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Search for Exotic Shapes of Hot Nuclei at Critical Angular Momenta

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Results from experiments aiming at searching for exotic shapes at very high spins in two different mass regions, namely A≈50 and A≈220 are presented. In particular, the light nucleus ^{46}Ti was studied to search for the Jacobi shape transition while the heavy ^{216}Rn nucleus was studied to investigate the shapes of nuclei on their way to fission. The experimental findings support evidence for shapes of the Jacobi type in ^{46}Ti and of shapes of large deformations in ^{216}Rn.

1. INTRODUCTION

Heated atomic nuclei when rotating with increasing frequency are expected to develop many different shapes. At low angular momentum, if their thermal energy is low, shell effects are dominant and nuclei are either spherical or prolate with rather small deformations. When the thermal energy is sufficiently large, the role of shell effects becomes smaller and according to the liquid drop model [1] the nucleus, under the influence of angular momentum, becomes oblate. In particular, the size of the oblate deformation increases with the angular speed of rotation.

In addition to the prolate(spherical)-oblate shape phase transitions, at a certain critical angular momentum the nucleus is expected to undergo to a second shape phase transition in which from oblate the nucleus becomes triaxially elongated (Jacobi transition). This transition is expected to be seen better in rather light nuclei where high rotational frequencies can be reached before the fission competition dominates.

In contrast, in the case of much heavier nuclei, the study of shapes of nuclei surviving fission at high angular momenta is interesting for the search of the more exotic shapes that the nucleus can have on his way to fission.

In this paper we discuss results on the compound nuclei ^{46}Ti and ^{216}Rn at temperatures of T≈1.5 MeV and with angular momentum close and/or larger than the expected critical values for Jacobi transition in the case of the light nuclei and for fission for the heavy compound. The data are based on experiments in which the high- energy γ-rays from the decay of the GDR were measured using particular configurations of the HECTOR array [2].

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2. JACOBI SHAPES IN ^{46}TI NUCLEI

In the search for exotic nuclear shapes, the light- and medium-mass nuclei are of special interest. This is because these nuclei are expected to undergo a Jacobi shape transition (from oblate via triaxial to very elongated prolate) at values of the angular momentum which are relatively low and below the fission limit. For example for nuclei with mass A≈45 the critical angular momentum for the Jacobi transition is expected to be at 29 $\hbar$.

The experimental signatures for Jacobi shapes for A≈45 nuclei would be a pronounced high energy bump at $E_\gamma \approx 25$ MeV in the strength function of the giant dipole resonance together with a rather pronounced anisotropy. In particular the anisotropy should be characterised by negative values of the A_2 coefficient below $E_\gamma \approx$18-19 MeV and by positive values at higher transition energies.

The first experimental evidence for the Jacobi shape transition was obtained for the ^{45}Sc compound nuclei by Seattle group [3] based on inclusive spectra. In the photon absorption cross-section a shoulder at $E_\gamma \approx 25$ MeV was found which becomes more and more visible with increasing bombarding energy. This has suggested large effective deformation of the compound system at high rotational frequencies. However, the corresponding A_2 coefficient of the angular distributions did not show the correct expected behaviour.

To understand whether or not the unexpected behaviour of the measured angular anisotropy was due to experimental limitations another experiment was made for the neighbouring ^{46}Ti nucleus which allowed to obtained more exclusive data corresponding to better selected regions of the angular momentum. For this experiment the HECTOR array and the accelerator facility of the Niels Bohr Institute in Risø (Denmark) were employed. The reaction used was 98 MeV ^{18}O on ^{28}Si target (1.1 mg/cm^2 thick), producing the compound nucleus ^{46}Ti at the excitation energy of 81 MeV, and with angular momentum distribution having $l_{max} \approx 32$ $\hbar$. The high-energy spectra, measured in the BaF_2 detectors at different angles, were obtained as a function of the multiplicity filter's folds.

The upper row of Fig. 1 shows the experimental spectra in the logarithmic scale for 3 different fold regions: 4-5, 6-8, 9-11. In light nuclei the preferred particle evaporation decay is via charged particles, which can remove substantial amounts of angular momentum from the compound system. Therefore the measurement of high-energy γ-rays associated with low-fold coincidences of low-energy γ-rays is rather insensitive to the angular momentum of the decaying system, and contains contribution both from low and high angular momenta. Only when gating on very high-fold coincidences (corresponding to high γ-multiplicity) one is favouring the selection of the events originating mainly from the highest angular momenta of the compound nucleus. The fold region 9-11 corresponds to angular momentum of 30±5 $\hbar$, indeed sensing the region where Jacobi transition is expected to appear. Folds higher than 11 did not contain the characteristic GDR bump, only background, and therefore were not considered for further analysis. The measured spectra of Figure 1 have superimposed on them the results of the best fitting CASCADE calculations in which the GDR strength function was assumed to be of 2 Lorentzian type. In addition, the experimental yrast line as well as the angular momentum distribution corresponding to the selected fold region were used in the calculations (see [4]).

To examine the details of the GDR part, the experimental spectra were converted into our best estimate of the photon absorption cross section (GDR cross section, shown in

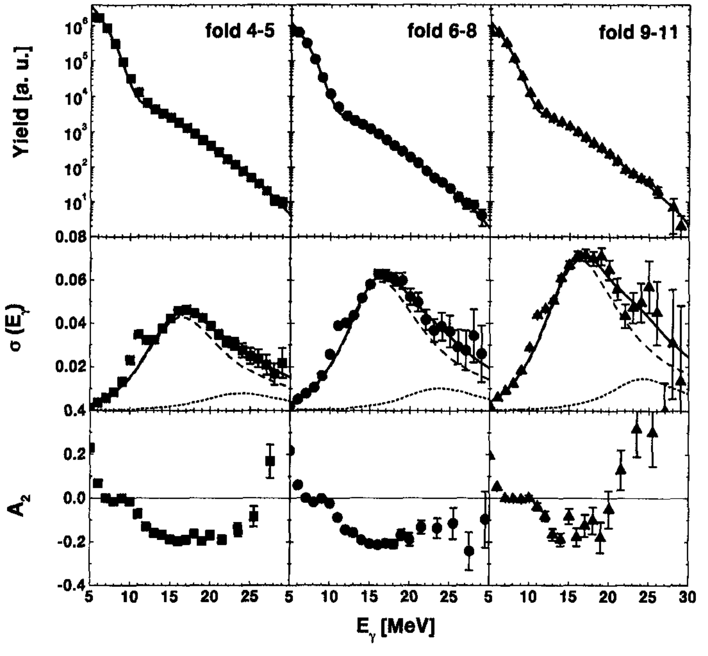

Figure 1. Upper row: measured high-energy spectra for 3 different fold bins, together with fitted statistical model calculations. Middle row: the photoabsorption cross-section determined from the fits (solid lines) and the extracted from the measured spectra (points); dashed line indicate 2 fitted Lorentzian components. Bottom row: experimental A_2-coefficient distributions.

linear scale in the middle row of Fig. 1), represented by the expression $F_{2L}{}^{*}Y_{exp}/Y_{fit}$. In this expression Y_{exp} is the experimental spectrum and Y_{fit} is the calculated spectrum assuming that the GDR decay can be represented by double Lorentzian function F_{2L}, being the best fit to the experimental spectrum. One can note a shoulder at around $E_\gamma \approx 24$ MeV similar to that seen in the ^{45}Sc nucleus [3]. The quadrupole deformation parameter deduced from the centroids of the 2 fitting Lorentzian components was $\beta \approx 0.4$.

The spectra of the A_2 coefficient from the angular distribution extracted from the data are displayed in the bottom row of Fig. 1. The values for the 2 lowest fold regions are negative in both regions of the low and high energy GDR components, showing a similar behaviour found in ^{45}Sc. In contrast, for the highest fold window, the behaviour of the A_2-coefficient changes and follows the expectation namely of being negative for the low energy component and positive for the high one. A possible explanation for the peculiar behaviour of the A_2-distrubutions for lower folds (and for the inclusive data of Seattle group) could be existence in the spectra of low multiplicity component, for example from incomplete fusion.

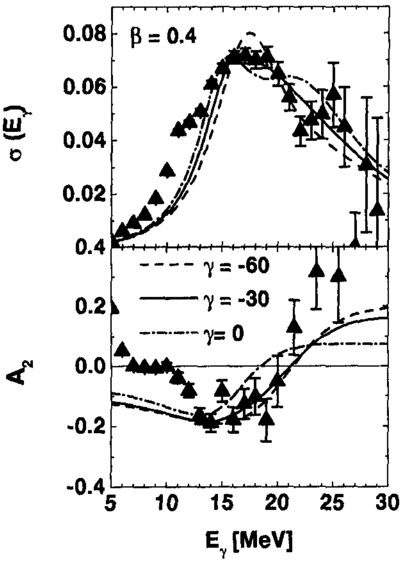

Figure 2. The results of simple calculations assuming 3 different nuclear shapes compared to the estimated experimental GDR strength function (upper part) and to the experimental A_2 spectrum (lower part).

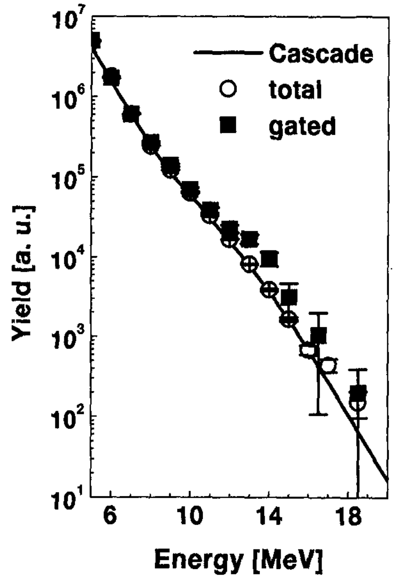

Figure 3. High-energy spectra from the decay of $^{216}Rn^*$: open circles - ungated spectrum; solid squares - spectrum gated by the long-lived isomers; line - statistical model fit to the ungated spectrum. All spectra are normalised at E_γ=6 MeV.

A simple estimate of the type of the effective shape probed by the giant dipole oscillation can be obtained by comparing the measured quantities (strength function and A_2) with the calculations corresponding to the fixed deformation parameter β=0.4, as obtained from the statistical model fit. These calculations, representing a first level analysis, are shown in Fig. 2 in comparison with the experimental quantities. Two of them correspond to axially symmetric shapes: $\gamma=0^o$ (collectively rotating prolate shape) and $\gamma=-60^o$ (oblate, non-collective rotation). The third calculation is for the 3-axial shape with $\gamma=-30^o$. In the case of the GDR strength function one can rule out the oblate shape (upper part of Fig. 2) while in the case of the A_2 coefficient (bottom part of Fig. 2) one sees that the prolate shape is the one that gives the worst fit to the data. Consequently, these very simple estimates suggest that these ^{46}Ti nuclei have an effective deformation with $\beta\approx0.4$ and of triaxial type with $\gamma\approx-30^0$, corresponding to the ratio of major axes 1.6:1.25:1. These shapes are those expected for nuclei undergoing the Jacobi shape transition.

The next step, needed to have a more complete discussion of the problem, will be the comparison with the thermal shape fluctuation mode taking into account not only the effective shapes but the full ensemble of shapes.

3. GDR SPECTRA TAGGED BY THE ISOMERIC DECAY IN ^{212}RN

Nuclei possessing large angular momenta, in the vicinity of the fission barrier, are expected to have large deformations. So far, the problem of shapes in fissioning nuclei has been studied with measurements in which GDR γ -decay was detected in coincidence with the fission fragments (eg. [5,6]). The analysis and interpretation of such experiments is however difficult, since the measured spectra contain contributions both from the GDR decay in the fission fragments (post-fission) and from the fissioning nucleus (pre-fission). It is therefore clear that measurements associated with nuclei close to the fission barrier but surviving the fission competition are extremely interesting since they allow to study the nuclear shapes in a new regime and in spectra free from fission fragments contribution. In addition, measurements of this type are important to test the model of thermal shape fluctuations in this extreme regime close to the fission, not yet explored.

For the investigation of this problem we have chosen the compound nucleus ^{216}Rn, formed in the reaction 96 MeV ^{18}O on ^{198}Pt and populated with an angular momentum distributions with $l_{max}\approx 42\ \hbar$ and with excitation energy E*=56 MeV. This choice is related to the fact that a possible decay path of this compound nucleus in competition with fission feeds strongly the long-lived ($T_{1/2}$=220 ns) 30^+isomer in ^{212}Rn. In addition, since only 1 or 2 discrete transitions feeding this isomer were found [7], one can expect that the fission limit is below 40 $\hbar$. Consequently, the detection of high-energy γ-rays in coincidence with the delayed radiation from the 30^+ isomeric state allows to select Rn-nuclei at angular momenta close to the fission barrier but still surviving the fission competition

The basic idea of the experiment was to use the recoil-catcher geometry technique, similar to that previously employed in discrete γ-spectroscopy of the Polonium [8] isotopes or in the GDR studies of Dy [9] isotopes. The ^{18}O beam (provided by LNL Legnaro accelerator facility) was pulsed, with a repetition period of 400 ns and 10 ns pulse width, allowing to measure the coincidences between prompt and isomeric γ-rays. The target (self-supported ^{198}Pt, 1 mg/cm^2 thick), where the prompt γ-decay takes place, was surrounded by the HECTOR array. The residual nuclei were stopped in a thin (8 μm) Mylar catcher (with a central hole) positioned at the distance 40 cm, covered by the recoiling nuclei during the lifetime of the long lived isomeric states. The delayed radiation emitted by the stopped residues was detected in a cylindrical eight-segmented BGO anti-Compton shield, which was inserted on the beam pipe and was surrounding the catcher. Its efficiency for the delayed radiation was around 80%. The prompt high-energy γ-rays from the target were recorded on tape only when followed by the delayed radiation detected in the catcher set-up. Additionally we measured the time between the reaction and the isomeric decay, and the sum energy of the delayed γ transitions.

The very preliminary results of this experiment are presented in Fig. 3, where the comparison between the total GDR spectrum with the one gated by the isomeric decay is shown. The total, ungated GDR spectrum from the decay of ^{216}Rn is shown by open circles. The 1 Lorentzian statistical model calculation fit to the total spectrum, shown as solid line, resulted in the GDR width Γ_{GDR}=12.2 MeV. This width is much larger than the ground state value ($\approx$4 MeV). This suggests that even in the total spectrum one sees the larger deformation and thermal fluctuation effects. The gated GDR spectrum was obtained requiring that the decay in the catcher took place later than 150 ns after the prompt radiation, and additionally that the sum energy was high enough to discriminate the low spin isomers and the background from the radioactivity. This spectrum, normalised to the total one at E_γ=6 MeV, is shown also in Fig. 3 with full squares. In spite of low statistics, one can notice that the gated spectrum has relatively higher yield in the interval E_γ= 12-16 MeV which could reflect the fact that by gating with the isomer nuclei with prolate shapes (typical of nuclei on their way to fission) have been preferentially selected. A confirmation of this interpretation need an analysis based the Monte-Carlo version of the statistical model code CASCADE. This analysis is in progress and is expected to provide more quantitative information on the shapes of decaying ^{216}Rn nuclei at very high spins.

4. SUMMARY AND CONCLUSIONS

The search of exotic shapes of nuclei induced by very fast rotation has been one of the very interesting subject both at T=0 and at finite temperature. Although it is well established that the GDR is sensitive to nuclear shapes at finite temperature one needs very exclusive experiments to isolate the cascade containing the signature of the more exotic shapes.

The data here presented, concerning the ^{46}Ti and ^{212}Rn nuclei have both shown the presence of large deformation around the critical angular momentum values. In particular, indication for the Jacobi transition is found in the ^{46}Ti case.

The more complete analysis of the present results together with the comparison with model predictions are expected to give a deeper insight to the interesting problem of nuclear shapes at finite temperature and very high spins.

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REFERENCES

1. S. Cohen, F. Plasil, W.J. Świątecki, Ann. Phys. (N.Y.) 82 (1974) 557.
2. A. Maj et al., Nucl. Phys. A571 (1994) 185.
3. M. Kicińska-Habior et al., Phys. Lett. B308 (1993) 225.
4. M. Kmiecik et al., Nucl. Phys. A674 (2000) 29.
5. R. Butsch et al., Phys. Rev. Lett. 41 (1990) 1530.
6. T.S. Tveter et al., Phys. Rev. Lett. 76 (1996) 1035.
7. G.D. Dracoulis et al., Phys. Lett. B246 (1990) 31.
8. A. Maj et al., Nucl. Phys. A509 (1990) 413.
9. J.P.S. van Schagen et al., Nucl. Phys. A581 (1995) 145.