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Giant Resonances in Single and Double Charge Exchange

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Abstract

A long-standing issue in nuclear physics is whether or not multiple excitations of the giant-dipole resonance do exist. Recent studies at LAMPF using pion-induced double-charge exchange reactions show the existence of previously unobserved giant resonances in the continuum at high-excitation energies. Based on their energies, characteristic angular distributions, and the cross section at which the resonances are observed, they have been identified as two different types of double-collective-excitation modes of the nucleus: (1) The isovector giant-dipole resonance built on the isobaric analog state and (2) the isovector giant-dipole resonance built on the giant dipole. In this report we will discuss the general features of these new resonances as they have emerged from DCX experiments performed recently at LAMPF.

1 Introduction

The isobaric analog state (IAS) and the isovector giant-dipole resonance (GDR) play an important role in pion single-charge-exchange reactions in which giant resonances are observed. These studies show that the isobaric analog state and the giant dipole resonance are the two most prominent features in the SCX spectra[1, 2]. The selectivity of pion SCX in exciting the IAS and the GDR have been discussed in previous works[3, 4, 5]. The selectivity arises from several features: (1) In pion single charge exchange, $\Delta T_z = \pm 1$ and therefore $\Delta T = 1$. Thus, $\Delta T = 0$ isoscalar transitions that are very strongly excited in inelastic scattering have no counterpart in the $\Delta T_z = \pm 1$ final nuclei. This reduces the background under the peaks. (2) A good match between the nuclear transition density of the GDR and the IAS and the surface region of the nucleus to which the incoming pions in the resonance region are most sensitive. (3) $\Delta S = 1$ spin-flip transitions are strongly suppressed at forward angles giving less background under the peak from numerous spin-flip transitions as observed for example in the (p,n) reactions.

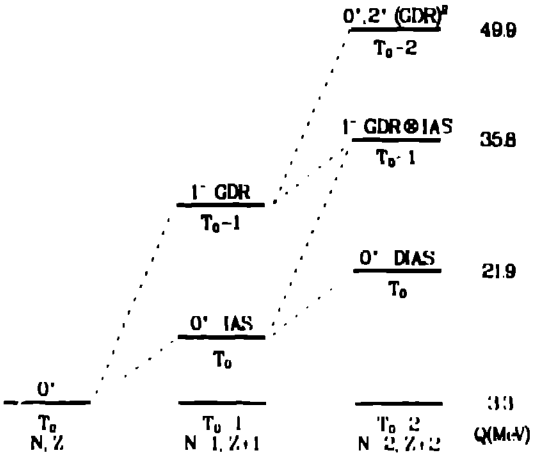

Figure 1: Schematic energy-level diagram of "single" and "double" resonances anticipated in pion single-charge-exchange (π^+, π^0) and pion double-charge-exchange (π^+, π^-) reactions, respectively. The numbers to the right are the Q values for the ground state and the three double resonances observed in the DCX experiment on ^{93}Nb.

At T_π = 295 MeV, pion double charge exchange is thought to proceed predominantly by a two step $(\pi^+, \pi^0)\otimes(\pi^0, \pi^-)$ mechanism, and therefore it was suggested[6] that it should be a unique probe for exciting isotensor double giant resonances in nuclei (*i.e.* states arising from a charge-exchange dipole operator and isospin lowering operator acting twice or in sequence on the ground-state wave function). The lowest energy of these is the well known double isobaric analog state IAS⊗IAS (DIAS) which can be viewed in this context as the simplest double resonance state. The GDR built on the IAS or vice versa is the second double resonance, and the GDR built on the GDR is the third double resonance expected in pion DCX. Figure 1 shows a schematic energy-level diagram of analog and dipole states observed in single charge exchange, and the three double resonances observable in pion DCX. The listed Q values refer to the case of DCX on ^{93}Nb discussed later. Only the lowest isospin component of the upper two resonances is labeled. Until recently, none of these higher multiple resonances have been observed. Sections 2 and 3 of this communication review the experimental results obtained at LAMPF supporting the identification of the two upper double resonances.

2 The giant-dipole resonance built on the isobaric analog state

In a mathematical notation the giant-dipole resonances built on the isobaric analog states GDR⊗IAS can be written in terms of charge-exchange dipole D_- and isospin lowering operators τ_- acting sequentially on the ground-state wave function[7, 8]. The GDR⊗IAS has a multipolarity of $L = 1$, and therefore, for an even-even target nucleus with $N - Z \geq 2$, the resonance has a single spin and parity value of 1^-. The transition gains its strength from coupling through both the IAS and the GDR intermediate states as illustrated in Fig. 1. Since the later have almost the same peak cross section in SCX, then for constructive interference the GDR⊗IAS is expected to be about four times larger than the DIAS.

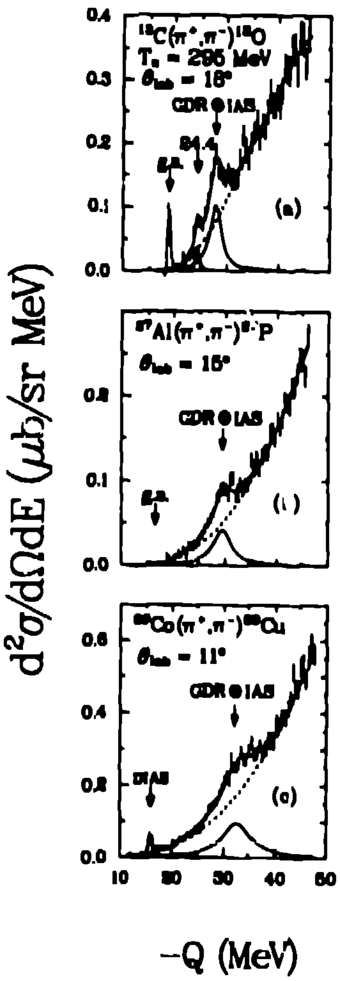

Figure 2 shows the results on three different targets, ^{13}C, ^{27}Al, and ^{59}Co. The measurements were done at an incident pion kinetic energy of 295 MeV (Ref. [9]). All three spectra show clearly the existence of a wide resonance located high in the continuum region at about 8.8 and 14.2 MeV above the ground state of ^{13}O and ^{27}P final nuclei, respectively. On the ^{59}Co target the resonance shows up at about 16.8 MeV above the DIAS in ^{59}Cu. The resonances are identified as the giant-dipole built on the isobaric analog state or vice versa (GDR⊗IAS). The identification is based on their energies, which are very close to the energy where the giant dipoles built on the isobaric analog states

Figure 2: Q value spectra for (π^+, π^-) pion double charge exchange reactions at $T_\pi = 295$ MeV on (a) ^{13}C at $\theta_{lab} = 18°$, (b) ^{27}Al at $\theta_{lab} = 15°$, and (c) ^{59}Co at $\theta_{lab} = 11°$. 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. The dashed lines are the fitted background with a polynomial shape, and the solid lines are the fits to the spectra using a line shape fitting code NEWFIT.

are expected to appear, on the characteristic dipole angular distribution of the resonance, and on the cross sections. Similar observations of the resonance have been confirmed on several other nuclei indicating that this collective mode is a general feature of all nuclei that have at least one excess neutron[7, 8].

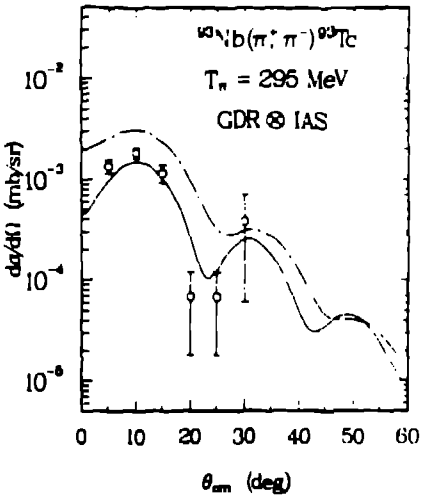

Figure 3: Angular distribution for GDR built on the IAS on ^{93}Nb shown in Fig. 5. The cross sections have been extracted using a Lorentzian line shape for the giant resonance with constant width of 5.8 MeV and a constant $Q = -35.8$ MeV (E_x = 32.5 MeV). The solid and chain dashed lines are sequential model calculations with use of surface and volume transition densities, repsectively, without any normalization factor.

Figure 2 shows clearly that the width of the GDR⊗IAS increases significantly with mass. For example, the resonance on ^{13}C has a width of 3.0 ± 0.6 MeV, but on ^{59}Co the resonance has a width of 7.0 ± 1.0 MeV (*i.e.*, more than twice as wide as that on ^{13}C). The increase of the width with mass is not yet fully understood[9]. This is one of the puzzles arising from these studies. Further details on these resonances can be found in Ref. [8], where some systematic features of the GDR⊗IAS are outlined. Figure 3 presents the angular distribution extracted for this resonance on ^{93}Nb at 295 MeV. The maximum cross section is observed at 10° and 15°. At scattering angles of 20 - 25° the resonance is very weak and can hardly be observed, but at 30° the peak shows up again above background. The solid and dashed lines in Fig. 3 are simple calculations in which sequential single charge exchange through the isobaric analog to the giant-dipole resonance is evaluated with two different transition densities for the IAS[7, 8].

For $T > 1$ target nuclei, the $\Delta T_z = -1$ charge exchange isovector giant dipole and the GDR⊗IAS split into three members (Fig. 4) with isospin $T-1$, T, $T+1$. For heavy nuclei with $T \gg 1$, the lowest isospin component is dominant, and the upper two are nearly negligible. The energy splitting between members $\Delta E^-(T, T-1)$ and $\Delta E^+(T+1, T)$ is a function of T and A and was discussed in references[10, 11, 12].

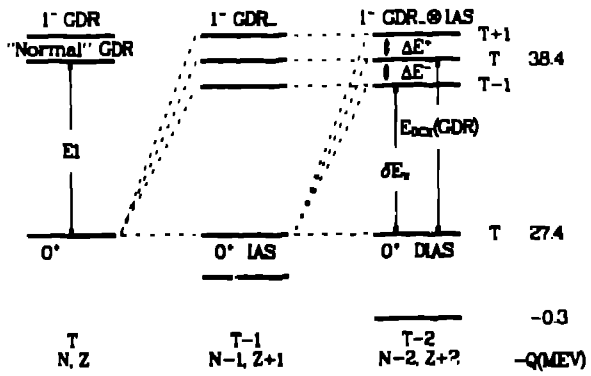

Figure 4: Schematic energy-level diagram of analog and dipole states observed in single and double charge exchange, compared with the E1 resonance in the target from photonuclear reactions. The listed Q values refer to the case of DCX on ^{138}Ba.

The energy of the $T = T_0 - 1$ member of the $\Delta T_z = -1$ GDR is related by symmetry energy to the "normal" ($T = T_0$) GDR in the target nucleus observed for example in photonuclear reactions. Figure 4 illustrates (for target nuclei with $T \geq 1$) the relation between the dipole energy in inelastic or photonuclear reactions and the corresponding single- and double-charge-exchange modes. Table V of Ref. [8] gives a comparison between GDR derived from DCX (column 6) and the corresponding energies measured or extrapolated from photonuclear reactions (column 9). The table indicates that the excitation energies of the GR above the DIAS plus the symmetry energy (ΔE^-) are in close agreement with the electric giant-dipole energies and can be well represented with either an $A^{-1/3}$ or $A^{-1/6}$ dependence (times a constant, 76.6 ± 1.5 and 35.0 ± 0.6 MeV, respectively).

3 The double isovector giant-dipole resonance

The double giant dipole state can be written[13] in terms of a charge-exchange dipole operator $D_\pm$, acting twice on the ground-state wave function, $|D_\pm; D_\pm\rangle = \Sigma_{i=1}^{A} r_i\, y_1(\theta_i)\, t_{\pm 1}(i)\, |D_{\pm 1}\rangle / \mathcal{N}$, where $|D_\pm\rangle = \Sigma_{i=1}^{A} r_i\, y_1(\theta_i)\, t_{\pm 1}|0\rangle$ is the usual isovector charge-exchange dipole operator, and $t_\pm$ are the usual isospin-raising and -lowering operators, changing a proton into a neutron or vice versa, respectively. $\mathcal{N}$ is a proper normalization factor. In principle, two isovector excitations can couple to $\Delta T = 0, 1, or\ 2$. However, in DCX reactions $\Delta T_z = \pm 2$ and therefore no isoscalar or isovector components are allowed, and only $\Delta T = 2$ isotensor transitions are accessible. Similarly, a coupling of two $\ell = 1$ multipoles give a total angular momentum transfer $\Delta L = 0,\ 1,\ or\ 2$. However, for a two-identical-phonon wave function $\Delta T + \Delta L$ must be even and therefore only $\Delta L = 0,\ 2$ are allowed[14]. This will also be the total J transfer for the double-dipole state in DCX, since $\Delta S = 0$ transitions dominate the spectra at this energy and forward angles. Thus, for example, for self-conjugate target nuclei the quantum numbers of the double-dipole resonance given in the above equation are $J^{\pi} = 0^+, 2^+;\ T = 2$.

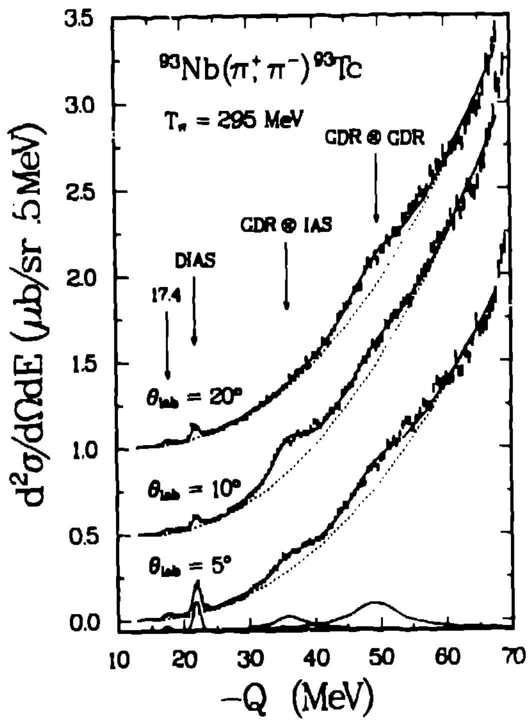

Figure 5: Doubly differential cross-section spectrum for the (π^+, π^-) reaction on ^{93}Nb target at $T_\pi = 295$ MeV and $\theta_{lab} = 5°,\ 10°$, and $20°$. The arrows indicate the three double resonances observable in pion DCX: (1) the DIAS, (2) the GDR⊗IAS, and (3) the GDR⊗GDR.

Figure 5 presents the ^{93}Nb Q value histograms at 5°, 10°, 20°. In addition to the DIAS ($T = 11/2$) at $E_x = 19.3$ MeV ($Q = -21.9$ MeV) which is clear at 5°, the spectrum contains two wide peaks labeled GDR⊗IAS (GR1) and GDR⊗GDR (GR2) at about 32.5 and 46.6 MeV above the ground state. The fit shown uses $\Gamma_{DIAS} = 0.8$ MeV, $\Gamma(GR1) = 5.8$ MeV, and $\Gamma(GR2) = 8.8$ MeV. At 20° GR1 vanishes but shows up clearly at 10°. The peak labeled GR2 has a different angular dependence. At 20° GR2 is almost as strong as in the 5° spectrum. The background (dashed line) is again a third-order polynomial shape.

Figure 6 presents the angular distribution extracted for the GR peak on ^{40}Ca and for both GR1 and GR2 on ^{93}Nb. The two resonances, GR1 and GR2, have different angular distributions. GR1 peaks around 10° and has a dipole shape, whereas the higher resonance (GR2) has a quadrupole distribution that is similar in shape and magnitude to the single GR peak observed on ^{40}Ca. The solid curves in Fig. 6 are simple sequential, two step calculations in which single charge exchange through the giant dipole resonance to the double dipole is evaluated. The calculated cross section for the double dipole with $J = 2$ is found to peak near 0° and 22° as would be expected for coupling of two dipoles, each peaking at this energy around 11°. Further details on these calculations and the normalization procedure to SCX data can be found in Ref. [15].

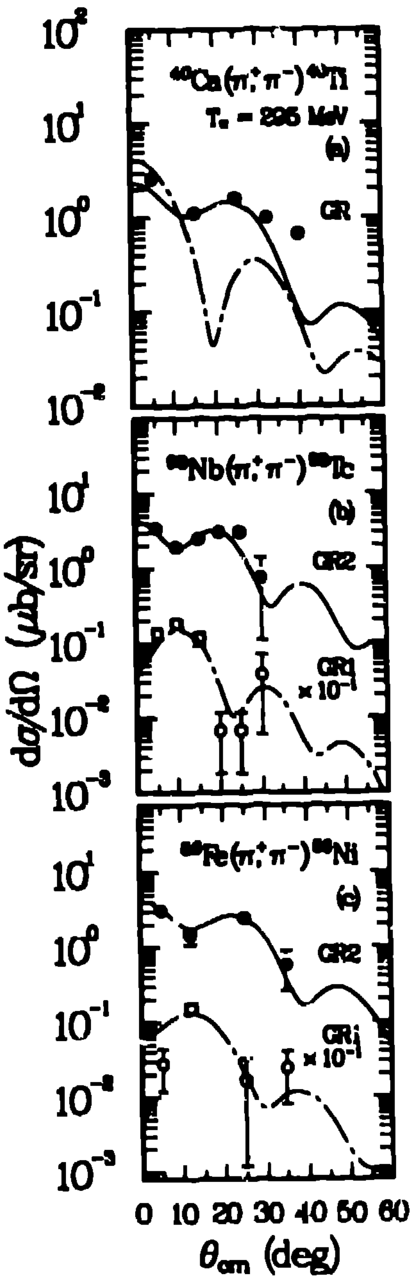

Table III of Ref. [15] summarizes the deduced energies, widths, and cross sections for the double giant dipole. Also listed are the calculated cross sections for the double-dipole states from sequential-model calculations and energies and widths available from the SCX data for the GDR on nearby nuclei from Ref. [4]. In (π^+, π^0) SCX data[4], the GDR appears at about 25 MeV. Its energy and cross section are very weakly dependent on A. If we assume that the second dipole has the same energy as the first dipole then $Q_{DCX}(GDR^2) = 2Q_{SCX}(GDR) \simeq -50$ MeV. This is surprisingly close to the energy at which the higher resonances are observed in the (π^+, π^-) reactions, although the approximation neglects the effect of isospin splitting. The data indicate that the width of the double-dipole states is larger than those observed for the GDR in SCX by a factor of about $1.5 \rightarrow 2.0$. This is in good agreement with

Figure 6: (a) Angular distribution for the peak labeled $(GDR)^2$ in the double-charge-exchange spectra on ^{40}Ca shown in Fig. 7(b). The solid curve is from a sequential model calculation for the double dipole ($J^\pi = 2^+$) state, but re-normalized as mentioned in Ref [15]. The chain-dashed curve for the double dipole ($J^\pi = 0^+$) state is shown without any normalization factor. (b) and (c) The same as (a) except for $^{93}Nb(\pi^+, \pi^-)$ and $^{56}Fe(\pi^+, \pi^-)$ reactions. The solid and chain dashed lines are the theoretical calculations for the double dipole and the dipole built on the isobaric analog state, respectively.

theoretical estimates for the widths of the double-dipole resonances in terms of two-phonon states[14, 15].

A unique feature of pion DCX reactions is the simplicity with which one can study the $\Delta T_z = +2$ DCX mode just by inverting the polarities of all magnets in the pion channel and the spectrometer. We utilized this feature in a recent experiment in order to further examine the nature of these resonances (Ref. [16]). Figure 7 shows the simplest case in which the (π^+, π^-) and the (π^-, π^+) reactions were measured under the same experimental conditions on a self-conjugate nucleus. Since the target nucleus has $N = Z$ the final nuclei reached in the two reactions are mirror nuclei, and therefore one would expect the double dipoles to appear at relatively the same excitation energy with respect to the individual final ground state. However, they should appear at significantly different Q values, since in (π^+, π^-) we add two Coulomb displacement energies and in (π^-, π^+) we subtract two Coulomb displacement energies. Thus, the difference in the Q values of the double dipole in the two reactions should be equal to four Coulomb energies minus four times the neutron proton mass difference. In the (π^+, π^-) reaction the resonance is observed at $Q = -54$ MeV, but in the inverse reaction the same resonance appears at much lower energy, around $Q = -31.1$ MeV. The energy difference between the two reaction modes is in excellent agreement with the above predictions and provides a strong support for the

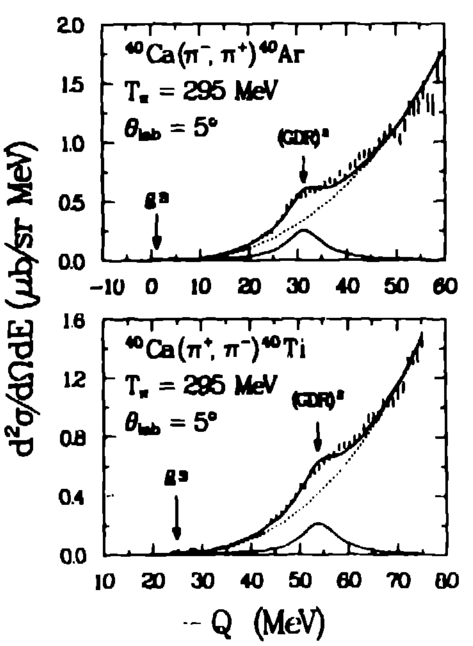

Figure 7: (a) Doubly differential cross-section spectrum for the (π^-, π^+) reaction on ^{40}Ca at $T_\pi = 295$ MeV and $\theta_{lab} = 5°$. The arrows indicate the fitted location of the ground state (g.s.) and the giant resonance $(GDR)^2$. Short vertical lines represent statistical uncertainties of the data. The dashed line is the fitted background with a polynomial shape, and the solid line is the fit to the spectrum. (b) Same as (a) except for the inverse ^{40}Ca$(\pi^+, \pi^-)^{40}$Ti reaction.

identification of the double giant-dipole state. The double dipoles in both DCX modes exhibit the same characteristic angular distribution. The cross section in the (π^-, π^+) reaction is found to be about 20% larger than in the (π^+, π^-) reaction. This result is consistent with the SCX data to the "single" GDR[4] as well as with simple theoretical predictions. Consistent results have also been obtained on non-self-conjugate nuclei[16, 17]. In this case the analysis is more complicated; however, valuable information on the isospin structure of the double giant dipole can be deduced from the data.

4 Acknowledgements

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