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# Comparison of the double giant-dipole states observed in $(\pi^-, \pi^+)$ and $(\pi^+, \pi^-)$ reactions on $^{40}$Ca and $^{27}$Al

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The double isovector giant-dipole state has been observed in the $(\pi^-, \pi^+)$ $\Delta T_z = +2$ and $(\pi^+, \pi^-)$ $\Delta T_z = -2$ double-charge-exchange reactions on $^{40}$Ca and $^{27}$Al. The resonances observed in the $(\pi^-, \pi^+)$ reaction are closely related via Coulomb energy and isospin symmetry to the resonances measured in the inverse $(\pi^+, \pi^-)$ reaction on the same nuclei. The new observations provide strong support for the identification of the double giant-dipole state in nuclei. The differences between the self-conjugate and non-self-conjugate cases are outlined.

In a recent paper[1] we reported the first observation of a double isovector giant-dipole state in nuclei via the $(\pi^+, \pi^-)$ pion double-charge-exchange (DCX) reaction. The main features of this exotic resonance as observed in the $\Delta T_z = -2$ DCX on a wide range of nuclei were reported in a subsequent paper.[2] It was found that the double dipole is a general collective feature of all nuclei and has a simple mass dependence. It appears at about twice the $Q$ value of the giant dipole resonance (GDR) observed[3] in pion single charge exchange (SCX), has a width of about 1.5 times that of the "single" dipole and a cross section which is consistent with the product of the strength of two ingredient giant-dipole transitions times an overall attenuation factor for DCX.[2] The angular distribution was measured for the double dipole on three nuclei and was found to have a predominantly quadrupole shape. All the above features support the identification of the resonance observed around $Q = -50$ MeV in the $(\pi^+, \pi^-)$ reaction as the double giant-dipole resonance [i.e., a state arising from a charge-exchange dipole operator acting twice on the ground state (g.s.) wave function]. However, a unique test for the identification of the double dipole can be provided by measuring the inverse reaction, i.e., the $(\pi^-, \pi^+)$ $\Delta T_z = +2$ DCX mode on the same target nuclei. Figure 1 shows a schematic energy-level diagram and isospin splitting of the single-dipole GDR and the double-dipole GDR$^2$ states anticipated in single- and double-charge-exchange reactions in the two charge-exchange modes on $T = 0$ and $T = \frac{1}{2}$ targets. Figure 1(a) illustrates the simplest case of a self-conjugate $^{40}$Ca nucleus, where no isospin splitting exists in either direction. The $T = 2$ double dipole (labeled GDR$^2_-$ and GDR$^2_+$ for the $\Delta T_z = -2$ and $\Delta T_z = +2$ modes, respectively) are expected to appear at about the same excitation energy in the final $^{40}$Ti—$^{40}$Ar mirror nuclei, but at significantly different $Q$ values corresponding to four Coulomb displacement energies (minus four times the neutron-proton mass difference). Figure 1(b) shows the states of interest in the case of a $T = \frac{1}{2}$ nucleus. Now GDR$^2_-$ splits into two isospin components $T = \frac{3}{2}$ and $T = \frac{5}{2}$, but GDR$^2_+$ still has only a single isospin value allowed, viz., $T = \frac{5}{2}$. The energy difference between GDR$^2_+$ and GDR$^2_-$ in this case is affected by the symmetry energy in addition to the Coulomb energy and will be discussed later. Also indicated in Fig. 1(b) is the giant dipole built on the isobaric analog state (GDR⊗IAS) which is observable in $(\pi^+, \pi^-)$ on non-self-conjugate nuclei,[4] but is absent in the inverse reaction and in $(\pi^+, \pi^-)$ on $T = 0$ nuclei, where no isobaric analog transition (IAS) is possible.

The observation of the double dipole in the $\Delta T_z = +2$ mode has three clear advantages relative to the inverse process: (1) In the $(\pi^-, \pi^+)$ reaction the double dipole is expected (as mentioned above) to appear at a much lower $Q$ value than in the $(\pi^+, \pi^-)$ mode. Therefore, the resonance is expected to appear on a lower background level and may have a smaller width. (2) For non-self-conjugate nuclei the double dipole reached in the $(\pi^+, \pi^-)$ splits into two (or up to five for $T \geq 2$ nuclei) isospin components arising from the coupling of two isovector transitions to the ground state, whereas no isospin splitting is possible in the $(\pi^-,\pi^+)$ reaction which excites only the upper isospin component. This restriction may also provide a smaller width of $\mathrm{GDR}^2_+$ relative to $\mathrm{GDR}^2_-$. (3) In $(\pi^-,\pi^+)$ the spectra are expected to be simpler, since the double isobaric analog state (DIAS) and in particular the overlapping GDR⊗IAS which exist in the $(\pi^+,\pi^-)$ spectra (on non-self-conjugate nuclei) are now absent, allowing a better determination of the double-dipole width and cross section. However, experimentally, the $(\pi^-,\pi^+)$ measurements are much more difficult: cross sections for the $T_>$ component of the double dipole are smaller because of the Pauli blocking effect, which is expected to be larger than in SCX reactions.[3] Furthermore, the $\pi^-$ beam fluxes are generally smaller by about a factor of five relative to the $\pi^+$ fluxes at the energies of interest for the present study, making the running time for a single measurement longer.

The measurements were performed at the Energetic Pion Channel and Spectrometer (EPICS) at LAMPF using the pion DCX setup.[5] We used $^{40}$Ca (96.9%, 2.38 g/cm$^2$) and monoisotopic (natural) $^{27}$Al (1.7 g/cm$^2$) for $(\pi^-,\pi^+)$, and a thinner (1.096 g/cm$^2$) $^{27}$Al target for $(\pi^+,\pi^-)$ . Measurements were taken at three angles on $^{40}$Ca and at a single angle (5°), with both polarities, on $^{27}$Al. The momentum acceptance of the spectrometer was measured by pion scattering from $^{12}$C. Absolute normalizations were obtained by measuring $\pi$–$p$ scattering from a polyethylene ($CH_2$) target of areal density 25.7 mg/cm$^2$ and comparing the yield with cross sections calculated from phase-shift analysis.[6]

Figure 2 shows the $^{40}$Ca$(\pi^-,\pi^+)^{40}$Ar and the $^{40}$Ca$(\pi^+,\pi^-)^{40}$Ti $Q$-value spectra measured under the same experimental conditions at $\theta_{\rm lab}=5°$ and incoming pion energy $T_\pi = 295$ MeV. The $(\pi^-,\pi^+)$ data are from the present measurement and the $(\pi^+,\pi^-)$ is a reanalysis of recent data which includes the low-lying states.[2] In addition to the weak transitions to the ground state, both spectra contain a wide peak labeled (GDR)$^2$ located in the continuum region. In the $(\pi^+,\pi^-)$ reaction the resonance is observed[2] at $Q=-54.0$ MeV, but in the inverse reaction, $(\pi^-,\pi^+)$, the resonance appears at a much lower energy around $Q = -31.1$ MeV. The GR peaks were fitted with a Lorentzian shape of variable width. The fits shown in Fig. 2 use $\Gamma(\mathrm{GDR})^2 = 9.0$ MeV for both reactions. Figure 2(a) shows also the existence of three low-lying states in $^{40}$Ar. The strongest of these is observed at an excitation energy of $3.6 \pm 0.5$ MeV, and may correspond to the single low-lying state observable in the $^{40}$Ti mirror nucleus [Fig. 2(b)]. Both transitions are probably the unresolved $0^+$, $2^+$, $4^+$ triplet of states.[7] The spectra have been corrected for the spectrometer acceptance as a function of momentum. The background (dashed line), which arises from the DCX

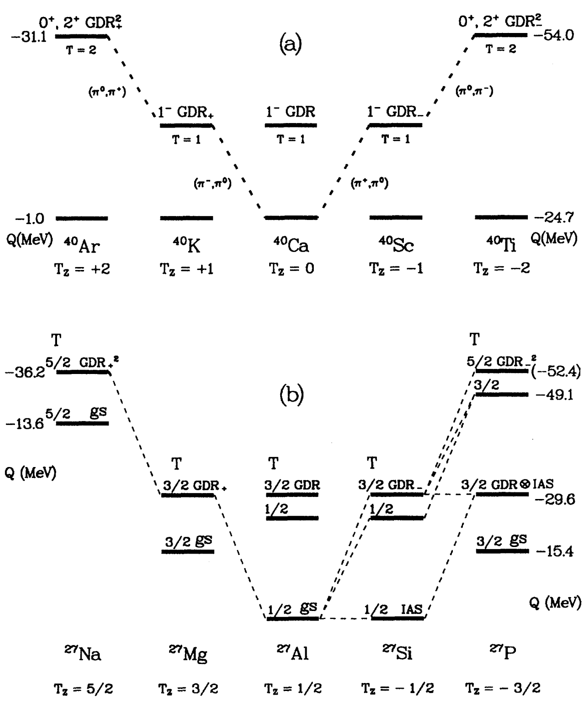


FIG. 1. (a) Schematic energy-level diagram of dipole and double-dipole states observable in single- and double-charge-exchange reactions. The listed $Q$ values refer to the case of DCX on $^{40}$Ca. (b) Same but for $^{27}$Al ($T=\frac{1}{2}$) nucleus. The figure shows also the isospin components reached in the $\Delta T_z=-1$ SCX and $\Delta T_z=-2$ DCX reactions. The listed $Q$ values are the experimental results from the present study.

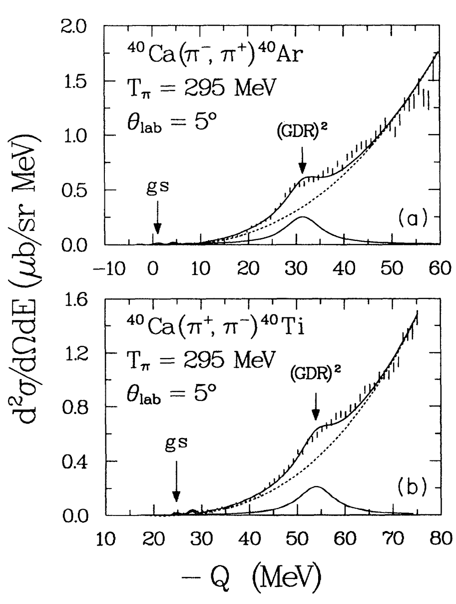


FIG. 2. (a) Doubly differential cross-section spectrum for the $(\pi^-,\pi^+)$ reaction on $^{40}$Ca at $T_\pi = 295$ MeV and $\theta_{\rm lab}=5°$. The arrows indicate the fitted location of the ground state (g.s.) and the giant resonance (GDR)$^2$. Short vertical lines represent statistical uncertainties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

TABLE I. Results from the $(\pi^+,\pi^-)$ and $(\pi^-,\pi^+)$ double-charge-exchange reactions on $^{27}$Al and $^{40}$Ca at $T_\pi = 292$ MeV and $\theta_{lab} = 5°$.

| Target | $(\pi^+,\pi^-)$ $Q_{DD}$ (MeV) | $d\sigma/d\Omega(5°)$ ($\mu$b/sr) | $\Gamma$ (MeV) | $(\pi^-,\pi^+)$ $Q_{DD}$ (MeV) | $d\sigma/d\Omega(5°)$ ($\mu$b/sr) | $\Gamma$ (MeV) | $\frac{\sigma(\pi^-,\pi^+)}{\sigma(\pi^+,\pi^-)}$ | $\Delta E_S$ [a] (MeV) |
|---|---|---|---|---|---|---|---|---|
| $^{27}$Al | $-49.1 \pm 0.5$ | $2.4 \pm 0.2$ | $8.4 \pm 2.0$ | $-36.2 \pm 0.3$ | $0.95 \pm 0.09$ | $6.4 \pm 1.0$ | $0.40 \pm 0.05$ | $3.3 \pm 0.8$ |
| $^{40}$Ca | $-54.0 \pm 0.5$ [b] | $2.6 \pm 0.2$ | $9.0 \pm 1.4$ | $-31.1 \pm 0.3$ | $3.2 \pm 0.2$ | $9.0 \pm 1.0$ | $1.23 \pm 0.12$ | $0.1 \pm 0.8$ |

[a]Using Eq. (1) from text and $\Delta E_C = 5.35$ MeV for $^{27}$Al and 7.05 MeV for $^{40}$Ca.
[b]Reanalysis of previous data from Ref. 2 (including the elastic offset in the DCX data) gives $Q_{DD} = -54.0$ MeV rather than $-51.1$ MeV reported for this resonance in Ref. 2.

cross section to discrete low-lying states and to the continuum, was fitted using a third-order polynomial function of the $Q$ value. In order to reduce uncertainties, the same background form and constraint GR width was used for both DCX modes. The solid lines are the resulting fits to the spectra. The resonance in the $^{40}\mathrm{Ca}(\pi^+,\pi^-)^{40}\mathrm{Ti}$ data was previously[2] identified as the double isovector giant-dipole resonance based on its energy, characteristic angular distribution and cross section. The double dipole reached in the $(\pi^-,\pi^+)$ reaction appears at almost exactly four Coulomb displacement energies (minus four neutron-proton mass differences) as expected. A partial angular distribution at $\theta_{lab} = 5°, 12°$, and $19°$ (not shown) was measured for the double dipole in the $^{40}\mathrm{Ca}(\pi^-,\pi^+)^{40}\mathrm{Ar}$ reaction. The results exhibit the same characteristic angular distribution as the one observed for the double dipole in the $^{40}\mathrm{Ca}(\pi^+,\pi^-)^{40}\mathrm{Ti}$ reaction.[2] Both angular distributions have a quadrupole shape with some extra strength at forward angles, which may indicate that if the energy difference between the double dipole $J^\pi = 0^+$ and $2^+$ states is small, then we actually observe the sum of the two states. This issue is addressed in further detail in Ref. 2. The experimental cross-section ratio for the double dipole at $\theta_{lab} = 5°$ is $\sigma_{DD}(\pi^-,\pi^+)/\sigma_{DD}(\pi^+,\pi^-) = 1.23 \pm 0.12$. This ratio is consistent with single-charge-exchange data on $^{40}$C for which the GDR cross section in $(\pi^-,\pi^0)$ was found to be $1.18 \pm 0.28$ times larger than in $(\pi^+,\pi^0)$ SCX reaction.[3] Similarly, the overall cross sections of the continuum in the above reactions at the same $Q$ values are larger in $(\pi^-,\pi^+)$ than in $(\pi^+,\pi^-)$ and have about the same ratio as that for the double dipole in this energy region. The results are summarized in Table I.

Figure 3 shows the $(\pi^+,\pi^-)$ and $(\pi^-,\pi^+)$ $Q$-value spectra on $^{27}$Al. For $T = \frac{1}{2}$ nuclei the double dipole in the $(\pi^+,\pi^-)$ reaction splits into two isospin components ($T_< = \frac{3}{2}$ and $T_> = \frac{5}{2}$). However, in the inverse reaction with $\Delta T_z = +2$ only the upper isospin component ($T_> = \frac{5}{2}$) is allowed from isospin considerations. These states are shown schematically in Fig. 1(b). Simple double-isospin coupling arguments for the $\mathrm{GDR}^2_-$ through the $\mathrm{GDR}_-$ show that the $T_>$ strength is expected to be weaker by a factor of about seven relative to $T_<$ using equal reduced matrix elements. Pauli blocking will further suppress the $T_>$ component. The observed resonance in the $(\pi^+,\pi^-)$ reaction therefore contains both unresolved isospin components and may be slightly wider ($\Gamma = 8.4\pm2.0$ MeV) than the double dipole reached in the $(\pi^-,\pi^+)$ reaction ($\Gamma = 6.4 \pm 1.0$ MeV). In general, the difference between the centroid energies of the double-dipole resonance in the two reactions can be written as

$$Q_{DD}(\pi^-,\pi^+) - Q_{DD}(\pi^+,\pi^-) = 4(\Delta E_C - \Delta m_{np}) - \Delta E_S, \quad (1)$$

where $\Delta E_C$ is the Coulomb displacement energy, $\Delta m_{np} = 1.29$ MeV is the neutron-proton mass difference, and $\Delta E_S$ is the symmetry energy. Using the experimen-

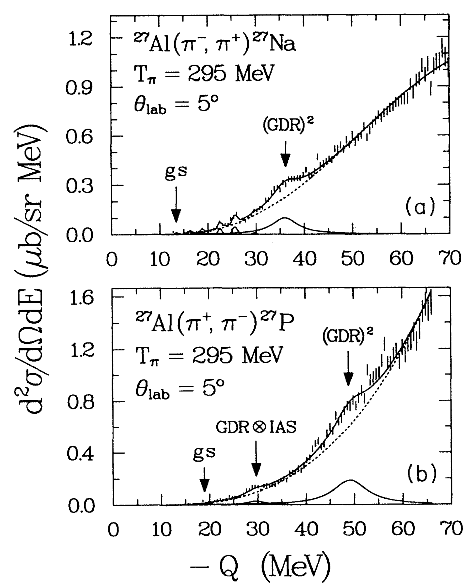


FIG. 3. (a) Same as Fig. 2(a) except for $^{27}$Al target. (b) Same as Fig. 2(b) except for $^{27}$Al target. The resonance labeled GDR⊗IAS is the giant dipole built on the $^{27}$Si(g.s.) isobaric analog state and shows up more clearly in the $\theta_{lab} = 15°$ measurement (Ref. 7).

tal values listed in Table I we obtain $\Delta E_S = 3.3 \pm 0.8$ MeV for the isospin splitting of the double dipole on $^{27}$Al. No theoretical calculations have been reported yet on the isospin splitting of the double giant dipole; however, the above result seems to be in reasonable agreement with the existing information on the isospin splitting of the giant dipole built on the ground state. For example, if we use the simple expression $\Delta E_S = U(T+1)/A$, and $U = 50$ MeV (Refs. 9 and 10) for the symmetry potential, the expected isospin splitting of the giant dipole on $^{27}$Al ($T_< = \frac{1}{2}$ and $T_> = \frac{3}{2}$) is $\Delta E_S = E_> - E_< = 2.8$ MeV. Our result indicates that the double dipole on $^{27}$Al has a symmetry energy which is consistent with the single dipole. The same calculations for $^{40}$Ca yield $\Delta E_S$ consistent with zero (Table I) as required for a $T = 0$ nucleus. Additional low-lying, previously unknown, states are also observable in $^{27}$Na [Fig. 3(a)]. They appear at excitation energies of 2.6, 5.2, 9.0, and 12.1 MeV above the ground state transition.

In contrast to the $^{40}$Ca, self-conjugate case, the cross-section ratio $\sigma_{DD}(\pi^-,\pi^+)/\sigma_{DD}(\pi^+,\pi^-)$ on $^{27}$Al is now less than one ($\approx 0.40$). The suppression of the double dipole in the $(\pi^-,\pi^+)$ reaction probably arises mainly from the Pauli blocking effect for the $T_>$ component. This effect is expected to increase with mass and is consistent with results from pion SCX data.[3] The $Q$-value effect between the double dipole in the two DCX modes arising from their different $Q$ values is quite negligible and is estimated from DWIA calculations to be only about 1% at $T_\pi = 295$ MeV. An interesting issue is the ratio of the background from the continuum DCX in the two reactions. Figure 3 shows that a similar blocking as observed for the double dipole exists also for the continuum in the region of the double-dipole resonance. An additional obvious difference between the spectra shown in Fig. 3 is the presence of the giant dipole built on the isobaric analog state (GDR⊗IAS) in the $(\pi^+,\pi^-)$ reaction. This resonance is weak in the $\theta_{\rm lab} = 5°$ spectrum but shows up very clearly at $\theta_{\rm lab} = 15°$.[8]

In conclusion, we have reported the observation of the double isovector giant-dipole resonance with both $(\pi^-,\pi^+)$ and $(\pi^+,\pi^-)$ $\Delta T_z = \pm 2$ nuclear probes. The double-dipole resonance is observed in the $^{40}$Ca$(\pi^-,\pi^+)^{40}$Ar reaction at almost exactly four Coulomb displacement energies (minus the neutron-proton mass difference) lower than the same state reached in the $^{40}$Ti mirror nucleus via the $^{40}$Ca$(\pi^+,\pi^-)^{40}$Ti reaction. A partial angular distribution was measured for the double dipole and found to have a quadrupole shape. The double-dipole resonances observed in the $(\pi^+,\pi^-)$ and $(\pi^-,\pi^+)$ reactions on $^{27}$Al are closely related via Coulomb energy and isospin symmetry. The new observations provide strong support for the identification of double giant-dipole states in nuclei.

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