Fragmentation of the low-energy octupole resonance in ^{48}Ca, ^{90}Zr, and ^{208}Pb

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The fine structure of the low-energy octupole resonance was studied for ^{48}Ca, ^{90}Zr, and ^{208}Pb by proton inelastic scattering at $E_p=65$ MeV. The low-energy octupole resonance was composed of many discrete levels of $L=3$ states. The total energy-weighted sum rule fraction of more than 10% was found in every nucleus. Especially in ^{208}Pb, the energy-weighted sum rule fraction amounted to 15%. The strength was finely fragmented in ^{90}Zr, but less fragmented in ^{208}Pb. It is suggested that the "degree of fragmentation" is correlated with the excitation energy and the distribution of the low-lying quadrupole phonon states.

I. INTRODUCTION

Investigation of the damping of nuclear collective vibrations is an important subject in the nuclear structure physics.[1] Various modes of nuclear collective vibrations have been observed as broad giant resonance bumps and their damping widths are explained by considering the contribution from the "particle decay width" and the "spreading width."[1]

Among giant resonances low-energy, octupole resonance (LEOR) is an isoscalar $E3$ resonance built from $1\hbar\omega$ excitations and has been observed in many nuclei ($27<A<200$) by means of (α,α') experiments[2,3] mostly as a 1—2 MeV wide broad bump exhausting around 20% of the energy-weighted sum rule (EWSR). The center of the bump is located at around $30A^{-1/3}$ MeV and lies in the region where the particle decay is forbidden or at least hindered. The strength of LEOR, therefore, should be found in discrete levels. Actually, in a ^{90}Zr(α,α') experiment[4] with an energy resolution of 70 keV, it was reported that the LEOR strength was split into discrete levels. In our high resolution ^{90}Zr(p,p$'$) experiment[5] with a resolution of 15 keV, many levels with $L=3$ character were clearly distinguished from the other levels with $L\neq3$. The widths of the individual levels were not wider than the instrumental one, implying the hindrance of particle emission in the "LEOR region." The fragmentation of the LEOR strength is then expected to be closely related with the "spreading width" which reflects the structure of individual nucleus.

The fragmentation of a collective 3^- state of one-particle—one-hole (1p-1h) nature will occur mainly from its coupling to the background states of 2p-2h configurations with $J^\pi=3^-$. Notice, however, that the peak energy of the observed resonance (LEOR) is below the $2\hbar\omega$ excitation region, where usual 2p-2h states are expected. That is, coupling of the collective 3^- state statistically to these 2p-2h states may not play a crucial role in the fragmentation of LEOR. It is then suggested that a special class of "collective" 2p-2h states, which have fairly low excitation energy, will be responsible for the fragmentation; they are two phononlike states or the ones containing a low-lying phonon mode especially with $J^\pi=2^+$ and a 1p-1h pair.[1]

From this point of view, it is interesting to study whether the distributions of $L=2$ and $L=3$ strengths are correlated to each other or not. In order to obtain precise distributions of these strengths, high resolution (p,p$'$) experiments of around 10 keV were performed for nuclei ^{48}Ca, ^{90}Zr, and ^{208}Pb. They are representative doubly closed-shell nuclei and the effect of nuclear deformation will be small.

The confirmation of the existence of LEOR in ^{208}Pb itself is an interesting subject. Moss *et al.*[2] concluded that no strength of LEOR was observed in ^{208}Pb in their (α,α') experiment. They suggested that little strength remained to the LEOR, because the $1\hbar\omega$ octupole strength was consumed by the extraordinary strong first 3^- state at 2.62 MeV, which exhausted about 20% of the EWSR strength. Using the same (α,α') reaction and nearly the same energy resolution of 120 keV, Harakeh *et al.*[6] reported that the octupole strength was found in a few fragmented states in the "LEOR region," contrary to the suggestion in Ref. 2. The reported strength distribution, however, did not coincide well in both the excitation energy and the strength with that obtained by a detailed (p,p$'$) study at $E_p=35$ MeV.[7] It is sometimes difficult to distinguish $L=3$ and $L=1$ states in an (α,α') experiment, and $L=3$ and higher spin states in a (p,p$'$) experiment, because of the similarity in the angular distribution. The present high resolution (p,p$'$) experiment was performed at higher incident energy of 65 MeV in order to separate various multipolarities more unambiguously.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

A proton beam from the Research Center for Nuclear Physics (RCNP) cyclotron at Osaka University was used to bombard isotopically enriched target foils of ^{48}Ca, ^{90}Zr, and ^{208}Pb (1.1 mg/cm^2 97.7%, 0.5 mg/cm^2 98.0%, and

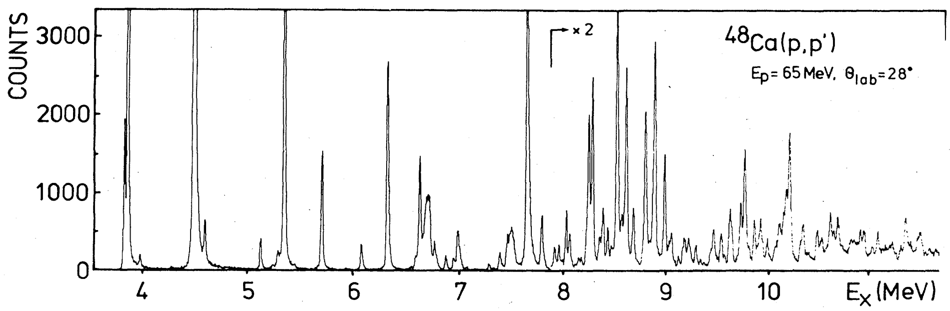

FIG. 1. Spectrum of inelastically scattered protons on the ^{48}Ca target at $E_p = 65$ MeV.

1.0 mg/cm^2 99.9%, respectively). Inelastically scattered protons were momentum analyzed by a magnetic spectrograph RAIDEN (Ref. 8) and detected with a focal plane counter system described in Ref. 9. Kinematic line broadening was always compensated by using a multipole magnet,[10,11] and overall resolutions of 10∼15 keV were achieved for the acceptance angles of 1.0∼3.2 msr.

With this high resolution, a large number of discrete levels were observed in these nuclei (see both Fig. 1 and Ref. 12 for ^{48}Ca, Ref. 5 for ^{90}Zr, and Fig. 2 for ^{208}Pb). It is worthy of notice that the background levels are apparently very low.

The spectra of ^{48}Ca were analyzed at angles from $\theta_{lab} = 8°$ to 70° up to $E_x = 10.2$ MeV. In order to obtain accurate cross sections for individual levels, a peak deconvolution program which uses the well-separated low-lying levels as peak shape standards was utilized in the analysis. For ^{90}Zr, analysis was performed at angles from $\theta_{lab} = 10°$ to 63° up to $E_x = 8.6$ MeV. The spectra of ^{208}Pb were analyzed at angles from $\theta_{lab} = 10°$ to 37.5° for the range of $E_x = 4.5$–7.5 MeV. Multipolarities of the various states below $E_x = 4.5$ MeV had been well established[13] and the angular distributions for some of the prominent peaks were obtained in order to make comparison with previous results. The angular distributions for some of the representative states are displayed in Fig. 3 for ^{48}Ca and ^{208}Pb (for ^{90}Zr see Ref. 5).

III. SUM-RULE ANALYSIS

The angular distributions were analyzed in the framework of distorted-wave Born approximation (DWBA) using a collective-model form factor.[14] The optical potential parameters of Sakaguchi *et al.*,[15] which were determined to fit the angular distributions of differential cross section and analyzing power for the elastic scattering of 65 MeV protons, were found to reproduce the inelastic scattering data for $L = 2$, 3, 4, and 5 as well (see Fig. 3).

In the present analysis, 25 levels in ^{48}Ca, 37 levels in ^{90}Zr, and 16 levels in ^{208}Pb were identified to have $L = 3$ character. In addition to isoscalar octupole states, proton scattering can excite isovector octupole states and unnatural parity 2^- and 4^- states by $L = 3$ transfer. It is surely impossible to exclude these possibilities for the $L = 3$ states obtained in the present work. However, in the "LEOR region" of ^{90}Zr, all of the strong $L = 3$ states observed in the present work correspond to the 3^- states reported in the (α,α') experiment,[4] which implies negligi-

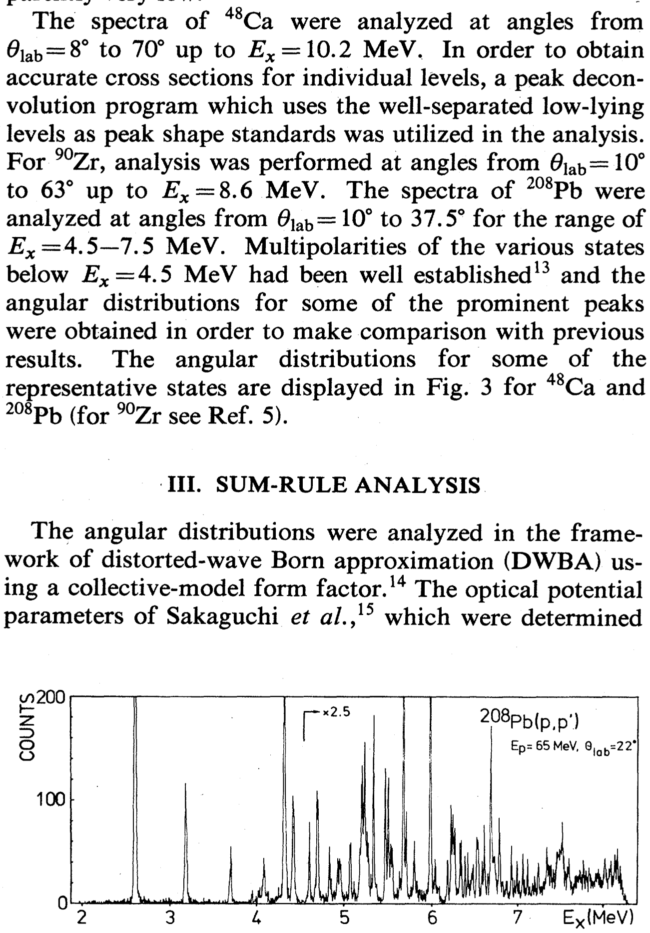

FIG. 2. Spectrum of inelastically scattered protons on the ^{208}Pb target at $E_p = 65$ MeV.

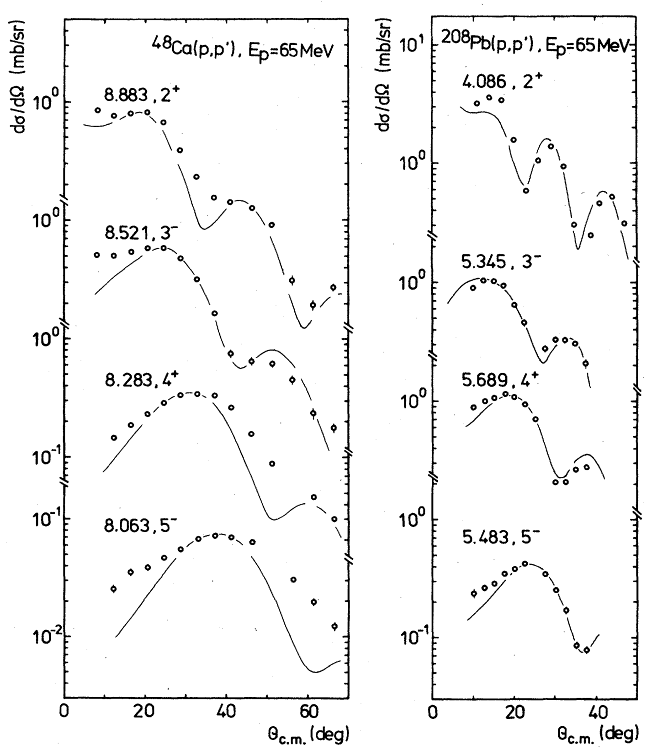

FIG. 3. The angular distributions for $J^\pi = 2^+$, 3^-, 4^+, and 5^- states in ^{48}Ca and ^{208}Pb. The DWBA calculations shown by the solid lines are normalized to the data. The optical model parameters were taken from Ref. 15, where $R_0 = 1.23A^{1/3}$ fm and $R_0 = 1.22A^{1/3}$ fm were assumed for ^{48}Ca and ^{208}Pb, respectively.

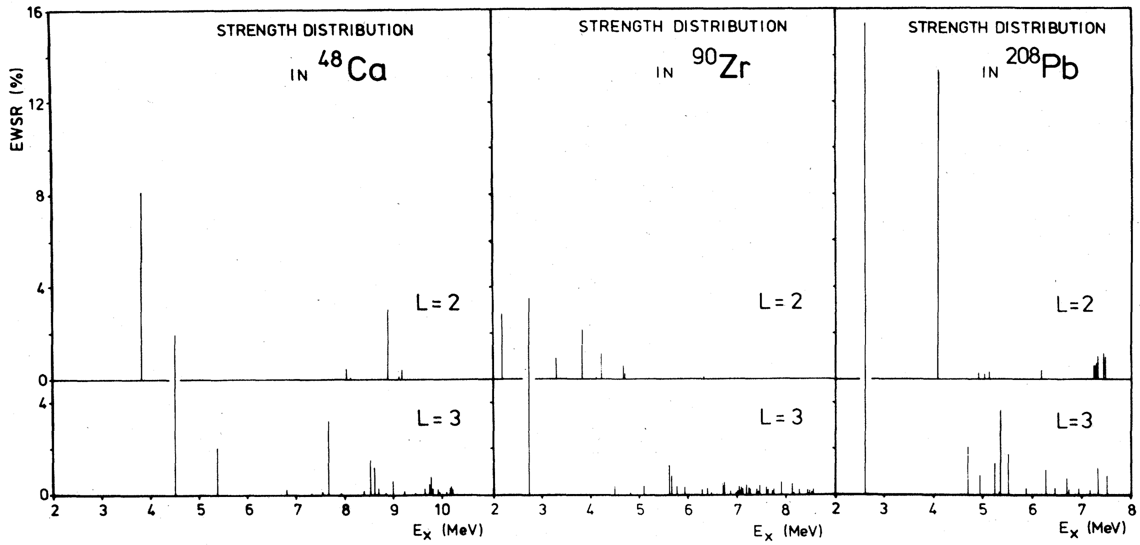

FIG. 4. The distributions of the EWSR percentages for the $L=2$ and $L=3$ strengths found in ^{48}Ca, ^{90}Zr, and ^{208}Pb. The octupole strength is shared by the first 3^- state (except in ^{48}Ca, in which two 3^- states are found in the low-lying energy region) and the LEOR centered at $31.5A^{-1/3}$. The low-lying $L=2$ strength is concentrated into a state in ^{48}Ca and ^{208}Pb, but is shared by several states in ^{90}Zr.

bly small contribution from isovector octupole excitations and unnatural parity states. We assume the same situation in ^{48}Ca and ^{208}Pb. The number of states identified to have $L=2$ were 6, 8, and 11 in ^{48}Ca, ^{90}Zr, and ^{208}Pb, respectively.

The energy weighted sum rule (EWSR) fractions were derived for these states by using the procedure given in Ref. 16. The obtained strength distributions are shown in Fig. 4 and tabulated in Tables I—III for the states with $L=2$ and $L=3$. In ^{208}Pb, several 2^+ states were observed above $E_x=7$ MeV (see Fig. 4). It is probable that these states are the lower tail of the giant quadrupole resonance (GQR), whose center is situated at $E_x=63A^{-1/3}$ MeV (10.8 MeV for ^{208}Pb).[17]

TABLE I. Deformation lengths (βR) and EWSR percentages (S) for the $J^\pi=2^+$ and 3^- states in ^{48}Ca.

E_x (MeV)	βR (fm)	S (%)	E_x	βR	S
Sum rule fractions for $J^\pi=2^+$ states					
3.832	0.619	8.14	8.883	0.247	3.02
8.026	0.102	0.47	9.117	0.050	0.13
8.119	0.035	0.06	9.176	0.094	0.45
Sum rule fractions for $J^\pi=3^-$ states					
4.507	0.765	6.97	9.214	0.078	0.15
5.370	0.379	2.04	9.430	0.045	0.05
6.794	0.113	0.23	9.638	0.097	0.24
7.303	0.049	0.05	9.727	0.132	0.45
7.537	0.076	0.12	9.764	0.174	0.78
7.661	0.398	3.20	9.860	0.099	0.26
7.911	0.063	0.08	9.920	0.097	0.25
8.439	0.094	0.20	9.942	0.068	0.12
8.521	0.258	1.50	10.078	0.068	0.12
8.615	0.230	1.20	10.150	0.108	0.31
8.685	0.111	0.28	10.178	0.118	0.37
8.835	0.062	0.09	10.191	0.097	0.25
8.982	0.161	0.61			

TABLE II. Deformation lengths (βR) and EWSR percentages (S) for the $J^\pi=2^+$ and 3^- states in ^{90}Zr.

E_x (MeV)	βR (fm)	S (%)	E_x	βR	S
Sum rule fractions for $J^\pi=2^+$ states					
2.186	0.355	2.87	4.236	0.168	1.25
3.309	0.161	0.89	4.686	0.113	0.62
3.843	0.233	2.17	4.707	0.081	0.32
4.135	0.043	0.08	6.347	0.043	0.12
Sum rule fractions for $J^\pi=3^-$ states					
2.748	0.79	8.53	7.215	0.11	0.41
4.501	0.13	0.36	7.250	0.09	0.30
4.826	0.04	0.04	7.278	0.09	0.27
5.122	0.12	0.39	7.417	0.08	0.23
5.636	0.21	1.28	7.438	0.06	0.12
5.673	0.17	0.81	7.476	0.10	0.40
5.785	0.11	0.35	7.629	0.10	0.38
5.946	0.10	0.31	7.648	0.08	0.22
6.305	0.07	0.14	7.737	0.07	0.19
6.415	0.10	0.30	7.765	0.08	0.23
6.494	0.05	0.09	7.917	0.12	0.55
6.724	0.11	0.39	8.138	0.11	0.50
6.757	0.13	0.56	8.183	0.05	0.09
6.882	0.07	0.14	8.291	0.08	0.25
6.989	0.06	0.10	8.427	0.07	0.22
7.017	0.06	0.14	8.445	0.07	0.20
7.062	0.09	0.28	8.530	0.06	0.14
7.104	0.10	0.33	8.554	0.07	0.22
7.135	0.09	0.26			

TABLE III. Deformation lengths (βR) and EWSR percentages (S) for the $J^\pi=2^+$ and 3^- states in ^{208}Pb.

E_x (MeV)	βR (fm)	S (%)	E_x	βR	S
Sum rule fractions for $J^\pi=2^+$ states					
4.086	0.37	13.41	7.287	0.06	0.62
4.923	0.05	0.33	7.301	0.06	0.74
5.036	0.05	0.28	7.320	0.08	1.06
5.124	0.06	0.38	7.455	0.08	1.14
6.082	0.05	0.41	7.491	0.08	1.03
7.265	0.06	0.62			
Sum rule fractions for $J^\pi=3^-$ states					
2.615	0.83	20.37	6.276	0.13	1.11
4.698	0.20	2.11	6.445	0.06	0.29
4.934	0.13	0.90	6.704	0.10	0.75
5.244	0.15	1.39	6.736	0.05	0.23
5.318	0.05	0.17	6.940	0.06	0.27
5.345	0.25	3.70	7.171	0.05	0.23
5.515	0.17	1.77	7.334	0.12	1.20
5.877	0.06	0.25	7.517	0.10	0.87

IV. RESULTS AND DISCUSSIONS

A. Strength distribution

In order to check the validity of the obtained $L=3$ strength, the EWSR values for the low-lying state were compared with those given in literatures.[2,18] As shown in Table IV, fairly good agreement is seen.

In the "LEOR region," as seen in Fig. 4, the $L=3$ strength is clearly concentrated in every nucleus including ^{208}Pb. The EWSR fractions amount to 10–15% as summarized in Table IV. The envelope of the distribution exhibits a resonancelike shape with a width of around 1 MeV. In order to know the width Γ and the central value of the excitation energy E_0, the cumulative strength sum for the observed discrete states was fitted to the integrated Breit-Wigner function

$$Y(E)=Y_0\left[\frac{1}{\pi}\tan^{-1}\frac{E-E_0}{\Gamma/2}+\frac{1}{2}\right],$$

where Y_0 is the integrated strength. The obtained values for E_0 and Γ are also shown in Table IV. The E_0 values can be well described by the systematics of $31.5A^{-1/3}$, which accords well with the $30A^{-1/3}$ systematics proposed by Moss et al.[2] The width Γ is the narrowest in ^{208}Pb, 1.8 times wider in ^{48}Ca, and the widest in ^{90}Zr. It is interesting to note that the ratio of width Γ is nearly proportional to the ratio of "number of states" observed in the experiment (see Table IV).

B. Fragmentation of the LEOR strength

Bohr and Mottelson pointed out that splitting of the low-frequency octupole strength in deformed nuclei might arise as a result of the coupling to quadrupole deformations[19] and the recent data on Kr isotopes supported the idea.[20] It is suggested that a similar mechanism is also the cause of fragmentation observed for LEOR, though nuclei we are concerned with are far from deformed regions. In order to see this, we examined the correlations between the observed distribution of $L=3$ states, and the distribution of low-lying 2^+ states. The theoretical distribution of $L=3$ states calculated by a random phase approximation (RPA) was referred to as a standard distribution expected by assuming only 1p-1h excitations. The used RPA code, written by Kishimoto,[21] is based on a Nilson-type harmonic oscillator potential with pairing plus octupole-octupole (OO) interactions. The strength of OO interaction and parameters for the proton and neutron energy gaps Δ_p and Δ_n were adjusted to reproduce the excitation energy and the strength of the first 3^- state in each nucleus (for ^{48}Ca, sum of the intensities and average excitation energy of 3_1 and 3_2 states). The result of calculation is displayed in Fig. 5.

When the strength distributions of low-lying 2^+ states shown in Fig. 4 are compared among ^{48}Ca, ^{90}Zr, and ^{208}Pb, they are apparently different from one another. In ^{208}Pb, the 2^+ strength is concentrated into one state at as high as $E_x=4.1$ MeV. A simple sum of the excitation energies of the 2^+ phonon and any 1p-1h pair, coupling to make a 3^- state, yields $E_x\simeq 9$ MeV, a value much higher than the excitation energy of LEOR. Therefore, the coupled states hardly mix with LEOR. This interpretation seems to be consistent with the fact that the $L=3$ distri-

TABLE IV. Observed properties of octupole strengths in ^{48}Ca, ^{90}Zr, and ^{208}Pb.

	^{48}Ca		^{90}Zr		^{208}Pb
E_x of low-lying 3^-	4.51 MeV 5.37 MeV		2.75 MeV		2.65 MeV
EWSR of low-lying 3^-	7.0% (5%[a]) 2.0% (2%[a])		8.5% (7%[b])		20.4% (20%[b])
E_x of LEOR (E_0)	8.57±0.10 MeV		7.25±0.06 MeV		5.38±0.06 MeV
EWSR of LEOR	10.9%		11.2%		15.2%
Γ of LEOR	1.26±0.28 MeV		1.87±0.12 MeV		0.69±0.20 MeV
Ratio of Γ	1.8	:	2.7	:	1
Number of $L=3$ states in LEOR region	23		36		15
Ratio of number	1.5	:	2.4	:	1

[a]Reference 18.
[b]Reference 2.

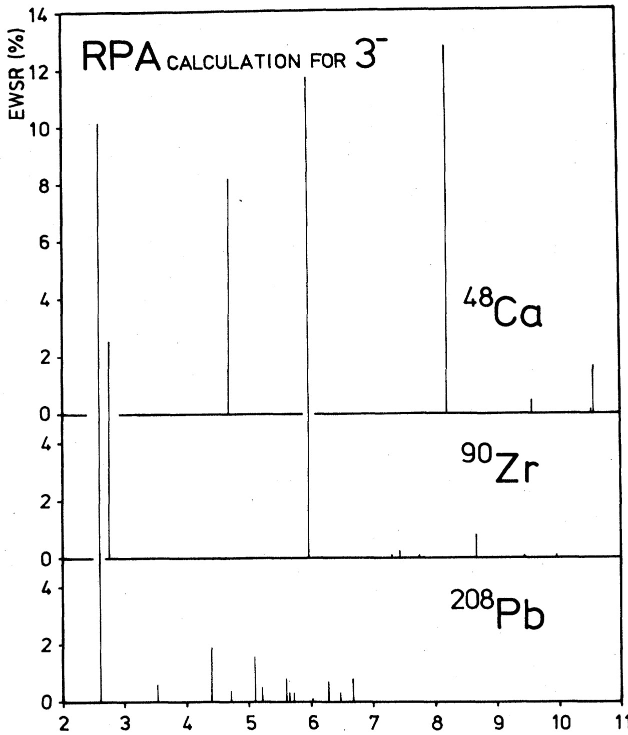

FIG. 5. The distribution of $J^{\pi}=3^-$ states expected by a RPA calculation for ^{48}Ca, ^{90}Zr, and ^{208}Pb. The strength of the OO interaction, the values Δ_p and Δ_n are adjusted to reproduce excitation energy and strength of the first 3^- state for each nucleus.

bution obtained in the experiment is alike with that of the RPA calculation, although the absolute value of the strength is not so fair.

In ^{90}Zr, the low-lying 2^+ strength is distributed into several states and their excitation energies are fairly low. These 2^+ phonon states can make many 3^- states at around $E_x=7$–8 MeV by coupling with 1p-1h pairs and also with the first 3^- state at $E_x=2.75$ MeV. It is expected that these background 3^- states mix with such a collective 3^- state (LEOR) in the same excitation region as predicted by the RPA calculation shown in Fig. 5, and then cause the fine fragmentation of the collective 3^- state. The ^{48}Ca is situated between these two cases, i.e., the low-lying 2^+ strength is concentrated into one state, although the excitation energy is not so high. From these evidences it is suggested that the distribution of the 3^- state in the LEOR region and the distribution of low-lying 2^+ states are correlated to each other and that the fragmentation of the LEOR is explained qualitatively by the coupling of the LEOR with collective 2p-2h states containing the 2^+ phonon mode as a component.

C. LEOR in ^{208}Pb

The EWSR fraction of 15% was found in the "LEOR region" of ^{208}Pb, which means that the EWSR fraction of as much as 35% is observed in the $1\hbar\omega$ excitation region if the above fraction is added to that of the low-lying 3^- state of 20%. This value is almost twice as large as that in each of ^{90}Zr (19%) and ^{48}Ca (20%).

It is interesting to compare the present result with some theoretical predictions. A number of advanced calculations have been performed using RPA.[22–25] In order to compare the gross features of the experimental and theoretical strength distributions, the excitation energies and the EWSR fractions are summarized for the low-lying states and for the LEOR region in Table V, where the results for $L=2$ strength are also tabulated, when possible. As seen from the table, the excitation energies as well as the EWSR values for the first 3^- state are consistent among the experimental value and the theoretical ones. For the LEOR, however, usually smaller values by a factor of 2 or 3 are predicted rather than the value of the present observation. It is interesting that as much as 39% of the EWSR is predicted for the total $1\hbar\omega$ excitations of ^{208}Pb based on a simple model using a harmonic oscillator potential and an octupole field proportional to

TABLE V. Experimental and theoretical distributions of EWSR percentage S for the quadrupole and octupole strengths in ^{208}Pb.

	$L=2$				$L=3$			
	Low lying		LEOR region		Low lying		LEOR region	
	E_x (MeV)	S (%)	E_x (MeV)	S (%)	E_x (MeV)	S (%)	E_x (MeV)	S (%)
Present experiment	4.09	13.4	4.9–7.5	6.6	2.62	20.4	5.4	15.2
Liu and Brown[a]	5.6	25.2			2.8	18.1	7.0	8.9
Rinker and Speth[b]	4.55	18.3	6.24	1.4	2.82	24.3	5.53	2.3
			6.89	7.7			6.28	1.2
Bernard and Giai[c]	6.06	22.0			2.8	19.0	7.0	9.5
Bortignon and Broglia[d]					2.57	24.0	6.7	4.0

[a]Reference 22.
[b]Reference 23.
[c]Reference 24.
[d]Reference 25.

the octupole multipole moment.[19] The value is in good agreement with the present value of 35%.

V. SUMMARY AND CONCLUSION

High resolution (p,p′) experiments were performed for the "LEOR region" of ^{48}Ca, ^{90}Zr, and ^{208}Pb. The obtained spectra were composed of many discrete levels. The width of each level was not wider than the instrumental one, which accords with the fact that particle decays are forbidden or hindered in this region. As a result of the DWBA analysis, the concentration of $L=3$ states became apparent for these nuclei and the existence of LEOR in ^{208}Pb was clearly confirmed. The envelope of the strength distributions showed resonancelike shapes. The width is the widest in ^{90}Zr and the narrowest in ^{208}Pb. Corresponding with this, the LEOR strength was finely fragmented in ^{90}Zr, but less fragmented in ^{208}Pb. The ^{48}Ca is situated between these two cases.

Comparing the obtained distribution with that of the RPA calculation and subsequently taking the strength distribution of low-lying 2^+ states into account, we believe that the fragmentation of the 3^- state (LEOR) is caused by the coupling of the 3^- state with collective 2p-2h states containing the 2^+ phonon mode as a component. Recently, the γ decay from the LEOR was studied for ^{90}Zr.[26] In the experiment, a rather strong feeding of γ rays from the LEOR to low-lying 2^+ states was observed, which suggests a strong coupling of the LEOR to the 2^+ phonon states.

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