RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 40, NUMBER 4 OCTOBER 1989

Shapes of ^{59}Cu nuclei at moderate excitation energies and spin

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(Received 7 March 1989)

Continuum γ-ray spectra from the decay of ^{59}Cu formed at excitation energies of 54 and 74 MeV and angular momenta up to $40\hbar$ have been measured and analyzed. The parameters of the giant dipole resonance have been extracted using the statistical model. The giant dipole resonance parameters for the lower excitation energy agree well with published data for spherical ^{63}Cu nuclei. At the higher excitation, the giant dipole resonance strength distribution is not described by a single Lorentzian fit in disagreement with the findings for ^{63}Cu at the same excitation energy. This seems to be correlated with the onset of spin driven deformations as recently evidenced from the shapes of evaporative particle spectra.

In recent years, growing interest has been devoted to nuclear structure far above the yrast line, studied through the decay of compound nuclei (CN) populated in heavy-ion reactions.[1] Direct information on the CN shapes may be obtained by measuring the strength distribution of the giant dipole resonance (GDR) built on excited states.[2] The spectral shapes of charged particles emitted from highly excited nuclei are sensitive to the nuclear shapes as well so that nuclear deformation may be inferred from the change of phase space (level density and emission barriers) needed in statistical models to fit the energy spectra of evaporated particles.[3] This method has been applied recently to ^{59}Cu formed in the ^{32}S+^{27}Al reaction,[4,5] showing deviation between the experimental particle spectra and those predicted for spherical nuclei, in qualitative agreement with rotating liquid drop model (RLDM) predictions[6] of sizable deformations for this nucleus in the angular momentum range $J=(30\text{-}40)\hbar$.

In a recent paper Kicinska-Habior *et al.* have reported[7] on a series of GDR measurements performed on ^{63}Cu populated with heavy-ion fusion reactions at excitation energies up to $E_X=77$ MeV and spin up to $J_{\text{crit}}\sim 35\hbar$. The derived GDR parameters, when compared with those of cold nuclei, suggest that the heavier Cu isotope retains a spherical shape up to the highest excitation energy and angular momentum investigated. These results prompted us to carry out further investigations on ^{59}Cu. We report here on measurements of the GDR in the ^{32}S+^{27}Al reaction at excitation energies of 54 and 77 MeV. These energies allow a direct comparison with both the charged particle emission for ^{59}Cu compound nucleus and the ^{63}Cu data. We will show that the ^{59}Cu GDR data are in good agreement with the ^{63}Cu data for the lower excitation energy (for which the particle spectra are well accounted for by standard statistical model calculations). At the higher bombarding energy the GDR line shape is not described by a single Lorentzian fit. The fitting procedure requires a large increase of the GDR width. This effect, not seen in the ^{63}Cu at the same excitation energy, seems to indicate the onset of nuclear deformations in agreement with those derived from the charged particle spectra and with the RLDM predictions.

The experiment was performed at the XTU Tandem of the Laboratori Nazionali di Legnaro. Targets of 1.6 mg/cm^2 of ^{27}Al were bombarded with 100 and 150 MeV pulsed ^{32}S beams. The energies at the center of the targets were 89 and 140 MeV. γ rays of energy up to 30 MeV were detected at $\theta=90°$ with respect to the beam by a 24×32 cm^2 NaI(Tl) crystal, surrounded by a plastic anticoincidence as well as passive paraffin, iron, and lead shielding.[8] Pulsed-beam techniques were used to separate prompt γ rays from neutron-induced events. Pileup was rejected by an appropriate electronic circuit. The stability of electronics was monitored with a light emitting diode and was better than 1% over the duration of the experiment (four days). The energy calibration was accomplished using radioactive sources at low energy and the well-known ^{12}C(p,p') reaction at $E_\gamma=15.11$ MeV. We emphasize the fact that the data presented here were taken in one experimental run and the same energy calibration and detector response function is used for both measured spectra.

In Fig. 1 the measured γ-ray spectra are presented. The GDR parameters (strength S, energy E, and width Γ) were determined by fitting the experimental spectra over the region $E_\gamma \geq 12$ MeV with those calculated by the modified version of the computer code CASCADE (Ref. 9) and folded with the detector response function. As in our previous work,[5] we used two different sets of input data for the statistical model calculation. The first (set A in the following) was determined by Pulhofer *et al.* in calculations of evaporation residue yield distributions for

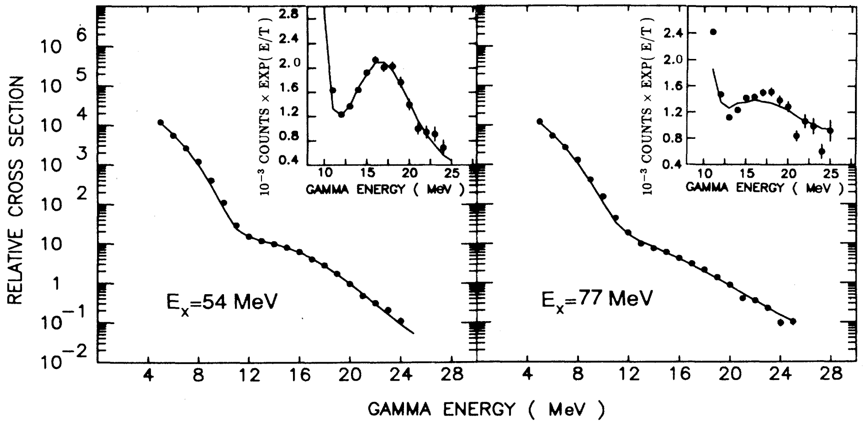

FIG. 1. Measured γ-ray spectra together with least-squares-fitted statistical model calculations (set C input). In the inset, data are multiplied by an exponential function to check the fit quality in a linear scale.

$^{32}S+^{27}Al$ at 160 MeV.[10] The second (set B) contains adjusted transmission coefficients and modified yrast line which are needed to reproduce the shapes of the charged particle spectra.[4,5] As a result of the observations of Ref. 7 on the sensitivity of the calculation to the energy dependence of the level density, we also used a third set (set C). This is the basic Pulhofer calculation with the inclusion of the level-density parametrization (labeled F in Table II of Ref. 7), which agrees better with experimentally measured level-density data in this mass region.

Results of the least-squares three-parameter fitting are reported in Table I together with the GDR parameters for ^{63}Cu. The values of the reduced chi-square χ^2/ν are quoted, where ν is the number of the degrees of freedom in the fit. The errors on the parameters quoted in Table I are those from the fitting procedure multiplied by $(\chi^2/\nu)^{1/2}$ to account for the quality of the fit. An example of the corresponding calculated spectra is shown in Fig. 1.

For $E_x=54$ MeV, a good reproduction of the experimental data is obtained with set C, yielding GDR parameters in perfect agreement with the corresponding ^{63}Cu data. Calculations with sets A and B are slightly worse and indicate higher strength of the GDR (~ 1.3 times the classical sum rule). This confirms the findings of Ref. 7 regarding the sensitivity of the GDR parameters to the energy dependence of the level density in the region 10–20 MeV above the yrast line.

The agreement of the ^{59}Cu GDR parameters with that of ^{63}Cu at the same excitation and lower spin populated in the ^{6}Li, ^{18}O, and ^{12}C induced reactions, indicates that the lighter Cu isotope also retains a prevalently spherical shape up to $J_{\text{crit}} \sim 26\hbar$.

At $E_x=77.4$ MeV the A, B, and C calculations yield reproductions of the experimental spectra of equivalent quality, but very poor ones with respect to that obtained at the lower excitation energy, evidencing the departure of the GDR strength function from the single Lorentzian shape. The χ^2/ν values demonstrate that the assumed Lorentzian distribution is not a good estimate of the experimental data. The GDR parameters extracted from

TABLE I. Summary of GDR parameters for Cu nuclei.

Reaction	A_{CN}	E_x (MeV)	J_{crit} ($\hbar$)	S	E_D (MeV)	Γ (MeV)	
$^{18}O+^{45}Sc$	63	52.2	13	1.10 ± 0.07	16.5 ± 0.4	9.6 ± 0.4	Ref. 7
$^6Li+^{57}Fe$	63	52.0	17	0.87 ± 0.07	16.5 ± 0.4	10.2 ± 0.3	Ref. 7
$^{12}C+^{51}V$	63	52.2	23	0.87 ± 0.07	16.8 ± 0.3	9.3 ± 0.3	Ref. 7
$^{32}S+^{27}Al$	59	54.0	26	1.37 ± 0.04	17.5 ± 0.2	9.3 ± 0.4	$\chi^2/\nu=1.2$ set A
				1.21 ± 0.04	17.9 ± 0.4	9.2 ± 0.7	$\chi^2/\nu=1.2$ set B
				0.96 ± 0.12	17.1 ± 0.4	9.6 ± 1.3	$\chi^2/\nu=1.0$ set C
$^{18}O+^{45}Sc$	63	77.4	35	0.90 ± 0.10	16.4 ± 0.3	10.6 ± 0.6	Ref. 7
$^{32}S+^{27}Al$	59	77.4	38	0.93 ± 0.20	16.6 ± 0.8	15.0 ± 3.1	$\chi^2/\nu=15.5$ set A
				0.64 ± 0.11	17.8 ± 1.1	16.7 ± 1.1	$\chi^2/\nu=13.8$ set B
				0.82 ± 0.11	15.7 ± 2.6	15.3 ± 0.7	$\chi^2/\nu=14.2$ set C

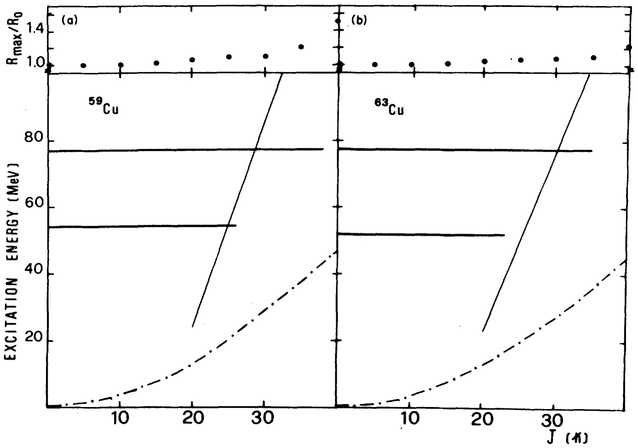

FIG. 2. Yrast plot for (a) ^{59}Cu and (b) ^{63}Cu. The heavy horizontal lines indicate the angular momentum ranges (using sharp cutoff model) and excitation energies associated with the fusion reactions studied in this work. The thin solid line marks the limit for the persistence of yrastlike deformation ($T_{\rm lim} \sim 40\delta A^{-1/3}$). In the upper part the RLDM prediction for the ratio of the major axis of the deformed nucleus to the spherical radius is reported. $T_{\rm lim}$ values have been calculated for RLDM deformations and converted in the excitation energy scale using the level density parameter $a = A/8$. Yrast lines are calculated following Ref. 10.

the fit show a fair amount of scatter between the different calculations, but all indicate the need of a value for the GDR width significantly larger than $\Gamma = 9-10$ MeV as determined for the lower excitation energy. Beyond the results reported in Table I, several different calculations were attempted to fit the GDR line shape with a single Lorentzian close to that determined for spherical Cu nuclei. As an example, we have performed calculations using set C in which the values of the energy and width of the resonance were fixed at those derived from the ^{18}O+^{45}Sc with only the strength left as a free parameter. This calculation converges at strength value $S = 0.60 \pm 0.24$ with a worsening in the reduced chi-square value $\chi^2/\nu = 36$. Calculation with the strength constrained at value $S = 1$ yields very broad resonance ($E = 15.9 \pm 2.2$, $\Gamma = 18.4 \pm 2.6$, and $\chi^2/\nu = 13.3$). Changes of the fit region with the exclusion of some data points do not yield results satisfying the χ^2/ν test of hypothesis.

Deviation of the GDR strength function from a single Lorentzian shape is a well-known effect in deformed nuclei.[1,2] The increase in the GDR width by increasing excitation energy may be due to dynamical deformations driven by the spin, as recently evidenced for lighter nuclei,[11] as well as to thermal fluctuations.[12] The comparison of the ^{18}O+^{45}Sc data with those for ^{32}S+^{27}Al suggests a spin driven contribution to the GDR broadening at $E_x = 77.4$ MeV, even though the critical angular momenta for the two reactions differ only by a few ħ units. In the ^{32}S+^{27}Al reaction at 140 MeV, the initial CN spin extends up to $J_{\rm crit} = 38\hbar$ with a sizable population of states in the angular momentum range for which the RLDM predicts strong deformations, as shown in Fig. 2(a). At these angular momenta the CN is at an excitation energy lower than that corresponding to the limiting temperature ($T_{\rm lim} \sim 40\delta A^{-1/3}$) (Ref. 13) for the persistence of yrastlike deformations. It is interesting to note that deformation develops very rapidly around $J = 36\hbar$, where the oblate-prolate transition for ^{59}Cu is predicted. The average deformation of the CN is therefore strongly influenced by the angular momenta near $J_{\rm crit}$ and by the diffuse boundary between CN formation and other reaction mechanisms at the higher spins.[14]

For the heavier Cu isotope populated in the ^{18}O+^{45}Sc reaction, $J_{\rm crit}$ is still lower than the angular momentum value for the oblate-prolate transition ($J = 39\hbar$) so that only mild deformations are involved. Furthermore, heavier mass and small deformation result in a lower limit for the persistence of the yrastlike structure, as shown in Fig. 2(b).

In conclusion, the present study of the GDR decay in ^{59}Cu at moderate excitation energies and spin show evidence for the onset of spin driven deformations. The same effect was previously indicated by the phase space changes needed in the statistical model calculations to reproduce the evaporative α particle spectra in the same nucleus. Systematic experimental work is needed to map out the mass, angular momentum, and excitation energy dependence of the deformation and to get a better understanding of the corresponding GDR line shape. The combined use of GDR and charged particle measurements is envisaged as an important tool to study the nuclear structure of hot and rotating nuclei.

We thank A. Bracco for giving us the modified version of CASCADE. This work was supported by the Istituto Nazionale di Fisica Nucleare, the U.S. Department of Energy, and the Robert A. Welch Foundation.

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