

*G. H. Bhat¹, J. A. Sheikh^{1,2}, *P. A. Ganai^{3,1}, and R. Palit⁴

¹Department of Physics, University of Kashmir, Srinagar, 190 006, India

²Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA

³Department of Physics, National Institute of Technology, Srinagar, 190 006, India

⁴Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Colaba, Mumbai, 400 005, India*

(Dated: September 23, 2011)

Atomic nucleus is a unique quantum many-body system which depicts co-existence of rotational, vibrational and quasiparticle modes of excitations. In spherical nuclei, the low lying excitation spectrum is primarily built on multi-quasiparticle excitations and constitutes an ideal place to apply shell model based approaches. In well deformed nuclei, rotational bands are observed and are classified using the deformed Nilsson picture. In transitional nuclei, the excitation spectrum shows interplay of all the three modes of excitations. Rotational bands built on vibrational and quasiparticle states are observed in most of the transitional nuclei. In particular, γ -bands, which are due to vibrations in the γ -degree of deformation, are known to exist in most transitional regions of the periodic table and form the first excited bands in many nuclei [1, 2].

There is a long history of phenomenological models that were introduced to study the transitional properties of the atomic nuclei. These theoretical models include the generalized coordinate method (GCM) [3], the self-consistent collective coordinate method (SCCM-1) [4], the quasiparticle-phonon nuclear model (QPNM) [5], the multi-phonon method (MPM) [6], the dynamic deformation model (DDM) [7], the self consistent cranking model (SCCM-2) [8] and random phase approximation approach (RPA) [9]. On the microscopic front, there are very few models capable of describing the three modes of excitations in a unified manner, in particular, at higher angular momenta. All these models can be viewed through a unified perspective of attempts to solve the many-body nuclear problem through the inclusive treatment of collective and single particle degrees of freedom to varying degrees. Most of these models are phenomenological in nature and require some aspects of the experimental data for fitting the parameters.

Recently, triaxial projected shell model (TPSM) [10], which is completely a microscopic approach, has been developed to describe the transitional nuclei. The main advantage of the TPSM is that apart from describing the deformed single-particle states microscopically as in QPNM, MPM, its many-particle states are constructed to be eigenstates of the angular momentum operator. This model was initially restricted to perform the projection from the vacuum configuration only and it was possible to study only low-spin states. In our recent study, the model space has been expanded by including the multi-quasiparticle states and it has been possible

to extend the study of yrast and other band structures to high-spin states [11–13]. The multi-quasiparticle TPSM approach has been employed to investigate the high-spin band structures in Er-isotopes and in the $A = 130$ region [12]. It has been demonstrated in these studies that γ -bands are built on each intrinsic configuration of the mean-field potential and generalizes the well known surface γ -vibration in deformed nuclei built on the ground-state configuration. It has been shown in some Er-isotopes that γ -bands built on the two-quasiparticle configurations can become yrast at higher angular-momenta.

Electromagnetic transition probabilities contain important information on the intrinsic structures of a quantum many-body system. For instance, the intrinsic deformation is directly related to the quadrupole transition strength. Transition probabilities have been measured for many nuclei in the rare-earth region, in particular, for the Er-isotopes. Therefore, we have applied TPSM to study inter-band transition probabilities for the yrast-band in $^{158-166}\text{Er}$. In an earlier investigation, large deviations from the measured values were noted for these transitions and it was suggested that non-inclusion of quasiparticle excitations in the earlier investigation could be the reason for the discrepancy [14]. The recent development of TPSM will also provide information on the interplay between quaiparticle and γ -vibrational excitations.

For even-even systems, the TPSM basis are composed of projected 0-qp state (or qp-vacuum $|\Phi\rangle$), 2-proton, 2-neutron, and 4-qp configurations, i.e.,

$$\begin{aligned} & \hat{P}_{MK}^I |\Phi\rangle; \\ & \hat{P}_{MK}^I a_{p_1}^\dagger a_{p_2}^\dagger |\Phi\rangle; \\ & \hat{P}_{MK}^I a_{n_1}^\dagger a_{n_2}^\dagger |\Phi\rangle; \\ & \hat{P}_{MK}^I a_{p_1}^\dagger a_{p_2}^\dagger a_{n_1}^\dagger a_{n_2}^\dagger |\Phi\rangle, \end{aligned} \quad (1)$$

where the three-dimensional angular-momentum operator [15] is given by

$$\hat{P}_{MK}^I = \frac{2I+1}{8\pi^2} \int d\Omega D_{MK}^I(\Omega) \hat{R}(\Omega), \quad (2)$$

with $\hat{R}(\Omega)$ being the rotation operator and $D_{MK}^I(\Omega)$ the D -function. It is important to note that for the case of axial symmetry, the qp-vacuum state has $K = 0$ where as in the present case of triaxial deformation, the vacuum state $|\Phi\rangle$, as well as any configuration in (1), is a superposition of all possible K -values.

As in the earlier TPSM calculations, we use triaxial Nilsson mean-field Hamiltonian, which is obtained by using the Hartree-Fock-Bogoliubov (HFB) approximation, is given by

$$\hat{H}_N = \hat{H}_0 - \frac{2}{3} \hbar \omega \left\{ \varepsilon \hat{Q}_0 + \varepsilon' \frac{\hat{Q}_{+2} + \hat{Q}_{-2}}{\sqrt{2}} \right\}. \quad (3)$$

*gwhr.bhat@gmail.com; prince_ganai@yahoo.co.uk

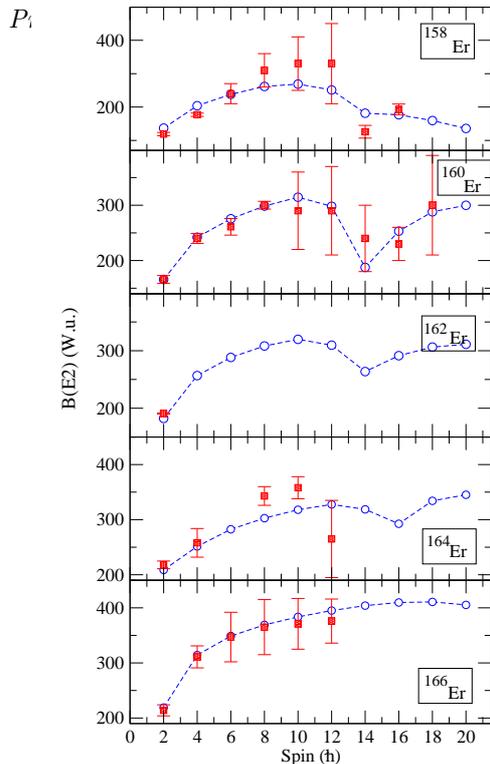


FIG. 1. Detailed comparison of the calculated B(E2) in $^{158-166}\text{Er}$ with experimental data

Here \hat{H}_0 is the spherical single-particle Hamiltonian, which contains a proper spin-orbit force. The interaction strengths are taken as follows: The QQ -force strength χ is adjusted such that the physical quadrupole deformation ε is obtained as a result of the self-consistent mean-field HFB calculation [15]. The monopole pairing strength G_M is of the standard form

$$G_M = (G_1 \mp G_2 \frac{N-Z}{A}) \frac{1}{A} \text{ (MeV)}, \quad (4)$$

where $-(+)$ is neutron (proton). In the present calculation,

we use $G_1 = 20.12$ and $G_2 = 13.13$, which approximately reproduce the observed odd-even mass difference in this region. This choice of G_M is appropriate for the single-particle space employed in the model, where three major shells are used for each type of nucleons ($N = 3, 4, 5$ for protons and $N = 4, 5, 6$ for neutrons). The quadrupole pairing strength G_Q is assumed to be proportional to G_M , and the proportionality constant being fixed as 0.16. These interaction strengths are consistent with those used earlier for the same mass region [11–13]. This choice of G_M is appropriate for the single-particle space employed in the model, where three major shells are used for each type of nucleons ($N = 3, 4, 5$ for protons and $N = 4, 5, 6$ for neutrons). In present calculations, the deformation parameters ε used are from Ref. [16]. The chosen values of ε for the present calculation are those from the measured quadrupole deformations of the nuclei, as is done in the previous projected shell model analysis. The triaxial parameter ε' is chosen so that the calculated energy of the γ -bandhead reproduces the measured value. To further clarify that the ε' values used in the present work are realistic, we have calculated the ground-state energies as a function of ε' . These energy surface calculations clearly depict a minimum for the values used in the present work.

In the present work, we have evaluated the B(E2) transition probabilities for yrast bands in $^{158-166}\text{Er}$ shown in Fig. 1. It is evident from Fig. 1 that calculated B(E2) describe the known transitions quite well up high angular momenta. The drop in B(E2) for $^{158-162}\text{Er}$ at $I=14\hbar$ is because of crossing of alignment qp-bands to the ground state band. It is quite interesting that in $^{158,160}\text{Er}$ B(E2) experimental values also depict a strong drop at $I=14\hbar$, which is nicely reproduced with calculations. In ^{164}Er the drop is observed at $I=16\hbar$, while in ^{166}Er , at $I=20\hbar$. This clearly implies that with increase in neutron number the band crossing is shifted to higher angular momentum [11]. It is notable to mention here that the drop at $I=14\hbar$ indicates a strong mixing between the quasiparticles and the ground-state band. In our recent development we have provided the detailed study of transition probabilities [17].

[1] A. Bohr and B. R. Mottelson, *Nuclear Structure*, Vol. II (Benjamin Inc., New York, 1975).
 [2] A. Bohr and B. R. Mottelson, *Phys. Scr.* **25**, 28 (1982).
 [3] P. Bonche, J. Dobaczewski, H. Flocard, and P. -H. Heemen, *Nucl. Phys. A* **530**, 149 (1991).
 [4] M. Matsuo and K. Matsuyanagi, *Prog. Theor. Phys.* **74**, 1227 (1985); **76**, 1235 (1987).
 [5] V. G. Soloviev, *Theory of Atomic Nuclei: Quasiparticles and Phonons* (IOP, London, 1992).
 [6] J. Leandri and R. Piepenbring, *Phys. Rev. C* **37**, 2779 (1988).
 [7] K. Kumar, *Nuclear Models and Search for unity in Nuclear Physics* (Universitetsforlaget, Bergen, Norway, 1984).
 [8] E. R. Marshalek and R. G. Nazinithdinov, *Phys. Lett. B* **300**, 199 (1992).

[9] E. R. Marshalek and J. Weneser, *Phys. Rev. C* **2**, 1682 (1970).
 [10] J. A. Sheikh and K. Hara, *Phys. Rev. Lett.* **82**, 3968 (1999).
 [11] J. A. Sheikh, G. H. Bhat, Y. Sun, G. B. Vakil, and R. Palit, *Phys. Rev. C* **77**, 034313 (2008).
 [12] J. A. Sheikh, G. H. Bhat, R. Palit, Z. Naik, and Y. Sun, *Nucl. Phys. A* **824**, 58 (2009).
 [13] J. A. Sheikh, G. H. Bhat, Y. Sun, and R. Palit, *Phys. Lett. B* **688**, 305 (2010).
 [14] P. Boutachkov, A. Aprahamian, Y. Sun, J. A. Sheikh, and S. Frauendorf, *Eur. Phys. J. A* **15**, 455 (2002).
 [15] K. Hara and Y. Sun, *Int. J. Mod. Phys. E* **4**, 637 (1995).
 [16] S. Raman et al., *Nucl. Data Tables* **36**, 1 (1987).
 [17] J. A. Sheikh, G. H. Bhat, Yan-Xin Liu, Fang-Qi Chen, and Yang Sun, submitted to *Phys. Rev. C*.