Microscopic Study of Some Very Neutron Deficient Barium Isotopes

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Abstract: *The observed excited states of neutron-deficient ^{118,120}Ba have been studied in the frame-work of projected shell model (PSM). The yrast bands of these isotopes have been studied up to spin $30\hbar$. The experimentally observed yrast bands in ^{118,120}Ba are reproduced well by the present calculation. The first band crossing in ^{118,120}Ba is due to the crossing of ground state band by 2-qp proton and neutron bands, arising from $1h_{11/2}$ orbital. The crossing of ground state band by multi-quasiparticle bands leads to the structural change in the yrast bands of these isotopes.*

Keywords: Projected shell model, band diagram, yrast energies

I. INTRODUCTION

The study of nuclear structure properties of the very neutron-deficient barium isotopes has been at the center stage of nuclear physics in recent years [1-3]. Due to the availability of very large γ-ray detector arrays, the level schemes of these isotopes have been extended to high spins. For the first time, the spectroscopy of very neutron-deficient ^{118}Ba was made possible by using the high resolving power of Gammasphere array by Smith et al. [1]. The ground state band in ^{118}Ba has been observed up to spin $20\hbar$. The cranked shell model (CSM) [4] calculations have been performed that predicted the alignment of a pair of $h_{11/2}$ neutrons at a rotational frequency of 0.41MeV/$\hbar$, followed almost immediately by the alignment of a pair of $h_{11/2}$ protons at 0.42 MeV/$\hbar$. The ground state band of this nucleus shows a large gain in aligned angular momentum between frequencies 0.3 and 0.5 MeV/$\hbar$ but Smith et al. [1] have proposed that the alignment observed in ^{118}Ba is due solely to $h_{11/2}$ protons.

In case of ^{120}Ba, the yrast band which was previously observed up to spin spin $20\hbar$ by Cederwall et al. [2] has been extended up to spin $42\hbar$ by Smith et al. [3]. Like in the heavier even-even barium isotopes, they observed two alignments in this nucleus that results in the apparent forking of the yrast band into two aligned bands. On the basis of CSM calculations and a comparison with alignments in the neighboring ^{119}Ba and ^{119}Cs nuclei, the aligned bands were assigned to have the $\nu(h_{11/2})^2$ and $\pi(h_{11/2})^2$ configurations. At higher spins in each of the aligned bands, they observed a second alignment which was attributed to $h_{11/2}$ protons in the $\nu(h_{11/2})^2$ band and $h_{11/2}$ neutrons in $\pi(h_{11/2})^2$ band. This results in the apparent recombination of the two-quasiparticle aligned bands into one four quasiparticle $\nu(h_{11/2})^2 \otimes \pi(h_{11/2})^2$ band. This was the first observation of the forking and recombination of the ground state band in this manner. It was first predicted by Wyss et al. [4] that this would occur in the neutron-deficient barium isotopes.

In order to investigate the band structure and alignments in neutron deficient ^{118,120}Ba, the projected shell model (PSM) approach has been employed in the present work. The PSM calculations has been performed and results have been obtained for yrast spectrum and band diagrams for these isotopes.

II. CALCULATIONAL FRAMEWORK

In this section, a brief presentation of the PSM approach is given and the detailed description of PSM can be found in the review article [5]. The PSM is based on the spherical shell model concept. It differs from the conventional shell model in that the PSM uses the angular momentum projected states as the basis for the diagonalization of the shell model hamiltonian.

The angular momentum projected wave function for the PSM is given by

$$\left| IM \right\rangle = \sum_k f_k \hat{P}^I_{MK} \left| \phi_k \right\rangle \tag{1}$$

where $\hat{P}^I_{MK}$ is the angular momentum projection operator and the coefficients f_k are the weights of the basis state k which are determined by the diagnolization of the shell model Hamiltonian in the space spanned by the projected basis states given above.

The projection of an intrinsic state $\left| \phi_k \right\rangle$ onto a good angular momentum generates a rotational energy

$$E_k(I) = \frac{\left\langle \phi_k \left| \hat{H}\hat{P}^I_{KK} \right| \phi_k \right\rangle}{\left\langle \phi_k \left| \hat{P}^I_{KK} \right| \phi_k \right\rangle} = \frac{H^I_{kk}}{N^I_{kk}} \tag{2}$$

The energies of each band, $E_k(I)$, are given by the diagonal elements of H_{kk}/N_{kk}. A diagram in which $E_k(I)$ for various bands is plotted against the spin I is referred as band diagram [6], which contains incredibly rich information.

In the numerical calculations, we have used the standard quadrupole-quadrupole plus (monopole and quadrupole) pairing force, i.e.

$$\hat{H} = H_0 - \frac{1}{2}\chi \sum_\mu \hat{Q}^\dagger_\mu \hat{Q}_\mu - G_M \hat{P}^\dagger \hat{P} - G_Q \sum_\mu \hat{P}^\dagger_\mu \hat{P}_\mu \tag{3}$$

The first term H_0 is the spherical single-particle Hamiltonion. The strength of the the quadrupole force χ is adjusted such that the known quadrupole deformation parameter ϵ_2 is obtained by the usual Hartree+BCSself consistent procedure. The monopole pairing force constants G_M are adjusted to give the known energy gaps. Thee monopole pairing strengths G_M used in the present calculations are same as employed in Rawan Kumar et al.[7] for heavier isotopes. The quadrupole pairing strength strength G_Q is assumed to be proportional to G_M. The proportionality constant is adjusted to reproduce the $h_{11/2}$ crossing at the right place. In the present calculations, G_Q is taken as 0.20 for both ^{118}Ba and ^{120}Ba.

The PSM calculations proceed in two steps : First an optimum set of deformed basis is constructed from the standard Nilsson model. The set of deformed basis is said to be optimum if increasing the basis further does not affect the calculated quantities. The Nilsson parameters are taken from the N-dependent values in [8] subject to modifications introduced by Zhang et al.[9] The present calculations are performed by considering three major shells (N=3,4 and 5) for both neutrons and protons. The multi-quasiparticle basis selection is carried out from N=5 intruder shell both for neutrons and protons. An energy cutoff has been introduced to exclude the levels far away from the Fermi level. The energy window around the Fermi surface is chosen in such a way that only intruder orbits, $h_{11/2}$ neutrons and protons are usually selected and this optimum set of deformed basis reproduces the experimental data in a better way. The chosen energy window around the Fermi surface gives rise to a basis space, $|\varphi_k\rangle$ in equation (1), of the order of 67. In the second step, these basis states are projected to good angular momentum states, and the projected basis is then used to diagonalize the shell model Hamiltonian. The diagonalization gives rise to the energy spectrum.

III. RESULTS AND DISCUSSION

A. Yrast Spectra

In figure1, the theoretical yrast spectra have been presented for ^{118}Ba and ^{120}Ba. The yrast spectra have been obtained for prolate deformation as these nuclei are observed to be prolate in their ground state. In the case of ^{118}Ba, the deformation parameters ϵ_2 and ϵ_4 are taken as 0.265 and -0.027, respectively. The experimental data for ^{118}Ba are available up to spin 20ℏ. From figure 1, it can be seen that the theoretical energy spectra reproduce the experimental data up to known spin satisfactorily. For example, the maximum difference between the theoretical and observed values of energy for the 12^+ state is 0.233MeV. In the case of ^{120}Ba, the values of deformation parameters ϵ_2 and ϵ_4 are taken as 0.275 and -0.061, respectively. The theoretical spectra have been obtained up to spin I=30ℏ. The theoretical spectra reproduce the experimental data up to I=30ℏ satisfactorily. For example, the maximum difference between the theoretical and observed values of energy for 14^+ state and is 0.382MeV.
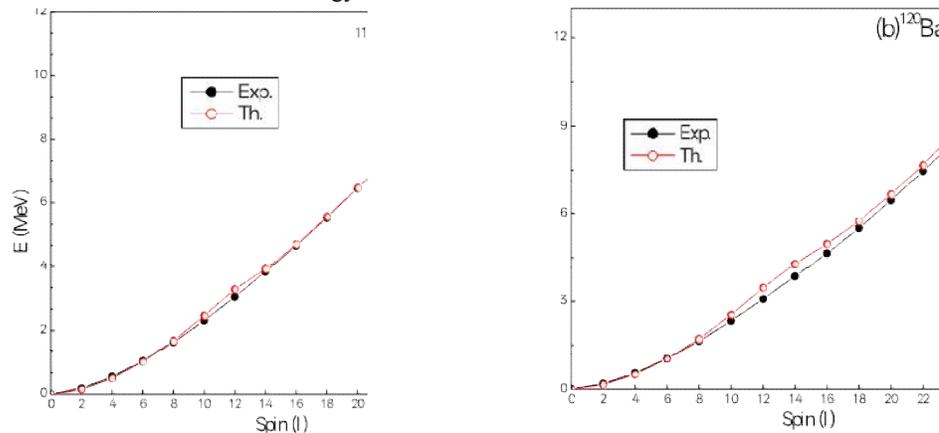

Figure- 1(a-b): Comparison of the calculated energies E(I) of the yrast band with the experimental data of ^{118,120}Ba isotopes.

B. Band Diagrams

In figure 2, the band diagrams for ^{118,120}Ba are displayed. From figure 2(a), for ^{118}Ba, one finds that the yrast spectrum up to spin 12ℏ is coincident with g-band arising from the zeroquasi particleintrinsic (qp) state. After spin 12ℏ, the g-band is crossed by two 2-qp neutron bands having configurations $2\upsilon h_{11/2}[-3/2,5/2]$, K=1 and $2\upsilon h_{11/2}[5/2,-7/2]$, K=-1 and one 2-qp proton band having configuration $2\pi h_{11/2}[1/2,-3/2]$, K=-1. Thus, the yrast states from 12ℏ-22ℏ arise from the superposition of two neutron 2-qp bands and one proton 2-qp band. A careful examination of figure 2(a) shows that the dominant contribution to the yrast states from spin 12ℏ-22ℏ is from proton band having configuration $2\pi h_{11/2}[1/2,-3/2]$, K=-1. After spin 22ℏ these bands are crossed by 4-qp bands having configurations $2\upsilon h_{11/2}[-3/2,5/2]+2\pi h_{11/2}[1/2,-3/2]$, K=0 and $2\upsilon h_{11/2}[-3/2,5/2]+2\pi h_{11/2}[1/2,1/2]$, K=1. Thus, the yrast states in the case of ^{118}Ba are pure 0-qp states up to spin 12ℏ, between spins 12ℏ and 22ℏ the yrast states are composed of 2-qp bands, and for spin I >22ℏ, the yrast states arise from 4-qp bands. So, in the PSM calculations there is almost simultaneous crossing of $1h_{11/2}$ neutron and proton bands as predicted by CSM calculations.

From figure 2(b), it is evident that for ^{120}Ba, the first band crossing takes place at spin 12ℏ. The yrast states from I=0 to 12ℏ belong to the g-band. As the g-band is crossed by one 2-qp proton and one 2-qp neutron bands having configurations $2\pi h_{11/2}[1/2,-3/2]$, K=-1 and $2\upsilon h_{11/2}[5/2,-7/2]$, K=-1, respectively around spin 12ℏ, the yrast states for I=14ℏ-26ℏ arise from the contribution of these two bands. As evident from the band diagram, 2-qp proton is dominant here. The second band crossing takes place between spins 26ℏ and 28ℏ. Here, one 4-qp band having configuration $2\pi h_{11/2}[1/2,-3/2]+2\upsilon h_{11/2}[-3/2,5/2]$, K=0 crosses the 2-qp bands and becomes yrast. So, in ^{120}Ba, the yrast states from I=0 to 12ℏ arise from 0-qp band, whereas the yrast states between spin 14ℏ-26ℏ arise from 2-qp proton and neutron

bands. Thus, in ^{120}Ba also there is simultaneous crossing of $1h_{11/2}$ proton and neutron bands but the proton band is having more contribution than neutron band. At higher spins the yrast states are arising from one 4-qp band as predicted by CSM calculations in Ref. [4].
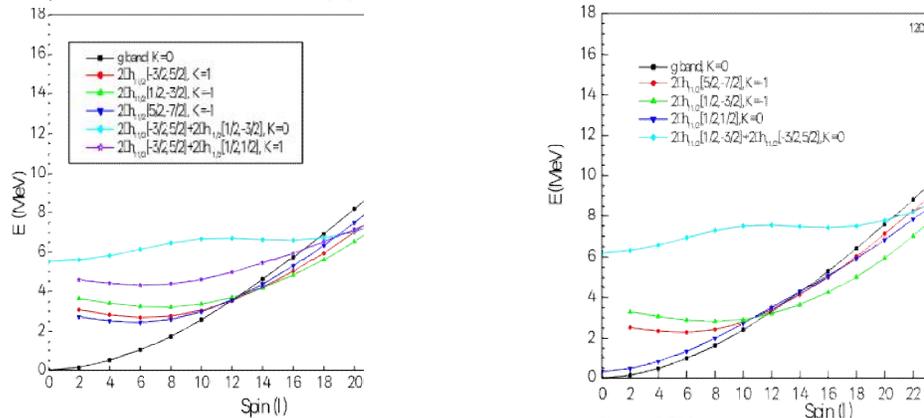

Figure 2(a-b): Band diagrams as a function of spin for ^{118,120}Ba isotopes.

IV. CONCLUSIONS

The study of neutron-deficient nuclei is a major current research in nuclear physics. Inspired by the experimental data available from Gammasphere array, the projected shell model has been applied to study the structure of yrast bands of very neutron-deficient barium isotopes. The yrast spectra and band structure of the yrast bands have been studied. The calculation has reproduced well the yrast bands. The analysis of band diagrams show that the first band crossing in ^{118,120}Ba is due to the crossing of ground state band by 2-qp proton and neutron bands, arising from $1h_{11/2}$orbital. The crossing of ground state band by multi-quasiparticle bands leads to the structural change in the yrast bands of these isotopes.

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