Reaction ^{12}C($e,e'p$) in the Dip Region

R. W. Lourie, H. Baghaei, W. Bertozzi, K. I. Blomqvist, J. M. Finn,[a] C. E. Hyde-Wright,
N. Kalantar-Nayestanaki, J. Nelson, S. Kowalski, C. P. Sargent, W. W. Sapp, P. Ulmer,
and J. Wiggins[b]
Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

B. H. Cottman,[c] P. K. Teng,[d] E. J. Winhold, and M. Yamazaki
Department of Physics, Rensselaer Polytechnic Institute, Troy, New York 12181

J. R. Calarco and F. W. Hersman
Department of Physics, University of New Hampshire, Durham, New Hampshire 03824

J. J. Kelly
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

M. E. Schulze
Department of Physics, Syracuse University, Syracuse, New York 13210
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The reaction ^{12}C($e,e'p$) in the dip region ($\omega = 200$ MeV, $\mathbf{q} = 400$ MeV/c) has been measured in parallel kinematics for missing energies up to 160 MeV. A coincidence yield considerably larger than that expected for a one-body reaction process is observed, though the one-body contribution from p- and s-shell knockout is also present. A uniform continuum strength extends from beyond the p shell to the highest measured missing energies. This continuum strength is the dominant contribution to the ($e,e'p$) reaction process in the dip region.

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The origin of the excess strength observed in the dip region between the quasielastic and Δ production peaks by inclusive (e,e') experiments has been a mystery in electromagnetic nuclear physics for several years. All attempts to predict the cross section, based on the known reaction processes of quasielastic nucleon knockout, quasifree Δ production, meson-exchange currents, and coherent pion production, have been insufficient to explain the data.[1,2] In particular, the dominant one-body process, quasielastic scattering, provides only 20%–30% of the experimental cross section in ^{12}C at $\mathbf{q} = 400$ MeV/c and $\omega = 200$ MeV. Laget,[1,3] using a phenomenological quasideuteron model, is able to account for a significant fraction of the excess strength, indicating that processes involving two correlated nucleons may be quite important in this kinematical region. Inclusive (e,e') experiments are unable to disentangle the various components of the reaction mechanism. However, the missing-energy spectrum measured in a coincidence ($e,e'p$) experiment may be capable of differentiating between the one-body and other contributions to the reaction.

In this Letter we report the first measurement of an ($e,e'p$) reaction in the dip region. The experiment was performed at the MIT-Bates Linear Accelerator using the South Hall spectrometer pair MEPS and OHIPS for the detection of electrons and protons, respectively. Table I gives the main characteristics of the spectrometers. Each spectrometer was instrumented with a two-plane vertical drift chamber[4] to measure the particle coordinates (x,y,θ,ϕ) and a scintillator array for trigger definition. The electron spectrometer was also equipped with an Aerogel ($n = 1.05$) Čerenkov counter for pion rejection.

When the exchange of only one virtual photon is considered, the coincidence cross section depends on four independent functions[5] of $\mathbf{q}$, ω, E_p (the proton energy), and θ_p (the proton angle with respect to $\mathbf{q}$):

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

where 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 elec-

TABLE I. Spectrometer characteristics.

	$\Delta p/p$ (%)	$\Delta\theta$ (mrad)	$\Delta\phi$ (mrad)	$\Delta\Omega$ (msr)	$P_{\max}$ (MeV/c)
MEPS	22.0	78	200	15.5	400
OHIPS	5.8	46	106	3.8	1300

tromagnetic current. ϕ_p is the angle between the electron scattering plane and the plane containing $\mathbf{q}$ and the detected proton while σ_M is the Mott cross section for scattering from a structureless Dirac particle. The interference response functions R_{LT} and R_{TT} do not contribute under parallel kinematics, i.e., when the protons are detected in the direction of $\mathbf{q}$. These kinematics reduce ambiguity in interpretation of the data and were chosen for this experiment.

The incident energy was 459 MeV and the electron kinematics was held constant at $\omega = 200$ MeV, $\mathbf{q} = 400$ MeV/c, and $\theta_e = 60°$. As the widths of the quasielastic and Δ production peaks grow approximately linearly with momentum transfer, we chose this $\mathbf{q}$ to maximize the definition of the two peaks while minimizing the effects of both Pauli blocking and the specifics of the nuclear structure. Protons in the kinetic energy range 60 to 200 MeV were detected at 34°, covering the missing-energy ($\epsilon_m = \omega - T_p$) range of 0 to 160 MeV. The proton kinetic energy was the only experimental quantity varied. In such a scan the recoil momentum ($\mathbf{p}_r = \mathbf{q} - \mathbf{p}_f$, where $\mathbf{p}_f$ is the momentum of the detected proton) tracks with the missing energy, varying from an average value of -180 MeV/c at the p-shell peak ($\epsilon_m = 18$ MeV) to 60 MeV/c at $\epsilon_m = 160$ MeV.

Calibration and normalization of the coincidence apparatus was accomplished via the reaction $^1\mathrm{H}(e,e'p)$. Resolutions of 1.8 MeV, 3.8 MeV/c, and 2.0 ns were obtained in missing energy, recoil momentum, and proton time of flight, respectively. The target was a 50.3-mg/cm^2-thick polyethelene ($\mathrm{CH_2}$) sheet. Several measurements of $^1\mathrm{H}(e,e'p)$ were made, both before and after the data-taking runs. The ratio of the known to measured cross sections did not vary by more than 3% from the average value of 1.05. Additional normalization checks were made on each spectrometer separately, via ^{1}H, ^{12}C, and ^{16}O elastic electron scattering. An overall normalization factor of 1.5 has been applied to the data in addition to electronic dead-time and focal-plane efficiency corrections. Since the electron kinematics was held constant during data taking, the $^{12}\mathrm{C}(e,e')$ cross section was sampled on a run-by-run basis by the singles rate in the electron spectrometer. This cross section, uncorrected for radiative effects and averaged over all runs, is 3.57 ± 0.11 nb MeV^{-1} sr^{-1} which can be compared with the radiatively corrected Saclay[1] value of 3.38 ± 0.04 nb MeV^{-1} sr^{-1}. The primary importance of our result was that the run-to-run variation in this cross section was $\pm 3\%$ and indicates that there was no time-dependent variation in the performance of the apparatus.

The $^{12}\mathrm{C}(e,e'p)$ measurements used natural carbon targets of 93.0 and 45.6 mg/cm^2 thickness at an average current of 10 μA. The duty factor was 0.9%. The reals-to-accidentals ratio for coincidences varied between 5:1 and 1:3 (before trajectory corrections) as the missing energy varied from 18 to 160 MeV. All coincidences within a 100-ns-wide timing window were accepted. Such a large timing window allows a direct measurement of the missing-energy distribution of accidental coincidences with high statistical accuracy. This distribution is then subtracted channel by channel from the missing-energy distribution of events in the timing peak where both real and accidental coincidences are present. Pions causing accidental coincidences are, of course, removed by this procedure. However, at the deepest missing energies a correlated pion contribution of some 30% was observed, presumably from the $(\gamma,\pi^- p)$ reaction. For this reason only events that also had a signal from the Aerogel were accepted. The missing-energy spectrum so obtained is shown in Fig. 1. The cross section is differential in $d\Omega_e\, d\Omega_p\, d\omega\, d\epsilon_m$. The vanishing of the cross section below the p-shell knockout threshold confirms the validity of the accidental-coincidence subtraction procedure.

Several features of the data are immediately obvi-

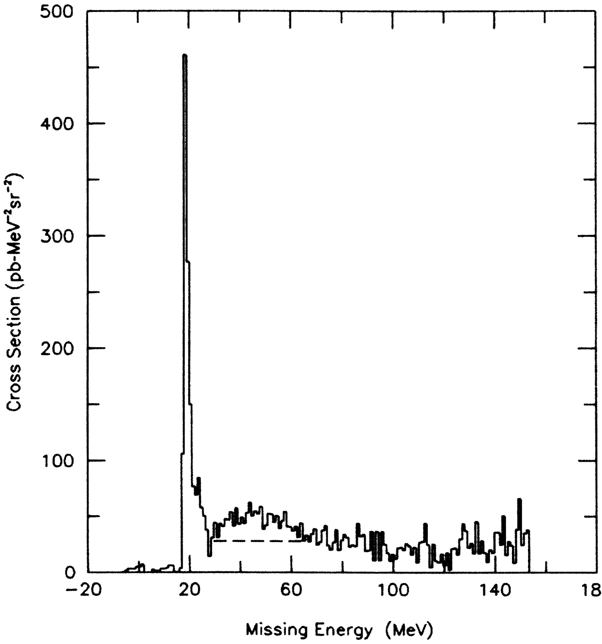

FIG. 1. Missing-energy spectrum for $^{12}\mathrm{C}(e,e'p)$ in the dip region (without radiative corrections). The area above the dashed line is attributed to the s shell. The bin width is 1.05 MeV.

ous. There is a pronounced *p*-shell peak from the one-body part of the reaction and then a strong, nearly uniform population of the continuum out to the largest missing energies we were able to measure. This is to be compared with the data in Fig. 2 which shows a missing-energy spectrum measured by Mougey *et al.*[6] in the quasielastic regime where no strength other than that in the *p* and *s* shells was observed. That experiment was performed with an incident energy of 497 MeV and an electron scattering angle of 52.9° and 87-MeV protons were detected over an angular range of 40°–80°. They were able to measure missing energies up to 80 MeV. In the experiment reported here, an indication of residual *s*-shell strength is seen in the region of 30–60-MeV missing energy. The *p*-shell cross section, integrated over missing energy (σ_{meas}), is consistent with the value obtained under quasielastic kinematics. The comparison was made to the factorized expression

$$\sigma_{\text{fact}} \equiv d^5\sigma / d\Omega_p \, d\Omega_e \, d\omega = K \sigma_{ep} |\phi_\alpha(\mathbf{p}_i)|^2,$$

where K is a kinematic factor,[6] σ_{ep} is an off-shell electron-proton cross section,[6] and $|\phi_\alpha(\mathbf{p}_i)|^2$ is the $1p$ momentum distribution determined by Mougey *et al.*[6] with use of this same expression under different kinematical conditions and averaged over the kinematic range of this experiment. The ratio of σ_{fact} to σ_{meas} is 1.08 ± 0.02 where this and all subsequent uncertainties only reflect the statistics of our data. In lieu of a model-independent method to extract the one-body contribution from the *s* shell we took it to be equal to 395 ± 29 pb MeV^{-1} sr^{-2}, the value obtained from σ_{fact} with the Saclay[6] $1s$ momentum distribution. This implies an additional contribution of 28 pb MeV^{-2} sr^{-2} in the region of 30–60 MeV as indicated by the dashed line in Fig. 1. The integrated continuum yield, excluding the *s*-shell contribution, is 3.20 ± 0.10 nb MeV^{-1} sr^{-2}. This yield is 6.8 ± 0.6 times that of the *s* shell and 2.22 ± 0.10 times that of the *p* shell. It is clear from these results that a process other than quasielastic single-nucleon knockout is present and indeed dominates.

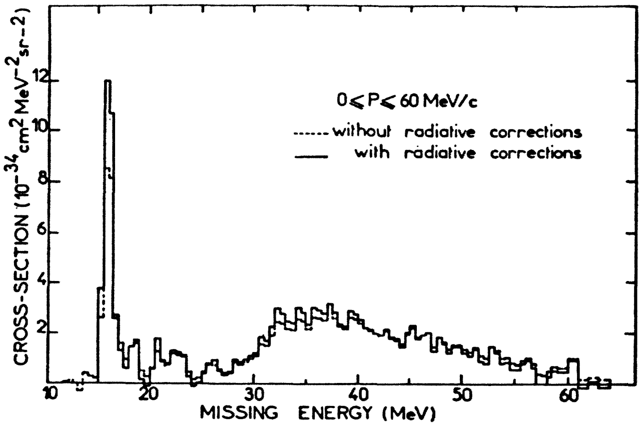

FIG. 2. Missing-energy spectrum for ^{12}C$(e,e'p)$ in the quasielastic region, from Ref. 6. Note the difference in the horizontal axis scale compared to Fig. 1.

Monte Carlo studies using harmonic-oscillator momentum distributions indicate that the angular distributions of the quasielastic $(e,e'p)$ and $(e,e'n)$ reactions are confined to a cone with an opening half-angle of about 6°. This results in a quasielastic contribution of just over 20% to the inclusive cross section. Since no coincidence data away from parallel kinematics are presently available we have no knowledge of the angular distribution of the process(es) responsible for the continuum strength. However, assuming an $(e,e'n)$ contribution in the proportion of σ_{en} to σ_{ep}, one can ask over what effective half-angle must the process be (uniformly) distributed in order to reproduce the inclusive cross section. A distribution $\approx 16°$ wide would be required if the processes observed here are to account for all the inclusive strength. A better understanding of the angular distribution awaits the availability of more extensive data and/or a realistic model of the reaction process.

A recent study[7] indicates that about 50% of the struck protons in the quasielastic reaction ^{16}O$(e,e'p)$ undergo a second (nuclear) scattering on their way out of the nucleus. This produces a continuum structure extending to large missing energies. We have estimated the contribution of this process assuming that the initial $(e,e'p)$ reaction was quasielastic. We calculated the fluxes of protons and neutrons produced at all angles $\leqslant 90°$ with respect to $\mathbf{q}$ by the quasielastic $(e,e'p)$ and $(e,e'n)$ reactions using the factorized expression for the cross section and harmonic-oscillator momentum distributions. These fluxes are then assumed incident on stationary free nucleons and scattering occurs according to the nucleon-nucleon cross sections weighted by the nuclear density which we took to be a uniform 0.17 nucleons/fm^3. The calculation then produces the energy distribution of protons emerging along $\mathbf{q}$, i.e., that are scattered into the spectrometer. We found that the resulting continuum strength is negligible for missing energies greater than 90 MeV. In addition, optical-model calculations[6,8] typically indicate a 30%–50% absorption from the *p* and *s* shells for these proton energies. Even if all the absorbed particles were to reappear in our spectrum at higher ϵ_m and had the same angular distributions as the direct process, they could account for at most 20% of the continuum strength.

Radiative corrections have only been computed for the *p*-shell peak and increase the cross section by a factor of 1.20. These corrections have not been included in the spectrum presented here. No attempt has been made to evaluate radiative corrections of the continuum since the correction at a given ϵ_m requires knowledge of the coincidence cross section at all lower missing energies over a wide range of recoil momenta. Either a theoretical model for the cross section or a more extensive data set under a variety of kinematical conditions would be required to evaluate the radiative corrections fully. Mougey *et al.*[6] were able to perform a true radiative unfolding of their data since the cross section was measured over a sufficiently wide range of kinematics. Because of the time-consuming nature of coincidence measurements, it may be more practical to compare the data directly to a radiatively corrected theory rather than applying corrections to the data for comparison to an unradiative theory. To that end we obtained an estimate for the magnitude of the radiative effects by calculating the radiative tails in the harmonic-oscillator shell model following the procedure of Borie and Drechsel.[9] The strengths of the p- and s-shell peaks were normalized to the data and assumed to be δ functions in missing energy. The cross section for radiation both before and after the $(e,e'p)$ reaction was calculated for all photon energies greater than the cutoff of 5 MeV. The continuum yield beyond the s shell produced by the radiative tails is nonnegligible but small: It accounts for 25% of the observed strength in the region $70 \leq \epsilon_m \leq 120$ MeV and 14% for $120 \leq \epsilon_m \leq 155$ MeV. The major portion of the deep continuum strength cannot be attributed to radiative effects.

We conclude that a new reaction process has been observed in the dip region. This process is not one-body in character and is the dominant contribution to proton knockout under parallel kinematics in the dip region. The process must be mainly transverse since the (e,e') data[1] show little longitudinal strength in this region. The one-body strength in the p shell is consistent with that measured in the quasielastic regime by Mougey *et al.*[6] but the combined p- and s-shell only accounts for approximately 35% of the coincidence yield.

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[a] Present address: The College of William and Mary, Williamsburg, Va. 23185.

[b] Present address: BBN Communications Corp., Cambridge, Mass. 02238.

[c] Present address: Bates Linear Accelerator Center, Middleton, Mass. 01949.

[d] Present address: Institute of Physics, Academic Sinica, Nan-Kang, Taipei 115, Taiwan, Republic of China.

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