Gamma Decay of Low-Energy Octupole Resonance in ^{90}Zr

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Gamma decay of the low-energy octupole resonance in ^{90}Zr was studied by inelastic α scattering at 99.3 MeV. Correlation functions measured for the ground-state transition support a spin-3 assignment for the low-energy octupole resonance. Observed branching ratios to the ground and the low-lying states around $E_x \sim 2.2$ MeV are respectively $(7.9 \pm 1.0)\%$ and $(32 \pm 10)\%$, which are significantly larger than those predicted by the statistical-decay model.

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In the past decade, existence of various new giant multipole resonances[1] has been successively confirmed by electron and hadron scatterings since the discovery of the giant quadrupole resonance (GQR). In recent years, one of our interests has been focused upon understanding of these fundamental modes of nuclear excitation. For this purpose, many works have been devoted to study decay properties of these multipole resonances. In comparison with calculations based on the random-phase approximation (RPA) and the Hauser-Feshbach model, it is now found that for giant resonances of light nuclei ($A \lesssim 40$) there remains a considerable amount of initial coherent one-particle, one-hole (1p-1h) configurations, while in heavier nuclei decay of giant resonances shows statistical behavior resulting from couplings to more complex np-nh degrees of freedom.[2] However, those works done so far have mainly been restricted to studies of light particle emissions.[3-9]

In the present work, we have, for the first time, studied gamma decay of the low-energy octupole resonance (LEOR)[10] located at $E_x \sim 30A^{-1/3}$ MeV in medium-mass nuclei. Gamma emission is the predominant decay process expected for the LEOR of these nuclei from Q-value considerations. In ^{90}Zr, the LEOR appears in hadron inelastic scatterings as a giant-resonance-like structure at $E_x \sim 7.5$ MeV with a width of ~2.5 MeV on an underlying continuum (dashed line) as shown in Fig. 1(a) and was confirmed,[10] from the angular distribution study, to have a spin 3 and an energy-weighted-sum-rule (EWSR) strength of ~20%. In the present measurement, we paid attention to whether or not high-energy gamma rays corresponding to transitions to the ground and the low-lying collective states exist, because these transition strengths are associated with an amount of initial coherent 1p-1h configurations and with couplings of the LEOR to nuclear surface oscillations in the same way as observed for the giant dipole resonance (GDR).[11]

Excitation of the LEOR in ^{90}Zr and subsequent gamma decay were studied by the ^{90}Zr$(\alpha, \alpha'\gamma)$ reaction with 99.3-MeV α beams from the isochronous cyclotron of the Research Center for Nuclear Physics, Osaka University. The target was a self-supporting metallic foil of enriched ^{90}Zr isotope with a thickness of 4 mg/cm^2. In order to enhance the coincidence counting rate, the scattered α particles were measured by a

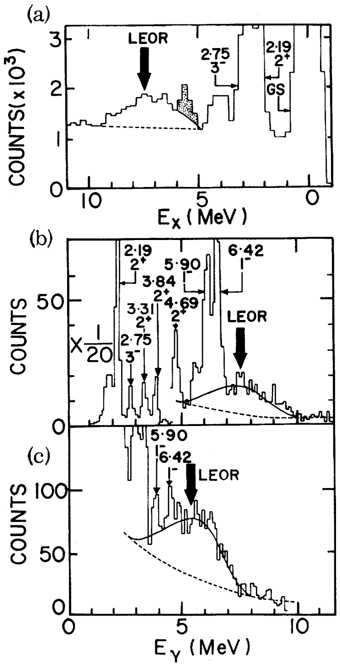

FIG. 1. (a) Energy spectrum of scattered α particles obtained by the $^{90}Zr(\alpha, \alpha')$ reaction at $E_\alpha = 99.3$ MeV. The dashed line is an assumed line shape of the underlying continuum. The shaded area is contributions from the states with $J \neq 3^-$. (b), (c) Energy spectra of the gamma rays gated, respectively, along a locus corresponding to the ground-state transition and to the transitions to the excited states at $E_x \sim 2.2$ MeV. Solid and dashed lines in the figures correspond to assumed line shapes of the LEOR and the underlying continua, respectively.

cluster of five 1-in.-diam detectors [one 5-mm thick Si(Li) and four 6-mm thick NaI(Tl)]. An opening angle for each detector was 13.2° and their total solid angle was 208 msr. They were located symmetrically about the beam axis at angular intervals of 72° with a scattering angle of $\theta_\alpha = 20°$, corresponding to the third maximum of the $L = 3$ (α, α') angular distribution. Since a nuclear alignment is expected along the beam axis for the present detector geometry, angular-correlation functions were expressed in a simple form,[12] which facilitated analyses of observed angular-correlation functions. Reaction gamma rays were observed by three sets of collimated NaI(Tl) detectors (two 6-in.-diam × 6-in. and one $5\frac{1}{2}$-in.-diam × $5\frac{1}{2}$-in.) arranged around the target chamber with detection angles of $\theta_\gamma = 60°$, 92°, and 148° with respect to the beam direction. Low-energy components of gamma rays were eliminated by inserting lead and brass absorbers ahead of each gamma-ray detector. The counting rate was kept below ~40 kcps during the measurement with a beam intensity of ~1 nA. Absolute efficiencies for the gamma-ray detectors were evaluated by measuring the 4.44-MeV gamma ray from the 2_1^+ state in ^{12}C and extrapolating these efficiencies up to higher energies.[13] The effect of sum peaks appearing in the gamma-ray spectra was determined to be negligible by changing the distance of each gamma-ray detector from the target.

Each coincidence event was recorded on a magnetic tape for an off-line analysis. Two-dimensional plots defined by axes of particle and gamma-ray energy indicated loci corresponding to transitions to the ground and low-lying states at $E_x \sim 2.2$ MeV for decay of the LEOR region. To show more clearly, gamma-ray energy spectra were gated along these loci and are shown in Figs. 1(b) and 1(c) after subtraction of random events. Contaminations from carbon and oxygen did not contribute to the region of interest in the final spectra. As shown in Fig. 1(b), a broad bump corresponding to the LEOR is distinguished at $E_\gamma \sim 7.5$ MeV with a width of ~2.5 MeV, besides two discrete 1^- states at $E_\gamma = 5.90$ and 6.42 MeV. Figure 1(c) also demonstrates evidence of a bump centered at $E_\gamma \sim 5.3$ MeV with a width of ~2.5 MeV, which implies the presence of the decay branch of the LEOR to the states at $E_x \sim 2.2$ MeV.

Shapes of the nuclear continua underlying the LEOR denoted by dashed lines in Fig. 1 were determined arbitrarily so that they might be smoothly connected with off-resonance regions. Accordingly, this uncertainty gives the most significant errors in evaluating yields of the LEOR and the underlying continua. However, it can be seen, exceeding above errors, that yield ratios of the LEOR to the underlying continua for coincidence spectra are remarkably larger than the singles case. This suggests that the nuclear structure of the underlying continuum is considerably different from that of the LEOR.

The observed angular-correlation function $W(\theta_\alpha, \theta_\gamma)$ of the ground-state transition for the LEOR is shown in Fig. 2 together with calculated ones obtained by the distorted-wave Born-approximation (DWBA) theory for $L = 1$, 2, and 3 transitions. The theoretical $W(\theta_\alpha, \theta_\gamma)$ is calculated by summing the correlation function[14] for each of the evenly spaced five particle detectors. The resulting $W(\theta_\alpha, \theta_\gamma)$ for an $L = 3$ transition is expressed by

$$W(\theta_\alpha,\theta_\gamma)=\sum_{K\ \mathrm{even}}^{2L}\rho_{K0}(\theta_\alpha)F_K(\gamma)P_K(\cos\theta_\gamma)+(-)^N\frac{2\cos(N\varphi_0)}{[(2N+1)!]^{1/2}}F_{N+1}(\gamma)\,\mathrm{Re}[\rho_{N+1,N}(\theta_\alpha)]P_{N+1}{}^N(\cos\theta_\gamma), \qquad (1)$$

where $\rho_{KQ}(\theta_\alpha)$ is a statistical tensor, $F_K(\gamma)$ is a parameter characterizing a gamma radiation, $P_K(\cos\theta_\gamma)$ and $P_K{}^Q(\cos\theta_\gamma)$ are, respectively a Legendre and an associated Legendre function, N is the number of particle detectors (=5), and φ_0 is the angle of the particle detectors relative to the gamma-detector plane. For $L=1$ and 2, on the other hand, the second term of Eq. (1) vanishes for the present detector geometry. The computer code TWOSTP[15] is used for the present DWBA calculations. The optical-potential parameters are those given by Bertrand *et al.*[16] Collective form factors are used for each transition. Isoscalar dipole form factors prescribed by Deal, Harakeh, and Dieperink[17] are tried for the $L=1$ transition in view of dominant excitation of isoscalar parts for α inelastic scattering.

The theoretical curves indicated in Fig. 2 are obtained by averaging $W(\theta_\alpha,\theta_\gamma)$ over the finite angular spread of the particle detectors. It is noted that for $L=3$ the second term in Eq. (1) gives rise to the asymmetry with respect to $\theta_\gamma=90°$. The observed $W(\theta_\alpha,\theta_\gamma)$ is reproduced best of all by the calculations with an $L=3$ transition. This result provides another confirmation that the LEOR has a spin 3. The high-resolution study of (p,p') scattering,[18] on the other

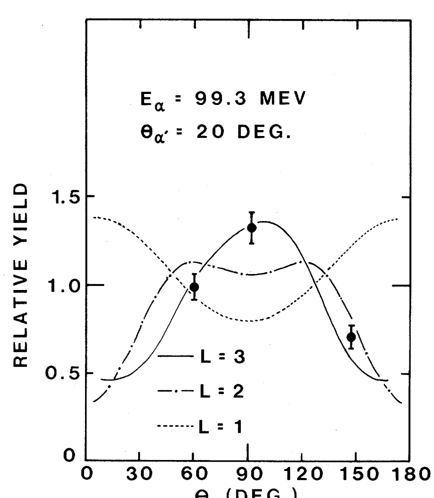

FIG. 2. Observed angular-correlation functions for the transition of the LEOR in ^{90}Zr to the ground state. Various lines correspond to the results of the DWBA calculations.

hand, argues that a considerable amount of an $L=4$ component is populated in the LEOR region. However, so far as the ground-state transition is concerned, the effect of such a hexadecapole component is expected to be negligible because of higher transition multipolarity.

Gamma-decay branching ratios of the LEOR to the ground and low-lying states in ^{90}Zr were determined by comparing coincidence cross sections with singles ones. The resulting values for the ground-state transition of the LEOR and the underlying continuum were $(7.9\pm1.0)\%$ and $(0.9\pm0.2)\%$, and those for the transitions to the $E_x\sim2.2$ MeV region were $(32\pm10)\%$ and $(7\pm2)\%$, respectively. For comparison, branching ratios were theoretically calculated by the statistical-decay model,[19,20] in which transition probabilities were expressed in terms of level densities, transition energies, and reduced transition probabilities. In this model, the LEOR was described as a compound state with a spin 3. The calculated value of the branching ratio was less than 0.5% for the ground-state transition of the LEOR with values of reduced transition probabilities $B(E\lambda)$ of recent compilations[20-22]: $B(E1)=10^{-4}$, $B(E2)=10^{-1}$, $B(E3)=10$, $B(M1)=10^{-2}$, $B(M2)=10$, in single-particle units (s.p.u.). The resulting calculated value was far smaller than the observed branching ratio. Even if unreasonably large values for $B(E3)$ (100 s.p.u.) were taken, only a quarter of the observed branching ratio was accounted for.

As for the transitions to the excited states at $E_x\sim2.2$ MeV, the model calculations were done by summing up the branching ratios for the transitions to 0^+ (1.76), 2^+ (2.19), 3^- (2.75), and 4^+ (3.08) states since each transition was not experimentally separated because of insufficient energy resolution of the particle detectors. The calculated branching ratio was at most 4%, which was again far smaller than the observed one.

On the other hand, the above model calculations qualitatively reproduced the branching ratios observed for the underlying continuum, when it was assumed that the configurations of the underlying continuum were states with admixtures of various L values up to 3.

It is summarized from the above calculations that, in distinction to the statistical behavior of the underlying continuum, the excess of the measured branching ratios for the LEOR over the statistical-decay model predictions provides indication of nonstatistical, i.e., semidirect and preequilibrium decay. These aspects are quite different from the results[2] for the GQR, in which statistical decay is dominant in nuclei with $A \geqslant 40$.

From a different point of view, evidence for enhanced transitions of the LEOR to the states at $E_x \sim 2.2$ MeV suggests nonstatistical decay through couplings of the LEOR to surface vibrations of the nucleus. On the basis of the collective model of Bohr and Mottelson,[23-26] a transition moment of an electric dipole transition arising from distortion of the nuclear shape is proportional to $\beta_2\beta_3$, where β_2 and β_3 are deformation parameters for the low-lying collective 2^+ state and the LEOR, respectively. Then the ratio $R = B(E1; \text{LEOR} \to 2_1^+)/B(E3; \text{LEOR} \to 0_1^+)$ is estimated to be $\sim 10^{-8}$ fm^{-4}, which is in qualitative agreement with the observed value $R = (1.3 \pm 0.4) \times 10^{-8}$ fm^{-4} derived from our observation on the assumption that transitions to states at $E_x \sim 2.2$ MeV are dominated by the $E1$ transition to the 2_1^+ (2.19) state.

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