RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 44, NUMBER 2 AUGUST 1991

Band termination in ^{121}I

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(Received 8 March 1991)

The rotational band in ^{121}I that initiates on the $\pi h_{11/2}[550]\frac{1}{2}^-$ orbital was observed to terminate via coincidence γ-ray studies following the ^{114}Cd(^{11}B,4n) reaction. The band termination occurred at $I^\pi=\frac{39}{2}^-$. Total-Routhian surface calculations reveal an yrast noncollective oblate state ($\gamma=+60°$) at $\hbar\omega=0.36$ MeV which consists of an aligned $\pi h_{11/2}(\pi g_{7/2})^2(\nu h_{11/2})^2$ configuration with $I^\pi=\frac{39}{2}^-$; this shape change from collective prolate to noncollective oblate provides an explanation for the observed band termination.

The nucleus as a unique many-body system possesses a rich variety of quantum-mechanical excitations. The competition and resulting balance between the single-particle and the collective degrees of freedom are important factors in the determination of the nuclear structure. The single-particle structure that exists for spherical nuclei near closed shells gives way to more collective rotational structure for deformed nuclei that have a large number of valence nucleons outside closed shells. As the rotational frequency and spin increases for such deformed nuclei, the Coriolis force leads to the breaking and aligning of individual pairs of these valence nucleons. Aligned high-spin particles, which contribute substantially to the total spin of the nucleus, have an oblate density distribution with respect to the rotational axis, if the Fermi surface is near the bottom of the respective subshells. The additional valence particles tend to produce triaxial softness and eventually with a sufficient number of aligned particles, the short-range force polarizes the nuclear shape to that of an oblate single-particle topology. The collective prolate nucleus can thus be driven as the spin increases to an oblate noncollective shape around the rotational axis achieving termination of the rotational band, provided the total spin of the valence-particle state can be experimentally populated. Because of favorable oblate shell effects, this noncollective terminating state can achieve its angular momentum in a more energy efficient way than collective rotation, namely it becomes yrast. In addition, the noncollective structure of terminating states would imply single-particle transition strengths rather than the collective $E2$ enhancements observed in collective rotational bands.

Such termination effects have been observed in low-mass nuclei, for example ^{20}Ne [1]. Similar phenomena were predicted [2,3] to occur in rare-earth nuclei with only a small number of particles outside of the closed ^{146}Gd core; they have recently been observed near spin $I=40$ for nuclei with 10–12 aligned valence nucleons [4]. Predictions for similar band termination in the $A=120$–130 mass region have been made [3], where ^{124}Ba was expected to be a favored case. Experimental investigations in ^{124}Ba up to spin $I=36$, however, did not show any evidence for terminating states [5]. It has been recently suggested [6] that nuclei around ^{122}Xe are more favorable for the observation of terminating states; they are predicted to compete with the collective structures near a spin $I=24$. Preliminary interpretations of very recent experiments in ^{118}Xe and ^{122}Xe suggest the possible observation of band termination in these even-even nuclei [7]. The present experiment involving ^{121}I shows the first evidence in odd-proton nuclei in the $A=120$–130 mass region for band termination resulting from noncollective oblate structure. Information on noncollective high-spin states in this mass region is of importance for determining the position of single-particle states in the $N=4$ shell, about which little is known at present. These noncollective states represent a test of theory such as the cranked Woods-Saxon calculations for which noncollective and collective excitations are treated on the same footing. In the case of ^{121}I, the configuration is rather limited with only three protons outside the closed $Z=50$ shell and four neutrons outside the semiclosed $N=64$ shell; however, band termination usually requires the nucleus to be near at least one closed shell.

The present study of the ^{121}I nucleus employed the ^{114}Cd(^{11}B,4n) fusion-evaporation reaction at a bombarding energy of 51 MeV; an earlier Stony Brook experiment [8], had identified the low-energy band structure. The target consisted of 5.3 mg/cm^2 of isotopically enriched ^{114}Cd rolled onto a lead backing of 30 mg/cm^2 thickness, which stopped the recoiling nuclei and the beam. The γ rays were studied with an array of five BGO suppressed Ge detectors and a BGO multiplicity filter. The multiplicity filter consisted of fourteen hexagonal BGO crystals covering a solid angle in excess of 80% of 4π; seven closely packed crystals were positioned above the target chamber and seven below. For the γ-γ coincidence data, two or more BGO multiplicity signals were required in coincidence with two or more Ge detectors, which greatly reduced radioactivity and Coulomb-excitation events. With this requirement, approximately 56×10^6 coincidence events were obtained, from which the level scheme for the ^{121}I nucleus was constructed. Directional correlation

(DCO) ratios were also extracted [9] from these coincidence results (stretched quadrupoles have DCO ratios of ~ 1.0 and stretched dipoles ≤ 0.7). In addition, γ-ray angular distributions were measured at five angles with a target-detector distance of 22 cm. These results allowed the extraction of multipolarity and $E2/M1$ mixing ratio information for the γ-ray transitions. The set of measurements resulted in the observation of seven band structures in ^{121}I; a complete presentation of the results is being prepared. For the present focus on band termination, only the yrast band sequence is shown in Fig. 1.

The yrast cascade, which initiates on the $\frac{11}{2}^-$ ($\pi h_{11/2}[550]\,\frac{1}{2}^-$) decoupled state, has been extended up to a spin of $\frac{45}{2}$. The energy levels have been determined by the γ-ray coincidence relationships and relative intensities. For spins $I \leq \frac{27}{2}^-$, a collective rotation pattern was clearly observed. The extracted DCO ratios (~ 1.0), and A_2/A_0 ($\sim +0.4$) and A_4/A_0 (~ -0.1) angular distribution coefficients are consistent with these stretched quadrupole assignments. A variation in the rotational sequence occurs for $\frac{31}{2}^-$ and $\frac{35}{2}^-$ suggesting the onset of valence-particle alignment, above which the 392-keV stretched quadrupole transition reveals a termination of the collective band. The transitions observed in coincidence above the $\frac{39}{2}^-$ state suggest a noncollective behavior. The 292- and 812-keV γ rays have A_2/A_0 values consistent with $\Delta I = 1$ transitions, the former being a pure dipole and the latter requiring a positive $E2/M1$ mixing ratio. The 688-keV transition has a stretched dipole DCO ratio, and the 1105-keV crossover has a DCO ratio that implies a stretched $E2$ transition. There are a number of other weak transitions feeding into the $\frac{39}{2}^-$ state, whose character is uncertain. The γ-ray coincidence spectrum gated by the 876-keV ($\frac{35}{2}^- \rightarrow \frac{31}{2}^-$) transition, which is displayed in Fig. 2, shows all the relevant γ rays.

The interpretation of these interesting results leads to arguments in favor of the rotational band terminating into a noncollective single particle state at $\gamma = +60°$. The $\frac{39}{2}^-$ state, which is yrast at 5433 keV, and levels observed above it, do not have the energy behavior consistent with collective rotation. To show these energy characteristics, the energy of the levels are plotted in Fig. 3 as a function of spin, with an average rigid-rotor energy subtracted. In addition, for the states above the $\frac{39}{2}^-$ state, the branching ratio and mixing ratio information are inconsistent with collective rotation and indicative of single-particle characteristics. From the discussion presented below, the $\frac{39}{2}^-$ terminating state is predicted by the total-Routhian surface (TRS) calculation in terms of a $\pi h_{11/2}(\pi g_{7/2})^2(\nu h_{11/2})^2$ aligned configuration being yrast at a $\gamma = +60°$ noncollective shape. The complete alignment of the four valence neutrons occurs at a higher energy.

Total Routhian surfaces have been calculated within the cranked Strutinsky-Bogolybov approach for the $A = 120$–130 mass region [10]. The calculations are based on the Woods-Saxon potential [11] with the short-range particle-particle interaction being approximated by a monopole pairing force. For low frequency, the $\pi h_{11/2}$ low-subshell configuration in the iodine isotopes favors a near-prolate deformation as shown in Fig. 4. This results in the $\Delta I = 2$ decoupled rotational band-structure observed experimentally in ^{121}I (see Fig. 1). Because the proton Fermi surface lies at the bottom of the $\pi h_{11/2}$ subshell, the favored signature of the rotationally aligned $h_{11/2}$ proton has a broad and deep energy minimum as a function of the γ-shape parameter from $\gamma = 0°$, a prolate shape, to near $\gamma = +60°$, an oblate density distribution relative to

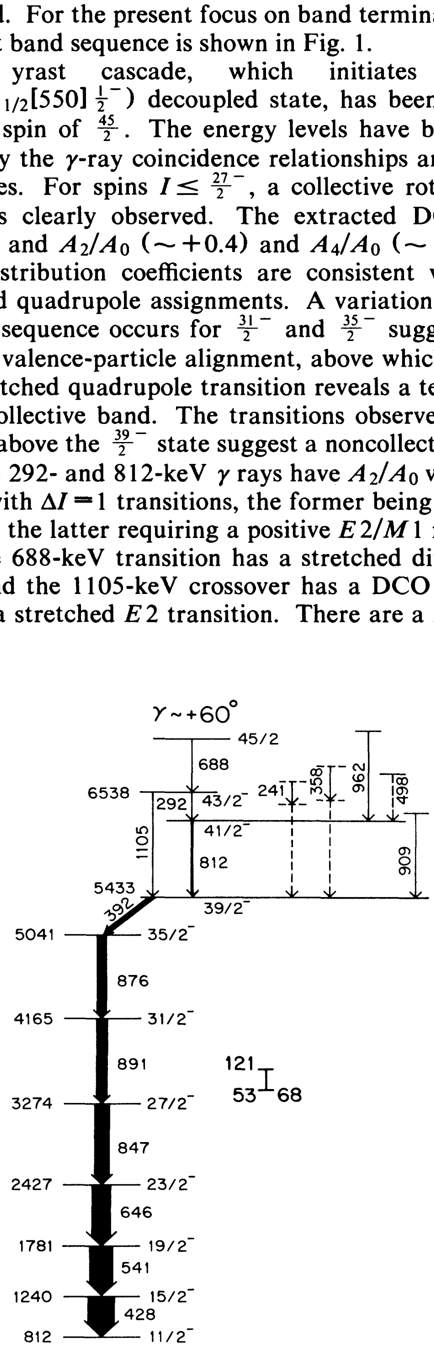

FIG. 1. The decay scheme of the yrast sequence in ^{121}I. The transition energies are given in keV and the widths of the arrows indicate their relative intensities. Excitation energies (in keV) are relative to the $\frac{5}{2}^+$ ground state (Ref. [8]).

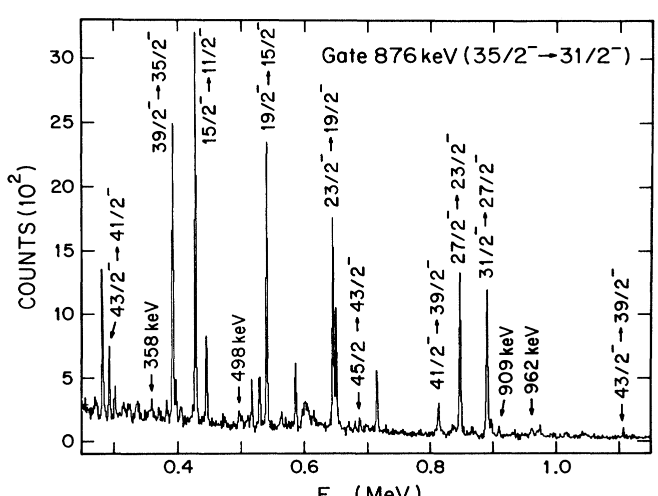

FIG. 2. A coincidence spectrum gated on the 876-keV ($\frac{35}{2}^- \rightarrow \frac{31}{2}^-$) transition. All relevant γ rays shown in Fig. 1 are labeled. Unlabeled γ rays correspond to transitions below the $\frac{11}{2}^-$ state.

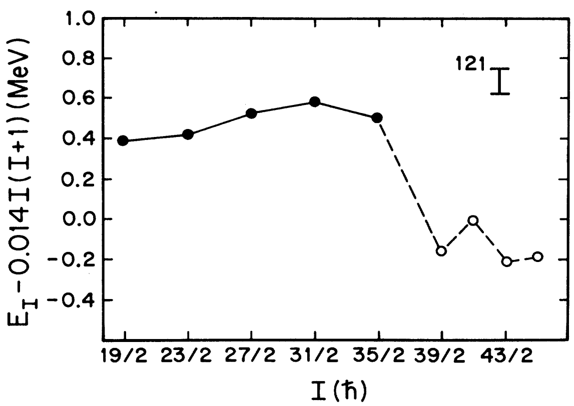

FIG. 3. Plot of observed level energies for states above $\frac{15}{2}^-$, with an average rigid-rotor energy subtracted. The dashed line follows the proposed single-particle states.

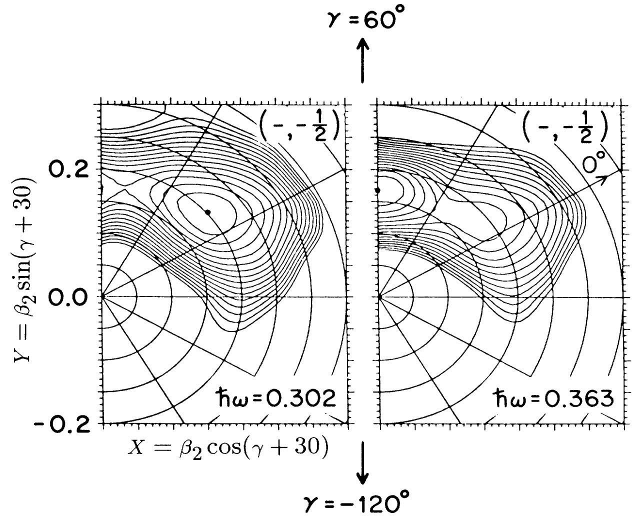

FIG. 4. TRS calculations for states of parity and signature, $(\pi,\alpha)=(-,-\frac{1}{2})$, showing the development of energy minima. The noncollective ($\gamma\sim+60°$) configuration becomes yrast at $\hbar\omega=0.36$ MeV ($I\sim21.0$), while at lower frequency $\hbar\omega=0.30$ MeV ($I\sim8.6$) the minimum corresponds to the near-prolate ($\gamma\sim+10°$) collective configuration.

the rotational axis; this minimum allows a shape change towards positive γ values. With increasing rotational frequency, the alignment of pairs of nucleons is expected. For the additional two protons outside the $Z=50$ closed shell, the aligned $(\pi g_{7/2})^2$ pair ($\pi g_{7/2}$ and $\pi d_{5/2}$ are mixed) has a low-lying potential energy surface with a similar γ dependence; an additional aligned $(\pi h_{11/2})^2$ pair occurs at higher frequency because of Pauli blocking. In the case of ^{121}I, the three protons outside the $Z=50$ closed shell together with neutron alignment results in yrast states involving a major shape change. This dramatic shape evolution is illustrated in Fig. 4 where at $\hbar\omega=0.36$ MeV another energy minimum has developed in the TRS. The minimum at $\gamma=+60°$ corresponds to a noncollective yrast state at $I^\pi=\frac{39}{2}^-$, i.e., single-particle excitation which is the lowest-frequency terminating state.

The TRS calculation shows that the microscopic proton structure consists of a fully aligned $\pi h_{11/2}(\pi g_{7/2})^2$ configuration coupled to $\frac{23}{2}^-$. For the three protons, this is the most favored noncollective configuration. For the four neutrons outside the semiclosed $N=64$ subshell, the calculation reveals for the $\gamma=+60°$ minimum shown in Fig. 4, a single aligned $(\nu h_{11/2})^2$ pair coupled to 8^+, which involves $\Omega=-\frac{9}{2}^-$ to $\Omega=+\frac{7}{2}^-$ promotion in the deformed mean field. This results in a total nuclear angular momentum $I^\pi=\frac{39}{2}^-$. A second possible terminating state from the calculations consists of $(\nu h_{11/2})^4$ maximally aligned to 16^+ giving a total angular momentum $I^\pi=\frac{55}{2}^-$. The predicted $\frac{39}{2}^-$ terminating state is consistent with the observed band termination in ^{121}I; the observed $\frac{43}{2}^-$ state at higher energy is perhaps related to a fully aligned neutron pair. The present experiment did not reach the second noncollective prediction at $I^\pi=\frac{55}{2}^-$.

This observed shape change involving band termination in ^{121}I seems to indicate subtle subshell effects in going from $Z=53$ to $Z=55$. No similar band termination was seen in $Z=55$ ^{123}Cs or other odd-Cs isotopes from recent Stony Brook experiments [12], although there are indications as mentioned in $Z=54$ ^{122}Xe and other Xe nuclei. Other odd-*I* nuclei have also been studied at Stony Brook [13]. An experiment in ^{119}I showed a similar noncollective state at $\frac{39}{2}^-$ as in ^{121}I; however, because this state was not yrast (the $\frac{39}{2}^-$ rotational state was 200-keV lower), the termination appeared to occur at $\frac{43}{2}^-$, consistent with a fully aligned neutron pair. Higher mass odd-*I* nuclei did not show terminations, which is perhaps related to the fact that these nuclei are less collective. The relatively low angular momentum of the terminating state in ^{121}I contrasts the higher-spin terminating states in the heavy rare-earth nuclei. These new experimental results provide opportunities for theoretical comparisons between, e.g., the shell model and the deformed mean field.

In summary, evidence is presented for the observation of a major shape change from a collective rotational structure to a noncollective band termination state at $\frac{39}{2}^-$ in ^{121}I in agreement with TRS calculations. The structure above this $\frac{39}{2}^-$ state indicates transitions of a single-particle character in accordance with this interpretation.

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