Exploration of single-particle and collective modes of excitation in nuclei around $A \sim 90$ region

P. Dey*

Department of Nuclear and Atomic Physics,
Tata Institute of Fundamental Research, Mumbai - 400005, INDIA

The atomic nucleus is a many-body fermionic system consisting of protons and neutrons, which are distributed separately over the different shells, called as orbitals. The concept of magic numbers emerged in closed-shell nuclei, when the outermost orbital becomes fully occupied and consequently the stability of these nuclei increases compared to the neighbouring nuclei [1]. However, the modification of shell structures due to the role of different components of nuclear force has been reviewed in Ref.[2]. Investigation of nuclear excitation continues to provide new insights into the evolution of shell structure and its impact on nuclear shapes. Nuclear excitations can be achieved by two very different physical processes, namely single-particle and collective excitations. Cross-shell excitation of one or few nucleons occurs in the nuclei in the vicinity of shell closures and the shell-model (SM) calculations provide good descriptions indicating the domination of single-particle configurations.

Closed-shell nuclei having spherical symmetry show less amount of quadrupole collectivity, however, they exhibit an excited 3_1^- state as one of the low-lying energy excitations. This state is of particular interest as it can be described in terms of surface vibration associated with an octupole phonon. The coherent motion of more than a few nucleons results to the observation of large $B(E3; 3_1^- \rightarrow 0_{\mathrm{g.s.}}^+)$ as a manifestation of octupole collectivity. Additionally, the coupling of a valence particle with an octupole phonon can induce octupole collectivity in the neighbouring odd-A nuclei having one particle outside the magic core by acquiring a permanent octupole deformation. Thus, an intriguing aspect of studying these nuclei is the manifestation of single-particle excitations and the emergence of collectivity.

*Electronic address: pikudey321@gmail.com

In view of these different excitation mechanisms occurring around the shell closure, semimagic ^{90}Zr remains one of the cornerstones to explore the excitation processes in the $A \sim 90$ region. Also, the coupling of a valence proton or neutron with the magic core allows to study the effects caused by the interaction of the valence particle and other factors. In this thesis work, the same has been probed via a series of experiments, namely, (i) spectroscopy of high-spin states in ^{90}Zr, (ii) modification of high-spin structures in ^{91}Nb due to the presence of one valence proton outside the ^{90}Zr core, (iii) study of octupole collectivity in ^{91}Zr as a result of the coupling between valence neutron and ^{90}Zr core, and, (iv) development and testing of a charged-particle detector set-up as a primary step to perform Coulomb excitation to study the low-lying octupole collectivity in ^{90}Zr.

All measurements have been carried out at the 14UD TIFR-BARC Pelletron-LINAC Facility (PLF), Mumbai with Indian National Gamma Array (INGA) [3] consisting of clover HPGe detectors. In two different works reported here, the high-spin states in ^{90}Zr and ^{91}Nb have been probed through heavy-ion fusion-evaporation reactions. The level schemes of these two isotones have been extended with the addition of several new γ-transitions [4, 5]. The multipolarity and electromagnetic character of the transitions have been obtained through their angular distribution, angular correlation, and linear polarization measurements which further determine the spin-parity of different excited states. One of the important observations of these studies is the presence of multiple $\Delta I = 1$, $M1$ sequences in both nuclei. The ambiguity of determining the parity of states in high-spin regime has been resolved by the use of clover detectors as Compton polarimeters employing γ-γ coincidence. This also changes the tentative parity assignments of the states in $M1$ sequences reported earlier which becomes useful for the description of these sequences.

For theoretical description, SM calculations have been performed using the GWBXG effective interaction and ^{68}Ni core. The truncation conditions are different for ^{90}Zr and ^{91}Nb – maximum one neutron each in the $2d_{5/2}$ and $3s_{1/2}$ orbitals is allowed for the former whereas, the other neutron orbitals above $N = 50$ shell gap have been made available for one neutron excitation in the latter case. However, no such restrictions have been imposed in the calculations for protons. The major contributions towards the structure of positive- and negative-parity low- and intermediate-spin states come from the configurations with proton excitations across the $Z = 40$ subshell gap. To generate larger spin, excitation of a neutron from $1g_{9/2}$ orbital to higher orbitals across $N = 50$ shell gap becomes necessary. It is important to note that, one of the salient features of the states of the high-spin $M1$ bands is the coupling of proton- and neutron-excited structures. SM calculations successfully explaining these states dominated by neutron excitations from the $1g_{9/2}$ orbital into the $2d_{5/2}$ and $1g_{7/2}$ orbitals have been observed in ^{90}Zr and ^{91}Nb, respectively. Variation obtained in the high-spin structures due to occupancy in $\pi[1g_{9/2}]$ orbital has also been discussed.

In a separate experiment, lifetime measurement for the $11/2^-_1$ state in ^{91}Zr has been carried out employing electronic fast-timing technique with a hybrid array of clover HPGe and $LaBr_3$(Ce) detectors used in synchronization mode. To measure the lifetime of this state at $E_x = 2171$ keV in ^{91}Zr, the time difference spectrum between the 91-keV (feeding) and 2171-keV (decaying) transitions has been constructed by the linear combination of four energy-gated timing spectra including the peaks and backgrounds of the transitions. Owing to poor energy resolution of $LaBr_3$(Ce) detectors, the cascade of 91- and 2171-keV transitions had to be cleaned by the energy gate of 860-keV transition on the clover detectors, lying above the same cascade. The final time spectrum thus generated has been fitted with a convolution function of a single component exponential decay, characterized by the mean-lifetime of the state and a Gaussian prompt-response function, as mentioned in Ref.[6]. Using the relative branching for the 2171-keV transition, the obtained partial half-life is $T^{\text{partial}}_{1/2} = 587 \pm 39$ ps, corresponding to $B(E3; 11/2^- \to 5/2^+) = 18.51 \pm 1.23$ W.u. [7].

Theoretical calculation with random-phase approximation (RPA) have been performed for explaining the enhanced $B(E3)$ as well as the excitation energy of the $11/2^-$ state. The calculated $B(E3)$ values with three different Skyrme interactions are in agreement with the experimentally measured one. In the filling approximation of the calculations, ^{91}Zr is presented as $^{90}\text{Zr} + 6$ neutrons in the $2d_{5/2}$ orbital with occupation probability 1/6. To explain the transition strength, proton and neutron transition densities corresponding to the $E3$ excitation in ^{91}Zr have been decomposed among the hole orbitals. The neutron transition density of $2d_{5/2}$ to $1h_{11/2}$ orbital contributes to the enhanced $B(E3)$ due to the valence neutron occupying the $2d_{5/2}$ orbital.

Since the enhanced $E3$ collectivity in ^{91}Zr has been confirmed to arise due to the coupling between the octupole phonon of ^{90}Zr core and the valence neutron, a large $B(E3)$ is expected in the core as well. However, in the aforementioned experiment, ^{90}Zr could not be suitably populated to permit a similar lifetime measurement. A direct experimental technique *viz.* Coulomb excitation expected to be an appropriate probe in this regard. As an extension of this work, a particle-γ coincidence set-up has been developed by coupling of an annular Si-detector with INGA. This newly developed set-up has been successfully tested with ^{229}Th radioactive source emitting multiple α-particles and γ-rays. In addition, extensive simulations have been carried out for Coulomb excitation of ^{90}Zr with ^{32}S beam at a safe energy using GOSIA code to test the feasibility of the in-beam measurement.

This work is supported by Department of Atomic Energy, Govt. of India (Project No. RTI4002). Staffs of central workshop of TIFR and TIFR-BARC PLF are acknowledged.

References

[1] M. G. Mayer, Phys. Rev. **74**, 235 (1948).
[2] T. Otsuka *et al.*, RMP **92**, 015002 (2020).
[3] R. Palit *et al.*, NIM A **680**, 90 (2012).
[4] P. Dey *et al.*, PRC **105**, 044307, (2022).
[5] P. Dey *et al., to be submitted.*
[6] Md. S. R. Laskar *et al.*, PRC **104**, L011301 (2021).
[7] P. Dey *et al., to be submitted.*