New decay scheme of the $^{136}_{51}Sb_{85}$ 6^- isomer

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We report new data on the ^{136}Sb 6^- yrast isomer with $T_{1/2} = 489(40)$ ns and $\pi g^1_{7/2} \times \nu f^3_{7/2}$ configuration, populated in the projectile fission of ^{238}U on a ^{9}Be target. The analysis confirms the lifetime, providing a good accuracy measurement. In addition, the decay of the isomer to the ground state is newly suggested. Our result for the isomeric decay scheme is in a good agreement with shell-model calculations.

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I. INTRODUCTION

Striking similarity was found between nuclei with few valence protons and neutrons beyond ^{132}Sn and those beyond ^{208}Pb [1]. Low- and intermediate-energy states were described in an analogy, e.g., in ^{134}Sb and ^{210}Bi [2–4], ^{136}Sb and ^{212}Bi [5,6], considered in the evolution of the equivalent $\pi g_{7/2} \nu f_{7/2}$ and $\pi h_{9/2} \nu g_{9/2}$ proton-neutron multiplets in the two different neutron-rich mass regions, emphasizing the role of the core polarization effects. For example, a manifestation of the dominant role played by the pairing correlations was found to be caused by the preferred coupling of the two additional protons or neutrons to a zero angular momentum. Although other components (from, e.g., $\nu f_{5/2}$, $\nu p_{3/2}$) were theoretically found as well, it was suggested that a larger weight of these contributions to the configuration of the states can be seen when a neutron rather than a proton pair is added. Thus, depending on the number of valence neutrons, these main ($\pi g_{7/2} \nu f_{7/2}$ and $\pi g_{7/2} \nu f^3_{7/2}$) components could be completely washed out by configuration mixings [6]. It was concluded, therefore, that the experimental differences in the particle spectrum of ^{136}Sb with respect to that of ^{134}Sb are caused by the extra neutrons [7]. This may have an influence on the formation of a neutron skin beyond the Sn isotopes [8], an effect that certainly weakens the neutron pairing and has visible impacts on the properties of nuclei [5,9].

II. EARLIER STUDIES

A long-lived (10.07(5) s [10]) β-decaying isomer was reported in ^{134}Sb ($T_{1/2}$(g.s.) $= 0.75(7)$ s [11]), assigned as a 7^- level, owing to the strong forbidden population of the 6^+ and the 8^- levels in ^{134}Te [12]. Levels in ^{134}Sb populated in the β decay of ^{134,135}Sn allowed placing the 7^- state at 279 keV [4], crucial to obtain the positions of other yrast states observed earlier in a fission fragment study [2]. The low-spin structure of ^{134}Sb was assigned from several β-decay studies: [13] suggested 0^- g.s. followed by a 1^- level 13 keV higher in energy, in contrast to the 1^- level suggested earlier at about

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300 keV [11]. Spins 2^-, 3^-, and 4^- were assigned to the other observed levels below 1 MeV and reasonably explained with the shell model (SM) and Kuo-Herling (KH) interaction KH5082 [13]. However, according to some of the calculations (using scaled and unscaled KH208 and KH5082 for p-n) in [4] also 1^- g.s. should be considered, although they could describe the data by [11] using the CD-Bonn potential (for n-n). The long-lived state was attributed to the lowest multiplet (0^- to 7^-) whose wave functions dominated (by 90% or more) with the $0g_{7/2}$-$1f_{7/2}$ p-n configuration and the isomeric state was attributed to their maximum-aligned configuration.

An isomer of the same p-n excitation with suggested configuration $\pi g_{7/2}\nu f_{7/2}^3$ was observed also in ^{136}Sb [7,14,15]. A spin/-parity 6^- was suggested due to its appearance as an yrast trap, in contrast to the maximum-aligned configuration trap 7^- as in ^{134}Sb. For ^{136}Sb, in ^{238}U projectile fission at relativistic energies only one isomeric γ ray of 173 keV was detected [14]. Though unobserved, the isomer was understood to appear due to a low-energy ($E2$) transition that causes the isomerism with $T_{1/2}$ of 565(50) ns. In a later work [7], the ^{136}Sb isomer with $T_{1/2}$ of 480(100) ns was populated using (thermal) neutron-induced ^{241}Pu fission together with other $A = 136$ isobars and detected using γ and conversion-electron spectroscopy. Except for the 173.0 keV transition, another low-energy γ ray of 53.4(3) keV was identified to belong to the isomeric decay. The conversion-electron (Si) spectrum in coincidence with the 173.0 (Ge) line suggested another candidate, calculated to be a 51.4(5) keV γ transition, which was consistent with their analysis of more than two transitions with $M1$-$E2$ multipolarity. It was set as the isomeric transition (followed by the cascade of the other two transitions) in the level scheme, constructed in accordance with SM calculations [5,7]. In a more recent ^{238}U fission run, however, no sign of this transition was seen, reporting 53.9 keV and 173.1 keV γ-rays with $T_{1/2}$ of 570(5) ns [15].

The g.s. of ^{136}Sb was suggested to have a spin/parity of 1^- from β-decay data [16]. One may note that this assignment was done mainly in analogy to ^{212}Bi (with g.s. of 1^-). It was questioned in some later theoretical works, supporting 2^-, as such a scenario allowed them to better describe experimental data in the neighboring ^{134,135}Sb, as well as the $N = 84$ isotones [17,18].

III. EXPERIMENTAL OBSERVATIONS

We populated a H-like charge state of ^{136}Sb after ^{238}U fission (at 345 MeV/u) on a ^{9}Be target in an isomer and β-decay experiment at the RIBF facility at RIKEN [19] in the framework of the EURICA project [20,21]. We recorded about 7.6×10^3 ions for this nucleus that were well separated from the rest of the ions (with about 1×10^7 total) ions collected after a passage through the spectrometers (typically for about 600 ns). The delayed γ rays were detected in twelve Ge Cluster detectors with an absolute efficiency of 7.5(3)% at 1.3 MeV after add-back (and 16.8(5)% at 150 keV). Timing information was extracted [using Digital Gamma Finder (DGF) readout] with a resolution of about 25 ns/channel. Further experimental details are given elsewhere [22,23].

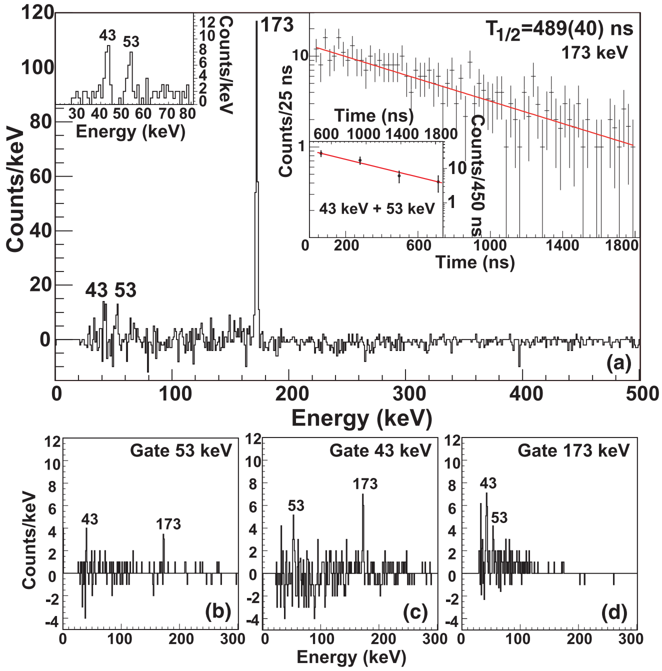

FIG. 1. (Color online) The delayed and background-subtracted γ-ray spectrum for ^{136}Sb (a). Lifetime fits and unsubtracted γ-ray spectrum for a short time window are shown in the insets. Coincidence-gate spectra on each of the transitions are plotted in (b), (c), and (d).

The delayed γ-ray spectrum for ^{136}Sb after a background subtraction is shown in Fig. 1(a) (for a time window of about 10 μs after the prompt flash). A strong known isomeric transition of 172.5(3) keV is observed with $T_{1/2}$ of 489(40) ns, whose lifetime fit is represented in an inset. It is in a reasonably good agreement with the earlier measurements. In addition, we clearly detect two low-energy transitions which appear in the same time window and follow the same isomeric decay as 172.5 keV. Lifetime fits on these 43.4 and 53.4 keV transitions result in $T_{1/2}$ of 490(100) and 510(100) ns, respectively. A sum-up spectrum of both (for four equal time bins of 450 ns each) is provided in another inset of Fig. 1(a). The relative intensities of the two low-energy lines are also provided in a zoom spectrum without any background subtraction (or add-back) in another inset of Fig. 1(a) for a shorter time window of about 1.8 μs. For the 53.4(3) keV transition we did not find any broadening of its γ peak due to the earlier suggested 51.4(5) keV line depopulating the isomer, despite the energy resolution of the detectors, which is better than the energy difference between these lines. Estimating that we should have observed of the order of 5–10 counts in the total time projection, we note that with the statistics of [15], regardless of their low-energy threshold, the 51.4 keV transition was also not seen. In our case, instead, we observe another low-energy transition of 43.4(3) keV, in a clear coincidence with this nucleus and its lifetime. The delayed coincidence relations for each of the three lines, presented in Figs. 1(b)–1(d), suggest their placement in a cascade, while their intensity suggests that strong conversion is present for the low-energy ones.

IV. RESULTS AND DISCUSSION

In the earlier studies, the multipolarity of the 172.5 keV line was suggested to be of $E2$ type, while $M1$ was suggested for the 53.4 keV transition. As the newly observed 43.4 keV γ ray shall not be of pure $E2$ type because it would have been difficult to detect due to the large conversion (this applies also to higher multipolarities), one may expect either an $M1$ type (theoretical α_{TOT} of 6.9(1) [24]) or a certain amount of $E2$ mixing. Comparing to the 53.4 keV transition of possibly $M1$ type [7] (α_{M_γ} of 3.8(1) [24]) one may conclude that, in order to fit our observed intensity ratio between these transitions ($I_{v43}/I_{g55} = 1.03(20)$) neither $M1/M1$ types nor mixing $M1+E2/M1$ for the 43.4 keV transition are probable, as ratios of, respectively, 0.6(1) and much lower (e.g., $\approx$0.3 for $\delta \approx 0.5$ [24]) are expected. However, assuming an $E2$ type for the 53.4 keV transition (α_{TOT} of 15.6(2) [24]) and comparing it to an $M1$ 43.4 keV line, a ratio of 1.15(3) can be expected when taking into account also the respective efficiency ratio, in agreement of the order of 1.5 standard deviations with the experimental intensities previously known.

The new assignment for the 53.4 keV γ-ray is not inconsistent with the earlier conversion electron measurement because in their spectrum only one group of $L+M$ electron lines were observed [7]. The source of this was attributed to a 51.4(5) keV γ line (after a correction of L binding energy of 4.3 keV for Sb) overtaken in intensity by the one at 53.4(3) keV. The electron lines were also corrected for energy loss (in a 2.5 μm Mylar foil used) that explains the shift in their spectrum with respect to the quoted value ($E_{e_L} = 47.1(5)$ keV and $E_{e_M} = 50.6(5)$ keV [24] to $E^{corr}_{e_L} = 43.6(5)$ keV and $E^{corr}_{e_M} = 47.2(5)$ keV) [25]. However, the difference in these energies if the electrons originate from the 53.1 keV line would be less than 2 keV, thus smaller than the (standard 5%) uncertainty of the calculations at these energies [26,27]. The observation of only one converted transition in the electron and in the γ-ray spectrum of [7] makes the 53.4 keV transition a candidate for an $E2$ multipolarity that is partially but not fully converted. Therefore, one may suggest that it is also a candidate for the isomeric transition, although without an earlier lifetime fit on it.

Furthermore, the intensity ratios we observe for these two low-energy transitions with respect to the 172.5 keV transition are inferior to the earlier data (e.g., for the 53.4 keV line, $I_{\gamma 173}/I_{\gamma 53} = 7.2(12)$ compared to 10.5(23) from [7], while the relative intensities in [15] seem to be influenced by a low-energy threshold). The multipolarity of this higher-energy line was already suggested to be $E2$ type (based on the measured $\alpha_K = 0.17(4)$ [7] in comparison to the theoretical $\alpha_K^{E2} = 0.19(2)$ [24]). Although, more consistent with our observed intensities, we note that higher multipolarity for this line, e.g., $M3$, would require the presence of a state with lifetime of seconds, which is not the case. Therefore, we exclude such a scenario. Some variance with respect to earlier data sets may be due the detector setup, efficiency, etc., as well as the loss of isomers while decaying in flight through the BigRIPS separator, as we have a charge state and non-negligible α_K for this isomer. Thanks to the strong isomeric population in our experiment, we calculated the isomeric ratio as high as 50(8)%, which is consistent with an yrast origin of the isomer, strongly populated in fission.

V. LEVEL SCHEME AND SHELL MODEL

Due to its appearance as an yrast trap in ^{136}Sb based on shell-model (SM) calculations, the spin-parity of 6^- was already suggested for this isomer [7]. The order of the reported transitions was also proposed in accordance with the calculations. With the newly collected experimental information one may suggest a rearrangement of the experimental level scheme, presented in Fig. 2, in turn implying that, instead of 51.4 keV, the isomer $6^- \to 4^-$ is depopulated by the 53.4 keV $E2$ transition. The decay is further followed by $E2$ transition out of the 4^- level, thus connecting to the state with spin/parity 2^-. The newly observed, predominantly $M1$ transition of 43.4 keV can then be placed at the bottom of the level scheme, connecting the 2^- and the 1^- states, thus in agreement with a g.s. spin/parity of most probably 1^-.

This scenario is in good agreement with the SM calculations performed in this work. For the description ^{132}Sn is used as a core nucleus, the three valence neutrons occupy the model space $f_{7/2}, h_{9/2}, f_{5/2}, p_{3/2}, p_{1/2}, i_{13/2}$, and the valence proton occupy the levels $g_{7/2}, d_{5/2}, d_{3/2}, s_{1/2}, h_{11/2}$. The KH interaction is employed, shown already to be successful in the description of the ^{134}Sb nucleus [13], and the neutron-rich isotones $N = 82$–84 near ^{132}Sn [28]. The SM results show that the energy levels of ^{136}Sb well reproduce the newly observed data of this work and of the previous one [7]. The g.s. and the first excited states are characterized by a dominant $\nu(f_{7/2})^3 \otimes \pi(g_{7/2})^1$ component, which contributes to 66% of the wave function. We may also note that, theoretically, the 2^- state can be expected at less than a keV distance from the 1^- state, thus one may clearly have both possibilities for g.s. spin/parity. Therefore, this new experimental information is extremely valuable for fixing one of them with a larger certitude. Although not discussed previously, other levels of spin/parity 3^- and 5^- can be theoretically expected in the few-tens of keV vicinity of the 6^- state. These can thus be potential candidates for γ-ray branches, requiring lower multipolarity. However, we have not observed such branches or, e.g., $M1$ character of the 172.5 keV transition, which would be in a disagreement with the experimental data.

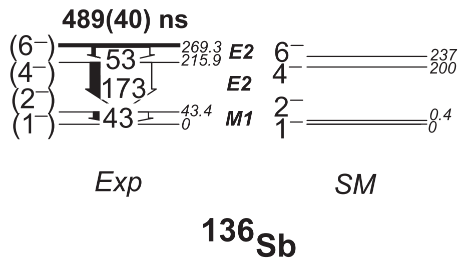

FIG. 2. Revised experimental level scheme of the 6^- isomer in ^{136}Sb compared to shell-model (SM) calculations.

The newly revised level scheme for the 6^- isomer in ^{136}Sb applies a scenario in which the 53.4 keV is the isomeric transition with $E2$ type. The SM isomeric energy is estimated to be very close to the experimental one. The result of the experimental $B(E2)$ amounts to 159(15) e^2fm^4 (4.1(4) W.u. compared to 7.7(7) W.u. expected in [14]). It is decreased by about 7% compared to the previously reported 170(40) e^2fm^4 value [7]. The theoretical results obtained in this SM approach, amount to 131 e^2fm^4, using effective charges of 0.7e and 1.7e for neutrons and protons respectively, agree well with the experiment and the earlier SM results. Thus, in conclusion one may emphasize that the KH interaction produces consistently good results, which constitutes a further step in testing the nucleon-nucleon effective interaction in this region of the nuclear chart and in particular its neutron-proton components.

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[1] J. Blomqvist, in *Proceedings of the 4th International Conference Nuclei Far From Stability, Helsingor, Denmark, 1981*, edited by P. G. Hansen and G. B. Nielsen (CERN, Geneva, 1981), p. 548.
[2] W. Urban *et al.*, Eur. Phys. J. A **5**, 239 (1999).
[3] B. Fornal *et al.*, Phys. Rev. C **63**, 024322 (2001).
[4] J. Shergur *et al.*, Phys. Rev. C **71**, 064321 (2005).
[5] L. Coraggio, A. Covello, A. Gargano, and N. Itaco, Phys. Rev. C **80**, 021305(R) (2009).
[6] A. Covello *et al.*, J. Phys. G: Conf. Ser. **205**, 012004 (2010).
[7] G. Simpson *et al.*, Phys. Rev. C **76**, 041303(R) (2007).
[8] J. Shergur *et al.*, Phys. Rev. C **65**, 034313 (2002).
[9] L. Coraggio, A. Covello, A. Gargano, and N. Itaco, Phys. Rev. C **87**, 034309 (2013).
[10] G. Rudstam *et al.*, At. Data Nucl. Data Tables **53**, 1 (1993).
[11] B. Fogelberg, B. Ekström, L. Sihver, and G. Rudstam, Phys. Rev. C **41**, R1890 (1990).
[12] J. P. Omtvedt *et al.*, Phys. Rev. Lett. **75**, 3090 (1995).
[13] A. Korgul *et al.*, Eur. Phys. J. A **15**, 181 (2002).
[14] M. Mineva *et al.*, Eur. Phys. J. A **11**, 9 (2001).
[15] D. Kameda *et al.*, Phys. Rev. C **86**, 054319 (2012).
[16] P. Hoff, J. P. Omtvedt, B. Fogelberg, H. Mach, and M. Hellström, Phys. Rev. C **56**, 2865 (1997).
[17] S. Sarkar *et al.*, J. Phys. IAC **53**(6), 1 (1999).
[18] S. Sarkar *et al.*, Eur. Phys. J. A **21**, 61 (2004).
[19] T. Ohnishi *et al.*, J. Phys. Soc. Jpn. **79**, 073201 (2010).
[20] S. Nishimura *et al.*, Prog. Theor. Exp. Phys. **2012**, 3C006 (2012).
[21] P.-A. Söderström *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **317**, 649 (2013).
[22] R. Lozeva *et al.*, RIKEN Accel. Prog. Rep. **47**, 4 (2014).
[23] R. Lozeva *et al.* (unpublished).
[24] T. Kibèdi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **589**, 202 (2008).
[25] http://physics.nist.gov/Star, accessed 2015-04-01.
[26] L. Pages *et al.*, At. Data Nucl. Data Tables **4**, 1 (1972).
[27] T. Tabata *et al.*, Nucl. Instrum. Methods **103**, 85 (1972).
[28] S. Sarkar and M. S. Sarkar, Phys. Rev. C **64**, 014312 (2001).