Q² and A Dependence of Δ(1232) Electroexcitation in Nuclei

R.M. Sealock
Institute of Nuclear and Particle Physics
University of Virginia, Charlottesville, Virginia 22901

Abstract

Inclusive electron scattering measurements from SLAC of Δ electroexcitation in nuclei are presented. Electrons with energies of 0.96, 1.1, 1.3 and 1.5 GeV were scattered from H, ⁴He, C, Fe and W at 37.5° and detected with the End Station A 1.6 GeV/c spectrometer. Q² at the Δ peak ranged from 0.2 to 0.5 (GeV/c)². For all nuclear targets the Δ peak position shifts to higher invariant mass as Q² increases and in all but one case is above that of the free nucleon. Cross sections have been fitted by the form σ = cA^b. For the Δ region b varies from 0.99 to 1.02 with uncertainties of ± 0.01. For the dip region A dependence is observed that is consistent with the effects of Fermi broadening of the quasielastic and Δ peaks. Transverse form factors have been calculated and fitted by the function 1/(1 + Q²/Λ²). The A and invariant mass dependences of Δ are discussed.

INTRODUCTION

Electron scattering from nuclei at sufficient energy loss can be used to study excitation of baryon resonances in the nuclear environment and its effects on the production, propagation and decay of these resonances. Since Δ electroproduction from the nucleon is well understood, the Δ is the most prominent baryon resonance and isolated from its neighbors, it is the logical choice for initial studies of nuclear medium effects on resonances. Nevertheless, such studies of the Δ are complicated by competing reaction mechanisms. Cross sections in the Δ region include the high energy loss tail from the quasielastic peak, poorly understood processes in the dip region, nonresonant π production, low energy tails from production of higher lying resonances and deep inelastic scattering. Thus it is not easy to separate effects that modify the fundamental Δ production process from the effects of competing reaction mechanisms. The primary nuclear
medium modification of $\Delta$ electroexcitation cross sections is a considerable fermi broadening of the peak width. To a lesser degree, Pauli blocking and $\pi$ reabsorption change the peak width by respectively increasing and decreasing the $\Delta$ lifetime compared to the free $\Delta$ lifetime. The $\Delta$ peak centroid energy is shifted due to the attractive $\Delta$-nucleus potential. Except for fermi motion these effects are expected to be small and difficult to observe, but they all provide information about the nuclear environment and $\Delta$-nucleus interactions. One can hope to partially disentangle these effects by studying the $A$ and $Q^2$ dependences of the cross sections.

Most recently $\Delta$ electroexcitation has been studied at low $Q^2 = 0.1$ (GeV/c)$^2$ - for nuclei with atomic numbers from 4 to 16.$^{1,2}$ For this data the cross section per nucleon is independent of $A$ for the $A$ region and nearly so for the dip region. Nuclear medium effects are clearly evident in the broadening of the $\Delta$ peak, the unexplained strength in the dip region and a shift of the $A$ centroid to lower energy loss than for production from the free nucleon. Barreau et al.$^3$ observed a similar shift in $^{12}$C at $Q^2 = 0.09$ (GeV/c)$^2$ but at $Q^2 = 0.13$ (GeV/c)$^2$ the $^{12}$C and free nucleon $\Delta$ were at nearly the same energy loss. In heavier nuclei, Ca and Fe, and at slightly higher $Q^2$, 0.16 (GeV/c)$^2$, Meziani et al.$^4$ observed $\Delta$ peak positions at higher energy loss than for the free nucleon. High energy heavy ion reactions also show $\Delta$ peak shifts of up to 70 MeV toward lower energy loss.$^{5,6}$ These shifts are not directly comparable to shifts observed in $\Delta$ electroexcitation because the heavy ions probe the nuclear surface rather than the volume.

Coincidence experiments by Loe et al.$^7$ indicate that 65% of the proton knockout cross section for the $^{12}$C(e,e'p) reaction in the dip region at $Q^2 = 0.1$ (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 similar measurements by Baghaei et al.$^8$ indicate that 30% and 12%, respectively, of the cross section is due to two nucleon knockout. Such contributions in the dip region will affect the observed $\Delta$ position and width. Any successful model of the 2 nucleon component will be consistent with the $A$ and $Q^2$ dependences of the cross sections.

Theoretical calculations have most often applied the $\Delta$-hole model to low $Q^2$ data, 0.1 (GeV/c)$^2$, for light nuclei.$^9,10,11$ This model includes an average $\Delta$ binding potential, a Pauli blocking term and a spreading potential which accounts for $\pi$ reabsorption. Typically these calculations reproduce the $\Delta$ position and strength but underestimate the cross section in the dip region. Other models have included up to 40% interaction with six quark states$^{12}$ and relativistic effects.$^{13}$
Previous studies of $\Delta$ electroexcitation in nuclei have concentrated on light nuclei and low $Q^2$. The $Q^2$ range in which the $\Delta$ peak is well defined is about 0.1 to 0.5 (GeV/c$^2$). At the low end of this $Q^2$ range quasielastic scattering is more probable than $\Delta$ excitation and at the high end deep inelastic scattering and low energy tails from the production of higher energy baryon resonances are becoming dominant. Figure 1 summarizes past data and new data by plotting the $Q^2$ at the $\Delta$ centroid versus the target's atomic number, $A$. Only those data sets are included for which the statistical accuracy and energy resolution are sufficient that modifications to the $\Delta$ peak can be discerned. The new data comprise a systematic study of $\Delta$ 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.

Figure 1. $Q^2$ at the $\Delta$ centroid versus $A$ of the target nucleus for past and present data sets with good statistical accuracy and energy resolution. $\times$: past data; $0,+$: new SLAC data from 1.6 and 8 GeV/c spectrometers, respectively.
EXPERIMENT

The experiment was performed at SLAC in End Station A using the facilities of the NPAS program. 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 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 atmospheres; other targets were thin solids of natural isotopic abundance. Supplementary data, to be described elsewhere, were taken with the 8 GeV/c spectrometer for \(^4\)He and Fe.

The electron detector consisted of 3 multiwire drift chambers each with 4 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. The Cherenkov detector and shower counter provided redundant \(\pi^-\) rejection. Information from the drift chambers was used to reconstruct the electron's trajectory through the detector. The spectrometer resolution combined with beam energy spread and uncertainties in trajectory reconstruction resulted in energy resolution of 5 to 7 MeV.

All data to be discussed here were taken at a spectrometer angle of 37.5°. For each 10 MeV interval in scattered electron energy about 1000 electrons were collected, giving 3% statistical uncertainty. At each beam energy the measurements covered the quasielastic peak, the dip region and up to about 200 MeV greater energy loss than that for the \(\Delta\) centroid. In all cases the maximum energy loss was less than 70% of the beam energy. Data were collected from empty H and \(^4\)He cells in order to subtract background from the container walls. Beam heating of the H and \(^4\)He targets caused less than 0.5% change in target density.

Elastic radiative tails were subtracted from the cross sections and continuum radiative corrections were made using the formulae of Mo and Tsai\(^{15}\) and of Stein et al.\(^{16}\) The elastic radiative 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.

Self consistency and accuracy of the data set has been checked by comparing H elastic scattering and \(\Delta\) production cross sections to published values.\(^{17,18}\) Also carbon cross sections were compared to measurements made with the SLAC 8 GeV/c spectrome-
ter. In all cases there was agreement to within a few per cent. The overall systematic uncertainty of the data is dominated by the uncertainty in the acceptance function of the spectrometer. 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. Acceptance function uncertainty is not relevant when comparing results from one solid target to results from another. In this case the total relative systematic uncertainty is about 2.5%.

RESULTS

Examples of preliminary results, those from C, are shown in Fig. 2. The doubly differential cross sections have been divided by 12 so that we can compare cross sections

![Figure 2. Cross section per nucleon versus invariant mass for C(e,e')x. All data were taken at a scattering angle of 37.5°. The incident electron energies used were, from top to bottom, 0.96, 1.1, 1.3 and 1.5 GeV. The uncertainties are statistical only.](image)
per nucleon to those for other nuclei. The quasielastic and $\Delta$ peaks appear at invariant masses of about 970 and 1250 MeV, respectively. The $\Delta$ peak is broadened, primarily by fermi motion, to about 250 MeV FWHM from the 118 to 127 MeV FWHM observed in our H data. The cross sections decrease rapidly as the momentum transfer increases from $0.20 \text{(GeV/c)}^2$ at the $\Delta$ centroid for 0.96 GeV beam energy to $0.52 \text{(GeV/c)}^2$ for 1.5 GeV beam energy.

One expects the impulse approximation to be valid, that is, the electron interacts with a nucleon in a nucleus as if it were free. Thus the cross section in the $\Delta$ region should scale with $A$ because of equality of the proton and neutron $\Delta$ electroexcitation cross section\textsuperscript{19} for $W \geq 1220$ MeV. Therefore we have plotted cross sections divided by $A$ in Fig. 3 for all of our target nuclei at incident electron energies of 0.96, 1.1 and 1.3 GeV. The curves shown are from least squares spline fits to the data. Obviously any $A$ dependence of the cross section per nucleon for the $\Delta$ region is slight. Near $W = 1100$ MeV for the H data there is a shoulder due to s wave pion production which will contribute, albeit fermi smeared, to the cross section for nuclei. The $\Delta$ peak for $^4\text{He}$ is consistently narrower and slightly higher than that for the other nuclei as is expected from the relatively low $^4\text{He}$ fermi momentum. In the work of O'Connell et al.\textsuperscript{1,2} $^4\text{He} \Delta$ peak is nearly indistinguishable from that of other nuclei.

At low $Q^2$ the $\Delta$ centroids for $^4\text{He}$ and C are at 10-20 MeV lower invariant mass than for excitation from the free nucleon,\textsuperscript{1,2} Such shifts are not observed for $^3\text{H}$ and $^3\text{He}$. For all but one of our data sets the $\Delta$ centroid occurs at higher $W$ for nuclei than for the nucleon and the peak position moves to higher $W$ as $Q^2$ increases. The exception is the data for tungsten at a beam energy of 0.96 GeV, for which the $\Delta$ peak (as for the other tungsten data) is ill defined so the centroid is difficult to determine. Table I gives values of the $\Delta$ centroid for our data as well as results from O'Connell et al.\textsuperscript{1,2} and Barreau et al. The position change with $Q^2$ observed by Barreau et al. continues in our data. Calculations by Azauryan and Troshenkova\textsuperscript{21} and by Koch and Ohtsuka\textsuperscript{11} have reproduced the $\Delta$ position seen in other data for high and low $Q^2$, respectively. We are not aware of any calculation that predicts the observed $\Delta$ position over the $Q^2$ range of Table I.
The A dependence of the cross sections we have measured can be discussed in terms of three partially overlapping regions - the quasielastic, dip and A regions. These three regions have differing mixtures of reaction mechanisms each of which has its own A dependence. However, because all of these mechanisms are essentially quasifree the cross
section roughly scale with A. A dependence arises in two ways - either from a nuclear property such as fermi motion or from neutron-proton cross section inequality coupled with A dependence of the neutron to proton ratio.

Of the three regions the quasielastic is the easiest to understand because a single reaction mechanism is responsible for the cross section except where the quasielastic peak blends into the dip region. Quasifree scattering occurs on both the neutron and proton but with unequal cross sections ($\sigma_n < \sigma_p$). Thus the cross section per nucleon decreases as the neutron to proton ratio increases with A. Also the fermi momentum increases with A causing an apparent A dependence due to fermi broadening. A very slight A dependence is due to A dependence of the average binding energy per nucleon which shifts the quasielastic peak to greater invariant mass.

Since the proton and neutron $\Delta$ production cross sections are equal for most of the $\Delta$ region,\textsuperscript{19} one expects the $\Delta$ production component of the $\Delta$ region cross section to scale with A. However, one also expects the $\Delta$ peak to broaden and be reduced in height as the fermi momentum increases with A. As with quasieelastic scattering, the $\Delta$ peak is shifted to greater W by the A dependent $\Delta$ - nucleus binding energy.

Cross sections in the dip region are the sum of high and low energy loss tails of the quasielastic and $\Delta$ peaks, respectively, and cross section due to one or more reaction mechanisms which have not been conclusively identified. A dependence in the dip region should show a transition from that of the quasielastic peak to that of the $\Delta$. A

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**TABLE I**

Invariant Mass of the $\Delta$ Centroid

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<th>$Q^2$ at $\Delta$ (GeV/c)$^2$</th>
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<th>C</th>
<th>Fe</th>
<th>W</th>
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<td></td>
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</tr>
</tbody>
</table>

* Values from ref. 2)

+ Values from ref. 3)
small correction to the $A$ dependence is caused by the fact that in the low $W$ tail of the $\Delta$ peak the neutron cross section is less than that of the proton (80% at $W = 1160$ MeV).\(^{19}\) Scattering from correlated nucleons may account for the unexplained strength in the dip region,\(^{7}\) in which case the number of possible nucleon pairs and the high momentum probability distribution will influence the cross section.

Cross sections can be expressed as a function of $A$ by $\sigma = cA^b$ where $b$ and $c$ are constants to be determined. We have fitted this function to the C, Fe and W data shown in Fig. 3 and values of the exponent, for beam energies of 0.96, 1.1, and 1.3 GeV 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. From the dip region

![Invariant Mass (MeV)](image-url)
to the $\Delta$ region $b$ falls to very nearly 1.0 and then rises again above the $\Delta$ region. This $W$ dependence of $b$ is roughly what is expected from the effects of fermi broadening alone but a complete understanding of the values of $b$ will require calculations.

The $Q^2$ dependence of the cross sections can be quantified through a form factor which is derived as follows. The doubly differential cross section can be expressed as a sum of transverse, $\sigma_T$, and longitudinal, $\sigma_L$, cross sections by the expression

$$\frac{d^2\sigma}{d\Omega dE} = \Gamma_T(\sigma_T + \epsilon \sigma_L)$$

where

$$\Gamma_T = \frac{\alpha(W^2 - M^2)E'}{2\pi^2 2MQ^2 E (1-\epsilon)}$$

and

$$\epsilon = \left[ 1 + 2\left( 1 + \frac{\omega^2}{Q^2}\tan^2(\theta/2) \right) \right]^{-1}.$$  

$\Gamma_T$ is the flux of virtual transverse photons, $\omega$ is the energy loss, $\alpha$ is the fine structure constant and $\epsilon$ is the ratio of longitudinal to transverse virtual photon fluxes. Measured values of $\sigma_L$ for $\Delta$ production from the free proton at these momentum transfers are consistent with zero$^{18}$ and at $Q^2 = 0.1$ (GeV/c)$^2$ $\sigma_L = 0$ for $\Delta$ production in nuclei.$^{22}$ Therefore we will assume that the longitudinal contribution to our cross sections is zero and that $\sigma_T$ is proportional to our measured cross sections. We can then define a transverse form factor $F_T$ by

$$F_T^2 = \frac{(\omega - Q^2/2M)\sigma_T}{2\pi^2 \alpha}.$$  

Figure 5 shows the transverse form factor squared versus $Q^2$ for carbon at $W = 1100$, 1230 and 1350 MeV. Since we do not have sufficient data to fit $F_T$ by the complicated expressions that might result from considering several contributing reaction mechanisms, we have chosen to quantify the $Q^2$ dependence by means of the simple form $1/(1+Q^2/A^2)$. The solid curves of Fig. 5 result from fitting the data by this form. In Fig. 5 one can see that for $W = 1100$ and 1350 MeV $F_T^2$ decreases less rapidly with increasing $Q^2$ than $F_T^2$ at $W = 1230$. A less rapid decrease of $F_T$ with increasing $Q^2$ corresponds to a larger value of $A$.

We have explored the $W$ dependence of $A$ by fitting $F_T$ at 10 MeV intervals of $W$. Results are plotted in Fig. 6 for all of our nuclear targets. For $^4$He, C and Fe, we find that $A = 0.71 \pm 0.01$ at $W = 1230$ MeV. For tungsten $A$ is slightly lower at 0.68. Since the various contributing reaction mechanisms have different form factors, values of $A$ for the function we have used do not have a direct interpretation. The general shape of the
Figure 5. Values of the transition form factor squared versus $Q^2$ for carbon at invariant mass values of 1100, 1230 and 1350 MeV. The solid curves are results of fitting the form $1/(1+Q^2/A^2)$ to the data.

$\Lambda$ versus $W$ curves is to be expected from the effects of fermi motion and kinematic broadening of the $\Delta$ peaks as $Q^2$ increases. These increase the cross section, and thereby the form factor, in the wings of the $\Delta$ as $\Lambda$ and $Q^2$ increase, leading to greater $\Lambda$.

CONCLUSION

The precise measurements presented here of the $\Delta$ centroid, $\Lambda$ dependence and $Q^2$ dependence of the cross sections must be explained in terms of the various reaction mechanisms that contribute as well as in terms of properties of the $\Delta$ resonance in nuclei. For example, it is possible that a strong two body contribution in the dip region is shifting the observed $\Delta$ peak position to lower $W$ and that this component decreases rapidly as $Q^2$ increases. Additional $(e,e'p)$ measurements in the dip and $\Delta$ regions at $Q^2$ of about 0.2-0.5 (GeV/c)$^2$ and for $\Lambda = 12$ and above would help to define the role, if any, of a two body component in the observed position of the $\Delta$. Ultimately, exclusive electropro-
duction cross sections will allow the complete separation of various processes. Until new
accelerators currently under construction are operating, the broad range in $Q^2$ and $A$ of
the present data will provide much more constraint on theoretical models than had been
available. It will be even more difficult to study nuclear effects on higher energy nuc-
leon resonances given their natural widths, separations from one another and the unavoi-
dable fermi motion in the nuclear environment. An exception to this picture is the $S_{11}$
resonance which can be uniquely identified by its $\eta$ decay channel.

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