Eur. Phys. J. A **11**, 9–13 (2001)

THE EUROPEAN PHYSICAL JOURNAL A

© Società Italiana di Fisica
Springer-Verlag 2001

A new μs isomer in ^{136}Sb produced in the projectile fission of ^{238}U

M.N. Mineva[1,a], M. Hellström[1,2], M. Bernas[3], J. Gerl[2], H. Grawe[2], M. Pfützner[4], P.H. Regan[5], M. Rejmund[6], D. Rudolph[1], F. Becker[6], C.R. Bingham[7], T. Enqvist[8], B. Fogelberg[9], H. Gausemel[10], H. Geissel[2], J. Genevey[11], M. Górska[2], R. Grzywacz[7], K. Hauschild[6], Z. Janas[4], I. Kojouharov[2], Y. Kopatch[2], A. Korgul[4], W. Korten[6], J. Kurcewicz[4], M. Lewitowicz[12], R. Lucas[6], H. Mach[9], S. Mandal[2], P. Mayet[2], C. Mazzocchi[2,13], J.A. Pinston[11], Zs. Podolyàk[5], H. Schaffner[2], Ch. Schlegel[2], K. Schmidt[2], K. Sümmerer[2], and H.J. Wollersheim[2]

[1] Division of Cosmic and Subatomic Physics, Lund University, SE-22100 Lund, Sweden
[2] Gesellschaft für Schwerionenforschung mbH, D-64291 Darmstadt, Germany
[3] Institut de Physique Nucléaire d'Orsay, IN2P3-CNRS, F-91406 Orsay Cedex, France
[4] Institute of Experimental Physics, Warsaw University, PL-00861, Poland
[5] Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom
[6] CEA Saclay, DSM/DAPNIA/SPhN, F-91191 Gif-sur-Yvette Cedex, France
[7] Department of Physics, University of Tennessee, Knoxville, TN 37996, USA
[8] Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 7ZE, United Kingdom
[9] Department of Radiation Science, Uppsala University, S-61182 Nyköping, Sweden
[10] Department of Chemistry, University of Oslo, Blindern, N-0315 Oslo, Norway
[11] Institut des Sciences Nucléaires, IN2P3-CNRS/Université Joseph Fourier, F-38026 Grenoble Cedex, France
[12] Grand Accélérateur National d'Ions Lourds, BP 5027, F-14021 Caen Cedex, France
[13] Università degli Studi di Milano, I-20133 Milano, Italy

Received: 23 April 2001
Communicated by D. Schwalm

Abstract. The neutron-rich isotope ^{136}Sb has been produced following the relativistic projectile fission of ^{238}U in an experiment performed at the Fragment Separator at GSI, Darmstadt. Delayed γ-ray spectroscopy of the fission products has been performed after isotope separation. A new isomeric state in ^{136}Sb has been populated, and its lifetime measured as $T_{1/2} = 565(50)$ ns. Realistic and empirical shell-model calculations have been performed and are compared to the experimental observables.

PACS. 21.10.Tg Lifetimes – 21.60.Cs Shell model – 25.75.-q Relativistic heavy-ion collisions

1 Introduction

In the vicinity of the magic $Z = 50$ and $N = 82$ shell closures, the coupling of valence particles and holes in relatively high-j orbitals frequently gives rise to isomeric states with moderate spin. Indeed, the presence of more than one β-decaying state in given nuclei is a characteristic feature for this region, and several nuclei are also known to have isomeric states with half-lives in the microsecond regime.

With its 51 protons and 85 neutrons, ^{136}Sb forms an interesting system with one proton and three neutrons outside the doubly magic ^{132}Sn core. Because of its odd-odd character, information about its lower-lying excited structure should give direct access to the proton-neutron interaction in this rather neutron-rich region of the nuclidic chart. Of special interest is the question of how these low-lying configurations develop as more protons and neutrons are added to ^{132}Sn. In analogy with the situation in the ^{208}Pb region, as investigated by Alexa and Sheline [1], it is expected that mixing will increase with the number of valence particles until, ultimately, quadrupole-deformed collective states form.

^{136}Sb was first observed as a β-delayed neutron precursor [2] produced in thermal neutron-induced fission of ^{235}U, and its βn-emission half-life was determined to be $T_{1/2} = 0.923(14)$ s [3]. Hoff *et al.* [4] studied the β-decay in detail and concluded from the population pattern of states in the daughter nucleus ^{136}Te that the ^{136}Sb ground state most likely has $I^\pi = 1^-$ and is dominated by the $\pi g_{7/2}\nu f^3_{7/2}$ configuration. Interestingly, Hoff *et al.* report only one β-decaying state, and no other excited states in ^{136}Sb have been observed.

In contrast, ^{134}Sb, which has two neutrons less than ^{136}Sb, has two β-decaying states: the $I^\pi = 0^-$, $T_{1/2} =$

[a] e-mail: Milena.Mineva@kosufy.lu.se

0.85 s ground state and a $I^\pi = 7^-$, $T_{1/2} = 10$ s isomer. Both levels are members of the $(\pi g_{7/2}\nu f_{7/2})_{0^-,\ldots 7^-}$ multiplet [5]. Although the excitation energy of the 7^- state and the placement of excited states between the 0^- and 7^- are still uncertain [6], a number of levels built on top of the 7^- isomer are known [5].

The ^{208}Pb region counterpart of ^{136}Sb is ^{212}Bi, which has the same number of protons and neutrons outside the doubly magic core. ^{212}Bi has an $I^\pi = 1^-$, $T_{1/2} = 60.5$ min ground state and an $I^\pi = 8^-(9^-)$, $T_{1/2} = 27$ min β-decaying isomer, both with the configuration $\pi h_{9/2}\nu g^3_{9/2}$ [7].

In principle, spectroscopic information about excited states in ^{136}Sb could be obtained by studying the β-decay of ^{136}Sn. Indeed, first results from the β-decay of very neutron-rich Sn isotopes have been obtained in a laser ion-source experiment at CERN/ISOLDE [8]. No γ-ray transitions in ^{136}Sb have been observed. It should be noted that in the β-decay the mother nucleus ^{136}Sn has ground-state spin and parity $I^\pi = 0^+$. Hence, population of high-spin states in the daughter ^{136}Sb is very unlikely. Recently, particle-tagged delayed-coincidence spectroscopy of isomers produced directly in nuclear reactions has emerged as a successful alternative method to study excited states in nuclei far from the valley of β-stability [9,10].

We have applied this new method to produce and investigate microsecond range isomers in the region around ^{132}Sn using projectile fission as a population mechanism. With the present study, ^{136}Sb becomes the most neutron-rich Sb isotope from which γ-rays have been observed. As pointed out in ref. [11], spectroscopy of exotic nuclei offers a unique test of the components of the effective interactions that depend on the isospin degree of freedom. Continued investigations of ^{136}Sb and other neutron-rich nuclei beyond ^{132}Sn will enhance the understanding of how the shell structure and nuclear mean field develop when approaching the neutron drip-line.

2 Experiment

The experiment was performed at the FRagment Separator (FRS) at GSI, Darmstadt [12]. Neutron-rich nuclei around ^{132}Sn were produced in the projectile fission of ^{238}U at the relativistic energy of 750 MeV/u impinging on a 1 g/cm^2 ^{9}Be target. The average beam intensity from the SIS heavy-ion synchrotron was 1×10^7 ^{238}U ions per second.

The ions of interest were separated by combining magnetic analysis with energy loss in matter [12]. The FRS was operated in a standard achromatic mode and a wedge-shaped degrader with thickness set to 50% of the range of the selected fragments was placed at the central focal plane of the spectrometer. Over a four days running period, we covered three different settings optimized for ^{131}Sn, ^{134}Sn, and ^{130}Cd, respectively. For each production setting of the FRS, between 12 and 20 different fragment species were transmitted to the final focal plane, and in total some 30 isotopes in the neutron-rich Cd to Te with neutron numbers N varying from 76 to 87 were observed.

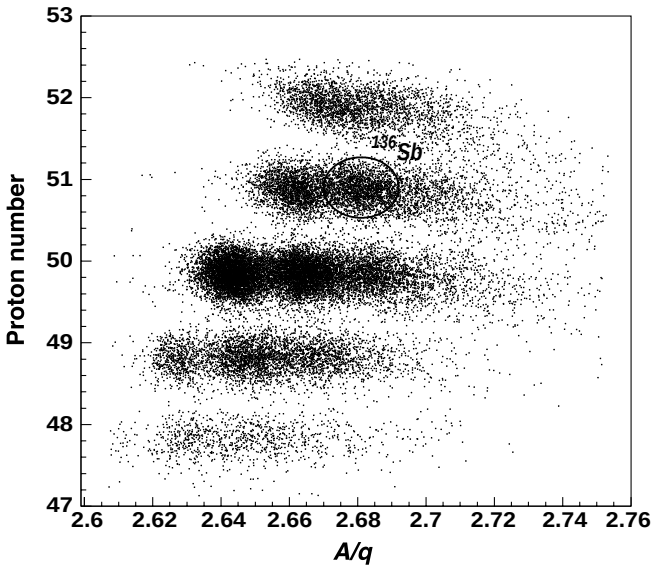

Fig. 1. Particle identification spectrum showing the proton number Z *vs.* the mass-to-charge ratio A/q for fragments reaching the final focal plane of the separator during the setting optimized for ^{134}Sn. Each group represents a single isotope, as schematically indicated for ^{136}Sb.

Due to the specific kinematics of in-flight fission, the total transmission (including nuclear absorption as well as straggling effects) from the production target to the final focal plane was $\approx 1\%$. The separated ions were identified event by event via combined time-of-flight, position tracking, and energy loss measurements. The FRS detectors were calibrated using the ^{238}U primary beam at different velocities.

Figure 1 presents the particle identification plot of the second setting, in which ^{136}Sb was transmitted. The transmission losses [10], due to the reaction products picking-up electrons (thereby altering their A/q ratio) while passing through the different layers of matter in the separator, was very small: 99.0% of the Sn and 98.7% of the Te fragments were fully stripped in the second stage of the FRS.

It should be noted here that the relativistic character of the in-flight fission process introduces a gain factor [13] with respect to the fission at rest: the high laboratory velocity of the fissioning projectile nucleus ($\approx 83\%$ of the speed of light) leads to an optimal transmission for those fragments that are emitted in a forward or backward direction with respect to the beam. The resulting "kinematic boost" implies that for equal fission rates, nuclei produced with cross-sections up to three orders of magnitude smaller can be separated and studied [13], thus significantly extending the possibilities for spectroscopy in very neutron-rich regions of the nuclidic chart [14].

At the final focus, the fragments of interest were slowed down using an adjustable aluminum degrader (6.3 g/cm^2 for the setting in which ^{136}Sb was identified) and subsequently implanted in a 6.5 mm thick aluminum catcher. By comparing the energy loss signal from plastic scintillator counters placed just in front of and after the adjustable degrader, those fragments (up to 30% for a given isotope!),

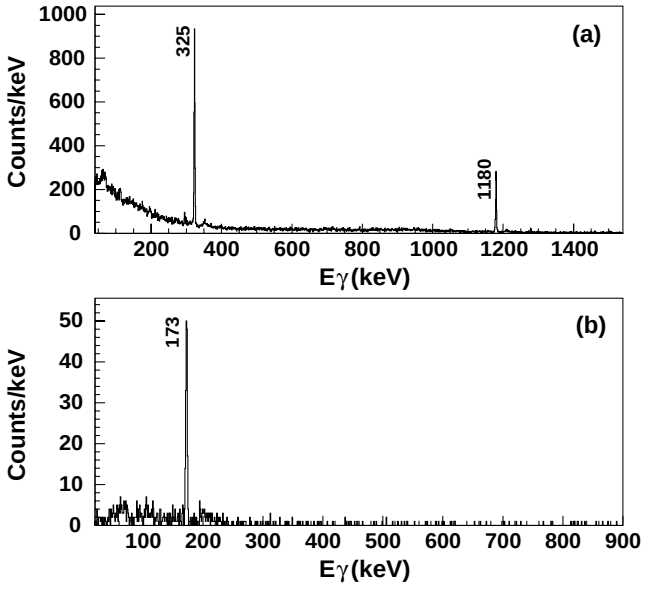

Fig. 2. γ-ray spectra measured in delayed coincidence with implanted ions of (a) ^{135}Te (delay interval 0.25–8.0 μs), and (b) ^{136}Sb (0.5–8.0 μs). The energy labels are in keV.

undergoing charge-changing reactions during the slowing-down process, could be rejected. In addition, a veto scintillator placed after the catcher helped to reject ions that were not implanted correctly.

The catcher was surrounded by four segmented Clover-type Ge detectors [15], in which delayed γ-rays emitted by the implanted ions were detected. The Ge detectors were energy and efficiency calibrated using standard sources.

The flight time of the ions through the separator is about 300 to 400 ns, which typically sets a lower limit of about 100 ns for the lifetimes which can be studied. γ-rays from the decay of any isomeric state were recorded within a 80 μs time gate, which was started with the detection of a heavy-ion event. This slow coincidence technique allowed us to correlate the detected γ-rays with the implanted heavy ions. The time interval between the implantation and delayed γ-ray was measured by using both TDCs (8 μs range) and TACs (80 μs range).

More details about the experiment can be found in ref. [16].

Table 1. Summary of determined half-lives

Isotope	I^π	$T_{1/2}$ (ns) present work	$T_{1/2}$ (ns) previous work
^{134}Te	6^+	165 (6)	164 (1) [17]
^{135}Te	$19/2^-$	512 (22)	510 (20) [18]
^{136}Sb	-	565 (50)	-

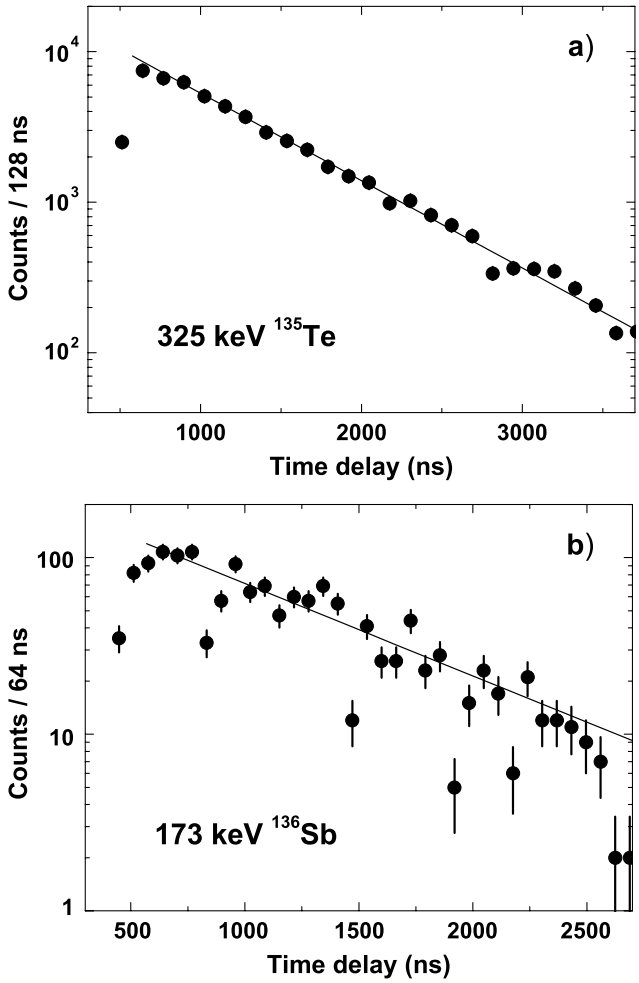

Fig. 3. Time distribution curves of the (a) 325 keV line from the decay of the $I^\pi = 19/2^-$ isomer in ^{135}Te, and (b) the 173 keV line identified in ^{136}Sb.

3 Analysis and results

By selecting events associated with a single isotope species, very clean γ-ray spectra can be obtained. Figure 2 shows delayed γ-ray spectra measured in coincidence with implanted ions of ^{135}Te and ^{136}Sb, respectively. The previously reported isomers in ^{134}Te ($I^\pi = 6^+$, $T_{1/2} = 164$ ns) [17] and ^{135}Te ($I^\pi = 19/2^-$, $T_{1/2} = 510$ ns) [18] have half-lives in the range (≈ 100 ns–1 ms) that can be studied using the described technique (see table 1). They were used as reference both for the particle identification in the first fragment setting, and to verify the procedure for the lifetime determination. The particle identification of the second setting (cf. fig. 1), where the ^{136}Sb isomer was observed, was firmly established using the well known $I^\pi = 8^+$, $T_{1/2} = 2.03$ μs isomer in ^{132}Sn [19].

Time spectra from the particle-delayed γ-coincidence measurements for the 325 keV γ-ray in ^{135}Te and the 173 keV transition in ^{136}Sb are shown in fig. 3. The prompt part of the decay time distributions have been subtracted. The half-lives were extracted by fitting the slope, assuming a single component decay. The results are summarized in table 1 and compared with previous measurements of known isomers.

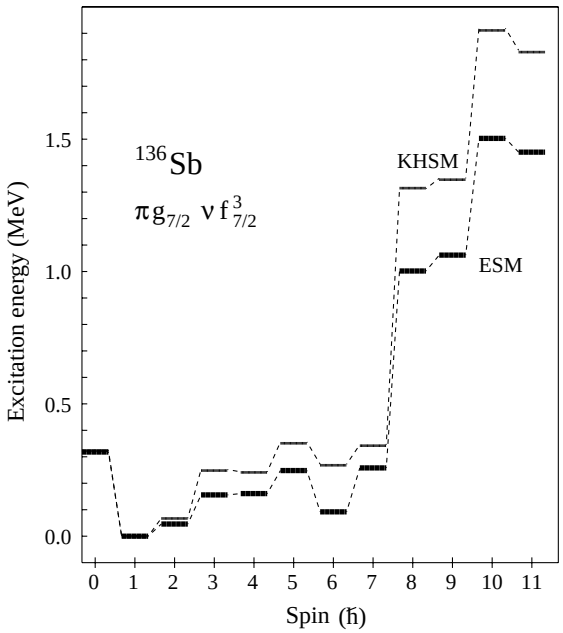

Fig. 4. Comparison of realistic (KHSM, thin lines) and empirical (ESM, thick lines) shell-model calculations for the $\pi g_{7/2}\nu f^3_{7/2}$ multiplet in ^{136}Sb. The two different approaches give very similar results. All states below 1 MeV have negative parity in the full (KHSM) calculation.

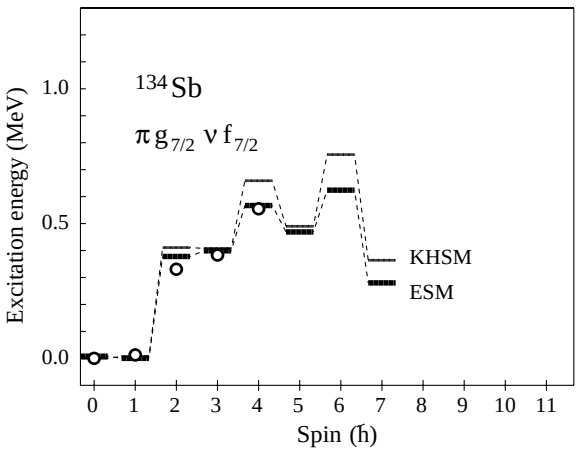

Fig. 5. KHSM and ESM shell-model calculations for the $\pi g_{7/2}\nu f_{7/2}$ multiplet in ^{134}Sb, see the caption of fig. 4 Experimental level energies from ref. [6] are indicated by open circles.

4 Discussion

Since the residual interaction and the quadrupole properties of the ^{132}Sn and ^{208}Pb regions are rather similar [17,20], and because the $E2$ effective charges are essentially equal, we can expect the shell-model descriptions for the lowest-lying $\pi\nu$ multiplets to be very similar [21]. This is especially true when comparing nuclei with ground-state configurations involving both protons and neutrons in orbitals with the same number of nodes in their radial wave functions ($\pi 1g_{7/2}$ and $\nu 2f_{7/2}$ in the ^{132}Sn region, corresponding to $\pi 1h_{9/2}$ and $\nu 2g_{9/2}$ in the ^{208}Pb region).

Indeed, after appropriate scaling with $A^{-1/3}$, interaction strengths and matrix elements obtained around ^{208}Pb can be applied also for nuclei close to ^{132}Sn [17,20,21]. (Note however that, as the collective negative-parity states in ^{132}Sn are higher than in ^{208}Pb, the *octupole* properties of the two regions may differ significantly.)

The observation of only a single delayed γ-ray transition associated with ^{136}Sb makes it difficult to reconstruct the properties of excited states in this nucleus. In order to provide more information, we have therefore performed spherical shell-model calculations, using two different sets of interactions, to estimate the excitation energies of the lowest-lying states. The latest experimental information on single-particle energies in the ^{132}Sn region were included [22,23].

The Kuo-Herling shell model (KHSM) uses realistic two-body matrix elements calculated for the ^{208}Pb region and scaled down by $A^{-1/3}$ in the full $Z = 50$ to 82 and $N = 82$ to 126 model space with mixing [24–26]. The empirical shell model (ESM), on the other hand, uses two-body matrix elements (TBME) scaled from the $\pi h_{9/2}\nu g_{9/2}$ multiplet in ^{210}Bi to $\pi g_{7/2}\nu f_{7/2}$, and $f^2_{7/2}$ TBME obtained from ^{134}Sn. Pure configurations are assumed.

The results of the calculations for ^{136}Sb are summarized in fig. 4. The two models predict very similar behaviour of the $\pi g_{7/2}\nu f^3_{7/2}$ multiplet members, and both correctly reproduce the observed ground-state spin and parity $I^\pi = 1^-$ [4].

Based on the calculations, several scenarios for the observed isomeric level in ^{136}Sb are possible. A high-spin ($I > 7$) isomer is highly unlikely due to the lack of observation of other, higher energy (≈ 1 MeV) γ-ray transitions. In principle, such a high-spin isomer may be possible if the isomeric structure was built on top of a β-decaying isomer. However, this is at variance with the fact that only one β-decaying state has been observed so far [4]. As a second scenario, favored by the ESM calculations we propose a 4^- isomer decaying to the 2^- state via the observed 173 keV $E2$ transition. The ESM predicts that the 6^- state would be a β-decaying isomer, which is again in disagreement with ref. [4]. The experimental $B(E2)$ value of the 173 keV isomeric transition is then deduced as 0.125(11)Wu, which appears low in comparison with $B(E2) = 4.5$ Wu given by the ESM model for an isomeric 4^- to 2^- transition.

To solve the discrepancy a third scenario can be considered. We assume a low energy (< 50 keV) unobserved primary transition 4^- to 2^-, and the detected 173 keV γ-ray would then be a 2^- to 1^- $M1$ transition. The conversion coefficient for a 50 keV $E2$ transition in ^{136}Sb is $\alpha_{\rm tot} = 20.2$, which leads to $B(E2) = 3.6(3)$ Wu. However, this scheme is at variance with the large energy splitting predicted for the 4^- to 2^- states in both models.

We, therefore, propose as the most probable scenario that the observed isomer results from the small energy spacing between the 6^- and 4^- members of the $\pi g_{7/2}\nu f^3_{7/2}$ multiplet. This scheme is favored by the more elaborate KHSM model, and is consistent with the predicted level spacing, the $B(E2)$ values, and the non-observation of a

high-spin (6^-) β-decaying state. The observed 173 keV γ-ray would in this case be the 4^- to 2^- $E2$ transition, and the low energy 6^- to 4^- and 2^- to 1^- transitions are not observed due to electron conversion and/or absorption in the aluminum catcher. Using the measured half-life, we deduce $B(E2) = 7.7(7)$ Wu for a 26 keV ($\alpha_{\rm tot} > 250$) 6^- to 4^- transition —the level spacing predicted by KHSM. This value is in good agreement with the KHSM theoretical prediction of 5.6 Wu (corresponding to a half-life of $\approx$ 780 ns), and is not strongly dependent on the precise energy of the unobserved transition.

We have also performed the corresponding calculations for the lowest-lying $\pi g_{7/2}\nu f_{7/2}$ multiplet in ^{134}Sb, as shown in fig. 5. Included for reference are the experimental level energies from ref. [6]. The agreement between the calculations and experiment is striking, as is the close similarity between the two models.

A comparison of the calculated 0^-–7^- level energies in the two even-mass antimony isotopes shows rather different trends. In ^{134}Sb, the lowest-lying multiplet members are those with the lowest and highest spins, whereas the intermediate-spin levels lie at significantly higher excitation energies. In contrast, the corresponding levels in ^{136}Sb are predicted (in both models) to have a much flatter distribution. A very similar behavior is also observed in the ^{208}Pb region, as exemplified by the corresponding nuclei ^{210}Bi and ^{212}Bi [1].

We interpret this flattening out to be a natural consequence of the presence of two additional neutrons. As the occupation of the neutron $f_{7/2}$ orbital increases, the $\pi\nu$ particle-particle interaction in ^{134}Sb should change into a particle-hole interaction in ^{140}Sb. The signature of such a Pandya transformation is a gradual change of the excitation *vs.* spin distribution shape from a parabola in ^{134}Sb to an inverted parabola in ^{140}Sb, via more flat distributions as the one predicted for ^{136}Sb.

Both the expected gradual onset of collectivity as well as effects related to the lowering of the neutron binding energy could influence this simple shell-model picture. It is therefore of great interest to further explore the evolution of low-lying nuclear structure in the antimony isotopes as a function of the neutron number.

5 Summary

γ-rays from an excited isomeric state in the very neutron-rich fission fragment ^{136}Sb have been observed for the first time, and the half-life of the isomer has been determined to be $T_{1/2}$ = 565 (50) ns. To interpret the experimental observations, we have performed spherical shell-model calculations using two different sets of interactions. The results indicate that the isomer most likely is the $I^\pi = 6^-$ member of the $\pi g_{7/2}\nu f^3_{7/2}$ multiplet.

However, although ^{136}Sb has only one proton and three neutrons outside the doubly magic ^{132}Sn core, the gradual onset of collectivity, as more valence particles are added, could influence the level ordering and spacing. Systematic studies, both experimental and theoretical, of the structure of ^{136}Sb and its neutron-rich neighbors are clearly needed.

The authors would like to thank LO Norlin, Stockholm, J. Nyberg, Uppsala, and K. Rykaczewski, Oak Ridge, for making electronic modules available. MN Mineva and M. Hellström gratefully acknowledge the support from the Swedish National Science Foundation. M. Pfützner acknowledges the support by the Polish Committee of Scientific Research under grant KBN 2 P03B 036 15.

References

1. P. Alexa, R. Sheline, Phys. Rev. C **56**, 3087 (1997).
2. E. Lund, G. Rudstam, Phys. Rev. C **13**, 1544 (1976).
3. G. Rudstam, K. Aleklett, L. Sihver, At. Data, Nucl. Data Tables **53**, 1 (1993).
4. P. Hoff, J.P. Omtvedt, B. Fogelberg, H. Mach, M. Hellström, Phys. Rev. C **56**, 2865 (1997).
5. W. Urban *et al.*, Eur. Phys. J. A **5**, 239 (1999).
6. A. Korgul, H. Mach, B. Fogelberg, W. Urban, W. Kurcewicz, P. Hoff, H. Gausemel, J. Galy, *NFL Annual Report 1999* (The Studsvik Radiation Science Laboratory, Uppsala University, 2000) p. 160.
7. C.F. Liang, P. Paris, R.K. Sheline, Phys. Rev. C **49**, 1872 (1994).
8. J. Shergur *et al.*, Nucl. Phys. A **682**, 493 (2001)c.
9. R. Grzywacz *et al.*, Phys. Rev. C **55**, 1126 (1997).
10. M. Pfützner *et al.*, Phys. Lett. B **444**, 32 (1998).
11. J. Dobaczewski, W. Nazarewicz, Philos. Trans. R. Soc. London, Ser. A **356**, 2007 (1998).
12. H. Geissel *et al.*, Nucl. Instrum. Methods B **70**, 286 (1992).
13. Ch.O. Engelmann, Ph.D. thesis, Universität Tübingen, DISS. 98-15, July 1998.
14. M. Bernas *et al.*, Phys. Lett. B **331**, 19 (1994).
15. J. Simpson *et al.*, Acta Phys. Hung. N. S. **11**, 159 (2000).
16. M.N. Mineva, M. Hellström, M. Bernas, J. Gerl, H. Grawe, M. Pfützner, Zs. Podolyàk, P.H. Regan, *Proceedings of the 2nd International Balkan School on Nuclear Physics, Bodrum, Turkey, September 2000*, Balkan Phys. Lett., in press.
17. J.P. Omtvedt, H. Mach, B. Fogelberg, D. Jerrestam, M. Hellström, L. Spanier, K.I. Erokhina, V.I. Isakov, Phys. Rev. Lett. **75**, 3090 (1995).
18. K. Kawade, G. Battistuzzi, H. Lawin, K. Sistemich, J. Blomqvist, Z. Phys. A **298**, 273 (1980).
19. B. Fogelberg, M. Hellström, D. Jerrestam, H. Mach, J. Blomqvist, A. Kerek, L.O. Norlin, J.P. Omtvedt, Phys. Rev. Lett. **73**, 2413 (1994).
20. J. Blomqvist, *Proceedings of the 4th International Conference on Nuclei Far From Stability, Helsingör 1981* (Report No. 81-09, CERN, Geneva, 1981) p. 536.
21. P. Bhattacharyya *et al.*, Phys. Rev. C **56**, (1997) R2363.
22. H. Grawe, M. Lewitowicz, submitted to Nucl. Phys. A (2001).
23. A. Korgul *et al.*, Eur. Phys. J. A **7**, 167 (2000).
24. J.B. McGrory, T.S.S. Kuo, Nucl. Phys. A **247**, 283 (1975).
25. B. Silvestre-Brac, J.P. Boisson, Phys. Rev. C **24**, 717 (1981).
26. W.T. Chou, E.K. Warburton, Phys. Rev. C **45**, 1720 (1992).