Rotational structures in ^{106}Sn: A new form of band termination?

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Two weakly populated rotational bands have been established in ^{106}Sn from the ^{54}Fe(^{58}Ni,$\alpha 2p$) reaction at 243 MeV. One of the bands shows evidence of termination. The result is consistent with cranked Nilsson model calculations, which predict band terminations with a smooth and gradual shape change from a prolate collective to an oblate noncollective structure.

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It is now well known that the even tin isotopes possess deformed rotational states at high spin. The first evidence for these structures was seen in $^{112-118}$Sn [1]. These bands result from two-particle–two-hole ($2p$-$2h$) excitations across the proton closed shell at $Z = 50$. Recently evidence has been presented for the existence of three rotational bands, which dominate the high-spin structure, in the very neutron-deficient isotope ^{108}Sn [2]. This is a rather surprising feature given that the nucleus resides so close to the doubly magic ^{100}Sn. One of the observed bands is a positive-parity structure which is thought to be based on the $2p$-$2h$ $\pi(g^2_{7/2}\otimes g^{-2}_{9/2})$ configuration, while the other two have been interpreted as signature partners resulting from an excited $\pi(g_{7/2}h_{11/2}\otimes g^{-2}_{9/2})$ negative-parity configuration. Lifetime measurements for the positive-parity band and one of the proposed negative-parity bands indicate that the quadrupole deformation $\beta_2 \sim 0.2$ ($\epsilon_2 \sim 0.19$). These results agree well with the predictions of standard Woods-Saxon calculations which indicate that the $\pi g_{7/2}$ and $\pi g_{9/2}$ orbitals cross at $\beta_2 \sim 0.2$ [2].

The bands in ^{108}Sn exhibit some very interesting properties with regard to their dynamic moments of inertia, $\mathcal{I}^{(2)}(\sim dI/d\omega)$. These features are also observed in the neighboring nucleus ^{109}Sb [3]. In particular, they have very low $\mathcal{I}^{(2)}$ values, ~ 15 MeV$^{-1}\hbar^2$, at $\hbar\omega \sim 1$ MeV. This is less than half the rigid-body value for a prolate nucleus with quadrupole deformation $\beta_2 \sim 0.2$. It has been suggested that this is indicative of a large single-particle contribution to the total spin, thus yielding a new and novel form of collective nuclear motion [2,3]. Also the bands, which extend to a rotational frequency of over 1 MeV, show no evidence for any particle alignments above a frequency of 0.7 MeV $\hbar^{-1}$ which suggests that both proton and neutron pairing are substantially reduced. A further intriguing feature is that the $\mathcal{I}^{(2)}$ values for several of the bands in the two nuclei appear to converge at very high frequency [3].

The aim of the present work was to investigate the nucleus ^{106}Sn to see if rotational bands possessing some of these novel properties exist with even fewer particles outside the doubly magic $N = Z = 50$ core.

Excited states in ^{106}Sn were populated with the ^{54}Fe(^{58}Ni,$\alpha 2p$) reaction at 243 MeV. The γ rays emitted from this reaction have been studied at various laboratories with different detector arrays. The first experiments were carried out at the Tandem Accelerator Superconducting Cyclotron facility, TASCC, Chalk River, the γ rays being detected in the 8π spectrometer, which comprises 20 Compton-suppressed HPGe detectors and a spherical shell of 71 bismuth germanate (BGO) detectors which provides γ-ray sum energy, H, and fold, K, information. Subsequent experiments, with the same reaction and beam energy, have been performed at both Daresbury Laboratory with phase I of the Eurogam array and at the Berkeley 88 in. cyclotron with the Gammasphere array. The latter two arrays consisted of 45 and 24 Compton-suppressed large-volume (70–80 % efficient) HPGe detectors, respectively. At Chalk River the first experiment was performed with two stacked 500 μg/cm^2 enriched ^{54}Fe foils and the second with a 600 μg/cm^2 enriched ^{54}Fe foil on a thick (~ 100 mg/cm^2) Au backing. In both the Eurogam and Gammasphere experiments a single 500 μg/cm^2 enriched self-supporting foil was used. The results presented below are primarily taken from an analysis of the 8π and Gammasphere data sets. In the case of the 8π data approximately 172×10^6 (self-supporting target) and 89×10^6 (backed target) γ-γ events were collected. In each case the trigger required a suppressed HPGe two-or-higher-fold coincidence together with a $K \geq 11$ fold coincidence from the BGO ball. These data were subsequently resorted with a higher BGO ball fold of $K = 15$ in order to enhance the three-particle evaporation channels. They were also used to construct 37°–37° and 37°–79° matrices which enabled angular correlation ratios to be determined and γ-ray multipolarities to be deduced from the method of directional correlation from oriented states (DCO) [4]. In the Gammasphere data a total of 240×10^6 events were recorded for which the trigger consisted of three or more suppressed HPGe detectors firing. The data were used to form an E_γ-E_γ-E_γ cube, and also unpacked into doubles and sorted into a matrix which contained 800×10^6 events. We enhanced the transitions in ^{106}Sn by using the triples data to gate on several of the known low-lying γ rays in this nucleus [5], the remaining two γ rays being used to increment a standard E_γ-E_γ matrix.

From the analysis of all these data two short cascades (bands 1 and 2) of γ rays have been observed (see Fig. 1). Part of the rotational band shown in Fig. 1(a) (1274 keV and above) was first observed in the Chalk River data, whilst the remaining transitions were identified in the Gammasphere data. The intensities of the two bands are approximately 7% and 3%, respectively, of the 811 keV ($4^+ \rightarrow 2^+$) transition. Unfortunately, it has not been possible to link in either of these bands to the known transitions. Indeed for the weaker structure the statistics are too low to be sure of the exact position of the band relative to the known transitions. A partial decay

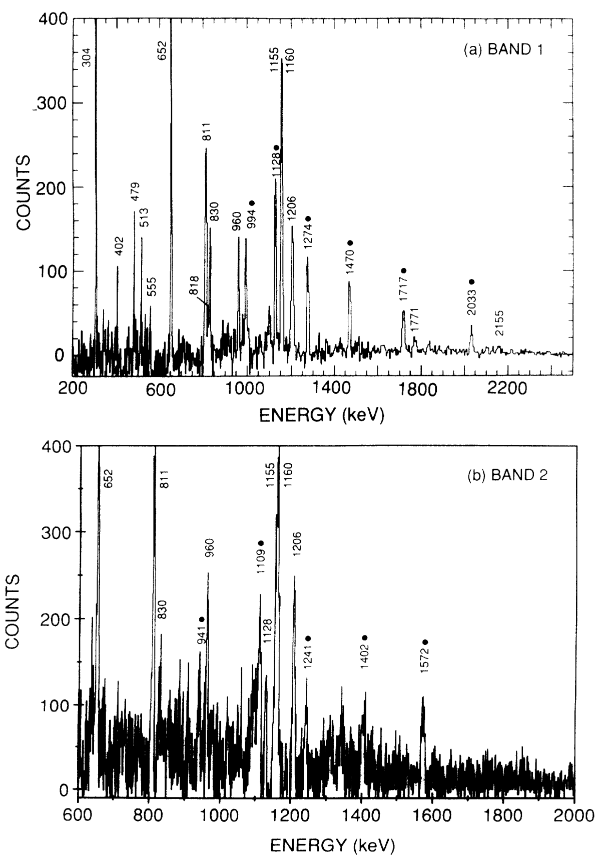

FIG. 1. Spectra showing the two new rotational bands in ^{106}Sn. Transitions within the bands are indicated by •. Panel (a) shows a sum of all possible combinations of double gates on the members of band 1 from the cube, while (b) shows a sum of the 1241, 1402, and 1572 keV gates from the ^{106}Sn gated matrix.

scheme indicating where the stronger band feeds into previously known states is shown in Fig. 2. We constructed this level scheme with the aid of previous work [5] and the present Gammasphere data set using the analysis packages ESCL8R (doubles) and LEVIT8R (triples) [6]. The present work has identified several new transitions which play an important role in the decay from band 1. Some of the previously known transitions have been reordered on the basis of intensity considerations.

The number of counts in the DCO matrices is rather low for these two bands; however, the indications are that the cascades are composed of stretched $E2$ transitions; a typical value being $W(37°\text{–}37°)/W(37°\text{–}79°) = 1.4(0.4)$. DCO ratios have also been measured for the previously reported states. In general the results obtained agree with the previous spin assignments [5]; however, in two cases, notably the 1771 and 830 keV transitions, there is disagreement. In the present work we obtain $W(37°\text{–}37°)/W(37°\text{–}79°)$ ratios of 0.78(17) and 1.54(10), respectively, for these two transitions when gating on stretched $E2$ γ rays. Several other known $E2$ transitions in ^{106}Sn have ratios of around 1.5 when gated on an $E2$ transition while known dipoles have values of around 0.75. This suggests that the level at 8205 keV (decaying via the 830 keV transition) reported previously [5] has a spin of 17 rather than 16. The previous assignment of a spin of 18 to the state immediately above this is, however, unaffected by the changes in the nature of the multipole radiation.

Two new transitions of 818 and 513 keV have been placed directly above the 1771 keV transition from the present work. The DCO measurements for these transitions yield values of 0.94(20) and 0.50(5), respectively. This suggests that they may be either pure dipole or mixed $M1/E2$ transitions. Thus new levels are proposed with tentative spins of 19 and 20$\hbar$ as shown in Fig. 2. Two further transitions (591 and 633 keV) have also been established at the top of the strongly coupled band in the present work.

The new bands, 1 and 2, exhibit some intriguing features. For example in Fig. 3 the dynamic moments of inertia, $\mathcal{I}^{(2)}$, are plotted for the two bands as a function of γ-ray energy together with the three bands seen in ^{108}Sn [2]. It is clear that band 1 has a somewhat lower $\mathcal{I}^{(2)}$ than the others for $\hbar\omega > 0.7$ MeV. This suggests that there is an even larger single-particle contribution to the total spin at high frequency for this particular band. This new and unusual mode of excitation has recently been observed in both ^{108}Sn [2] and ^{109}Sb [3]. Although there is some ambiguity in the spins for band 1 the $\mathcal{I}^{(2)}$ values are expected to be significantly less than the $\mathcal{I}^{(1)}$ (kinematic moment of inertia) values at high rotational frequencies. The possibility of this type of behavior was predicted in Ref. [7]. However, the extremely low values of $\mathcal{I}^{(2)}$ were not expected.

The second feature is the apparent termination of the stronger band (see Fig. 1). From the present data there is no evidence for γ-ray transitions belonging to this rotational sequence beyond the 2033 keV γ ray. A similar effect also appears to be present for the weaker band; however, because of the poor statistics in this latter case it is rather more difficult to confirm this. For band 1 there is also no evidence for lower energy transitions decaying to the level from which this 2033 keV γ ray emanates. It would appear that the nucleus simply carries on rotating until the contribution to the total spin from the particles involved in the configuration is exhausted. This is the first time that it has been possible to confirm such behavior from experimental quantities alone in a heavy nucleus. The present situation is in direct contrast to the more common abrupt termination of rotational sequences and sudden shape change seen in the neighboring I [8] and Xe [9] isotopes, for example, where single particle levels, resulting from noncollective oblate shapes, are found to be built directly on top of prolate rotational sequences at high spins.

In order to ascertain which configurations may be responsible for the terminating band we have performed cranked Nilsson model calculations using a modified harmonic oscillator potential [7]. The parameters used were those of Ref. [10]. A new feature of the present calculations is that for the first time it has been possible to specify the number of particles occupying the high-j orbits separately, i.e., in our case the normal-parity $g_{9/2}$ protons. Figure 4(a) shows the results of such

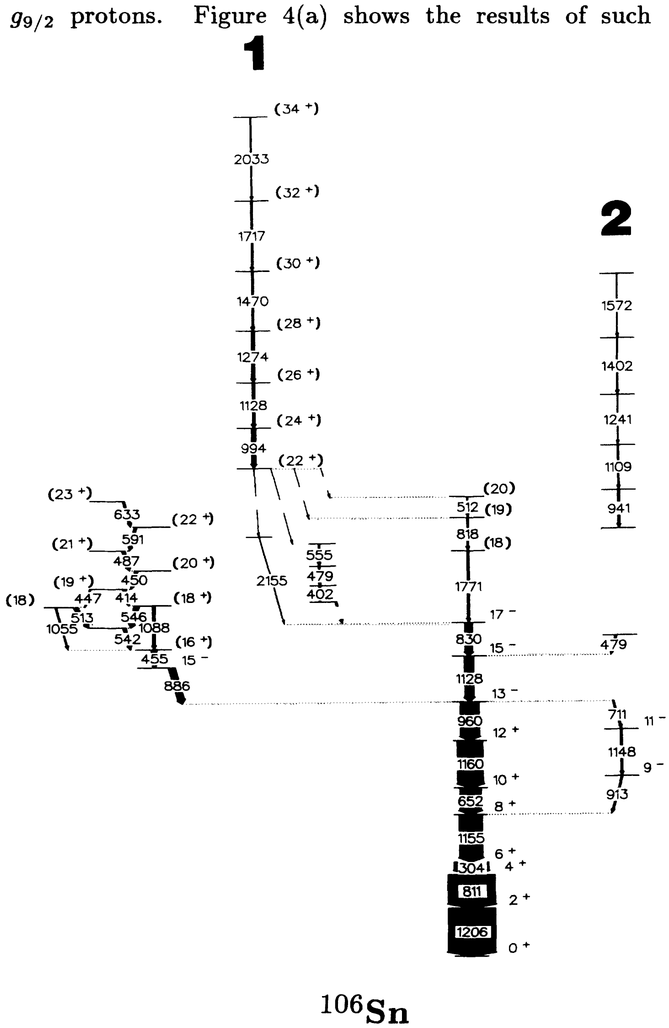

FIG. 2. Partial decay scheme for ^{106}Sn. γ-ray intensities are proportional to the widths of the arrows. Note, unlabeled transitions do not necessarily represent single unobserved γ rays.

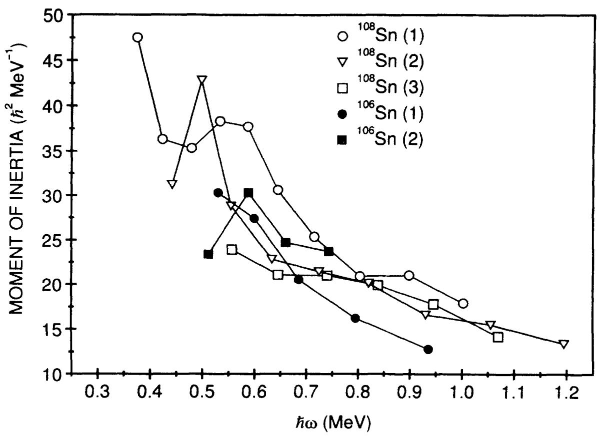

FIG. 3. Dynamic moments of inertia vs rotational frequency for the rotational bands in ^{106,108}Sn.

calculations for various configurations in the yrast region in the spin range $I \sim 20$–$42\hbar$. In view of the proposed level scheme it is tempting to assign band 1 the $\nu[(g_{7/2}d_{5/2})^4 \otimes (h_{11/2})^2] \otimes \pi[(g_{7/2})^2 \otimes (g_{9/2})^{(-2)}]$ configuration[1] which terminates at spin 34^+. It should be noted however that Fig. 4 indicates that the configuration which terminates at spin 37^- is slightly more favored at high spin than the 34^+ terminating state. Since there is still some ambiguity in the decay scheme it is not possible to rule out this later configuration for band 1. Calculations, shown in Fig. 4(b), for a typical configuration suggest that as the band proceeds to termination the nuclear shape gradually shifts from a collective prolate to a noncollective oblate shape, with the largest change occuring over the last transition. Such a scenario would imply that the highest transitions should be less collective than those lower in the band. This feature clearly needs investigating further through the measurement of lifetimes.

The strongly coupled band, seen on the left in Fig. 2, may possibly be explained by an odd number of particles in the $g_{9/2}$ orbital, hence the most likely explanation for this band is a proton $1p$-$1h$ excitation from the $g_{9/2}$ orbit to either the $d_{5/2}$ or $g_{7/2}$ orbits. It is possible that this structure may be associated with the $\nu[(g_{7/2}d_{5/2})^2(h_{11/2})^2] \otimes \pi[(g_{7/2} \otimes g_{9/2}^{-1})]$ configuration, which terminates at spins 27^+ or 28^+ depending on the signature [see Fig. 4(a)]. If this is the case then the band is not observed to termination. As indicated previously the second decoupled band, band 2, is very weakly populated and only contains a very short sequence of transitions. Because of this it is very difficult to determine exactly where the band feeds into the known decay scheme. A possible structure for this band is the $\nu[(g_{7/2}d_{5/2})^4 \otimes (h_{11/2})^2] \otimes \pi[(g_{9/2})^{-2} \otimes (g_{7/2})(h_{11/2})]$ configuration which terminates at spin 37^-. According

[1]Note that our labeling of the configurations is only approximate. In the calculations couplings between different shells and subshells are accounted for as discussed in detail in Ref. [7].

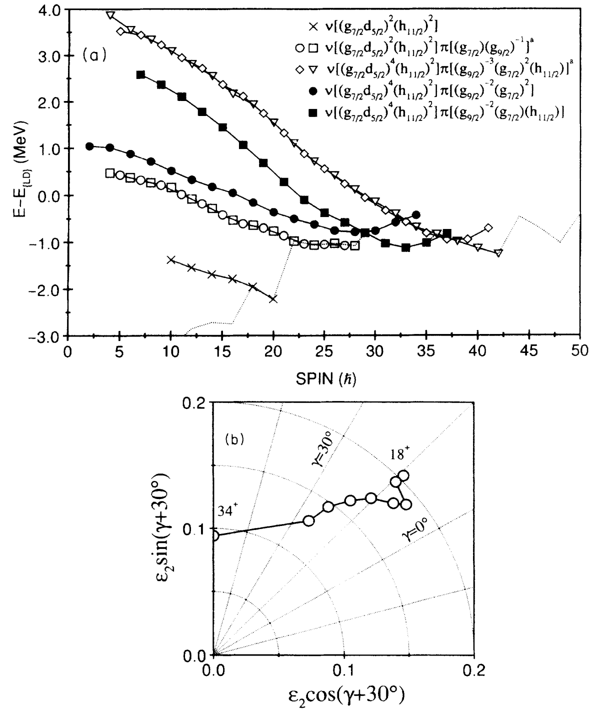

FIG. 4. (a) Cranked Nilsson model calculations for ^{106}Sn. The figure shows the energies of various configurations (minus a liquid drop energy) as a function of spin. Structures marked with an a are expected to have two signatures. The dotted line indicates the locus of yrast states. (b) An ϵ-γ plot showing how the calculated nuclear shape evolves for the structure which terminates at spin 34^+.

to the calculations this configuration rapidly becomes nonyrast below spin 30 and thus may decay out to spherical states somewhat earlier than band 1. However, it may be expected that the transition energies at the top of this band would be comparable to if not higher than those of band 1. A further puzzling feature of both the decay scheme and the calculations is that the spin 17 and 20 states in the middle of Fig. 2 seem to be naturally understood as the highest spins in the $\nu[(g_{7/2}d_{5/2})^5(h_{11/2})^1]$ and $\nu[(g_{7/2}d_{5/2})^4(h_{11/2})^2]$ configurations, respectively. If this is the case it is very difficult to understand why the spin 20 state, for example, is so far above yrast [see Fig. 4(a)]. A better candidate for this state may be the one from which the 555 keV γ ray depopulates. If the 402 keV γ ray decays directly to the spin $17^{(-)}$ level and all the transitions in this short sequence (i.e., 402, 479, and 555 keV) are dipoles then the top state will have spin 20. This is very much closer to being yrast. Clearly more data are required to help elucidate the level scheme so that more firm assignments can be made.

Finally, a further point of interest is that band 1, which extends over a moderately large frequency range, shows no evidence for any band crossings at high frequencies. This indicates that both the neutron and proton pairing may be drastically reduced. Note however, without pairing, particle alignments may take place gradually with no obvious manifestation of this occurrence in the $\mathcal{I}^{(2)}$, the only sign being the gradual reduction in the $\mathcal{I}^{(2)}$ with increasing frequency. A similar situation exists in ^{108}Sn and ^{109}Sb.

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