Nuclear triaxiality in the A $\sim$ 160$-$170 mass region: the story so far

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Introduction

Nuclear triaxiality has been a subject of major discussion and extensive theoretical and experimental investigations ever since its conception as one of the aspects of nuclear deformation. Considerable progress has been made over the last decade to affirm nuclear triaxiality by observation of phenomena like wobbling excitation and nuclear chirality, which are uniquely related to nuclear triaxial shape. Wobbling motion of nucleus, which is an unambiguous fingerprint of stable nuclear triaxiality, has been observed in even-N ^{163,165,167}Lu$_{92,94,96}$, ^{167}Ta$_{94}$, and possibly in ^{161}Lu$_{90}$. While the wobbling mode was first predicted in even-even systems, it has only been observed in odd-A Lu and Ta isotopes. A number of triaxial strongly deformed (TSD) bands have also been identified in neighboring odd-odd Lu isotopes, centered around ^{163}Lu$_{92}$, thus validating the predicted existence of TSD island in this mass region.

Theoretical calculations based on different approaches predicted large shell gaps at large triaxiality around Z = 71, 72 and N = 94, 97 [1]. But, the occurrence of TSD bands in Lu (Z=71) and Hf (Z=72) isotopes is not consistent with the predicted proton and neutron shell gaps, because the high-j orbitals at large triaxiality are poorly known. According to the calculated shell gaps, among Lu isotopes, ^{165}Lu$_{94}$ and ^{168}Lu$_{97}$ are good candidates for TSD structures. But, the strongest TSD band in ^{163}Lu$_{92}$ is three times stronger than that in ^{165}Lu$_{94}$, and the TSD structure has not been even observed in ^{168}Lu$_{97}$. In addition, more TSD bands are observed in ^{163}Lu, and the wobbling bands in ^{163}Lu are by far the best example for wobbling excitation. Also, no TSD bands have been observed in ^{166}Hf$_{94}$, which is located at the centre of the predicted TSD island. These facts seem to indicate that at large triaxiality N = 92 could be a better shell gap than N = 94. On the other hand, due to the recent observation of wobbling mode of excitation in the ^{167}Ta$_{94}$ nucleus [2], the N = 94 shell gap seemed more favorable for triaxiality than the N = 92 gap. However, further attempts to look for wobbling excitation in the N = 94 isotones in this mass region has not yet been successful.

Recently, it has come to light that the excitation energy of the TSD bands relative to the Normal Deformed (ND) yrast line may also play an important role. It is possible that the relative position of TSD and ND structure has a greater role on the population of TSD bands than the predicted neutron shell gaps. In a comprehensive study of TSD structures in the A$\sim$160 region, R. Bengtsson determined that the yrast lines of some normal deformed N = 92 isotones are systematically higher in excitation energy at high spin than those of their neighbors. In the experimental data, it is observed that in the Lu chain of isotopes, the TSD band in ^{163}Lu has the lowest excitation energy relative to the yrast line, and it has maximum population. This might be because of the fact that the yrast line of the N = 92 nucleus ^{163}Lu sits higher than ^{165}Lu and ^{167}Lu. So, population of TSD bands may not be because of the TSD bands coming down in energy in this mass region, but a consequence of the fact that the band at normal deformation coming up in energy for this neutron number. This requires a deeper experimental investigation.

Motivated by these considerations, an experiment has been carried out recently at the

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ATLAS facility at Argonne National Laboratory to look for TSD structures in ^{164}Hf. The reaction ^{94}Zr(^{74}Ge,4n) with a beam energy of 330 MeV was used to populate the high-spin states in ^{164}Hf. Coincident γ rays were measured using the Gammasphere array which consisted of 99 Compton-suppressed Ge detectors at the time of this experiment. In the data analysis, two new bands of distinct character have been identified and linked to known states, allowing the determination of the level spins, energies, and parities of the bands. Based on their rotational properties and on comparisons with cranking calculations with a modified-oscillator potential, the bands are suggested to be the long-predicted TSD bands in ^{164}Hf [3]. Proposed configurations for the bands involve four quasiparticles, including the high-j intruder $(i_{13/2})^2$ proton orbitals. Furthermore, the new bands are substantially more intense and are observed at lower spins than the previously reported TSD bands in ^{168}Hf, making ^{164}Hf the best even-even system so far for the study of TSD structures in the A$\sim$160 mass region [3]. Further investigations in this direction is planned.

In parallel to the above-mentioned investigations, efforts were being put to understand a number of high-spin strongly deformed bands in some heavier Hf isotopes, which were reported earlier and were suggested to be of TSD nature. But, such assignments raised several questions. In fact, a convincing description consistent with the experimental results was not available for any of the proposed TSD structures in the heavier Hf isotopes. Based on a systematic investigation of the properties of all the strongly deformed bands in $^{170-175}$Hf, on cranking calculations employing the UC code, and on cranked relativistic mean-field (CRMF) calculations, it was suggested that these structures fall into two groups: the enhanced deformed (ED) and the superdeformed (SD) bands.

In order to clarify the situation, an experiment was performed again at the ATLAS facility at Argonne National Laboratory to measure the transition quadrupole moments for the strongly deformed bands in ^{171}Hf and ^{172}Hf. The measured value of $Q_t\sim$9.5 eb for band ED in ^{171}Hf strongly supports the recent suggestion that this sequence and similar bands in the ^{168,170,175}Hf isotopes are associated with little triaxiality and deformations enhanced relative to that of normal deformed structures [4]. Theoretical calculations indicate that these structures involve an $i_{13/2}h_{9/2}$ proton configuration, which is largely responsible for the enhanced deformation. The measured values of $Q_t\sim$14 eb for the strongly deformed bands in ^{172}Hf has confirmed that these sequences are associated with a prolate superdeformed shape. Further consideration about the excitation energies and the intensities of these bands in ^{172}Hf provides additional support for this SD interpretation [4]. Similar bands in $^{173-175}$Hf are also likely to be associated with superdeformed shapes. The observations were in contrast to the predictions of cranking calculations performed with the ULTIMATE CRANKER code, which suggested a triaxial strongly deformed shape for $^{172-174}$Hf at high spins.

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