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STUDY OF ISOVECTOR RESONANCES WITH PION CHARGE EXCHANGE *

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ABSTRACT

Studies with the pion charge exchange reactions ($\pi^{\pm}, \pi^0$) at 164 MeV using the LAMPF π^0 spectrometer are yielding new results on the existence and systematic features of isovector resonances in nuclei. These experiments possess an unusually high signal/background ratio for isovector resonances of low-multipolarity. Results obtained to date are:

1. Observation and angular distribution measurement of the giant dipole resonance in nuclei ^{12}C , ^{40}Ca , ^{90}Zr , and ^{120}Sn .
2. Observation and angular distribution measurements in the (π^{-}, π^0) reaction on ^{90}Zr and ^{120}Sn of large signals possessing the expected angular distribution shapes and magnitudes for the isovector monopole resonance. Excitation energies are near the hydrodynamical model values $170 \text{ A}^{-1/3} \text{ MeV}$. Differential cross sections are approximately $0.7 J_1^2(qR) \text{ mb/sr}$.

An overview of this experimental program, with emphasis on new results and how they correlate with existing knowledge on the isovector resonances, will be presented.

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STUDY OF ISOVECTOR RESONANCES WITH PION CHARGE EXCHANGE

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I. INTRODUCTION

Pion charge exchange reactions offer significant advantages to the study of collective isovector states. These are:

- (1) The $\Delta T = 0$ transitions which dominate inelastic scattering are turned off in charge exchange, since $\Delta T_z = \pm 1$.
- (2) The $\Delta S = 1$ (spin-flip) transitions are greatly suppressed at forward angles since the pion has spin -0 .
- (3) The strong absorption of pions with energies 100 to 300 MeV leads to sharply oscillating angular distributions. This provides a good signature to the L-transfer in the scattering.
- (4) One can use both (π^+, π^0) and (π^-, π^0) reactions in the same experiment under identical kinematic conditions. Comparison of the two reactions aids in separating the continuum from the resonance. It allows one to observe the isospin splitting directly in the spectra as a displacement in the π^0 kinetic energy. The ratio of cross sections $\sigma(\pi^+, \pi^0)/\sigma(\pi^-, \pi^0)$ reflects directly the Pauli exclusion principle with respect to the excess neutrons.
- (5) Measurements at 0° (and 180°) can be performed routinely since the photon detectors for the measured $\pi^0 \rightarrow 2\gamma$ decay are out of the beam line.

Figure 1 shows the expected angular distributions at forward angles for the $^{40}\text{Ca}(\pi^-, \pi^0)$ and $^{120}\text{Sn}(\pi^\pm, \pi^0)$ reactions at 164 MeV. For these DWIA calculations¹⁾ we used Tamari²⁾ model transition densities,

$$\rho_T(r) = M(3\rho + d\rho/dr) \quad L = 0.$$

$$D \, d\rho/dr \quad L = 1$$

$$= r \, d\rho/dr \quad L = 2$$

where $\rho = \rho_n + \rho_p$ is the sum of neutron and proton transition densities. The form factors were normalized to exhaust the appropriate energy-weighted sum rule, neglecting the isospin dependence of the nuclear potential. We note that with these transition densities, the calculations show the monopole cross section at 0° as being much larger than either the dipole or quadrupole maximum cross sections. This is quite favorable to the detection of the monopole state. Also, the clear signature to L-value given by the angular distribution shapes is evident from the figure. Cross sections in the range 0.3 to 1.0 mb/sr can be measured in several hours of running using the LAMPF π^0 spectrometer mounted at the low-energy pion (LEP) channel in Los Alamos.

II. EXPERIMENTAL PROCEDURES

The data reported here were measured³⁾ in a six-week period March 1981. Target thicknesses were 2-3 g/cm². Pion fluxes were typically 10^7 sec^{-1} . The π^0 spectrometer³⁾ was mounted in its two-post configuration which gives a vertical scattering plane. The target-to-converter distance was 1 m and the detector separation angle was 61.3° . The data were taken with the spectrometer set for scattering angles 0 and 20° . Since the angular acceptance is broad, the data taken at each setting could be sorted into several narrower ranges of scattering angle. The energy and angular dependence of the spectrometer acceptance, as well as the line shape, were calculated using Monte Carlo techniques. The absolute spectrometer acceptance was measured using the reaction $\pi^-p \rightarrow \pi^0n$ on a CH₂ target. The experimental energy resolution was typically 5-MeV FWHM and was accurately reproduced with the Monte Carlo

alculation. The analyses presented here used cuts that gave large efficiencies while maintaining reasonable energy resolution. In particular, values of the energy balance parameter $|X| \leq 0.2$ were accepted. The one exception is the ^{40}Ca data shown in Fig. 4, which represents an analysis with $|X| \leq 0.1$.

III. DIPOLE RESULTS

The electric giant dipole resonance (GDR) is the only well established isovector resonance. It is a prominent feature of the photon absorption spectrum of all nuclei. The SU_4 generalizations⁴⁾ of the photonuclear GDR allow for spin transfer ($\Delta S = 1$) and charge transfer ($\Delta T_z = \pm 1$) in the excitation. These generalizations are based on spin and isospin symmetries of the nuclear Hamiltonian. The dynamical aspects, particularly the spreading and decay widths of these excitations, were quite unknown. Significant progress on the verification of the SU_4 model came recently with the discovery⁵⁾ of resonance-like peaks in the (p,n) spectra at $q \approx 80 \text{ MeV/c}$. These peaks are a systematic feature of the charge-exchange scattering on nuclei with $A \geq 40$. They have a width of approximately 10 MeV FWHM. The transferred quantum numbers are $\Delta L = 1$, $\Delta S = 1$, $\Delta T = 1$, $\Delta T_z = -1$. For heavy, even-even nuclei this produces states with $J^\pi = 0^-, 1^-, \text{ and } 2^-$ and $T = T_0 - 1$ where $T_0 \equiv (N - Z)/2$ is the isospin of the target nucleus.

Further important tests of the generalized dipole resonance are possible with pion charge exchange reactions. Unlike the (p,n) reaction, the $(\pi^\pm, \pi^0)$ reactions are dominated by $\Delta S = 0$ transitions. This means that dipole states observed with pions are closer analogs to the photonuclear GDR. This is important for measuring isospin-splitting energies $\Delta E^+ \equiv E_x(T_0 + 1) - E_x(T_0)$ and $\Delta E^- \equiv E_x(T_0) - E_x(T_0 - 1)$, where $E_x(T_0)$ is the excitation energy of the spin-independent E1 GDR as measured in photo-nuclear experiments. It will be of

interest to compare the resonance parameters E_x and Γ of spin-dipole and spin-independent-dipole states. This is possible for the $T_0 - 1$ component by comparing results of the (π^+, π^0) and (p, n) reactions. Another attractive possibility with pions is the study of the properties of the $T_0 + 1$ resonance using the (π^-, π^0) reaction. This component differs fundamentally from the T_0 and $T_0 - 1$ states since it occurs at an energy in the excitation spectrum where the level density is low for states of the same isospin. In ^{120}Sn , to be discussed below, the $T = T_0 + 1 = 11$ dipole resonance occurs at 3 MeV above the lowest $T = 11$ state. The spreading width of states at 3 MeV excitation is negligibly small. Thus the $T_0 + 1$ component is a discrete collection of sharp 1^- states (GDR) or 0^- , 1^- , and 2^- states (spin-GDR). In the $T_z = T_0$ or $T_0 - 1$ nuclei these sharp states will be broadened by the decay width. In the $T_z = T_0 + 1$ nucleus the decay width is negligibly small or zero for nuclei with $A \geq 90$.

$^{40}\text{Ca}(\pi^\pm, \pi^0)$. The strength of the pion-induced dipole signal and the signal-to-background ratio may be seen in Fig. 2(b). For comparison we show also the $^{40}\text{Ca}(p, n)$ spectrum.⁵⁾ The arrows in Fig. 2(a) and 2(b) show the expected positions of the GDR at 20 MeV in ^{40}Ca . The momentum transfer q is ≈ 65 MeV/c for both spectra. The two spectra look quite similar, and one might be tempted to conclude that the two charge exchange reactions, when compared at the same q value, excite the same states. From our present understanding, this is not the case. Nearly the entire (p, n) cross section in the GDR region is being interpreted as due to $\Delta L = 1$, $\Delta S = 1$ transitions to 0^- , 1^- , and 2^- states. We interpret the (π^+, π^0) cross section in the GDR region as being due to $\Delta L = 1$, $\Delta S = 0$ transitions to 1^- states.

In Fig. 3 we give the comparison of the dipole signal for ^{40}Ca in the (π^+, π^0) and (π^-, π^0) reactions. The Coulomb shift in mass of the state due to the addition of two units of charge is expected⁶⁾ to be 12 MeV. The data show this shift nicely, yielding a measured value 12.1 ± 0.4 MeV. The displayed spectra have the continuum subtracted. The assumed shape for the continuum is the measured spectrum at 4.5° . The availability of both the (π^+, π^0) and the (π^-, π^0) data on the same target nucleus is a useful feature. The comparison is an aid in distinguishing resonance peaks from the continuum. A nuclear eigenstate must shift according to the Coulomb displacement energy, whereas the continuum will be subject to the influence of various channel thresholds and due to effect of the Coulomb barrier in inhibiting charged particle emission in a multiparticle final state.

Figure 4 shows the $^{40}\text{Ca}(\pi^+, \pi^0)$ data in six angular bins. The dipole state is seen to have a sharp angular structure, with a maximum cross section near 15° . Second, we note that the continuum to the left of the dipole, corresponding to an excitation energy of 20-60 MeV in ^{40}Sc , has a rather constant cross section as a function of angle for $\theta \leq 22^\circ$. This seems to be a general feature of the $(\pi^\pm, \pi^0)$ reactions at forward angles. Thus, to extract resonance cross sections, we generate difference spectra which are obtained by a channel-by-channel subtraction of the measured double-differential cross sections at different angles. For ^{40}Ca , we subtracted the 4.5° spectrum from the other spectra. The excess counts in a 12-MeV interval centered on the dipole state were taken for the cross-section determination. The angular distributions obtained in this manner are shown in Fig. 5. The curves in the figure represent DWIA calculations using the Goldhaber-Teller transition density $D \, dp/dr$. One sees that the calculations represent the shape of the measured angular distribution quite well. The cross-section magnitudes are coming out

factors of 2-3 too low. The source of this discrepancy is not known at this time. One should note that absolute cross sections for pion inelastic scattering to strong states are at best accurate to a factor of two.

$^{90}\text{Zr}(\pi^-, \pi^0)$. In Fig. 6 we show the measured spectrum for this reaction at 15° . One can see a peak near 8-MeV excitation in ^{90}Y . To extract the peak parameters we generated difference spectra as discussed above. One such spectrum is shown in Fig. 7. These data were fit for two states, the monopole resonance to be discussed in Sec. IV, and a dipole state. The resulting dipole energy is $E_x(^{90}\text{Y}) = 7.8 \pm 0.8 \text{ MeV}$ for an assumed width $\Gamma = 0$. The angular distribution determined from the difference spectra is shown in Fig. 8(a). The maximum dipole cross section for ^{90}Zr is 0.42 mb/sr which occurs at 14° . The curve shown with the data represents a DWIA calculation with a transition density of form $D \, dp/dr$. The good agreement between the shape of the data and the curve identify the state as a dipole excitation.

The analog of the observed dipole state in ^{90}Y occurs in ^{90}Zr at $20.9 \pm 0.8 \text{ MeV}$. The known⁷⁾ $T = 5$, GDR is centered at 16.9 MeV and has a width $\Gamma = 4.0 \text{ MeV}$. The expected splitting of the GDR is $60(T_0 + 1)/A = 4.0 \text{ MeV}$. Thus an excitation energy of approximately 21 MeV is expected for the $T = 6$ GDR in ^{90}Zr .

In the study of the $^{89}\text{Y}(p, \gamma)^{90}\text{Zr}$ reaction by Hasinoff et al.,⁷⁾ two states at 19.4 and 21.0 MeV were identified as 1^- , $T = 6$ states. The $E1 \, \gamma$ -width for the 21.0-MeV state is approximately five times larger than for the 19.4-MeV state. In view of the proportionality of the $(\pi^-, \pi^0)\text{GDR}$ cross sections with $E1$ strength as seen in the $^{40}\text{Ca}(\pi^\pm, \pi^0)$ reactions, it seems reasonable to associate most of the cross section to the $7.8 \pm 0.8 \text{ MeV}$ state with the 21.0-MeV state observed in the (p, γ) study.

$^{120}\text{Sn}(\pi^-, \pi^0)$. The angular distribution for the dipole state is shown in Fig. 8(b). It was determined from the difference spectra using the 4.5° spectrum as the reference spectrum. The maximum dipole cross section occurs at approximately 12° where it has a magnitude of 0.15 mb/sr. The extracted excitation energy corresponds to 3.2 ± 0.9 MeV in ^{120}In and 21.3 ± 0.9 MeV in ^{120}Sn . This is in good agreement with the 20.9 MeV obtained by Shoda⁸⁾ by use of the $(e, e'p)$ reaction.

$^{120}\text{Sn}(\pi^+, \pi^0)$. The limited data we have on this reaction does show the presence of the dipole resonance. The partially measured angular distribution is shown in Fig. 8(c). The measured excitation energy is 20.7 ± 1.2 MeV in ^{120}Sb . This is close to the value 21.9 ± 0.3 MeV obtained by Sterrenburg et al.⁹⁾ from the (p, n) reaction. The maximum (π^+, π^0) GDR cross section occurs at 11° and has the value 0.54 mb/sr.

Dipole Summary

Our dipole results are summarized in Table I. Our conclusions from these results are:

- (1) Pion charge exchange produces a clear GDR signal in both (π^+, π^0) and (π^-, π^0) reactions. Our data demonstrate this for $A = 12-120$.
- (2) The angular distributions are sharply oscillating and thereby give a good $\Delta L = 1, \Delta S = 0$ signature. The shapes can be described approximately by $J_1^2(q_\perp R)$ where $q_\perp$ is the perpendicular component of the momentum transfer and R is the interaction radius.

- (3) The maximum values of the (π^-, π^0) cross sections are given approximately by $0.7 \text{ mb/sr} \times B$, where B is an A and T dependent blocking factor which takes into account the Pauli principle.
- (4) The $T_0 + 1$ GDR components are observed for ^{90}Zr and ^{120}Sn . These measurements constitute the first observation of the parent states ($M_T = \pi$) and thereby provide the first definitive isospin determination for these states.
- (5) The $^{120}\text{Sn}(\pi^\pm, \pi^0)$ data are the first measurement of the ratio

$$\frac{\sigma(T_0 - 1)}{\sigma(T_0 + 1)} = \frac{\sigma(\pi^+, \pi^0)}{\sigma(\pi^-, \pi^0)} \approx 4.$$

This ratio reflects directly the role of the excess neutrons in blocking proton-to-neutron conversion in the (π^-, π^0) scattering, and the enhancement of neutron-to-proton conversion (as compared to inelastic scattering) made possible by the excess neutrons.

IV. MONOPOLE RESULTS

Macroscopic¹⁰⁾ as well as microscopic¹¹⁾ theories of nuclear structure predict the existence of a collective isovector monopole (IVM) excitation in nuclei. The expected excitation energy is near $170 A^{-1/3}$. There has been no clear experimental evidence for such a state. We give here evidence for the existence of an isovector monopole resonance in ^{90}Zr and ^{120}Sn based on the (π^-, π^0) reaction at 164 MeV.

$^{120}\text{Sn}(\pi^-, \pi^0)$. Figure 9 shows the measured π^0 spectra at angles 4.5, 7, and 11°. These spectra are seen to consist of a narrow feature at a π^0 energy of 145 MeV that diminishes as the scattering angle is decreased, superimposed on a broad continuum. A difference spectrum of the 4.5 and 11° data is shown in Fig. 10. For π^0 energies below 135 MeV there is statistically perfect cancellation indicating isotropy for this part of the spectrum. A positive peak is seen near 150 MeV, and there is a smaller negative peak near 160 MeV. The line is a fit to two peaks. The amplitudes and positions of each of the peaks were varied. The measured instrumental line shape was used for the high energy peak and the lower peak width was varied. The monopole resonance parameters determined from this fit are $E_x(^{120}\text{In}) = 12.9 \pm 0.9$ MeV and $\Gamma = 7.2 \pm 2.0$ MeV. Assuming a value⁶⁾ of 13.53 MeV for the Coulomb displacement energy, we obtain an energy of 30.9 ± 0.5 MeV for this state in ^{120}Sn .

To extract the monopole and dipole angular distributions, the peak centroids and widths were held fixed and the other difference spectra were fit for peak areas. The resulting angular distribution for the monopole state is shown in Fig. 11(b). The line is a DWIA calculation with a Tassí model transition density. The shape of the measured angular distribution is well described and thereby establishes an $L = 0$ transition multipolarity. The magnitude of the calculated curve was multiplied by 0.68 to account for blocking and by 0.88 to give the best overall fit to the data points. Since the Tassí model represents a collective monopole oscillation, the size of the measured cross section indicates a collective nature for the observed state.

$^{120}\text{Sn}(\pi^+, \pi^0)$. The three measured spectra are shown in Fig. 12. The isobaric analog state is a prominent feature in spectra at forward angles. Evidence for the dipole and monopole states is also present in the difference spectrum shown in Fig. 13. The data were analyzed as follows. The IAS peak was taken to have the instrumental line shape. The width of the GDR was fixed at 3.6 MeV as determined⁹⁾ by the (p,n) reaction. It was not possible to simultaneously fit the position and width of the IVM peak, which appears to be broad and overlapping with the dipole peak. Its width was allowed to vary and its position was fixed assuming an isospin splitting of 7.3 MeV between the $T = 9$ and $T = 11$ components. This value was given as the result of an RPA calculation of Auerbach and Klein.¹²⁾ This procedure gave the angular distribution shown in Fig. 11(c). Although the data are limited, they are consistent with a forward-peaked feature at the expected monopole position.

A summary of extracted monopole parameters is given in Table II. A complete representation of the IAS, monopole, and dipole isovector resonances built on ^{120}Sn is shown in the level diagram of Fig. 14. These data constitute the most complete knowledge of isovector resonances we have on any nucleus.

$^{90}\text{Zr}(\pi^-, \pi^0)$. The data on this reaction also show the presence of a monopole signal. A difference spectrum for the 4.5 and 22.0° data is shown in Fig. 15. The monopole state is broader in ^{90}Zr than in ^{120}Sn and it appears to overlap with the dipole state. A two-peak analysis similar to that done for ^{120}Sn was performed. This yielded for the monopole state $E_x(^{90}\text{Y}) = 21.3 \pm 1.3$ MeV and $\Gamma = 14.4 \pm 2.3$ MeV. This gives 34.4 ± 1.3 MeV for the state in ^{90}Zr . The measured angular distribution, together with the DWIA calculation, is shown in Fig. 11(a). The good agreement on the shape of the angular distribution identifies this component as having $L = 0$. The magnitude of the

calculated curve was multiplied by 0.99 to account for blocking and by 1.03 to give the best fit to the data.

Monopole Summary

Our monopole results are summarized in Table II. Our conclusions from these results are:

- (1) The observed signal in the (π^-, π^0) reaction on ^{90}Zr and ^{120}Sn has a forward-peaked angular distribution as expected for the monopole state. It can be described approximately by $d\sigma/d\Omega \approx 0.7J_0^2(q_\perp \bar{R})$ mb/sr, where the interaction radius $\bar{R}$ has a value close to that deduced from elastic pion scattering.
- (2) The excitation energies for the observed states are several MeV lower than given by $170 A^{-1/3}$. This is in agreement with recent RPA calculations.
- (3) The resonance widths vary from approximately 14 MeV in ^{90}Y to 7 MeV in ^{120}In .
- (4) The magnitudes of the cross sections agree closely with DWIA calculations that use the Tassl model transition density $M(3p + rdp/d\Omega)$ where M is determined from an energy-weighted sum rule limit and that are scaled downward to account for Pauli blocking effects by the factors expected from RPA calculations.

TABLE I. DIPOLE RESULTS

Observable	This Work		Other	Source
$\frac{d\sigma}{d\Omega_{\max}} (\pi^-, \pi^0), \frac{\text{mb}}{\text{sr}}$	0.85	^{12}C	0.25	DWIA (B = 1)
	0.84	^{40}Ca	0.26	DWIA (B = 1)
	0.42	^{90}Zr	0.24	DWIA (B = 1)
			0.12	DWIA (B = 0.5) ^a
	0.15	^{120}Sn	0.23	DWIA (B = 1)
			0.045	DWIA (B = 0.2) ^a
$\frac{d\sigma}{d\Omega_{\max}} (\pi^+, \pi^0), \frac{\text{mb}}{\text{sr}}$	0.54	^{40}Ca	0.23	DWIA (B = 1)
	0.56	^{120}Sn	0.23	DWIA (B = 1)
			0.39	DWIA (B = 2.02) ^a
$E_x(T_0 + 1), \text{ MeV}$	23.0	^{12}C	23.0	$\sigma(\gamma, \text{abs})$
	20.0	^{40}Ca	20.0	$\sigma(\gamma, \text{abs})$
	20.9	^{90}Zr	21.0	$^{89}\text{Y}(p, \gamma)^b$
	21.3	^{120}Sn	20.5	$\sigma(e, e'p)^c$
$\Delta E^+ = E_x(T_0 + 1) - E_x(T_c)$	4.0 ± 0.8	^{90}Zr	3.9	$\sigma(e, e'p)^c$
	5.9 ± 0.9	^{120}Sn	5.5	$\sigma(e, e'p)^c$
$\Delta E^- = E_x(T_0) - E_x(T_0 - 1)$	5.2 ± 1.2	^{120}Sn	3.6	$\sigma(p, n)^d$

B is blocking factor to account for Pauli exclusion principle.

- ^a Ref. 12.
^b Ref. 7.
^c Ref. 8.
^d Ref. 9.

TABLE II. MONOPOLE RESULTS

Observable		This Work	Other	Source
<u>^{120}Sn</u>				
$\bar{R},^a$	fm	6.7 ± 0.5	6.6	π -elastic
$\frac{d\sigma}{d\Omega}(0^\circ),$	$\frac{\text{mb}}{\text{sr}}$	0.56 ± 0.06	0.93	DWIA ($B = 1$)
			0.64	DWIA ($B = 0.68$) ^b
$E_x(T_0 + 1),$	MeV	30.9 ± 0.5	34.5	$170 A^{-1/3}$
			31.2	TDA ^b
			35.9	RPA ^b
$\Gamma,$	MeV	7.2 ± 2.0	?	
<u>^{90}Zr</u>				
$\bar{R},$	fm	6.0 ± 0.4	6.05	π -elastic
$\frac{d\sigma}{d\Omega}(0^\circ),$	$\frac{\text{mb}}{\text{sr}}$	0.88 ± 0.13	0.85	DWIA ($B = 1$)
			0.85	DWIA ($B = 0.99$) ^b
$E_x(T_0 + 1),$	MeV	34.4 ± 1.3	37.9	$170 A^{-1/3}$
			34.6	TDA ^b
			34.5	RPA ^b
$\Gamma,$	MeV	14.4 ± 2.3	?	

^a $\bar{R}$ was determined by fitting the function $aJ_0^2(q\bar{R})$ to the data allowing a and $\bar{R}$ to vary.

^b Ref. 12.

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Fig. 1. Representative DWIA calculations with Tass' model transition densities for pion charge exchange scattering on ^{40}Ca and ^{120}Sn . The labels identify the isovector states as follows: M = monopole, D = dipole, Q = quadrupole, IAS = isobaric analog states. Note that the $L = 0$ transitions (M and IAS) have considerably larger maxima than other transitions.

Fig. 2(a). $^{40}\text{Ca}(p,n)$ data shown by K. Gaarde.⁵⁾

Fig. 2(b). The π^0 spectrum for the $^{40}\text{Ca}(\pi^+, \pi^0)$ reaction at an angle where the GDR has the maximum cross section. The measured spectrum (smoothed) at 4.5° is shown for comparison. The arrow in both (a) and (b) marks the expected positions of the GDR at 20 MeV excitation in ^{40}Ca .

Fig. 3. The π^0 spectra at 14° after subtraction of the continuum. The arrows mark the expected position of the GDR. The peaks are displaced by 12 MeV due to the difference in Coulomb energies.

Fig. 4. The measured π^0 spectra for the $^{40}\text{Ca}(\pi^+, \pi^0)$ reaction at 164 MeV. The arrow marks the expected position of the analog of the giant dipole resonance at 20-MeV excitation in ^{40}Ca . The solid line in all panels is the smoothed, but not renormalized, 4.5° spectrum.

Fig. 5. The measured cross section differences $d\sigma/d\Omega(0) - d\sigma/d\Omega(4.5^\circ)$ are compared with DWIA calculations for $\Delta L = 1$, $\Delta S = 0$ transitions. The error bars reflect the statistical error associated with the analysis that assumed that the background underneath the GDR is given by the measured 4.5° spectrum.

Fig. 6. The spectrum at 15° for the $^{90}\text{Zr}(\pi^-, \pi^0)$ reaction at 164 MeV. The arrow indicates the measured position of the $T = 6$ dipole state at 7.9 ± 0.8 MeV in ^{90}Y .

Fig. 7. The difference spectrum for the $^{90}\text{Zr}(\pi^-, \pi^0)$ reaction used to determine the energy of the dipole state. The line shows the fit assuming a monopole (M) and dipole (D) state.

Fig. 8. Measured dipole angular distributions for $N > Z$ nuclei. The lines represent DWIA calculations adjusted in magnitude to fit the data.

Fig. 9. Spectra at three forward angles for the $^{120}\text{Sn}(\pi^-, \pi^0)$ reaction. The arrows mark the measured positions of the $T = 11$ monopole (M) and dipole (D) states. The excitation energies in ^{120}In are 12.9 ± 0.9 MeV and 3.3 ± 0.9 MeV, respectively. The measured monopole resonance width is $\Gamma = 7.2 \pm 2.0$ MeV.

Fig. 10. The difference spectrum for the $^{120}\text{Sn}(\pi^-, \pi^0)$ reaction used to determine the monopole and dipole peak parameters.

Fig. 11. Measured monopole angular distributions for $N > Z$ nuclei. The lines represent DWIA calculations adjusted in magnitude to fit the data. The lowest panel is for the IAS state of the $^{120}\text{Sn}(\pi^+, \pi^0)$ reaction.

Fig. 12. Spectra at three forward angles for the $^{120}\text{Sn}(\pi^+, \pi^0)$ reaction at 164 MeV. The forward-angle peaking of the isobaric analog state (IAS) and the rise of the dipole state (D) with increasing angle are clearly visible in the data. The arrow marked M shows the expected position of the $T = 9$ monopole (M) state. The difference spectrum (Fig. 13) shows forward-angle peaking for the region of the spectrum.

Fig. 13. The difference spectrum for the $^{120}\text{Sn}(\pi^+, \pi^0)$ reaction used to extract IAS dipole and monopole state parameters.

Fig. 14. Level diagram showing the measured isovector resonance built on the ^{120}Sn ground state. The energies of the T = 11 monopole and dipole states measured for ^{120}In are projected to ^{120}Sn and ^{120}Sb using Coulomb displacement energies.

Fig. 15. The difference spectrum for the $^{90}\text{Zr}(\pi^-, \pi^0)$ reaction used to extract the monopole and dipole state parameters.