Observation of the Nuclear Isovector Monopole Resonance

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Observation of the $T+1$ component of the isovector monopole and the giant dipole resonances in the reactions ^{90}Zr and ^{120}Sn(π^-,π^0) at $T_{\pi^-}=165$ MeV is reported. The isobaric analog state and $T-1$ component of the giant dipole resonance in the reaction ^{120}Sn(π^+,π^0) were also observed. Excitation energies and widths of the monopole are given.

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Macroscopic[1] as well as microscopic[2] theories of nuclear structure hypothesize the existence of a collective isovector monopole (IVM) excitation of the nucleus. The possibility of experimentally observing the IVM was discussed as early as 1958 by Danos,[3] who estimated the electroexcitation cross section. Isoscalar collective excitations with angular momentum $l=0$, 2, and 3 have been observed and studied in hadron and electron scattering while the isovector dipole or giant dipole resonance (GDR) is a prominent feature of the scattering of electrons and photons from nuclei. Evidence has been given for the observation of the isovector quadrupole resonance.[4] However, at present there is no clear experimental evidence for the IVM.[5]

Recently, arguments have been given that the (π^-,π^0) reaction at energies near the (3, 3) resonance might detect the IVM.[6] These arguments are supported by the previously reported observation[7] of the GDR in the $(\pi^\pm,\pi^0)$ reactions on ^{40}Ca. Pion charge-exchange excitation of the IVM is expected to have the following qualitative properties: (1) a zero-degree cross section of a few hundred microbarns per steradian; (2) a forward-peaked angular distribution; and (3) an excitation energy of approximately $170/A^{1/3}$ MeV in the parent nucleus.

Here we report the observation of the IVM in the (π^-,π^0) reaction at pion kinetic energy 165 MeV on ^{90}Zr and ^{120}Sn. Results for ^{120}Sn(π^+,π^0) are also discussed. The experiments were carried out at the low-energy pion channel at the Clinton P. Anderson Meson Physics Facitity (LAMPF). The LAMPF π^0 spectrometer[8] was used to measure the direction and energy of the outgoing π^0. Data were taken at spectrometer angles of 0° and 20° and sorted into several narrower ranges of scattering angle. The spectrometer acceptance and line shape were measured with the reaction $\pi^-p\to\pi^0n$ at 165 MeV. The ratio of calculated to measured acceptance was found to be independent of scattering angle to within the 4% statistical errors of the measurement.

Figure 1 shows the double-differential cross sections for the reactions ^{120}Sn(π^+,π^0) and ^{120}Sn(π^-,π^0) as functions of π^0 energy for scattering angles of 4.5°, 6.8°, and 11.0°. The isobaric analog state (IAS) is clearly visible in the (π^+,π^0) data at a π^0 energy of 157 MeV. The cross section for excitation of this $l=0$ state is seen to decrease as the scattering angle increases. The IVM is seen in the (π^-,π^0) data at a π^0 energy of 150 MeV. The angular dependence is similar to that of the IAS as expected.

To perform a quantitative analysis we make the assumption that the double-differential cross section consists of resonance peaks superimposed

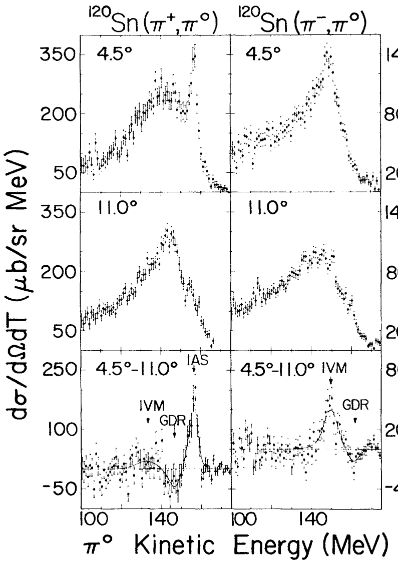

FIG. 1. Double-differential cross sections for reactions $^{120}Sn(\pi^{\pm},\pi^0)$ at angles of 4.5° and 11.0° and the results of subtracting the 11.0° spectra from the 4.5° spectra.

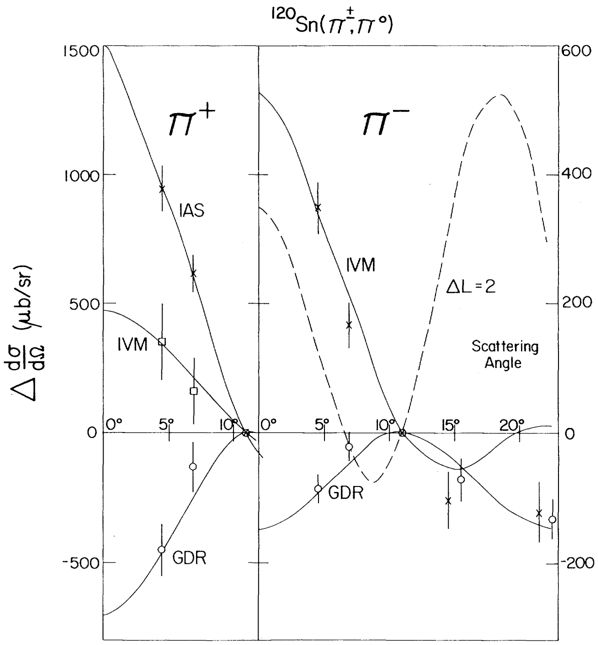

FIG. 2. Angular distributions for difference spectra. The angle used as a reference has no error bar. The solid lines are distorted-wave impulse approximation shapes normalized to the data. The dashed curve is the quadrupole shape.

on an isotropic background. Figure 1 also shows the spectra that result from subtracting the 11.0° spectra from the 4.5° spectra. The π^+ (π^-) difference spectra are consistent with isotropy for π^0 energies below 120 (135) MeV where no giant resonance peaks are expected. The IAS and IVM peaks are clearly seen in the π^+ and π^- difference spectra, respectively.

We extracted angular distributions by performing least-squares fits to the difference spectra. The energy dependence of the trial functions was the instrumental line shape convolved with a Gaussian function. The energy and width of each peak were held constant from angle to angle. For the π^- data the width of the GDR peak was taken to be the instrumental width since it is expected to be quite narrow as a result of its low excitation energy (3.3 MeV in ^{120}In). For the π^+ data the IAS peak was assumed to be sharp, and the GDR peak was broadened by 3.6 MeV as measured by Sterrenburg *et al.*[9] The π^+ difference spectrum appears to have an excess of cross section near 130 MeV which may be the $T-1$ component of the IVM. A width of 20 MeV was taken from Ref. 10 and its energy was fixed at 136.1 MeV by taking the $T+1$, $T-1$ isospin splitting to be 11.1 MeV from Ref. 10. The extracted angular distributions for the IAS, GDR, and IVM, in which the fitted peak areas are plotted versus angle, are shown in Fig. 2. In Table I we show the energies and widths and the results of random-phase-approximation (RPA) calculations.[10]

We calculated theoretical angular $d\sigma/d\Omega(\theta)_t$ distributions by adopting the zero-range distorted-wave impulse approximation (DWIA). The isoscalar and isovector parameters of the elementary t matrix were taken from Rowe, Salomon, and Landau.[11] For transition densities, we used the Tassie[12] form. Transition densities were normalized to saturate the energy-weighted sum rule. The ratios of reduced matrix elements for transitions to $T+1$, T, and $T-1$ components of each resonance were taken from Ref. 10.

The experimental peak areas were fitted by the calculated angular distributions by using trial functions of the form $R[d\sigma/d\Omega(\theta)_t - d\sigma/d\Omega(\theta_{Ref})_t]$. Here R is a normalization and θ_{Ref} is the angle of the subtracted spectrum. The (π^-,π^0) monopole angular-distribution data are inconsistent with an orbital angular momentum transfer of 2 since there is no second maximum at $\theta = 18°$. The fitted normalizations given in Table II establish the collective nature of the observed resonances. The cross section of the broad peak which we tentatively identify as the $T-1$ com-

TABLE I. Excitation energies and widths of nuclear resonances observed in the reactions ^{120}Sn and ^{90}Zr with $(\pi^{\pm}, \pi^0)$.

A	Resonance (T, T_z)	Excitation energies[a] (MeV) This work	Other expts.	RPA theory	Γ[b]
120	IVM (11,11)	19.6 ± 0.5		23.7	7.0 ± 2.0
	GDR (11,11)	9.1 ± 0.85	8.7[c]	7.75	0[c]
	IAS (10,9)	12.6 ± 0.2	12.4		≈ 0
	GDR (9,9)	22.8 ± 1.2	24.2[d]	24.3	3.6[d]
90	IVM (6,6)	24.1 ± 1.3		24.2	13.2 ± 2.3
	GDR (6,6)	10.3 ± 0.7	10.4[e]	9.5	1.5[e]

[a]With respect to the ground state of ^{120}Sn (^{90}Zr).

[b]The width of the IVM resonances in ^{120}Sn and ^{90}Zr were determined in the present work. Other widths were determined in other experiments and held fixed in this analysis.

[c](e, ep): K. Shoda, Phys. Rep. 53, 341 (1979). The T_0+1 component of the GDR in ^{120}Sn is seen at 20.9 MeV. Its analog in ^{120}In occurs at an excitation energy of 2.9 MeV. Therefore its width was taken to be zero. The Coulomb shifts used for this and other cases were taken from W. J. Courtney and J. D. Fox, At. Data Nucl. Data Tables 15, 141 (1975).

[d](p,n): W. A. Sterrenburg *et al.*, Phys. Rev. Lett. 45, 1839 (1980).

[e](p,γ): M. Hasinoff *et al.*, Nucl. Phys. A216, 221 (1973). They observed two narrow $T+1$ components of the GDR in ^{90}Zr at 19.4 and 21.0 MeV.

ponent of the IVM in the (π^+, π^0) reaction is $\frac{1}{3}$ of the predicted value. This may result from its large excitation energy and the high density of states of isospin 9 at that energy or from a small deviation from isotropy in the background.

The same analysis procedure was carried out on data obtained for the reaction ^{90}Zr(π^-, π^0). Both the GDR and IVM peaks were observed. The magnitudes and shapes of the DWIA calculations are in good agreement with the data as shown in Table II.

In conclusion, we have observed the isovector monopole resonance in the (π^-, π^0) reaction at resonance pion energy for ^{90}Zr and ^{120}Sn. The analysis procedure used to extract the isovector monopole signal is based on the assumption of an isotropic background. This procedure reproduces the well-known collective isovector GDR in ^{120}Sn$(\pi^{\pm}, \pi^0)$, ^{90}Zr(π^-, π^0), and ^{40}Ca$(\pi^{\pm}, \pi^0)$, and the IAS in ^{120}Sn(π^+, π^0). The extracted angular distributions agree quantitatively with sum-rule-normalized DWIA calculations.

TABLE II. Cross sections for exciting the nuclear resonances observed. The maximum differential cross sections result from fitting the peak areas of the difference spectra with DWIA calculations by adjusting the normalization.

Experiment	Resonance	Extracted maximum cross section (μb/sr)	Calculated maximum cross section (μb/sr)	Ratio data/DWIA
^{120}Sn(π^-, π^0)	IVM	578 ± 48	629	0.92 ± 0.09
	GDR	154 ± 32	135	1.14 ± 0.24
^{120}Sn(π^+, π^0)	(IVM)[a]	(375 ± 153)[a]	1157	0.32 ± 0.09
	IAS	1872 ± 142	1414	1.32 ± 0.10
	GDR	704 ± 151	1158	0.61 ± 0.13
^{90}Zr(π^-, π^0)	IVM	891 ± 125	849	1.05 ± 0.15
	GDR	403 ± 61	360	1.12 ± 0.17

[a]Note that the identification of this component of the IVM is tentative; see text.

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