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High energy component of giant octupole resonance in medium and heavy mass nuclei

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Inelastic scattering of ^{3}He particles at 110–140 MeV from ^{90,92}Zr, ^{116,118,120}Sn, ^{144}Sm, and ^{208}Pb nuclei exhibits the presence of a new giant resonance at $E_x \sim 118A^{-1/3}$ MeV with a width of about 7 MeV. The angular distributions are consistent with those for $L=3$ transfer and octupole energy-weighted sum-rule fractions of 47–95% are exhausted for the resonance.

[NUCLEAR REACTIONS ^{90,92}Zr, ^{116,118,120}Sn, ^{144}Sm, ^{208}Pb (^{3}He, ^{3}He'), $E = 110-140$ MeV. Measured $\sigma(\theta,E)$. Deduced giant octupole resonance, E_x, β_3, EWSR. Enriched target.]

Many works have been done to study giant multipole resonances in nuclei in both experimental and theoretical aspects. Among them, the isoscalar resonances with a multipolarity higher than quadrupole are not yet well known experimentally although they are predicted theoretically.[1,2] It is interesting to know whether these resonances really exist or not. In this paper we report an experimental result on a new giant octupole resonance.

In a schematic model based on the harmonic oscillator shell model,[1] the isoscalar giant octupole resonance is predicted to split into two components at excitation energies of $E_x \sim 1\hbar\omega$ and $3\hbar\omega$. Existence of the $1\hbar\omega$ component was established by Moss *et al.*[3] recently; they found an octupole resonance, which exhausted energy-weighted sum-rule (EWSR) fractions of about 20%, at the excitation energy of $E_x \sim 30A^{-1/3}$ MeV in medium and heavy mass nuclei. This resonance was called a low-energy octupole resonance (LEOR). On the other hand, it was well known that the low-lying 3^- states exhausted EWSR fractions of about 10%. Adding both fractions together, EWSR fractions of about 30% were exhausted below $E_x \sim 1\hbar\omega$. These fractions were almost equal to those predicted for the $1\hbar\omega$ component.

Remaining octupole EWSR fractions ($\sim$70%) are expected to be exhausted by the resonance at $E_x \sim 3\hbar\omega$, which is called a high-energy octupole resonance (HEOR). Signatures of the HEOR have been reported by a few authors from scattering experiments with electron,[4–6] proton,[7] and heavy ion[8] beams. However, existence of the HEOR has not been thoroughly established experimentally because of difficulties mentioned below: (1) Since electron scattering excites isovector resonances located in the excitation region of the HEOR, the HEOR is masked by these resonances. (2) The HEOR is masked by bumps caused by breakup of ejectiles after pickup reactions in α and heavy ion scattering. (3) Since the width of the resonance in the region of high excitation energy becomes large, the HEOR is hardly distinguishable from an underlying continuum.

We have previously reported the first confirmative indication of the HEOR in tin isotopes.[9] The present work is an extension to a wider range of target nuclei. We used ^{3}He particles because they excited the isoscalar collective states more strongly than isovector ones and there was no additional structure caused by

breakup reactions in the energy spectra of scattered ^{3}He particles. We observed spectra up to excitation energy of about 50 MeV with sufficient statistics and could reliably identify the broad resonance on the underlying continuum.

The experiment was performed using 110, 120, and 140 MeV ^{3}He beams from the AVF cyclotron of Research Center for Nuclear Physics, Osaka University. Targets were self-supporting metallic foils of enriched ^{90,92}Zr, ^{116,118,120}Sn, ^{144}Sm, and ^{208}Pb with thicknesses of 4.0, 2.4, 6.4, 8.5, 12.4, 4.0, and 6.2 mg/cm^2, respectively. Scattered particles were detected by two sets of silicon detector telescopes in a 1-m scattering chamber. Overall energy resolution was 150–300 keV. The amount of contributions from carbon and oxygen contaminations were estimated from the spectra obtained with polyethylene and mylar targets and those were subtracted from the spectra measured for each target.

Figure 1 shows spectra of inelastically scattered ^{3}He particles from various targets. In all the spectra except for that of ^{208}Pb, we observed prominent peaks at $E_x \sim 7$ and 15 MeV which are known[3] as the LEOR and the giant quadrupole resonance (GQR), respectively. In addition to these resonances, a broad resonancelike structure was observed at $E_x \sim 25$ MeV. The width of this resonance was found to be about 7 MeV, but in ^{208}Pb it was about 5 MeV.

Angular distributions of the resonance were measured for ^{90}Zr and ^{208}Pb at 140 MeV, for ^{118,120}Sn at 120 MeV and for ^{116}Sn at 110 MeV incident energies, respectively. In the extraction of cross sections for the resonances, the underlying continua must be subtracted from the experimental spectra. We assumed that the shape of the continua was smooth throughout the energy region from $E_x \sim 5$ to 40 MeV; the shape of continua was linear in the region of excitation energy higher than that of the resonance and had a smooth curvature down to the minimum between the LEOR and the discrete states at low excitation, as shown by solid lines in Fig. 1.

In Fig. 2, the angular distributions of the $E_x \sim 25$ MeV resonance thus obtained are presented. Error bars indicate the estimated uncertainty due to the choice of the shape of continua; statistical errors are considerably smaller. The angular distributions for the continua exhibit a monotonic decrease as a function of increasing laboratory angle. Figure 2 shows a typical example for ^{90}Zr. On the other hand, the angular distributions of the 25 MeV resonance display oscillatory behavior. Diffraction patterns of the angular distributions were not very sensitive to the choice of the shape of the continua. Therefore, the 25 MeV resonance had a different character from the continua and was not a part of the continua.

The angular distributions were analyzed by the distorted-wave Born approximation (DWBA) calculations using the code DWUCK 4.[10] Optical potential parameters were obtained from the work of Hyakutake *et al.*[11] Form factors were of a conventional col-

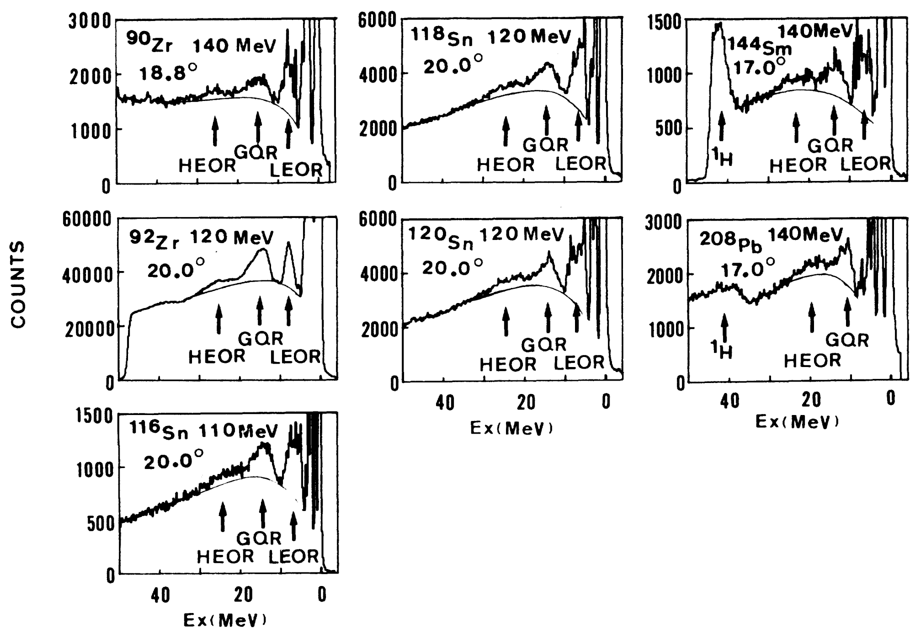

FIG. 1. Energy spectra of inelastically scattered ^{3}He particles. The LEOR, the GQR, and the presently observed resonance are indicated. In ^{144}Sm and ^{208}Pb, hydrogen contaminations are also indicated. Solid curves in the figures present assumed continuum shapes.

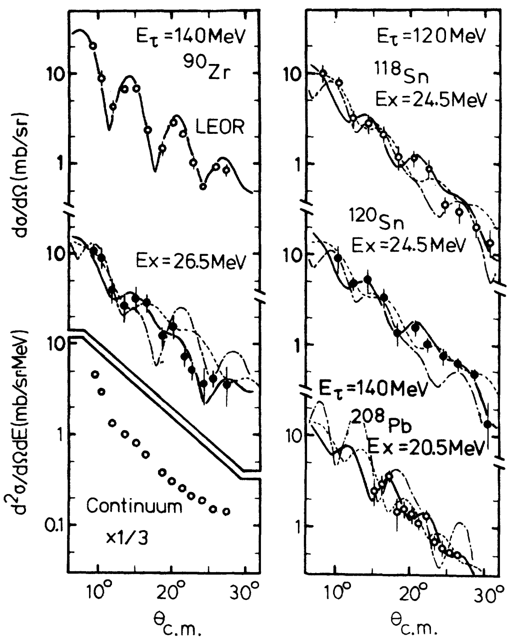

FIG. 2. Angular distributions of the resonance. In ^{90}Zr, those of the LEOR and the continuum are also displayed. Solid, dashed, and dot-dashed lines denote DWBA predictions for $L = 3$, 4, and 1 transfers, respectively.

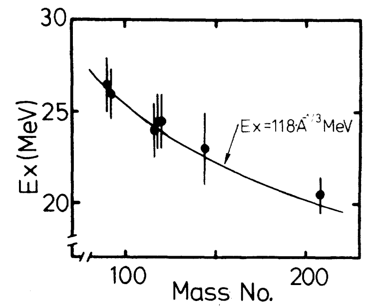

FIG. 3. Mass number dependence of the excitation energy of the presently observed resonance.

lective type. In the calculation of the isoscalar dipole transition, the form factor was that given by Deal.[12] The angular distributions of the LEOR were well reproduced by the DWBA calculation for $L = 3$ transfer in each nucleus, as typically presented for ^{90}Zr.

For the resonance at $E_x \sim 25$ MeV, results of DWBA calculations for $L = 1$, 3, and 4 transfers gave similar gradients to the experimental angular distributions as shown in Fig. 2; results of calculations for other L transfers ($L = 2$ or 5) did not fit the observed angular distributions. However, calculated results for $L = 1$ transfer showed deeper diffraction patterns than observed in the experimental angular distributions and those for $L = 4$ transfer were out of

TABLE I. Excitation energies, J^π, and EWSR fractions obtained in the present work.

Nucleus	Present work E_x (MeV)	J^π	EWSR (%)	Other works[a] E_x (MeV)	EWSR (%)	Ref.
^{90}Zr	2.8 ± 0.1	3^-	6.8 ± 1.0	2.75	7.1	3
	7.5 ± 0.4	3^-	19.5 ± 2.8	7.2	20	3
	26.5 ± 1.5	3^-	47 ± 20	6–10	16	13
				10–20	28	13
^{92}Zr	7.0 ± 0.4					
	26.0 ± 1.5					
^{116}Sn	2.3 ± 0.1	3^-	~9	2.325	11.3	14
	7.0 ± 0.4	(3^-)	~24	5–10	39	15
	24.4 ± 1.5	(3^-)	~74	15–35	54	15
^{118}Sn	2.3 ± 0.1	3^-	8.1 ± 1.3	2.359	11.7	14
	6.9 ± 0.4	3^-	24.7 ± 3.0	6.9	~20	3
	24.5 ± 1.5	(3^-)	65 ± 14			
^{120}Sn	2.4 ± 1.0	3^-	9.5 ± 1.8	2.410	10.8	14
	6.9 ± 0.4	3^-	25.3 ± 3.0			
	24.5 ± 1.5	(3^-)	95 ± 29			
^{144}Sm	6.5 ± 0.5			6.5	21	3
	23.0 ± 2.0					
^{208}Pb	2.6 ± 0.1	3^-	25.0 ± 1.6	2.61	20	3
	20.5 ± 1.0	3^-	78 ± 15	16.0	47–180	4
				17.5	90	5

[a]Values are taken from (α, α') and (e,e') experiments. Only the isoscalar octupole transitions are presented.

phase with respect to the experimental angular distributions. On the other hand, experimental angular distributions of the resonance were well reproduced by the calculations for $L = 3$ transfer. Therefore, contributions of $L = 1$ and 4 transfers were considered to be minor in the resonance.

Exhausted octupole EWSR fractions of the resonance are derived and are summarized in Table I. Excitation energies and EWSR fractions of other prominent $L = 3$ transitions observed in the present work are also summarized in Table I together with those in other works. Since only a few angles were taken for ^{116}Sn, rough estimated values of the EWSR fractions were given. Present results on the low-lying 3^- states and the LEOR were in good agreement with α and electron scattering results. On the other hand, concentration of $L = 3$ components above the LEOR has not been reported except for the case of ^{208}Pb and ^{197}Au.[4–6] In ^{208}Pb, the excitation energy of the octupole resonance (20.5 MeV) reported in this work was somewhat higher than that reported in electron scattering experiments, though its width and exhausted EWSR fraction were consistent with the results of electron scattering.

The excitation energies of the observed resonance studied here can be presented as $E_x \sim 118A^{-1/3}$ MeV, as shown in Fig. 3. This excitation energy and exhausted EWSR fraction (47–95%) are compatible with those predicted from the schematic model[1] and more sophisticated theories[2] for the HEOR. Thus we conclude that the $118A^{-1/3}$ MeV resonance is the HEOR.

Recently, other information on the HEOR has been reported for ^{40}Ca, ^{116}Sn and ^{208}Pb.[16,17]

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