Conf-9110236-7

NUCLEAR SPINS AND MOMENTS: FUNDAMENTAL STRUCTURAL INFORMATION

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CONF-9110236--7

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Abstract: Predictions for the low energy structure of well deformed odd-A Pm and Sm nuclei in the $A \approx 130$ region are given, based on the particle-rotor model. Distinctive magnetic dipole properties (static moments and transition rates) are expected for certain Nilsson configurations, and comparisons to recent data are made for ^{133}Pm , ^{135}Sm and ^{137}Sm .

1. INTRODUCTION

As current nuclear structure studies move farther from the line of beta stability, exciting new information is often left incomplete due to a lack of firm spin and parity assignments. Sometimes this occurs because no transitions are found to well-established states (often the case in high spin studies), and sometimes simply because a particular nucleus does not yet have well-established states. Reliable bandhead spins are generally a first requirement for sensible structure interpretations, and nuclear orientation, especially when augmented with NMR, can determine the spin and magnetic moment of a ground or isomeric state unambiguously. Magnetic dipole properties (static moments and transition matrix elements) may vary strongly between different Nilsson configurations, while electric quadrupole matrix elements often directly reflect the nuclear shape. Examples are taken from the $A \approx 130$ region, where such measurements would be particularly helpful. Detailed predictions, based on the particle-rotor model, are given for configurations, spins and electromagnetic properties expected at low energy in ^{133}Pm , ^{135}Sm , and some neighbors.

2. OUTLINE OF THE MODEL

The "Lund version" of the particle-rotor model, originally presented in /1/ and recently reviewed in /2/ and /3/, is employed here. Briefly stated, this model describes odd-mass nuclei in a particle + core coupling approach, in which the collective core is approximated as a shape-fixed, deformed rotor. The major portion of the interaction between the odd particle and the core is assumed to be contained in the deformed mean field, which is not necessarily axially symmetric (triaxial shapes are included), but must be reflection symmetric (no octupoles). A monopole pairing interaction between like nucleons is included, and is treated within the BCS approximation. With the choice of a strong coupling basis, the simplicity of the intrinsic state description can be retained in a formalism that conserves angular momentum. One advantage of this choice is that it is possible to make contact with other theoretical approaches (e.g., cranking models) by using a common mean field description. In the original version /1/, the mean field was

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parameterized with a Modified Oscillator potential, although in principle other potentials can readily be used. The extension to the "Warsaw" Woods-Saxon potential was made a few years ago /4/, and that version is applied here.

3. APPLICATIONS TO THE $A \approx 130$ REGION

In the neutron deficient rare earth region ($A \approx 130$) both protons and neutrons are filling the same major shell. As the neutron number decreases from the $N = 82$ spherical shell gap, collective effects become important, and eventually static quadrupole deformation must set in. Along the way, many interesting questions arise: How does the nuclear shape evolve with Z and N and/or with angular momentum? Do different shapes coexist in a single nucleus? Are the proton-neutron effects especially strong since the valence particles are occupying similar orbitals? Interest in the ground state properties of nuclei in this region was sparked by predictions of Leander and Möller /5/ that strong deformation may set in quite abruptly, especially for Sm and Pm nuclei where the deformed shapes were predicted for $N \leq 74$. Those calculations used a Folded Yukawa parameterization of the mean field with axially symmetric shapes only. The transitional region has long been expected to contain γ -soft shapes /6/, with possibly large shape polarization effects due to unpaired nucleons that should be especially sensitive to rotationally aligned particles /7/. Indeed, prolate-oblate shape coexistence has been observed through in-beam experiments in a number of nuclei in this region /8/, including 1- and 3-qp states (in both odd- Z and odd- N nuclei) and 2-qp states (in even-even and odd-odd nuclei). Further, recent calculations with a Woods-Saxon potential /9/ suggest a transition through ground state triaxial shapes (not just γ -soft), especially in the light Sm isotopes. Thus, many interesting effects are expected that deserve close study by both high spin and low spin methods.

The evolution of the nuclear shape with Z and N is directly reflected by the systematic behavior of low energy, low spin states in odd- A nuclei. Much of the information currently available in this region is from in-beam experiments, which typically probe yrast or near yrast states only, and which rely on other measurements to establish bandhead spins. Radioactive decay studies provide very important complementary information, and such a program is being pursued at UNISOR. Since these studies naturally proceed away from the line of stability, i.e., through the transitional nuclei and out into the deformed region, it is useful to consider what distinctive properties should be observable for a well deformed nucleus. To address this question, calculations were made for $^{131-137}\text{Pm}$ and $^{131-137}\text{Sm}$. These results are predictive in the sense that all parameters were taken at their "standard values", and the same Woods-Saxon potential was used as in /9/. Specifically, the deformation parameters were taken as simple averages of the values tabulated for the $Z \pm 1$ even-even neighbors /9/, and the Fermi level and pairing gap were derived from a standard BCS calculation. The moment of inertia was estimated by Grodzins' rule. The core magnetic g -factor was taken as Z/A , and the nucleon spin g -factor was taken as 70% of the free value. Results are presented below for ^{131}Pm and $^{131,135}\text{Sm}$ as "benchmark" examples of the expected low energy properties for well deformed isotopes.

3.1 Odd-Mass Pm Isotopes

The low lying portion of the calculated spectrum of ^{131}Pm is shown

in fig. 1. The negative parity states, shown at the right side of the figure, originate almost entirely from the spherical $h_{11/2}$ j-shell. Although the band is mainly built on the $[532]5/2$ Nilsson orbital, the calculated energy pattern clearly deviates from the simple $I(I+1)$ energy law of the strong coupling limit. Instead, a characteristic staggering (signature splitting) of the energy levels is observed. This staggering is due to the lower K components in the wave function, which are mixed in by the Coriolis interaction. The Coriolis mixing is fairly strong because the proton Fermi level lies low in the j-shell, slightly above the $[532]5/2$ orbital and thus rather close to the low-K Nilsson orbitals. Because of this staggering, the decay strength of these states is usually dominated by stretched E2 transitions, and thus high spin experiments on nuclei in this region typically observe only the favored signature of the $h_{11/2}$ band, corresponding to the sequence of levels with $I = j \pm 2n$, i.e., $I = 11/2, 15/2, 19/2, \dots$ (Any states of the favored sequence that may occur below the $I = j$ state are usually not observed in in-beam experiments because the transitions are low in energy and may be highly converted.) Also, because of the distortion of the band and the mixing over a number of Nilsson states, the lowest observed state may not provide much information on the positions and splitting of the Nilsson states. Note that the $5/2^-$ state is predicted to be slightly above the $7/2^-$ in these calculations; if the Fermi level were a little lower or the deformation a bit smaller (e.g., $\beta \approx 0.25$) stronger decoupling would result, with a bandhead of $I = j = 11/2$ and the unfavored sequence shifted higher in energy.

¹³¹Pm ₆₁ ⁷⁰ Calculations: W-S potential $\beta = 0.305$ $\gamma = 0$ $\beta_4 = +0.012$

Fig. 1. Predicted level structure for ¹³¹Pm.

Conversely, an advantage of this distorted band pattern is that the low lying states may have observable lifetimes that could provide a useful measure of the deformation. For example, the $11/2^- \rightarrow 7/2^-$ transition is predicted to have a BE2 of 0.84 (eb)^2 . For a 99 keV transition, this corresponds to a partial lifetime of 10 nsec, or a total lifetime (including internal conversion also) for the $11/2^-$ state of a few nsecs. The $9/2^-$ state is expected to have a shorter lifetime ($\approx 1 \text{ nsec}$) due to M1 and E2 branches to the $7/2^-$, as well as the E2 to the $5/2^-$ state indicated in the figure. These lifetime estimates depend sensitively on the transition energies, of course, and are only intended to suggest important features that might be observable with standard spectroscopic methods. At somewhat smaller deformations, the $7/2^-$ state would still be expected at low energy, although perhaps above the $11/2^-$, and would decay to the $11/2^-$ bandhead. In that case, the $7/2^-$ state would probably be isomeric, and again that BE2 would provide a good measure of the deformation.

Similarly, the calculated positions of the various bandheads are not expected to be as reliable as the general structure of the bands. For example, the overall splitting between the negative and positive parity states might be a bit different, so that the $7/2^-$ could be isomeric or even the ground state. In such a case, the static moments might be observable, and these are shown in Table 1. The negative spectroscopic quadrupole moment for the $7/2^-$ state ($Q = -0.06 \text{ b}$) is a clear indicator of the low-K components of the wave function, but if such a small value were determined experimentally, it would be very difficult to extract the intrinsic shape reliably. The predicted moments of the $5/2^-$ state are also shown; because this state is much closer to the simple limit of an $I = K$ bandhead, the quadrupole moment is close to its maximum value for this deformation. Note that the magnetic moments of these two states are sufficiently different that these could distinguish between the two states if no direct spin determination (e.g., by NMR/ON) were possible. The predicted magnetic moments are generally expected to be rather independent of the deformation, but the associated band pattern would change somewhat.

Table 1. Possible bandheads for the negative parity ($h_{11/2}$) states in ^{131}Pm , and their predicted moments. The squared amplitudes for the $[532]5/2$, $[541]3/2$ and $[505]1/2$ components of the wave functions are also given.

I	$A_{5/2}^2$	$A_{3/2}^2$	$A_{1/2}^2$	$\mu \text{ (I=K)}$ (n.m.)	$Q \text{ (I=K)}$ (b)
$7/2^-$	65%	25%	7%	+4.7	-0.06
$5/2^-$	85%	14%	1%	+3.6	+1.7

The calculated positive parity spectrum suggests different possibilities to the experimentalist. Two, and possibly three, Nilsson states are expected to be close enough to the Fermi level to be observable at low energies. These are the $[411]3/2$, $[413]5/2$ and $[404]9/2$, which originate mainly from the $d_{5/2}$, $g_{7/2}$ and $g_{9/2}$ spherical j-shells, respectively. The Coriolis couplings between their rotational bands should be weak, so that the positions of the bandheads should reflect the positions and splittings of the intrinsic

Nilsson states rather directly, in contrast to the situation for the negative parity states. For example, the $[404]9/2$ is strongly upsloping on a Nilsson diagram, and as a result, simply observing the bandhead at low energy for Pm is an indication of strong deformation, since it is not expected within an MeV of the ground state unless $\beta \geq 0.27$. Also, because these rotational bands are expected to be quite pure ($\geq 95\%$ for the orbitals named), the simple analytic results for the strong coupling limit /10/ should be valid. This can greatly facilitate the identification of these orbitals, even if the bandhead spins are not known.

For example, the M1 properties of a rotational band sometimes provide a characteristic fingerprint of the Nilsson orbital, and the bands calculated here are excellent examples. Both the $[411]3/2$ and the $[404]9/2$ orbitals are "spin up" configurations, in which the intrinsic nucleon spin is primarily aligned with the orbital angular momentum, while the $[413]5/2$ orbital mainly has antialigned spin and orbital angular momenta. As a result, the intrinsic magnetic g -factors should be rather different, leading to quite different observable magnetic properties in the lab frame. The expectation value of the nucleon spin along the intrinsic symmetry axis and the derived g_K factor for these orbitals are listed in Table 2, and some of the expected M1 properties are shown in the figure. Although the predicted magnetic moments of the $5/2+$ and $3/2+$ bandheads are not so different, note that the M1 transitions nearly vanish for the $[413]5/2$ band, because $g_K \approx Z/A$ for that orbital. Clearly, the absolute M1 transition rates would easily distinguish these Nilsson orbitals, but the corresponding lifetimes are expected to be too short (a few psecs) to be easily measurable. Fortunately, relative M1/E2 strengths can provide substantial information and are much easier to determine. The $B(M1; I \rightarrow I-1)/B(E2; I \rightarrow I-2)$ ratio can be determined from the relative γ -ray intensities if the $I \rightarrow I-1$ mixing ratio is also known. As shown in the ovals in the figure, this ratio is expected to vary strongly from one band to another, with the M1's weakest in the $[413]5/2$ band, moderately strong in the $[411]3/2$, and very strong in the $[404]9/2$. The relative γ -ray intensities, shown inside the boxes, also show these clear distinctions. Thus the decay patterns of the bands should be sufficient to identify these Nilsson orbitals, even if spins and moments are not measured. The moments, of course, are especially useful when the description of the bandheads are simple, as here. In particular, the quadrupole moments of the bandheads would provide very direct information on the nuclear shape, free from the theoretical difficulties noted above for the $7/2-$ bandhead.

Table 2. Positive parity neutron orbitals expected close to the Fermi level for $Z = 61$ and $\beta \approx 0.27$, with the matrix elements needed for M1 properties, and the predicted moments for their bandheads.

Orbital	$\langle s_z \rangle$	g_K	$\mu (I=K)$ (n.m.)	$Q (I=K)$ (b)
$[411]3/2$	+0.40	+1.78	+2.0	+1.2
$[413]5/2$	-0.38	+0.56	+1.4	+2.1
$[404]9/2$	+0.50	+1.32	+5.3	+3.2

Finally, similar calculations have been performed for heavier Pm

nuclei with smaller deformations, but the results presented here provide a useful benchmark for the expected structure at strong deformation. As such, these results should be appropriate for ^{133}Pm or ^{135}Pm if these have $\beta \approx 0.30$, and still qualitatively appropriate if $\beta \geq 0.25$ or so. In fact, ^{133}Pm is predicted to be strongly deformed in both /5/ and /9/, as is ^{135}Pm in /5/. Very recently, in-beam measurements have been reported for ^{133}Pm /11/ that show both signatures of the $h_{11/2}$ band and a strong coupled band, assumed to be positive parity. The positive parity states are assigned as the [413]5/2 band in /11/, but strong dipole as well as stretched quadrupole transitions were observed there. Based on the calculations presented above, that positive parity band must be the [411]3/2. Indeed, the agreement between these calculations and those experimental results appears quite good, although additional low spin states are expected.

3.2 Odd-Mass Sm Isotopes

In the Sm isotopes, strong deformation is predicted for $N \leq 73$ in the Folded Yukawa calculations /5/ and for $N \leq 74$ for the Woods-Saxon /9/. However, unlike the Pm isotopes, ^{135}Sm and ^{137}Sm should show some differences in their low energy structure even if the deformations are very similar, because the neutron Fermi level is changing. Estimates of the expected bandhead positions in $^{133-139}\text{Sm}$ were given in /5/, but without additional information that might help identify these states and their rotational bands. The low energy spectra calculated with the Woods-Saxon version of the particle-rotor model differ somewhat from the results of /5/, and some simple features emerge particularly for ^{135}Sm . First, two Nilsson orbitals of each parity are expected close to the Fermi level for ^{135}Sm ; these are the [402]5/2, [404]7/2, [541]1/2 and [514]9/2. Secondly, the calculated rotational bands are quite pure at this deformation ($\beta \approx 0.29$) and particle number ($N = 73$), and thus the strong coupling limits are sufficient. Note that this is even true for the $h_{11/2}$ band, since the neutron Fermi level is rather high in the j-shell (closest to the [541]9/2). Also, as in the case of the well deformed Pm isotopes, these orbitals should have distinctive M1 properties that can be used to identify them. The relevant single particle matrix elements, intrinsic g_K factors and calculated bandhead moments are given in Tables 3 and 4, for these orbitals and two others discussed for ^{133}Sm .

Table 3. Neutron orbitals expected close to the Fermi level for $N = 73$ and $\beta \approx 0.29$, with relevant matrix elements and the predicted moments for their bandheads.

Orbital	$\langle s_z \rangle$	g_K	μ (I=K) (n.m.)	Q (I=K) (b)
[402]5/2	+0.46	-0.49	-0.8	+2.0
[404]7/2	-0.47	+0.36	+1.3	+2.5
[514]9/2	+0.47	-0.28	-0.9	+3.0
[523]7/2	+0.43	-0.33	-0.8	+2.6

Table 4. $\Omega = 1/2$ neutron orbitals expected close to the Fermi level for $N = 73$ and $\beta \approx 0.29$, their matrix elements relevant for M1 properties, and the predicted bandhead moments.

Orbital	$\langle n s_z n \rangle$	g_K	$\langle n j_z n \rangle$	$\langle n s_z n \rangle$	$\mu (I=K)$ (n.m.)
[411]1/2	-0.37	+1.98	+0.75	-0.13	+0.48
[541]1/2	+0.20	-1.07	+0.12	+0.70	+0.62

Note that the [402]5/2 and [404]7/2 orbitals are "spin up" and "spin down", respectively, and the bandhead magnetic moments are expected to have opposite signs. Also, the M1 transitions should be very weak in the [404]7/2 band because $g_K \approx Z/A$, but rather strong in the [402]5/2 band. Next, the $\Omega = 1/2$ orbitals have diagonal j_z and s_z contributions to the M1 properties, and these matrix elements are shown in Table 4 (with the phase convention for the conjugate orbitals of /10/). For the [541]1/2 orbital, the resulting "magnetic decoupling factor" is $b = +1.26$; the usual decoupling factor is just the negative of the j_z matrix element. This leads to an energy staggering in the band (1/2, 3/2), (5/2, 7/2), etc., and also in the BM1's with the low energy transitions favored (i.e., 3/2 $\rightarrow$ 1/2 strong, 5/2 $\rightarrow$ 3/2 weak, etc.). For the [514]9/2 band, strong M1 transitions and little staggering is expected. In the calculations for ^{135}Sm , the 5/2+ bandhead is the predicted ground state, followed by the 1/2-, 9/2- and 7/2+ bandheads, all within about 350 keV. These M1 matrix elements are not very sensitive to the deformation, but of course, the exact ordering is sensitive to this and other small details. The quadrupole moments listed in the table are essentially the strong coupling values, and thus reflect the deformation directly. Also, for ^{135}Sm , two other Nilsson orbitals are expected at low energy; these are the [523]7/2 and the [411]1/2 (with $b = +0.010$), as indicated in the tables. If the [523]7/2 is indeed close to the Fermi level, then Coriolis mixing in the $h_{11/2}$ band would probably invalidate the simple strong coupling description presented above. The positive parity bands, however, should remain nearly pure.

Finally, some data exist for ^{135}Sm and ^{136}Sm that can be compared with these predictions. For ^{135}Sm a positive parity bandhead (perhaps the ground state?) has been suggested with $I = 7/2$ /12/, 5/2 or 3/2 /13/, and also a negative parity bandhead (ground state?) with $I = 7/2$ /12/, 9/2 or 11/2 /13/. Two rotational bands were found at low energies in /12/, one with significant staggering in the energies, and both with $I \rightarrow I-1$ γ -transitions, although the intensities were not reported. The band with staggering is likely a mixed $h_{11/2}$ band as suggested in /12/; if so, this implies that the deformation is not as large as assumed here, and ^{135}Sm may be more transitional in character. Lifetime measurements in the even-even neighbors /14/ indicate that ^{134}Sm is strongly deformed ($\beta \approx 0.33$) while ^{136}Sm is somewhat less ($\beta \approx 0.25$), so ^{135}Sm is indeed at the boundary. The presence of $I \rightarrow I-1$ transitions in the second band strongly suggests that this is the [402]5/2 and not the [404]7/2 band. Similarly, in ^{136}Sm two strong coupled bands with connecting dipole transitions were reported in /11/, and were assigned to the [523]7/2 and [402]5/2 orbitals. The present calculations support those assignments. For both these

nuclei, ^{138}Sm and ^{139}Sm , moment measurements would be very valuable in establishing the dominant Nilsson components and the nuclear deformation.

4. CONCLUSIONS

In summary, the particle-rotor model with the "Warsaw" Woods-Saxon potential has been applied to well deformed odd-A Pm and Sm nuclei in the $A \approx 130$ region. The equilibrium deformations used here were taken from previous potential energy surfaces calculated with the same Woods-Saxon potential. All other parameters were taken at their standard values, and specific predictions for the expected low energy structure and electromagnetic properties of ^{131}Pm and ^{135}Sm are given, including the single particle configurations, bandhead spins and moments, and B_{M1}/B_{E2} ratios within rotational bands. Distinctive $M1$ properties are predicted for a number of Nilsson orbitals, and comparison with recent data for ^{131}Pm , ^{135}Sm and ^{139}Sm supports some earlier band assignments but also suggests some revisions. These results should help guide and stimulate further experimental work in this region, both at low and high spins.

ACKNOWLEDGEMENT

This work was supported by the U. S. Department of Energy under the grant DE-FG05-92ER40694.

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