Neutron-Proton Interaction in Doubly Odd Deformed Nuclei

Nunzio Itaco, Aldo Covello, and Angela Gargano

Dipartimento di Scienze Fisiche, Università di Napoli Federico II, and Istituto Nazionale di Fisica Nucleare, Complesso Universitario di Monte S. Angelo, Via Cintia, I-80126 Napoli, Italy

Abstract. In this paper, we present some results of a particle-rotor model study of $^{176}$Lu. In particular, we consider the two lowest $K^\pi=1^+$ bands, which present a rather large odd-even staggering. This effect, which may be traced to direct Coriolis coupling with Newby-shifted $K^\pi=0^+$ bands, is of great interest since it gives information on the neutron-proton interaction. We use both zero-range and finite-range interactions with particular attention focused on the role of the tensor force. Comparison of the calculated results with experimental data evidences the importance of the tensor-force effects in the description of the odd-even staggering in $K \neq 0$ bands.

1 Introduction

It is well known that the two most important effects associated with the residual neutron-proton interaction in doubly odd deformed nuclei are the Gallagher-Moszkowski (GM) splitting [1] and the odd-even or Newby (N) shift [2]. Further information on the neutron-proton interaction may be obtained by studying the odd-even staggering [3] in $K \neq 0$ bands. In fact, the main mechanism responsible for this effect is the mixing, through the Coriolis interaction, of $K \neq 0$ bands with one or more N-shifted $K=0$ bands. Bands which exhibit odd-even staggering represent therefore an indirect source of knowledge of the effective neutron-proton interaction.

In a previous paper [4], we have performed a complete Coriolis band-mixing calculation for the doubly odd deformed nucleus $^{176}$Lu within the framework of the particle-rotor model. Our aim was to assess the role of the effective neutron-proton interaction, with particular attention focused on the tensor force. Here, we report on our results concerning the two lowest $K^\pi=1^+$ bands in $^{176}$Lu, which exhibit a rather large odd-even staggering.

The paper is organized as follows. In Sec. 2 we give a brief description of the model and some details of our calculations. In Sec. 3 we compare our results with the experimental data. Some concluding remarks are given in Sec. 4.

2 Outline of the model and calculations

We assume that the unpaired neutron and proton are strongly coupled to an axially symmetric core and interact through an effective interaction. The total
The Hamiltonian is written as

\[ H = H_0 + H_{\text{RPC}} + H_{\text{ppc}} + V_{np}. \]  

The term $H_0$ includes the rotational energy of the whole system, the deformed, axially symmetric field for the neutron and proton, and the intrinsic contribution from the rotational degrees of freedom. It reads

\[ H_0 = \frac{\hbar^2}{2J}(I^2 - I_3^2) + H_n + H_p + \frac{\hbar^2}{2J}(J_{n3}^2 - J_{n3}^2) + (J_{p3}^2 - J_{p3}^2). \]  

The two terms $H_{\text{RPC}}$ and $H_{\text{ppc}}$ stand for the Coriolis coupling and the coupling of particle degrees of freedom through the rotational motion, respectively. Their explicit expressions are

\[ H_{\text{RPC}} = -\frac{\hbar^2}{2J}(I^+ J^- + I^- J^+), \]

\[ H_{\text{ppc}} = \frac{\hbar^2}{2J}(J_n^+ J_p^- + J_n^- J_p^+). \]

The effective neutron-proton interaction is given the general form

\[ V_{np} = V(r)[u_0 + u_1 \sigma_p \cdot \sigma_n + u_2 P_M + u_3 P_M \sigma_p \cdot \sigma_n + V_T S_{12} + V_{TM} P_M S_{12}], \]

with standard notation [5]. In our calculations we have used a finite-range force with a radial dependence $V(r)$ of the Gaussian form

\[ V(r) = \exp(-r^2/r_0^2), \]

as well as a zero-range force. In the latter case, $V_{np}$ takes the simple form

\[ V_{np}^\delta = \delta(r)[v_0 + v_1 \sigma_p \cdot \sigma_n]. \]

As basis states we use the eigenvectors of $H_0$ properly symmetrized and normalized,

\[ |\nu_n \Omega_n \nu_p \Omega_p I M K \rangle = \left( \frac{2I + 1}{16\pi^2} \right)^{\frac{1}{2}} \left[ D_{MK}^I |\nu_n \Omega_n \rangle \right] |\nu_p \Omega_p \rangle + \left( - \right)^I + K \frac{D_{MK}}{D_{M-K}} |\nu_n \Omega_n \rangle |\nu_p \Omega_p \rangle, \]

where the state $|\nu \Omega \rangle$ is the time-reversal partner of $|\nu \Omega \rangle$.

We have used the standard Nilsson potential [6] to generate the single-particle Hamiltonians $H_n$ and $H_p$. The parameters $\mu$ and $\kappa$ have been obtained from the mass-dependent formulas of Ref. [7]. As regards the deformation parameter $\beta_2$ we have used the value 0.26, according to Ref. [8].

The single-particle energies for the odd proton and the odd neutron and the rotational parameter $\hbar^2/2J$ have been derived from the experimental spectra [9] of the two neighboring odd-mass nuclei $^{175}\text{Yb}$ and $^{175}\text{Lu}$. The explicit values of the parameters involved in the calculation may be found in Ref. [4].
For the neutron-proton interaction, as already mentioned above, we have used both a finite-range force with a Gaussian radial shape and a zero-range interaction. As regards the former, we have performed two different calculations, with and without the tensor terms. For the parameters of this interaction we have adopted the values determined by Boisson et al. [5] in their analysis of the GM splittings and N shifts in the rare-earth region. As regards the δ force, no value of the strength of the spin-spin term $v_1$ gives a satisfactory description of the N shifts. We have used the value $v_1 = -0.20$ MeV, which leads to the lowest possible disagreement between theory and experiment. More details about the choice of the parameters of the potentials as well as their explicit values are given in Ref. [4].

3 Results and comparison with experiment

In the low-energy spectrum of $^{176}$Lu two $K^\pi = 1^+$ bands have been observed, which both exhibit a rather large odd-even staggering [3].

![Fig. 1. Experimental and calculated odd-even staggering of the $K^\pi = 1^+ p_{1/2}[514]n_{5/2}[514]$ band in $^{176}$Lu. Solid circles correspond to experimental data. The theoretical results are represented by open circles (Gaussian central plus tensor force), diamonds (Gaussian central force), and stars (δ force).](image)

They are the $K^\pi = 1^+ p_{1/2}[514]n_{5/2}[514]$ band starting at 197 keV, and the $K^\pi = 1^+ p_{3/2}[624]n_{3/2}[404]$ band, whose bandhead lies at 339 keV.

The experimental ratio [10] $|E(I) - E(I-1)|/2I$ for the lowest $K^\pi = 1^+$ band is plotted vs $I$ and compared with the calculated ones in Fig. 1. We see that the experimental behavior is satisfactorily reproduced by the calculation including the tensor force. When using the pure central Gaussian force the staggering is
almost nonexistent and in the case of the $\delta$ force not only is its magnitude very small, but it has also the opposite phase. To better understand our results let us discuss the structure of the states of this $K^\pi = 1^+$ band. In all of our three calculations we find that the wave functions of these states contain significant components (5 – 10 %) with $K^\pi = 0^+ p_{3/2}^{[523]}n_{1/2}^{[514]}$. The mixing between the two bands is obviously due to the Coriolis interaction, whose effects are enhanced by the presence of the $\frac{3}{2}[514]$ and $\frac{7}{2}[523]$ single-proton orbitals arising from the $h_{11/2}$ shell-model state. The fact that only the calculation including the tensor terms gives the right staggering implies that only this force is able to reproduce a sizable N shift for the $K^\pi = 0^+ p_{3/2}^{[523]}n_{1/2}^{[514]}$ band. Unfortunately, this band has not been definitely recognized, so that a direct comparison is not possible at present.

Let us now come to the $K^\pi = 1^+ p_{3/2}^{[404]}n_{1/2}^{[624]}$ band. In Fig. 2 we plot the experimental ratio $[10] (E(I) - E(I - 1))/2I$ vs $I$ and compare it with the calculated ones.

![Fig. 2](image)

**Fig. 2.** Same as Fig. 1, but for the $K^\pi = 1^+ p_{3/2}^{[404]}n_{1/2}^{[624]}$ band.

We see that also in this case only the calculation including the tensor force is able to reproduce the correct experimental odd-even staggering, the main discrepancy being a downshift of the calculated value of about 2 keV. The analysis of the wave functions of the states of this $K^\pi = 1^+$ band shows that it is considerably mixed with the $K^\pi = 0^+ p_{3/2}^{[404]}n_{1/2}^{[633]}$ band. In fact, in all of our three calculations the wave functions contain significant components (5 – 15 %) with $K^\pi = 0^+$. While this band has not been observed in $^{176}$Lu, it has been recognized in $^{174}$Lu with a N shift of $-44$ keV [11]. For the latter band we find a N shift of $-26$, $1$, and $6$ keV, using a Gaussian force with tensor terms, a pure
central Gaussian force, and a $\delta$ force, respectively. This provides evidence that the odd-even staggering in the $K^\pi = 1^+$ band is to be traced to tensor force effects in the description of the N-shifted $K^\pi = 0^+ p_7^\pi[404]n_7^\pi[633]$ band.

4 Concluding remarks

In this paper, we have presented the results of a study of the two lowest $K^\pi = 1^+$ bands in $^{176}$Lu within the framework of the particle-rotor model. Our aim was to assess the role of the effective neutron-proton interaction in the description of $K \neq 0$ bands in doubly odd deformed nuclei. In Ref. [4] we showed that the space-exchange and spin-spin space-exchange forces as well as the tensor force are very relevant in the description of the N shifts in $K = 0$ bands. The results of the present work evidences the role of these forces in the description of some $K \neq 0$ bands. In particular, we show that, owing to the Coriolis coupling, the odd-even staggering observed in the two lowest $K^\pi = 1^+$ bands in $^{176}$Lu appears to be a manifestation of the tensor force effects. In conclusion, we feel that it is well worth extending the present study to other $K \neq 0$ bands which exhibit a rather large odd-even staggering. Work in this direction is in progress.

References

1. C. J. Gallagher and S. A. Moszkowski, Phys. Rev. 111, 1282 (1958).
2. N. D. Newby, Jr., Phys. Rev. 125, 2063 (1962).
3. A. K. Jain, J. Kvasil, R. K. Sheline, and R. W. Hoff, Phys. Rev. C 40, 432 (1989).
4. A. Covello, A. Gargano, and N. Itaco, Phys. Rev. C 56, 3092 (1997).
5. J. P. Boisson, R. Piepenbring, and W. Ogle, Phys. Rep. 26, 99 (1976).
6. C. Gustafson, I. L. Lamm, B. Nilsson, and S. G. Nilsson, Ark. Fys. 36, 613 (1967).
7. S. G. Nilsson, C. F. Tsang, A. Sobiczewski, Z. Szymánski, S. Wycech, C. Gustafson, I. L. Lamm, P. Möller, and B. Nilsson, Nucl. Phys. A131, 1 (1969).
8. D. Elmore and W. P. Alford, Nucl. Phys. A273, 1 (1976).
9. A. O. Macchiavelli and E. Browne, Nucl. Data Sheets 69, 903 (1993).
10. N. Klay et al., Phys. Rev C 44, 2801 (1991).
11. E. Browne, Nucl. Data Sheets 62, 1 (1991).
12. A. Covello, A. Gargano, and N. Itaco, to be published.