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Semidecoupling in doubly odd deformed nuclei

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Structures in which a neutron occupies an $\Omega=\frac{1}{2}$ orbit with decoupling parameter $a_n \simeq 1$ and a proton is in an $\Omega \neq \frac{1}{2}$ orbit have been found in a doubly odd deformed nucleus. These bands are almost identical to the $\Omega \neq \frac{1}{2}$ bands in neighboring odd proton nuclei. This behavior is reproduced analytically within the two-quasiparticle-plus-rotor model.

During the last few years a significant effort has been done to understand doubly odd deformed nuclei, particularly in the upper rare-earth region.[1] This work is revealing a wealth of very interesting structures and is starting to lead to a general classification of the ways two distinguishable particles couple to each other.[2]

In this context, structures in which $\Omega=\frac{1}{2}$ orbitals are involved (as expected in decoupling phenomena) play a special role. Just one by now firmly established example is that of the doubly decoupled band in which both particles occupy predominantly $\Omega=\frac{1}{2}$ orbits.[3-6]

We report here on a new type of semidecoupled structure[1,3] in which one of the odd valence quasiparticles is in an $\Omega=\frac{1}{2}$ orbit while the other moves mainly in one, or several, intrinsic states with $\Omega \neq \frac{1}{2}$.

We shall first explore the most simple model which contains the essential ingredients, namely (to fix ideas) the coupling of $\Omega_n=\frac{1}{2}$ to $\Omega_p \neq \frac{1}{2}$. This coupling produces two intrinsic states in the doubly odd system characterized by the total projection quantum number $K_{\gtrless}=\Omega_p \pm \Omega_n$, which are degenerate except for the possible presence of a proton-neutron (p-n) residual force, V_{pn}. For each value of the total angular momentum I (except $I=K_<$) one has two states coupled by a matrix element proportional to the neutron's decoupling parameter a_n. The 2×2 matrix to be diagonalized is

$$A\begin{pmatrix} I(I+1)-K_>^2 & -a_n[(I-K_<)(I+K_<+1)]^{1/2} \\ -a_n[(I-K_<)(I+K_<+1)]^{1/2} & I(I+1)-K_<^2 \end{pmatrix}, \tag{1}$$

where A is the inertia parameter $\hbar^2/2J$.

The intrinsic energy is a scalar matrix if the p-n force is neglected. Actually this force would enter as the Gallagher-Moszkowsky splitting[7,8] through the diagonal of matrix (1) due to the $\Delta K=0$ selection rule (here $K_<=K_>-1\equiv K-1$).

The two eigenvalues of matrix (1) in units of A are

$$E_\pm=I(I+1)-\tfrac{1}{2}[K^2+(K-1)^2] \pm[a_n^2 I(I+1)+\tfrac{1}{4}-K(K-1)(a_n^2-1)]^{1/2}. \tag{2}$$

(The $K=1$ case corresponds to the doubly decoupled band and has to be treated separately.)

For $a_n=\pm 1$ one gets for the lowest eigenvalue

$$E_-=(I-\tfrac{1}{2})(I+\tfrac{1}{2})-(K-\tfrac{1}{2})^2-\tfrac{1}{2}. \tag{3}$$

If one defines $I'=I-\frac{1}{2}$, this expression goes over into

$$E_-=I'(I'+1)-\Omega_p^2-\tfrac{1}{2}, \tag{4}$$

which is exactly the same law followed by the Ω_p band in the neighboring odd proton nucleus (except for the small constant shift $\frac{1}{2}$ which is not reflected in the transition energies). The $\Omega_n=\frac{1}{2}$ quasiparticle acts as a spectator. Furthermore, the bandhead energy given by (4) [or (3)] for $I=K$ (or $I'=K-\frac{1}{2}=\Omega_p$) coincides with the energy of the unmixed state $I=K_<=K-1$ and the difference between the two eigenvalues for each value of $I(\geq K)$ is

$$E_+-E_-=2I+1, \tag{5}$$

which is exactly the energy difference between consecutive transitions along the lowest lying band. Summarizing, one obtains two degenerate rotational bands: $I=K_>$, $K_>+1,\ldots$ and $I=K_<, K_<+1,\ldots,$ which have exactly the same transition energies (in units of A) as the Ω_p band in the neighboring odd proton nucleus but have spin values shifted by one unit. The deviations with respect to this behavior will allow us to obtain the difference $\langle K_>|V_{pn}|K_>\rangle-\langle K_<|V_{pn}|K_<\rangle$ of the p-n interaction expectation value in the unperturbed bandhead states.

Figure 1 shows a comparison between the $\tilde{\pi}\frac{7}{2}^+[404]$ band in ^{173,175}Lu (Ref. 9) and the $\tilde{\pi}\frac{7}{2}^+[404]\otimes\tilde{\nu}\frac{1}{2}^-[521]$ band in ^{174}Lu (Ref. 10). At least one of the predictions made above seems to be fulfilled with a striking accuracy on account of the fact that in the neighboring odd N nuclei of Hf and Yb one finds[11,12] low-lying $\frac{1}{2}^-[521]$ bands with decoupling parameters $a_n \simeq 1$. The second prediction, namely the existence of the nonyrast $I=K_<$, $K_<+1,\ldots$ sequence essentially degenerate with the yrast one, is also verified (see Fig. 1) but with less accuracy. However as the spin increases (and the residual p-n interaction becomes less important than the Coriolis coupling which depends on the magnitude of the spin) one

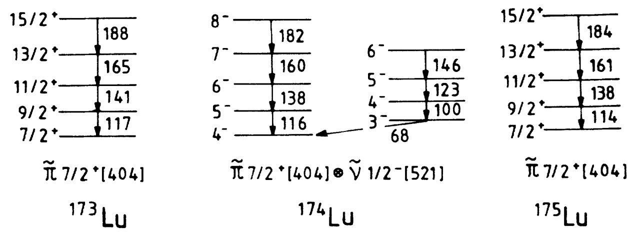

FIG. 1. Comparison between $\tilde{\pi}\frac{7}{2}^+[404]$ bands in odd ^{173,175}Lu and the $\tilde{\pi}\frac{7}{2}^+[404]\otimes\tilde{\nu}\frac{1}{2}^-[521]$ band in ^{174}Lu.

clearly sees a tendency of the state of spin I of the nonyrast structure to have the same energy as the state of spin $I+1$ of the yrast one (see, e.g., the $I^\pi = 7^-$ state and the second $I^\pi = 6^-$ state in Fig. 1). For instance, from the energy splitting of states of the same spin it is possible to obtain the quantity $\langle K_> | V_{pn} | K_> \rangle - \langle K_< | V_{pn} | K_< \rangle$ which turns out to be -70 keV.

The results discussed above are not restricted to the simple two-band ($K_{\gtrless}$) system. If an $\Omega_a = \frac{1}{2}$ quasiparticle is coupled to another one which is allowed to move in a whole set of Nilsson orbits $\{\Omega_b\}$ one obtains an yrast band in the doubly odd system which is identical to the yrast band of the odd mass nucleus ($\{\Omega_b\}$ system) provided $a_a = \pm 1$.

For example, one such $\Omega_a = \frac{1}{2}$ particle (which just enters into the calculation through its decoupling parameter) has been coupled to another one moving in the seven $i\frac{13}{2}$-parentage Nilsson orbits. From a mathematical point of view the problem amounts to diagonalize a 14×14 matrix where now also the intrinsic energy (which is no longer a scalar) has been taken into account. If $a_a = \pm 1$ the results are numerically identical to the ones obtained by diagonalizing the 7×7 matrix in the odd mass system. This behavior is related to the one displayed by the semidecoupled bands discussed in doubly odd Tl (Ref. 13) and Ir (Refs. 1 and 3) nuclei ($\tilde{\pi}h\frac{9}{2}\otimes\tilde{\nu}i\frac{13}{2}$ system). The semidecoupled band follows the general behavior of the nondecoupled particle (for instance, the staggering behavior); however since in this case the decoupling parameter of the decoupled particle is larger than one (and also states other than the $\Omega = \frac{1}{2}$ orbit participate) it turns out that the doubly odd system presents a sequence of compressed transitions until it reaches transitions of the same magnitude as those found in the nondecoupled band.

The coupling scheme discussed here may also be relevant for the understanding of two-quasiparticle bands in even-even nuclei where both particles move in different orbits (e.g., negative parity bands). Here the problem becomes identical to the one in a doubly odd nucleus. For example, the lowest lying negative parity band in ^{180}Os (Ref. 14) shows an odd-even staggering of very similar magnitude than the $i\frac{13}{2}$-parentage bands in ^{179,181}Os (Refs. 15 and 16), where one also finds as low lying bands the $\frac{1}{2}^-$ [521] structures. We hence propose for the 4^- band in ^{180}Os an intrinsic structure dominated by the $\tilde{\nu}\{\frac{1}{2}^-[521]i\frac{13}{2}\}$ configuration at variance with the earlier interpretation.[14]

Summarizing, rotational structures, recently found in a doubly odd deformed nucleus, which are almost identical to bands known in neighboring odd proton isotopes can be described analytically by coupling an $\Omega = \frac{1}{2}$ neutron with decoupling parameter near unity to $\Omega \neq \frac{1}{2}$ states. The relevance of this semidecoupled scheme for distorted negative parity two-quasiparticle bands in even-even nuclei is suggested pointing to the importance of spectroscopic studies on doubly odd nuclei for the understanding of band structure in general.

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