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Analog of the $T_>$ giant dipole resonance in light nuclei

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Giant resonances were observed in (π^+, π^-) double charge exchange on ^{13}C, ^{27}Al, and ^{59}Co at excitation energies of 8.8, 14.2, and 27.9 MeV, respectively, where the giant dipoles built on the isobaric analog states are expected to appear. Partial angular distributions were measured for both ^{13}C and ^{27}Al and observed to have a dipole shape. The resonance on the $T = \frac{1}{2}$ targets has a single isospin value ($T = \frac{3}{2}$) and is the analog of the $T_>$ giant dipole state in the above nuclei. The results are in good agreement with photonuclear reactions and indicate a new general method for an accurate determination of the $T_> = T + 1$ giant dipole state in $T = \frac{1}{2}$ nuclei.

Several experiments have been carried out at the Los Alamos Meson Physics Facility (LAMPF) to search for double giant resonances. The difficulties in observing double resonances arise from the high background encountered from the continuum in the nucleus at high excitation energy and from the large width of the double resonances arising from their decay and spreading widths. In a recent work[1] we reported the first observation of giant dipole resonances (GDR) built on the isobaric analog states (IAS) in (π^+, π^-) double charge exchange (DCX). The main features of this resonance as observed in pion DCX have been outlined in a subsequent study.[2] For nuclei with $T \geq \frac{3}{2}$ the giant dipole built on the isobaric analog state (GDR⊗IAS) splits into three components with isospin $T-1$, T, and $T+1$ arising from the isovector character of the electric dipole operator. A surprising feature was observed for the width of the resonance. It was found that the width of the lowest component of the GDR⊗IAS increases approximately linearly with A. For $T = \frac{1}{2}$ nuclei, only the upper member ($T = \frac{3}{2}$) is allowed from isospin arguments, and therefore the GDR⊗IAS provides an accurate tool to determine the $T_>$ component of the GDR in the target nucleus.

The measurements were performed at the Energetic Pion Channel and Spectrometer (EPICS) at LAMPF with use of the pion DCX setup.[3] We used a ^{13}C target enriched to 90%, 0.329 g/cm^2 in areal density, and monoisotopic ^{27}Al and ^{59}Co targets of thickness 1.096 and 1.079 g/cm^2, respectively. Measurements were taken at three angles on ^{13}C and ^{27}Al and at two angles on ^{59}Co. The momentum acceptance of the spectrometer was measured by pion scattering from ^{12}C. Absolute normalizations were obtained by measuring π-p scattering from a polyethylene (CH_2) target of areal density 25.7 mg/cm^2 and comparing the yields with cross sections calculated from a phase-shift analysis.[4]

Figure 1 shows the missing-mass spectra obtained from the DCX reaction on ^{13}C, ^{27}Al, and ^{59}Co. All three spectra show the existence of a wide resonance located in the continuum region at about 8.8 and 14.2 MeV above the ground states of ^{13}O and ^{27}P, respectively, and at about 16.8 MeV above the DIAS in ^{59}Cu (i.e., 27.9 MeV above the ground state of ^{59}Cu). The resonances are labeled GDR⊗IAS in the figure. The ground state and/or the

DIAS were fitted with a Gaussian, and the resonances with a Lorentzian shape of variable widths. The background (dashed lines), which arises from DCX to the continuum, was fitted using a third-order polynomial shape. Using fourth- or higher-order polynomial shapes for the background gives a comparable fit and does not appreciably affect the extracted cross sections for the resonances. The figure shows clearly that the width of the resonance increases significantly with mass. For example, the resonance on ^{59}Co is more than twice as wide as that on ^{13}C. The broadening may arise partly from the increase in Coulomb energy with mass as well as from isospin splitting, discussed later.

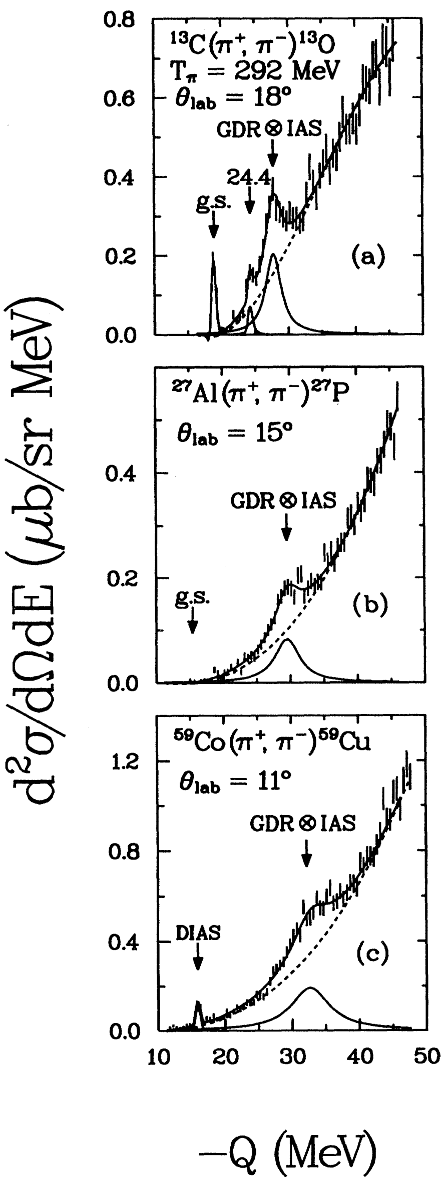

FIG. 1. Doubly differential cross-section spectra for (π^+, π^-) reactions at $T_\pi = 292$ MeV on (a) ^{13}C at $\theta_{\rm lab} = 18°$, (b) ^{27}Al at $\theta_{\rm lab} = 15°$, and (c) ^{59}Co at $\theta_{\rm lab} = 11°$. The arrows indicate the fitted location of the ground state, the DIAS, and the giant resonance (GDR⊗IAS). Short vertical lines represent statistical uncertainties of the data.

A suppression of the cross section for the GDR built on the IAS on the $T = \frac{1}{2}$ nuclei (by a factor of 2–3) is expected due to isospin considerations. Since pion DCX is a probe causing T_z to change by two units, the resonance has a single isospin $T_> = \frac{3}{2}$ and can be reached only through the IAS and the $T_>$ component of the GDR (see Fig. 2). Therefore the coupling through the GDR has only $\frac{1}{3}$ of its normal strength. For a heavier nucleus with $T \geq 1$ (i.e., ^{59}Co) the GDR⊗IAS will arise by coupling through both the IAS and the full GDR intermediate states. We note, however, that for $T = \frac{1}{2}$ nuclei the GDR⊗IAS may gain some extra strength through the IAS coupling since in these cases the IAS is also the ground state of the intermediate nuclei.

Table I summarizes the deduced energies, widths, and cross sections for the giant resonances extracted with a line-shape fitting code that uses the CERN MINUIT optimization package[5]. The listed values are for fitting the GR peaks as a whole with a single Lorentzian peak. The energies and widths were varied simultaneously to minimize χ^2 for the entire fit. The table also lists the predicted cross sections for the GDR⊗IAS in a simple sequential-model calculation, using the pion coupled-channels impulse-approximation (CCIA) code[6] NEWCHOP. The coupled-channel calculations include the ground state, the IAS, the GDR, and the GDR⊗IAS (see Fig. 2). The strength of each SCX transition has been adjusted to reproduce the measured (or extrapolated) SCX cross section to the GDR[7] and the IAS.[8] Two different transition densities have been used for the IAS: one surface-peaked (model I) and the other volume transition density (model II). For ^{13}C and ^{27}Al the calculations in-

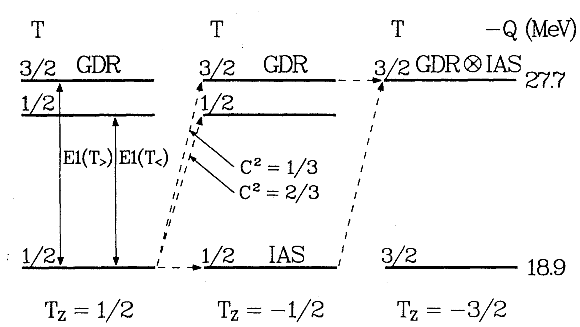

FIG. 2. Schematic energy-level diagram of isospin fragments of dipole and analog-dipole states observed in single and double charge exchange on $T = \frac{1}{2}$ nuclei compared with $E1$ from photonuclear reactions. The figure shows the $T = \frac{3}{2}$ multiplet of the giant dipole in the $T_z = \frac{1}{2}, -\frac{1}{2}, -\frac{3}{2}$ nuclei, and illustrates the absence of the $T_<$ GDR⊗IAS state, which is forbidden from isospin considerations. The listed Q values refer to the case of DCX on ^{13}C.

TABLE I. Results from the double-charge-exchange reaction on ^{13}C, ^{27}Al, and ^{59}Co at T_π = 292 MeV, compared with theoretical CCIA calculations.

Target	Q(g.s./DIAS)[a] (MeV)	Q(GR) (MeV)	Γ(GR) (MeV)	$\theta_{\rm lab}$ (deg)	$d\sigma/d\Omega$ (GR) Expt (μb/sr)	Theory[b] (μb/sr)	Theory[c] (μb/sr)
^{13}C	-18.9 ± 0.1	-27.7 ± 0.5	3.0 ± 0.6	18	0.98 ± 0.09	0.83	0.82
^{27}Al	-15.4 ± 0.1	-29.6 ± 0.5	4.4 ± 0.9	15	0.59 ± 0.06	0.41	0.48
^{59}Co[d]	-15.9 ± 0.1	-32.7 ± 0.4	7.0 ± 1.0	11	2.11 ± 0.17	1.08	1.68

[a]Ground-state Q value for ^{13}C(π^+, π^-) ^{13}O and ^{27}Al(π^+, π^-)^{27}P. DIAS Q value for ^{59}Co(π^+, π^-)^{59}Cu.
[b]Model I: Calculated cross sections for the GDR built on the IAS using NEWCHOP and surface transition density for the IAS.
[c]Model II: Same as (c) except for the use of volume transition density for the IAS.
[d]Fitting the GR on ^{59}Co with two peaks gives the values listed in Table III.

clude the isospin factor for $T = \frac{1}{2}$ nuclei shown in Fig. 2. The calculations using both models reproduce the measured cross sections for all three targets reasonably well without any normalization factor. Further details on these calculations can be found in Ref. 2.

Tables II and III give a comparison between the GDR energies derived from DCX and the corresponding $E1$ energies measured or extrapolated from photonuclear reactions. Since pion DCX involves a transfer of two units of charge, one can extract the $E1$ energies just from the measured Q values of the resonance by subtracting two Coulomb displacement energies minus the neutron-proton mass difference. Table II shows that the $E1$ deduced from DCX using the above method is in excellent agreement with the $T_> = \frac{3}{2}$ GDR state reported[9] in the ^{13}C(γ,p) reaction. In ^{27}Al the $T_>$ GDR is not well assigned. Our measurements give $E1(T_>)$ = 21.0 MeV in agreement with the highest member (at 21.4 MeV) of the structure observed in the GDR region in the ^{27}Al(γ, n) reaction.[10] Agreement with photonuclear results is also obtained [illegible] ^{59}Co. In the case of ^{59}Co, where the GDR⊗IAS resonance can be fitted also with two peaks (Table III) and the DIAS transition exists, we can calculate $E1$(DCX) also from the energy difference of the two components of the GR with respect to the DIAS, after correcting for the symmetry energy. The calculations using this method are given in Table III. Both methods give comparable results for ^{59}Co that are in good agreement with $E1$ deduced from photonuclear reactions[12,13].

Figure 3 presents the partial angular distributions extracted for the resonances in ^{13}C, ^{27}Al, and ^{59}Co. The maximum cross section is observed at 18° for ^{13}C, 15° for ^{27}Al, and 11° for ^{59}Co. The solid and dashed lines are the sequential model calculations using volume and surface peaked transition densities for the IAS, respectively. The calculated cross sections using both models reproduce the dipole shape of the data. This is an expected result for coupling an isobaric analog transition (which peaks at 0°) with a dipole transition which peaks at this energy around 18° for ^{13}C, 15° for ^{27}Al, and 11° for ^{59}Co. The calculations for all three targets account also surprisingly well for the measured cross sections. The results are shown in Fig. 3 without any normalization factor.

The giant dipole in non-self-conjugate nuclei has two isospin components $T_< = T$ and $T_> = T + 1$, where T is the isospin of the target nucleus (Fig. 2). The energy splitting, $\Delta E = E_> - E_<$, is given approximately by $\Delta E = U\,(T+1)/A$, where U is the symmetry energy.[14] For example, if we use U = 50 MeV then ΔE = 5.8 and 2.8 MeV for ^{13}C and ^{27}Al, respectively. Generally, it is difficult to measure the energy centroids of the two isospin components of the GDR, since the resonances are wide and fragmented (especially in light nuclei). Additional difficulties occur in deformed nuclei, where deformation splitting of the GDR may obscure the $T_>$ assignment of the observed structure. Furthermore, the presence of the giant quadrupole in this energy region adds to the complexity of the assignments. A widely used method to determine $T_>$ and $T_<$ is to measure both

TABLE II. Giant dipole energies derived from the present study compared with $E1$ from photonuclear reactions.

Target	Q(GR) (MeV)	$\overline{\Delta E_C}$[a] (MeV)	$E1$(DCX)[b] (MeV)	$E1$(DCX) $A^{1/3}$ (MeV)	$E1$(DCX) $A^{1/6}$ (MeV)	$E1$(photo) (MeV)
^{13}C	-27.7 ± 0.5	3.16	24.0 ± 0.5	56.4 ± 1.2	36.8 ± 0.8	23.8[c]
^{27}Al	-29.6 ± 0.5	5.59	21.0 ± 0.5	62.7 ± 1.5	36.2 ± 0.9	21.4[d]
^{59}Co	-32.7 ± 0.4	9.23	16.8 ± 0.4	65.4 ± 1.6	33.2 ± 0.8	17.2[e]

[a]Averaged Coulomb displacement energies.
[b]$E1(\mathrm{DCX}) = |Q(\mathrm{GR})| - (\Delta E_{C_1} - \delta) - (\Delta E_{C_2} - \delta)$, where $\delta = m_n - m_p = 1.29$ MeV.
[c]Centroid energy of the $T_>$ giant dipole state on ^{13}C (Ref. 9).
[d]Higher-energy component of the GDR on ^{27}Al (Ref. 10).
[e]$E1$ on ^{65}Cu (Ref. 14) scaled by $A^{1/3}$. See also Ref. 13.

TABLE III. Giant dipole energies derived from DCX on ^{59}Co compared with the results from photonuclear reactions.

Target	T(GR)	Q(GR) (MeV)	Γ(GR) (MeV)	$E1$(DCX)	$E1$(DCX) $A^{1/3}$ (MeV)	$E1$(DCX) $A^{1/6}$ (MeV)	$E1$(photo) (MeV)
^{59}Co	$T_<$	-30.9 ± 0.5	3.7 ± 0.9	17.2 ± 0.6[a]	67.0 ± 2.3	33.9 ± 1.2	17.2
^{59}Co	$T_>$	-34.3 ± 0.6	5.0 ± 1.6	18.4 ± 0.6[b]	71.6 ± 2.3	36.3 ± 1.2	17.2

[a]Calculated using $E1(\text{DCX}) = Q(\text{DIAS}) - Q_{T_<}(\text{GR}) + \Delta E^-$, where $\Delta E^- = 2.2$ MeV (Ref. 11) is the symmetry energy.
[b]Calculated using $E1(\text{DCX}) = Q(\text{DIAS}) - Q_{T_>}(\text{GR})$.

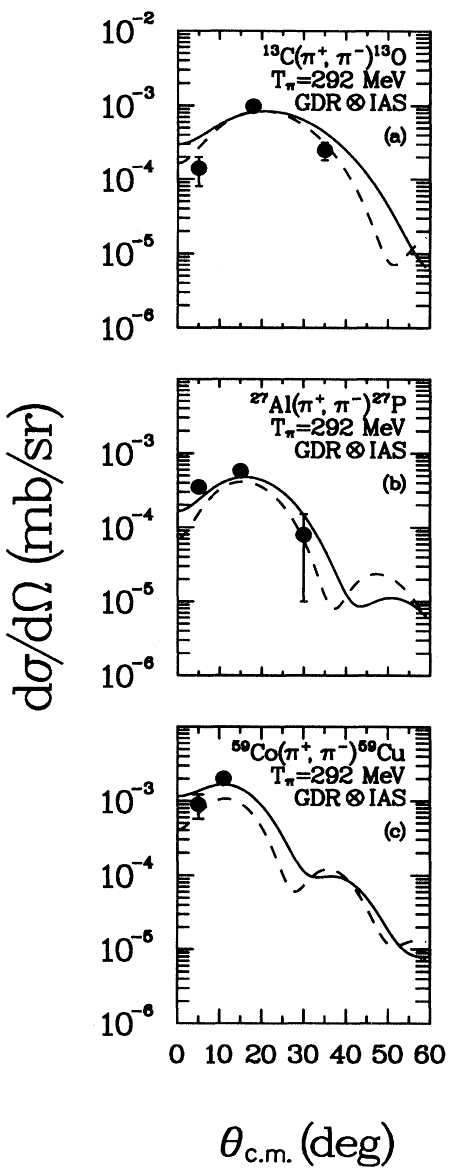

FIG. 3. Partial angular distributions for the peaks labeled GDR⊗IAS in the double-charge-exchange spectra on ^{13}C, ^{27}Al, and ^{59}Co shown in Fig. 1. The solid and chain-dashed lines are sequential model calculations with volume and surface transition densities, respectively, without any normalization factor (see text).

photoneutron and photoproton reactions.[9,14] If isospin is conserved, both members can decay via proton emission, but in the absence of mixing the neutron decay from the $T_>$ state to the low-lying $T - \frac{1}{2}$ states in the residual nucleus is forbidden. Therefore a comparison of the two reactions helps in measuring the position of $T_>$. The present work shows that for $T = \frac{1}{2}$ nuclei, pion DCX may provide a new powerful tool in determining the upper-isospin component of the GDR by measuring its analog state in the $T_z = T - 2$ nucleus.

In Ref. 2 we derived a semiempirical relation, Eq. (8), which gives the peak cross section for the GDR⊗IAS as a function of N, Z, and A. If we include the new data points then a new relation could be derived for the cross section of the GDR⊗IAS for the whole region $13 \leq A \leq 208$. We find that the data are well represented by $(d\sigma/d\Omega)_{\text{GDR}\otimes\text{IAS}}(\text{peak}) = 24(N - Z)\,N\,Z/A^{2.71}$ μb/sr. This cross section can be factored in terms of the two ingredient resonances—the IAS and the GDR. It is likely that the $(N - Z)$ factor arises from the IAS transition, which occurs only on valence neutrons. The NZ factor arises from the GDR form factor, and the $A^{-2.71} = A^{-2.04}A^{-2/3}$ factor represents the overall A-dependent pion attenuation factor for DCX. This result is quite reasonable. It implies that pion attenuation in DCX is about double the pion attenuation factor measured in SCX for the GDR[7] or the IAS,[8] as would be expected from the simplest sequential mechanism for DCX.

In conclusion, we have reported the observation of giant dipole resonances built on the isobaric analog states (or vice versa) in pion double-charge-exchange reactions on ^{13}C, ^{27}Al, and ^{59}Co. The width of the resonance increases significantly with A and does not follow the corresponding width of the "regular" giant dipole built on the ground state. The $E1$ energies derived from DCX are consistent with the results from photonuclear reactions. For the $T = \frac{1}{2}$ nuclei the observed resonance is the analog of the $T_>$ giant dipole state in the target nuclei. Pion DCX may provide a new tool for a direct determination of the $T_>$ giant dipole state in $T = \frac{1}{2}$ nuclei.

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