Electroexcitation of the Δ resonance in the $(e,e'p)$ reaction

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The $^{12}C(e,e'p)$ reaction at the delta resonance has been measured for protons detected parallel to the momentum transfer at two kinematical situations: at the maximum and the low-energy-loss side of the peak. The cross section was measured for missing energies up to 320 and 220 MeV, respectively. In the missing energy spectrum two distinct structures are observed, which correspond to multinucleon knockout and quasifree pion production processes. In addition, there is a remnant of the quasifree knockout process.

Inclusive deep inelastic electron scattering from nuclei at intermediate energies generally shows two broad peaks corresponding to quasifree elastic scattering from the nucleon (QE) and quasifree Δ(1232) resonance production, with a "dip" region between them. The inclusive cross section at the QE peak and at the Δ resonance is predominantly due to one-body processes. However, there are indications that the (e,e') reaction does not proceed solely via a simple one-body mechanism. In the dip region the measured cross section shows an excess compared to one-body calculations augmented by meson exchange currents.[1–3] Laget, using a phenomenological quasideuteron model,[1,3] accounts for a significant fraction of this excess strength, indicating that processes involving two correlated nucleons may be important. In the Δ region the cross section for light nuclei shows several features:[4] (1) The location of the peak is about 10 MeV lower than for hydrogen, (2) the peak width ($\simeq 250$ MeV) is larger than that obtained by simply folding the width of the free Δ peak ($\simeq 120$ MeV) with the observed width of the quasifree peak ($\simeq 100$ MeV), and (3) the integrated cross section per nucleon of the Δ peak is enhanced by 34% relative to the free nucleon. These results suggests that the delta is modified by the nuclear medium and that other than one-body reactions contribute to the (e,e') process.

We report here the results of measurements of the $^{12}C(e,e'p)$ reaction in the Δ-resonance region for two different kinematics. The experiment was performed at the MIT-Bates Linear Acceleration Center using the South Hall spectrometers MEPS and OHIPS for the detection of electrons and protons respectively. The main characteristics of the spectrometers are given elsewhere.[5] Each spectrometer was instrumented with a two-plane vertical drift chamber[6] 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.

In the one-photon-exchange approximation when the proton is detected along the direction of the momentum transfer $\mathbf{q}$ (parallel kinematics) the coincidence cross section can be written in terms of two nuclear structure functions[7]

$$\frac{d^4\sigma}{d\Omega_p d\Omega_e d\omega d\epsilon_m} = \sigma_M[v_L R_L(\mathbf{q},\omega,T_p) + v_T R_T(\mathbf{q},\omega,T_p)] , \qquad (1)$$

where σ_M is the Mott cross section, $R_L(R_T)$ is the longitudinal (transverse) response function, the v's are functions of the electron kinematics, ω is the energy transfer, T_p is the final proton kinetic energy and $\epsilon_m = \omega - T_p$ is the missing energy. While a separation of the longitudinal and transverse responses has not been performed, inclusive (e,e') measurements indicate that the transverse component dominates in this region.

We measured missing energy spectra for two different electron kinematics in the Δ region. For kinematics I we chose a beam energy $E_0 = 460$ MeV, $\omega = 275$ MeV, $|\mathbf{q}|$

=401 MeV/*c*, and electron-scattering angle $\theta_e = 60°$ corresponding to a point roughly halfway between the dip region and the Δ resonance peak. The proton kinetic energy was the only experimental quantity varied. Protons with kinetic energy from 55 to 275 MeV, covering the missing energy range of 0 to 220 MeV, were detected at −23.6°. For kinematics II, the electron kinematics were fixed at the maximum of the quasifree Δ production peak: $E_0 = 647$ MeV, $\omega = 382$ MeV, $|\mathbf{q}| = 473$ MeV/*c*, and $\theta_e = 39.5°$. Protons in the kinetic energy range of 62 to 382 MeV, covering the missing energy range of 0 to 320 MeV, were detected at −20.8°.

Normalization was accomplished via the ^{1}H$(e,e'p)$ elastic-scattering reaction. The target was a 52.8 mg/cm^2 thick rotating polyethylene (CH_2) disk. We achieved a missing energy resolution of 1.8 MeV and a relative time-of-flight resolution of 2.0 ns. Additional normalization checks were made via ^{1}H and ^{12}C elastic electron-scattering. An overall normalization factor of 1.17 was applied to the coincidence data in addition to electronic deadtime corrections and corrections for spatial variations of the focal plane relative efficiency.

Natural carbon targets of 93.0, 45.7, and 24.2 mg/cm^2 thickness were used for the ^{12}C$(e,e'p)$ measurements. Accepting all coincidences within a 100 ns timing gate allowed a direct measurement of the missing energy distribution of accidental coincidences with high statistical precision. The pions in the electron arm were rejected by using an Aerogel Čerenkov counter. The separation of protons from positrons, pions, and deuterons was made using pulse height differences in scintillation counters and flight time differences.

The coincidence cross section versus missing energy for kinematics I and II is shown in Fig. 1 Although we achieved an energy resolution of 1.8 MeV, due to limited statistics the data are displayed in 14.4 and 21.7 MeV bins, respectively. In kinematics I, one sees strength in three regions: (1) The region below 30 MeV missing energy which dominated by the quasifree knockout process (region *A*). (2) The region between 30 and 165 MeV (region *B*). Region *B* corresponds to multinucleon knockout processes. The missing mass spectrum in this region follows the kinematic behavior of the quasifree $\gamma_v +$ "d" $\rightarrow p+n$ reaction (assuming a 30 MeV binding energy for deuteron). This behavior is also exhibited by (γ,p) data (see below), which has been explored in more detail and shown to be dominated by the two-body knockout process. Thus we conclude that this region is mainly populated by two-nucleon knockout processes. (3) The region above the real pion production threshold ($\epsilon_m \geq 165$ MeV), which is dominated by Δ(1232) resonance production and is distinguished by a sharp increase in the coincidence cross section at pion threshold (region *C*). The same general features are observed at kinematics II.

These ^{12}C$(e,e'p)$ spectra are qualitatively similar to the (γ,p) spectra obtained by Homma *et al.*[8,9] They measured the proton momentum spectra for several light nuclei at different tagged photon energies and fit each spectrum with two Gaussians. From the variation of the peak centroids with incident photon energy, from comparing the ^{12}C data with the deuterium data, and from (γ,pn), (γ,pp), and $(\gamma,p\pi)$ measurements on ^{12}C, they concluded that the peak at lower proton momentum (corresponding to our higher missing energy peak) is due to the reaction $\gamma +$ "N" $\rightarrow p+\pi$, and the smaller peak at higher proton momentum is due to the reaction $\gamma +$ "pN" $\rightarrow p+N$, where "N" and "pN" denote the quasifree nucleon and quasifree two-nucleon systems in the nucleus, respectively. From the photon energy dependence of the cross sections they concluded that the Δ resonance contribution is important in both peaks.

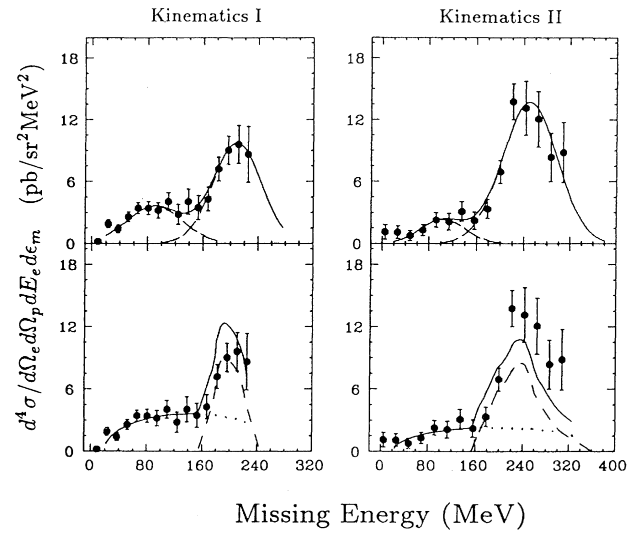

FIG. 1. The missing energy spectrum for two kinematical situations at the Δ resonance region. The bin width is 14.4 MeV for kinematics I and 21.7 MeV for kinematics II. In the upper half the solid curve is the sum of the two Gaussians. In the lower half the dashed curve is the result of the quasifree calculation with harmonic oscillator momentum distributions, the dotted curve is the three-body phase space result and the solid curve is their sum.

For comparison with (γ,p) results, the ^{12}C$(e,e'p)$ missing energy spectra were fit with two Gaussians. The solid curves in the upper half of the Fig. 1 show the sum of the fits. The cross section in region *C* increases going from the low-ω side to the peak of the Δ (kinematics I to kinematics II), and when integrated over the missing energy, using the Gaussian fit to region *C*, it increases by a factor of 2.3±0.4. If the process is proceeding through the Δ-resonance, one would expect its strength increases as ω approaches the maximum value of the Δ peak. Our results are thus consistent with the assumption of Δ dominance. The integrated multibody strength (region *B*) decreases by a factor of 0.54±0.2 in going from kinematics I to kinematics II consistent with the (γ,p) results[9]. Optical model calculations of proton absorption[10] show a differential effect of about 5% between the two kinematics. This does not alter the preceding results. Another interesting quantity is the fraction of the total integrated strength in the multibody knockout process. For kinematics I (II), the multinucleon processes account for 30%

(12%) of the yield. In the previous comparisons we assumed the strength in region B to be Gaussian, distributed as in the upper half of the Fig. 1. However, from the present data one cannot eliminate the possibility that the many-nucleon knockout strength may extend into the pion production region.

In the lower half of Fig. 1, the data are compared with a calculation for the pion production region using a quasifree nucleon model and assuming the process proceeds through the Δ resonance production

$$e+p \to e+\Delta^{+} \to e+p+\pi^{0} ,$$
$$e+n \to e+\Delta^{0} \to e+p+\pi^{-} . \tag{2}$$

The coincidence cross section can be written as

$$\frac{d^4\sigma}{dE_e d\Omega_e dE_p d\Omega_p} = \int K \sum_{fi} |M_{e\Delta}|^2 S(\mathbf{p}_i,\epsilon_m) d^3 p_i , \tag{3}$$

where the integral is over the nucleon initial momentum, $\mathbf{p}_i$. K is a kinematical factor

$$K = \frac{1}{32(2\pi)^5} \frac{E_f |\mathbf{p}_p|}{E E_i} \frac{\delta(\omega+E-E_p-E_n)}{E_\pi} ,$$

where $E_i(E_f)$ is the electron initial (final) energy, $E=(m_p-\epsilon_b)$ is the energy of the initial nucleon with binding energy ϵ_b,

$$E_\pi = [m_\pi^2 + (\mathbf{q}+\mathbf{p}_i-\mathbf{p}_p)^2]^{1/2}$$

is the pion energy, and $\mathbf{p}_p(E_p)$ is the knockout proton momentum (energy). $S(\mathbf{p}_i,\epsilon_m)$ is the spectral function, which we modeled with harmonic oscillator momentum distributions ($b=1.67$ fm) and δ functions in the missing energy located at the centroids of the experimental shell energies of the p shell and s shell. The amplitude $M_{e\Delta}$ is derived from the elementary reactions (Eq. 2) in the rest frame of the initial nucleon (keeping only the magnetic dipole term)[11]

$$\sum_{fi} |M_{e\Delta}|^2 = \frac{3}{2} \frac{\alpha_2}{2|q_\mu|^2} \frac{4}{1-\epsilon} |M_1|^2 [\tfrac{5}{2} - \tfrac{3}{2}\cos^2\theta_c - \tfrac{3}{2}\epsilon \sin^2\theta_c \cos(2\phi)] , \tag{4}$$

and transforming to the proton moving frame. In the above equation θ_c is the proton angle with respect to $\mathbf{q}$ in the c.m. frame of the Δ, ϕ is the corresponding azimuthal angle,

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

is the virtual photon polarization parameter, and[11]

$$|M_1|^2 = \frac{12\pi(M_\Delta+m_p)^2}{4m_p^2} \frac{p_c^2}{p_c'} \frac{M_\Delta}{E_c+m_p} \frac{\sin^2\delta}{\Gamma} |G_M^*(q_\mu^2)|^2 , \tag{5}$$

where $p_c(p_c')$ is the momentum of the incoming (outgoing) proton in the c.m. frame of the Δ, $M_\Delta(m_p)$ is the delta (proton) mass, Γ is the Δ width, δ is the phase shift, and $G_M^*(q_\mu^2)$ is the magnetic dipole $\gamma N \Delta$ form factor.

The calculated cross section (dashed curve) underestimates the data, especially for kinematics II. This may be due to the approximations we used in these calculations, which will be discussed later, or to other processes. The recent (γ,pp) and (γ,pn) results[9] show that there is some two-nucleon contribution in this region not accounted for by a two Gaussian fit. Takaki[12] has recently investigated the contributions of the many body processes to the $(e,e'p)$ reaction at the dip region. The dominant feature of the measured cross section at the dip region ($\omega=200$ MeV, $q=400$ MeV/c) (Ref. 5) is a nearly uniform strength extending from the one-body knockout region up to the highest measured missing energy (160 MeV). Takaki's calculations show that the cross section for the two-body process at missing energies above 100 MeV is negligible. He suggests that to understand the data one has to include processes which involved three or more nucleons. His qualitative investigation of the three-nucleon process indicates that it populates the region of $\epsilon_m > 100$ MeV. For both of our kinematics for $\epsilon_m > 160$ MeV, the average initial momentum of the pN center of mass in the γ_v + "pN"$\to p+N$ reaction is larger that 375 MeV/c, making a large contribution from this two-body process unlikely. However, processes involving three or more nucleons can contribute to this region. Takaki's calculations indicate that the ratio of the three-body cross section to the two-body cross section at their respective peaks in the missing energy spectrum for kinematics I is about 1.1. This ratio for kinematics II is about 1.8. To study this possible contribution we used a three-body phase space calculation (dotted curve) normalized to the experimental strength in region B. The solid curve, in the lower half of Fig. 1, is the sum of the quasifree results and a three-body phase space calculation.

In our calculations we made several approximations: (1) We neglected the contribution of the nonresonant (Born) terms. This contribution was estimated from free e-p cross section data[13] to be less than 35%. (2) We also neglected the $C2$ (longitudinal Coulomb quadrupole) and $E2$ (transverse electric quadrupole) resonant terms. The ratios of $C2/M1$ and $E2/M1$ are estimated to be less than 10% and 5%, respectively.[14] (3) We used the on-shell amplitude for the reactions (2). The off-shell effects for quasielastic kinematics are usually small (at the 10%

level) and we assume this holds for the Δ. (4) We neglected final state absorption of the outgoing proton which is estimated from a distorted wave calculation[10] to be about 45%. Approximations 1 and 2 nearly compensate for approximation 4. Thus, we expect the net effect to be small.

Following Borie and Dreschel[15] we estimated the contribution of the radiative tail from the p and s shells to the higher missing energies. The nonradiative cross section was calculated in the factorized plane wave impulse approximation (PWIA) using harmonic oscillator momentum distributions and δ functions in missing energy. The magnitude of the radiative tail increases with missing energy but always remains small compared to the data. For kinematics I it is always less than 1%. For kinematics II the estimated contribution of the radiative tail for $\epsilon_m < 200$ MeV is less than 1%. For the highest measured missing energy, $\epsilon_m \simeq 320$ MeV, it could account for as much as 20% of the data. These corrections have not been applied to the data or to the theoretical calculations shown in Fig. 1. Lacking theoretical or experimental information about other processes, we did not treat the radiative tails from processes other than p- and s-shell knockout.

In summary, we have shown that the missing energy spectra measured in an $(e,e'p)$ experiment can distinguish, to some extent, between different reaction mechanisms that contribute to the electron-scattering process. We see three different processes contributing to the $(e,e'p)$ reaction at the delta region: one-nucleus knockout, multinucleon knockout, and pion production. The one-body knockout is the dominant process at missing energies below 30 MeV. The pion production is distinguished by a sharp increase in the cross section at pion threshold. The many-nucleon process observed below the pion threshold has been identified as a two nucleon process from its kinematic behavior and from the similarity to (γ,p) results. The failure of our model to provide sufficient strength to describe the data along with the calculations of Takaki suggest the existence of significant three or more body processes about the pion threshold. The multinucleon process may be able to account for the enhancement of the integrated (e,e') cross section per nucleon in light nuclei compared to hydrogen in the region of the quasifree Δ production peak.

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