Electroexcitation of the Δ(1232) in Nuclei

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(Received 7 November 1988)

Inclusive electron-scattering measurements of Δ electroexcitation in nuclei are reported. Electrons with energies of 0.96, 1.1, 1.3, and 1.5 GeV were scattered from ^{1}H, ^{4}He, C, Fe, and W at 37.5°, corresponding to $Q^2=0.20$–0.52 $(\mathrm{GeV}/c)^2$ at the Δ peak. The centroid of the Δ-region cross-section peak is above that for the free nucleon and it shifts to higher invariant mass as Q^2 increases. The A dependence in the dip region and ratios of nuclear to nucleon integrated cross sections indicate that at these Q^2 values there is little specifically nuclear, e.g., quasideuteron, background contribution.

PACS numbers: 25.30.Fj

Electron scattering from nuclei at sufficient energy loss can be used to study the excitation, propagation, and decay of nucleon resonances in the nuclear environment. Through such studies one ultimately expects to understand how the strong interaction is influenced by baryon structure. Since electroproduction of the Δ(1232) from the nucleon is well understood and the Δ is the most prominent nucleon resonance, it is the logical choice for initial studies of nuclear-medium effects on resonances. Fermi motion, nuclear binding, pion reabsorption, and Pauli blocking modify the width of the Δ resonance and its location in energy. Except for Fermi motion these effects are expected to be small, but they all provide information about the nuclear environment. Contributing to the Δ-region cross section are the high-energy-loss tail from the quasielastic peak, two-body processes in the dip region, nonresonant π production, low-energy tails from production of higher-lying resonances, and deep-inelastic scattering. The A and Q^2 dependences of these mechanisms can be exploited to partially disentangle them.

Electroexcitation of the Δ has been studied at low Q^2, 0.1 $(\mathrm{GeV}/c)^2$, for nuclei with atomic numbers from 4 to 56.[1-3] For these data the cross section per nucleon is independent of A for the Δ region and nearly so for the dip region. Nuclear-medium effects are clearly evident in the broadening of the Δ peak, the large strength in the dip region, and a shift of the Δ centroid to lower energy loss than for production from the free nucleon. Barreau *et al.*[4] observed a similar shift in ^{12}C at $Q^2=0.09$ $(\mathrm{GeV}/c)^2$, but at $Q^2=0.13$ $(\mathrm{GeV}/c)^2$ the ^{12}C and free-nucleon Δ were at nearly the same energy loss. In heavier nuclei, Ca and Fe, and at slightly higher Q^2, 0.16 $(\mathrm{GeV}/c)^2$, Meziani *et al.*[5] observed Δ-peak positions at higher energy loss than for the free nucleon. High-energy heavy-ion charge-exchange reactions[6,7] which probe the nuclear surface also show Δ-peak shifts of up to 70 MeV toward lower energy loss. In the dip region ^{12}C$(e,e'p)$ coincidence experiments[8] indicate that 65% of the proton knockout cross section for Q^2 near 0.1 $(\mathrm{GeV}/c)^2$ and an invariant mass W of 1066 MeV is due to other than one-nucleon processes. At $W=1145$ and 1232 MeV, Baghaei *et al.*[9] identify 30% and 12%, respectively, of the cross section as due to two-nucleon knockout. At high Q^2, inclusive measurements[10,11] for ^{6}Li and C are available. Other data[12,13] for Q^2 near 0.2 and 0.3 $(\mathrm{GeV}/c)^2$ and a wide range of A are of insufficient energy resolution and statistical accuracy to determine nuclear-medium effects on resonances. Higher-quality data over the full A and Q^2 ranges are required.

In this Letter we present an extensive new data set that comprises a systematic study of Δ electroexcitation in nuclei. We have measured inclusive electron-scattering cross sections for $A=1$ to 184 in order to cover the widest practical range of nuclear volume, density, and binding energy. Values of Q^2 varied from 0.20 to 0.52 $(\mathrm{GeV}/c)^2$ at the Δ centroid. At the low end of this Q^2 range quasielastic scattering is more probable than Δ excitation and at the high end deep-inelastic scattering and low-energy tails from the production of higher-energy resonances are becoming dominant.

The experiment was performed at the Stanford Linear Accelerator Center (SLAC) in End Station A using the facilities of the Nuclear Physics at SLAC program

(NPAS). Electron beams with energies of 0.96, 1.1, 1.3, and 1.5 GeV were provided by the nuclear physics injector. The 1.6-GeV/c spectrometer[14] and a new electron detector constructed for this experiment were used. The targets and their thicknesses in radiation lengths were as follows: ^{1}H (1.7%), ^{4}He (1.5%), C (0.8%), Fe (0.9%), and W (3.3%). The ^{1}H target was a 15-cm-long recirculating liquid target while the ^{4}He target was a 25-cm-long, high-pressure, recirculating gas target at a pressure of 25 atm; other targets were thin solids of natural isotopic abundance. The electron detector consisted of three multiwire drift chambers each with four planes of wires, an atmospheric-pressure, isobutane-filled Cherenkov detector, two planes of scintillator hodoscope, and a 35-segment Pb-glass shower counter. The event trigger was a coincidence between the hodoscopes and either the Cherenkov detector or the shower counter.

All data reported here were taken at a spectrometer angle of 37.5°. For each 10-MeV interval about 1000 electrons were collected, giving 3% statistical uncertainty. The scattered electron energy was always greater than 30% of the beam energy. Data were collected from empty H and ^{4}He cells in order to subtract background from the container walls. Studies of identical H and ^{4}He targets during previous experiments indicated that for the beam currents used in this experiment, $< 0.2\ \mu$A, beam heating caused less than 0.5% change in target density. After converting yields to cross sections, a calculated elastic radiative tail was subtracted from the results. Continuum radiative corrections were then made using the formulas of Mo and Tsai[15] and of Stein *et al.*[16] The elastic raidative tail as a percentage of the cross section at $W=1400$ MeV varied from 39% (25%) at a beam energy of 0.96 (1.3) GeV for H to 6% (<1%) for Fe at 0.96 (1.3) GeV. Continuum radiative corrections were roughly 10% of the cross-section values.

Cross sections for elastic scattering from hydrogen were within 1% of a fit to all available published data.[17] Uncertainties for the target thickness, beam-current integration, efficiencies of the individual detector elements, and electronic dead time were all less than 1%. We estimate that radiative corrections were accurate to about 1% of the cross-section values. Uncertainty in the spectrometer acceptance function was about 5% for the two extended targets and about 3% for the thin solid targets. When comparing results from one solid target to another the total relative systematic uncertainty is about 2.5%.

Examples of the data obtained (from C) are shown in Fig. 1. We have plotted the doubly differential cross section, $d^2\sigma/d\Omega\, dE'$, where E' is the scattered electron energy, divided by A versus W to facilitate comparison among cross sections for different beam energies and nuclei. The quasielastic and Δ peaks appear at W values of about 970 and 1250 MeV, respectively. The Δ peak is broadened, primarily by Fermi motion, to about 250 MeV full width at half maximum (FWHM) from the 118 to 127 MeV FWHM observed in our H data. The cross sections decrease by a factor of 5 as the momentum transfer increases from 0.20 (GeV/c)^2 at the Δ centroid for 0.96 GeV beam energy to 0.52 (GeV/c)^2 for 1.5 GeV beam energy.

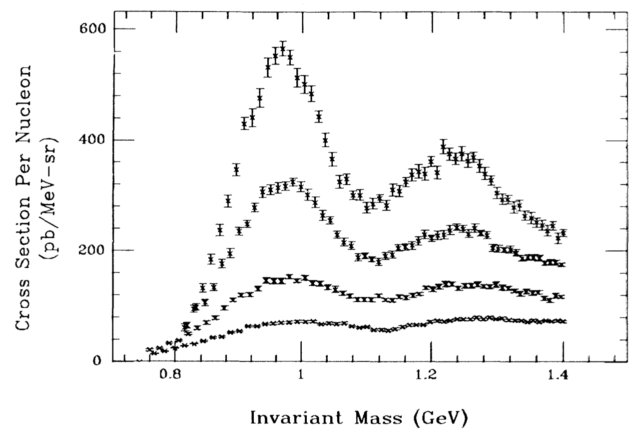

FIG. 1. Inclusive electron-scattering cross sections, with statistical uncertainties, for C as a function of invariant mass. All the data were taken at a spectrometer angle of 37.5° with beam energies, from top to bottom, of 0.96, 1.1, 1.3, and 1.5 GeV. Quasielastic scattering produces the peak centered at $W=970$ MeV and Δ excitation produces that at $W=1250$ MeV. Four-momentum transfers at the centroid of the Δ peak range from 0.20 (GeV/c)^2 for the lowest beam energy to 0.52 (GeV/c)^2 for the highest.

Figure 2 shows least-squares spline fits to cross sections divided by A for all of our targets at incident electron energies of 0.96, 1.1, and 1.3 GeV. At all three beam energies any A dependence of the cross section per nucleon for the Δ region is slight. The Δ peak for ^{4}He is consistently narrower and slightly higher than that for the other nuclei as is expected from relatively low ^{4}He Fermi momentum. In the data of O'Connell *et al.* the ^{4}He Δ peak is nearly indistinguishable from that of other nuclei, but in that work the ^{4}He cross sections were scaled upwards by 18% to "fulfill the quasifree-nucleon sum rule." O'Connell *et al.*[1,2] also reported a 34% enhancement in integrated cross section per nucleon for nuclear compared to nucleon Δ production. At higher Q^2 we find about 8% (1%) enhancement for $E_0=0.96$ (1.3) GeV when integrating the cross sections from $W=1100$ to 1400 MeV. A specifically nuclear background contribution, i.e., one not possible for the free nucleon, which decreases rapidly with increasing Q^2, perhaps scattering from quasideuterons, could account for these observations.

At low Q^2 the centroid of the Δ-region peak for excitation in light nuclei is up to 30 MeV lower in energy loss than for excitation from the free nucleon.[1,2,4] We find that except for the lowest-Q^2 tungsten data the apparent Δ centroid occurs at higher invariant mass for nuclei than for the nucleon. Figure 3 shows values of the centroid for our nuclear data as well as the results from

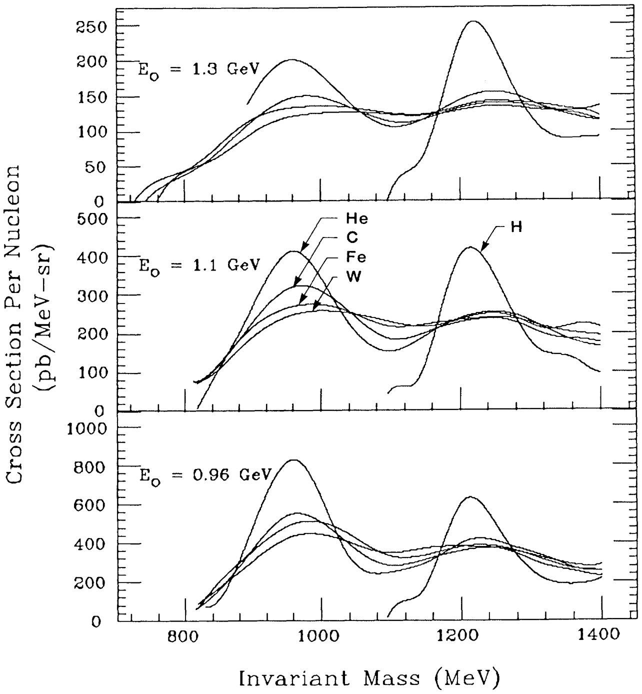

FIG. 2. Least-squares spline fits to the cross sections per nucleon for H, ^{4}He, C, Fe, and W. For H the elastic peak is not shown. At the quasielastic peak for all three beam energies the cross section per nucleon decreases as A increases as shown for the $E_0 = 1.1$-GeV data.

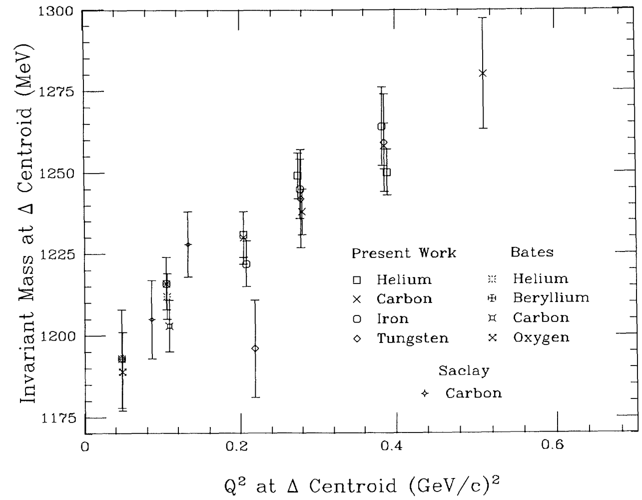

FIG. 3. Invariant mass vs Q^2 at the Δ-region peak centroid for all the present nuclear data and data for light nuclei from Refs. 2 and 4. For the nucleon the Δ centroid appears at about 1220 MeV independent of Q^2.

O'Connell *et al.* and Barreau *et al.* The position change with Q^2 noted in Ref. 4 continues in our data. Excluding the one tungsten point the peak position is, within uncertainties, independent of nuclear mass, as was found by Contardo *et al.*[7] for the (^{3}He,t) reaction. Present knowledge of competing reaction mechanisms cannot rule out the possibility that much of the observed shift is merely due to background contributions. Using simple models of broad, Gaussian peaks on sloping backgrounds we have been able to generate peak shifts of -20 to 50 MeV. The slopes of the model backgrounds were constrained by dip-region $(e,e'p)$ data[8,9] and above the Δ by a parametrization of the nonresonant contributions.[18]

Because the contributing reaction mechanisms are essentially quasifree the cross sections roughly scale with A. Any A dependence can arise in two ways—either from nuclear properties such as Fermi motion and binding energy or from neutron-proton cross-section inequality coupled with A dependence of the neutron-to-proton ratio. For scattering from correlated nucleons[8] the number of possible nucleon pairs and the high-momentum probability distribution will influence the cross section . To quantify the A dependence we have fitted the form $\sigma = cA^b$, where c and b are constants, to our measured cross sections for C, Fe, and tungsten. Values of the exponent versus W are shown in Fig. 4. The main feature for all three beam energies is a rise in b and a sign change as W increases from the quasielastic peak to the dip region. In the dip region, b is typically 1.05, which is distinctly lower than the value of 1.7 found by Dytman

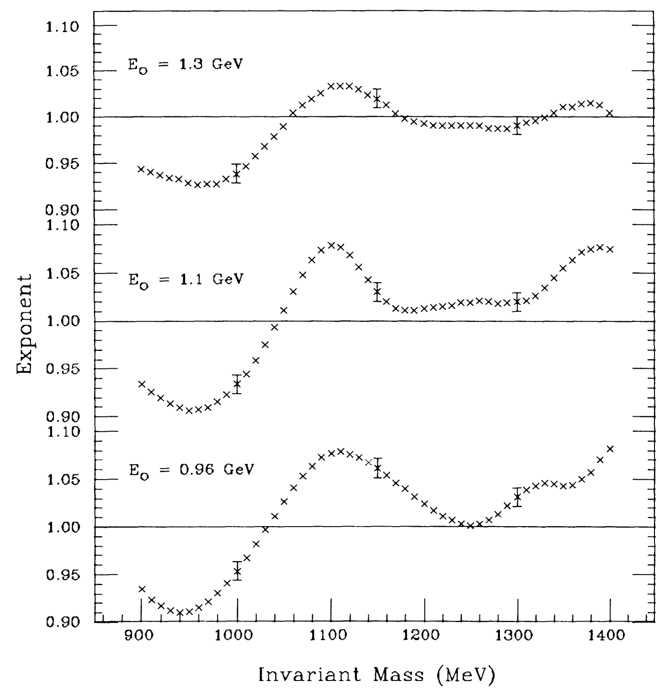

FIG. 4. Values of the exponent b vs invariant mass for a least-squares fit of the form cA^b to the cross sections. Only data from the solid targets C, Fe, and W were used. Uncertainties are approximately ± 0.01.

et al.[19] for data on ^{2}H, ^{3}He, and ^{4}He. From the dip region to the Δ region, b falls to very nearly 1.0 and then rises again above the Δ region. This W independence of b is to be expected from the effects of peak broadening by Fermi motion alone.

The measurements presented here of the Δ centroid and A dependence of the cross sections must be explained in terms of the contributing reaction mechanisms as well as properties of the Δ resonance in nuclei. For example, it is possible that the rise and fall of sloping backgrounds at high and low Q^2, respectively, as Q^2 increases are responsible for a large part of the observed shift in the Δ-region peak centroid. Such effects must be accounted for before drawing conclusions from the peak positions about the strength or velocity dependence of the Δ-nucleus potential. At the Q^2 values of the present measurements the comparison between nuclear and nucleon integrated cross sections and the dip-region A dependence suggest that a two-body reaction mechanism plays a very minor role. Further $(e,e'p)$ data in the dip and Δ regions for $Q^2=0.2$ to 0.3 $(\mathrm{GeV}/c)^2$ would be valuable. Detailed theoretical calculations are required for a complete understanding of these data, and the broad range in A and Q^2 of the present data will provide much more of a constraint than has been available.

Construction and testing of the electron detector used in this experiment was done in collaboration with physicists from Argonne National Laboratory and Northwestern University. Particularly helpful were Dr. M. Green, Dr. P. Seidel, and D. Baran. The work of Dr. Rosemary Altemus who originally proposed this experiment is gratefully acknowledged. R. Fisher was of great help with the data reduction. The advice of Dr. R. Arnold is appreciated. This work was partially supported by the U.S. Department of Energy Grants No. DE-FG05-86ER40261 and No. DE-FG05-88ER40390 and National Science Foundation Grant No. PHY-8603874.

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