Pion Double Charge Exchange to the Double Dipole Resonance

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We report the first observation of a double isovector giant dipole state in nuclei (i.e., an isovector giant dipole resonance built on another giant dipole). Two new resonances were observed in (π^+,π^-) double charge exchange (at $T_\pi=292$ MeV) on ^{nat}S at excitation energies of 24.7 and 28.7 MeV. The energy centroid is very close to the energy at which the double dipole ($J^\pi=0^+,2^+$; $T=2$) state is expected to appear. The angular distributions for the resonances have a clear quadrupole shape. The measured cross sections and the angular distribution agree well with a simple sequential two-step calculation in which single charge exchange through the giant dipole resonance to the double dipole is evaluated.

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The subject of giant dipole excitations built on excited nuclear states has recently attracted much interest. These excitations were predicted by the Brink-Axel hypothesis in the early sixties.[1] However, actual experimental observations of the phenomena were made possible only in recent years,[2] mainly via γ-ray spectra from heavy-ion fusion reactions[3-5] and proton-capture (p,γ) reactions.[6-7] Results from these studies indicate some remarkable general features of the giant dipole resonances (GDR's) in excited nuclei when compared with the regular well-known ground-state GDR observed, for example, in photonuclear reactions. These features are summarized in a recent review by Snover.[8]

For pion single-charge-exchange (SCX) reactions in which giant resonances are observed, isovector giant dipole resonances and isobaric analog states (IAS's) are the two most prominent features in the spectra.[9-11] They have both been observed in (π^+,π^0) and the GDR is also populated in the (π^-,π^0) reaction with typical maximum cross section around 0.5–1.0 mb/sr. Therefore a combination of these two resonances could, in principle, be reached in (π^+,π^-) pion double charge exchange (DCX). The difficulty in observation of double giant resonances arises mainly from the fact that these states are located high in the continuum so that they are in a region of very high density of states and have a large decay width. An advantage of pion DCX reaction is that the $\Delta T=0$ states in the target nucleus that are very strongly excited in inelastic scattering have no counterparts in the nucleus $(N-2,\ Z+2)$. An example of this unique feature of pion DCX as an excellent tool to study double resonances is the well-known double isobaric analog state (DIAS) which can be viewed in this context as the simplest double resonance state. None of the higher double resonances have been observed. In a recent work[12] we reported the first observation of a GDR built on the isobaric analog state in pion DCX. In this Letter we report the first observation of nuclear double isovector dipole resonance.

An "ideal" giant resonance state built on an excited state $|n\rangle$ can be written as

$$|Q_\alpha;n\rangle=Q_\alpha|n\rangle/|\langle n|Q_\alpha^+Q_\alpha|n\rangle|^{1/2}, \qquad (1)$$

where Q_α is a one-body operator obtained by our taking a coherent sum of one-nucleon operators $q_\alpha(i)$,

$$Q_\alpha=\sum_{i=1}^{A}q_\alpha(i). \qquad (2)$$

If $|n\rangle$ itself is a giant resonance state built on a ground state $|0\rangle$, then the state in Eq. (1) will be a double giant excitation of the type

$$|Q_\alpha;\alpha'\rangle=Q_\alpha Q_{\alpha'}|0\rangle/N, \qquad (3)$$

where N is a proper normalization factor. If the multipole isovector operators, Q_α (and $Q_{\alpha'}$), are of the type

$$Q_{L,\mu}=\sum_{i=1}^{A}r_i^L Y_L(\theta_i)t_\mu(i), \qquad (4)$$

where $\mu=+$, 0, or $-$, then by taking $\mu=-$ and $L=1$ we may write the model state

$$|D_-;D_-\rangle=\sum_{i=1}^{A}r_iY_1(\theta_i)t_-(i)|D_-\rangle/N, \qquad (5)$$

where

$$|D_-\rangle=\sum_{i=1}^{A}r_iY_1(\theta_i)t_-(i)|0\rangle. \qquad (6)$$

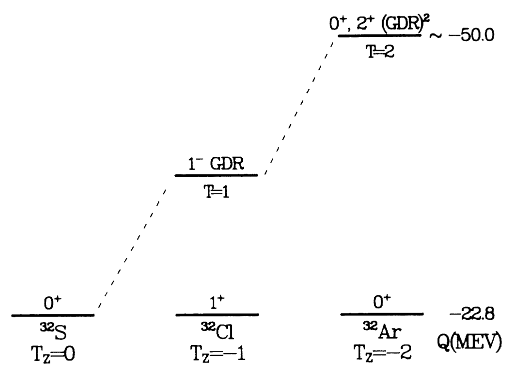

FIG. 1. Schematic energy-level diagram of nonanalog ground state and double isovector giant dipole states anticipated in (π^+,π^-) reaction on ^{32}S target.

Equation (5) describes the $\Delta T_z = -2$ component of a giant dipole state built on a dipole state. We label this state as $(\mathrm{GDR})^2$ in Fig. 1. It is this state that we consider here.

The measurements were performed at the Energetic Pion Channel and Spectrometer (EPICS) at the Los Alamos National Laboratory with use of the pion DCX setup.[13] We used a $^{\mathrm{nat}}$S (95% ^{32}S) target, 2 g/cm^2 thick. Measurements were taken at scattering angles 5°–40° in 5° steps. Electrons were eliminated by a freon-gas Cherenkov detector in the focal plane. A set of veto scintillators separated by graphite wedges in the focal plane was used to reject muons. The system was fine tuned by placement of a variable-thickness aluminum absorber in front of the first scintillator.

Figure 2 shows the $^{\mathrm{nat}}$S missing-mass spectra at two angles, 10° and 20°. In addition to the ground-state transition the spectra show the existence of two wide peaks very high in the continuum region at 24.7 and 28.7 MeV above the ground state ($Q = -47.5$ and -51.5 MeV). These bumps are labeled GR1 and GR2 in the figure. The GR peaks were fitted by a Lorentzian shape of variable width. The background (dashed line) that arises from DCX cross section to discrete low-lying states and the continuum was fitted with a five-parameter polynomial shape. The solid lines are the resulting fits to the spectra. Further fits at different angles used the same widths for all angles.

Figure 3 presents the angular distributions extracted for (a) GR1 and (b) GR2. The maximum cross section

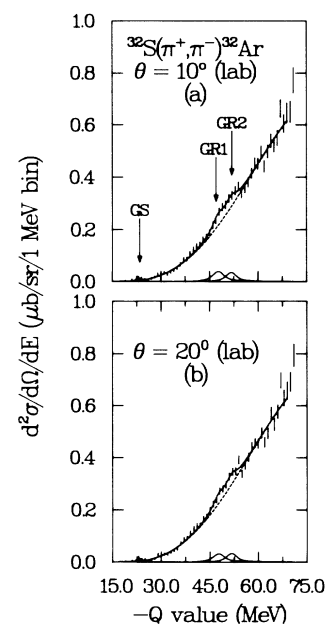

FIG. 2. Double differential cross-section spectra for the (π^+,π^-) reaction on a $^{\mathrm{nat}}$S target at $T_\pi = 292$ MeV: (a) $\theta_{\mathrm{lab}} = 10°$, (b) $\theta_{\mathrm{lab}} = 20°$. The arrows indicate the fitted location of the ground state and the giant resonances. Short vertical lines represent the statistical uncertainty of the data. The dashed line is the fitted background with a polynomial shape and the solid line is the fit to the spectra with NEWFIT.

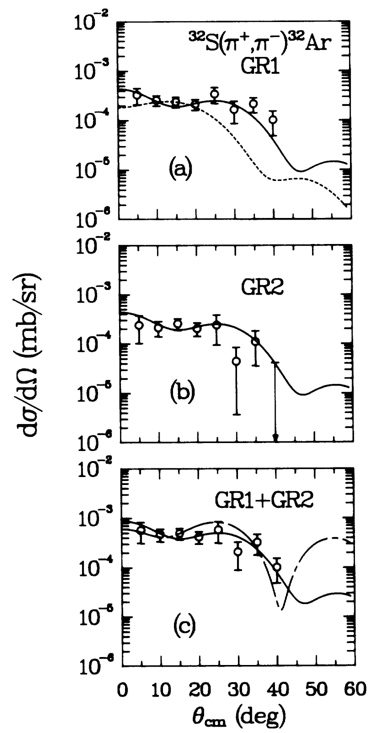

FIG. 3 (a) Angular distribution for the peak labeled GR1 in Fig. 2. The cross sections were extracted by a Lorentzian line shape for the giant resonance with a constant width of 4.0 MeV and $E_x = 24.7$ MeV. The solid line is the result of sequential-model calculations multipled by a factor of 0.5, and the dashed line is an $l = 1$ angular distribution (see text). (b) Same as (a) but for GR2 with a constant width of 3.6 MeV and $E_x = 28.7$ MeV. (c) Summed cross section of GR1 and GR2. Solid line is the result of sequential-model calculations without any normalization factor. The dashed line is a Bessel-function fit to the data.

was observed at 25°. At larger angles the cross section drops by a factor of 3 or more. Figure 3(c) shows the summed cross section of GR1 and GR2. The solid lines are the results of sequential-model calculations discussed later. The dashed line is a Bessel-function fit to the data of the form $J_0^2(qr)+3J_2^2(qr)$ with strong absorption radius $R=1.20\ A^{1/3}$ normalized arbitrarily to the 5° data point. This form represents $\Delta J=2$ angular distributions and is expected for a surface-dominated diffractive pion scattering process.[14,15]

A simple sequential model has been used to predict the cross section and angular distribution for the double dipole state. We used the pion coupled-channel impulse-approximation code (CCIA) NEWCHOP.[16] The calculations include the ground state, the GDR, and the $(\mathrm{GDR})^2$ of Fig. 1. The collective model has been used to obtain the radial shape of the transition density for the dipole. The strength of each SCX has been adjusted to reproduce the measured (π^+,π^0) cross section of the GDR on ^{40}Ca at 165 MeV.[11] The transition strength thus obtained was used at 292 MeV for both SCX processes. The validity of this method was tested against the available SCX data for the GDR at lower energies.[17] The calculated cross sections for the $(\mathrm{GDR})^2$ with $J=2$ is found to peak near 0° and 26°. This is an expected result for coupling of two dipoles, each peaking at this energy around 13°. The calculated solid curves shown in Figs. 3(a) and 3(b) are multiplied by a factor of 0.5. In Fig. 3(c) the calculated cross section (solid curve) is shown without any renormalization factor. Therefore simple sequential-model calculations normalized properly to the one-step SCX cross section account surprisingly well for the measured cross section and strongly support the identification of these resonances as two members of a double giant dipole state. These results are quite remarkable in view of the recent work[18] on pion DCX to the DIAS in nuclei in which the excess neutrons are from a j^n configuration. It was found that for low-energy pions a single-channel sequential process might not be sufficient and contributions from many intermediate states must be considered. Here we deal with non-analog core excited states in which the GDR is the only prominent state in SCX. Another interesting newly discovered resonance is the giant dipole built on the isobaric analog state (GDR⊗IAS) reported in our previous work.[12] We note that the GDR⊗IAS (which has an $l=1$ character) is *not accessible* in the present case since ^{32}S has $N=Z$ where no IAS or DIAS is possible. Therefore this interpretation should clearly be ruled out for the present data. Figure 3(a) shows an $l=1$ angular distribution (dashed) together with the data to emphasize also the difference between the angular distributions of these two modes of excitations.

Table I summarizes the deduced excitation energies, widths, and cross sections for the ground state and the giant resonances. The energy centroid of the GR's Q values is about -50 MeV, which is nearly double the energy of the $\mu=-$charge-exchange GDR observed in (π^+,π^0).[11,17] The measured cross sections indicate that the GR's are much stronger (more than an order of magnitude) than the ground-state transition at 5°. The confidence level for these observations is about 4 standard deviations in the individual spectra, and more than 8 standard deviations in the angle-integrated cross section. If we treat the two members as a single peak, then the total width of the GR bumps is ≈8–10 MeV. This is about 50% larger than the charge-exchange GDR width of 6.4 MeV reported for ^{40}Ca.[11,17] As illustrated in Fig. 1, the double dipole model state can be either 0^+ or 2^+. However, the data do not show a forward angle rise typical of 0^+ transitions. The reason for the suppression of the double dipole 0^+ state is not known, but it might be due to pion strong-absorption effects at very forward angles and/or nuclear-structure effects.

We turn now to the energy splitting and cross-section ratio of the two members. For self-conjugate nuclei the $(\mathrm{GDR})^2$ has no T-splitting, and only one member $(T=2)$ is possible. Therefore splitting of the double dipole in the present case may arise either from dipole-quadrupole interaction (for nuclei with quadrupole de-

TABLE I. Results from the DCX (π^+,π^-) reaction on $^{\mathrm{nat}}$S at an incident pion energy $T_\pi=292$ MeV and $\theta_{\mathrm{lab}}=5°$ compared with a sequential-model analysis.

Peak	E_x (MeV)	Γ (MeV)	Expt.[a] $d\sigma/d\Omega$ (μb/sr)	Theory $d\sigma/d\Omega$ (μb/sr)
Ground state	0.0	1.4 ± 0.2[b]	0.040 ± 0.013[c]	
GR1	24.7 ± 0.3	4.0 ± 1.5	0.33 ± 0.12	0.72[d]
GR2	28.7 ± 0.4	3.6 ± 1.5	0.24 ± 0.13	

[a]Cross sections were extracted by the assumption of a Gaussian line shape for the ground-state transition and a Lorentzian line shape for GR1 and GR2. The uncertainties in cross sections for the GR's are significantly smaller at angles larger than 5°. At 15°, for example, the cross sections are 0.24 ± 0.06 μb/sr (GR1) and 0.25 ± 0.07 μb/sr (GR2).

[b]Resolution width only, mostly as a result of target thickness.

[c]The cross section for the ground state is corrected for the isotopic enrichment of the target.

[d]Calculated cross section for the double dipole state with $J^\pi=2^+$.

formation) and/or dipole-dipole intereaction, which should be the dominant contribution in spherical nuclei. The nucleus ^{32}S has a prolate deformation with an intrinsic quadrupole moment of $Q_0=55$ fm^2.[19] We can make two simple estimates of the expected energy splitting of the double dipole resonance on ^{32}S. In a prolate nucleus with equal minor axes a dipole splits into two components corresponding to vibrations along the major and minor axes. If the $(GDR)^2$ relates to deformation similar to the dipole, then the above intrinsic quadrupole moment gives $\Delta E=4.5$ MeV. This is indeed very close to the observed splitting.

Alternatively, we can assume that the $(GDR)^2$ in a deformed nucleus behaves like the giant quadrupole resonance. In this case we expect a splitting into three components with $m=\pm 2$, ± 1, 0 and with eigenfrequencies;[20]

$$\begin{aligned} \omega(2,0) &= \sqrt{2}\bar{\omega}(1-\tfrac{1}{3}\delta), \\ \omega(2,1) &= \sqrt{2}\bar{\omega}(1-\tfrac{1}{6}\delta), \\ \omega(2,2) &= \sqrt{2}\bar{\omega}(1+\tfrac{1}{3}\delta), \end{aligned} \tag{7}$$

where $\delta=\Delta R/R$ is the deformation parameter. Using $\delta=0.25$ (a value consistent with the above quadrupole moment) and $\bar{\omega}=\bar{E}_x=26.7$ MeV, we obtain $\Delta E_2=\omega(2,2)-\omega(2,1)=4.6$ MeV and $\Delta E_1=\omega(2,1)-\omega(2,0)=1.5$ MeV. Thus the splitting between $m=0$ and $m=\pm 1$ members is small, so they are actually observed as one peak. This rough estimate also gives good agreement with the observed splitting of 4 MeV. It could be that the two approaches are, in fact, equivalent.

The above quadrupole splitting also gives a qualitative argument to understand the observed cross-section ratio of the two members (GR2/GR1=0.7). If the different m substates are populated equally and if the lower GR contains both $m=0$ and $m\pm 1$, we would expect the upper/lower ratio to be $\frac{2}{3}$—not very different from the observed value. Clearly, a more theoretical approach for double giant resonances in nuclei is highly desirable in order to understand these exciting phenomena. A theoretical work on some of the above properties of double giant resonances is now in progress.[21]

In conclusion, we have reported a possible first observation in nuclei of double isovector giant dipole resonance using pion double charge exchange on ^{32}S. The energy centroids of the observed resonances are close to the expected energy of double dipole state. The angular distributions measured for the GR's have a clear quadrupole shape. Simple CCIA calculations for the double dipole resonance give qualitatively—and surprisingly also quantitatively—a correct description of the measured cross section and the angular distribution. Future theoretical studies should, however, go beyond the simple CCIA and examine the effect on the cross sections of including several intermediate states. We conclude that pion DCX is a promising reaction to identify double giant resonances in nuclei.

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