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Observation of a Low-Energy Octupole Resonance in Medium-Mass Nuclei*

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(Received 7 July 1976)

A giant-resonance-like structure at $E_{\text{exc}} \sim 32/A^{1/3}$ MeV is observed in (α, α') spectra in nuclei from ^{90}Zr to ^{154}Sm. Analysis of the angular distributions leads to an assignment of $J^\pi = 3^-$ and an energy-weighted sum-rule fraction of 16–22% for this structure. Comparison with random-phase-approximation calculations shows that $\sim \frac{2}{3}$ of the expected $1\hbar\omega$ octupole energy-weighted sum-rule strength is found at $\sim 32/A^{1/3}$ MeV; the remainder occurs in low-lying 3^- states.

The giant dipole resonance and the more recently discovered giant quadrupole resonance are excellent examples of collective modes of motion whose properties are strongly influenced by nuclear shell structure. The excitation energies and large energy-weighted sum-rule (EWSR) strengths of these resonances are understandable in terms of a schematic model.[1,2] which has as its basis the harmonic oscillator shell model. The harmonic oscillator model may also be used as a guide for vibrational modes of higher multipolarity.[2] In particular, for $L = 3$ there are two fundamental modes, i.e., degenerate groups of states, at excitation energies of $1\hbar\omega$ and $3\hbar\omega$ which carry 25% and 75%, respectively, of the octupole EWSR strength. Coupling of these modes with an octupole-octupole (O-O) residual interaction results in two "giant resonances" which we term low-energy and high-energy octupole resonances (LEOR and HEOR) that exhaust ~35% and ~65%, respectively, of the octupole EWSR (the exact partitioning depends on the strength of the coupling). Whether or not real nuclei generally exhibit such octupole giant-resonance-like structures is not known. The existence of a very collective low-energy 3^- state has been known for many years. However, with exceptions in the Pb isotopes, only a few percent (generally less than 10%) of the EWSR is accounted for by these states. Recent electron scattering data[3] indicate that a large portion of the missing $E3$ strength is between 5 and 10 MeV in ^{116}Sn. We present here evidence from the inelastic scattering of 96- and 115-MeV α particles that the isoscalar octupole EWSR strength in nuclei between $A = 90$ and $A = 154$ exhibits a giant-resonance-like structure in a broad state (or group of states) at $\sim 32/A^{1/3}$ MeV. The EWSR strength observed in this region is from $\frac{1}{2}$ to $\frac{2}{3}$ of that expected for the lower state predicted by the schematic model; thus we will refer to the structure at $32/A^{1/3}$ MeV as the LEOR. Combination of the octupole EWSR observed in the LEOR plus that from low-lying 3^- states accounts for essentially all of the oscillator strength expected to lie at $E_x \lesssim 1\hbar\omega$ in these nuclei.

The experimental apparatus and procedure used has been throughly described in a recent publication.[4] Spectra from the (α, α') reaction near expected maxima for $L = 3$ are shown in Fig. 1 for several targets. Also shown for comparison is a portion of the spectrum of ^{148}Sm at a minimum angle for $L = 3$, maximum for $L = 2$. Energy resolution varied from 150 keV at forward angles to 240 keV at backward angles. Analysis of the broad group of states at $\sim 32/A^{1/3}$ MeV was accomplished in the following manner. First, impurity peaks due to ^{16}O and ^{12}C were fitted with Gaussian peak shapes and subtracted from the spectra. A multiple-peak fit consisting of a superposition of narrow (~200 keV) and broad (1–2 MeV) Gaussians plus background was then applied to the spectra. Backgrounds were chosen by drawing a line from the minimum just above the broad peak to one just below. The angular distribution of the subtracted background showed a monotonic decrease with increasing angle. In ^{90}Zr and ^{142}Nd, states of multipolarity different from 3^- were recognized by their angular distribution and are indicated by shading in Fig. 1. Octupole strength in ^{90}Zr was found in a multiplet consisting of at least six levels plus high-energy tail which was not resolved into separate peaks.

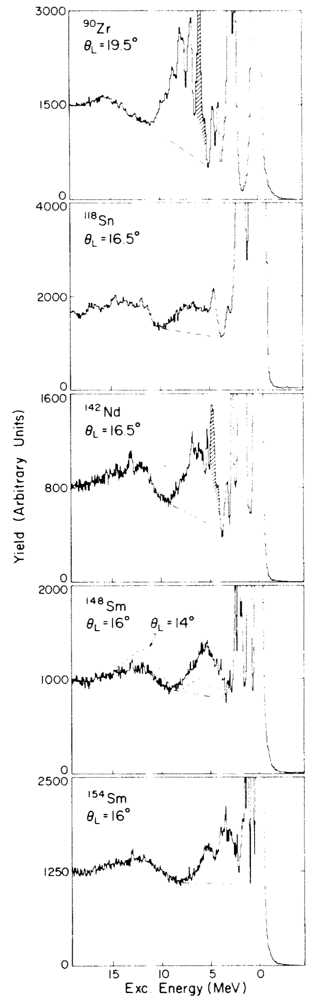

FIG. 1. Spectra from the (α,α') reaction at $E_\alpha = 115$ MeV (96 MeV for ^{90}Zr) at angles near the maximum for $L = 3$. The structures above the dashed background lines are the low-energy octupole resonances. A portion of the ^{148}Sm spectrum at $\theta_L = 14°$ is shown as a smooth dot-dashed line on the corresponding spectrum at 16°.

In ^{154}Sm the strength is concentrated in two broad peaks at 3.7 and 5.7 MeV. The angular distributions for both are fitted nicely by $L = 3$ calculations and EWSR fractions were derived individually for these states. Although there is obviously fine structure superimposed on the broad peaks in the other targets, statistical uncertainties prevented meaningful angular distributions from being obtained for the individual peaks. Thus for the derived quantities it was assumed that all counts above the background line with the exception of the shaded peaks (Fig. 1) were of octupole character.

Angular distributions of the LEOR are shown

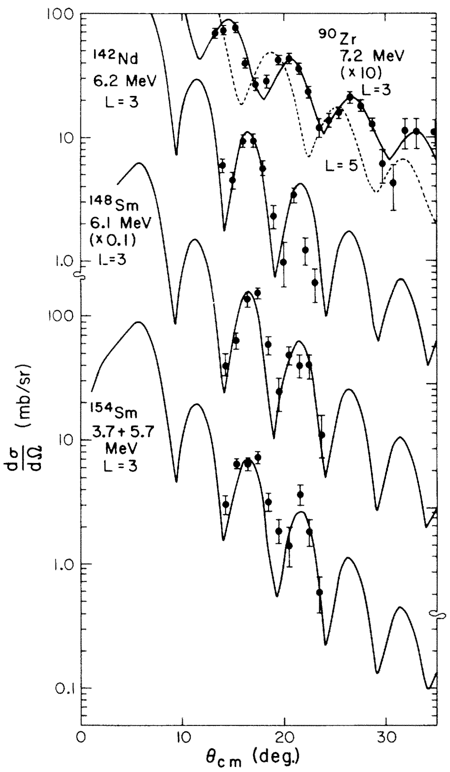

FIG. 2. Angular distributions for the (α,α') reaction exciting the LEOR. The error bars reflect uncertainties in the choice of the subtracted background. The DWBA calculations are normalized to the data. The optical model parameters were taken from Ref. 4.

in Fig. 2 with distorted-wave Born-approximation (DWBA) fits.[5] The error bars indicate the estimated uncertainty due to the choice of background; statistical errors are considerably smaller. Optical-model parameters were derived from elastic scattering data at 96 MeV for ^{90}Zr and at 115 MeV for ^{148}Sm (see Ref. 4). The ^{148}Sm parameters were also used to calculate the DWBA fits for ^{142}Nd, ^{144}Sm, and ^{154}Sm. The fits are generally in very good agreement with the data, indicating a dominance of $L = 3$. The odd multipoles $L = 1$ and $L = 5$ could conceivably make some contribution. However as is seen in Fig. 2 for ^{90}Zr, $L = 5$ would give a phase shift if the contribution were greater than 15 to 20% (the same applies for $L = 1$). The deformation lengths βR derived from the DWBA fits are given in Table I. Only a few angles were taken for ^{118}Sn with a target of uncertain thickness; therefore only a rough estimate of βR could be made. The EWSR fractions were derived using a procedure described in the literature.[4,8] A state of multipolarity L located at E_{res} which completely exhausts the EWSR has

TABLE I. Deformation lengths (βR), transition strengths (G_3) (Ref. 5), and EWSR percentages (S) for the isoscalar octupole strength. The errors on G_3 and S are ± 15% for the lowest 3^- states and ± 25% for the LEOR. EWSR percentages from published data are also given. A dash indicates that a value was not obtained in the present experiment.

Nucleus		E_x (MeV)	βR (fm)	G_3 Single-Particle Units	S (% EWSR) Present Work	Other Values
^{90}Zr		2.75	0.72	13.4	7.1	11,[a] 17.6[b]
		5.60	0.37	3.6	3.8	
		6.36	0.28	2.1	2.5	
		6.70	0.31	2.5	3.2	
		7.39	0.30	2.3	3.3	
		8.19	0.27	1.9	3.0	
^{90}Zr	LEOR	7.2[c]	0.73	14	19	
^{90}Zr		Total 0 to 9			26	
^{116}Sn		2.28	--	--	--	13[a]
^{116}Sn	LEOR	5 to 10	--	--	--	39[d]
^{116}Sn		Total 0 to 10				52
^{118}Sn		2.32	--	--	--	10[a]
^{118}Sn	LEOR	6.9	~0.67	~14	~20[e]	
^{118}Sn		Total 0 to 8			~30	
^{142}Nd		2.03	0.68	17.4	7.3	
^{142}Nd	LEOR	6.2	0.67	17	22	
^{142}Nd		Total 0 to 7.5			29	
^{144}Sm		1.81	0.80	27	9.2	7.2[f]
^{144}Sm	LEOR	6.5	0.64	17	21	
^{144}Sm		Total 0 to 7.5			30	
^{148}Sm		1.15	0.84	29	6.6	11[a]
^{148}Sm	LEOR	6.1	0.58	13	17	
^{148}Sm		Total 0 to 7.5			24	
^{154}Sm		1.01	--	--	--	4[a]
		1.58	--	--	--	3[a]
^{154}Sm	LEOR	3.7	0.51	9.9	8.1	
		5.7	0.28	3.2	3.8	
^{154}Sm		Total 0 to 7.5			19	

[a]Values derived from (α,α') or (d,d') reactions compiled in Ref. 6.

[b]Values derived from electromagnetic measurements compiled by Ref. 6.

[c]Summed strength of all the individual states in the LEOR plus the high-energy tail.

[d]Ref. 3.

[e]Errors are roughly 50% because of an uncertainty in the thickness of the target.

[f]Ref. 7.

a deformation length

$$(\beta R)^2 = L(2L+1)(\hbar^2/2ME_{\rm res})(4\pi/3A).$$

The experimentally observed EWSR fractions are given in Table I for the LEOR's and selected low-energy 3^- states. Also given are isoscalar transition strengths evaluated according to Bernstein's method.[6] Agreement with previous lower-energy inelastic scattering work is only fair. Comparison of the present isoscalar transition strengths with the corresponding electromagnetic values is not meaningful because of a paucity of measured $B(E3)$'s. Equality of isoscalar and electromagnetic strengths is found only if $\beta_{\rm charge} \sim \beta_{\rm matter}$. Evidence that this is not the case for the 2.75-MeV 3^- state in ^{90}Zr is seen in Table I. It is possible that similar differences may be observed in the LEOR region. There is some indication that a larger LEOR strength is seen in ^{116}Sn from (e, e') experiments[3] (Table I) than is seen in (α, α') measurements in nearby nuclei.

The existence of two fundamental octupole modes complicates the decision as to what constitutes the LEOR. Solution of the schematic random-phase-approximation (RPA) equation for a nucleus of $A=100$ yields 35% of the EWSR in the lower state when the O-O interaction is adjusted to give the observed centroid energy. More realistic RPA calculations (discussed below) yield a value of 27% below 10 MeV in ^{90}Zr. Thus, within experimental and theoretical uncertainties all of the isoscalar octupole strength expected in the $1\hbar\omega$ region has been observed in the spherical nuclei covered in this work. The splitting of the $1\hbar\omega$ strength into a very collective low-energy octupole state and a LEOR containing 2 to 3 times as much EWSR strength is not understandable in the schematic RPA model. Sophisticated continuum RPA calculations using a Skyrme interaction have been performed by Bertsch and Tsai.[9] They find in the response function of ^{90}Zr three major concentrations of octupole strength at 2.6, ~7.1, and ~24 MeV. The lowest is in agreement with the properties of the 2.75-MeV 3^- state. They find the $B(E3)$ associated with the 7.1-MeV region to exceed slightly that of the first 3^-. This is in excellent accord with the observed LEOR. The third region at ~24 MeV is $3\hbar\omega$ strength. More realistic RPA calculations[10] have also been performed for ^{90}Zr at this Institute using an O-O residual interaction.[11] The results, which are in good agreement with Bertsch and Tsai, indicate a large component of the $(p_{3/2}^{-1}g_{9/2})_{3^-}{}^{\pi}$ configuration in the 2.75-MeV state whereas the LEOR contains many particle-hole configurations, none of which is dominant. Spin-orbit splitting which results in a large decrease in the energy of certain particle-hole configurations is undoubtedly responsible for the partitioning of octupole strength in the other nuclei studied here. The surprising result of the present work is that a major portion of the $1\hbar\omega$ EWSR strength remains in a well-defined LEOR in spite of a large spread in single particle-hole energies.

On the basis of general considerations one expects an octupole phonon to yield four states characterized by angular momentum projections K ranging from 0 to 3 with excitation energy increasing as K for a nucleus with a permanent prolate deformation. In Fig. 1 it is apparent that the transition from spherical ^{148}Sm to deformed ^{154}Sm does indeed produce a splitting of the LEOR. Whether the two peaks seen in ^{154}Sm contain some or all of the expected K components is not clear on the basis of the present data. The observed reduction of the EWSR strength due to the lowering of the centroid energy in ^{154}Sm suggests that one or more K components (not observed) may lie at higher excitation energies. One must await further experimental evidence and more sophisticated theoretical work on the splitting of the LEOR before its exact nature is understood.

In summary, evidence has been presented of a large concentration (16–22%) of isoscalar octupole EWSR strength in a relatively narrow low-energy octupole resonance at $\sim 32/A^{1/3}$ MeV in medium-mass nuclei. Comparison with RPA calculations indicates that most or all of the $1\hbar\omega$ oscillator strength has now been located in the nuclei studied. Approximately $\frac{1}{2}$ to $\frac{2}{3}$ of this strength is concentrated in the LEOR. Preliminary evidence indicates a large effect on this resonance due to nuclear deformation.

The authors would like to thank T. Kishimoto for many informative discussions about the theoretical aspects of this work and for performing the RPA calculations for ^{90}Zr.

*Work supported in part by the National Science Foundation and the Robert A. Welch Foundation.

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Reaction $^{12}C(\gamma, \pi^-)^{12}N$ near the Threshold

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The total cross section for the reaction $^{12}C(\gamma,\pi^-)^{12}N$ has been determined by observation of the residual ^{12}N radioactivity. The cross section was extracted from the bremsstrahlung excitation function which was measured in the region between 3.6 and 12.6 MeV above the threshold, with one point 33.5 MeV above the threshold. The variation of the measured cross section with energy is far more rapid than is predicted by calculations using the $\vec{\epsilon}\cdot\vec{\sigma}$ interaction. Even when the full interaction Hamiltonian is used, the experimental cross section rises somewhat more rapidly than predicted.

Photomeson production in complex nuclei can be used as a probe of the nuclear mesonic field. Because of its fundamental importance, this process and its inverse, radiative capture, have received considerable theoretical attention.[1-5] This reaction has, in addition, considerable potential for applications in studies of the isospin analogs of nuclear vibrations.[3,6] However, because of the experimental difficulties, only a few experiments have been performed in which transitions to dis-