第 30 卷 第 12 期 高 能 物 理 与 核 物 理 Vol. 30, No. 12
2006 年 12 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Dec., 2006

Signature Inversion in the Odd-Odd Nuclei with Mass $A\sim 80$ *

SHEN Shui-Fa[1,2,3;1)] WANG Feng-Ge[4] PENG Nie[2] CHEN Heng-Gui[2] LU Hao[2] WU Yong-Peng[2]

1 (Key Laboratory of Nuclear Resources and Environment (East China Institute of Technology),
Ministry of Education, Nanchang 330013, China)
2 (School of Nuclear Engineering and Technology, East China Institute of Technology, Fuzhou 344000, China)
3 (School of Physics, Peking University, Beijing 100871, China)
4 (School of Electric and Information Engineering, Zhongyun University of Technology , Zhengzhou 450007, China)

Abstract To understand the microscopic origin of the signature inversion in the yrast positive-parity bands of doubly odd Rb nuclei, as an example, we performed calculations using the projected shell model (PSM) to describe the energy spectra in ^{82}Rb. It can be seen that the main features are reproduced in the calculations. This analysis shows clearly that the signature splitting and especially the signature inversion are reproduced only by a varying γ deformation with increasing spin.

Key words projected shell model(PSM), yrast state, quadrupole deformation, rotational frequency

1 Introduction

Doubly odd nuclei with mass $A\sim 80$ exhibit a complex low spin structure with an evolution to regularly spaced rotational levels above an excitation energy of 0.5—1.0MeV. The positive parity levels in these nuclei result from the occupation of the unique parity high-j $g_{9/2}$ subshell. Signature inversion in the vicinity of $11\hbar$ is a feature commonly observed in the yrast bands of odd-odd nuclei in this mass region, and it is indicative of an underlying $\pi g_{9/2}\otimes\nu g_{9/2}$ quasi-particle configuration. The angular momentum of the states below spin $9\hbar$ consists of contributions from both rotation and the realignment of the intrinsic spins, while rotation is the only mechanism for generating angular momentum above this value of the spin. The negative parity bands in these nuclei, however, do not exhibit systematic behavior with regard to signature splitting and inversion. This is due to the relatively high density of orbitals that can generate negative parity states in combination with either a proton or neutron in the $g_{9/2}$ orbital. Signature inversions in odd-odd nuclei have been found systematically in regions of mass number $A\sim 80$, 130 and 160, and although several explanations have been proposed to interpret this phenomenon, no conclusive evidence for this explanation has been presented so far. Bengtsson et al.[1] explained it in terms of the effect of the γ deformation in a cranked shell model calculation. Hamamoto[2], using the particle-plus-rotor model, suggested that the γ deformation may not be so important. The work of Jain et al.[3] within the framework of a model incorporating an axially symmetric rotor plus two particles suggests the mechanism of Coriolis mixing between a large number of bands, and Hara et al.[4] proposed the crossing of decoupled bands to describe it. In addition, other studies have analyzed the effect introduced by including a proton-neutron interaction between the odd nucleons, for example, the works of Matsuzaki[5] and Tajima[6], and the effect introduced by considering different dynamical symmetries in the interacting

---

Received 30 April 2006
* Supported by National Natural Science Foundation of China (10547140, 10525520) and Natural Science Foundation of Jiangxi Province (0612003)

1) E-mail: shfshen@ecit.edu.cn

1234 — 1237

boson model, for example, the work of Yoshida et al.[7]. Recently, signature inversion in the A-80 region was investigated in detail by Zheng et al. on the basis of a model incorporating an axially symmetric rotor plus two quasiparticles model[8]. The results indicate that the competition between the n-p interaction and the Coriolis force in low-K space is possibly the signature inversion mechanism. On the other hand, the signature inversion around spin I=16 in the negative-parity band of nucleus ^{72}Br was observed in 2000 by Plettner et al. in their in-beam study[9]. The interpretation within the cranked Nilsson-Strutinsky approach shows that this signature pattern is a signal of a substantial triaxial shape change with increasing spin where the nucleus evolves from a triaxial shape with rotation about the intermediate axis at low spin through a collective prolate shape to a triaxial shape but with rotation about the shortest principal axis at high spin. More recently, the signature inversion phenomenon in ^{74}Br, ^{76,78}Rb, and ^{80,82}Y was studied in detail via the projected shell model approach[10]. In the calculations the basis deformation ε_2 is separately fixed for each nucleus. However, the calculation does not reproduce the signature inversion observed at low spins in these nuclei. The failure that their final results do not reproduce the signature inversion may indicate that we should consider other mechanism that may cause the inversion.

As seen above, the mechanisms proposed by various research groups differ to a certain degree, and signature inversion in odd-odd nuclei has been studied even less for the $A\sim80$ region. In this work we present the results of our investigation of yrast positive-parity states, in particular with regard to the signature inversion in this band of ^{82}Rb in the framework of the projected shell model (PSM). Prior to the present work, there was no information concerning the mechanism of signature inversion in this nucleus.

In recent years, the projected shell model (PSM) has become quite successful in describing a broad range of properties of deformed nuclei in various regions of the nuclear Periodic Table. The most striking aspect of this quantum mechanical model is its ability to describe the finer details of the high-spin spectroscopy data with simple physical interpretations[10]. In this work, in order to study the mechanism of signature inversion in the mass $A\sim80$ region, as an example, we attempt to apply this model to the nucleus ^{82}Rb. The theoretical model is described in Ref. [10], and in the present work we stress the calculations and discussion aimed at the elucidation of this nucleus.

2 PSM calculations for ^{82}Rb

In an experiment performed in 1999, the high-spin states in the odd-odd nucleus ^{82}Rb were studied by means of the ^{68}Zn (^{18}O, p3n) ^{82}Rb reaction with a 56MeV beam energy employing a thin target coincidence measurement[11]. Signature inversion has been observed around spin 11, which is slightly shifted to higher spin in comparison with the corresponding value for the lighter odd-odd isotopes ^{76,78}Rb, which have a signature inversion at spin 9. This shift could be a consequence of the conjectured decrease in the quadrupole deformation (^{76,78}Rb: $\beta_2\approx0.38$ and ^{82}Rb: $\beta_2\approx0.2$) as N increases in odd-odd Rb isotopes. In addition, for positive parity states at low rotational frequency, i.e., for $\hbar\omega\leqslant0.292$MeV, the total Routhian surface (TRS) calculations in Ref. [11] predict that the nucleus ^{82}Rb is very γ soft, with a quadrupole deformation of at most $\beta_2\approx0.23$. As the frequency increases, the nucleus becomes slightly more deformed and more stiff, with an oblate shape ($\beta_2\approx0.25$, $\gamma=-57°$). Here the quantity $\hbar\omega$ (ω: rotational frequency) is defined as follows[12]:

$$\hbar\omega=\frac{\mathrm{d}E}{\mathrm{d}\sqrt{I(I+1)}}\ , \tag{1}$$

where $\sqrt{I(I+1)}$ is often replaced by I at high spin. In practice, this parameter is extracted from the observed energies of the γ-transitions within a band by, for example, the following finite difference approximation of Eq. (1) (E_γ in MeV)

$$\hbar\omega=\frac{E_I-E_{I-2}}{\sqrt{I(I+1)}-\sqrt{(I-1)(I-2)}}\mathrm{MeV}\ . \tag{2}$$

It should be pointed out here that for doubly even nuclei the Eq. (2) could be used directly, whereas for other kind of nuclei, just as the odd-ddd nuclei ^{82}Rb studied in the present Letter, the band should be devided into the two signature partner bands (favored and unfavored partner bands) first, then calculated using this equation separately. When $I=9\hbar$ is adopted, we result in that the $\hbar\omega$ equals 0.303MeV, which is very close to $\hbar\omega=0.292$MeV. Here the experimental datum $E_I-E_{I-2}=608.2$keV is taken from Ref. [11]. In the present work, the pairing gaps are calculated using the four-point formula[13]. The values of the total nuclear binding energy, B, are taken from Ref. [14], and experimental data are adopted if only they can be supplied. The results we obtain are $\Delta_{\rm p}$=1.3375MeV and $\Delta_{\rm n}$=1.1675MeV. Here the Nilsson parameter values are taken from Ref. [15], and the calculations are performed by considering three major shells (N=2, 3, and 4) for both neutrons and protons. Shape calculations using the Nilsson+BCS formalism were carried out for the nucleus ^{82}Rb. The Hartree-Fock-Bogoliubov energy $E_{\rm HFB}$ (approximately equivalent to the deformation energy from the calculations using the Nilsson+BCS method[16]) of ^{82}Rb as a function of the quadrupole deformation ε_2 is displayed in Fig. 1. It is seen that the energy $E_{\rm HFB}$ has three minima, which correspond to a slightly-deformed prolate shape (ε_2=0.05), a moderately-deformed prolate shape (ε_2=0.25), and an oblate shape ($\varepsilon_2=-0.25$).

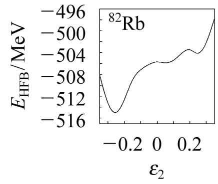

Fig. 1. Hartree-Fock-Bogolyubov energy $E_{\rm HFB}$ of ^{82}Rb as a function of the quadrupole deformation parameter ε_2.

These three minima are considered possible forms of the equilibrium deformation. So, as mentioned above, it's reasonable to take the quadrupole deformations to be ε_2=0.25 ($6\leqslant I\leqslant 8$) and $\varepsilon_2=-0.25$ ($I\geqslant 9$), respectively, in calculating the yrast positive-parity states. The hexadecapole deformation parameter ε_4=0.000 is taken from the compilation of Möller et al.[14]. In the calculations, the configuration space is constructed by selecting the qp states close to the Fermi energy in the N=4 (N=4) major shell for neutrons (protons), i.e. the K=5/2, 7/2 orbitals of the $g_{9/2}$ subshell and the K=1/2 of the $d_{5/2}$ subshell (the K=1/2, 3/2, 5/2 orbitals of the $g_{9/2}$ subshell) when ε_2=0.25 is adopted, and the K=1/2, 3/2, 5/2 orbitals of the $g_{9/2}$ subshell (the K=7/2, 9/2 orbitals of the $g_{9/2}$ subshell) when $\varepsilon_2=-0.25$ is adopted, and forming multi-qp states from them. Comparisons of the experimentally observed signature inversion in the yrast positive-parity levels of ^{82}Rb with the predictions of the PSM are given in Fig. 2(a) (ε_2=0.25) and Fig. 2(b) ($\varepsilon_2=-0.25$). The experimental data are taken from Ref. [11]. Very recently, an in-beam study of ^{82}Rb using the ^{76}Ge (^{11}B, 5n) reaction[17, 18] was reported. The level scheme of ^{82}Rb deduced from that work is for the most part consistent with the results of a previous work[11]. From neither of these figures do we find signature inversion from our calculations. However, if we take the quadrupole deformations to be ε_2=0.25 ($6\leqslant I\leqslant 8$) and $\varepsilon_2=-0.25$ ($I\geqslant 9$), respectively, in calculating the yrast positive-parity states, as shown in Fig. 2(c), it is seen that the calculated results fit the data reasonably well, except that the energy spacing between the states with $I^\pi=10^+$ and $I^\pi=11^+$, i.e. the ascription of this small region, is not satisfactory. The cause of this problem could be that in this region, the nucleus may be triaxial, and our computer code was written assuming an axially symmetric system. Thus the present result is the best we can do at the moment[16]. However, we find that the most noteworthy feature of Fig. 2(c) is that

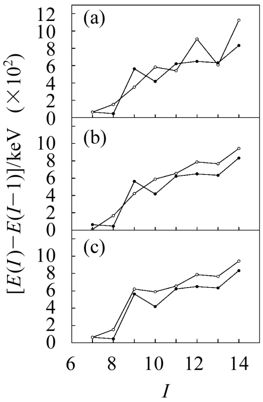

Fig. 2. The transition energies of the yrast positive-parity band of ^{82}Rb. The energy difference $E(I)-E(I-1)$ is compared between theory (open circles) and experiment (solid circles). The data are taken from Ref. [11].

the signature inversion appears at the correct value of I. In addition, the relatively small energy spacing between the levels 8^+ and 7^+, as compared to that between the levels 7^+ and 6^+, can not be accounted for yet with the present approach, but it don't affect the main result. In addition, an interesting aspect of the yrast positive-parity band of the ^{82}Rb nucleus which should be explored is the fact that the strong M1 transitions at lower spin region($6 \leqslant I \leqslant 8$) turn to strong E2 transitions at higher spin region($I \geqslant 9$). This feature, which is characteristic of the shape change[19], has also been observed in neighboring isotope ^{84}Rb[20].

3 Summary

In the present work, as an example, we carried out theoretical analysis of low-lying band in ^{82}Rb designated as yrast positive-parity band that starts from 6^+, and we compared our results with the experimental data, especially the signature inversion at intermediate spin around 11^+ in the positive-parity yrast band is discussed in the framework of projected shell model. Our results suggest that the signature inversion in the yrast positive-parity bands of doubly odd nuclei in $A \sim 80$ region may be understood within the projected shell model approach if the variation of the triaxial deformation parameter γ along with the spin I is taken into account, especially, as for nuclei ^{80,82,84}Rb, the quadrupole deformation is assumed to be positive (prolate, $\gamma = 0^\circ$) at lower spin region ($I \leqslant 8$) and negative (oblate, $\gamma = -60^\circ$) above it ($I \geqslant 9$), the condition necessary for signature inversion. Such a situation is reported here for the first time for $A \sim 80$ nuclei.

References

1 Bengtsson R, Frisk H, May F R et al. Nucl. Phys., 1987, **A415**: 189
2 Hamamoto I. Phys. Lett., 1990, **B235**: 221
3 Jain A K, Goel A. Phys. Lett., 1992, **B277**: 233
4 Hara K, Sun Y. Z. Phys., 1991, **A339**: 15
5 Matsuzaki M. Phys. Lett., 1991, **B269**: 23
6 Tajima N. Nucl. Phys., 1994, **A572**: 365
7 Yoshida N et al. Nucl. Phys., 1994, **A567**: 17
8 ZHENG R et al. Phys. Rev., 2001, **C64**: 014313
9 Plettner C et al. Phys. Rev. Lett., 2000, **85**: 2454
10 Palit R et al. Phys. Rev., 2003, **C67**: 014321
11 Döring J et al. Phys. Rev., 1999, **C59**: 71
12 Szyma ski Z. Fast Nuclear Rotation. Oxford: Clarendon Press, 1983
13 Aage Bohr, Ben R. Mottelson. Nuclear Structure. Vol 1. Benjamin; New York: Amsterdam, 1969, 169
14 Möller P, Nix J R, Myers W D et al. Atomic Data and Nuclear Data Tables, 1995, **59**: 185
15 ZHANG J Y et al. Phys. Rev., 1989, **C39**: 714
16 Hara K, Sun Y. Int. J. Mod. Phys., 1995, **E4**: 637
17 Schwengner R et al. Phys. Rev., 2002, **C66**: 024310
18 Schnare H et al. Phys. Rev. Lett., 1999, **82**: 4408
19 Dejbakhsh H, Mouchaty G, Schmitt R P. Phys. Rev., 1991, **C44**: 119
20 HAN Guang-Bing, WEN Shu-Xian, LIU Xiang-An et al. HEP & NP, 1999, **23**: 890(in Chinese)
(韩广兵, 温书贤, 刘祥安等. 高能物理与核物理, 1999, **23**: 890)

$A \sim 80$区奇–奇核的旋称反转*

沈水法[1,2,3;1)]　王凤歌[4]　彭聂[2]　陈亨贵[2]　卢浩[2]　吴永鹏[2]

1 (核资源与环境教育部重点实验室(东华理工学院)　南昌　330013)
2 (东华理工学院核工程技术学院　抚州　344000)
3 (北京大学物理学院　北京　100871)
4 (中原工学院电子信息与工程学院　郑州　450007)

摘要　为了理解奇–奇Rb核正宇称晕带旋称反转的微观起源, 作为一个例子, 用投影壳模型(PSM)计算了核^{82}Rb的能谱. 可以看出计算结果能重现主要的特征. 这个分析清楚地显示只要考虑γ形变随着自旋增加而变化, 旋称劈裂特别是旋称反转就能再现.

关键词　投影壳模型　转晕态　四极形变　转动频率

2006 – 04 – 30 收稿
∗ 国家自然科学基金(10547140, 10525520)和江西省自然科学基金(0612003)资助

1) E-mail: shfshen@ecit.edu.cn