PHYSICAL REVIEW C, VOLUME 63, 061304(R)

Observation of chiral doublet bands in odd-odd $N=73$ isotones

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(Received 17 January 2001; published 3 May 2001)

Three odd-odd $N=73$ isotones, namely ^{128}Cs, ^{130}La, and ^{132}Pr, have been studied via (HI, $xn\gamma$) reactions. In all three cases, $\Delta I=1$ side bands of the $\pi h_{11/2}\nu h_{11/2}$ yrast bands were discovered. This extends the systematic observation of nearly degenerate $\pi h_{11/2}\nu h_{11/2}$ doublet bands in the neighboring $N=75$ isotones; these were interpreted as resulting from chiral symmetry breaking in the intrinsic body-fixed frame.

DOI: 10.1103/PhysRevC.63.061304 PACS number(s): 21.10.Re, 23.20.Lv, 23.90.+w, 27.60.+j

The observation of nearly degenerate doublet $\Delta I=1$ bands in ^{134}Pr and the surrounding triaxial $N=75$ odd-odd isotones, ^{130}Cs, ^{132}La, and ^{136}Pm, has been interpreted as the result of the existence of chirality in the intrinsic body-fixed frame leading to a doubling of states for the $\pi h_{11/2}\nu h_{11/2}$ yrast configuration [1,2]. In these triaxial nuclei, left- and right-handed chiral geometries in the body-fixed frame can be formed from the mutually perpendicular angular momenta of the $h_{11/2}$ particles and the core rotation. Since the Fermi level for these nuclei is located in the lower part of the $\pi h_{11/2}$ subshell but in the upper part of the $\nu h_{11/2}$ subshell, the $\pi h_{11/2}$ and the $\nu h_{11/2}$ angular momenta are aligned along the short and long axes of the triaxial core, respectively; this maximizes the overlap of the valence particle wave functions and the core and thus minimizes the interaction energy. Likewise, the angular momentum of the rotational core is oriented along the intermediate axis because the moment of inertia is the largest along this axis for irrotational-like flow, which minimizes the rotational energy. Chirality thus attained in the body-fixed frame leads to a doubling of states, which manifests in the laboratory frame as degenerate doublet bands. It should be noted, however, that the doublet bands do not represent pure right- or left-handed states, but rather combinations of the two which restore the chiral symmetry that is broken in the intrinsic frame. These chiral effects are dependent on the triaxial shape of the nucleus and a delicate balance of the three angular momenta involved. In fact, the observation of chiral properties represents the first direct evidence for stable triaxial shapes in nuclei.

As suggested in Ref. [2], it is important to explore the extent of these nuclear conditions for chirality to further pursue a complete understanding of this novel phenomenon, including related effects such as collective chiral vibrations representing a weaker symmetry breaking. For this purpose, experiments have been performed in the odd-odd $N=73$ isotones, ^{128}Cs, ^{130}La, and ^{132}Pr, where the $\pi h_{11/2}\nu h_{11/2}$ bands are still yrast. (The spin/parity assignments for the yrast band in ^{130}Cs [3] are based on electron conversion and angular distribution measurements for a series of transitions connecting the yrast band to the $T_{1/2}=3.46$ min 5^- isomeric state, which was rigorously assigned on the basis of atomic-beam magnetic resonance [4] and β-decay measurements [5]. Systematic trends of the yrast bands in $A\sim130$ odd-odd nuclei [6] imply that these bands are built on the same positive-parity configuration, $\pi h_{11/2}\nu h_{11/2}$.) An isomer at the bandhead in ^{128}Cs allows for a particularly sensitive examination of possible chiral effects by the use of isomer delayed tagging. In all three cases, $\Delta I=1$ side bands were observed achieving similar doublet-band characteristics as previously seen for the $N=75$ isotones. This Rapid Communication presents the new $N=73$ results which reveal an extension of the $N=75$ region of nuclear chirality.

Excited states in ^{128}Cs, ^{130}La, and ^{132}Pr have been populated via the ^{122}Sn(^{10}B, $4n$) fusion evaporation reaction at 47 MeV, ^{124}Te(^{10}B, $4n$) at 51 MeV, and ^{117}Sn(^{19}F, $4n$) at 88 MeV, respectively. The targets of ^{122}Sn, ^{124}Te, and ^{117}Sn were 3.0, 2.2, and 3.6 mg/cm^2 thick, respectively, each with lead backing sufficient to stop the recoils in order to reduce Doppler broadening of the low-energy γ rays of interest. The FN-tandem injected superconducting LINAC at Stony Brook provided pulsed beams with a period of 106 ns. A Compton-suppressed HPGe detector array with detectors positioned at $\sim\pm30°$, $\pm90°$, and $\pm150°$ relative to the beam axis was used in conjunction with a 14-element BGO multiplicity filter. A total of $\sim5.2\times10^7$, 5.1×10^7, and 1.31×10^8 time-gated prompt γ-γ events were collected for the ^{128}Cs, ^{130}La, and ^{132}Pr experiments, respectively. A pulsed beam-γ time resolution of FWHM$\sim$10 ns was maintained over the accepted γ-ray energy range. The energy resolution for these events was FWHM$\sim$2 keV at $\sim$550 keV.

Positive-parity side bands are newly identified from the present studies in the ^{128}Cs and ^{130}La isotones; these side bands are shown in the partial level schemes in Fig. 1 along with the corresponding $\pi h_{11/2}\nu h_{11/2}$ yrast bands. Previous information was available on the yrast bands for these nuclei [7,8]. A less well-developed side band was observed in ^{132}Pr, as shown. Most of these ^{132}Pr transitions were reported in previous works [9,10] without interpretation. As in the case for the $N=75$ isotones, angular correlation analyses along with timing information uniquely determined that the linking transitions between the side and yrast bands are of $\Delta I=1$ mixed $M1/E2$ character. This leads to the current relative-spin assignments as indicated in Fig. 1 and positive parity for the side bands. The presentation of the level schemes with a common bandhead spin of I is the same as that used in Ref. [2], where also only relative-spin assign-

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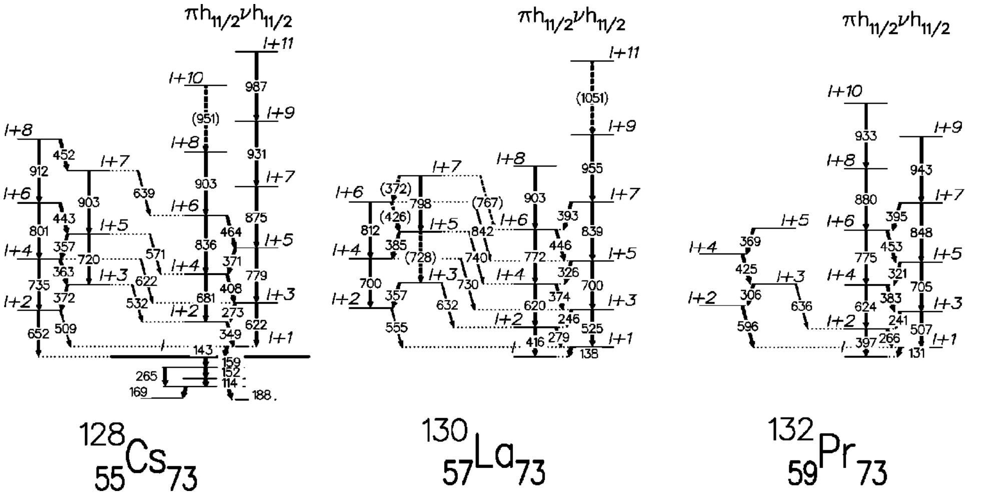

FIG. 1. Partial level schemes deduced from the present study for the $N=73$ isotones ^{128}Cs, ^{130}La, and ^{132}Pr are presented in the format adopted from Ref. [2]. For each isotone, the side band is placed on the left of the $\pi h_{11/2}\nu h_{11/2}$ yrast band.

ments were made; the systematic band properties as shown are remarkably similar. Considering all of the $N=73$ and 75 isotones, the best consistent choice for the absolute bandhead spin is $I=9$ [6]. As pointed out in Ref. [2], information on the relative spins is sufficient for the discussion of chiral properties.

Of the nuclei investigated so far regarding chiral doublets in the $A\sim130$ region, ^{128}Cs is a unique case in that both bands decay mainly through the isomeric state labeled spin I, indicated by the thick horizontal line in Fig. 1. Several transitions below the bandhead were included in the partial level scheme of ^{128}Cs to show the γ rays used for the isomer delayed tagging. The earlier work [7] had observed this 50-ns isomer in ^{128}Cs, but with the 143-keV transition placed below the isomer. In the current experiment, the 143-keV γ ray was observed to be in strong coincidence with the prompt in-band γ rays above the isomer, but very weakly with the delayed γ rays below the isomer. These observations, therefore, define the 143-keV γ ray as the bottom transition of the yrast band. Delayed tagging on the γ rays below the isomer reduces the background and enhances both the side-band and the yrast-band transitions as well as the linking transitions as shown by the spectrum in Fig. 2. The present ^{128}Cs level scheme shown in Fig. 1, along with those of the other $N=73$ isotones, is consistent with the systematic pattern of the $\pi h_{11/2}\nu h_{11/2}$ doublet bands for the $N=75$ odd-odd nuclei. This isomer delayed tagging technique could prove to be advantageous for future experiments involving detailed studies of the doublet-band transition strengths.

The observed side bands in the $N=73$ isotones share common characteristics with those in the $N=75$ isotones. Figure 3 is a plot of the experimental excitation energies versus spin showing near degeneracy for the side bands and the yrast bands. In all three $N=73$ cases, the side-band curve (open symbols) is displaced slightly higher in energy above the yrast curve (closed symbols). The amount of displacement, hence the deviation from degeneracy, is approximately 200 keV for ^{128}Cs and 400 keV for ^{130}La and ^{132}Pr. These doublet bands never achieve equal energies at any of the observed spins unlike the case of the ^{134}Pr nucleus. All of the side bands are linked with the yrast bands via mixed $M1/E2$ transitions. As argued in Ref. [2], the $\pi h_{11/2}\nu h_{11/2}$ configuration is the only reasonable basis for these side bands. Since the yrast-band $\pi h_{11/2}\nu h_{11/2}$ configuration is comprised of two unique-parity single-particle orbitals (for nuclei between the 50 and 82 proton and neutron closed shells), other possible low-lying positive-parity configurations representing the side bands would necessarily involve positive-parity orbitals (such as $d_{5/2}$ and $g_{7/2}$) for both the valence proton and neutron. No transitions of $M1/E2$ multipolarity, however, would then be allowed between such a band and the yrast band since one-body electromagnetic operators do not have transition matrix elements involving a change of two particles. Thus, as in Ref. [2], this near degeneracy of the doublet bands is attributed to the doubling of states for the $\pi h_{11/2}\nu h_{11/2}$ configuration because of the mutually perpendicular orientation in the body-fixed frame of the angular momenta of the two valence particles and the core rotation, which results in the chiral symmetry breaking.

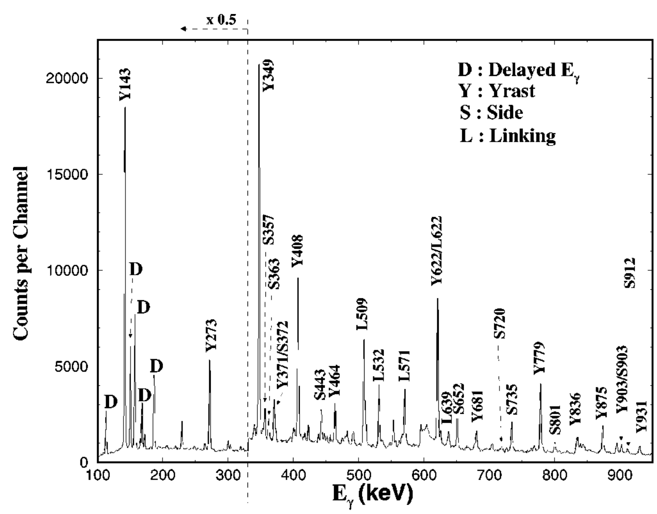

FIG. 2. A γ-ray spectrum for ^{128}Cs obtained by tagging on delayed transitions, which are labeled as D, below the isomer. The numbers correspond to energies in keV and are preceded by Y, S, and L for transitions in the yrast band, the side band, and those linking the two bands, respectively. Counts per channel have been scaled down by a factor of 2 for energies to the left of the dashed line.

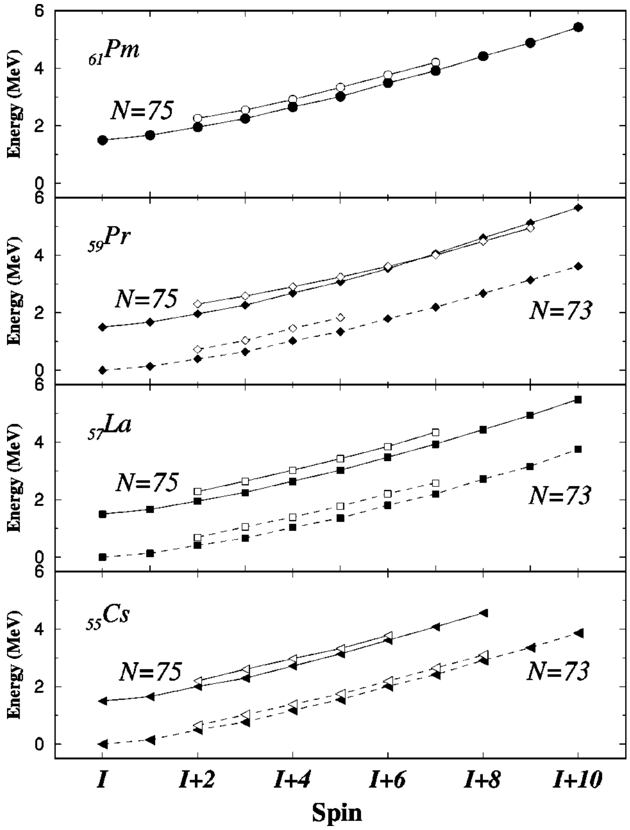

FIG. 3. Experimental excitation energy versus spin plot. Curves with closed (open) symbols connected by dashed lines are of the yrast (side) bands in the $N=73$ isotones. Similar curves with solid lines, representing the four $N=75$ isotones from Ref. [2], are plotted 1.5 MeV above the reference energy of the corresponding isotopes.

Among the $N=73$ isotones, ^{128}Cs reveals doublet bands closest to degeneracy. Reference [2] attributes the small energy displacements between the doublet bands to a collective chiral vibration; collective chiral vibrations in relation to chiral symmetry breaking would be analogous to collective octupole vibrations in relation to parity symmetry breaking.

The extended $N=73$ and 75 systematics of the observed doublet bands with near degeneracy further support their common physical origin as the breaking of chiral symmetry in the body-fixed frame. Since the rotational angular momentum changes gradually with spin, the chiral geometry and the degree of the associated symmetry breaking can change with spin; this gives a reasonable explanation for the energies of the doublet band members in ^{134}Pr approaching each other with increasing spin and achieving degeneracy for a small range of spin starting at $(I+6)$, as shown in Fig. 3. A gradual transition from weaker to stronger chiral symmetry breaking seems to evolve with increasing spin in ^{134}Pr. In the odd-odd nuclei surrounding ^{134}Pr, the symmetry appears to remain moderately broken, as suggested by the small energy displacements as a function of the observed spin.

While experimental studies of doublet bands continue, the present experimental results require further theoretical investigation to address quantitatively these interesting chiral-symmetry properties. Currently two theoretical approaches have been used to address these experimental results. Microscopic three-dimensional tilted axis cranking (3D TAC) calculations [1], based in a body-fixed rotational frame, have been successful in elucidating the microscopic origin of the chiral-symmetry breaking in these nuclei. In this model, the orientation of the total angular momentum **J**, characterized by the tilting angles θ and φ, can be calculated self-consistently. Aplanar chiral solutions, in which the total angular momentum **J** tilts away from all three principal axes with both θ and φ differing substantially from 0° and 90°, were found for the $\pi h_{11/2}\nu h_{11/2}$ configuration in ^{134}Pr [1] for a range of frequencies ω. The calculations showed that the nucleus was triaxial with γ near 30° and that the core rotational vector was aligned along either the $\pm$ intermediate axis, representing the right- and left-handed geometries. These solutions imply chiral symmetry breaking in the intrinsic frame and achieve the doubling of states in the transformation to the laboratory frame where the symmetry has to be restored. Subsequently, the same 3D TAC approach was applied to all of the $N=75$ odd-odd isotones ($Z=55$–63) of ^{134}Pr where doublet bands were observed; results of these calculations were reported in Ref. [2]. In all five isotones, chiral solutions were found over a limited range in ω with a triaxial deformation $\gamma\sim 30°$. Indicative of the strength of chiral symmetry breaking is the energy difference between the Routhian minima and the lowest saddle point at $\varphi=0°$ denoted as E_b in Ref. [2]. A large E_b confines **J** to one of the minima (or the rotational angular momentum to the $\pm$ intermediate axes) corresponding to either the right- or left-handed solution; this would lead to strong chiral symmetry breaking and achieve energy degeneracy for the doublet bands. A small E_b, on the other hand, would not completely constrain **J** to one of these minima, leading to weaker symmetry breaking and an energy displacement between the doublet bands; this was discussed in Ref. [2] in terms of collective chiral vibrations. The trend of the calculated E_b agrees qualitatively with the observed energy displacements in the $N=75$ isotones; the largest E_b was obtained for ^{134}Pr at $\omega\sim 350$ keV/$\hbar$ in comparison to all the other isotones as a function of frequency. Such calculations have not been performed for comparison to the current $N=73$ isotone results, although experimentally they are similar to the $N=75$ results.

The second approach, a phenomenological particle-hole plus core coupling model employs weak coupling between the valence particle/hole and the core; basis states $|\mathbf{j}_\pi\times\mathbf{j}_\nu\rangle_{LM}\times|\mathbf{R}\rangle$ are used to diagonalize the Hamiltonian that includes a triaxial core, a single-particle Hamiltonian, and quadrupole-quadrupole interactions, where $\mathbf{j}_\pi$, $\mathbf{j}_\nu$, and **R** are the angular momenta of the valence proton, the valence neutron, and the core, respectively [11]. This approach is carried out in the laboratory frame where the Hamiltonian requires restored chiral symmetry. Calculated observables such as excitation energy, total spin, and branching ratios can be directly compared to experimental values, although the core properties have to be externally provided. Calculations using a rigid triaxial core with $\gamma\sim 30°$ [11] yield degenerate doublet bands consistent with the microscopic 3D TAC calculations discussed above; expectation values of the orientation of the angular momenta obtained with these wave functions agree with the aplanar chiral geometry. Theoretical studies using γ-soft triaxial cores have revealed deviations from degeneracy for the doublet bands [12]. A reduced moment of inertia along the intermediate axis from γ softness has been suggested as a possible mechanism for the rotational angular momentum not being completely constrained to the intermediate axis, thereby mixing the right- and left-handed chiral systems and resulting in a weaker symmetry breaking [2]. It should be stressed that the observed systematics cannot properly be explained by principal axis cranking. Reference [2] rules out quasiparticle excitations for the side bands in the $N=75$ isotones, as well as γ vibrations coupled to the yrast band; expected energy differences between the yrast and the side bands from these alternative interpretations are more than twice the experimental values.

In conclusion, the experimental results for three $N=73$ isotones are presented as an extension of the earlier investigation of chirality in the $N=75$ isotones. In all three cases, a $\Delta I=1$ side band with the same $\pi h_{11/2}\nu h_{11/2}$ configuration as the yrast band was identified. The ^{128}Cs isotone appears especially promising for future experimental studies on the doublet bands because of the isomer feeding. The small energy displacements of the side band from the yrast band imply the existence of chiral symmetry breaking in the $N=73$ isotones, extending the $N=75$ region surrounding ^{134}Pr where near degenerate doublet bands were interpreted as collective chiral vibrations. Further exploration is important for the complete definition of the Z,N boundaries of this region of chirality.

This work was supported by U.S. NSF Grant No. PHY9870280. The authors acknowledge helpful theoretical discussions with Dr. Jing-ye Zhang.

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