Exploring the Structure of Cold and Warm Nuclei Using Particle Accelerators in India

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ABSTRACT

The Indian National Gamma Array (INGA) and the VECC Array for Nuclear Spectroscopy (VENUS), both consisting of clover high-purity germanium (HPGe) detectors, are two of the high-resolution gamma ray spectrometers in India. Several γ -ray spectroscopic studies have been done using these arrays for the experimental investigation of the structure of nuclei at low, medium and at high angular momenta and excitation energies. These investigations reveal important information about the single particle states, their roles in inducing deformation in nuclei, the evolution of nuclear shape, various quantum mechanical symmetries, exotic shapes in nuclei, etc. Some of the studies performed at the three accelerator centers in India have been presented for elucidation.

INTRODUCTION

The study of the structure of nuclei is an extremely important aspect of experimental nuclear physics. It provides information on the basic nuclear forces and their manifestation, the knowledge of the effect of the individual nucleonic orbitals in determining the shape of a nucleus, on widening our understanding on different quantum mechanical symmetries, etc. Moreover, the structure of a nucleus plays a very crucial role in determining the dynamics of different nuclear reactions, particularly in the fusion and fission of nuclei. The shell effect in nuclei, which is one of the main reasons for the stability of super-heavy nuclei, is highly dependent on the shape and structure of a nucleus. Another important aspect of nuclear structure study is the experimental determination of the variation of nuclear shape as a function of spin, iso-spin and excitation energy. These determinations provide important information on nuclear shape dynamics and their dependence on the above nuclear properties and on the individual proton and neutron orbitals, which are crucial tests of nuclear model predictions.

METHOD AND INSTRUMENTS

Experimental nuclear structure studies are mostly done through γ -ray spectroscopy measurements. The Indian National Gamma Array (INGA), consisting of clover HPGe detectors (maximum up to 24) has been setup through a national collaboration [1] for high-resolution γ -ray spectroscopy studies in India. The detectors moved between the three major accelerator centers in India, i.e, the Variable Energy Cyclotron Centre (VECC), Kolkata; the Tata Institute of Fundamental Research (TIFR), Mumbai; and the Inter University Accelerator Centre (IUAC), New Delhi. Moving the detectors allowed researchers to utilize complementarities in terms of accelerated beams and the other available experimental facilities in these institutions.

The alpha beams of energies from about 28 MeV to about 60 MeV (or more), available only at VECC in India, are useful to study nuclei with proton and/or neutron numbers close to the spherical magic numbers and around the stability line. Moreover, the light ion induced reactions produce the non-yrast nuclear states, which otherwise do not get excited in the heavy-ion induced reactions. At VECC heavy ions with higher energies (7 – 10 MeV / nucleon) were delivered in the past and will also be available in the near future. Therefore, the availability



Fig. 1: The INGA setup at IUAC, New Delhi (left); at TIFR, Mumbai (middle); and at VECC, Kolkata (right).

of light ion beams, higher energy heavy-ion beams and also the beams of inert atoms (e.g, Ne, Ar, etc.) are the unique features at VECC for the γ -ray spectroscopic studies using INGA.

The use of the recoil separator HYRA (Hybrid Recoil Analyser) in conjunction with INGA provides a very unique setup at IUAC which enables us to study not only recoil and isomer gated γ -ray spectroscopy but also allows us to study isomer decay at its focal plane.

At TIFR, the mechanical structure of the INGA array provides the maximum number of clovers to be placed at several angles for better angular distribution measurements and the lifetime measurements by the Doppler Shift Attenuation Method (DSAM). Moreover, a charged particle detector array with CsI(Tl) scintillators is also available at TIFR for particle tagged gamma ray spectroscopy. Digital data acquisition systems are used at TIFR and at VECC. Pictures of INGA at the three institutes are shown in Fig. 1. Apart from INGA, VECC also has a separate array of clover detectors, VENUS (VECC Array for Nuclear Spectroscopy), for γ -ray spectroscopic investigations [2]. This array consists of six clover HPGe detectors in the horizontal plane as shown in Fig. 2. This array will be upgraded to eight such detectors in the near future along with a few LaBr₃(Ce) / CeBr₃(Ce) scintillator detectors for facilitating lifetime measurements of nuclear states.

The advantages of the clover HPGe detector (which is composed of 4 separate crystals in a single cryostat, over a single-crystal HPGe detector) are that:

a) the clover detectors can be used as a γ -ray polarimeter to determine the type (E/M) of a gamma ray, which is very important to assign the parity of a nuclear state; and b) the possibility of doing "addback" in the clover detectors increases the efficiency of the detector by adding back some part of the Compton events to the photo peak.

The γ - γ or γ - γ - γ - γ coincidence data are taken and a level scheme (sequence of excited states in a nucleus) is obtained by analyzing the coincidence and the intensity relations among the γ -rays in an event. The spin and parity of the states are assigned from multipolarity (λ) and the type (E/M) of the de-exciting γ -ray. The λ and type of a γ -ray is determined from the angular distribution or the directional correlation of oriented states ratio and the polarization measurements, respectively.

EXPERIMENTS AND RESULTS

Several experiments were performed at all of the aforementioned three accelerator centers, to study γ -ray spectroscopy of nuclei by various research groups from institutes and universities across the world. However, I



Fig. 2: The VENUS setup at VECC, Kolkata with 6 Compton suppressed clover HPGe detectors placed in the horizontal plane. The target chamber can be seen at the middle and the beam enters the target chamber from the right.

shall discuss only a few cases studied by our group in the heavy mass region.

Study on bismuth nuclei

The study of the high spin states in ¹⁹⁵Bi nucleus reveals that the neutron number N = 112 plays a crucial role in generating deformation in the Bi isotopes. The Bi isotopes for neutron number $N \ge 114$ are spherical in nature and the lighter ones with $N \le 110$ have a deformed nature. The experiment at VECC was performed using a ²⁰Ne beam and INGA was used to detect the γ -rays [3] to study the excited states in ¹⁹⁵Bi. The level scheme obtained from this work is shown in Fig. 3, along with the rotational model fit of the E vs. J plot, where E and J are the excitation energy and angular momentum of the states built on the 13/2⁺ band-head. The fitting clearly indicates the excited states are generated due to the rotation of a deformed nucleus.



Fig. 3: The level scheme of 195 Bi as reported in ref. [3] and [4] is shown. The plot of excitation energy vs. spin for the $13/2^+$ band is also shown in the inset along with the rotational model fit (red line).

The importance of the N = 112 neutron number, corresponding to ¹⁹⁵Bi lies in the fact that the high-j neutron orbital $i_{13/2}$ becomes available to generate angular momentum in the Bi isotopes with neutron numbers N \leq 112. The involvement of the high-j $i_{13/2}$ orbital helps in breaking the spherical symmetry in the nucleus to generate a deformed shape and is thus termed as the deformation driving orbital. Isomeric states at higher spins are also expected in this nucleus because of the closeness

of such high-j orbitals near the Fermi levels (spin isomer) and the deformation (K-isomer). However, knowledge of the high-spin excited states in this nucleus was, until recently, very limited. Another experiment on ¹⁹⁵Bi was performed at IUAC, New Delhi at the focal plane of HYRA and a new isomer (T1/2 = 1.6(1) micro-sec) was identified at a higher excitation energy for the first time in this nucleus [4] as shown in Fig. 3. The theoretical calculations suggested an oblate deformed nature of this isomer. Later, more detailed spectroscopy of this nucleus was performed at Jyväskylä that confirmed the existence of the new isomer and a more detailed level scheme was reported, which corroborates our conjecture that N =112 indicates the onset of deformation in Bi isotopes. In the odd-odd nucleus ¹⁹⁸Bi, magnetic rotational (MR) bands and band crossing in those MR bands have been observed for the bands with large multi-quasiparticle configurations, i.e., for the warm states of this nucleus after the breaking of 2 and 3 pairs of neutrons [5].



Fig. 4: (Top) Moment of inertia (*A*) are plotted with mass number A for the proton $h_{9/2}$ bands in Tl isotopes obtained by fitting the Ex vs. J plot by the rotational model formula (an example of ¹⁹³Tl is shown in the inset). (Bottom) The plot of deformation parameter β_2 obtained from the total Routhian surface calculations using the Woods-Saxon potential and Strutinsky shell correction method for the same bands in Tl.

Study on thallium nuclei

Systematic investigations of the high-spin excited states in Tl nuclei from mass number A = 194 to A = 201have been carried out at VECC and TIFR using the INGA facility. The proton Fermi level in Tl nuclei lies just below the Z = 82 shell gap for the ground state. However, at a moderate excitation energy, the h_{9/2} orbital, which is also a high-j and shape-driving orbital like i13/2, intrudes into the proton Fermi level of Tl isotopes and consequently an excited state with spinparity, $I^{\pi} = 9/2^{-}$ is experimentally observed in these isotopes. Rotational bands, indicating deformed structure, are developed based on this 9/2- state. In our study, we have probed even higher excitation, the socalled warm states, of these nuclei, at which the nuclear Coriolis interactions are strong enough to break the neutron and proton pairing correlation and the states corresponding to the unpaired protons and/or neutrons with 3-quasiparticle (one broken pair), 5-quasiparticle (2 broken pair), etc. states arise. Several interesting high-spin phenomena have been observed in these studies, including a shape variation with neutron number and excitation energy. All the isotopes of Tl in the A = 190 - 200 mass region have been identified with rotational bands based on proton h_{9/2} orbital. Therefore, unlike in Bi isotopes, the Tl isotopes show deformed structure even for neutron number N = 120, which is a much higher neutron number than the neutron number for the onset of deformation in Bi isotopes (i.e., $N \leq 112$). The excitation energy (Ex) vs the angular momentum (J) plots for the states in the band structures based on the 9/2- bandhead, observed in Tl isotopes, are fitted with the rotational energy formula

Ex = $(h^2/2\mathcal{J}) * J^*(J+1)$, where \mathcal{J} is the moment of inertia corresponding to the rotational band

The value of \mathcal{J} obtained from the fitting indicates the deformation of the nucleus. A plot of \mathcal{J} obtained this way are plotted in Fig. 4 as a function of mass number A in Tl isotopes. The calculated values of the deformation parameter β_2 obtained from model calculations are also shown. It can be observed that a change in shape, indicated by the sudden drop of moment of inertia, is very well reproduced in the calculation as a reduction in the value of the deformation β_2 .

At higher excitation, the 3- and 5-quasiparticle bands have been identified in ^{195,197}Tl [6] nuclei and 4- quasiparticle bands are identified in odd-odd ^{194,196}Tl. In ¹⁹⁴Tl, a magnetic rotational band has been observed at higher excitation [7] whereas in ¹⁹⁵Tl, chiral doublet bands have been observed [8]. The chirality in nuclear medium is a new type of symmetry breaking in the angular momentum space for triaxial nuclei with unpaired particle(s) and hole(s) in the high-j orbital, referred as, chiral symmetry breaking and was proposed in 1997 [9]. Such a chiral geometry is manifested in the occurrence of a pair of nearly degenerate $\Delta J = 1$ bands. In such a nucleus, the three angular momentum vectors, the proton angular momentum, neutron angular momentum and the triaxial core can form a certain configuration that is symmetric under chiral operation (reflection followed by rotation by π) i.e., the three angular momentum vectors form a handedness configuration. The other properties of the twin bands remain the same except that one of them (the side band) has much less intensity.

In ¹⁹⁵Tl, the chiral twin bands are realized for both 3-quasiparticle and 5-quasiparticle configurations, making this nucleus one of the rare ones that show multiple chiral doubled bands (M χ D) and hence indicates the coexistence of triaxial shapes in a nucleus, which has been theoretically predicted recently [10]. The average separation of Δ Eav ~ 25 keV (with maximum value Δ Emax = 59 keV) observed for the 5-quasiparticle band corresponds to one of the best degenerate bands observed so far. The theoretical TRS calculations suggest a change in shape for this nucleus from an oblate shape at low excitation energy to a trixial shape at higher excitation energy after the breaking of neutron pairs, which is in excellent agreement with the occurrence of chiral doublet bands in this nucleus.

Study of nuclei in other mass regions

The occurrences of chiral doublet bands and the MR bands depend on the delicate balance of the nuclear triaxiality and the planar and aplanar configuration of the angular momentum vector. It was shown, in the case of the ¹³⁴Cs nucleus that, as the nuclear potential sur-



Fig. 5: The plot of aligned angular momentum (ix) and the rotational frequency of the ground state bands of ^{165,169}Tm isotopes. While "backbending" is observed for ^{165,169}Tm, an "upbending" has been seen for ¹⁶⁷Tm.

face becomes softer, the aplanar chiral configuration in ¹³²Cs, leading to chiral doublet bands, changes over to a planar one giving rise to MR band in ¹³⁴Cs for the same particle-hole configuration [11]. This was interpreted as due to the fact that the potential energy surface becomes very gamma-soft and a stable triaxial shape is not realized for ¹³⁴Cs.

The band crossing in a nucleus has been identified long ago but it remained a topic of interest for experimental as well as theoretical nuclear physics as the nature of the band crossing and the interaction strength between the g- and the s-bands, which cross each other to give the band crossing, are not well understood. The observation of band crossing in ¹⁶⁹Tm [12] reveals that in the case of Tm isotopes the nature of the band crossing in ¹⁶⁷Tm is "upbending", which is in sharp contrast to the "backbending" observed for the nearest neighbors ^{167,169}Tm, as shown in Fig. 5. It was argued that the presence of N = 98 deformed shell-gap near the neutron Fermi level induces larger interaction strength between the gand s-bands in ¹⁶⁷Tm compared to that in the other two isotopes, which brings about the different band crossing behavior among the nearest neighbors [12].

Summary

In summary, the INGA and the VENUS clover HPGe detector arrays have been used for gamma ray spectroscopic studies at the three major accelerator centers in India and important experimental nuclear structure information at low and at higher excitation energies have been obtained for several nuclei. The importance of the high-j shape driving orbitals in determining the shape evolution and occurrence of chiral symmetry at different excitation energies in Tl and Bi nuclei, for which proton Fermi level lies very close to the spherical shell closure at Z = 82, have been identified. It was shown that a transition from planar to aplanar orientation of the angular momentum vectors is affected by the softness in the potential energy surfaces in A = 130 region. The classical band crossing phenomenon in Tm isotopes has also been discussed, with an interesting observation.

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