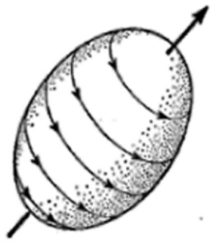
एकल-कण एवं सामूहिक तरीके

12

^{90}Zr के पास नाभिकीय संरचना के रोचक पहलू

आर. पालित
नाभिकीय एवं परमाणु भौतिकी विभाग, टाटा मूलभूत अनुसंधान संस्थान, मुंबई-400005, भारत



^{89}Zr में सबसे लंबा अक्ष परिभ्रमण

सारांश

एकल कण एवं सामूहिक उत्तेजना विधियों की प्रतिस्पर्धा का अध्ययन करने के लिए A~90 क्षेत्र के आसपास ^{88}Sr, $^{88,89,90,91}Zr$, $^{89,90,91,92,93}Nb$ और ^{92}Mo आइसोटोप की उत्तेजित अवस्थाओं की भारी आयन संलयन प्रतिक्रियाओं का उपयोग करके अन्वेषण किया गया। हमारे माप इन नाभिकों में उच्च स्पिन तक एकल कण उत्तेजनाओं के प्रभुत्व का संकेत देते हैं, जो इस आइसोटोप में निम्न चतुर्ध्रुव सामूहिकता का सुझाव देते हैं। ^{91}Zr में जीवनकाल माप ^{90}Zr कोर की अष्टध्रुव सामूहिक स्थिति के साथ एक कण के युग्मन को मापने के लिए एक त्वरित-समय तकनीक का उपयोग करके किया गया है। ये परिणाम विभिन्न आधुनिक नाभिकीय संरचना मॉडलों के परीक्षण के लिए महत्वपूर्ण हैं। उच्च स्पिन पर ^{89}Zr में एक द्विध्रुवीय पट्टी को सबसे लंबे अक्ष के बारे में नाभिक के परंपरागत रूप से प्रतिकूल घूर्णन के रूप में चिह्नित किया गया है।

Single-particle and Collective Modes

12

Intriguing Aspects of the Nuclear Structure Near ^{90}Zr

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Longest axis rotation in ^{89}Zr

ABSTRACT

Excited states of ^{88}Sr, $^{88,89,90,91}Zr$, $^{89,90,91,92,93}Nb$ and ^{92}Mo isotopes around A ~ 90 region have been investigated using heavy ion fusion reactions to study the competition of single particle and collective excitation modes. Our measurements indicate the dominance of single particle excitations up to high spin in these nuclei, suggesting lower quadrupole collectivity in this isotope. The lifetime measurement in ^{91}Zr has been carried out using a fast-timing technique to measure the coupling of a particle with the octupole collective state of the ^{90}Zr core. These results are crucial for testing various modern nuclear structure models. A dipole band in ^{89}Zr at high spin has been identified as the classically unfavoured rotation of the nucleus about the longest axis.

KEYWORDS: *High spin states, Shell model and Cranked Nilsson-Strutinsky model*

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Introduction

Nuclear shape is a fundamental property of atomic nuclei that determines the various excitation modes of atomic nuclei. These excitation modes are understood dominantly by single particle and collective motion of nucleons in the nuclei. The competition between these two modes and their coupling generates a wide variety of spectra in nuclei and continues to provide new insights about the atomic nuclei. As described by Bohr and Mottelson [1,2], "The problem of reconciling the simultaneous occurrence of single particle and collective degrees of freedom and exploring the variety of phenomena that arise from their interplay" remains a central theme of nuclear physics. The high-resolution gamma-ray spectroscopy using a large array of High-Purity Germanium (HPGe) detectors at a heavy-ion accelerator continues to play a pivotal role in the study of excited states of nuclei, which unravel a variety of phenomena related to novel shapes and modes of excitation in nuclei. In this context, a 24 Clover HPGe detector array with a total photo-peak detection efficiency of ~5%, named as Indian National Gamma Array (INGA), was conceived, designed and assembled within the country. This facility rotates between the three accelerator centres at TIFR (Mumbai), IUAC (New Delhi) and VECC (Kolkata). INGA is a powerful "femtoscope" for the study of the structure of atomic nuclei at high spins [3,4].

Several experiments have been performed to study the excited states of ^{88}Sr [5], ^{88,89,90,91}Zr [6,7,8,9], ^{89,90,91}Nb [10,11,12] and ^{92}Mo [13] isotopes around the A ~ 90 region at the BARC-TIFR Pelletron Linac Facility (PLF) at TIFR, Mumbai [3]. Some exciting physics results related to single particle and collective excitation around ^{90}Zr from the experimental campaigns are highlighted here. This spectrometer can measure lifetime ranges from hundreds of picoseconds (ps) to microseconds (μs) using fast timing method and Doppler shift attenuation method (DSAM) is used for measuring lifetimes in the sub-ps range. Recently, the INGA has been augmented with a Si-CD detector to study the low-lying octupole collectivity in this region through coulex.

The spin-parity of the gamma transitions are measured using Directional correlation of Oriented states ratio (R_{DCO}) or Angular Distribution of oriented states ratio (R_θ) and polarization methods. The typical values for stretched E1, M,1 and E2 and non-stretched M1, E2 are shown in Fig.1.

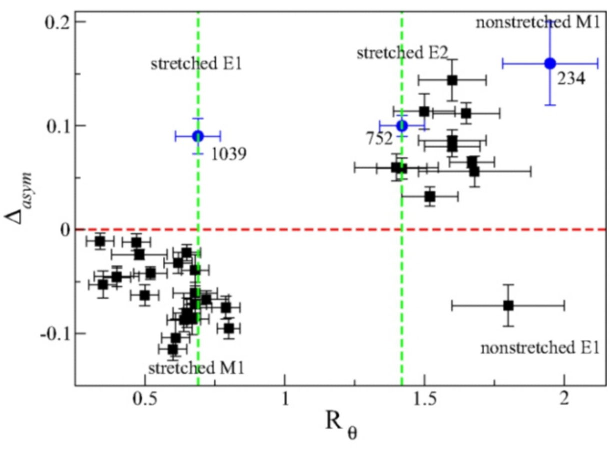

Fig.1: Experimental polarization asymmetry parameter (Δ_{asym}) plotted against R_θ for the trasitions belonging to ^{89}Nb [10].

Selected Results

Many attempts to study the structural features of closed-shell nuclei in different mass regions have been made over the past few decades in recent time. The A ~ 90 region (with Z ~ 40 and N ~ 50) remains one of the cornerstones to study the underlying mechanisms of excitation in atomic nuclei. The excitation of protons and neutrons across their respective shell gaps enables more active orbitals to generate high spin states. Extending SM calculations to higher excitation that incurs a larger model space and increased valence nucleons is now computationally feasible.

A comparison of the experimental excitation energies of the positive-parity states of ^{90}Zr [8] with those from shell-model calculations using the GWBXG effective interaction is shown in Fig.2. The shell-model calculations, with the extended model space including neutron excitations across the N = 50 shell gap, give a good description of both the positive- as well as the negative- parity states up to highest observed excitation energy and spin. This indicates the dominance of single-particle excitations in this nucleus.

The stability of a particular nucleus increases compared to the neighbouring nuclei when the outermost orbital is fully occupied and consequently, the concept of magic numbers emerged in closed-shell nuclei. Spectroscopy of nuclei near closed shells provides essential insight into the competition of these two modes as a function of excitation energy and angular momentum. Another aspect is the coupling of single particle motion with various collective degrees of freedom. In this connection, the lifetime of $11/2^-$ was measured with fast timing method. This results in a B(E3; $11/2^- \rightarrow 5/2^+$) = 18.51 ± 1.23 W.u indicating collective nature of $11/2^-$ state [9].

Investigation of nuclear excitation continues to provide new insight into the evolution of shell structure and its impact on nuclear shapes across the nuclear landscape. Different types of nuclear shapes can be seen depending on the number of valence particles in the active orbitals. In this context, the level scheme of ^{89}Zr has been extended up to spin I=49/2 with the observation of a new dipole band (Fig.3). Line shapes of several transitions have been analyzed to determine lifetimes of the levels. Possible configurations of the band have been discussed using the cranked Nilsson-Strutinsky model (CNS). The calculations suggest a triaxial shape of the nucleus at high spins, and the band may represent the rotation of the nucleus about the longest axis [14].

Another interesting aspect of the high-spin region of the nuclei in mass 90 region is the investigation of the tensor component of nucleon-nucleon (NN) interaction between valence proton(s) in the $1g_{9/2}$ orbital and the excited neutron in the orbitals above the N = 50 shell gap. For describing the generation of the states in band II in ^{91}Nb [12], configurations can be compared to those of band II and band III in ^{90}Zr [8]. In these two N = 50 isotones, one neutron in $1g_{9/2}$ gets excited across this neutron major shell gap. However, the applied truncation conditions are different for these two nuclei. In the calculation reported in Ref. [8], a maximum of one neutron

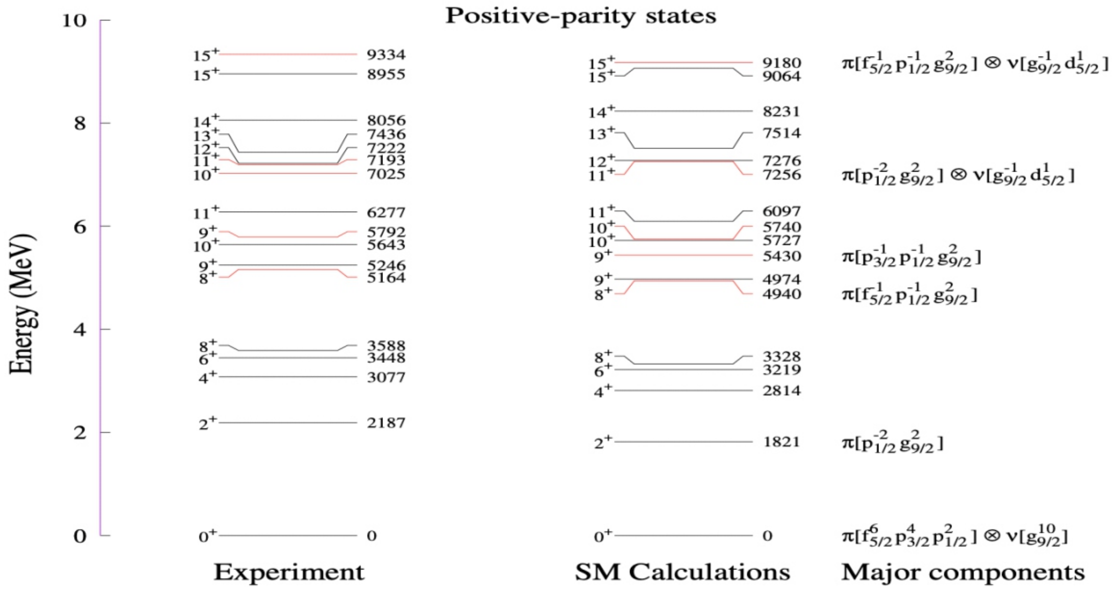

Fig.3: Comparison of experimental levels and shell model calculated levels using GWBXG interaction for positive parity states in ^{90}Zr [8].

excitation each in $2d_{5/2}$ and $3s_{1/2}$ is allowed. The calculations provide a reasonable description for the experimentally observed levels, and the average energy difference between them is ≈200 keV for neutron-core excited states [12]. If the neutron $1g_{7/2}$ orbital is made available for the excited neutron to occupy, as mentioned here, the average energy difference increases to ≈300 keV. This indicates the previous calculations [8] involving excitation in the ν[$2d_{5/2}$] orbital work better with no significant contribution from them ν[$1g_{7/2}$] orbital, as its role is not crucial for generating states up to the highest observed spin-parity in ^{90}Zr. On the other hand, for ^{91}Nb [12], including the neutron $1g_{7/2}$ orbital improves the agreement between experimentally observed and theoretically calculated energy states. One possible reason for the change in high-spin configurations moving from ^{90}Zr to ^{91}Nb could be the presence of one valence proton in the π[$1g_{9/2}$] orbital [12]. This suggests the possible manifestation of the tensor force between the proton in $1g_{9/2}$ and neutron in $1g_{7/2}$ orbitals, which has an attractive interaction between them. This attractive nature would eventually lower the energy of the neutron-core excited levels. This effect can further be studied by probing the high-spin structures in the heavier N = 50 isotones with increasing number of protons in the $1g_{9/2}$ orbital.

The level scheme of ^{90}Nb and ^{92}Mo was investigated with ^{30}Si + ^{65}Cu fusion-evaporation reaction [11,13]. A comparison of the shell-model predicted levels with experimental data suggests that high-spin states in ^{90}Nb do not involve neutron excitation across the N = 50 shell gap [11]. At high spin, the shell model (SM) calculations fail to reproduce the correct

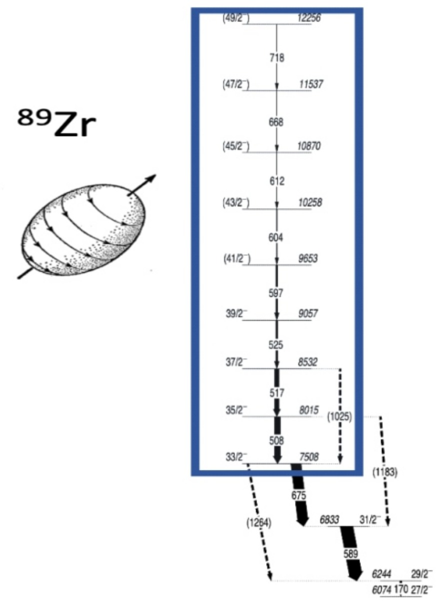

Fig.4: Partial level scheme of ^{89}Zr showing a regular structure of M1 transitions above $I^{\pi} = 29/2^{-}$ [13].

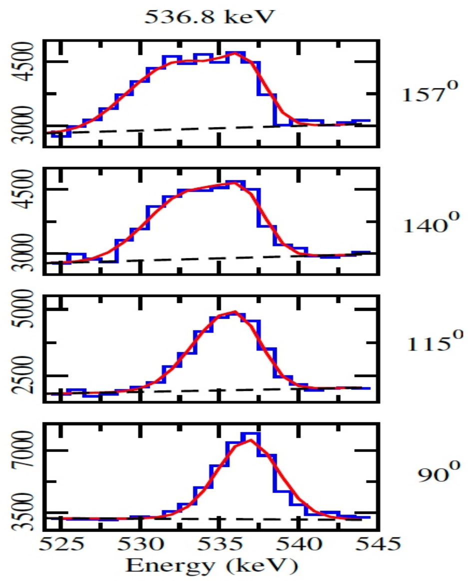

Fig.4: Spectra generated using a gate on 244.0 keV transition along with the simulated lineshape in different angles for few ΔI = 1 transitions in ^{92}Mo [13].

energies of the experimental levels for ^{90}Nb. In contrast, for odd-even nucleus, ^{91}Nb, a good agreement is observed between SM and experimental levels [12], describing the structure of odd-odd nuclei remains particularly challenging. A new transition E3 transition, decaying from 11^- to 8^+ was found out. The B(E3) value of this transition was determined to be 0.020(4) W.u., indicating the suppression of collective motion in ^{90}Nb [11]. In the case of ^{92}Mo, the high-spin states primarily originate from the coupling of proton and neutron-core structures in an almost stretched manner. Other fusion-evaporation reaction, ^{18}O + ^{80}Se was used for measuring the lifetimes of $\Delta I = 1$ sequence in ^{92}Mo. The lifetime of few states of high-spin $\Delta I = 1$ sequence was measured using DSAM (Fig.4) [13]. A relatively large B(E1) of 1075.1 keV transition was interpretated as the mutual enhancement of proton and neutron excitation [13].

Another interesting aspect in 90 mass region is the observation of decreasing transition energy with increasing spin in a $\Delta I = 1$ band of ^{88}Sr. The extracted transition strengths from the measured lifetimes initially increase with spin and then decrease beyond $I^{\pi} = 10^-$. The observed gamma- ray energy behaviour and that of transition rates were explained using a novel stretched coupling scheme. In this geometrical model, an interplay between a particle-particle attractive shears and two particle-hole repulsive shears has been invoked to explain the observed behaviour. This confirms the existence of an attractive shears between two particle blades for the first time in any nuclei [5].

In these aforementioned studies, a number of heavy-ion induced fusion reactions are used. Most of the cases, the nucleus does not develop a well-deformed band structure even at high excitation energy. It is also rather surprising that, although the expected angular momentum imparted classically in the heavy-ion fusion evaporation reactions [5,6,7,8,10] used in TIFR recently being ~ 40 - 60 ħ, we were not able to observe any further excited states. This could possibly indicate a large change in structure of this nucleus at high-spin which may involve a highly fragmented decay path consisting of several weak high-energy gamma rays. This suggests a complex fragmentation of the level scheme at high spin and poses experimental challenge for the identification of exotic shapes at high spin.

Conclusion and future scope

Selected results from the gamma-ray spectroscopy carried out at PLF have been discussed. High spin spectroscopy studies were carried out to develop the level schemes of ^{88}Sr, ^{88,89,90,91}Zr, ^{89,90,91,92,93}Nb and ^{92}Mo isotopes around A ~ 90 region. The lifetime of 11/2- in ^{91}Zr was measured using a fast timing method. The measured B(E3) strength for $11/2^- \rightarrow 5/2^+$ transition established octupole collectivity in ^{91}Zr. In ^{92}Mo lifetime of few high-spin $\Delta I = 1$ transitions are measurement using DSAM. The lifetime measurements are the stingiest test to the theoretical models. The deviations of the shell model predictions from the experimental data suggest the scope for improving the shell model calculations. The involvement of neutron particle in $1g_{7/2}$ orbital hints towards the tensor force between $\pi[g^{9/2}]$ and $\nu[1g_{7/2}]$. A systematic study in N = 50 isotones is required to understand this observation. A comparison of the experimental energy levels of the dipole band consisting of $\Delta I = 1$ M1 transitions with CNS calculation suggests a triaxial shape of ^{89}Zr and represents the nuclear rotation along the long axis. The enhancement of M1 transition rates may be due to tilted-axis rotation. The level schemes of nuclei in 90 mass regions populated using fusion-evaporation are extended up to spin 20 - 25 ħ; however, classically, it should be more. The CNS calculation for ^{90}Zr suggests shape evolution towards the Jacobi shape transition above $I = 30$ ħ. These studies will be possible with a ^{50}Ti beam at 200 MeV from the upgraded PLF. Such heavy beams will be also useful for coulomb excitation studies to probe the low-lying collectivity in nuclei near ^{90}Zr.

Acknowledgements

The author would like to acknowledge the INGA collaborators for the success of the experiments. The author acknowledges the contributions of Dr. S. Saha, Dr. P. Singh, Dr. P. Dey, Dr. B. Das, and Mr. Vishal Malik are acknowledged. The author thanks Prof. P. C. Srivastava, Prof. E. Ideguchi, Prof. T. Inakura, and Prof. S. Nag for the theoretical calculations. This work was partially funded by the Department of Atomic Energy, Government of India (Project Identification No. RTI 4002) and the Department of Science and Technology, Government of India (No. IR/S2/PF-03/2003-II). The author also thanks the Pelletron LINAC Facility staff for providing excellent beams during all experimental campaigns.

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