New information on medium-spin structure of ^{133}Sb

W. Urban,[1,2] A. Złomaniec,[2] G. S. Simpson,[1,3] H. Faust,[1] T. Rząca-Urban,[2] and M. Jentschel[1]
[1] *Institut Laue-Langevin, B. P. 156, F-38042 Grenoble Cedex 9, France*
[2] *Faculty of Physics, University of Warsaw, ul. Hoża 69, PL-00-681 Warsaw, Poland*
[3] *Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS/Univ. J. Fourier, F-38026 Grenoble Cedex, France*
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Excited states in the nucleus ^{133}Sb, populated in the fission of ^{235}U induced by thermal neutrons were studied using the Lohengrin fission-fragment separator. A new 4191.8 keV level in ^{133}Sb, populated in the decay of the 16.6 μs isomer, was observed. The level is interpreted as the 11/2$^+$ member of the $\pi g_{7/2} \otimes$ core configuration, predicted by the shell model at 4095 keV. Levels corresponding to octupole excitation of the ^{132}Sn core, identified previously in prompt-γ measurement, were now observed in the isomeric decay.

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The ^{133}Sb nucleus with one proton outside the doubly magic ^{132}Sn core is a key system for testing the nuclear shell model. It provides energies of single-particle proton excitations for the ^{132}Sn region as well as the data to study couplings of a proton to excitations of the doubly magic core. All proton excitations in ^{133}Sb have been determined [1–4]. However, the knowledge about their coupling to core excitations, in particular about the $\pi g_{7/2} \otimes$ core multiplet, is still incomplete. The present work improves this.

Two recent works [5,6] provided a consistent picture of this part of the $\pi g_{7/2} \otimes$ core multiplet in ^{133}Sb, which is populated in the decay of the 17 μs isomer, interpreted as the $I^\pi = 21/2^+$ member of this multiplet. However, some information is not common to both works. Reference [6] could not verify the existence of the 3 μs isomer proposed in ^{133}Sb [2] and rejected in Ref. [5]. On the other hand, in Ref. [5], the 13/2$^-$, octupole excitation was not observed because of experimental limitations. As proposed in Ref. [6], this isomer should be populated by the decay of the 17 μs isomer. To clear these uncertainties and to search for the remaining members of the $\pi g_{7/2} \otimes$ core multiplet, we reinvestigated the ^{133}Sb nucleus, using improved experimental techniques [7].

The ^{133}Sb nucleus was produced in the fission of ^{235}U induced by thermal neutrons inside the reactor at ILL Grenoble and analyzed using the Lohengrin fission-fragment separator [8]. Mass $A = 133$ ions from Lohengrin, passing through an ionization chamber with a thin Mylar exit window, were collected on a stopper, surrounded by nine Ge crystals in close geometry, one 60% GammaX detector, and two clover detectors. Signals from Ge detectors and the ionization chamber were stamped with time marks from a 40 MHz clock [7]. To lower the number of γ signals uncorrelated with ions, a 50 μs hardware window was imposed on the time distance between an ion and subsequent γ signals. In the measurement, about 3.4×10^8 ion signals and about 5.1×10^8 γ signals were collected. Coincidence relations between γ and ion signals were created during the off-line analysis.

We sorted a two-dimensional histogram with γ energy on one axis and its time, counted from the time of the preceding ion, on the other axis (gt matrix). The total projection of this matrix on the γ axis is shown in Fig. 1(a). The spectrum is dominated by γ lines corresponding to β decays in the $A = 133$ mass chain (2755.0 keV in ^{133}Te, 312.1 and 912.7 keV in ^{133}I, and 529.9 keV in ^{133}Xe). However, lines due to the decay of the 17 μs in ^{133}Sb are also seen (162.5, 1510.3, and 2791.7 keV). In Fig. 1(b), we show γ spectrum gated on the time axis in a range from 0 to 15 μs, from which a background spectrum, gated on the time axis in a range from 40 to 50 μs, was subtracted. The background was normalized at the 312.1 keV β-decay line. The strongest γ lines seen in Fig. 1(b) are those corresponding to transitions in the isomeric cascade from the 17 μs isomer in ^{133}Sb (61.7, 162.5, 1510.3, and 2791.7 keV, and the K_α x-ray line at 26.3 keV).

In Fig. 2(a), we show the time-delayed spectrum gated on the 162.5 keV line from the isomeric cascade. An exponential fit to this spectrum provides a half-life of $T_{1/2} = 14.43(16)$ μs, which is consistent with, but clearly shorter than, the literature value of 16.8(5) μs [5]. This possibly results from the high intensity of the ion beam. For isomeric decays with long half-lives, measured at high beam intensity, it is quite likely that another ion arrives before the ion with isomeric state deexcites. Consequently, the observed time intervals between the ion and a γ are, on average, shorter than they should be for unaffected isomeric decay. We note that the fraction of ions with the 17 μs isomer in the $A = 133$ ion beam in our measurement was only about 5%, but it was not possible to differentiate between "isomeric" ions and other ions at Lohengrin, and the $A = 133$ ion beam intensity was 6000/s, on average.

We calculated a correction factor to account for this effect, as described in Ref. [9]. At an ion beam intensity of 6000 ions/s (with a conservative uncertainty of 10% on this intensity) the correction is 0.876(16) [i.e., the 17.00 μs isomer will be seen with a half-life of 14.89(27) μs]. Applying this correction, we obtain the half-life of $T_{1/2} = 16.6(3)$ μs for the isomer in ^{133}Sb. This value is in good agreement with the half-life of 16.8(5) μs reported in Ref. [5].

As seen in Fig. 2(a), the exponential fit is of good quality. Similar quality fits were obtained for time-delayed spectra gated on the 1510.3 and 2791.7 keV lines, which are below the 162.5 keV line in the isomeric cascade. Attempts to fit two half-lives to any of these spectra were not successful. This confirms the conclusion of Genevey *et al.* [5] that the 3 μs

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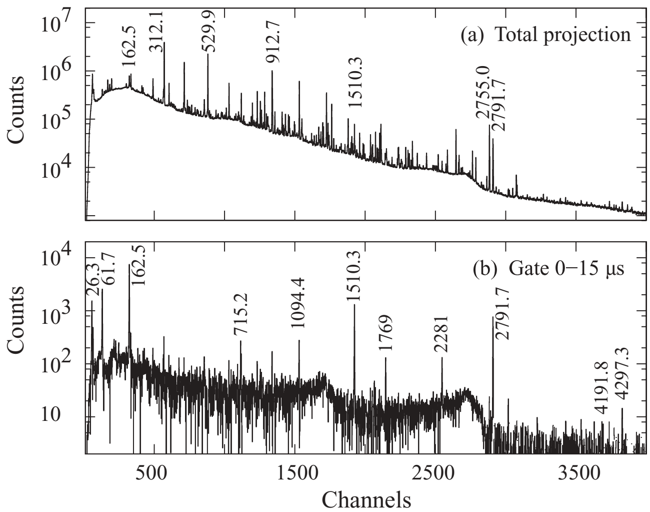

FIG. 1. (a) Total projection on γ axis of the gt matrix (b) γ spectrum gated on the time axis of the gt matrix in a range 0–15 μs. γ energies are given in keV. Constant-peak-width calibration was applied to accommodate a wide range of energies.

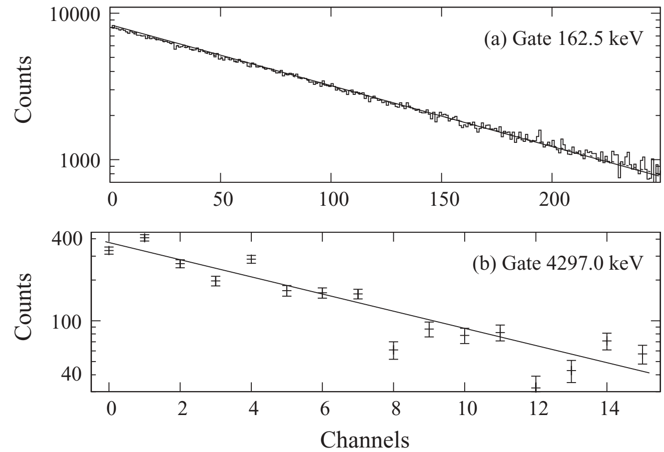

FIG. 2. (a) Time-delayed spectrum gated on (a) the 162.5 keV line in the gt matrix, time calibration is 200 ns per channel, and (b) the 4297.0 keV line in the gt matrix, time calibration is 3.2 μs per channel.

medium-spin isomer proposed in ^{133}Sb [2] is not present in this nucleus.

We note that the half-life of $T_{1/2} = 18.2(4)$ μs obtained from fitting the time-delayed spectrum gated on the 2791.7 keV line and corrected due to ion-beam intensity is slightly longer than that obtained for the other two time-delayed spectra [the corrected half-life for the 1510.3 keV gated spectrum is $T_{1/2} = 16.2(3)$ μs]. The likely explanation is an extra feeding of the 2791.7 keV level in ^{133}Sb in β^- decay of ^{133}Sn (both direct and indirect via γ cascades) [10]. Although the 162.5 keV line does not depopulate the isomer, it depopulates a level with sufficiently high spin to avoid such an extra population.

Apart from the cascade depopulating the 16.6 μs isomer, one observes also other delayed lines in Fig. 1(b). Among them, the 2281 and 1769 keV are the first and second "escape" of the 2791.7 keV line, respectively; and the 715.2 and 1094.4 keV lines correspond to the 4 μs isomer in ^{127}Sn (mass $A = 127$ was a contaminant in our mass $A = 133$ measurement) and a line at 4297.0 keV. The 4297.0 keV transition in ^{133}Sb was reported in Ref. [6], where we proposed that it should be populated in decay of the 16.6 μs isomer. This might explain the 4297.0 keV line in Fig. 1(b). Indeed, the time-delayed spectrum corresponding to this line, which is shown in Fig. 2(b), shows a half-life of 17(2) μs (because of low statistics, the spectrum was binned to 3.2 μs per channel). This observation firmly establishes the 4297.0 keV level in ^{133}Sb.

To study in more detail the decay of the 16.6 μs isomer, we sorted a two-dimensional histogram containing γ-γ coincidences (gg matrix), where the two γ signals were registered within a 600 ns period. The high-energy part of the total projection of gg matrix is shown in Fig. 3, where one sees a line at 4297.0 keV. A spectrum gated on the 4297.0 keV line is shown in Fig. 4(a). In the first spectrum, the 61.7 and 167.3 keV lines are present, which confirms the 167.5 keV decay branch of the 4464.3 keV level, proposed in Ref. [6] and seen now in the decay of the 16.6 μs isomer. A gate on the 61.7 keV line provides a more precise energy of 167.7 keV for this transition.

In Ref. [6], a 4359.7 keV level was proposed, deexcited by the 62.7 keV transition. In Fig. 4(a), the line at 62 keV has two components. A fit of two Gaussian functions provides energies of 61.7 and 63.1 keV. We note that the 167.3 keV line in Fig. 4(a) is broadened. Fitting two Gaussians, with one fixed at 167.7 keV, provides an energy of 166.1 keV for the other component. These results suggest that there is a level at 4360.2 keV, which is populated in the decay of the isomer in ^{133}Sb. An alternative explanation, that this level is populated in β decay, is less likely, considering its spin of $15/2^-$, as proposed in Ref. [6]. One could also ask about a possible 104 keV feeding from the 4464.6 keV level. However, there is no sign of a 104 keV line in Fig. 4(a).

In Fig. 3, there is also a line at 4191.8 keV. A γ-ray spectrum gated on this line is shown in Fig. 4(b). One can

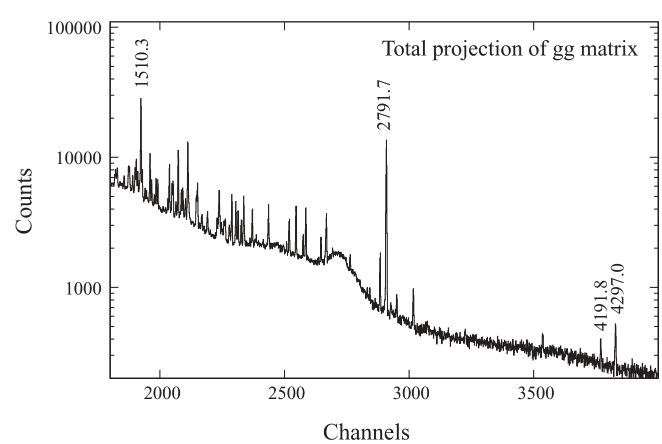

FIG. 3. High-energy part of the total projection of the gg matrix. γ energies are given in keV.

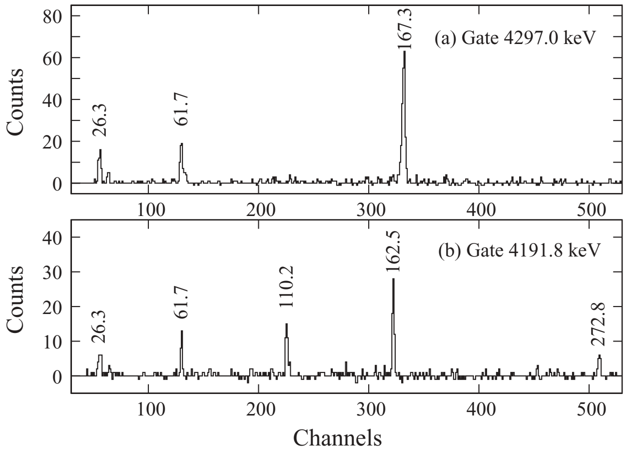

FIG. 4. Low-energy part of a spectrum gated on (a) the 4297.0 keV line in gg matrix and (b) the 4191.8 keV line in gg matrix. γ energies are given in keV.

see in the spectrum new lines at 110.2 and 272.8 keV but also the known 61.7 and 162.5 keV lines. Based on this observation, we propose a new level at 4191.8 keV fed by 110.2 and 272.8 keV transitions, as shown in Fig. 5. Because of the observed branchings, spin of the 4191.8 keV level is limited to 11/2 or 13/2 values. The nonobservation of any decay to the 2791.7 keV level makes both the $13/2^+$ and $13/2^-$ assignments rather unlikely. The $11/2^-$ solution is rejected by the 272.8 keV decay. Therefore, we propose spin and parity of $11/2^+$ for the 4191.8 keV level in ^{133}Sb.

The 4191.8 keV is seen in Fig. 4(b). An exponential fit to the time-delayed spectrum gated on this line in the gt matrix gives (after ion-intensity correction) a half-life of 13.5(2.6) μs. This further confirms that the 4191.8 keV belongs to the cascade depopulating the 16.6 μs isomer in ^{133}Sb.

It was proposed in Ref. [5] that the $E2$ isomeric transition with an estimated energy lower than 20 keV feeds the 4526.3 keV level. In the spectrum gated on the 2791.7 keV line, the 61.7 keV and the x-ray lines of ^{133}Sb are clearly seen, but there is no candidate for the isomeric transition. This is not surprising, though, considering that for an $E2$ transition of 20 keV, the total conversion coefficient is $\alpha_t = 991$, and the γ intensity is in this case below the detection limit of our measurement. Taking into account this limit, the limits imposed by the half-life of the isomer and assuming a single-particle rate for the $E2$ isomeric transition, one estimates the excitation energy of the isomer at 4545(10) keV.

In Table I, we show γ branching ratios for the decays of levels in ^{133}Sb, as determined in this work. We note that the intensity of the 4191.8 keV transition is about ten times lower than the intensity of the 4297.0 keV transition, as can be deduced from branchings in Table I. In contrast, in Fig. 3, intensities of the two lines differ by only a factor of 2. This suggests that the 4191.8 keV level receives appreciable feeding in β^- decay of ^{133}Sn. In this case, the 4191.8 keV transition is in coincidence with high-energy electrons from β^- decay, which are also seen by our Ge detectors.

In the doubly magic ^{132}Sn nucleus, the lowest-lying excited states, which are located in the 4–5 MeV range, are due to

TABLE I. γ branchings for levels in the ^{133}Sb nucleus, as observed in this work.

E_{level} (keV)	E_γ (keV)	I_γ (rel.)	E_{level} (keV)	E_γ (keV)	I_γ (rel.)
2791.7	2791.7	100(5)	4464.6	162.5	100(5)
	1829.5	0.7(3)		167.7	8(1)
4297.0	4297.0	100(10)		272.8	0.7(2)
	1505.3	20(5)	4526.3	61.7	100(10)
4302.0	1510.3	100(5)		166.1	7(3)
	110.2	0.8(2)			

cross-shell, particle-hole type excitations. For neutrons, these are primarily the $\nu f_{7/2} h_{11/2}^{-1}$ excitation, producing positive-parity states, for instance, the 2^+ level at 4041.2 keV [11], which is the first excited state in ^{132}Sn; or the $\nu p_{3/2} h_{11/2}^{-1}$ excitation, producing negative-parity states, including the

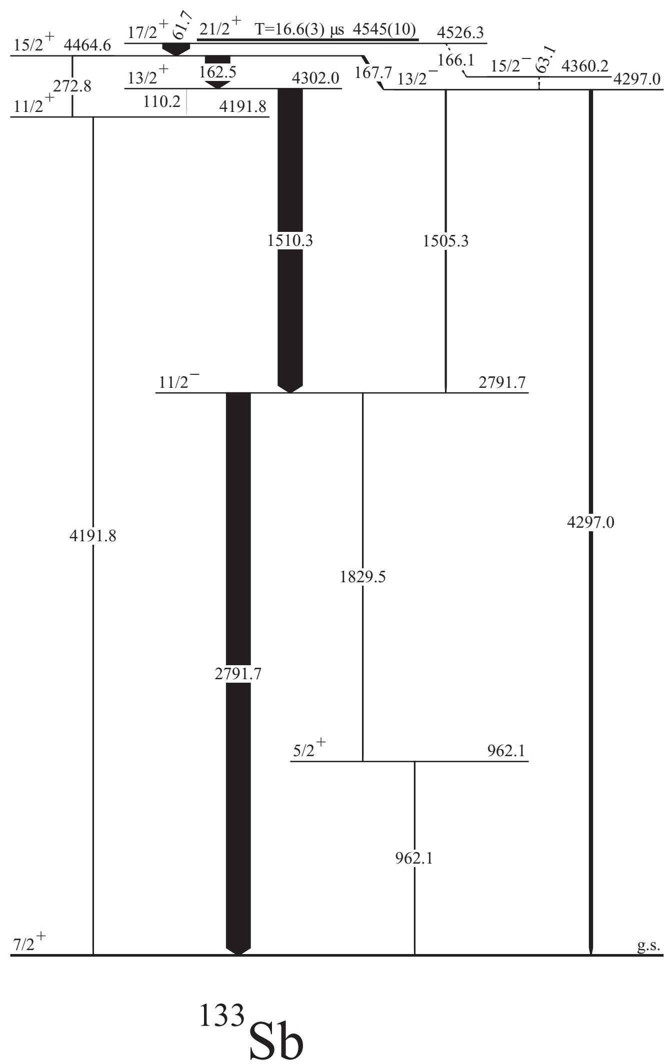

FIG. 5. Partial level scheme of ^{133}Sb as obtained in the present work. Excited levels and γ transitions are labeled with energies given in keV.

3^- octupole state at 4351.9 keV [11]. One may also ask about contributions from other particle-hole excitations such as $\nu f_{7/2} d_{3/2}^{-1}$ or proton particle-hole excitations across the $Z = 50$ shell gap such as the $\pi g_{7/2} g_{9/2}^{-1}$. The presence of such contributions can be tested by studying properties of the odd-A neighbors of ^{132}Sn, where the coupling of the odd nucleon to the ^{132}Sn core excitations should depend on the composition of these core excitations. The odd-neutron nucleus ^{133}Sn, with its neutron-binding energy of only 2.4 MeV, is not a good candidate for such studies. However, the odd proton in the ^{133}Sb nucleus is well bound, making this nucleus a good testing case.

The lowest positive-parity states in the 4–5 MeV range in ^{132}Sn were proposed to be due to the $\nu f_{7/2} h_{11/2}^{-1}$ excitation [12]. It was also shown that the $\pi g_{7/2} g_{9/2}^{-1}$ proton excitations are observed more than 1 MeV above neutron excitations [13]. This coincides with sizes of $N = 82$ neutron and $Z = 50$ proton gaps of about 4.9 and 6.1 MeV, respectively. Coupling the ^{132}Sn core states to an odd proton should produce a multiplet of proton-neutron states in ^{133}Sb at energies similar to the core state energies if these states are due to the neutron $f_{7/2} h_{11/2}^{-1}$ excitation, or at somewhat higher energies if the core states have admixture from proton excitations resulting in three-proton states in ^{133}Sb.

In our previous study of ^{133}Sb, the $\pi g_{7/2} \nu(f_{7/2} h_{11/2}^{-1})$ multiplet was calculated (see Fig. 4 in Ref. [6]) using the same two-body interactions, which reproduced successfully excited levels in the two-valence proton nucleus ^{134}Te [14]. The comparison of these calculations against experimental data can now be extended to the $11/2^+$ member of the multiplet. The experimental energy of 4191.8 keV is in fair agreement with the calculated energy of 4095 keV. We can also compare the estimated energy of the 16.6 μs isomer with the calculated energy of 4470 keV. One observes that there is a small but systematic shift between theoretical and experimental energies for the $11/2^+$, $13/2^+$, $15/2^+$, $17/2^+$, and $21/2^+$ levels. Experimental energies are about 75 keV higher, on average, than their calculated counterparts. This suggests a possible small contribution of the $\pi g_{7/2}^2 g_{9/2}^{-1}$ configuration to the dominating $\pi g_{7/2} \nu(f_{7/2} h_{11/2}^{-1})$ configuration, though the effect is at the accuracy limit of the calculations.

In Ref. [10], two levels populated in β^- decay of ^{133}Sn were observed in ^{133}Sb at 4028.7 and 4060 keV. These levels could not be seen in the prompt-γ fission data [6], indicating their nonyrast character. They are also not seen in the present work, suggesting that their spins are lower than 11/2. It was proposed that these two levels may belong to the $\pi g_{7/2} \otimes$ core multiplet [10]. The $9/2^+$ and $7/2^+$ members of the $\pi g_{7/2} \nu(f_{7/2} h_{11/2}^{-1})$ multiplet were calculated at 3889 and 3997 keV, respectively. The calculated levels are about 75 keV lower than the experimental levels, hence the shell-model calculations support the proposition that the 4028.7 and 4060 keV levels observed in Ref. [10] are $9/2^+$ and $7/2^+$ members of the $\pi g_{7/2} \otimes$ core multiplet.

In summary, high-energy states in ^{133}Sb, populated in the decay of the 16.6 μs isomer in this nucleus produced in fission of ^{235}U induced by thermal neutrons, were studied using the Lohengrin fission-fragment separator. A new level was observed in ^{133}Sb at 4191.8 keV, which we interpret as the $11/2^+$ member of the $[\pi g_{7/2} \nu(f_{7/2} h_{11/2}^{-1})]_j$ multiplet. Shell-model calculations, performed in our previous work, support this assignment. The 4028.7 and 4060 keV levels in ^{133}Sb populated in β^- decay of ^{133}Sn but not populated in fission may correspond to the $9/2^+$ and $7/2^+$ members of the $\pi g_{7/2} \otimes$ core multiplet, respectively, which is also supported by the shell-model calculations. The present measurement confirms the presence of the 4297.0 keV level in ^{133}Sb, observed previously in prompt-γ measurement, which probably corresponds to an octupole excitation.

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