Energy Dependence of Double Giant Resonances in Pion Double Charge Exchange

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The energy dependence of the giant dipole resonance built on the isobaric analog state was measured in pion-induced double charge exchange on ^{13}C at incident pion energies of 140–295 MeV. The cross section increases with energy. The excitation function has a typical non-spin-flip signature, expected from simple considerations and verified by sequential model calculations. Three narrower previously reported low-lying states in ^{13}O ($E_x=3.1$, 4.5, and 6.1 MeV) exhibit a spin-flip signature and may correspond to the giant Gamow-Teller strength built on the isobaric analog state.

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Several experiments have been carried out at the Los Alamos Meson Physics Facility (LAMPF) to study the properties of double giant resonances in nuclei. Two such exotic vibrational nuclear modes have been observed by these studies: the giant dipole resonance built on the isobaric analog state ($|\mathrm{GDR}\otimes\mathrm{IAS}\rangle$) [1] and the double giant dipole resonance ($|\mathrm{GDR}\otimes\mathrm{GDR}\rangle$) [2]. These resonances have been measured recently on a wide range of nuclei. The first is observable only in the (π^+,π^-) $\Delta T_z=-2$ double-charge-exchange (DCX) reaction and was found to be a general feature of all nuclei with $N-Z\geq 1$. The latter is observed in both the (π^+,π^-) and (π^-,π^+) DCX modes and is a general collective feature of all nuclei [3]. However, all previous data have been measured at a single pion beam energy of 295 MeV [4,5]. The present work is the first measurement of the energy dependence of double resonances in nuclei excited by DCX. The main object of this Letter is to present the first data for the energy dependence of the cross section of the giant dipole resonance built on the isobaric analog state in the $^{13}\mathrm{C}(\pi^+,\pi^-)^{13}\mathrm{O}$ reaction, and to shed more light on the exact mechanism in which a double resonance state is excited. The excitation of multiphonon states also becomes a very likely process in relativistic heavy ion reactions, where a direct identification of the double giant dipole resonance has been reported recently [6].

The measurements were performed at the energetic pion channel and spectrometer (EPICS) at LAMPF with the standard pion double-charge-exchange setup [7]. The isotopic purity and areal density of the ^{13}C target were 90% and 0.425 g/cm^2. Measurements were taken at a constant momentum transfer that corresponds to the peak cross section of the $|\mathrm{GDR}\otimes\mathrm{IAS}\rangle$ angular distribution at five different energies ranging between 140 and 295 MeV. Electrons were eliminated using an isobutane velocity-threshold Cherenkov detector in the focal plane. A scintillator placed behind a series of aluminum and graphite wedges was used to veto muon events [8]. The remaining background was pions resulting from continuum DCX in the target.

The acceptance of the spectrometer was measured with a ^{12}C target using inelastic scattering to the 4.44-MeV state at an energy $T_\pi=180$ MeV and a scattering angle of 35°, which corresponds to the peak cross section. The spectrometer field was varied to move the 4.44-MeV peak across the focal plane, covering approximately ±10% of the central momentum of the spectrometer. Absolute normalization was obtained at each energy using a polyethylene (CH$_2$) target of areal density 0.029 g/cm^2 to measure the hydrogen elastic cross section and comparing the yields with cross sections calculated from π-nucleon phase shifts [9]. Elastic-scattering data have been measured on the ^{13}C target to determine the total energy offset and the elastic peak shape at each energy.

Figure 1 shows the $^{13}\mathrm{C}(\pi^+,\pi^-)^{13}\mathrm{O}$ missing-mass spectra at five different incoming pion beam energies. The scattering angles have been chosen to correspond to the peak cross section of the giant dipole built on the isobaric analog state. In addition to the ground state (g.s.) and the three low-lying narrow states reported earlier [10] (at $Q=-22.0$ MeV, $Q=-23.4$ MeV, and $Q=-25.0$ MeV), most spectra clearly show the existence of a wider peak located in the continuum region at $Q=-27.6$ MeV ($E_x=8.7$ MeV above the g.s. of ^{13}O). This resonance was previously identified, based on its energy, characteristic dipole angular distribution, and observed cross section as the $T_>=\frac{3}{2}$ component of the giant dipole resonance built on the isobaric analog state [11]. In Fig. 1 this resonance is labeled $|\mathrm{GDR}\otimes\mathrm{IAS}\rangle$. For $T=\frac{1}{2}$ nuclei the $T_<=\frac{1}{2}$ component of the $|\mathrm{GDR}\otimes\mathrm{IAS}\rangle$ is forbidden as illustrated in Fig. 2 of Ref. [11]. The g.s. was fitted with a Gaussian shape of variable width, the three low-lying narrow states were fitted with Gaussian shapes of fixed widths, and the giant resonance was fitted with a Lorentzian shape of variable width. The background (dashed line), which arises from DCX to the continuum, was fitted using a third-order polynomial

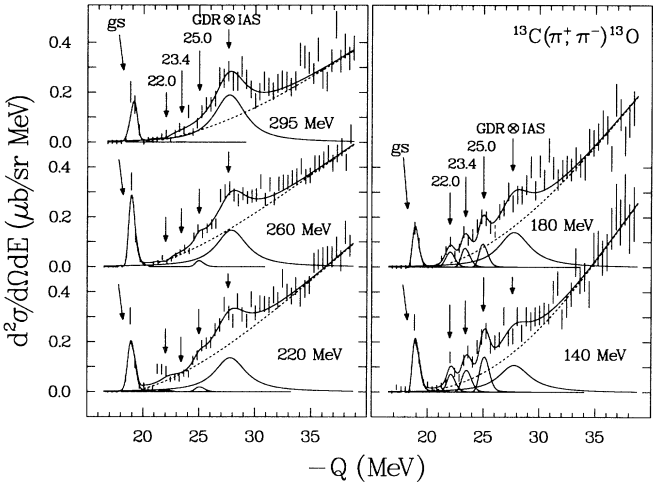

FIG. 1. Double-differential cross section spectra for (π^+,π^-) reaction on a ${}^{13}C$ target at $T_\pi = 295$, 260, 220, 180, and 140 MeV at the scattering angles listed in Table II. The arrows indicate the fitted location of the g.s., the three low-lying states, and the giant resonance. Short vertical lines represent statistical uncertainty 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 NEWFIT.

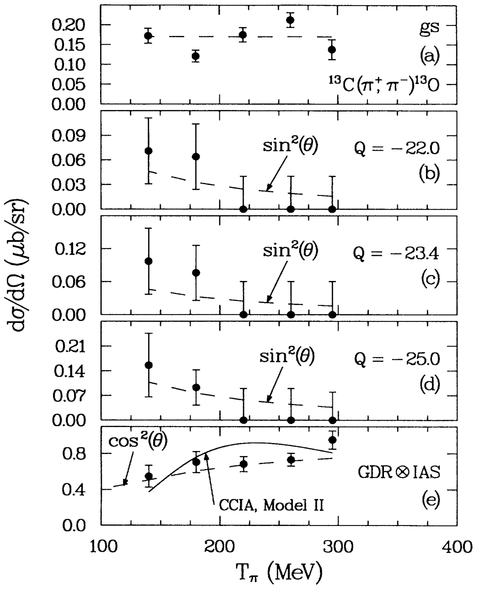

FIG. 2. Excitation function at 140–295 MeV for the g.s. ($Q = -18.9$ MeV), the three low-lying states ($Q = -22.0$, -23.4, and -25.0 MeV), and the giant dipole built on the isobaric analog state ($Q = -27.6$ MeV). The dashed lines are constant, $\sin^2(\theta)$ or $\cos^2(\theta)$ curves, normalized arbitrarily to the data. The solid line labeled CCIA in (e) is the result of simple sequential model calculations using the computer code NEWCHOP (see text).

shape. Using fourth- or higher-order polynomial shapes does not appreciably affect the extracted cross sections for the resonance or for the lower states. Figure 1 demonstrates that the cross section for the |GDR⊗IAS⟩ increases significantly with beam energy. The resonance shows up clearly in the 295-MeV spectrum, but almost vanishes in the 140-MeV measurement. The weak transitions to the three lower excited states at $E_x = 3.1$ MeV ($Q = -22.0$ MeV), $E_x = 4.5$ MeV ($Q = -23.4$ MeV), and $E_x = 6.1$ MeV ($Q = -25.0$ MeV) exhibit a substantially different excitation function. Their cross sections decrease with increasing beam energy. These states have been observed earlier [10], but little is known of their nature. Figure 2 displays the excitation functions for the g.s., the states at 3.1, 4.5, and 6.1 MeV, and the |GDR ⊗IAS⟩.

Table I summarizes the deduced energies and widths for the low-lying states and the giant resonance extracted with the line-shape fitting code NEWFIT [12]. For the strong transitions (the g.s. and the |GDR⊗IAS⟩) the energies and widths were varied simultaneously to minimize χ^2 for the entire fit. Table II lists the observed cross sections for the above states at all different energies. The uncertainties listed in Tables I and II come only from the fitting procedure, with no account taken of the uncertainties associated with lack of knowledge of the overall spectrum shape of the DCX reaction to the continuum. Table II also lists the predicted cross sections for the |GDR⊗IAS⟩ in a simple sequential-mode calculation, using the pion coupled-channel impulse-approximation (CCIA) code NEWCHOP [13]. The coupled-channel calculations include the g.s., the IAS, the GDR, and the |GDR⊗IAS⟩. The strength of each SCX transition has been adjusted to reproduce the extrapolated SCX cross section to the GDR [14] and the IAS [15]. The same transition strength was used at all energies. Two different transition densities have been used for the IAS: one a volume transition density (model I) and the other a surface-peaked transition density (model II). A widely accepted collective Tassie form factor for the transition density, $r^{L-1}\rho'(r)Y_{LM}(\hat{r})$, with $L = 1$ was used for the GDR [16], where $\rho(r)$ is the nuclear g.s. density. The calculations (using both models) take into account the suppression of the |GDR⊗IAS⟩ on $T = \frac{1}{2}$ nuclei due to

TABLE I. Energies and widths of the states observed in the ${}^{13}C(\pi^+,\pi^-){}^{13}O$ reaction at $T_\pi = 140$–295 MeV.

State label	Q (MeV)	E_x (MeV)	Γ (MeV)
g.s.	-18.9 ± 0.04	0.0	0.40 ± 0.06
22.0	-22.0 ± 0.06	3.1 ± 0.07	0.60 ± 0.40
23.4	-23.4 ± 0.08	4.5 ± 0.09	0.60 ± 0.40
25.0	-25.0 ± 0.08	6.1 ± 0.09	0.60 ± 0.40
|GDR⊗IAS⟩	-27.6 ± 0.2	8.7 ± 0.2	3.1 ± 0.5

TABLE II. Measured calculated cross sections for the g.s., the states at $Q=-22.0$, -23.4, and -25.0 MeV, and the $|\mathrm{GDR}\otimes\mathrm{IAS}\rangle$ from DCX on ^{13}C.

		$d\sigma/d\Omega$ (Experimental)					$d\sigma/d\Omega$ (Theory) $|\mathrm{GDR}\otimes\mathrm{IAS}\rangle^{\mathrm{b}}$	
T_π (MeV)	θ_{lab} (deg)	g.s. (μb/sr)	22.0 (μb/sr)	23.4 (μb/sr)	25.0 (μb/sr)	$|\mathrm{GDR}\otimes\mathrm{IAS}\rangle^{\mathrm{a}}$ (μb/sr)	Model I (μb/sr)	Model II (μb/sr)
295	17.0	0.14 ± 0.02	<0.04	<0.06	<0.08	0.95 ± 0.10	1.32	0.81
260	18.8	0.21 ± 0.02	<0.04	<0.06	<0.09	0.73 ± 0.07	1.30	0.89
220	21.3	0.17 ± 0.02	<0.04	<0.06	<0.09	0.68 ± 0.08	1.16	0.91
180	24.8	0.12 ± 0.02	0.06 ± 0.04	0.08 ± 0.05	0.09 ± 0.05	0.70 ± 0.12	0.88	0.76
140	29.9	0.17 ± 0.02	0.07 ± 0.04	0.10 ± 0.06	0.16 ± 0.09	0.55 ± 0.12	0.51	0.37

[a] Peak cross sections (at the listed energies and angles) for the giant dipole resonance built on the isobaric analog state.

[b] Sequential model calculations using volume transition density (model I) and surface transition density (model II) for the isobaric analog state, normalized properly to pion single-charge-exchange data.

isospin arguments [11], and reproduce the measured cross sections without any additional normalization factor.

In order to understand the observed energy dependence in a simple model we can use an expression for the energy dependence of the inelastic cross section derived by Siciliano and Walker [17] in a strong absorption model assuming the dominance of the [3,3] resonance:

$$\sigma(\theta)=\alpha(E)[4M^2(q_0)\cos^2(\theta)+S^2(q_0)\sin^2(\theta)] . \quad (1)$$

Here q_0 is a constant momentum transfer near the maximum of the differential cross section, and $\alpha(E)$ contains the energy dependence of the elementary π-N force. In general only the S form factor can contribute to $\Delta S=1$ spin transitions. The equation indicates that the $\Delta S=0$ non-spin-flip transition cross section increases with energy like $\cos^2(\theta)$ at a constant momentum transfer since $q_0=2k\sin(\theta/2)$, where k is the beam momentum. Using the same argument, the spin-flip transitions should decrease with energy like $\sin^2(\theta)$. This technique for distinguishing spin-flip from non-spin-flip transitions by examining the constant-q excitation function was used successfully earlier on ^{13}C [18], to identify $\Delta S=0$ and $\Delta S=1$ transitions in pion scattering. It should, however, be noted that these relations are only approximate, since the central part of the pion-nucleus interaction may contribute to $\Delta S=1$ transitions due to current corrections.

Figure 2 indicates that the $|\mathrm{GDR}\otimes\mathrm{IAS}\rangle$ can be fitted with a $\cos^2(\theta)$ dependence, similar to non-spin-flip transitions in inelastic scattering. The three excited states at $E_x=3.1$, 4.5, and 6.1 MeV [10] are only weakly populated in the present study; however, the data indicate that they can be better described by $\sin^2(\theta)$, the signature expected for spin-flip transitions. This behavior ($\Delta S=1$), along with the small angle and low momentum transfer, which suggest a low angular momentum transfer, leads to the conclusion that these states may contain the Gamow-Teller⊗IAS ($|\mathrm{GT}\otimes\mathrm{IAS}\rangle$) transition strength.

From simple arguments the expected energy for the $|\mathrm{GT}\otimes\mathrm{IAS}\rangle$ in pion DCX is

$$Q(|\mathrm{GT}\otimes\mathrm{IAS}\rangle)=-[E(M1)+2(\overline{\Delta E_C}-\delta)] , \quad (2)$$

where $\overline{\Delta E_C}$ is the average Coulomb energy, and $\delta=m_n-m_p=1.29$ MeV is the neutron-proton mass difference. In inelastic scattering a strong isovector $M1$ transition has been observed on ^{12}C for the 15.11 MeV ($T=1$, $J^\pi=1^+$) state [19,20]. Using $\overline{\Delta E_C}=3.16$ MeV yields $Q(|\mathrm{GT}\otimes\mathrm{IAS}\rangle)=-18.85$ MeV, surprisingly close to the g.s. of ^{13}O. In the simplest model a coupling of the 1^+ Gamow-Teller transition to the $^{13}\mathrm{N}_{\mathrm{g.s.}}$ (the isobaric analog of $^{13}\mathrm{C}_{\mathrm{g.s.}}$) gives a pair of states with $\frac{1}{2}^-$ and $\frac{3}{2}^-$. Can we identify these states in ^{13}O in the present study? It is most likely that $^{13}\mathrm{O}_{\mathrm{g.s.}}$ has $J^\pi=\frac{3}{2}^-$, the same as the mirror nucleus $^{13}\mathrm{B}_{\mathrm{g.s.}}$ [10]. From the $A=13$ isobar diagram it is also obvious [10] that $^{13}\mathrm{O}_{\mathrm{g.s.}}$ is the analog of the well-known Gamow-Teller states at 15.06 and 15.11 MeV ($T=\frac{3}{2}$, $J^\pi=\frac{3}{2}^-$) in ^{13}N and ^{13}C, respectively, and thus is a natural candidate for the $\frac{3}{2}^-$ member of the $|\mathrm{GT}\otimes\mathrm{IAS}\rangle$. It is, therefore, puzzling that in the present study this transition does not show the expected spin-flip character. This may result from the fact that a g.s.($\frac{1}{2}^-$) $\rightarrow$ g.s.($\frac{3}{2}^-$) transition may proceed via both $L=0$, $S=1$ Gamow-Teller, and $L=2$, $S=0$ electric quadrupole transitions built on the IAS. This is consistent with the nearly constant angular distribution, observed for the $^{13}\mathrm{O}_{\mathrm{g.s.}}$ in an earlier DCX reaction on ^{13}C at two pion energies, 164 and 292 MeV [21]. The two multipoles would mask the characteristic angular distribution and the spin-flip nature of the transition. A good candidate for the $\frac{1}{2}^-$ state in ^{13}O is the 4.5-MeV state. This state is fitted in our work with a $\sin^2(\theta)$ dependence and thus might be the missing $\frac{1}{2}^-$ member of the $|\mathrm{GT}\otimes\mathrm{IAS}\rangle$. In addition, a close state (4.2 MeV) was reported in the work of Seidl *et al.* [21]. It was tentatively assigned $J^\pi=\frac{1}{2}^-$ based on its forward-peaked angular distribution, which exhibits a simple diffractive $\Delta J=0$ shape. The GT resonance was not observed in any previous pion SCX data due to limited energy resolution of previous π^0 spectrometers. Therefore no reliable calculations can be done at this time to quantitatively compare the measured cross sections with the predicted cross sections for the $|\mathrm{GT}\otimes\mathrm{IAS}\rangle$. This issue poses a new experimental and theoretical challenge in pion physics. However, one can make a very simple estimate for the expected cross section for the $|\mathrm{GT}\otimes\mathrm{IAS}\rangle$ assuming a sequential mechanism (i.e., a GT transition followed by an IAS transition in the second step or vice versa):

$$\sigma(\mathrm{GT}\otimes\mathrm{IAS})\simeq\sigma(\mathrm{GT})\frac{\sigma(\mathrm{IAS})}{\sigma_{\mathrm{tot}}}\,. \quad (3)$$

If we use the isovector $M1$ on $^{12}\mathrm{C}$ for the GT cross section [19], an extrapolated IAS cross section on $^{13}\mathrm{C}$ [15], and a total reaction cross section on carbon from Ref. [22], the predicted cross section for the $|\mathrm{GT}\otimes\mathrm{IAS}\rangle$ around $T_\pi=180$ MeV is about 0.12 μb/sr, surprisingly close to the measured cross section for the low-lying states in the present study.

The solid line shown in Fig. 1(e) is the result of the simple sequential model analysis discussed earlier. The calculations with a fixed transition strength for the GDR and the IAS give an adequate representation of the measured excitation function for this resonance. This analysis indicates that the excitation of the $|\mathrm{GDR}\otimes\mathrm{IAS}\rangle$ in this energy region proceeds by a two-step sequential (π^+,π^0), (π^0,π^-) mechanism and, therefore, pion DCX should be a unique probe for exciting isotensor double giant resonances in nuclei.

In conclusion, we have reported the first measurement of a constant-q excitation function for the giant dipole resonance built on the isobaric analog state. The cross section increases with energy by a factor of 1.73 ± 0.42 between 140 and 295 MeV. The excitation function has a characteristic non-spin-flip signature. Results from simple sequential model calculations indicate that pion DCX excites this resonance predominantly via a two-step sequential process. Three low-lying states in $^{13}\mathrm{O}$ at $E_x=3.1$, 4.5, and 6.1 MeV have been observed. They have a spin-flip signature and thus may be associated with the giant Gamow-Teller resonance built on the isobaric analog state.

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