Eur. Phys. J. A **15**, 181–184 (2002)
DOI 10.1140/epja/i2001-10250-8

THE EUROPEAN
PHYSICAL JOURNAL A

The neutron and proton two-particle nucleus ^{134}Sb: New low-spin states observed in the decay of ^{134}Sn and an estimate of the energy of the 7^- isomer

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Received 21 March 2002 /
Published online: 31 October 2002 –

Abstract. Excited states in the ^{134}Sb nucleus, populated in the β^--decay of ^{134}Sn, have been studied at the mass separator OSIRIS. The ^{134}Sn activity was produced via fast neutron-induced fission of ^{238}U target. A main result was the discovery of a very low-lying first-excited state of ^{134}Sb, at 13 keV, which has led to a strong revision of the level scheme. The new results are compared with different theoretical calculations and with the known data for the analogous neutron and proton two-particle nucleus in the ^{208}Pb region. On the basis of this comparison, the energy of the $(\pi g_{7/2} \nu f_{7/2})_{7^-}$ isomer is estimated to be about 250 keV, some 100 keV lower than previously reported.

PACS. 23.40.-s Beta decay; double beta decay; electron and muon capture – 23.20.Lv Gamma transitions and level energies – 21.60.Cs Shell model

1 Introduction

The shell gaps at ^{132}Sn are exceptionally large. The lowest states of neighbouring nuclei are therefore rather unperturbed single- or two-particle excitations. Our present study of the low-spin and low-energy states of ^{134}Sb was intended to give additional information on the members of the lowest proton-neutron particle multiplets, and to search for possible connections to the $I^\pi = 7^-$ isomer from the low-spin states. The recent observation [1] of high-spin excitations involving the $\nu i_{13/2}$ orbital built on the $I^\pi = 7^-$ isomeric state, makes the precise location of this isomer a means for a better definition of the $\nu i_{13/2}$ single-particle energy in the ^{132}Sn region.

In this work we present the new experimental data from the β^--decay to ^{134}Sb including a strongly revised level scheme. We also present a summary of calculations of relevance for the lowest-lying proton-neutron multiplet, the $(\pi g_{7/2} \nu f_{7/2})$ with states ranging from $I^\pi = 0^-$ to $I^\pi = 7^-$.

2 Experiment, results and calculations

The experiment was performed using a beam of mass-separated fission products from the OSIRIS facility at Studsvik, where the ^{134}Sn decay was first studied [2] using thermal fission of ^{235}U for the nuclide production.

In the present experiment, we employed fast neutron fission of ^{238}U to improve the experimental sensitivity. The extra neutrons in the compound system of the latter reac-

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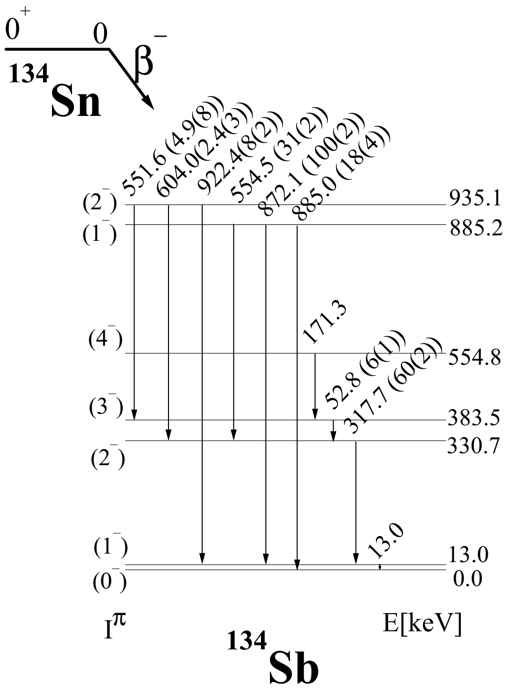

Fig. 1. Partial level scheme of ^{134}Sb as observed in the present work.

tion give a substantial relative enhancement of the most neutron-rich and the shortest-lived fission product isobars, despite a loss in the absolute production rates due to a lower-fission cross-section.

The mass separated beam of $A = 134$ was deposited on an aluminized mylar tape. The $\bar{\gamma}$-ray singles spectra and γ-γ coincidence were measured at the collection position using 15%, 80% and LEP Ge detectors, in coincidence with β-particle events in a thin plastic scintillator placed closed to the tape.

The β^--decay chain of $A = 134$ isobars involved the following decays: ^{134}Sn ($T_{1/2} = 1.2\,\mathrm{s}$) $\rightarrow$ ^{134}Sb [2], ^{134}Sb ($T_{1/2} = 0.75(7)\,\mathrm{s}$) $\rightarrow$ ^{134}Te [2] and ^{134}Te ($T_{1/2} = 41.8(8)\,\mathrm{m}$) $\rightarrow$ ^{134}I [3]. A time sequential measurement procedure was used in order to identify the different activities and to permit subtraction of contributions to the spectra from the long-lived activities.

The γ-radiation following the β^--decay of ^{134}Sn was measured in cycles of 7.2 seconds. The cycles consisted of eight time intervals each covering 0.9 of a second. During the first three time intervals, the beam was accumulated on the tape, followed by 5 time intervals with the beam off. At the end of each cycle the tape with the old activity was moved away to permit starting the next beam collection on a fresh point on the tape.

The γ-lines following the ^{134}Sn decay were easily identified by using the spectra collected at different time intervals, and from the observed coincidence relations. The main experimental results are included in the new decay scheme shown in fig. 1. The γ-ray intensities are from the singles data, except for the 551.6 + 554.5 keV doublet line and the 604.0 keV line (which overlaps in energy with a transition in the ^{134}I nucleus) where the coincidence information was used for intensity determinations. The placement of the 13.0 keV line as the ground-state transition was based on the coincidence with the 317.7 and 52.5 keV lines. (The 52.5 keV line was previously observed [2] but not placed in the scheme.) The level scheme also includes the 171.3 keV transitions in ^{134}Sb, seen in prompt γ-radiation in the study of spontaneous fission of ^{248}Cm [4], where 171.4 keV transitions were observed in coincidence with the 52.8 and 317.7 keV transitions. The spin assignments given in fig. 1 are tentative but represent the most probable and consistent choice in view of the available data. We have used the fact that the ground state is almost certainly $I^\pi = 0^-$ from the known β-decay properties [2] and also the observation that the prompt de-excitation of fission fragments tends to be an yrast cascade. Our conclusion is that the new level scheme of ^{134}Sb now includes five out of eight low-lying states belonging to the $(\pi g_{7/2} \nu f_{7/2})_j$ multiplet. We found no connection between the low-spin states and the $I^\pi = 7^-$ isomer.

The present experimental work has been complemented by a comprehensive theoretical study which will be fully described in a forthcoming publication [5]. Briefly, we mention that the theoretical work includes two shell model calculations, one based on the RPA method using the effective interaction of ref. [6] but now using the empirical values of the single-particle energies, and the other being a calculation with a realistic Bonn A potential, somewhat updated from a similar calculation [7] for ^{132}Sb. Both calculations are "global" in the sense that they were not optimized for the particular case of ^{134}Sb. Both give level spectra in good agreement with the new experimental data. A different treatment, based on the analogies between the shell structures in ^{132}Sn and ^{208}Pb regions [8] gives predicted level energies with only small deviations from the observed values for the lowest levels. The predictions are based on the observed empirical level energies of the analogous neutron and proton nuclide ^{210}Bi. The results of these calculations are shown as RPA, Bonn A and empirical in fig. 2. In yet another approach, the OXBASH code was used to calculate the level energies of the lowest multiplet members with the specific aim to obtain a realistic prediction of the $I^\pi = 7^-$ state energy. These latter calculations will be briefly described here since they were especially optimized for the case of ^{134}Sb, including adjustments to improve agreement with the new experimental data.

The OXBASH calculations were performed using a model space consisting of the ^{132}Sn core and all orbitals between ^{132}Sn and ^{208}Pb except the $\pi(s_{1/2}, d_{3/2})$ and $\nu(p_{1/2}, p_{3/2}, f_{5/2})$ orbitals. The single-particle energies were taken from experiment (see [9] for details). The values of the proton single-particle energies were determined from the differences in masses of ^{133}Sb and ^{132}Sn [10]. The residual interaction used, denoted KH5082 [11], was obtained from the Kuo-Herling (KH) matrix elements, determined for the ^{208}Pb region [12], after the following

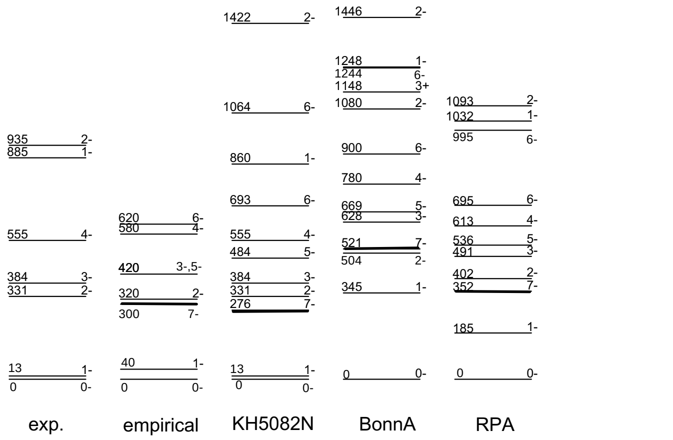

Fig. 2. A comparison of the ^{134}Sb experimental levels with the lower-lying states obtained in the different theoretical calculations. The set of levels denoted empirical include only the members of the lowest n-p multiplet as given earlier in [13]. All energies are in keV.

Table 1. The properties of low-lying levels of ^{134}Sb as found in the OXBASH calculation using the KH5082 parameters are shown in the first three columns. The corresponding diagonal neutron-proton interaction energies (keV) are given next. The last column shows the modified interaction energies of the KH5082N parameters. See the text for details.

E_{level} (keV)	J^π	Dominant configurations	KH5082	KH5082N
0	0^-	100% $\pi g_{7/2}\nu f_{7/2}$	−714	−721
8	1^-	99.5% $\pi g_{7/2}\nu f_{7/2}$	−721	−698
279	7^-	99.5% $\pi g_{7/2}\nu f_{7/2}$	−430	−430
404	3^-	99.4% $\pi g_{7/2}\nu f_{7/2}$	−303	−321
421	2^-	99.5% $\pi g_{7/2}\nu f_{7/2}$	−293	−381
485	5^-	99.4% $\pi g_{7/2}\nu f_{7/2}$	−221	−221
628	4^-	99.9% $\pi g_{7/2}\nu f_{7/2}$	−91	−164
693	6^-	98.9% $\pi g_{7/2}\nu f_{7/2}$	−22	−22
993	1^-	79.8% $\pi d_{5/2}\nu f_{7/2}$ + 16.2% $\pi g_{7/2}\nu h_{9/2}$		
1037	6^-	99.4% $\pi d_{5/2}\nu f_{7/2}$		
1395	2^-	97.6% $\pi d_{5/2}\nu f_{7/2}$		

changes. First, according to the expected mass dependence of the residual interactions, all two-body matrix elements were scaled by a factor of $(132/208)^{1/3}$. In addition, six neutron-neutron $J = 0$ interactions, which are too attractive, were reduced by a factor of 0.6. The results of calculations with the KH5082 model space are shown in fig. 2 together with the experimental level energies of ^{134}Sb. The KH5082 interaction was further modified in this work. Five diagonal proton-neutron matrix elements, shown in table 1 in the KH5082N column, were changed in such a way that the known experimental level energies for the $(\pi g_{7/2}\nu f_{7/2})$ multiplet member states, are exactly reproduced. The impact on the energies of other multiplet members was only slight, as both the KH5082 and KH5082N interactions result in practically identical predictions of 279 and 276 keV for the energy of the $I^\pi = 7^-$ isomeric state.

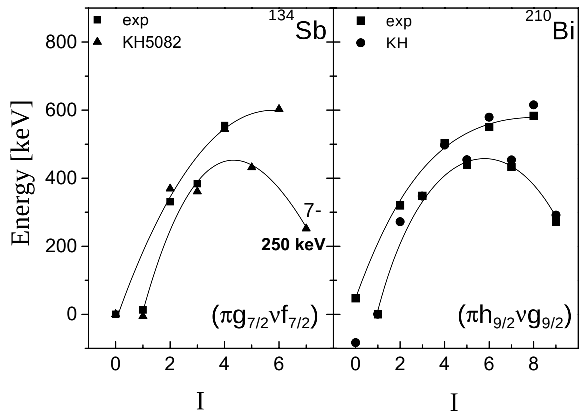

Fig. 3. Experimental and theoretical energy levels for ^{134}Sb (this work) and ^{210}Bi [12,14] plotted *versus* the spin values.

The question whether this predicted $I^\pi = 7^-$ energy value is realistic can perhaps be addressed by drawing further on the analogy between ^{134}Sb and ^{210}Bi nuclei and using the fact that all members of the corresponding $(\pi g_{9/2}\nu h_{9/2})$ multiplet are known in the latter nucleus. Any observed deviation between calculated and known level energies in ^{210}Bi may thus be taken as an indication that a corresponding adjustment of the calculated energy is applicable also to ^{134}Sb.

In a plot of the energies of excited states as a function of spin for the ^{210}Bi $(\pi g_{9/2}\nu h_{9/2})$ multiplet, the values fall onto two regular parabolas, as shown in fig. 3. One can see that the OXBASH calculations with KH interactions reproduce these parabolas very well. In ^{134}Sb not all members of the $(\pi g_{7/2}\nu f_{7/2})$ analogous multiplet are known. The known states, $(I^\pi = 0^-, 1^-, 2^-, 3^-, 4^-)$, define only parts of the parabolas. The missing parts can in principle be obtained from the OXBASH calculations which, as in the ^{210}Bi case, are expected to reproduce the experimental parabolas. As can be seen in fig. 3, the OXBASH calculations with the KH5082 interaction somewhat underbind higher-spin members of the ^{210}Bi multiplet. Consequently, the energy of the ^{134}Sb $I^\pi = 7^-$ multiplet member, calculated at 279 keV using the KH5082 interaction, may also be on the high side. Under the assumption that a parabolic energy dependence is strictly applicable, we have rescaled the calculated excitation energies to get the best parabolic fit to the experimental energies. The resulting curves are shown with full lines in the left-hand panel of fig. 3, and suggest that the excitation energy of the $I^\pi = 7^-$ isomer can be estimated at about 250 keV, some 100 keV lower than in a previous study [11]. The crucial question about the uncertainty in this estimate is difficult to answer. Seen only as a mathematical problem, the good quality of the fit shown in fig. 3 suggests that the uncertainty could be as low as about 50 keV. This would allow an estimate of the $\nu i_{13/2}$ single-particle level energy in the ^{132}Sn region with a much better precision than the 200 keV uncertainty reported in our previous study. The regularity of the ^{210}Bi multiplet evident from fig. 3, and the generally very good correspondence between some details in the structures of the ^{132}Sn and ^{208}Pb regions appear to support our estimate of the $I^{\pi} = 7^{-}$ state energy. The precise magnitude of the estimate is dependent on the OXBASH calculation, however, which implies that additional uncertainties arise due to, *e.g.*, the limited model space.

The OXBASH results are only a part of the theoretical calculations which will be presented in a forthcoming paper [5]. The results include both level spectra and electromagnetic matrix elements. The small, but important, question about the $I^{\pi} = 7^{-}$ excitation energy will be further discussed against the full background of theoretical results.

This work was supported in part by the Swedish-Polish Scientific Exchange Programme, by the Committee for Scientific Research (Poland) in particular under grant number 5 P03B 008 21 and the Bilateral Scientific Technological Cooperation between Poland and Flanders. The authors acknowledge the scholarship from the Foundation for Polish Science (A.K.) and support from the Royal Swedish Academy of Sciences under Cooperation between Sweden and the Former Soviet Union (V.I.). The work was supported by the Swedish Natural Science Research Council.

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