

# Quasielastic Reaction Mechanism Studied Using the Reaction $^{12}\text{C}(e,e'p)$

L. B. Weinstein,<sup>(1)</sup> H. Baghaei,<sup>(1)</sup> W. Bertozzi,<sup>(1)</sup> J. M. Finn,<sup>(1)</sup> J. Glickman,<sup>(1)</sup> C. E. Hyde-Wright,<sup>(1)</sup> N. Kalantar-Nayestanaki,<sup>(1)</sup> R. W. Lourie,<sup>(1)</sup> J. A. Nelson,<sup>(1)</sup> W. W. Sapp,<sup>(1)</sup> C. P. Sargent,<sup>(1)</sup> P. E. Ulmer,<sup>(1)</sup> B. H. Cottman,<sup>(2)</sup> L. Ghedira,<sup>(2)</sup> E. J. Winhold,<sup>(2)</sup> J. R. Calarco,<sup>(3)</sup> J. Wise,<sup>(3)</sup> P. Boberg,<sup>(4)</sup> C. Chang,<sup>(4)</sup> D. Zhang,<sup>(4)</sup> K. Aniol,<sup>(5)</sup> M. B. Epstein,<sup>(5)</sup> D. J. Margaziotis,<sup>(5)</sup> C. Perdrisat,<sup>(6)</sup> and V. Punjabi<sup>(6)</sup>

<sup>(1)</sup>*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

<sup>(2)</sup>*Department of Physics, Rensselaer Polytechnic Institute, Troy, New York 12181*

<sup>(3)</sup>*Department of Physics, University of New Hampshire, Durham, New Hampshire 03824*

<sup>(4)</sup>*Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742*

<sup>(5)</sup>*Department of Physics and Astronomy, California State University, Los Angeles, California 90032*

<sup>(6)</sup>*Department of Physics, College of William and Mary, Williamsburg, Virginia 23185*

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We have measured missing-energy spectra for the reaction  $^{12}\text{C}(e,e'p)$  in the quasielastic region in parallel kinematics at momentum transfers  $q$  of 585, 775, and 827 MeV/c. We observed  $^1p$  and  $^1s$  single-proton knockout peaks and large broad strength attributed to multinucleon knockout. We saw no increase in strength at pion threshold. The ratio of single-particle knockout to a distorted-wave impulse-approximation calculation is approximately constant with  $q$ . Multinucleon knockout is 25%–40% of the total cross section; it increases with  $q$ . This quasielastic non-single-nucleon knockout is much stronger than previously observed.

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At quasielastic kinematics,  $\omega = q_\mu^2/2m_p$  ( $q_\mu$  and  $\omega$  are the four-momentum and energy transfers), we expect interactions with single-nucleon currents to dominate the nuclear electromagnetic response. However, inclusive  $(e,e')$  measurements have cast doubt on the interpretation of the quasifree scattering process solely in terms of interactions with free-nucleon currents. Separated inclusive data on  $^{12}\text{C}(e,e')$  reported by Barreau *et al.*<sup>1</sup> reveal a transverse-to-longitudinal ratio approximately 60% in excess of that predicted by nonrelativistic impulse-approximation calculations with unmodified nucleons.<sup>2</sup> Many theoretical ideas have been invoked to explain these separated response functions, including the Dirac  $\sigma$ - $\omega$  model and nucleon modifications. Van Orden and Donnelly<sup>3</sup> showed that meson-exchange currents (MEC's) leading to two-nucleon knockout are negligible at quasielastic kinematics and are not strong enough to explain the dip-region cross section. Blunden and Butler<sup>4</sup> predict that MEC's leading to one-nucleon knockout enhance the transverse response at quasielastic kinematics. Alberico *et al.*<sup>5</sup> predict that two-particle-two-hole excitations mediated by pion exchange contribute a significant fraction of the  $^{56}\text{Fe}$  transverse response at  $q = 410$  MeV/c even at quasielastic kinematics.

There are many different models of deep-inelastic inclusive electron scattering, each of which attempts to treat aspects of the reaction correctly, but no model can explain all of the data. Coincidence  $(e,e'p)$  scattering can distinguish among the  $(e,e')$  reaction mechanisms. Different reaction mechanisms occur at different missing energies,  $\epsilon_m = \omega - T_p$ , where  $T_p$  is the proton final kinetic

energy. Below the two-particle emission threshold  $\epsilon_m = 28$  MeV, the  $^{12}\text{C}(e,e'p)$  process is dominated by  $^1p$ -shell knockout. From 28 to 50 MeV, the process contains contributions both from the more deeply bound  $^1s$ -shell and from two-or-more-particle knockout. Above 50 MeV, two-or-more-particle emission dominates. Above  $\epsilon_m \approx 150$  MeV, pion production, either nonresonant or through the  $\Delta$  resonance, is energetically possible.

Separated  $^{12}\text{C}(e,e'p)$  coincidence data reported by Ulmer *et al.*<sup>6</sup> show a dramatic increase in the transverse-to-longitudinal ratio above the two-particle emission threshold. This enhancement indicates the presence of an additional, transverse, nonquasielastic reaction mechanism. The longitudinal response becomes consistent with zero above  $\epsilon_m = 50$  MeV, indicating that single-particle knockout is very small above this point.

In this Letter, we report a study of reaction mechanisms in the quasielastic region and their variation with momentum transfer. We performed the experiment at the Massachusetts Institute of Technology Bates Linear Accelerator Center using the spectrometers MEPS and OHIPS to detect electrons and protons. The properties of the spectrometers are described elsewhere.<sup>7</sup> Each spectrometer was instrumented with a two-plane vertical drift chamber to measure the particle coordinates  $(x, y, \theta, \phi)$  and a scintillator array for trigger definition. The electron spectrometer was also equipped with an aerogel ( $n = 1.05$ ) Čerenkov counter for pion rejection.

We measured missing-energy spectra in parallel kinematics ( $\mathbf{p}_f \parallel \mathbf{q}$ ) for three  $(q, \omega)$  points (see Table I) varying only the proton final momentum  $p_f$  at each point. We calibrated the solid angles and efficiencies of the

TABLE I. Electron kinematics.

$E_0$ (MeV)	$ \mathbf{q} $ (MeV/c)	$\omega$ (MeV)	$\theta_e$ (deg)
505.4	585	210	90
698.0	775	355	90
686.1	827	325	100

spectrometer singly and in coincidence using the  $^1\text{H}(e,e')$ ,  $^{12}\text{C}(e,e')$ , and  $^1\text{H}(e,e'p)$  reactions. The systematic errors of 4.6% ( $q=585$  MeV/c), 6.9% ( $q=775$  MeV/c), and 4.1% ( $q=827$  MeV/c) are due primarily to uncertainty in the beam energy and to statistical uncertainty in the calibration measurements. The missing-energy resolution (FWHM) was 1.5 MeV for  $q=585$  MeV/c and 2.5 MeV for  $q=775$  and 827 MeV/c, consistent with the energy spread of the beam. The coincidence-time resolution (FWHM) was 2 ns. For each kinematics we sampled the accidental-coincidence background and subtracted it from the real-coincidence missing-energy spectrum.

Evaluating radiative corrections at a given  $\epsilon_m$  requires knowledge of the coincidence cross section at all lower missing energies over a wide range of recoil momenta. In the absence of this knowledge, we used the plane-wave impulse-approximation (PWIA) harmonic-oscillator shell model normalized to our data to model the  $^1p$ - and  $^1s$ -shell cross sections. We calculated the shape and magnitude of the radiative tails of the  $^1p$ - and  $^1s$ -shell peaks in this model following the procedure of Borie and Drechsel.<sup>8</sup> We subtracted these tails from the data. We applied the Schwinger corrections to the  $^1p$ - and  $^1s$ -shell peaks and to the continuum ( $\epsilon_m > 50$  MeV) with a hard photon cutoff of 11.5 MeV. We made no attempt to calculate radiative tails for the continuum since there is no good model of the continuum cross section. To estimate the effects of not subtracting the continuum-caused radiative tail from the continuum, we calculated the Schwinger correction for a hard photon cutoff of 100 MeV. For all three kinematics, using a Schwinger correction with a 100-MeV cutoff would reduce the continuum cross section by only 15%.

The radiatively corrected coincidence cross sections versus missing energy are shown in Fig. 1. We see strength in three regions: (1) the peak centered at 18 MeV due predominantly to  $^1p_{3/2}$ -shell knockout (" $p$  shell"), (2) the region from 26.5 to 50 MeV due to single-particle knockout from the  $^1s_{1/2}$  shell and to two-particle knockout (" $s$  shell"), and (3) the region above 50 MeV due to two-or-more-particle knockout ("continuum"). At  $q=775$  MeV/c there is strength up to  $\epsilon_m=250$  MeV; at the other kinematics there is a strength up to the highest  $\epsilon_m$  measured:  $\epsilon_m=130$  MeV at  $q=827$  and  $\epsilon_m=160$  MeV at  $q=585$  MeV/c. At  $q=775$  MeV/c, despite the large energy transfer

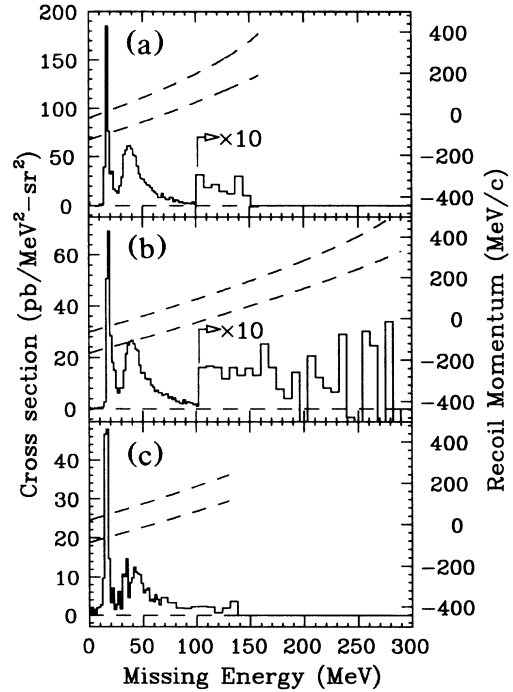


FIG. 1. Missing-energy spectra for  $^{12}\text{C}(e,e'p)$  at quasielastic kinematics (histogram). (a)  $q=585$  MeV/c,  $\omega=210$  MeV; (b)  $q=775$  MeV/c,  $\omega=355$  MeV; and (c)  $q=827$  MeV/c,  $\omega=325$  MeV. The data are radiatively corrected. The bin size is 1.8 MeV at low missing energy and 3.6 MeV at high missing energy. The recoil momentum range at each missing energy is indicated by the dashed curves.

( $\omega=355$  MeV), we see no increase in the cross section at pion threshold ( $\epsilon_m \approx 160$  MeV) in contrast to our previous measurement in the  $\Delta$  region.<sup>9</sup> We see less strength above pion threshold than is predicted by Baghaei's PWIA  $M1$ -dominance  $e+N \rightarrow e+\Delta \rightarrow e+p+\pi$  calculation.

We have estimated the contribution of multistep processes,  $(e,e'n)-(n,p)$  and  $(e,e'p)-(p,p')$ , to the measured continuum coincidence cross section. In the absence of a comprehensive theory of inelastic proton scattering from carbon we had to devise our own models of the proton rescattering process. We convoluted PWIA nucleon knockout with two different nucleon-nucleus scattering models. The first is a multiple-scattering model which describes the nucleus by a density distribution of noninteracting nucleons using the cascade code MECC-7 developed by Bertini *et al.*<sup>10</sup> The second model uses  $^{12}\text{C}(p,p')$  data at 20° and 30° for 200- (Ref. 11) and 300-MeV (Ref. 12) incident protons. For  $q=585$  MeV/c, both models predict about a 10% contribution to the continuum strength for  $50 < \epsilon_m < 100$  MeV and about a 20% contribution to the strength for  $100 < \epsilon_m < 160$  MeV. For  $q=775$  and 827 MeV/c, both models predict contributions of less than 5% for  $\epsilon_m > 50$  MeV.

The continuum strength ( $\epsilon_m > 50$  MeV) is similar to that observed in our previous measurement in the dip region at  $q=400$  MeV/c and  $\omega=200$  MeV where the inclusive  $^{12}\text{C}(e,e')$  response is dominantly transverse.<sup>13</sup> We observed a large, flat cross section extending from the two-particle knockout threshold out to the largest measured missing energy of 150 MeV. Final-state interactions can account for only 10% of this strength.<sup>14</sup> Models of two-nucleon correlations, either in the initial state<sup>15</sup> or in the final state,<sup>14</sup> do not provide strength beyond  $\epsilon_m \approx 80$  MeV. According to these models, three-or-more-nucleon knockout is required to explain the large cross section beyond  $\epsilon_m = 80$  MeV. This observed multiparticle knockout strength could account for the previously unexplained excess inclusive dip-region cross section.

We now see this large, non-single-particle, reaction process contributing to the nuclear electromagnetic response at quasielastic kinematics. This process is a significant fraction of the total observed strength. The strength from 50 to 150 MeV of  $\epsilon_m$  compared to the single-particle knockout strength ( $12.5 < \epsilon_m < 50$  MeV) is  $0.33 \pm 0.02$  for  $q=585$ ,  $0.44 \pm 0.02$  for  $q=775$ , and  $0.53 \pm 0.08$  for  $q=827$  MeV/c. Thus multiparticle knockout increases relatively with momentum transfer. For  $q=775$  MeV/c, the strength from 50 to 250 MeV of  $\epsilon_m$  is 60% of the single-particle knockout strength. These comparisons underestimate the contribution of this reaction process to the inclusive cross section for two reasons: (1) there is two-nucleon knockout strength in the  $^1s$ -shell region and (2) we expect multinucleon knockout to have a wider angular distribution than single-nucleon knockout. This new reaction process or processes must be included in any theory of the quasielastic region.

We have also compared the observed single-particle knockout strength to a factorized nonrelativistic distorted-wave impulse-approximation (DWIA) calculation:

$$\frac{d^6\sigma}{d\Omega_p d\Omega_e d\epsilon_m d\omega} = K \sigma_{ep} |\phi_a^D(\mathbf{p}_m, \mathbf{p}_f)|^2 f_a(\epsilon_m),$$

where  $K = E_f p_f$ , and  $f_a(\epsilon_m)$  is the missing-energy distribution of shell  $a$  normalized to 1.  $|\phi_a^D(\mathbf{p}_m, \mathbf{p}_f)|^2$  is the distorted momentum distribution.  $\sigma_{ep}$  is deForest's CC1 prescription for the off-shell electron-proton cross section.<sup>16</sup> We calculated the momentum distributions  $|\phi_a^D(\mathbf{p}_m, \mathbf{p}_f)|^2$  using the program PEEPSO which is based on the  $(e,e'p)$  formalism of Boffi *et al.*<sup>17</sup> For a given proton orbital with a given separation energy, PEEPSO calculates the unfactorized  $(e,e'p)$  cross section at specified kinematics by solving the Schrödinger equation for the outgoing proton with a given spin-orbit-dependent optical potential. We used a Woods-Saxon  $p$ -shell proton wave function with an rms radius of 2.8 fm as measured by van der Steenhoven *et al.* at NIKHEF with  $^{12}\text{C}(e,e'p)$ .<sup>18</sup> We used several different optical poten-

tials covering overlapping energy ranges,<sup>19</sup> each of which fitted  $^{12}\text{C}(p,p')$  data well. PEEPSO then divides this unfactorized cross section by  $K\sigma_{ep}$  to get an effective distorted momentum distribution for that proton orbital. For our kinematics and acceptances, this factorization induced an uncertainty of about 5% which is much smaller than other theoretical uncertainties. We calculated the effective momentum distribution for the  $^1p$  and  $^1s$  shells over the entire range of  $\omega$ , the electron energy loss. We averaged the factorized DWIA cross section over the six-dimensional experimental acceptance,  $\{\omega, p_f, \theta_e, \phi_e, \theta_p, \phi_p\}$ . We then compared the experimental cross section with the DWIA cross section to determine spectroscopic factors for the  $^1p$  and  $^1s$  shells. The lowest-order shell model predicts spectroscopic factors of 4 for the  $^1p$  shell and 2 for the  $^1s$  shell. The spectroscopic factors determined using the different optical potentials varied by up to 20%.

Figure 2 shows the  $^1p$ - and  $^1s$ -shell spectroscopic factors from this experiment and from previous Bates measurements at  $q=400$  MeV/c.<sup>20</sup> The vertical error bars include statistical and systematic experimental uncertainties and estimated model uncertainties. We observe  $2.42 \pm 0.39$ ,  $1.87 \pm 0.40$ , and  $2.53 \pm 0.38$   $^1p$ -shell protons for  $q=585$ , 775, and 827 MeV/c, respectively. We observe  $0.87 \pm 0.13$ ,  $0.75 \pm 0.14$ , and  $0.89 \pm 0.13$   $^1s$ -shell protons for  $q=585$ , 775, and 827 MeV/c, respectively. These spectroscopic factors are slightly lower than previous Bates values obtained at  $q=400$  MeV/c ( $N_p = 2.7 \pm 0.2$ ,  $N_s = 1.15 \pm 0.09$ ). The NIKHEF group measured the  $^1p$  momentum distribution at fixed  $\omega$  by varying  $q = p_f + p_m$  from 155 to 519 MeV/c. Using DWEEPY, a program based on the Boffi formalism that also includes electron distortion, and the Comfort and Karp op-

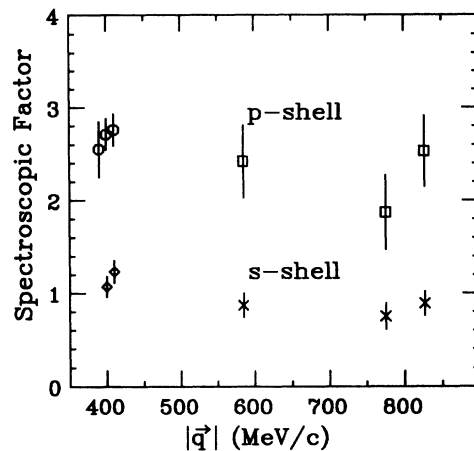


FIG. 2. Spectroscopic factor as a function of momentum transfer for  $^{12}\text{C}(e,e'p)$ . The  $^1p$ -shell data are represented by squares (this work) and circles (Ref. 20). The  $^1s$ -shell data are represented by crosses (this work) and diamonds (Ref. 20). The model used to determine the spectroscopic factors is described in the text.

tical potential, they fitted a  $^1p$  proton rms radius of 2.8 fm and a spectroscopic factor of  $2.42 \pm 0.25$ .<sup>18</sup>

The  $^1p$ -shell spectroscopic factors are approximately constant with momentum transfer. This constancy indicates that the data have the same  $q$  dependence as free-nucleon form factors, i.e., that  $^1p$ -shell protons are unmodified in the nucleus. The  $^1s$ -shell spectroscopic factors are constant or decrease slightly with momentum transfer. The cross section in the  $^1s$ -shell region also contains contributions from two-nucleon knockout. Lack of knowledge of the size of these contributions increases the uncertainties of the  $^1s$ -shell spectroscopic factors. Theoretical uncertainties are too large to draw any conclusions about nucleon modifications. This constancy of spectroscopic factor with momentum transfer is consistent with Saclay measurements of  $^4\text{He}(e,e'p)^3\text{H}$  (Ref. 21) and  $^{40}\text{Ca}(e,e'p)$ .<sup>22</sup>

The main sources of uncertainty in these calculations are the nonrelativistic DWIA and the optical-potential description of the final-state interactions. At the large momentum transfers of these measurements, the nonrelativistic description of the electron-nucleon interaction is less accurate. DWIA also does not include non-nucleonic degrees of freedom such as MEC and multinucleon knockout. Optical potentials are determined from elastic proton scattering from unexcited nuclei. Elastic proton scattering constrains only the asymptotic part of the distorted proton waves; the part inside the nucleus is not well constrained. The  $(e,e'p)$  final-state interaction is very sensitive to the proton distorted wave inside the nucleus. For the  $s$  shell, where the residual nucleus is highly excited, the validity of elastic-scattering-derived optical potentials is highly suspect. The uncertainties due to optical potentials are exacerbated by the lack of a single experimental optical-potential parametrization extending from 80 to 380 MeV.

In conclusion, these data strongly support the growing realization that the inclusive  $(e,e')$  quasielastic peak contains much more many-body physics than was origi-

nally thought. To quantitatively interpret these data, we need a much greater understanding of the final-state interaction and we need a relativistic theory of deep-inelastic electron scattering that includes single-nucleon, multinucleon, and non-nucleonic degrees of freedom.

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- <sup>1</sup>P. Barreau *et al.*, Nucl. Phys. **A402**, 515 (1983).
  - <sup>2</sup>J. M. Finn, R. W. Lourie, and B. H. Cottman, Phys. Rev. C **29**, 2230 (1984).
  - <sup>3</sup>J. W. van Orden and T. W. Donnelly, Ann. Phys. (N.Y.) **131**, 451 (1981).
  - <sup>4</sup>P. G. Blunden and M. N. Butler, Phys. Lett. B **219**, 151 (1989).
  - <sup>5</sup>W. Alberico *et al.*, Ann. Phys. (N.Y.) **154**, 356 (1984).
  - <sup>6</sup>P. E. Ulmer *et al.*, Phys. Rev. Lett. **59**, 2259 (1987).
  - <sup>7</sup>L. B. Weinstein, Ph.D. thesis, MIT, 1988 (unpublished).
  - <sup>8</sup>E. Borie and D. Drechsel, Nucl. Phys. **A167**, 369 (1971).
  - <sup>9</sup>H. Baghaei *et al.*, Phys. Rev. C **39**, 177 (1989).
  - <sup>10</sup>H. Bertini *et al.*, "MECC-7, Medium Energy Intra-nuclear Cascade Code," Oak Ridge National Laboratory, Internal Report No. CCC-156 (unpublished).
  - <sup>11</sup>C. C. Chang (private communication).
  - <sup>12</sup>R. Segal (private communication).
  - <sup>13</sup>R. W. Lourie *et al.*, Phys. Rev. Lett. **56**, 2364 (1986).
  - <sup>14</sup>T. Takaki, Phys. Rev. Lett. **62**, 395 (1989).
  - <sup>15</sup>J. M. Laget (private communication).
  - <sup>16</sup>T. deForest, Nucl. Phys. **A392**, 232 (1983).
  - <sup>17</sup>S. Boffi *et al.*, Nucl. Phys. **A336**, 437 (1980).
  - <sup>18</sup>G. van der Steenhoven *et al.*, Nucl. Phys. **A480**, 547 (1988).
  - <sup>19</sup>J. Comfort and B. Karp, Phys. Rev. C **21**, 2162 (1980); H. O. Meyer *et al.*, Phys. Rev. C **27**, 459 (1983); H. O. Meyer *et al.*, Phys. Rev. C **37**, 544 (1988).
  - <sup>20</sup>P. E. Ulmer *et al.*, Phys. Rev. Lett. **61**, 2001 (1988).
  - <sup>21</sup>A. Magnon *et al.*, Phys. Lett. B **222**, 352 (1989).
  - <sup>22</sup>D. Reffay-Pikeroen *et al.*, Phys. Rev. Lett. **60**, 776 (1988).