Title	Observation of the low energy octupole resonance in ^<208>Pb by inelastic α scattering
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Citation	Physical Review C. 1992, 45(3), p. 993-996
Version Type	VoR
URL	https://hdl.handle.net/11094/23137
rights	Fujita, Y. , Shimoda, T. , Miyatake, H. , Takahashi, N. , Fujiwara, M. , Morinobu, S. , Yamagata, T. , Takamatsu, J. , Terakawa, A. , Folger, H., Physical Review C, 45, 993-996, 1992 "Copyright (1992) by the American Physical Society."
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Observation of the low-energy octupole resonance in ^{208}Pb by inelastic α scattering

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(Received 6 November 1991)

A high-resolution (α,α') experiment has been performed in order to confirm the existence of the low-energy octupole resonance (LEOR) in ^{208}Pb. Until now there was a puzzling discrepancy; an (α,α') experiment denied the existence, while a (p,p') measurement affirmed it. The present (α,α') reaction with an improved resolution of 27 keV has identified clustering $L=3$ levels in the "LEOR region" in agreement with the former (p,p') measurement. The observed strength, however, is weaker than the (p,p') results, suggesting the coexistence of the isovector strength.

PACS number(s): 21.10.Re, 25.55.Ci, 27.80.+w

I. INTRODUCTION

In the harmonic-oscillator shell-model picture, the $L=3$ strength is predicted at excitation energies of $1\hbar\omega$ and $3\hbar\omega$. The low-energy octupole resonance (LEOR) is a resonancelike structure expected in the region of $1\hbar\omega$ excitation energy. It shares the $1\hbar\omega$ strength with the low-lying 3^- state(s). Evidence for the LEOR was first reported by Moss *et al.* using inelastic α scattering [1,2]. With a resolution of 150–200 keV (full width at half maximum, FWHM) they observed 1–2-MeV-wide broad bumps at $E_x \sim 30A^{-1/3}$ MeV in a variety of medium- and medium-heavy-mass nuclei. The bumps exhausted 10–20% fractions of the $E3$ isoscalar energy-weighted sum rule (EWSR). In ^{208}Pb, however, no bump structure of $L=3$ was observed after a subtraction of a background smoothly interpolating the region of low-lying states and the higher-excitation region of the giant quadrupole resonance (GQR). They suggested that this result could be qualitatively understood by assuming that all of the $1\hbar\omega$ octupole strength was consumed by the low-lying collective 3^- state at 2.62 MeV exhausting as much as 20% of the EWSR strength and that little strength remained to the LEOR [2].

In the energy region of the LEOR, i.e., $E_x < 10$ MeV in most nuclei, the particle decay is forbidden or at least hindered. The strength of the LEOR, therefore, should be found in discrete levels. Actually a LEOR bump could be dissolved into discrete levels in (p,p') experiments performed at Osaka with a high resolution of less than 20 keV. Many $L=3$ levels have been distinguished from other levels with $L\neq3$ in various nuclei [3–10]. In ^{208}Pb as well, clustering levels with $L=3$ character have been found in the expected LEOR region in addition to the first 3^- state mentioned above. It is reasonable to think that the levels are the components of the LEOR because the envelope of the strength distribution of these $L=3$ levels shows a bumplike structure and these levels exhaust about 15% of the EWSR [4]. Another interesting result of the ^{208}Pb(p,p') reaction is the finding that many discrete states with $L\neq3$, such as $L=4$, coexist in the same energy region as that of the LEOR [10]. The background level, in contrast with the previous (α,α') result, is very low, and practically no background is observed up to around $E_x=7$ MeV, where the neutron decay channel opens and the continuum from the (p,pn) reaction should begin.

It is an interesting subject to understand how the striking difference came out for the strength of the LEOR as well as for the feature of the background between the (p,p') [4] and (α,α') reactions [2]. In the present (α,α') experiment, we tried to achieve a high resolution enabling us a separation of levels which should be discrete in the LEOR region in ^{208}Pb. Then it will be possible to discuss the features of the octupole strength observed by an (α,α') experiment from the same standpoint as that of the high-resolution (p,p') measurement.

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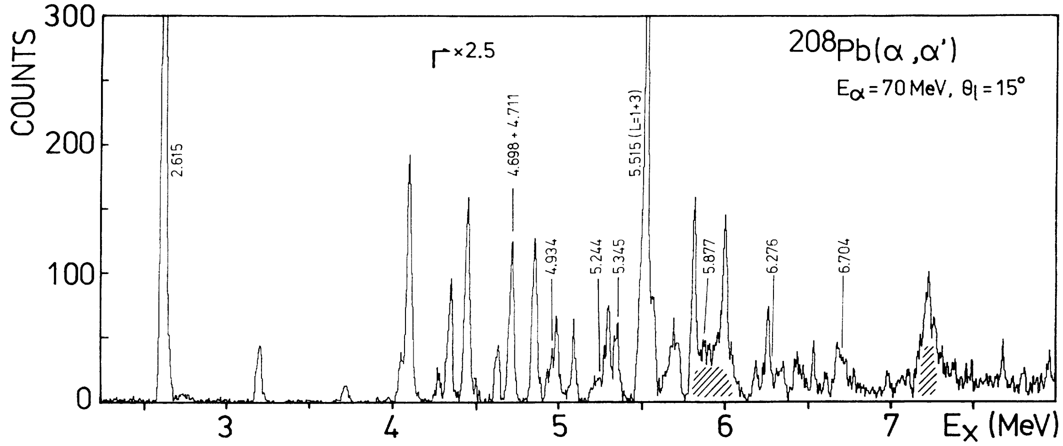

FIG. 1. Spectrum of inelastically scattered α particles on the ^{208}Pb target at an angle near the maximum for the $L=3$ angular distribution. The $L=3$ states are indicated by the excitation energy (in MeV). Broad peaks corresponding to contaminating light nuclei are shadowed.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The experiment was performed at the Research Center for Nuclear Physics (RCNP), Osaka, using a 70-MeV alpha beam provided from the RCNP cyclotron. The ^{208}Pb target used was a 300-μg/cm^2-thick self-supporting foil with an enrichment of 98.7%. Inelastically scattered alpha particles were momentum analyzed by a magnetic spectrograph Raiden [11] and were detected by a two-dimensional position-sensitive proportional counter system [12]. Kinematic line broadening was compensated in order to attain high resolution [11–13]. The overall resolution of 25–29 keV was achieved at the acceptance solid angle of 1.16 msr. With this resolution many discrete levels were observed as shown in Fig. 1. It is worthy of notice that the background level is apparently very low like the high-resolution (p,p') experiment [4] and not like the reported (α,α') experiment [2].

The spectra of ^{208}Pb were analyzed at angles from $\theta_{lab}=8°$ to 29° up to $E_x=6.9$ MeV. Typical angular distributions for the states with various multipolarities are shown in Fig. 2. 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. Some of the close multiplet states were analyzed by giving the peak positions estimated from the previous (p,p') experiment performed with a resolution of less than 15 keV [4]. In spite of these efforts, it was sometimes hard to identify a weakly excited member of a multiplet. Above $E_x=6$ MeV, where the level density becomes high, unambiguous angular distributions have been obtained only for prominent levels.

The angular distributions were analyzed with a distorted-wave Born approximation (DWBA) code using a collective-model form factor [14]. Deep-type optical-potential parameters of Ref. [15] determined at an α in-

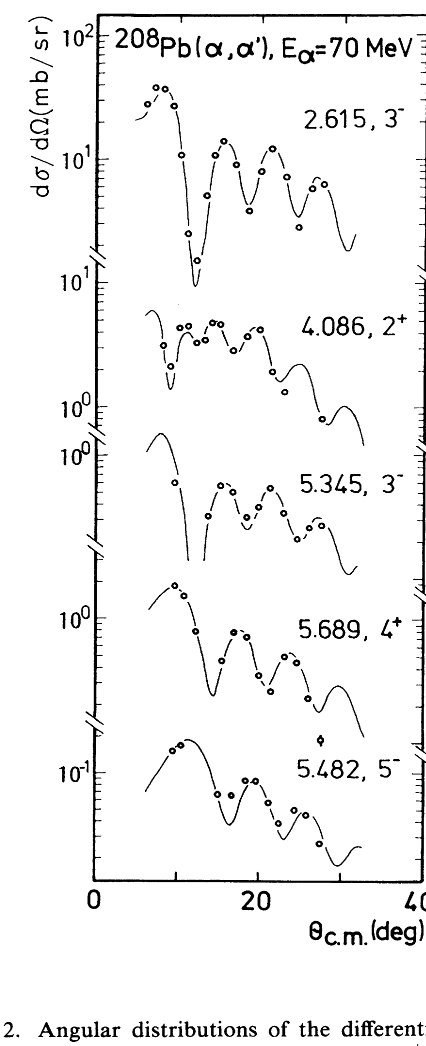

FIG. 2. Angular distributions of the differential cross sections for the first 3^- state and the typical $J^\pi=2^+$, 3^-, 4^+, and 5^- states in the energy region of the LEOR.

TABLE I. EWSR percentages for the $J^{\pi}=3^-$ states in ^{208}Pb.

E_x (MeV)	(p,p')[a] (%)	(α,α')[b] (%)	(α,α')[c] (%)
Low lying			
2.615	20.4	21.0	20
LEOR region			
4.698	2.1	<2.8	
4.934	0.9	0.6	
5.244	1.4	0.6	
5.318	0.2		
5.345	3.7	2.1	
5.515	~1.8	<2.0	
5.877	0.3	0.2	
6.276	1.1	d	
6.445	0.3		
6.704	0.8	d	
6.736	0.2		
6.940	0.3		
7.171	0.2		
7.334	1.2		
7.517	0.9		
	LEOR total 15.2	LEOR total 8.3	

[a]Reference [4].
[b]Present experiment.
[c]Reference [2].
[d]There exists a state with an L value not being analyzed.

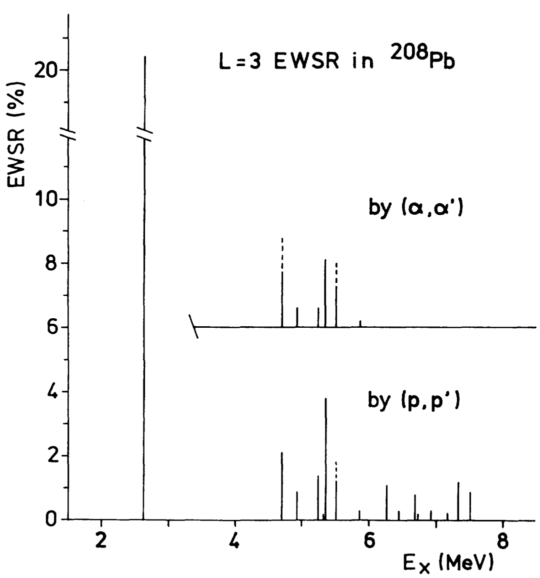

FIG. 3. Strength distributions of $L=3$ states as a function of excitation energy. The strength distribution observed by the present (α,α') experiment is compared with that by the (p,p') measurement of Ref. [4]. The strength is given by the percentage of the EWSR. Estimated ambiguity of the strength is shown by a dotted line (see text for details).

cident energy of 79 MeV and based on the wide range of angular distribution data were used in the analysis. It was found that the parameters reproduce the angular distribution of the elastic scattering at $E_\alpha=70$ MeV as well. The effect of Coulomb excitation was included in the calculation. Angular distributions of many levels were found to be in good agreement with the DWBA calculations for $L=3,4,5$, and higher-L transitions. The fit to the experimental data is shown in Fig. 2 by solid lines. The deformation length $\beta_L R$ was obtained for every state by comparing the data with the results of the DWBA calculation (for the detail see Ref. [7]). The $E3$ EWSR fractions were derived by using the procedure given in Ref. [16]. The obtained EWSR percentages for the $L=3$ states are summarized in Table I and compared with the previous (p,p') and (α,α') results. The distribution of strengths is shown in the upper part of Fig. 3 and compared with the (p,p') results.

III. EXPERIMENTAL RESULTS

As listed in Table I, for the low-lying collective 3^- state we obtained a sum-rule fraction of 21% in good agreement with both the published (α,α') result [2] and the (p,p') measurement [4]. It should be noted that all of the prominent $L=3$ states observed in the previous (p,p') experiment are also observed in the present (α,α') measurement at $E_x<6$ MeV, showing the reliability of these experiments. Apparently the main part of the LEOR identified in the previous (p,p') experiment has been observed in the present (α,α') measurement. The resonancelike structure of the LEOR, however, is less clear. This is mainly due to the limited resolution of the present experiment, which made it difficult to identify the weakly excited $L=3$ levels expected to exist above $E_x>6$ MeV. In addition to this, it was sometimes difficult to clearly identify a member of a multiplet state. For example, the 6.276-MeV state identified in the (p,p') experiment is a member of a quartet. Similarly we know that the 4.698-MeV state forms a doublet with a 4.711-MeV state, and only the upper value of the $L=3$ strength has been obtained for the 4.698-MeV state.

The sum of the EWSR percentages of the octupole strength is 8.3% in the LEOR region. This value should be thought to be the lower limit since the strengths in the region above $E_x>6$ MeV are not included. We believe at least 9%, more probably 10–11 %, is a reasonable number as a total strength of the LEOR.

IV. DISCUSSION AND SUMMARY

The summed LEOR strength of about 10% of the EWSR estimated from the present (α,α') experiment is lower than that of 15% in the (p,p') measurement, although similar values have been obtained for the low-lying collective 3^- state. It should be noted that the strength in the (α,α') reaction is weaker than that in the (p,p') reaction even if the strengths are compared state by state in the LEOR region. For example, the EWSR strength of the 5.345-MeV state, which is most clearly identified in both (α,α') and (p,p') experiments, is reduced by about 40%. The strength of the 5.244-MeV state is also reduced by nearly the same amount. The finding can be qualitatively understood from the fact that the (p,p') and (α,α') reactions have different isospin character; the (α,α') reaction is almost purely isoscalar, while the (p,p') reaction can excite the isovector component as well. In a recent calculation using the random-phase approximation, Unkelbach *et al.* predicted an EWSR fraction of 8% as a pure isoscalar strength in the energy region between 4 and 8 MeV [17], which agrees rather well with our observation.

We point out that the octupole strength in ^{208}Pb could have been easily missed in a low-resolution experiment, since many discrete states with various L, such as $L=4,5$, and higher-L values, coexist in the same energy region as that of the LEOR. Particularly, as reported by our (p,p') measurement, the total sum of the $L=4$ strengths in this energy region is as strong as that of the $L=3$ strengths, and the distribution of the $L=4$ strengths even shows a resonancelike structure which may be called a "low-energy hexadecapole resonance (LEHR)" [10]. Consequently, it is possible that the unresolved mixture of these states behaves like a continuum with an angular distribution having no specific structure. The mixture could have been treated as a poorly understood "background" although it was known to arise from real reaction processes.

In conclusion, the existence of the LEOR in ^{208}Pb has been confirmed by the present (α,α') measurement in accordance with the result of previous (p,p') experiment [4]. The EWSR fraction observed in the (α,α') experiment was less than that obtained from the (p,p') measurement, which can be qualitatively understood by the different isospin nature of these two reactions.

ACKNOWLEDGMENTS

The authors are grateful to Dr. K. Muto for valuable discussions and comments. They are grateful to the cyclotron crew of RCNP, Osaka University, for their kind support. Part of this work was performed in Gesellschaft für Schwerionenforschung (GSI) at Darmstadt when one of the authors (Y.F.) was staying in the Federal Republic of Germany. He expresses his gratitude to the members of the Target Laboratory at GSI for the preparation of the target. He is grateful to the Alexander von Humboldt Foundation for its support. The experiment was performed at RCNP under Program No. 30A12.

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