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Shape changes and isospin purity in highly excited light mass nuclei

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The statistical decay of the Giant Dipole Resonance built on highly excited states of light mass nuclei was studied in inclusive experiments. We report on results of the search for a shape change of hot, fast rotating ⁴⁵Sc and the test of the isospin purity at high excitation in ²⁸Si and ²⁶Al.

1. INTRODUCTION

Some features studied by the statistical decay of the Giant Dipole Resonance (GDR) built on highly excited states seem to be more pronounced for light-medium mass nuclei than for heavy systems. For example, shape changes should occur in these species at much lower angular momenta than in heavy nuclei due to the smaller moment of inertia and hence a faster increase of rotational frequency with spin. Also the sensitivity to the isospin mixing is larger in cases where the compound nucleus is formed with isospin zero, which can only be achieved in light-medium mass compound nuclei.

There are also some disadvantages appearing when studying statistical GDR decay of light mass nuclei. The observed γ -ray yields are smaller than in heavy nuclei because of the lower Coulomb barrier, which permits charged particle decay, and because of the smaller E1 sum rule magnitude. The GDR yield extends up to higher γ -ray energies due to a larger mean GDR energy and large GDR width. In statistical model calculations isospin has to be taken into account explicitly and deuteron emission should be included, and this increases the computation time. Because of the small value of the moment of inertia for light mass nuclei the rotational energy constitutes an important contribution to the energy at which the level density is calculated and hence it should be accurately estimated, taking into account the dependence of the moment of inertia on spin. Shell effects on the level density are very important as may be seen from the ratio of calculated and experimental level spacing, due to the close vicinity of closed shells, so the Reisdorf level density formulation should be used [1-3].

We have studied the statistical GDR decay in a number of light-medium mass nuclei from $A = 26$ up to $A = 63$ in inclusive experiments at projectile energies $E_{proj}/A < 7$ MeV/nucleon [1, 2, 4-9]. Measured inclusive γ -ray spectra have been least-squares fitted in the E_γ range above 12 MeV using the statistical model CASCADE [10]. One or two component GDR strength function with 3 or 6 free parameters, respectively was applied, and the γ -decay strength function (equivalent photon absorption cross section) was determined from the fits.

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2. EXPERIMENT

Compound nuclei of interest have been formed in heavy-ion fusion reactions using self-supporting targets and heavy-ion beams from the University of Washington tandem linac. Gamma ray spectra at a laboratory angle of 90° with respect to the beam axis and five-angle angular distributions from the decay of the compound nuclei studied were measured in a 25.4 cm x 38.1 cm NaI(Tl) crystal surrounded by plastic anticoincidence and lead shields. Prompt γ rays produced in the target were separated from neutron induced events by time of flight with respect to the pulsed beam. Cosmic-ray events were rejected by an anticoincidence condition with pulses from the plastic shield. The spectrometer gain was stabilized by the combined active transistor-stabilized bases and a light-emitting diode stabilization system.

All absolute cross sections were obtained by direct calculation from the measured γ -ray yields, after correcting for pileup and deadtime as described in Ref.[2]. The measured detector response was folded into statistical model calculation for comparison with experiment.

3. SHAPE CHANGE STUDIES

It is well known that the sensitivity of the GDR decay to the nuclear deformation manifests itself by a splitting of the GDR strength function, which is usually approximated by two components. Additional information about the nuclear shape is carried by the angular distribution of γ rays emitted during the GDR decay [11, 12, 4]. The measured angular distribution may be described in the CM-system as $W(E_\gamma, \theta_\gamma) = A_0(E_\gamma)[1 + a_1(E_\gamma)P_1(\cos\theta_\gamma) + a_2(E_\gamma)P_2(\cos\theta_\gamma)]$. For a deformed nucleus a characteristic dispersion shape of a_2 versus E_γ is expected to occur centered about the mean GDR energy, while for a spherical nucleus $a_2 \approx 0$.

For a quantitative description one has to take into account that at final temperature the nucleus undergoes thermal shape and orientation fluctuations. This spreads out the GDR strength function, increasing the observed width and affecting $a_2(E_\gamma)$. To determine the most probable shape of the hot, fast rotating nucleus the experimental values of photoabsorption cross section and a_2 coefficient have to be compared with the results of calculations including thermal shape and orientation fluctuations.

In our earlier studies of the statistical GDR decay in the $^{39}\text{K}^*$, $^{45}\text{Sc}^*$ [2] and $^{46}\text{Ti}^*$ [9] nuclei at $E_x = 60.0, 66.6$ and 58.1 MeV, respectively, corresponding to average temperatures $T = 1.7, 1.8$ and 1.9 MeV and average spins $\bar{I} = 16, 18.5$ and $19 \hbar$ populated by the $^{12}\text{C} + ^{27}\text{Al}$, $^{18}\text{O} + ^{27}\text{Al}$ and $^{19}\text{F} + ^{27}\text{Al}$ reactions, the a_2 coefficient of the measured angular distributions was found to have negative values of -0.1 to -0.15 just below the GDR centroid, indicating large deformations of those nuclei at temperatures and spins studied. In those cases the GDR strength function might be described by one Lorentzian function with a large width of about $13 - 15$ MeV.

We would expect that at those temperatures the pairing and shell effects should be dissolved and the shape of the nucleus should be well described by the rotating liquid drop model (RLDM) [13]. According to the RLDM with increasing angular momentum L , the shape of the nucleus becomes oblate deformed, rotating non-collectively. With further angular momentum increase, the deformation of the oblate shape increases and at

some value $L = L_I$, the oblate shape is expected to become unstable, favouring a triaxial ellipsoid, strongly deformed with an approximately prolate shape rotating collectively.

Fig. 1. Measured raw γ -ray spectra $\sigma_{\gamma}^{exp}(E_{\gamma})$ and fitted statistical model calculations $\sigma_{\gamma}(E_{\gamma})$ (top row). Middle row: fitted a_1 angular distribution coefficient. Bottom row: the photoabsorption cross section $\sigma_{abs}(E_{\gamma})$ determined from the fits (lines) and $\sigma_{abs}^{exp}(E_{\gamma})$ (points with errors) extracted from the raw data according to the formula given in the text.

In the light nucleus ^{45}Sc , the transition from oblate to triaxial shapes should occur at $29\hbar$ (this may be compared to ^{90}Zr , for example, where the shape change is predicted at $54\hbar$). In order to search for this effect we have studied the $^{18}\text{O} + ^{27}\text{Al} \rightarrow ^{45}\text{Sc}^*$ reaction at four different bombarding energies, $E_{proj} = 44.9, 72.5, 89.4$ and 109.6 MeV, corresponding to grazing angular momenta $L_0 \approx 20, 28, 33$ and $36\hbar$. Compound nuclei of $^{45}\text{Sc}^*$ were formed at initial excitation energies $E_x = 50.0, 66.6, 76.7$ and 88.9 MeV, and average spins $\bar{I} = 13, 18.5, 21.4$ and $23.5\hbar$. Gamma rays produced by the decay of $^{45}\text{Sc}^*$ were detected at angles $\theta_{\gamma} = 40, 55, 90, 125$ and 140° . Calculated average spin values of the populated

states on which the GDR is built are all below $29\hbar$, however for the 2 highest energy cases about 1/3 of the total high energy γ -ray cross section is associated with spins above $29\hbar$.

The measured raw γ -ray spectra $\sigma_{\gamma}^{exp}(E_{\gamma})$ from decays of $^{45}\text{Sc}^*$ at $\theta_{\gamma} = 90^\circ$ are shown in Fig. 1 (top row). A continuous low energy background as well as a discrete line at $E_{\gamma} = 15.1$ MeV are clearly visible in the spectra with high projectile energy. This low energy background is correlated with a non-zero $a_1(E_{\gamma})$ coefficient (Fig. 1, middle row). At $E_{\gamma} > 12$ MeV the a_1 coefficient was found to be zero within errors, consistent with statistical emission, except near the 15.1 MeV line present in the spectra at higher projectile energies.

Fig. 2. Points: $\sigma_{\gamma}^{exp}(E_{\gamma})$ (top row) and $a_2(E_{\gamma})$ (bottom row), both extracted from the data corrected only for 15.1 MeV discrete line. Lines: thermal shape and orientation fluctuation calculations in each case averaged over spin: with shape transition included (thick line) and with shape transition removed (thin line).

The measured spectra shown in Fig. 1 have been least-squares fitted in the E_{γ} range above 12 MeV by the statistical model CASCADE calculations. A narrow energy range near the 15.1 MeV line was excluded from the spectrum during the fitting process. Results of the best fits $\sigma_{\gamma}(E_{\gamma})$ are shown by solid line in Fig. 1 (top row). In the bottom row of Fig. 1 the photoabsorption cross section $\sigma_{abs}(E_{\gamma})$ determined from the CASCADE fits together with the best estimate of the "experimental" photoabsorption cross section $\sigma_{abs}^{exp}(E_{\gamma})$ averaged over the ensemble of states populated by GDR decay, obtained from the uncorrected data are shown, where $\sigma_{abs}^{exp}(E_{\gamma}) \equiv \sigma_{\gamma}^{exp}(E_{\gamma}) \cdot \sigma_{abs}(E_{\gamma}) / \sigma_{\gamma}(E_{\gamma})$. For a better visual comparison of the calculated $\sigma_{abs}(E_{\gamma})$ and the experimental $\sigma_{abs}^{exp}(E_{\gamma})$ the low energy

continuous background as well as the discrete line at 15.1 MeV were subtracted from the $\sigma_{\gamma}^{exp}(E_{\gamma})$ data at all 5 angles, as shown in [5]. However, we have found that the low energy (nonstatistical) background correction cannot be made unambiguously, hence we show only the uncorrected results here. The $\sigma_{16\frac{1}{2}}^{exp}(E_{\gamma})$ values shown in Figs. 1-3 are not valid for $E_{\gamma} < 12$ MeV due to the presence of this background. In any case, the low energy corrections do not affect our interpretation since they do not affect the data at $E_{\gamma} > 12$ MeV.

In the shape of the photon absorption cross section a shoulder at $E_{\gamma} \simeq 25$ MeV is clearly visible for all three higher spin cases (Fig. 1, bottom row) suggesting large equilibrium deformations occurring at high rotational frequencies. The a_2 is relatively large and negative below the γ -ray energy corresponding to the GDR centroid, with $|a_2|$ increasing from ~ 0.1 for the lowest spin up to ~ 0.2 for the higher spin cases (Fig. 2, bottom row), independently indicating the presence of large deformations which increase with spin and temperature.

The quantitative interpretation of the measured angular distributions and spectrum shapes requires comparison with a theory including shape and orientation fluctuations [14]. Such calculations have been done for these cases by Alhassid and Whelan [5]. As expected, the nuclear free energy is found to have an oblate minimum for angular momenta less than $29 \hbar$. For higher spins the minimum is triaxial, nearly prolate. For spins near and above critical value, potential energy surface become very soft along the $\beta \sin \gamma$ axis. The results of thermal shape fluctuation calculations with these surfaces are shown as thick line in Fig. 2. Because the deformation increases rapidly with spin above the critical value, the calculations were averaged over spin. This was done in each case by approximating the spin distribution by three spins of equal weight, performing the calculations at each of the three spins and averaging.

The $\sigma_{16\frac{1}{2}}^{exp}(E_{\gamma})$ is well reproduced by the adiabatic fluctuation theory [5]. In order to clarify the effect of the shape change into triaxial on the $\sigma_{16\frac{1}{2}}(E_{\gamma})$, calculations with free-energy surfaces in which the transition to triaxial shapes has been removed were performed [5]. The results, shown by the thin line, do not reproduce the shape of the measured photoabsorption cross section for two higher spin cases, demonstrating the importance of shape transition in describing the data. On the other hand the angular distributions at high γ -ray energies for high spin cases are not reproduced by any calculation. The measured a_2 values are negative, while the calculated values are positive, and this difference is still not understood.

It is also instructive to compare the data to calculations performed with the full liquid drop free energy surfaces, but at a single value of the angular momentum given by the average spin in each case. The agreement with the data is not much worse than in the full spin-averaged calculation (Fig. 3). This suggests that the spectrum shape is mainly sensitive to increased softness in the potential energy surfaces along the prolate direction.

The same effect has been found more recently in a study of the $^{32}\text{S} + ^{27}\text{Al}$ reaction populating $^{59}\text{Cu}^*$ at five different excitation energies $E_{\gamma} = 54, 68, 78, 93$ and 111 MeV corresponding to average temperatures $T = 1.7, 1.8, 1.9, 2.0$ and 2.2 MeV and average spins $I = 13, 18, 22, 27$ and $27 \hbar$ [15]. The critical angular momentum for oblate-triaxial shape transition in ^{59}Cu predicted by the RLDM is $36 \hbar$. Shape of the $\sigma_{16\frac{1}{2}}^{exp}(E_{\gamma})$ is very well reproduced by the thermal shape and fluctuation calculations performed for average

spin, and averaged over spin [16]. A similar $a_2(E_\gamma)$ dependence was also measured which is not reproduced by the calculations.

Fig. 3. Data points as in Fig. 2. Lines: thermal shape and orientation fluctuation calculations performed at average spin in each case (thin line) and averaged over spin shown by thick line (as in Fig. 2), both for shape transition included.

There are some simplifications in the calculations which we thought might explain observed discrepancies. It is known that for the dipole transitions corresponding to the GDR vibrations along the spin axis the angular momentum of the nucleus remains unchanged, $\Delta I = 0$, while for the transitions corresponding to the vibrations perpendicular to the spin axes $\Delta I = \pm 1 \hbar$. Hence, for the transitions with $\Delta I = 0$ the level density of the final states for the γ -ray emission from the GDR decay equals $\rho(E_x - E_\gamma, I)$, while for the transitions with $\Delta I = \pm 1 \hbar$ the level density equals $\rho(E_x - E_\gamma, I \pm 1)$. In the thermal fluctuation theory differences in the level densities for different ΔI values are neglected. Taking this effect into account one may obtain a non-zero value of the a_2 coefficient ($|a_2| < 0.025$) even for a spherical nucleus, if the level density changes rapidly with spin [11]. A simple estimate of this level density effect (see also [17]) was done in case of the $^{18}\text{O} + ^{27}\text{Al}$ reaction for single initial spin values assuming a fixed axially-symmetric deformed shape of the $^{15}\text{Sc}^*$ nucleus and neglecting averaging over deformations, according to the formulas:

$$\sigma(E_\gamma, I) = \frac{\sum \rho_f(E_x - E_\gamma, I + \Delta I) \cdot \sigma_{\text{abs}, \Delta I}(E_\gamma, I)}{\frac{1}{3} \sum \rho_f(E_x - E_\gamma, I + \Delta I)}, \quad (1)$$

$$a_2(E_\gamma, I) = \frac{\sum \rho_f(E_x - E_\gamma, I + \Delta I) \cdot a_{2,\Delta I} \cdot \sigma_{abs,\Delta I}(E_\gamma, I)}{\sum \rho_f(E_x - E_\gamma, I + \Delta I) \cdot \sigma_{abs,\Delta I}(E_\gamma, I)} \quad (2)$$

Results of these calculations for $^{45}\text{Sc}^*$ at $E_x = 88.9$ MeV (with level density calculated in the Reisdorf formulation) assuming an oblate shape at $I = 23.5 \hbar$ and a prolate shape at $I = 32.3 \hbar$, with GDR parameters taken from CASCADE fits to the measured spectrum shape, with oblate (2:1) and prolate (1:2) strength constraints, respectively are shown in Fig. 4. It is clear that including the effect of the different level densities of the final states improves agreement between the calculated and experimental $a_2(E_\gamma)$, but the change is too small to explain the differences observed at high γ -ray energies.

Fig. 4. Level density effect on $\sigma_{abs}(E_\gamma)$ and $a_2(E_\gamma)$ estimated assuming axially symmetric shapes for $^{45}\text{Sc}^*$ at $E_x = 88.9$ MeV; left: $I = 23.5 \hbar$ (oblate noncollective shape assumed); right: $I = 32.3 \hbar$ (prolate collective shape assumed). The top panels show the assumed GDR strength decomposition. The dashed lines show the results of averaging over final spin (averaging over $\Delta I = 0, \pm 1$) including level density factors as in equations 1 and 2, and the solid line the result of the same computation without level density factors included.

We have made some estimates of possible other sources of high-energy γ rays [5] to the $^{18}\text{O} + ^{27}\text{Al}$ reaction studied at $E_{proj} = 109.6$ MeV. We have considered contributions of incomplete fusion, deep inelastic reactions, fission and bremsstrahlung. We made tests of the importance of the Giant Quadrupole Resonance (GQR) yield, changing parameters

of the isovector GQR strength function according to Ref. [18]. All these contributions seems to be negligible at energies and spins studied. The biggest uncertainty in the γ -ray yields at high E_γ is a possible contribution from bremsstrahlung. It is known that the angular distributions of high-energy photons emitted in reactions at $E_{proj}/A > 9$ MeV/nucleon are forward peaked in the laboratory frame. Since the $^{18}\text{O} + ^{27}\text{Al}$ reaction is nearly mass-symmetric, even though our $a_1(E_\gamma)$ coefficients are consistent with zero we cannot exclude bremsstrahlung contributions on this basis. Also estimates of the bremsstrahlung cross section failed because our spectra are very well described by the statistical calculation up to the highest energies. If we assume that the bremsstrahlung contribution scales according to $(E_{proj} - V_{c,lab})/A$ then the strongest argument in a favour of the small bremsstrahlung yield is coming from the results of the recent studies of more asymmetric reaction $^{18}\text{O} + ^{45}\text{Sc}$ at $E_{proj} = 52, 68, 105, 125$ and 149 MeV, corresponding to $(E_{proj} - V_{c,lab})/A = 1.0, 1.9, 3.9, 5.0$ and 6.4 MeV/nucleon [19]. A non-zero forward-backward asymmetry was observed here for the two highest energy cases only, while at lower energies the $a_1(E_\gamma)$ was consistent with zero. If we assume a scaling according to $(E_{proj} - V_{c,lab})/A$, then our data with $E_{proj} \leq 92$ MeV, corresponding to ≤ 3.5 MeV/nucleon, should not contain a significant bremsstrahlung contribution.

A similar reaction, $^{18}\text{O} + ^{30}\text{Si}$, was studied by one of us at $E_{proj} = 69$ and 100 MeV in collaboration with A. Maj et al.[20] at the Niels Bohr Institute at Riso using the γ -ray multi-detector array Hector and the multiplicity filter Helena. Preliminary results indicate a similar $a_2(E_\gamma)$ dependence as shown in Fig. 2.

4. TEST OF ISOSPIN SYMMETRY AT HIGH EXCITATION ENERGY

The results presented in this section have been obtained by John Behr et al. [7] and form his PhD thesis [8].

It is known that the isospin mixing is small in low-lying states but can be substantial in the region of overlapping resonances. In a compound nucleus state with isospin $T = 0$ an admixture of states with $T = 1$ can be determined in first-order perturbation theory as

$$\alpha^2 = \sum \frac{|\langle T = 1 | H_{\Delta T=1} | T = 0 \rangle|^2}{(E_{T=1} - E_{T=0})^2}, \quad (3)$$

where $H_{\Delta T=1}$ is the isovector part of the Coulomb potential. The Coulomb potential varies slowly over space inside the nucleus and hence will produce large matrix elements only between states with similar wavefunctions and of course, the same spin and parity. At low excitation such states lie usually far apart from each other, so the denominator of (3) is large and consequently the isospin mixing is small.

At higher excitation energy states are more dense; thus with increasing excitation energy, isospin mixing should increase. When the excitation energy exceeds the particle threshold, a finite particle decay width Γ has to be included [21] in expression (3):

$$\alpha^2 = \sum \frac{|\langle T = 1 | H_{\Delta T=1} | T = 0 \rangle|^2}{(E_{T=1} + (\Gamma_{T=1}/2) - (E_{T=0} + (\Gamma_{T=0}/2)))^2}. \quad (4)$$

Maximal α^2 is expected when level spacings are about equal to decay widths, i.e. in the region of overlapping resonances. At even higher excitation energy the compound

nuclear decay widths become very large, much larger than the Coulomb interaction matrix elements. This, as was first suggested by Wilkinson [22], is expected to restore good isospin symmetry to the reactions.

In terms of the spreading width Γ^1 the isospin mixing admixture is, for small mixing, determined in compound nuclear reaction theory [23] by the quantity $\alpha^2 \approx \frac{\Gamma^1}{\Gamma}$, where Γ is the compound nuclear decay width. This means that α^2 is the inverse ratio of the time for isospin mixing to the time for decay of the system.

The sensitivity of the statistical GDR decay to isospin mixing occurs because the GDR is a pure isovector excitation and so, in $N = Z$ compound nuclei, E1 transitions between states of the same isospin are forbidden. In the absence of isospin mixing, in $N = Z$ compound nuclei formed in heavy-ion fusion reactions with stable targets and projectiles, only states with $T = 0$ can be populated. These states will then γ -decay only to $T = 1$ final states, for which density is much lower than for states with $T = 0$. Therefore the statistical GDR γ -ray yield in this reaction in case of pure isospin would be small. If isospin is mixed then the $T = 1$ initial states will also be populated, and which will decay to the more numerous $T = 0$ final states, producing an enhancement of the high-energy γ -ray yield. In $N \neq Z$ compound nuclei, E1 decays are not isospin forbidden, and thus the γ -ray yield depends much less on isospin mixing.

We decided to test isospin symmetry in compound nuclear reactions at high excitation energy and measure the isospin violating spreading width that characterises the admixture of $T = 1$ states into $T = 0$ states. We measured inclusive γ -ray cross-sections for ^{28}Si and ^{26}Al with isospin $T = 0$, for ^{29}Si with $T = \frac{1}{2}$ and for ^{28}Al , ^{30}Si and ^{26}Mg with $T = 1$ at initial excitation energies $E_r \approx 33, 45$ and 65 MeV. In order to extract the isospin mixing in the $N = Z$ compound nucleus measured and calculated ratios of cross sections for reactions forming $N = Z$ and $N \neq Z$ compound nuclei at similar excitation energies were compared assuming a constant isospin violating spreading width in neighboring nuclei. In this manner dependences on GDR parameters and level density formulation were minimized. The deduced isospin mixing admixture α^2 in $^{28}\text{Si}^*$ and $^{26}\text{Al}^*$ at $E_r \approx 34$ - 63 MeV [7] is smaller than at $E_r \approx 20$ MeV as known from other experiments. This is consistent with the idea that isospin is a better symmetry at higher excitation because the compound nucleus decays before the Coulomb interaction has time to equilibrate the isospin degree of freedom.

Our method has however some limitations appearing with increasing excitation energy. The first one is connected with the level density. At higher excitation energy shell effects are less important so the statistical model should work better. However, the level density of $T = 1$ states is a larger fraction of the total level density; also the fraction of the yield due to γ -decay of the daughters populated by particle decay is greater. This reduces the sensitivity to isospin mixing. The second limitation is connected with the presence of a nonstatistical reaction mechanism, namely bremsstrahlung. We have also measured γ -decay spectra from ^{28}Si , ^{29}Si and ^{30}Si at $E_r \approx 85$ and 105 MeV. They have a visible nonstatistical component which is impossible to isolate reliably from the data. Hence we cannot extract the degree of isospin mixing at those energies.

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