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First observation of a rotational band in odd $_{50}$Sn nuclei: ^{111}Sn

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Proton particle-hole excitations across the $Z=50$ closed shell are responsible for inducing low-lying prolate deformation in even-$_{50}$Sn nuclei. Although related rotational bands have been studied in odd-$_{51}$Sb isotopes involving the coupling of a valence proton, none had been found in odd-$_{50}$Sn nuclei. Using the ^{96}Ru(^{19}F,3pn) reaction, a decoupled band has been observed in ^{111}Sn extending to a spin-parity of (67/2$^-$) and feeding out at 23/2$^-$ into spherical states. This band is interpreted as the $\nu h_{11/2}$ valence orbital coupled to the deformed $[(\pi g_{7/2})^2\otimes(\pi g_{9/2})^{-2}]$ ^{110}Sn core. The extracted band properties are compared to those in ^{111}Sb with the same deformed core.

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Nuclei near the closed proton shell at $Z=50$ have recently been shown to possess a wealth of both spherical and deformed structures. Spherical states are to be expected considering the influence of the shell gap, as demonstrated by the ground-state positive parity level sequences of the even $_{50}$Sn nuclei and in particular the large 2$^+$ energies, which are remarkably uniform over a large range of neutron numbers [1]. Odd-$_{51}$Sb nuclei also possess a variety of spherical levels [2–4]. The states are composed of the valence proton, occupying the $\pi g_{7/2}$, $\pi d_{5/2}$, and $\pi h_{11/2}$ orbitals, coupled to spherical states of the neighboring Sn core nucleus.

Despite the strong influence of the shell gap, deformed states are known to exist in $Z=50$ Sn and $Z=51$ Sb nuclei. Proton particle-hole excitations across the $Z=50$ gap are responsible for low-lying deformed states, which result in collective rotational bands. In even-Sn nuclei, rotational bands based on a two-particle two-hole (2p2h) configuration, $(\pi g_{7/2})^2\otimes(\pi g_{9/2})^{-2}$, have been observed from ^{106}Sn to ^{118}Sn [5–9]. The slopes of these orbitals with respect to the quadrupole deformation parameter β_2 induce a deformation, which is regulated by the point at which these orbitals cross, at approximately $\beta_2=0.2$. In the case of ^{108}Sn, a rotational band initiating from such a deformed 2p2h configuration has been observed to a spin of 34$^+$ and to a rotational frequency exceeding 1 MeV/$\hbar$, which at the higher spins includes the alignment of the valence nucleons [6]. In odd-Sb nuclei from $A=109$ to 119, $\Delta I=2$ decoupled rotational bands have been observed, and attributed to a valence proton orbital coupled to this 2p2h state of the $A-1$ Sn core nucleus [2,4,10,11]. In ^{117}Sb, three such bands have been reported [2] with the valence proton occupying the $\pi d_{5/2}$, $\pi g_{7/2}$, and $\pi h_{11/2}$ orbitals coupled to the deformed 2p2h state of ^{116}Sn. Single proton excitations across the gap also show collectivity in the odd-Sb isotopes, namely, $\Delta I=1$ strongly coupled bands, based on the two-particle one-hole configuration, $(\pi g_{7/2})^2\otimes(\pi g_{9/2})^{-1}$, which induces the deformation. Such deformed one proton-hole states have shown their influence in $^{109-123}$Sb [3,11–13], and in I ($Z=53$) [14] and Cs ($Z=55$) [15] nuclei. Thus there is considerable information concerning rotational bands arising from a *proton* coupled to these deformed proton particle-hole excitations in the Sn cores. However, as yet nothing is known regarding the possibility of a *neutron* coupled to these deformed Sn states, and the effect of such a coupling on the deformed core. Previous experimental information on ^{111}Sn can be found in Ref. [16]. The purpose of this paper is to report the first observation of such deformed states in an odd-Sn nucleus, namely ^{111}Sn.

The reaction ^{96}Ru(^{19}F,3pn) was used to populate states in ^{111}Sn, using the FN tandem/LINAC facility at Stony Brook. Although the beam energy, 90 MeV, produced ^{111}Sb via the 2p2n channel, the 3pn channel populated ^{111}Sn with significant strength. The target consisted of a single foil of enriched ^{96}Ru, 540 μg/cm^2 thick, which was backed by 15 mg/cm^2 ^{208}Pb. The backing stopped the recoiling nuclei, eliminating the γ-ray Doppler broadening for all but the fastest transitions. Gamma rays were detected using the Stony Brook array, which consisted of six Compton-suppressed Ge detectors, and a 14-element BGO multiplicity filter. For this experiment it was required that $\geqslant 2$ Ge detectors and at least two BGO elements fired as an event trigger. The resulting coincidence data were then sorted into an $E_\gamma - E_\gamma$ matrix. A total of 157×10^6 events were recorded. Directional correla-

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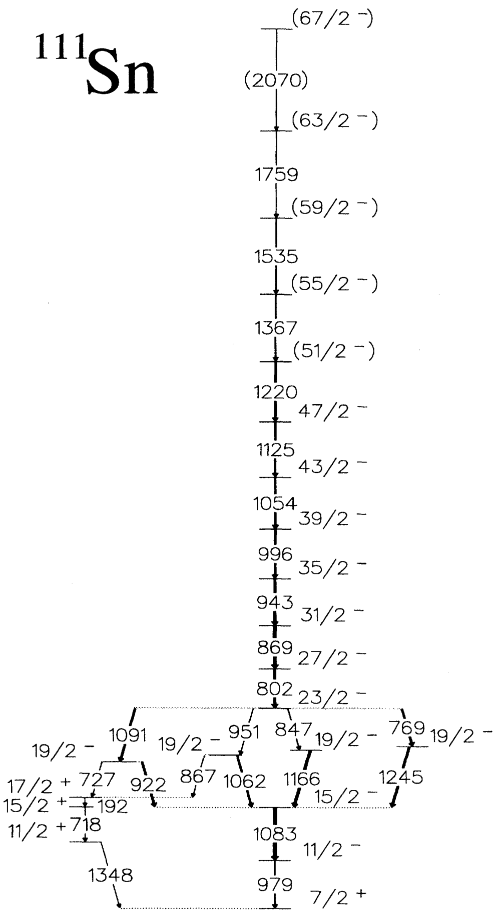

FIG. 1. The level scheme of ^{111}Sn extracted from this work. Gamma-ray energies are given in keV, and the widths of the arrows represent the relative intensities of the transitions.

tion (DCO) analysis [17] was also performed in order to determine the multipolarities of transitions in ^{111}Sn. DCO ratios were calibrated using known transitions; stretched quadrupole transitions had DCO ratios of 1.0, and pure stretched dipole transitions had DCO ratios of approximately 0.5, when gated by a stretched quadrupole transition.

Subsequently, the high-spin states in ^{111}Sn were extended via the ^{64}Ni(^{56}Fe,$\alpha p4n$) reaction using the Early Implementation (EI) of Gammasphere at Lawrence Berkeley Laboratory. The beam energy, 236 MeV, was selected to maximize the production of ^{115,116}Te; however, ^{111}Sn was populated with considerable intensity. Two thin self-supporting targets of 95% enriched ^{64}Ni, each 500 μg/cm^2 thick, were employed in this experiment. The Gammasphere (EI) array consisted of 36 Compton-suppressed large volume Ge detectors at the time of the experiment, with 30 detectors in a forward/backward ($\Delta\theta \leq 37°$) geometry and the remaining detectors at 90°. An event trigger of 3 suppressed Ge signals was required. The resulting 10^9 events were then sorted into an $E_\gamma - E_\gamma - E_\gamma$ cube for off-line analysis [18].

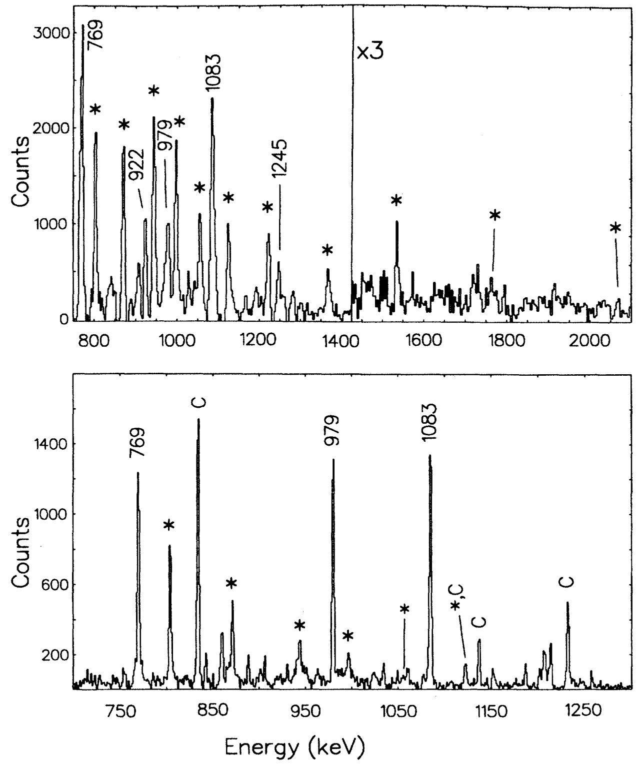

FIG. 2. Bottom: A coincidence spectrum from the backed-target data, gated by the 1246-keV transition, showing the rotational band uncovered in this study. Top: The high energy part of the rotational band, created by summing several double gates on the thin-target Gammasphere data. In both spectra, in-band transitions are labeled with an asterisk, transitions between normal deformed states in ^{111}Sn are labeled by their energy, and transitions in other nuclei are marked with the letter C.

The level scheme extracted from the coincidence data and DCO analysis is shown in Fig. 1. The new feature of this level scheme is the band shown in the center of the figure; a sequence of mutually coincident γ-ray transitions is observed, starting from the $I^\pi = 23/2^-$ state at 4076 keV. The backed-target Stony Brook experiment observed the sequence up to the 1125-keV γ ray, which depopulates the $I^\pi = 47/2^-$ state. The spins of these levels were determined from the extracted DCO ratios for the γ-ray transitions, which showed a stretched quadrupole character. The subsequent thin-target Gammasphere (EI) experiment extended the band to $I^\pi = 67/2^-$. A spectrum gated on the 1245-keV decay-out transition from the backed-target data is shown at the bottom of Fig. 2. The top spectrum of this figure, which was generated by adding several double gated spectra from the thin-target data, shows the high energy transitions of the band. The roughly constant energy spacings of the γ-ray transitions for at least the lower part of the band indicate a collective rotational structure. Values of the dynamic moment of inertia ($\mathcal{J}^{(2)}$) extracted from this band are shown in Fig. 3. At a rotational frequency of 0.48 MeV, the $\mathcal{J}^{(2)}$ shows a quasiparticle alignment, above which only a slow decrease is observed as the γ-ray energy spacings increase.

The negative parity assigned to the rotational band in the present work suggests the occupation of the $h_{11/2}$ orbital by the valence neutron. The $\nu h_{11/2}$ orbital alone does not have the shape-driving ability to deform the rigid ^{110}Sn core. This

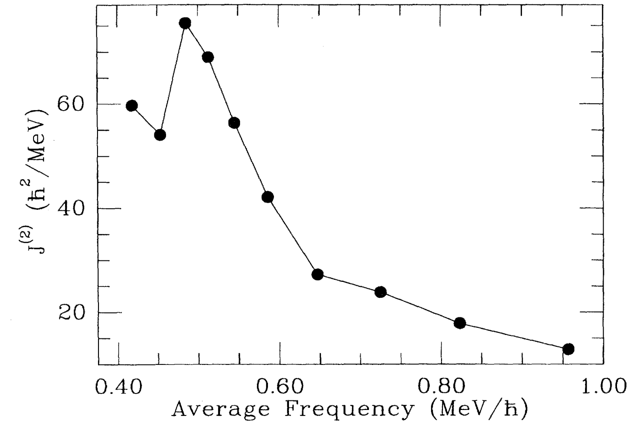

FIG. 3. A plot of the dynamic moment of inertia extracted from the band in ^{111}Sn.

is evident from the noncollective spherical 11/2$^-$ state at 979 keV. However, the sought-after configuration consisting of the $\nu h_{11/2}$ orbital coupled to the deformed proton $2p2h$ state, discussed earlier, would provide the deformation consistent with the observed rotational band. Thus, the proposed configuration for this structure is $\nu h_{11/2}\otimes[(\pi g_{7/2})^2(\pi g_{9/2})^{-2}]$.

The features observed in the $\mathscr{J}^{(2)}$ plot of the band in ^{111}Sn can be explained assuming the above configuration. Cranked Hartree-Fock-Bogoliubov (HFBC) calculations have been performed to identify the observed quasiparticle alignment, using the deformation parameters $\beta_2=0.2$ and $\gamma=0°$. These calculations indicate that the first pair of $h_{11/2}$ neutrons would align (the AB crossing) at a rotational frequency of approximately 0.3 MeV/$\hbar$; although the rotational band was not observed down to this low rotational frequency, this alignment would be blocked due to the occupation of the $\nu h_{11/2}$ orbital. The HFBC calculations predict the second pair of $h_{11/2}$ neutrons (the BC crossing) to align at approximately 0.45 MeV/$\hbar$. The calculations also predict the alignment of a pair of $g_{7/2}$ protons to occur at a frequency of 0.5 MeV/$\hbar$. Experimentally it is difficult to distinguish between the two alignments. The plot of the dynamic moment of inertia suggests an increase in alignment of approximately 6$\hbar$ from $\hbar\omega=0.4$ to $\hbar\omega=0.6$ MeV. From the HFBC calculations, the BC $\nu h_{11/2}$ crossing should contribute approximately 6–7 $\hbar$, and the $\pi g_{7/2}$ crossing can contribute no more than 6$\hbar$. Thus, although it is not possible to distinguish between the two alignments, the presence of an alignment at the observed rotational frequency is consistent with the configuration proposed for this band.

A comparison between the level schemes of ^{111}Sn and ^{111}Sb [19] relative to their common core nucleus ^{110}Sn is interesting in that they should manifest the different interactions of the valence neutron and the valence proton, respectively, with this common core. First for the current ^{111}Sn results, many of the states in the level scheme of ^{111}Sn can be described as the valence neutron coupled to spherical states of the ^{110}Sn core. The 11/2$^-$ state at 979 keV results from the occupation of the $\nu h_{11/2}$ orbital coupled to the core ground state, while the 15/2$^-$ state feeding this state represents a coupling of the $\nu h_{11/2}$ orbital to the spherical 2$^+$ state of the core. There are several 19/2$^-$ states observed in ^{111}Sn; these arise from coupling the $h_{11/2}$ neutron to admixtures of the spherical and deformed 4$^+$ and 6$^+$ states of ^{110}Sn [16]. The sequence of $E2$ transitions in ^{111}Sn, 11/2$^+$–7/2$^+$ 1348 keV and 15/2$^+$–11/2$^+$ 718 keV, can be explained as the $g_{7/2}$ neutron orbital coupled to the ground-state sequence of the ^{110}Sn core. It is interesting to note that only one 15/2$^+$ state in ^{111}Sn was observed in these experiments. The absence of a 15/2$^+$ state based on the $g_{7/2}$ neutron coupled to the deformed 4$^+$ state of ^{110}Sn may indicate that any collectivity resulting from the $\nu g_{7/2}\otimes[(\pi g_{7/2})^2(\pi g_{9/2})^{-2}]$ configuration is higher in excitation energy than that originating from the β-driving $\nu h_{11/2}$ orbital. This could explain why no positive parity rotational band was observed to feed directly into the positive parity sequence.

The rotational bands associated with the $h_{11/2}$ valence neutron and proton in ^{111}Sn and ^{111}Sb [19], respectively, show similarities. In both nuclei, the bands originate from a 23/2$^-$ state, corresponding to a configuration $\nu h_{11/2}\otimes 6^+$ for ^{111}Sn, and $\pi h_{11/2}\otimes 6^+$ for ^{111}Sb. This demonstrates that the deformation driving property of a low-K $h_{11/2}$ neutron or proton orbital causes the deformed minimum to develop at a lower core spin than in the ^{110}Sn core nucleus, where the band is observed [7] to start at the ($2p2h$) 10$^+$ member. Both bands have similar decay patterns, feeding out to several mixed spherical and deformed 19/2$^-$ states, and then down through the 11/2$^-$ spherical single-particle state. Their excitation energies, measured relative to the spherical 11/2$^-$ state, are 3098 and 2966 keV, respectively. These comparisons indicate that the underlying nuclear structure of the bands, $h_{11/2}\otimes[(\pi g_{7/2})^2(\pi g_{9/2})^{-2}]$, produces these similar properties at low excitation with either a valence $h_{11/2}$ neutron or proton.

The general feature of these intruder bands near $Z=50$, where the dynamic moment of inertia $\mathscr{J}^{(2)}$ gradually decreases with increasing spin, is observed in both ^{111}Sn and ^{111}Sb, although the discontinuities in $\mathscr{J}^{(2)}$ caused by particle alignment are different. In ^{111}Sn, Pauli blocking by the valence $h_{11/2}$ neutron prevents the first $\nu h_{11/2}$ alignment (AB crossing), unlike in ^{111}Sb where the AB crossing is observed at $\hbar\omega\sim$ 0.42 MeV. Both nuclei appear to show the $g_{7/2}$ pair alignment, which would not be blocked, in the predicted frequency range $\hbar\omega\sim$ 0.5–0.6 MeV. Crossing frequencies can be affected by valence particle-core interactions. The decrease in $\mathscr{J}^{(2)}$ at higher spin is believed to be related to the gradual alignment of the valence particles outside the ^{100}Sn double shell closure with the nuclear shape slowly changing from a collective prolate to a noncollective oblate shape over many transitions. This process results in smooth band termination when all the valence spin is exhausted as described by Ragnarsson *et al.* [20]. These calculations predict a band termination spin for this configuration of 79/2$^-$, which was not reached in this experiment.

In summary, a new deformed structure has been identified experimentally in the odd $Z=50$ nucleus ^{111}Sn. Several deformed structures have been previously identified in even-Sn nuclei, based on a $2p2h$ proton excitation. Deformed states are also known in odd-$_{51}$Sb nuclei. These states are composed of the valence proton coupled to the same $2p2h$ configuration. However, the new structure found in this experiment is the first to be found in an odd-Sn nucleus. It has been shown to be composed of the valence neutron occupying the $\nu h_{11/2}$ orbital coupled to the $2p2h$ deformed core of ^{110}Sn. This discovery extends the knowledge about low-lying collectivity near the $Z=50$ shell gap.

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