitudinal strength extends to higher missing energies than seen in previous experiments. These results also serve as a caution that the nuclear transparency, measured as the ratio of the experimental yield to the PWIA yield, may overestimate the true proton transparency at low Q^2 due to the excess transverse strength but become a better measure as Q^2 increases.

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