Δ Electroproduction and Inelastic Charge Scattering from Carbon and Iron

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Electroproduction of the Δ isobar in C and Fe has been studied for incident electrons with energies between 0.6 and 1.6 GeV. A longitudinal-transverse decomposition of the inclusive cross section has been made for $q_\mu^2 = 0.1$ $(\text{GeV}/c)^2$. The residual longitudinal cross sections measured do not provide the additional strength needed above the quasifree region to satisfy the Coulomb sum rule. The transverse cross sections are in good agreement with data from photoabsorption.

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Excitation of the Δ(3,3) resonance is the dominant feature of electromagnetic and hadronic interactions with nuclei in the region of energy transfer between pion threshold and 500 MeV. Because of strong interactions with other nucleons in the nuclear interior, one expects the Δ to be broadened and possibly shifted in energy when excited as a constituent nucleon in nuclear matter. The nuclear response in inelastic electron scattering has been studied[1-3] in the Δ region for energy transfers to the nucleus up to 550 MeV. To date, theoretical models for electron scattering have not given a satisfactory description of the data.[4] Although calculations which include nuclear-medium effects do predict a reduction of the peak cross section and a spreading of the Δ width, they do not account for the ≃34% enhancement in the integrated strength which O'Connell *et al.*[4] observe in the Δ region. It has been speculated that the origin of this enhancement may be a "quasideuteron electrodisintegration" mode of excitation[5,6] which is strongest in the region between the quasifree peak and the Δ peak in the nuclear response function.

The experiment reported here extends high-energy (> 1.5 GeV) measurements to the medium-heavy nucleus, Fe, and includes for the first time a longitudinal-transverse decomposition of the inclusive cross section from pion threshold through the Δ region. Such a decomposition is vital to understanding the nuclear response to relatively large transfers of energy and momentum. The new data provide limits on the contributions of charge-dependent processes including the longitudinal tail of quasifree scattering into the Δ region. Because Δ excitation on the free nucleon results from a transverse $\gamma N \Delta$ coupling, experimental sensitivity to Δ processes is increased in the transverse component of the inclusive cross section.

The experiment was performed at the Stanford Linear Accelerator Laboratory with the NPAS (Nuclear Physics at SLAC) facility. Electron beams with energies of 653, 1300, 1500, and 1650 MeV were scattered from natural targets of C and Fe. Scattered electrons were observed in the 8-GeV/c spectrometer whose detector system includes a gas Cherenkov counter, ten planes of wire chambers, and a total-absorbing segmented lead-glass shower detector array. The thicknesses of the carbon and iron targets were 324 and 122 mg/cm^2, respectively. Observation of elastic scattering from a hydrogen target provided the absolute calibration of the spectrometer. Cross sections for the C and Fe were measured at fixed values of the four-momentum transfer q_μ and energy transfer ω at different scattering angles. Corrections for radiation processes were made by the subtraction of a calculated elastic radiation tail from the data and then radiatively correcting the reduced data for continuum processes with the standard Mo and Tsai[7] treatment. Continuum corrections were typically 5%–15%. At the higher beam energies, the elastic radiative tail was negligible in the region under study. $R_L(q,\omega)$ and $R_T(q,\omega)$, the response functions for longitudinally and transversely polarized virtual photons, were obtained with the use of the one-photon-exchange approximation to the inclusive cross section,

$$\frac{d^3\sigma}{d\Omega\, d\omega}\sigma_M^{-1} = \left\{ \left(\frac{q_\mu^2}{q^2}\right)^2 R_L(q,\omega) + \left[\frac{1}{2}\left(\frac{q_\mu^2}{q^2}\right) + \tan^2\frac{\theta}{2}\right] R_T(q,\omega) \right\},$$

where σ_M is the Mott cross section and $q_\mu^2 = q^2 - \omega^2$. The kinematic conditions were constrained to provide a determination of the cross section for a four-momentum transfer, $q_\mu^2 = 0.1$ $(\text{GeV}/c)^2$, so that the resultant Δ's propagate un-

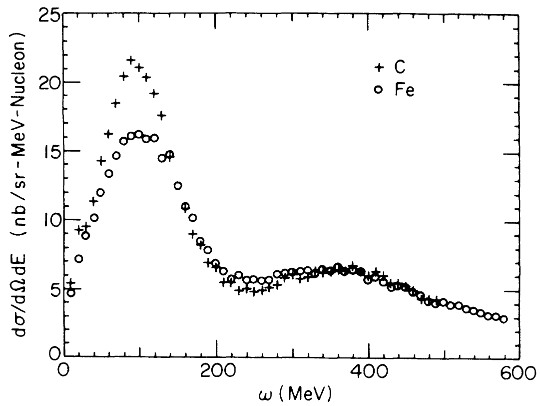

FIG. 1. Cross sections for scattering of 1.65-GeV electrons from C (crosses) and Fe (circles) at 13.5°. Data have been corrected for radiative effects. Statistically, errors are comparable to the symbol size.

der kinematic conditions similar to those in pion interactions near resonance. Measurements were made at scattering angles of 11.9° to 13.5° for beam energies of 1300, 1500, and 1650 MeV and at scattering angles of 33° to 53° for 653 MeV. Corrections to the first Born approximation due to Coulomb distortion of the incident electron wave were made following the effective-momentum-transfer approximation; effects of Coulomb focusing are expected to be negligible for the kinematics under study.[8]

Corrected cross sections per nucleon are shown in Fig. 1 for 1650-MeV incident electrons scattered through 13.5°. As observed for light nuclei the cross section in the Δ region scales with A, suggesting a universal nuclear response. The quasifree $(e,e'N)$ peak in Fe is broader than that of carbon, because of the increased Fermi momentum, and a quasifree tail appears to extend into the region between the two peaks. The integrated quasifree strength in the peak in Fe shows a quenching ($\simeq 15\%$) relative to carbon. This quenching is known[3,9,10] to characterize heavy nuclei. It is interesting to note that the cross section in the region $200 < \omega < 300$ MeV scales faster than A. This mass dependence is consistent with the results[1] for the light nuclei and with the presence of a multistep process in the absorption of the virtual photon. Results for the longitudinal-transverse separations are presented in Fig. 2 in the form of cross sections for longitudinally and transversely polarized virtual photons.[12] The relations to the corresponding response functions are

$$\sigma_L = \frac{4\pi^2\alpha}{K}\left(\frac{q_\mu}{q}\right)^2 R_L(q,\omega), \quad \sigma_T = \frac{2\pi^2}{K}\alpha R_T(q,\omega),$$

where $K = \omega - q_\mu^2/2M$. The total cross section for virtual photons is $\sigma = \sigma_T + \epsilon\sigma_L$, where ϵ lies between 0 and 1 depending on the photon polarization.

Since analyses with the 653-MeV data and with com-

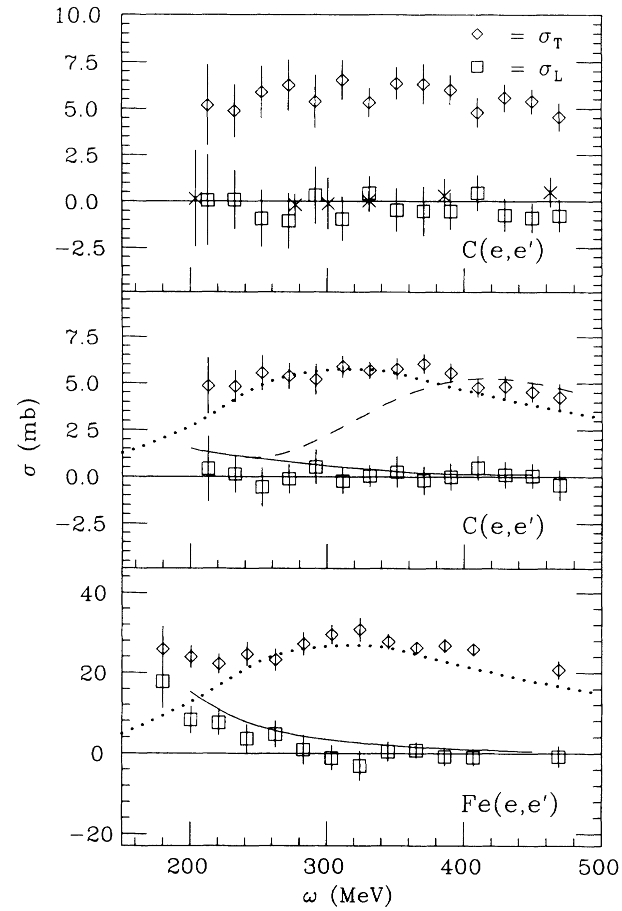

FIG. 2. Photoabsorption cross sections for longitudinally (squares) and transversely (lozenges) polarized virtual cross sections for C and Fe. The solid curves represent the contribution of a tail of longitudinal quasifree scattering suggested in Ref. 11. The dashed curve describes cross sections calculated for quasifree Δ production with a phenomenological model discussed in the text. The dotted curves are predictions based on photoabsorption data. The upper section compares the results of a longitudinal-transverse separation with use of only the data from the measurement reported here with results (crosses) of an alternate analysis with the data of Refs. 3 and 10 in place of the SLAC back-angle data. The center and lower sections contain the results of a global analysis in which all data from the two experiments have been used. Error bars include statistical and systematic errors.

parable data obtained previously[3,10] yield separations with acceptable values of χ^2, as shown for carbon in Fig. 2 (top), to extend the range of ϵ, and also improve statistical accuracy, a "global" separation was performed with all of the data. For carbon, the measured cross section is, within errors, completely transverse for $\omega > 200$ MeV. No measurable longitudinal strength is observed for either target in this energy region, except for a small component in Fe for $\omega < 280$ MeV, presumably the $(e,e'N)$ quasifree tail.

The longitudinal strength is of particular interest because it is constrained by the Coulomb sum rule.[13] This constraint provides a test of the ground-state nuclear wave function and the properties of the proton form factor in the nuclear medium. Recent measurements[3,9,10] of inclusive quasifree electron scattering for a range of nuclei have revealed integrated strength significantly less than expected if the sum rule is valid. This apparent quenching has been attributed[14-16] to modifications of the nucleon current in the nuclear medium, which might manifest themselves in substantially altered nucleon form factors. However, to date measurements of quasifree scattering[17] are consistent with free-nucleon values. Alternatively, Schiavilla, Fabrocini, and Pandharipande[11] have suggested that part of this missing strength may be accounted for by a contribution from a quasifree scattering tail which extends to energies above those accessible in previous measurements. Such strength at high ω could arise from nucleon correlations. To estimate the strength of the tail postulated, they connect to the existing data an exponential tail whose parameters are fixed by application of the energy-weighted sum rule for extended nuclear matter. Using their parametrization of the surface of $R_L(q,\omega)$ we have calculated R_L for C and Fe along the contour corresponding to $q_\mu^2=0.1$ $(\mathrm{GeV}/c)^2$. The curves are included in Fig. 2. As in the case of the analysis in Ref. 11, they join smoothly to the data available in the region of the quasifree peak. For C $\simeq 0.1$ of the Coulomb sum rule is accounted for by the exponential tail. For Fe, $\simeq 0.2$ of the sum rule strength is in this tail for $350 < q < 500$ MeV/c. For both targets these predictions lie above the data, which suggests that they provide upper limits on the amount of Coulomb strength in this region of excitation.

Although the Coulomb sum rule is defined for $q=\mathrm{const}$,

$$C(q) \equiv \int [R_L(q,\omega)/ZG_E^2(q,\omega)]d\omega,$$

a useful estimate of the contribution of the data of Fig. 2 to this integral, $\delta C(q)$, is obtained by our ignoring the variation of q and using the estimate obtained with $q_\mu^2=0.1$ $(\mathrm{GeV}/c)^2$ in the integral over the interval $200 < \omega < 400$ MeV. Over this range of integration the following relations hold: $380 < q < 510$ MeV/c and $\langle q \rangle = 435$ MeV/c. For carbon, we find $\delta C(q) = 0.00 \pm 0.05$, and for Fe we find $\delta C(q) = 0.03 \pm 0.04$. The data for Fe are of particular interest in view of the work of Meziani *et al.*,[10] in which only about 0.6 of the expected Coulomb sum is observed for $\omega < 240$ MeV at the relevant momentum transfer. This result suggests that the residual longitudinal cross section above $\omega = 200$ MeV does not provide the additional strength needed to satisfy the sum rule. For carbon, the present data also suggest that there is no substantial longitudinal strength for $\omega > 200$ MeV, although one cannot rule out the tail contribution $\delta C(q) \simeq 0.1$, the value postulated by Schiavilla, Fabrocini, and Pandharipande. For carbon, 0.3 would be the value required to satisfy the sum rule. In both cases the data indicate that only a limited fraction of the quenching of longitudinal strength previously reported can be attributed to the existence of substantial strength for excitation energies above 200 MeV.

The data for σ_T are compared with two predictions in Fig. 2. The dotted curves are obtained from the transverse response function measured in real-photon absorption.[6] In spite of the neglect of any q^2 dependence, this curve is in good agreement with the data and suggests that electroexcitation of the Δ accounts for most of the transverse strength, just as for photoabsorption. The dashed curve is obtained from a microscopic calculation[18] starting from a phenomenological Hamiltonian for interactions between pions, nucleons, and Δ. It includes only the contributions from the removal of one and two nucleons from the nuclear ground state, which are calculated respectively from a one-body and a two-body pion-exchange current operator constrained to fit $\gamma N \rightarrow \pi N$ and $\gamma d \rightarrow pn$ data. Both contributions are dominated by Δ excitation, although a Born term contribution is also significant. The very divergent prediction of this result is striking and indicates the importance of mechanisms involving removal of more than two nucleons from the nuclear ground state. Laget[6] used an approach qualitatively similar to that of Ref. 18 except that a Levinger factor[19] is introduced to reproduce the total-absorption cross section for real photons. Hence, his prediction is expected to be closer to the data, as shown in his results[6] in the lower-energy region. The dominance of the Δ excitation is evident in the photon-energy dependence of his empirical Levinger factor. This suggests that the multinucleon processes, neglected in Ref. 18, are also dominated by the Δ excitation. Results for the location and shape of the transverse strength based on the Δ-hole model[20] are similar to those of the phenomenological Hamiltonian theory. Therefore, our conclusions are not unique to the Hamiltonian approach. In addition, multinucleon modes beyond the simple two-nucleon mode have also been found to be strong[21] in pion absorption in the Δ region. Thus, it is evident that an accurate theoretical description of the transverse response incorporating modes involving meson-exchange currents and all Δ absorption channels will be vital to understanding our data.

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