PHYSICAL REVIEW C VOLUME 33, NUMBER 6 JUNE 1986

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Rotational band structure in ^{133}Pr

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(Received 27 December 1985)

The level structure of the odd proton nucleus ^{133}Pr has been investigated. Excited states up to spin $\frac{45}{2}$ have been observed. The yrast band, built on a decoupled $h_{11/2}$ proton, shows an up-bend at $\hbar\omega = 0.43$ MeV when two additional $h_{11/2}$ protons align. Two positive parity side bands, based on the $g_{7/2}\frac{5}{2}^+[413]$ proton configuration, are established with opposite signature. Both show a band crossing at $\hbar\omega_c = 0.27$ MeV with a gain in alignment $\approx 8\hbar$, when two $h_{11/2}$ protons decouple. This low crossing frequency is partly explained by a reduction in the proton pairing gap caused by the $g_{7/2}$ proton.

Band crossings are of current interest in deformed, γ-soft nuclei. For a rotating nucleus, the Coriolis force can become sufficiently strong at some rotational frequency to overcome the pairing interaction between specific nucleons, which results in the decoupling of their angular momenta and the subsequent alignment along the axis of collective rotation.[1] High-j orbitals with a small spin projection Ω on the nuclear symmetry axis are influenced most strongly by the Coriolis force in this manner. Systematic studies of the resulting band crossings as a function of proton and neutron numbers can be used to identify the structure of the bands using "blocking effect" arguments. Signature splitting of the band members both above and below band crossings is sensitive to the asymmetry shape γ as well as to the valence orbitals. The crossing frequencies are also related to the strength of the pairing force; a reduction of the pairing will decrease the rotational frequency needed to decouple and align a nucleon pair.

Experiments in the light La and Ce isotopes have shown that the first band crossing in the mass $A = 130$ region is due to the alignment of a $h_{11/2}$ proton pair.[2,3] In the odd proton nuclei, the yrast band is based on a decoupled $h_{11/2}$ proton and thus the band crossing of this $\pi h_{11/2}$ pair is blocked. In nonyrast side bands, however, this $\pi h_{11/2}$ pair alignment can still occur. The crossing frequencies for such side bands are of particular interest because of the influence of the odd proton on the nuclear shape and on the proton pairing gap Δ_p. In order to understand better the nuclear properties in this mass region, a study of the odd proton nucleus ^{133}Pr has been undertaken. With 59 protons and 74 neutrons, this nucleus is expected to have a prolate deformation but be soft with respect to γ deformations (see, e.g., Ref. 4). No level scheme has been reported for this nucleus, although the ground state is known to have a half-life $t_{1/2} = 6.5$ min (Ref. 5), and spin $I = \frac{5}{2}$ (Ref. 6). If a prolate deformation is assumed, the available Nilsson orbitals imply a positive parity for this state.[7] Similar studies in ^{131}Pr (Ref. 8) and ^{135}Pr (Ref. 9) have been initiated.

The ^{133}Pr nucleus was produced by the ^{118}Sn(^{19}F,4n) reaction. ^{19}F beams at energies of 72–104 MeV were provided by the Stony Brook Tandem-LINAC accelerator with a typical beam intensity of 1–3 pnA. Gamma-ray excitation functions, angular distributions, and pulsed-beam γ timing were measured using a BGO Compton suppressed Ge spectrometer. Timing information was also obtained from a small Ge detector with better time resolution at low energies. The γ-γ-t data were taken at a beam energy of 92 MeV using three γ-ray detectors of which one was Compton suppressed. Some examples of Compton suppressed gated spectra with background subtracted are shown in Fig. 1. Finally, conversion electrons have been measured with a mini-orange spectrometer.

The assignment of γ rays to ^{133}Pr is based on the excitation functions. Strong γ-ray lines of 310, 552, and 709 keV show a maximum intensity at the same beam energy as known transitions in ^{133}Ce,[10] the p3n channel. It is reasonable to assume that they come from the four-neutron evaporation channel. The K binding energies observed from the conversion electrons confirm their assignment to ^{133}Pr. From the γ-γ coincidence data, a level scheme was constructed as shown in Fig. 2. The ordering of the γ rays is based on coincidence relationships, γ-ray intensities, and systematic properties. Dashed transitions indicate those transitions that are seen only when adding several gated spectra within the same band. The spin and parity assignments are based on the angular distribution and conversion coefficient data. Tentative assignments have been made for the weakest γ rays based on a rotational behavior and these are shown within parentheses. Besides the 130 keV level discussed below, no isomeric state has been found with $t_{1/2} > 5$ ns.

Two of the bands shown in Fig. 2 are found to decay to the same level, which is assumed to be the $\frac{5}{2}^+$ ground state. This establishes the spins and parities of the band

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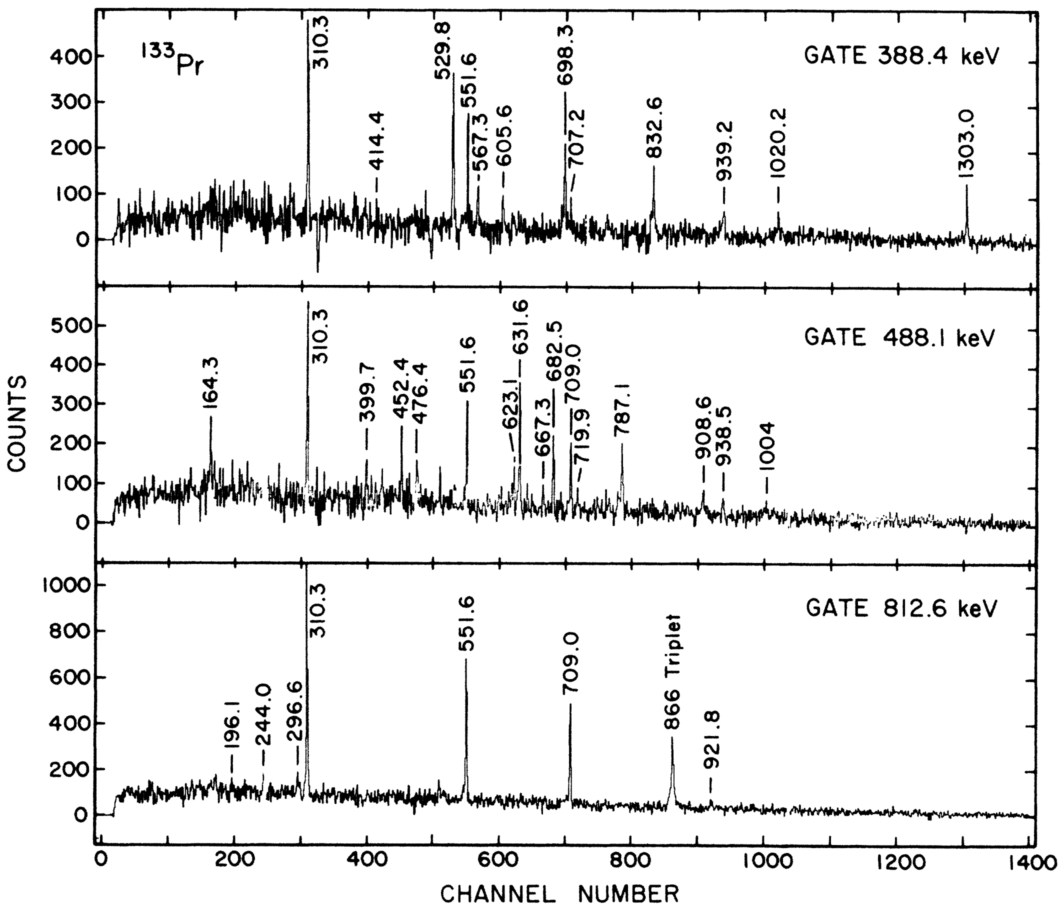

FIG. 1. Background subtracted γ-γ coincidence spectra gated on γ rays in the three $\Delta I = 2$ bands in ^{133}Pr.

members giving them the parity and signature quantum numbers $(\pi,\alpha) = (+,+)$ (far left in Fig. 2) and $(+,-)$. With the exception of the low spin part, no interband transition is observed between the two bands. The bands show crossings at spin $I = \frac{21}{2}$ and $\frac{19}{2}$, where the deexcitation branches and decays mainly to the yrast band.

The spin and parity assignments of the yrast band are established by the stretched 1303.0 keV and nonstretched $(\Delta I = 0)$ 682.5 keV dipole transitions from the two positive parity side bands. The conversion coefficient for the latter is compatible only with an $E1$ transition. This gives $I^\pi = \frac{11}{2}^-$ for the band head at 130 keV which probably is an isomer. The expected $E3$ transition of 130 keV to the ground state does not appear in any coincidence spectra. Although the conversion coefficient at this energy is high $(\alpha \approx 9)$, this sets a lower limit for the lifetime $t_{1/2} \geq 1$ μs from the coincidence resolving time. In the singles γ-ray spectra, a transition of 130 keV is observed, but this energy is also associated with another cascade in a different nucleus.

It is convenient, when discussing the properties of the ^{133}Pr nucleus to transform the energies and spins of Fig. 2 to intrinsic variables. This has been done using the prescription given in Ref. 11; the resulting quasiparticle energies (Routhians) and aligned angular momenta are plotted in Fig. 3. The reference configuration is given by using the Harris formula for the moment of inertia[12] with $\mathscr{I}_0 = 13.2$ MeV$^{-1}\hbar^2$ and $\mathscr{I}_1 = 40.3$ MeV$^{-3}\hbar^4$. These parameters have been extracted from ^{132}Ce for states above the backbend $I = 16 - 26$ in the yrast cascade.[13,14]

The two positive parity bands show a similar behavior with a small alignment ($i_x \lesssim 1.5\hbar$) at low rotational frequencies, a band crossing at $\hbar\omega_c = 0.27$ MeV and, above the band crossing, a constant alignment of $i_x \approx 9.5\hbar$. This common behavior suggests that they are the two different signatures of the same proton configuration. The small alignment at low spin and the small energy splitting are indicators of a strongly coupled particle. When considering the Nilsson orbitals for 59 protons at a deformation $\epsilon_2 \approx 0.2$,[7] the obvious choice is the $g_{7/2}$ proton orbital $\frac{5}{2}^+[413]$ for the band head. The crossing frequency $\hbar\omega_c = 0.27$ MeV and the gain in the alignment $\Delta i_x \approx 8\hbar$ are close to those observed in the Ce isotopes.[3,13-16] Consequently, the crossing is interpreted as the decoupling and alignment of a $h_{11/2}$ proton pair.

The negative parity band shows a constant alignment $i_x \approx 4.5\hbar$ for $\hbar\omega \leq 0.4$ MeV, consistent only with a band based on a decoupled $h_{11/2}$ proton. Blocking arguments explain why this band does not show a crossing at low rotational frequencies. The up-bend at $\hbar\omega = 0.43$ MeV is only present in the negative parity band, showing that it is due to protons, probably the alignment of the second and third $h_{11/2}$ protons. Because the two positive parity bands already have two decoupled $h_{11/2}$ protons at high spin, blocking effects explain why the up-bend is not seen in these bands. A similar up-bend has been observed in the decoupled $h_{11/2}$

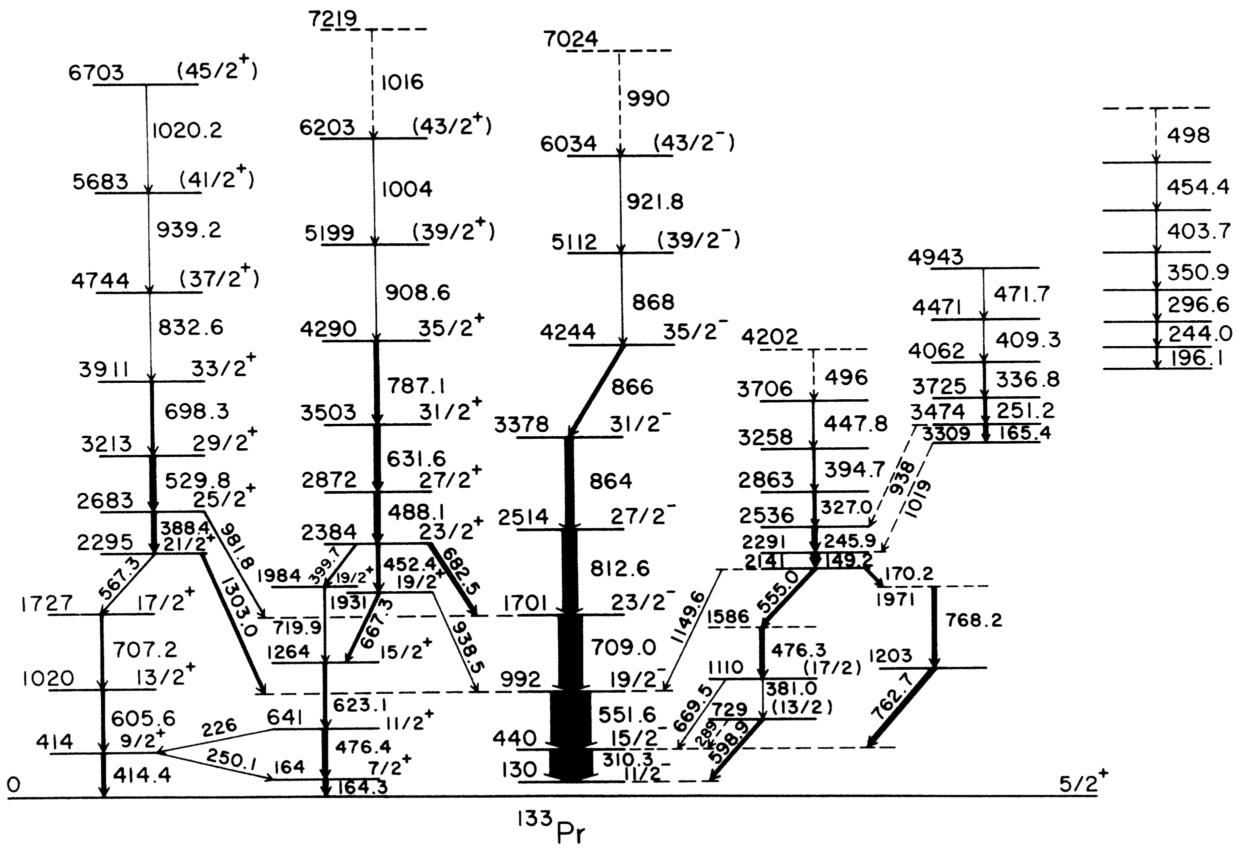

FIG. 2. Proposed level scheme for ^{133}Pr. The energies listed are in keV.

proton bands in ^{131}Pr (Ref. 8) and ^{135}Pr (Ref. 9).

A calculation has been performed within the cranked shell model (CSM) for comparison with the experimental results. The deformation parameters used are $\epsilon_2=0.2$, $\epsilon_4=0.0$, and $\gamma=0°$; the proton and neutron pairing gap $\Delta_p=\Delta_n=1.2$ MeV; and the chemical potential has been chosen to reproduce the particle numbers $Z=59$ and $N=74$. The calculations predict a band crossing at $\hbar\omega=0.29$ MeV due to the alignment of $h_{11/2}\frac{3}{2}^-[541]$ protons. This crossing frequency is not strongly sensitive to changes in the deformation ϵ_2 and γ. A second band crossing is predicted at $\hbar\omega=0.45$ MeV for the decoupling of the second and third $h_{11/2}$ protons. The predicted crossing frequencies are close to those experimentally observed, respectively, in the side bands and yrast band, and give an additional confirmation of the band structures. The calculated positive parity proton orbitals do not show any crossing below $\hbar\omega=0.50$ MeV. The first neutron backbend is predicted at $\hbar\omega=0.46$ MeV for $h_{11/2}$ neutrons.

The crossing frequency $\hbar\omega_c=0.27$ MeV in the positive parity bands is the lowest observed in this mass region and is well below that of the even-even core ^{132}Ce ($\hbar\omega_c=0.34$ MeV).[13,14] A possible mechanism explaining the low value of $\hbar\omega_c$ is a reduction in the proton pairing gap Δ_p caused by the odd proton. The effect is known in rare earth nuclei where an odd neutron decreases the crossing frequency for the $\nu i_{13/2}$ pair with $\Delta\hbar\omega_c\leq 50$ keV.[17] This reduction depends on the odd neutron orbital and is found to increase with its quadrupole moment $q_2(\nu)$. For large negative $q_2(\nu)$, no reduction in $\hbar\omega_c$ is observed. If a similar behavior is true for the protons in this region, the reduction in Δ_p for ^{133}Pr should only be moderate since the quadrupole moment of the $\pi g_{7/2}\frac{5}{2}^+[413]$ orbital is close to zero.

The higher crossing frequency in ^{132}Ce can be partially explained by the γ instability of the ground state band (GSB). The two decoupled $h_{11/2}$ protons in the superband tend to stabilize the shape around $\gamma=0°$,[18] while the GSB is more soft with respect to γ deformations and is able to gain energy by changing its deformation shape. This will give a small increase in the crossing frequency. It is therefore expected that the crossing frequency would be lower in ^{133}Pr, where the similar signature splitting above and below the band crossing indicates a constant γ deformation close to 0°. The effect of deformation changes has also been investigated in ^{129}Ce (Ref. 16) where a shift of $\Delta\hbar\omega_c\sim 25$ keV has been observed between bands having $\gamma\sim -30°$ and $\gamma\sim 0°$ below the band crossing and $\gamma\sim 0°$ above for both bands.

In summary, three $\Delta I=2$ rotational bands have been found in ^{133}Pr. The yrast negative parity band is a decoupled $h_{11/2}$ proton band; the $\frac{11}{2}^-$ band head at 130 keV is an isomeric state. The band shows an up-bend at $\hbar\omega_c=0.43$ MeV when two additional $h_{11/2}$ protons align. The two positive parity side bands with different signatures are based on the $\pi g_{7/2}\frac{5}{2}^+[413]$ ground state. At $\hbar\omega_c=0.27$ MeV, they are crossed by three quasiparticle bands where two $h_{11/2}$ protons align. The relatively large reduction by 70 keV for the crossing frequency in ^{133}Pr compared to ^{132}Ce is probably caused by both a reduction in the proton pairing gap and a shape change. A systematic study of the crossing frequencies in odd proton nuclei is needed to get more quantitative information on the pairing reduction.

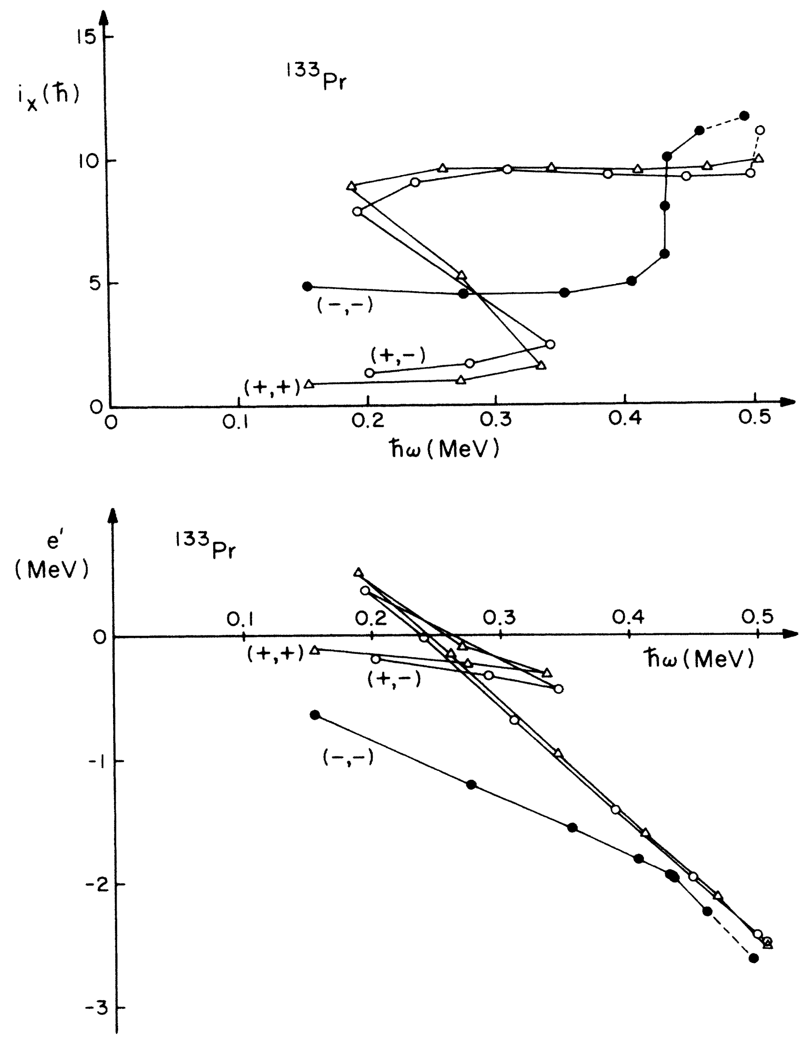

FIG. 3. Aligned angular momentum i_x and energy (Routhian) in the rotational frame vs rotational frequency for the three bands in ^{133}Pr with parity and signature quantum numbers (π, α).

This work was supported in part by the National Science Foundation.

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