Observation of Analogs of the Giant-Dipole Resonance in Pion Single Charge Exchange on ^{40}Ca

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The pion single-charge-exchange reactions ^{40}Ca($\pi^{\pm}$, π^0) were measured at 164 MeV in the angular range 0° to 30°. The spectra show pronounced peaks at energies corresponding to the analog states of the isovector electric dipole resonance in ^{40}Ca. The maximum (π^-, π^0) cross section is 1.69 ± 0.24 times the (π^+, π^0) cross section. The measured angular distribution shapes and magnitudes are quite well described by distorted-wave impulse-approximation calculations based on the Goldhaber-Teller transition density.

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The giant-dipole resonance (GDR) is the fundamental mode of absorption of electric dipole radiation by the nucleus. For ^{40}Ca, it appears as a well formed peak[1] in the photon absorption spectrum at an excitation energy of 20 MeV and has a width of approximately 4.5 MeV [full width at half maximum (FWHM)]. It has a cross section of 750 mb MeV integrated between excitation energies of 10 and 35 MeV, which is 1.25 times the Thomas-Reiche-Kuhn sum-rule limit[1] of $60NZ/A$ mb MeV. In this Letter, we report the first observation of a GDR state in pion charge-exchange scattering.

In self-conjugate nuclei the GDR has the single isospin value $T = 1$, with isospin projections $M_T \equiv (N - Z)/2 = +1, 0, -1$. A consequence of isospin invariance is that the differential cross sections for exciting $T = 1$ states in pion scattering are independent of M_T. Performing the measurements in the charge-exchange channels has several advantages. First, the measurements near 0° are not difficult because the beam does not go into the detectors. Therefore, one can measure the GDR differential cross sections over the full angular range of the first diffraction peak. Second, one can study the GDR analogs in two nuclei, by using the equally accessible ($\pi^{\pm}$, π^0) reactions. The two measurements aid in determination of the shape of the continuum under the GDR peaks. They also provide data on the M_T dependence of the GDR widths and cross sections. Third, the charge-exchange scattering is not obscured by $\Delta T = 0$ transitions as is inelastic scattering. Specifically, the isoscalar monopole and quadrupole resonances are close in excitation energy to the GDR, and make the study of the GDR difficult[2] in inelastic scattering. Fourth, resonant pion scattering angular distributions are diffractive and hence the shapes are characteristic of the orbital angular momentum transfer.

This experiment was performed with the π^0 spectrometer mounted in the low-energy-pion (LEP) channel at the Clinton P. Anderson Meson Physics Facility (LAMPF). The spectrometer[3] was in its two-post configuration (vertical scattering plane), with a target-to-first-converter distance of 100 cm and an opening-angle setting of 61.26°. The Ca target consisted of a hot-rolled plate of natural Ca having dimensions $10 \times 10 \times 1.59$ cm^3 and area density of 2.28 g/cm^2.

The data sample consists of four runs, ^{40}Ca(π^+, π^0) at 0° and 20° and ^{40}Ca(π^-, π^0) at 0° and 20°, at an incident pion energy of 164 MeV. Each of these runs took approximately 8 h. Pion fluxes were approximately 10^7 s^{-1}. The absolute flux determinations were made with the scintillator activation technique.[4] Several analyses of the data were performed by using different cuts on the energy balance parameter $X=(E_1-E_2)(E_1+E_2)^{-1}$. The analysis presented here was performed with $|X|\leq 0.1$, which gave the best π^0 energy resolution. The selected events were binned into six histograms according to π^0 scattering angle, θ. The solid angle for each θ bin was determined with use of CH_2 data and $\pi^- p\to\pi^0 n$ cross sections.[5] The relative acceptance as a function of π^0 energy and the mean acceptance angle for each θ bin were calculated by Monte Carlo simulation.

The π^0 kinetic energy spectra for the six θ bins are presented in Figs. 1 and 2. These are the acceptance-corrected and normalized spectra presented in terms of the double differential cross sections $d^2\sigma/d\Omega\, dT$ in μb/sr MeV. The expected π^0 energies for the GDR analogs are 155.2 MeV for the (π^+,π^0) reaction and 143.2 MeV for the (π^-,π^0) reaction. The peak locations in the spectra are displaced downward from the kinematic values by 1 MeV as a result of the finite extent of the target and beam spot. The π^0 kinetic energies for the two states of an isospin triplet produced by the $^{40}Ca(\pi^{\pm},\pi^0)$ reactions are related by

$$\Delta T_{\rm analogs}\simeq\Delta Q=\Delta E_c(^{40}K)+\Delta E_c(^{40}Ca)-2\Delta_{np},$$

where $\Delta E_c(^{40}K)=7.13$ MeV and $\Delta E_c(^{40}Ca)=7.45$ MeV are the Coulomb displacement energies[6] and $\Delta_{np}=1.293$ MeV is the neutron-proton mass difference. This gives $\Delta T=12.0$ MeV for the expected shift in the GDR states. The measured displacement in the 15.1° spectra is 12.1 ± 0.4 MeV, where the error represents the statistical uncertainty. The observed peak positions and the displacement of the two peaks identify them as the GDR analogs.

Inspection of the $^{40}Ca(\pi^+,\pi^0)$ data (Fig. 1) shows that the structure of the continuum between 100 and 135 MeV remains quite constant for angles $\lesssim 22°$. The solid line shown with each spectrum is the measured 4.5° spectrum, which was smoothed with a Gaussian. In view of the constancy of the spectral shape in the regions adjacent to the GDR peak, we extracted the GDR peak areas by performing a channel-by-channel subtraction of the measured 4.5° spectrum from

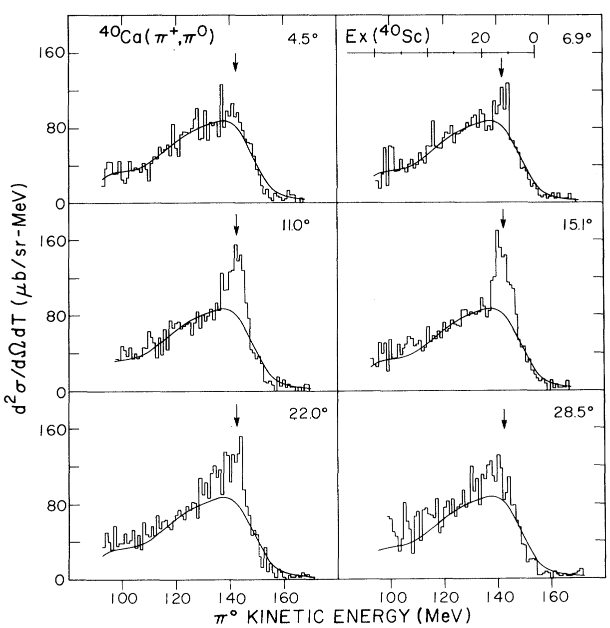

FIG. 1. The measured π^0 spectra for the reaction $^{40}Ca(\pi^+,\pi^0)$ at 164 MeV. The arrow marks the expected position of the analog of the giant-dipole resonance at 20-MeV excitation in ^{40}Ca. The solid line is the smoothed 4.5° spectrum shown in each panel to allow comparison of the spectra.

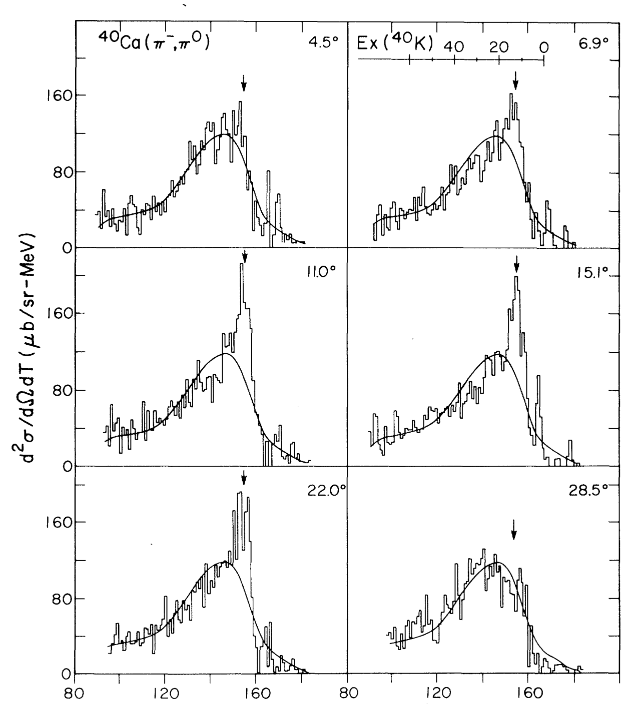

FIG. 2. Same as Fig. 1 except for the reaction $^{40}Ca(\pi^-,\pi^0)$.

each of the other spectra. The net counts in a 12-MeV interval centered on the expected position of the GDR were taken for the determination of the difference cross sections $d\sigma/d\Omega(\theta) - d\sigma/d\Omega(4.5°)$. This procedure applied to both $^{40}Ca(\pi^\pm, \pi^0)$ reactions gives the cross sections shown in Fig. 3. The shape of these cross sections is similar for π^+ and π^- and indicates an angular momentum transfer $L = 1$.

The difference spectra were analyzed for the GDR peak widths and centroids. For the three angles 11.0°, 15.1°, and 22.0° the peak centroids were constant to ±1 MeV. The widths appear to be angle dependent, with a minimum width observed at 15.1°. The fits to the data at this angle with a Gaussian function gave (FWHM) 6.6 ± 0.7 MeV for the (π^+, π^0) spectrum and 6.1 ± 0.5 MeV for the (π^-, π^0) spectrum. These values are larger than the (5.0 ± 0.2)-MeV instrumental resolution and yield widths of 4.3 ± 1.0 MeV in ^{40}Sc and 3.5 ± 0.8 MeV in ^{40}K, consistent with the width of the photonuclear GDR in ^{40}Ca.

There is the suggestion in the $^{40}Ca(\pi^-, \pi^0)$ data (Fig. 2) that the continuum in the interval 122–142 MeV is not as constant at forward scattering angles as it is in the (π^+, π^0) reaction. The statistical significance of this difference was evaluated and analyzed for possible evidence of excitation of a broad forward-peaked state. These results will be discussed in a forthcoming article.

To see if the measured cross sections are consistent with previous knowledge of the GDR, distorted-wave impulse-approximation (DWIA) calculations[7] were performed with the Goldhaber-Teller[8] form of the transition density:

$$\rho_1 = \hbar c(8\pi NZ)^{1/2}(3A^3\hbar\omega m_p c^2)^{-1/2}\rho_0' Y_{1m}(\theta, \varphi).$$

This is normalized to exhaust the classical $E1$ sum rule,[1,9] where $\hbar\omega$ is the excitation energy, ρ_0' is the derivative of the nuclear density $\rho_0 = \rho_n + \rho_p$, Y_{1m} is the spherical harmonic of order 1, A is the atomic number, and m_p is the proton mass. A two-parameter Fermi function was assumed for ρ_0, with half-density $c = 3.51$ fm and diffuseness $a = 0.52$ fm, as derived from electron scattering[10] and corrected for the finite size of the proton. The DWIA calculations normalized to the data in the interval 11° to 22° are shown in Fig. 3. The shapes of the angular distributions are well described. The theoretical curves were multiplied by 0.78 for the (π^+, π^0) reaction and 1.15 for the (π^-, π^0) reaction. The extracted maximum cross sections are 0.51 ± 0.05 mb/sr for π^+ and 0.87 ± 0.09 mb/sr for π^-. The ratio of calculated π^- to π^+ maximum cross sections is 1.16, which is smaller than the observed ratio of 1.69 ± 0.24.

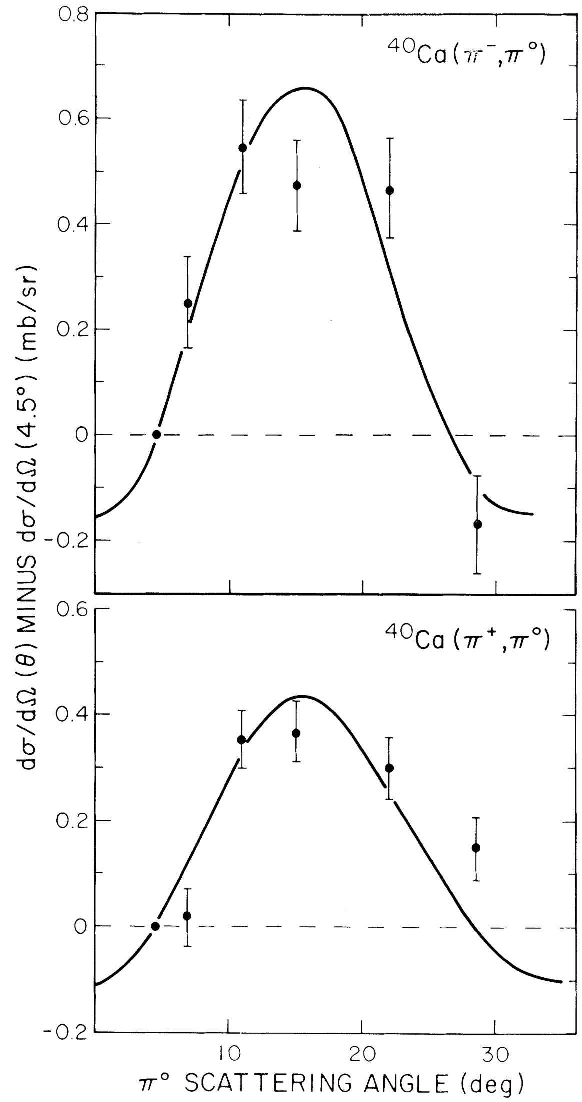

FIG. 3. The measured cross-section differences, $d\sigma/d\Omega(\theta)$ minus $d\sigma/d\Omega(4.5°)$, are compared with DWIA calculations for $\Delta L = 1$, $\Delta S = 0$ transitions. The error bars reflect the statistical error associated with the analysis which assumed that the background underneath the GDR is given by the measured 4.5° spectrum.

From the DWIA calculations, one sees that the observed GDR cross sections exhaust nearly the full energy-weighted sum rule. This closely parallels the $E1$ transition strength[1] to the GDR in ^{40}Ca, which also exhausts the sum-rule value. We performed additional DWIA calculations with a transition density consisting of a single harmonic-oscillator particle-hole configuration ($1f_{7/2}$-

$1d_{5/2}^{-1}$) coupled to $J^{\pi}=1^{-}$. This component is thought to be the largest in the GDR wave function[11] for ^{40}Ca. The calculated maximum cross section for this configuration for the (π^{-}, π^{0}) reaction was 0.33 mb/sr, which is lower by a factor of 0.4 than that given by the collective model calculation. Thus a collectivity of approximately 2.5 "single-particle units" is indicated for the GDR. The electric dipole transition strength in the decay of the ^{40}Ca GDR was found[12] to be 3.5 Weisskopf units. Thus the degree of collectivity in terms of single-particle estimates is also quite similar for both processes.

A secondary feature of the data is the angle-dependent broadening of the GDR peak which is particularly noticeable in the 22° and 28.5° spectra of Fig. 1. To the extent that the background in this region is given by quasifree scattering, with the prompt emission of a nucleon, this angle-dependent broadening cannot be due to a coherent interference between quasifree and GDR transition amplitudes. It is more likely that the data are indicating the excitation of states near 25 MeV in ^{40}Ca. The angular distribution for these states appears to have a minimum near 15° and to rise at the larger angles. An intriguing possibility, consistent with the data, is that this excess cross section is due to transitions with $\Delta L=1$, $\Delta S=1$ (spin-flip) producing 1^{-} or 2^{-} states. Such states, with predominant particle-hole configurations ($1f_{5/2}1d_{5/2}^{-1}$) are expected[11] at several megaelectronvolts above the GDR. Our DWIA calculations as well as eikonal model calculations[13] with collective form factors indicate that such 2^{-} states have angular distributions with the first peak near 30°. The 1^{-}, $\Delta S=1$ states have a maximum at 0°. Further studies of this feature are of interest.

In conclusion, we have reported here the first observation and angular distribution measurements of the GDR in pion single-charge-exchange scattering. The excellent signal-to-background conditions seen in these data make a program of study of the T_0+1 component of the GDR in $N>Z$ nuclei by use of the (π^{-}, π^{0}) reaction appear quite promising. DWIA calculations with the Goldhaber-Teller transition density give a quantitative description of the measured cross sections. This result serves as a benchmark for analyzing pion excitation of other isovector giant resonances. The (π^{-}, π^{0}) maximum cross section is 1.69 ± 0.24 times larger than the (π^{+}, π^{0}) maximum cross section in violation of isospin symmetry. Study of the role of Coulomb force effects on the transition density would seem to be warranted.

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