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First evidence for smooth band termination in valence space in the mass 130 region: Spectroscopy of ^{127}La

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High spin states in ^{127}La have been studied using the $^{32}S(^{100}Mo,p4n)$ reaction at a beam energy of 155 MeV. Gamma rays were detected using the EUROBALL III spectrometer. One of the side bands in ^{127}La is observed to be populated to a spin of $\frac{83}{2}^+$. These data are compared with cranked Nilsson-Strutinski calculations which suggest that the structure is a smoothly terminating band, in valence space, based upon a $\pi[(g_{7/2}d_{5/2})^5(h_{11/2})^2]\otimes\nu[(g_{7/2}d_{5/2})^{12}(h_{11/2})^6(d_{3/2}s_{1/2})^2]$ configuration, which can carry a maximum spin of $47.5\hbar$. This is the first identification of such a structure in this mass region.

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An interesting feature of the nuclei with up to 10–20 valence particles outside the ^{100}Sn core is the smooth terminating bands which have been studied extensively in recent years (e.g., see [1–9]). In these nuclei the bands arise from proton two-particle–two-hole $(2p\text{-}2h)$ excitations across the $Z=50$ shell gap and the smooth termination results from the gradual alignment of the individual spin vectors of all the valence particles with the rotation axis [10,11]. At medium spins these structures are essentially prolate and have a quadrupole deformation, $\varepsilon_2\sim0.25$, which is induced through the promotion of protons from the up-sloping (with increasing ε_2) $\pi g_{9/2}$ orbital to the down-sloping $\pi(d_{5/2},g_{7/2})$ and $\pi h_{11/2}$ orbitals. At higher frequencies, as the valence protons and neutrons align their spin vectors with the axis of rotation and the nucleus gradually changes to a noncollective oblate shape, the dynamic moments of inertia, $\mathfrak{I}^{(2)}$, decrease with increasing spin to about one third of the rigid body value. Moreover, the energy of the last few states in the bands is observed to increase rather than decrease when a rotating liquid drop reference energy is subtracted $(E-E_{RLD})$. As the number of valence particles increases there are two different scenarios for the continuation of these bands. First, there is the possibility of bands which are based on two $g_{9/2}$ proton holes in the $Z=50$ core, i.e., like the smooth terminating bands in the $Z=50-53$ nuclei [1–9]. As the mass number increases, however, the maximum spin for these structures will soon become greater than can be observed in experiment, because of the large number of valence particles and holes involved in the configurations. Indeed, the superdeformed bands around ^{132}Ce are interpreted to be of this type [12] and to terminate with spins of the order of $80\hbar$. Secondly, bands with no holes in the $Z=50$ core are possible. These will have a maximum spin of $I\sim40-50\hbar$. To date, however, there is no clear evidence for terminating structures of this type. Furthermore, it has generally been assumed that such terminations would be difficult to observe because most of them are predicted to have high excitation energy [12].

At present, *smooth* terminating bands have only been observed in special configurations having one or two holes in well-defined cores. All terminating bands built from valence-space configurations, e.g., in the $A=100$ region [13,9] and in the $A=155-160$ region [14,9], show clear irregularities. It is therefore of special interest to find out if it is possible to follow *smooth* bands, built purely on valence space configurations, to termination. In the present work we have studied excited states in ^{127}La. These data have revealed the first evidence for a smooth terminating structure in valence space based on two $h_{11/2}$ protons and six $h_{11/2}$ neutrons.

High spin states in ^{127}La were populated using the $^{32}S(^{100}Mo,p4n)$ reaction at a beam energy of 155 MeV. Gamma rays were detected using the EUROBALL III [15] spectrometer, located at the Legnaro National Laboratory, Italy. For this experiment the array contained 27 large coaxial HPGe detectors, 25 clovers, and 13 cluster detectors. The target consisted of two stacked, enriched (>97%) self-supporting ^{100}Mo foils, each of thickness 600 $\mu g/cm^2$. A total of 1.3×10^9 events were recorded to digital linear tape. These data were unfolded and sorted into a symmetrized hypercube [16] which contained approximately 7×10^9 events. This was used to extend the previously published level scheme for ^{127}La [17,18] (see Fig. 1). In addition to the hypercube, the data were also sorted into 1d spectra. These were generated by directly unfolding the high fold data using certain gating constraints, i.e., three or four simultaneous gates from a list of transitions. The unfolding procedure of Ref. [19] was used to create these spectra. In this Rapid

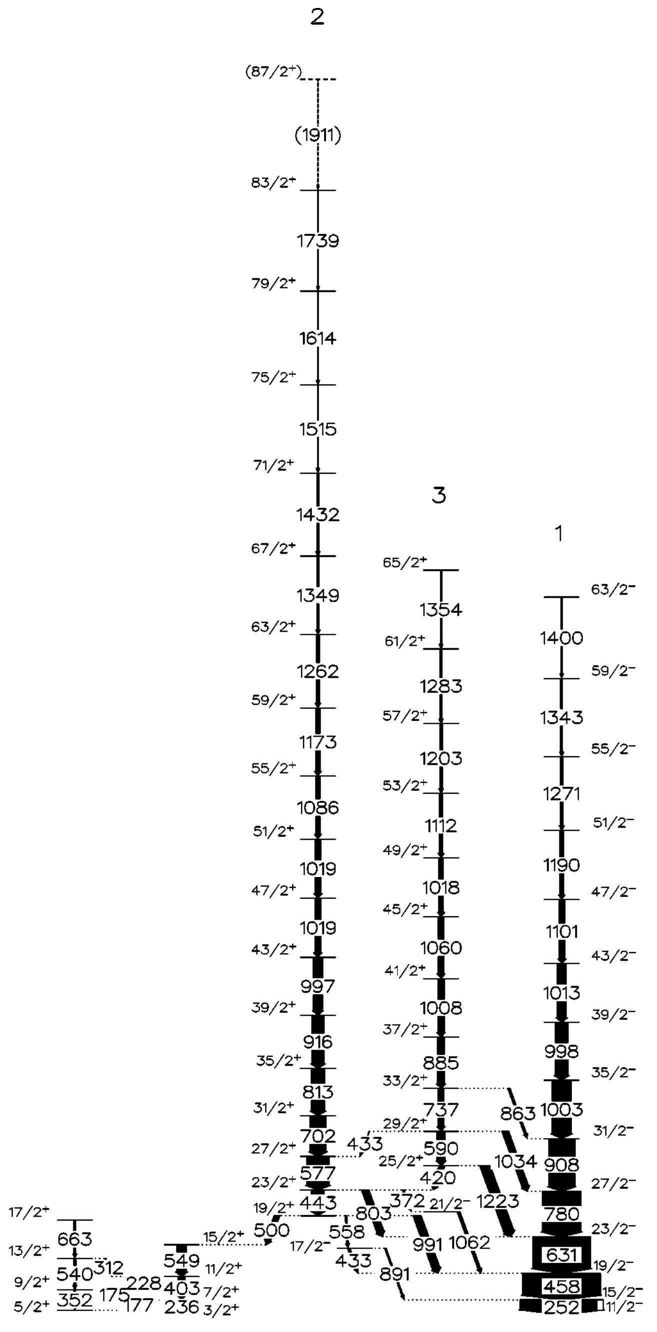

FIG. 1. Partial decay scheme for ^{127}La deduced from the present work.

Communication we wish to focus on band 2 (band 4 of Ref. [18]), which has previously been assigned a $\pi([422]\frac{3}{2} \otimes (h_{11/2})^2)$ configuration. However, some discussion will also be presented on band 1 which is built on a $\pi h_{11/2}$ configuration at low spin.

Figure 2 shows a spectrum of the transitions in band 2 obtained in the present work. This band has been extended by eight transitions, excluding the tentative 1911 keV γ ray at the top of the band, from that of Ref. [17]. The present work has firmly established the presence of a doublet at 1019 keV within this band, in agreement with the decay scheme published in Ref. [17]. Bands 1 and 3 have also been extended by 5 and 7 transitions, respectively, in the present work. A directional correlation from oriented states [20] analysis was carried out using all of the clover detectors (which are located at $\sim 90°$ to the beam direction) and five of the cluster detectors, located at an angle of approximately 155°. A matrix was constructed of all clover detectors on one axis and the five cluster detectors on the other axis. Gates were set on known electric quadrupole ($E2$) transitions on both axes and the directional correlation ratios, $I(\theta \sim 90°)/I(\theta \sim 155°)$ were determined. Using this method it was possible to show that all transitions in band 2 up to the 1432 keV gamma ray are electric quadrupoles. The discussion below assumes that all transitions in band 2 above this are also $E2$'s.

Figure 3 shows the dynamic and kinematic moments of inertia, $\Im^{(2)}$ and $\Im^{(1)}$, for band 2 as a function of rotational frequency. Total Routhian surface calculations and systematics suggest that the rise in $\Im^{(2)}$ at $\hbar\omega \sim 0.5$ MeV results from the alignment of a pair of $h_{11/2}$ neutrons and that the small hump at $\hbar\omega \sim 0.7$ MeV is due to the alignment of a $g_{7/2}$ proton pair. Beyond $\hbar\omega \sim 0.7$ MeV the dynamic moments of inertia show features similar to those observed in the smooth terminating bands in the $A \sim 110$ mass region, decreasing to values which are much lower than the kinematic moments of inertia see (Fig. 3).

Calculations have been performed, without pairing, for ^{127}La, using the configuration dependent shell correction approach and a cranked Nilsson potential, with single-particle κ and μ parameters from Ref. [22]. Note that since pairing is not included in the calculations, they are not expected to show good agreement with the experimental data until spins in excess of $30\hbar$. The results for all parity and signature, (π,α), configurations are shown in Fig. 4 along with the experimental data for bands 1–3. The nomenclature used to identify the structures in this figure is $[p_1 p_2(p_3), n_1(n_2, n_3)]$, which is equivalent to a configuration of $\pi(g_{9/2})^{-p_1}(h_{11/2})^{p_2}(i_{13/2})^{p_3} \otimes \nu(h_{11/2})^{n_1}(h_{9/2}f_{7/2})^{n_2}(i_{13/2})^{n_3}$ relative to a ^{100}Sn closed core. Note that n_2 and n_3/p_3 have been omitted for configurations with no particles in the $(h_{9/2}f_{7/2})$ or $(i_{13/2})$ orbitals. These calculations indicate that terminating bands, with configurations which do not involve $g_{9/2}$ proton holes, are yrast (or very close to yrast) between $\sim 25\hbar$ and $\sim 40\hbar$ for all four possible (π,α) configurations. Comparison of the theoretical calculations with the experimental results (Fig. 4) indicates that band 2 has a $(\pi,\alpha)=(+,-\frac{1}{2})$, ([02,6]), configuration. This structure is predicted to terminate at $47.5\hbar$ with the

$$\pi[(g_{7/2}d_{5/2})^5(h_{11/2})^2]_{21.5}$$
$$\otimes \nu[(g_{7/2}d_{5/2})^{12}(h_{11/2})^6(d_{3/2}s_{1/2})^2]_{26}$$

configuration, relative to a ^{100}Sn core. Unfortunately, the band is not observed up to termination, however, the results do suggest that this band represents the first observation of a smooth terminating structure in valence space in this mass region.

The [02,6] configuration describes the properties of band 2 with a reasonable degree of success. It is also possible to

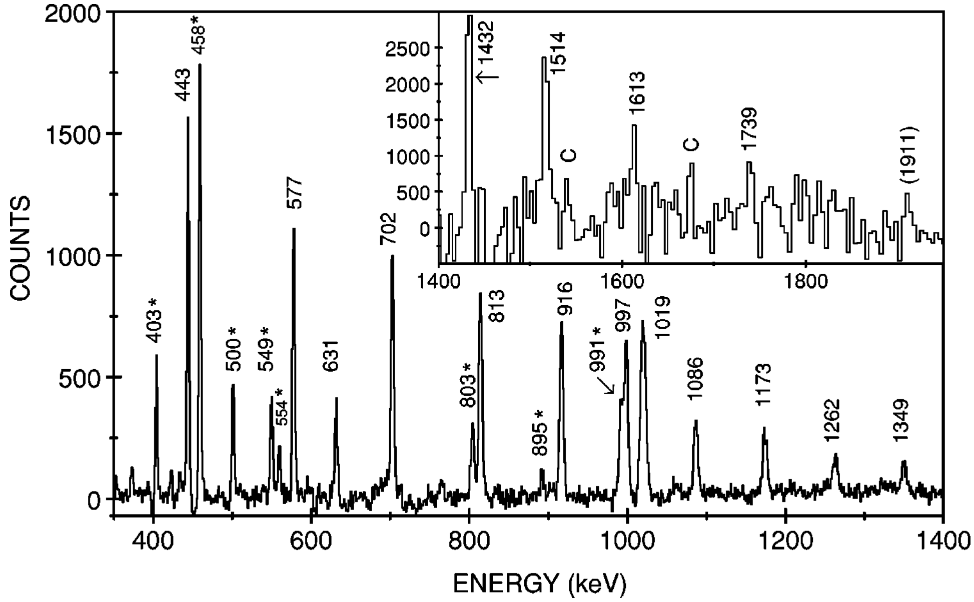

FIG. 2. Spectrum showing band 2 in ^{127}La produced using the 1d unfolding technique mentioned in the text. Four fold data were used in this analysis. All γ rays in the band, up to the 1739 keV transition, were included in the gate list. The spectrum results from taking any three coincident gamma rays from the gate list, the fourth coincident gamma ray being used to increment the spectrum shown. Transitions in band 2 are labeled by their energies in keV. The inset shows the continuation of the band at high spin. The inset spectrum results from taking a sum of coincidences between two gate lists from the cube. These were comprised of all transitions in the band up to and including the 1019 keV doublet and all transitions from 1086 keV up to and including the 1739 keV γ ray. Transitions marked with an asterisk represent decays out from the bottom of the band or transitions within other bands fed by band 2. Transitions marked with a C in the inset are contaminants.

conclude that when the band reaches high spin (where pairing is of minor importance) this is essentially the only possible configuration for this band. Starting from low spin, the band has positive parity with an odd number of protons and it has previously been assigned a $[422]\frac{3}{2}\otimes(h_{11/2})^2$ proton configuration [18]. Furthermore, it is very unlikely that the configuration will contain more protons in the $h_{11/2}$ subshell than in the $g_{7/2},d_{5/2}$ shells. Moreover, a configuration with no $h_{11/2}$ protons would not yield sufficient spin to account for the observed band. From this we can fix the full proton configuration, relative to the $Z=50$ shell gap, as $\pi(g_{7/2},d_{5/2})^5(h_{11/2})^2$. In this process, we have also excluded configurations with two proton holes in the $g_{9/2}$ subshell, since in ^{127}La, which has seven protons outside the $Z=50$ core, no proton holes of this type are expected at low spin in normal deformed configurations. Furthermore, if band 2 involved holes of this type it would not be expected to show the rather simplistic decay pattern seen for this band to the lower spin states. This is also consistent with the fact that configurations with holes in the $g_{9/2}$ shell are predicted to lie at high excitation energy at low spin (see Fig. 4).

Similar reasoning to that presented above indicates that the neutron configuration must have an even number of both $h_{11/2}$ particles and $N=4$ $(g_{7/2},d_{5/2},d_{3/2},s_{1/2})$ particles, i.e., the neutron configuration must have positive parity. The possibilities then are four, six, and eight $h_{11/2}$ neutrons. The calculated bands for the corresponding configurations, [02,4], [02,6], and [02,8] are shown in the $(\pi,\alpha)=(+,-\frac{1}{2})$ panel of Fig. 4. The [02,4] configuration can be excluded because it is too high in energy at low spin, moreover, it terminates at a spin lower than the maximum observed for band 2 in ^{127}La. The low terminating spin is caused by the configuration having only two $(d_{3/2},s_{1/2})$ neutrons leading to filled $(g_{7/2},d_{5/2})$ subshells. Thus, in this case, the $(g_{7/2},d_{5/2})$ subshells do not contribute any spin at termination. On the other hand, configurations with more than two $(d_{3/2},s_{1/2})$ particles are highly unfavored energetically at high spin because of a high energy cost, with essentially no angular-momentum contribution, to excite more particles to these subshells. Figure 4 also shows that the [02,8] configuration is highly unfavored on energy grounds at high spin. Therefore, we would not expect to be able to

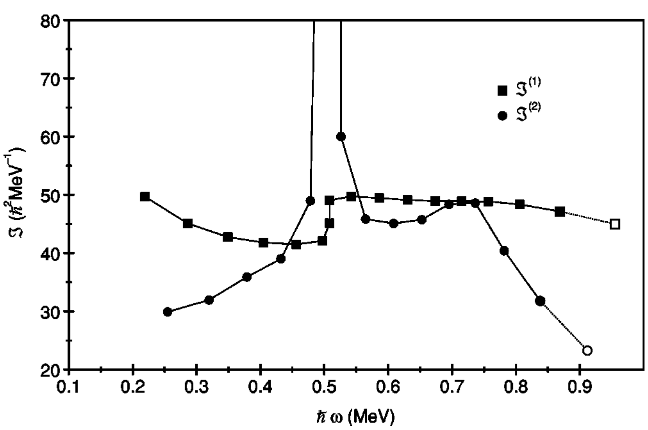

FIG. 3. Kinematic ($\Im^{(1)}$) and dynamic ($\Im^{(2)}$) moments of inertia for band 2 in ^{127}La as a function of rotational frequency. The open symbols are obtained from the tentative transition.

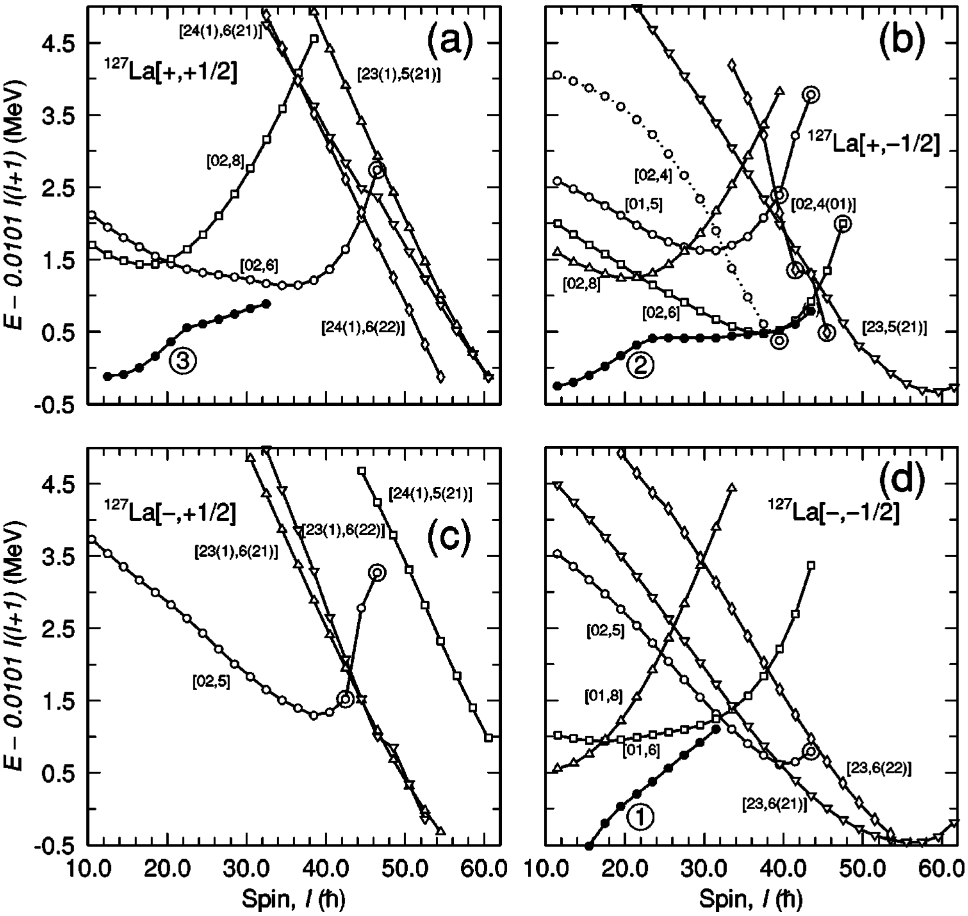

FIG. 4. Theoretical (open symbols) and experimental (filled symbols) energy minus rigid rotor reference values for all parity, signature (π,α) configurations in ^{127}La as a function of spin. The calculated and observed bands are normalized so that for $I^{\pi}=\frac{79}{2}^{+}$ band 2 coincides with the calculated [02,6] configuration. Large open circles indicate the terminating states for various configurations. (Note the calculations do not include pairing, hence they only become valid for spins in excess of $30\hbar$.)

follow such a configuration to spin values close to termination.

For the structures with four, six, and eight $h_{11/2}$ neutrons, it is interesting to compare these $N=70$ configurations with the equivalent proton configurations in the $Z=68$ nucleus ^{158}Er [21,14]. In this nucleus it is well established that the $\pi(h_{11/2})^8$ configuration goes away from yrast with increasing spin, while the $\pi(h_{11/2})^4$ configuration terminates in a favored way at high spin, which means that it is close to yrast only for high spin values. It is only the $\pi(h_{11/2})^6$ configuration which stays close to yrast over a large spin range, in a similar way to that observed for band 2. This analogy clearly points to the $(h_{11/2})^6$ neutron configuration as being the only reasonable candidate for band 2 in ^{127}La.

A further interesting feature is that the yrast negative-parity band (band 1) in ^{127}La, which is built on an $h_{11/2}$ proton at low spin, is only populated up to a spin of $\frac{63}{2}^{-}$. Band 1 clearly shows evidence of an alignment at $\hbar\omega\sim0.5$ MeV, which total Routhian surface calculations and systematics suggest is due to a pair of $h_{11/2}$ neutrons. This structure can be associated with the $(\pi,\alpha)=(-,-\frac{1}{2})$, [01,6], configuration shown in Fig. 4(d). Furthermore, it is observed from this figure that this structure is crossed at a spin of $\sim33.5\hbar$ by the [23,6(21)] configuration, which becomes yrast at very high spins. This latter configuration has a somewhat higher deformation ($\varepsilon_2\sim0.36$) than the $h_{11/2}$ band ($\varepsilon_2\sim0.2$) and is related to the superdeformed bands in the Ce isotopes, which are also predicted to have two $g_{9/2}$ proton holes in their configurations. The population, at high spin, of such a highly deformed structure may explain why band 1 is not seen beyond a spin of $\frac{63}{2}^{-}$. The future identification of a highly deformed negative parity band would help confirm this hypothesis.

It should be noted that in Fig. 4 bands 1–3 appear to approach the calculated curves in a similar way for spins around $\sim30\hbar$, where the present calculations, which neglect pairing, are expected to become realistic. Moreover, the experimental signature splitting observed between the $(+,-\frac{1}{2})$ and $(+,+\frac{1}{2})$ bands (bands 2 and 3) is consistent with the calculations, lending further support to the interpretation presented above. In addition, Fig. 4 shows that a remarkable correlation in the experimental alignments of bands 1–3 and the crossings between the [01,8]/ [01,6] and [02,8]/ [02,6] configurations. It is clear that in the unpaired regime the bands under discussion simply differ in the number of $h_{11/2}$ neutrons present in the configuration. In standard cranking calculations, however, there is no attempt made to track the numbers of high-j particles ($h_{11/2}$ neutrons in this case) before and after the crossing, it is therefore possible that band 2, for example, could be closer to the [02,8] configuration before the $\nu(h_{11/2})^2$ crossing and [02,6] configuration after the crossing. Features of this nature are discussed in [23]. These results therefore suggest that the present unpaired calculations may be able to represent a paired crossing, a feature clearly worthy of further investigation.

In summary, high spin states in ^{127}La have been populated using the ^{100}Mo(^{32}S,$p4n$) reaction and the γ decay studied using the EUROBALL III spectrometer. All the previously observed bands have been seen to higher spin. Comparison of the experimental data with cranked Nilsson calculations provides consistent evidence for the interpretation of band 2 as a smooth terminating band which is built upon the

$$\pi[(g_{7/2}d_{5/2})^5(h_{11/2})^2]\otimes\nu[(g_{7/2}d_{5/2})^{12}(h_{11/2})^6(d_{3/2}s_{1/2})^2]$$

configuration, with a terminating spin of $47.5\hbar$. This band is observed up to three transitions away from the terminating state, with tentative evidence for the second from last transition. These data provide the first evidence for a band which smoothly terminates in valence space in this mass region. Band 1, which has a $\pi h_{11/2}$ configuration at low spin, has been extended up to a spin of $\frac{63}{2}^-$. The present calculations predict that it is crossed at around this spin by a highly deformed structure which involves two $g_{9/2}$ proton holes.

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