DECAY–OUT OF THE HIGHLY–DEFORMED BANDS IN THE A=130–140 MASS REGION*

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Transitions linking the highly deformed band to low deformation states have been established in ^{137}Nd, ^{137}Sm, ^{139}Sm and ^{139}Gd with experiments performed at GASP. Whereas in ^{137}Nd the linking transitions account for 25% of the band intensity, in the other three nuclei almost 100% of it is found. The data prove that the HD bands are built on the $\nu i_{13/2}[660]1/2^+$ intruder orbital. In all cases, the sudden termination of the HD band is explained through the disappearance of the second minimum in the potential energy surface. A wide systematic of excitation energies and spin is now available for detailed comparison with calculations.

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1. Introduction

Several superdeformed (SD) or highly-deformed (HD) rotational bands have been discovered in recent years in the $A = 130 - 140$ region. These bands originate from a secondary prolate minimum in the potential energy surface at β_2=0.27÷0.35, associated with the occupation of the $\nu i_{\frac{13}{2}}[660]\frac{1}{2}^+$ intruder orbital [1]. Many features of the HD rotational bands are analogous to those of the superdeformed bands in the $A = 150$ and $A = 190$ mass regions. One of the characteristic features is the sudden depopulation of the bands to levels at normal deformation. The decay-out is fragmented into many pathways and is therefore very difficult to detect. Many attempts have been made in order to identify discrete transitions linking the states in the SD energy minimum to the normally-deformed structures. In the mass $A = 130 - 140$ region, the deformation in the second minimum is somewhat smaller than in the other two mass regions; furthermore, the so-called "normal deformed states" have a sizeable deformation β_2=0.20÷0.25. Because of these two reasons, it is believed that the decay out of the SD structure to the normal deformed one should be here relatively easy to observe.

The advent of the new generation of large detector arrays has greatly improved the sensitivity in detecting very weak transitions and by now the decay-out of the HD bands in the nuclei ^{133}Nd [2] and ^{135}Nd [3] has been studied in detail thus allowing the excitation energy and the spin of the bands to be determined. In ^{133}Nd, the decay of the HD band has been explained, in a quantitative way, in terms of an accidental mixing of the HD states with the normal deformed levels. A different interpretation of the decay out has been given in ^{135}Nd where the HD band ends at spin $25/2^+$ and no mixing with normal deformed levels has been observed; the sudden disappearance of the band seems here to be related to the disappearance of the HD potential energy minimum, as indicated by Total Routhian Surface (TRS) calculations.

With the purpose to understand in a more systematic way the decay-out mechanism of the HD bands in the mass $A = 130 - 140$ region, we have studied the nuclei ^{137}Nd [4], ^{137}Sm [5], ^{139}Sm [6, 7] and ^{139}Gd [8] where HD bands were already reported in the literature.

Concerning the decay-out of the HD bands, the situation is somewhat different for the four nuclei we will discuss in this lecture.

In ^{137}Nd no connection at all with normal deformed states has been found up to now whereas in the isotone ^{139}Sm a HD band has been recently reported [7] and connected through one single linking transitions to the normal deformed states. The transitions at the bottom of the HD band of this nucleus were also seen in a previous work where a different ordering was given. As we will show in the following, our results and the decay-out are in contrast with the preceding works.

The deformation parameter β_2 is known for all these bands from lifetime measurements using the Doppler Shift Attenuation Method [9].

In the $N = 75$ nucleus ^{137}Sm one linking transition of 1232 keV , connecting the lower member of the band with the $15/2^-$ level belonging to the [514]9/2 yrast band, has been reported. This transition however does not exhaust the band intensity and, due to the lack of other pathways, the excitation energy of the band may still be uncertain.

In ^{139}Gd a 616 keV E1 linking transition has been reported [8]: it feeds a band not connected to known states so that the excitation energy and the spin of the HD band are undetermined.

2. The experimental details

All the reactions reported have been studied by means of the Gamma Spectrometer GASP [10] consisting of an array of 40 Compton suppressed HP n-type Germanium detectors and an inner ball of 80 BGO scintillators. Events were collected when at least three suppressed Ge detectors and three inner ball detectors fired in coincidence. In the analysis of the data, a proper selection of the BGO ball parameters yields much cleaner spectra for the selected final nucleus, with respect to those obtained using only the triples Ge data.

By comparing data obtained with thin and thick targets it has been possible to clearly determine the transitions in coincidence with the HD cascade that belong to the decay-out. In fact, in the coincidence spectra the connecting transitions appear as sharp lines where, in the same energy range, the transitions of the highly deformed band are completely smeared by Doppler broadening.

The excellent timing performances of the CFD discriminators has allowed to discriminate neutrons from gammas reducing considerably the $(n, n'\gamma)$ background contribution in the 500–800 keV energy region were in some cases most of the interesting gamma rays are located.

2.1. The decay-out of the HD band in ^{137}Nd

The ^{137}Nd nucleus was populated via the ^{110}Pd(^{30}Si,3n) reaction at a beam energy of 125 MeV. Actually, this beam energy has been chosen for the study of HD bands in the nuclei ^{136}Nd and ^{136}Pr, but the ^{137}Nd nucleus was also populated with appreciable cross-section. Two different experiments have been performed with the ^{30}Si beam, one with a gold-backed target and one with a stack of thin ^{110}Pd foils. The first experiment had as a main purpose the establishment of the level scheme of ^{137}Nd where only few levels were known in the literature [11]. The highly deformed band of ^{137}Nd is populated in the reaction at the same level as that of the ^{136}Nd nucleus which is anyway the dominant reaction channel. As discussed above, the comparison of the γ-ray spectra in coincidence with the HD band obtained from the two different targets has allowed to establish that some transitions with energy around 1 MeV are linking the HD band to the normal deformed (ND) states. In order to better characterize the linking transitions we have performed a new experiment with the reaction ^{123}Sb + ^{19}F at 97 MeV. Only a gold-backed target has been used in this case.

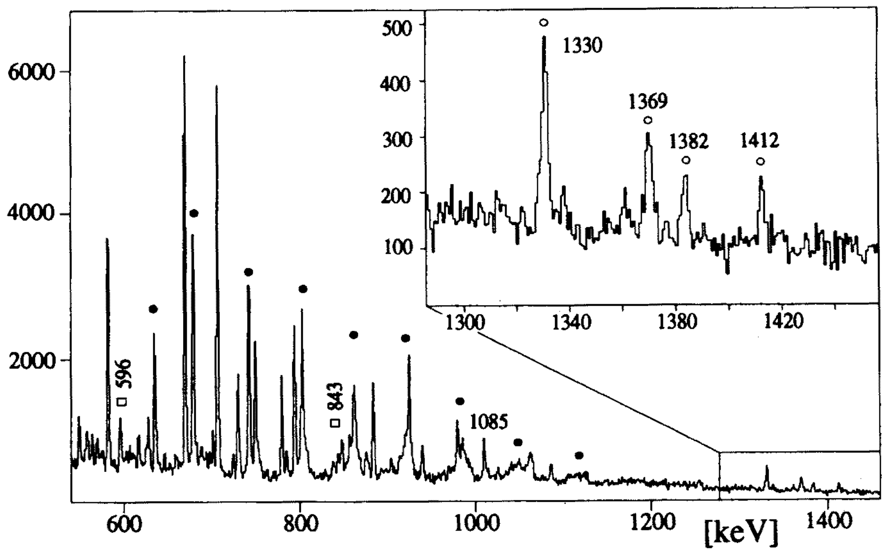

Fig. 1. High energy part of a doubly gated spectrum with gates set on some transitions in the ^{137}Nd HD band as obtained from the ^{123}Sb + ^{19}F with a gold-backed target. The transitions in the HD band are labelled with full dots; transitions connecting the HD band to the normal deformed states are labelled with open dots; open squares denote other transitions related to the decay-out.

In Fig. 1 we show the high energy part of a doubly gated spectrum, obtained with gates set on all transitions previously assigned to the ^{137}Nd band. In that spectrum it is evident that the band is in coincidence with the just mentioned transitions in the energy range 1–1.5 MeV.

With the high statistics obtained in the ^{19}F experiment ($380 \cdot 10^6$ events), we could establish coincidence relationships between four of the newly found linking transitions and the other transitions both in the HD band and in the normal deformed part of the nucleus. We could then place them (1330, 1369, 1382 and 1412 keV) in a level scheme thus fixing unambiguously the

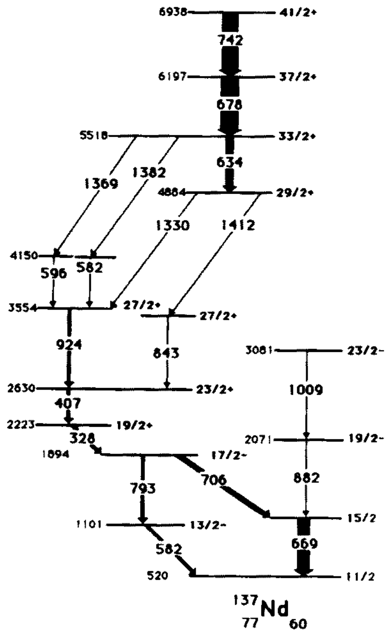

Fig. 2. Partial level scheme of ^{137}Nd showing the bottom of the HD band and the transitions linking the HD band to the normal deformed states.

excitation energy of the HD band in ^{137}Nd (see Fig. 2). From the analysis of the angular correlation data a $\Delta I = 1$ character is derived for the four linking transitions placed in the level scheme.

These transitions show a strong anisotropy which is similar to that of known $M1$ and very different from that of the $E1$ transitions which are also seen in the reaction. This fact implies that the high energy linking transitions are of mixed $M1 + E2$ character. Spin and parity $29/2^+$ is therefore fixed for the lowest HD band level at 4884 keV.

Many other transitions which link the HD band to the normal deformed levels are also seen in the data but we could not place them in the level scheme. The four linking transitions of Fig. 2 account for only $\approx 25\%$ of the band intensity.

2.2. The decay-out of the HD band in ^{137}Sm

The ^{137}Sm nucleus has been studied through the ^{104}Pd(^{37}Cl,$p3n$) reaction at a beam energy of 172 MeV. The target of 1 mg/cm^2 was on a 10 mg/cm^2 gold-backing, and the beam current was 35 nA. In this experiment $420 \cdot 10^6$ events were recorded.

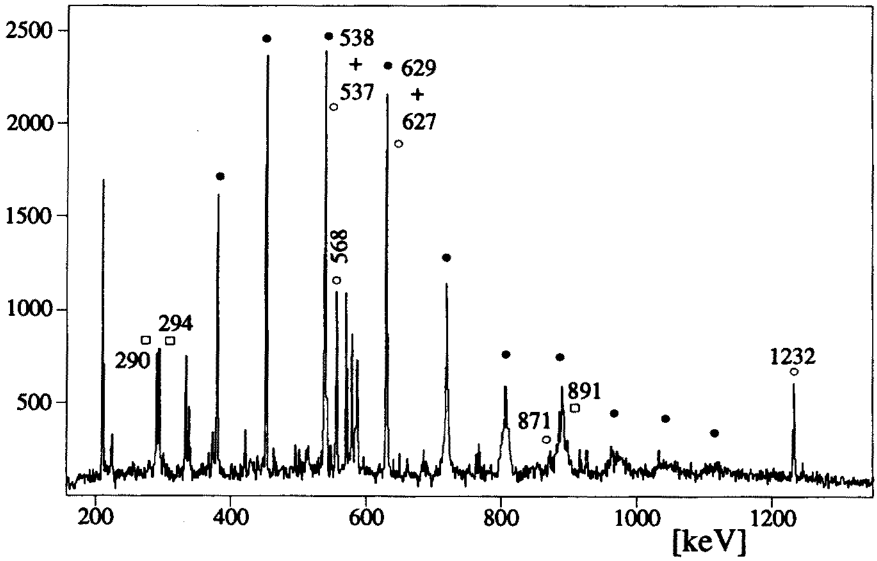

Fig. 3. Single gated spectrum with gates set on transitions in the ^{137}Sm HD band (379, 538, 629, 719 and 807 keV) as obtained from the ^{104}Pd + ^{37}Cl reaction with the gold-backed target.

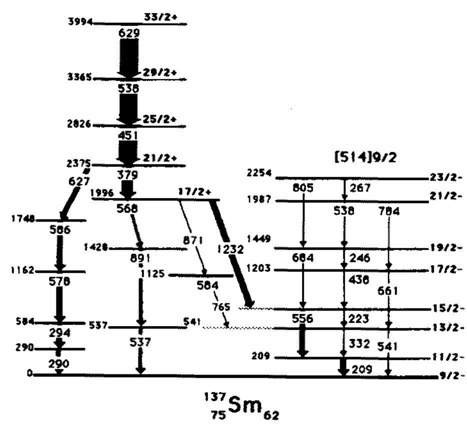

Fig. 4. Partial level scheme of ^{137}Sm showing the bottom of the HD band and the transitions linking the HD band to the ND states.

The evidence for a 1232 keV linking transition, which connects the lowest state of the HD band to the 15/2$^-$ state of the [514]9/2 band, was found by Ma *et al.* [6]. In that measurement the DCO ratio for the linking transition was measured and found compatible with a dipole character.

In Fig. 3 the single gated gamma spectrum, with gates set on several member of the HD band, is shown. Besides the 1232 line, three new linking transitions of 871, 568 and 627 keV respectively have been found. The partial level scheme resulting from the analysis of the coincidence data is displayed in Fig. 4.

With the new determined linking transitions the excitation energy and the spin of the lowest level of the HD band are fixed to be 2375 keV and $17/2^+$ respectively. The good energy resolution of GASP (2.4 keV mean energy resolution for the ^{60}Co 1.332 keV line) was essential to clarify the new decay paths as the lines are often part of complex peaks. The reported decay paths account for more than 80% of the band intensity. Further analysis of the data is in progress.

2.3. The decay-out of the HD band in ^{139}Sm

The ^{139}Sm nucleus has been studied through the ^{110}Pd (^{34}S,5n) reaction at a beam energy of 150 and 165 MeV.

The target of 0.9 mg/cm^2 was on a 10 mg/cm^2 gold-backing, and the beam current was typically 40 nA; 800·10^6 events were recorded. Angular correlation information was extracted from the coincidence data.

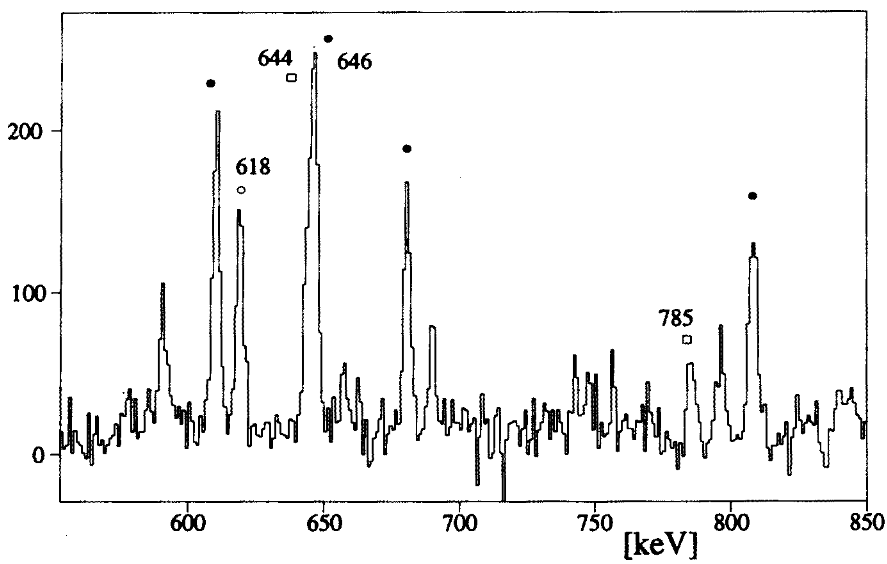

Fig. 5. Single gated spectrum with gate set on the ^{139}Sm HD band 734 keV transition.

The decay scheme derived from the analysis of both experiments, confirms the results reported in Ref. [8] and extends up to 13.5 MeV in excitation energy and to $I^\pi = 65/2^+\hbar$ in spin.

A study on the HD band of ^{139}Sm has been recently published. The band is connected to the ND states through a 609 keV transition which is supposed to have a ΔI=1 character but DCO ratios could not be measured.

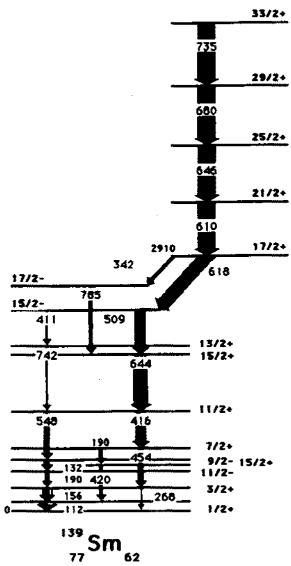

Fig. 6. Partial level scheme of ^{139}Sm.

In Fig. 5 we report the single gated spectrum with gates set on the ^{139}Sm HD band members, as obtained from our data. The 616 keV line appears weaker when compared with the 609 one and this fact favours the 616 keV transition as the linking one being other pathways for the decay-out possible. In fact we have seen another transition of 342 keV which decay into the $19/2^-$ level belonging to the same band as the $15/2^-$ populated by the 616 keV line. The DCO analysis of the 616 keV transition gives a dipole character of this line. In this way we have unambiguously fixed excitation energies and spin of the HD band. In Fig. 6 the partial decay scheme of ^{139}Sm is shown.

The decay out of this HD band is much simpler than that of the previous cases. Most of the decay intensity is carried out by the 616 keV line (80%) with the 342 keV line accounting for the remaining 20%.

2.4. The decay-out of the HD band in ^{139}*Gd*

The ^{139}Gd nucleus has been studied through the ^{92}Mo(^{50}Cr,2*pn*) reaction at a beam energy of 220 MeV. The target of 0.9 mgr/cm^2 was on a 15 mg/cm^2 gold-backing. The beam intensity was typically 15 nA; 250·10^6 events were recorded.

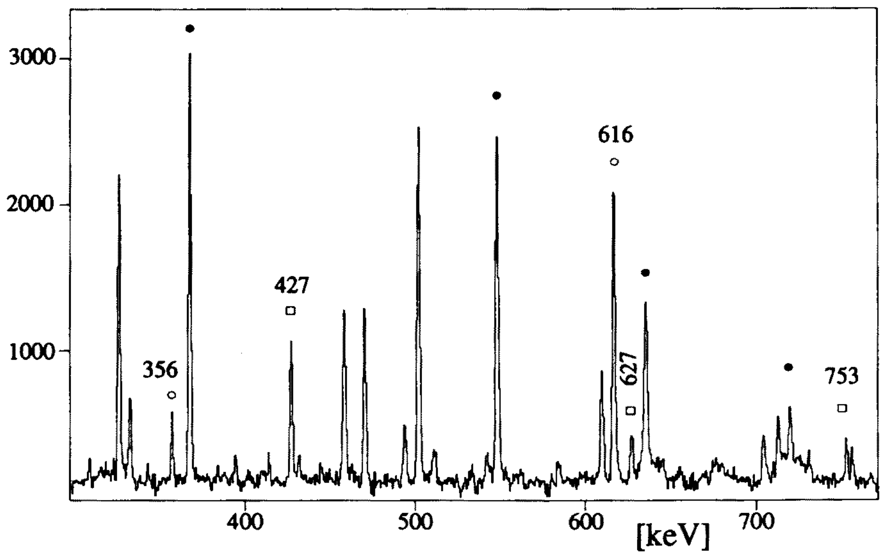

Fig. 7. Single gated spectrum with gate set on the ^{139}Gd HD band 458 keV transition.

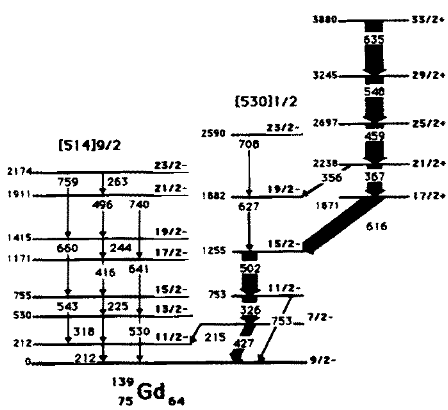

Fig. 8. Partial level scheme of ^{139}Gd.

The HD band based on the $i_{13/2}$ intruder orbital and its connection to a normal deformed state, was reported by Ma *et al.*[9]. Anyway, this second band, which is supposed to be based on the [530]1/2 orbital, is not connected to the [514]9/2 ground state band and therefore also the excitation energy of the HD band remains undetermined.

In Fig. 7 we report a gated spectrum which clearly shows the already known 618 keV line (80% of the HD band intensity) and a new 356 keV transition (20%) together with the two 753 and 427 keV transitions de exciting the $11/2^-$ and $7/2^-$ levels of the mentioned [530]1/2 band.

Furthermore in (Fig. 8) the 215 keV line connecting the $7/2^-$ [530]1/2 level to the $11/2^-$ ground state band is shown. The partial level scheme is displayed in (Fig. 9) where the $17/2^+$ lowest level of the HD band is located at 1871 keV with respect to the $9/2^-$ ground state. Further analysis of the data is in progress.

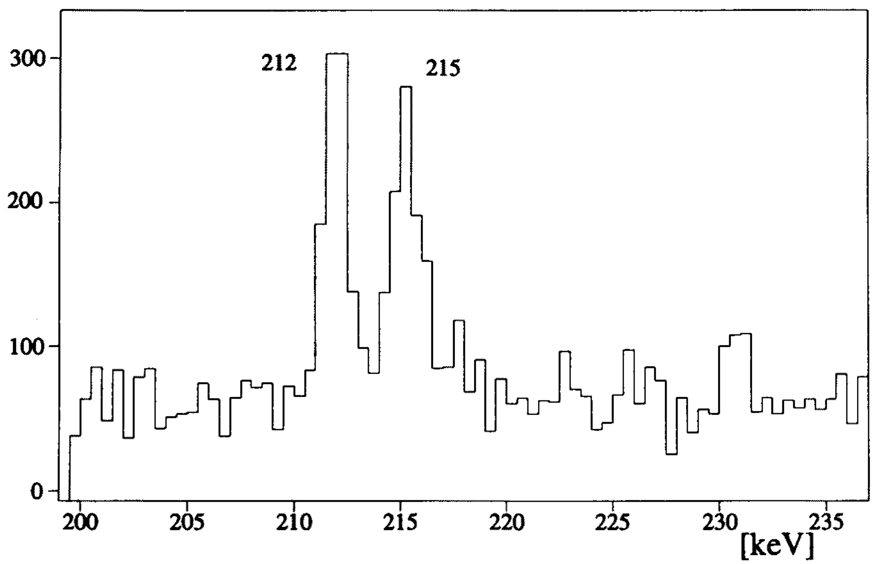

Fig. 9. Single gated spectrum with gate set on the ^{139}Gd 326 keV transition.

3. Discussion

The present results, together with our previous work on ^{133}Nd and the results in ^{135}Nd obtained by the Berkeley group, have proven definitively the predicted $i_{13/2}$ character of the superdeformed and highly deformed bands in the $A = 130$ mass region. It is therefore now possible to compare the data with Total Routhian Surface Calculations that are predicting the decay-out details of the $i_{13/2}$ HD bands.

In ^{137}Nd TRS calculations shows a triaxial minimum ($\beta_2 = 0.27$, $\gamma \approx 15°$) at high rotational frequencies for the $i_{13/2}$ configuration. With decreasing frequencies the shape changes to a more prolate one ($\beta_2 = 0.29$, $\gamma \approx 2°$) until this minimum disappears at $\hbar\omega \approx 0.3$ MeV where an oblate shape ($\beta_2 = 0.18$, $\gamma \approx -30°$) minimizes the total energy of the nucleus. This is exactly the point where the HD band in ^{137}Nd disappears.

Also in ^{137}Sm and ^{139}Gd there is a fairly good agreement between experiment and calculations. In both cases the minimum disappears at $\hbar\omega \approx 0.25$ MeV and the shape changes from a pure prolate ($\beta_2 = 0.35$) to an oblate one.

In ^{139}Sm the TRS calculations give a triaxial shape at $\hbar\omega \approx 0.50$ MeV with ($\beta_2 = 0.27$, $\gamma \approx 21°$) and the minimum disappears at $\hbar\omega \approx 0.50$ MeV while experimentally the band continues down to $\hbar\omega \approx 0.3$ MeV before decaying to normal deformed states.

In conclusion we established the detailed decay-out of the HD bands in ^{137}Nd, ^{137}Sm, ^{139}Sm and ^{139}Gd establishing the excitation energy, the spin and parity of the band levels. In all the studied nuclei we confirm the predicted $i_{13/2}$ character of the band. The ^{137}Sm, ^{139}Sm and ^{139}Gd decay to normal deformed states from the $17/2^+$ state and 100% of the band intensity has been seen. In ^{137}Nd the band ends at $29/2^+$ and only 25% of its intensity has been placed in the decay scheme. Although the presented experiments are still under analysis, a wide set of data is now available for a more complete comparison with detailed model calculations.

REFERENCES

[1] R.A. Wyss, J. Nyberg, A. Johnson, R. Bengtsson, W. Nazarewicz, *Phys. Lett.* **B215**, 211 (1988).

[2] D. Bazzacco, F. Brandolini, R. Burch, S. Lunardi, E. Maglione, N.H. Medina, C. Rossi–Alvarez, G. deAngelis, D. DeAcuña, M. De Poli, J. Rico, D. Bucurescu, C. Ur. *Phys. Rev.* **C49**, R2281 (1994).

[3] R.M. Clark, M.A. Deleplanque, J.A. Becker, M.J. Brinkman, B. Cederwall, R.M. Diamond, J.E. Draper, C. Duyar, P. Fallon, L.P. Farris, E.A. Henry, H. Hübel, J.R. Huges, W. Korten, I.Y. Lee, A.O. Macchiavelli, E.C. Rubel, F.S. Stephens, Proc. Conf. on Physics with large Gamma-ray detector Arrays, Berkeley 1994, Proceedings Vol. 1, p. 9.

[4] R. Wadsworth, A. Kirwan, D.J.G. Love, Y-X. Luo, J-Q. Zhong, P.J. Nolan, P.J. Bishop, M.J. Godfrey, R. Hughes, A.N. James, I. Jenkins, S.M. Mullins, J. Simpson, D.J. Thornley, K.L. Ying, *J. Phys. G* **13**, L207 (1987).

[5] R. Ma, C.W. Beausang, E.S. Paul, W.F. Piel, Jr., S. Shi, N. Xu, D.B. Fossan, J. Burde, M.A. Deleplanque, R.M. Diamond, A.O. Macchiavelli, F.S. Stephens, *Phys. Rev.* **C40**, 156 (1989).

[6] D. Bazzacco, S. Lunardi, G.C. Nardelli, M. De Poli, G. deAngelis, *Z. Phys.* **A335**, 1363 (1994).

[7] P. Vaska, S. Bhattacharjee, D.B. Fossan, D.R. LaFosse, Y. Liang, H. Schnare, K. Starosta, M.P. Waring, I. Hibbert, R. Wadsworth, K. Hauschild, C.W. Beausang, S. Clarke, S.A. Forbes, P.J. Nolan, E.S. Paul, A.T. Semple, S.M. Mullins, H. Grawe, K.H. Maier, *Phys. Rev.* **C50**, 104 (1994).

[8] R. Ma, D.B. Fossan, E.S. Paul, N. Xu, R.J. Poynter, P.H. Regan, R. Wadsworth, Y-J. He, I. Jenkins, M.S. Metcalfe, S.M. Mullins, P.J. Nolan, *J. Phys. G.* **16**, 1233 (1990).

[9] S.M. Mullins, I. Jenkins, Y-J. He, A.J. Kirwan, P.J. Nolan, J.R. Hughes, R. Wadsworth, R.A. Wyss, *Phys. Rev.* **C45**, 2683 (1992).

[10] D. Bazzacco. Proc. Intern.Conf. on Nuclear structure at high angular momentum, Ottawa, 1992, Vol.2, Proceedings AECL 10613.

[11] J. Gizon, A. Gizon, M.R. Maier, R.M. Diamond, F.S Stephens, *Nucl. Phys.* **A222**, 557 (1974).