Medium-spin structure of single valence-proton nucleus ^{133}Sb

W. Urban, W. Kurcewicz, and A. Korgul
Institute of Experimental Physics, Warsaw University, ul.Hoża 69, 00-681 Warszawa, Poland

P. J. Daly, P. Bhattacharyya, and C. T. Zhang
Chemistry Department, Purdue University, West Lafayette, Indiana 47907

J. L. Durell, M. J. Leddy, M. A. Jones, W. R. Phillips, A. G. Smith, and B. J. Varley
Schuster Laboratory, Department of Physics, University of Manchester, Manchester M13 9PL, United Kingdom

M. Bentaleb,* E. Lubkiewicz,† and N. Schulz
Institut de Recherches Subatomiques, CNRS-IN2P3 et Universite Louis Pasteur, F-67037 Strasbourg, France

I. Ahmad and L. R. Morss
Argonne National Laboratory, Argonne, Illinois 60439

J. Blomqvist
Department of Physics Frescati, Royal Institute of Technology, S-10405 Stockholm, Sweden
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Excited states in the nucleus ^{133}Sb, populated in spontaneous fission of ^{248}Cm, were studied with EUROGAM2. Medium-spin structure, described as the $\nu(f_{7/2}h_{11/2}^{-1})$ multiplet of the ^{132}Sn core coupled to the odd proton in the $g_{7/2}$ orbital, has been identified in this nucleus. Levels corresponding to the octupole excitations of the ^{132}Sn core were also identified. Some uncertainities concerning isomeric decays in ^{133}Sb, observed in previous works, have been resolved.

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In the ^{133}Sb nucleus, having one proton outside the doubly magic ^{132}Sn core, the lowest excited levels are due to single-proton excitations and above 4 MeV excitations of the ^{132}Sn core coupled to the valence proton are expected. Investigation of this nucleus provides the most stringent test of the shell model. Despite several measurements of ^{133}Sb performed to date, the medium-spin yrast structure of this isotope, where core excitations are expected, is still not known well enough to allow comparison with model predictions.

Up to now the only way to populate ^{133}Sb has either been directly in fission of heavy nuclei or in β^- decay of the fission product ^{133}Sn. The ^{133}Sb nucleus was first identified and studied in β^- decay of ^{133}Sn [1]. In addition to the $7/2^+$ ground state, the 963 keV excited level was found and interpreted as the $d_{5/2}$ proton state. Spins of levels populated in β^- decay are close to the ground-state spin of the parent nucleus and are usually low. Study of higher-spin excitations requires observation of nuclear levels populated directly in fission. If there are isomers in the studied nucleus, mass separators can be used to study such isomeric decays, if half-lives are long enough to allow the separation process. In ^{133}Sb two isomeric levels in the microsecond range were reported [2], which allowed medium-spin studies in this nucleus. An excited state at 2792 keV was identified and interpreted as the $h_{11/2}$ proton excitation. Further β-decay studies [3,4] confirmed the $h_{11/2}$ and identified the $d_{3/2}$ proton level at 2439.5 keV. Thus, all proton states, except the $s_{1/2}$ predicted at around 2 MeV, were found in ^{133}Sb.

Less complete is the information about possible core-excited states coupled to the valence proton. Two isomers with half-lives of 3 and 16 μs and spins $I \geq 13/2$, reported in Ref. [2] populate the 2792-1510-61-162 keV cascade of γ rays, defining levels at 2792, 4302, 4363, and 4526 keV, respectively. The 3 μs isomer was not observed directly and for the 16 μs isomer the 4526 keV level was proposed, though no convincing arguments were given and the authors of Ref. [2] left open a possibility that the isomeric level may be placed still higher and decay by an unobserved (highly converted) transition of an energy $E_\gamma < 50$ keV.

Recent progress in spectroscopy of γ radiation, connected with the construction of high efficiency arrays of anti-Compton spectrometers [5], enabled systematic studies of medium-spin levels populated directly in fission. Instead of mass separation, one utilizes here the high resolving power of multiple γ coincidences. Measurement of threefold coincidences between prompt γ rays accompanying fission usually allows unique assignment of cascades of γ decays to individual fission fragments. In the present work we used three and higher-fold γ coincidence data collected in the measurement of prompt γ radiation, following spontaneous fission of ^{248}Cm. The measurement was performed using the EUROGAM2 array [5] at Strasbourg. The experiment was described previously in a number of works and we refer the reader to Ref. [6] for more experimental details.

*Present address: Université de Kénitra, Kénitra, Morocco.
†Present address: Department of Physics, Jagiellonian University, Kraków, Poland.

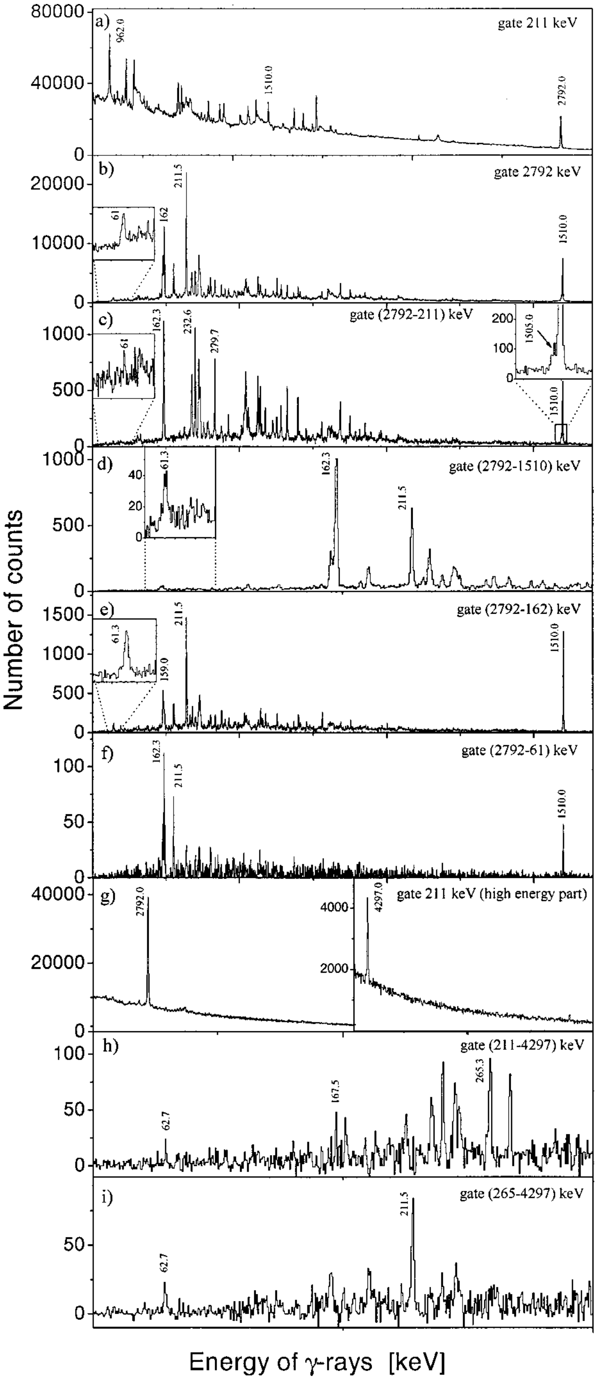

FIG. 1. Coincidence spectra gated on the lines in ^{133}Sb.

The 2792.0 keV transition in ^{133}Sb, known from previous works [2,4], produces a pronounced, separate line in a spectrum of prompt γ rays following fission of ^{248}Cm, as illustrated in Fig. 1(a). The spectrum is gated on the 211 keV line in ^{111}Rh, which is the most pronounced fission partner to ^{133}Sb. Lines at 962.0 and 1510.0 keV, identified in Ref. [2], are also seen. A spectrum gated on the 2792 keV line, displayed in Fig. 1(b), shows lines in Rh isotopes and known 162.3 and 1510.0 keV lines in ^{133}Sb [2]. This is further confirmed by a spectrum double-gated on the 2792 and 211 keV lines, shown in Fig. 1(c). In Fig. 1(d) a spectrum double gated on the 2792 and 1510 keV lines is shown, where the 162.3 keV line from ^{133}Sb and lines from Rh isotopes are seen. This spectrum confirms that the 2792.0, 1510.0, and 162.3 keV lines are in one cascade. However, a spectrum double gated on the 2792 and 162 keV lines, shown in Fig. 1(e) indicates that the 162.3 keV transition is not an isomeric one, as suggested in Ref. [2]. Prompt feeding of the level depopulated by the 162.3 keV transition is evident because of the observed prompt coincidences of the 162.3 keV transition with transitions in ^{111}Rh and ^{112}Rh isotopes.

In Fig. 1(e) there is also a line at 61.3 keV. A spectrum double gated on the 2792 keV and 61 keV lines, displayed in Fig. 1(f), confirms that the 61.3 keV transition is in a cascade with the 2792.0, 1510.0, and 162.3 keV transitions, as reported in Ref. [2]. Intensities observed in our data indicate however that the 61.3 keV transition should be placed above the 162.3 keV one, in contrast to suggestions of Ref. [2], where it was placed below the 162 keV transition. Therefore, we introduce the 4464.3 keV level instead of 4364 keV level proposed in Ref. [2].

The inset in Fig. 1(c) shows that there is a line at 1505.0 keV, which is in coincidence with the 2792.0 keV transition. The 1505.0 keV transition defines a new level at 4297.0 keV in ^{133}Sb. Figure 1(g) shows the high-energy part of a spectrum gated on the 211 keV line in ^{111}Rh. In addition to the 2792.0 keV line, a strong line at 4297.0 keV is observed, which confirms the new, 4297.0 keV level in ^{133}Sb. In a spectrum double gated on the 211 and 4297 keV lines, shown in Fig. 1(h), a new line at 167.5 keV is seen. Further gating shows that the 167.5 keV transition links the newly proposed 4464.3 and 4297.0 keV levels in ^{133}Sb, confirming these two levels further.

Two other new lines at 62.7 and 265.3 keV are seen in Fig. 1(h). Double gate on the 265 and 4297 keV lines, displayed in Fig. 1(i), shows that these two new transitions are in a cascade and belong to ^{133}Sb. The γ intensity of the 62.7 keV transition is more than twice γ intensity of the 265.3 keV transition. Therefore we place the 62.7 keV transition below the 265.3 keV one, introducing new levels in ^{133}Sb at 4359.7 and 4625.0 keV. The present data allowed the construction of the level scheme of ^{133}Sb as shown in Fig. 2.

Spins and parities were assigned to excited levels in ^{133}Sb based on angular correlation and linear polarization measurements performed with EUROGAM2 [6]. In Fig. 3 the 1510–2792 keV angular correlation is shown. Assuming a quadrupole character for the 2792 keV transition [2,4], one concludes that the 1510.0 keV transition has dipole character. Consequently, the spin of the 4302.0 keV level is $I^{\pi}=13/2$. If it was less than 13/2 one should observe a 4302 keV transition to the ground state, which is not seen in our data. Positive parity for the 4302.0 keV level is deduced from linear polarization of the 1510.0 keV line, $P=+0.2(1)$. This result is consistent with an $E1$ character of the 1510 keV transition. Similar analysis suggests polarization $P<0$ for the 1505 keV line and spin and parity of $I^{\pi}=13/2^{-}$ for the 4297 keV level. The 4464.3 keV level decays to both the 4302 and 4297 keV levels via low-energy transitions. They can not be both of quadrupole character, because one of them should have an $M2$ multipolarity,

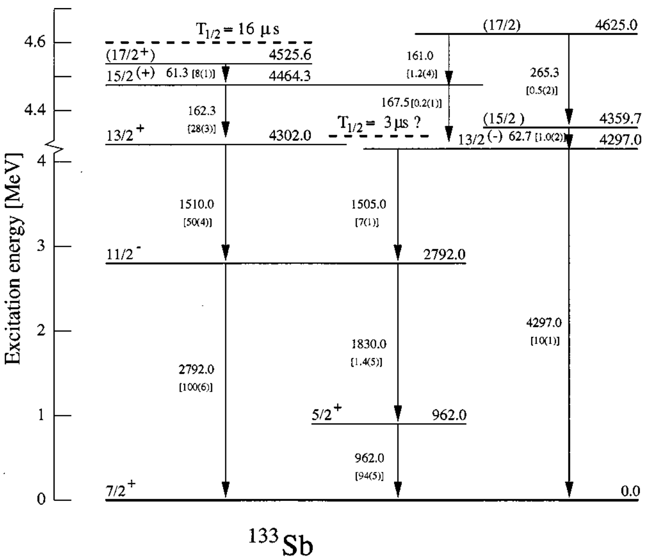

FIG. 2. Partial level scheme of ^{133}Sb as obtained in the present work. Excited levels and γ transitions are labeled with energies given in keV. For each transition, its γ intensity is given (in arbitrary units).

which is excluded by the observed prompt character of both decays. This fact limits the spin of the 4464.3 keV level to $I \leqslant 15/2$. If the spin were 13/2, this level would preferably decay to the 2792.0 keV level, which is not observed. Therefore we assign spin 15/2 to the 4464.3 keV level. This assignment is further supported by the 1510-162 keV angular correlations shown in Fig. 3, which is consistent with the dipole character for both transitions. Positive parity is preferred for the 4464.3 keV level because the decay of this level to the 2792.0 keV level is not observed. Otherwise, an $E2$ transition of 1672 keV should strongly compete with an $E1$ transition of 162 keV, if one assumes rates of 10^{-5}–10^{-4} W.u. for the $E1$ and 10^{-1} W.u. for the $E2$ transition, in analogy to the ^{208}Pb region.

As mentioned earlier, the observed $T_{1/2} = 16$ μs decay of the 162, 61, 1510, and 2792 keV, γ-ray cascade was tentatively associated in Ref. [2] with a 4526 keV isomeric state in ^{133}Sb. In addition, a $T_{1/2} = 3\,\mu$s decay component was reported in Ref. [2] for the 1510 keV and possibly the 61 keV transition. However, the 162 keV γ-ray decayed with a clear 16 μs half-life, showing no 3 μs component. The only possibility of accommodating the 3 μs isomer in the ^{133}Sb level scheme now established (see Fig. 2), is to place it above the 4302.0 keV level and to assume a low-energy, isomeric transition, that was detected neither in Ref. [2] nor in the present work. Such a placement coincides with another observation. If the isomeric level is located just above the 4302.0 keV level it may decay to the 4297.0 keV level. The high-energy part of the ''isomeric'' γ radiation, observed in Ref. [2] (see Fig. 5 in Ref. [2]), shows a line at about 4.3 MeV, which may correspond to the 4297 keV transition, identified in the present work. It is difficult to imagine what the spin of such an isomeric state might be. It should be higher than $I = 13/2$, otherwise this level should decay to the 2792 keV level or even to the ground state, which is not observed. On the other hand, if the spin were higher than 15/2, the isomer would be of an yrast character and should receive strong population in fission and its decay should be clearly observed in Ref. [2]. On balance we conclude, that the evidence thus far available for a 3 μs isomer in ^{133}Sb is not convincing and that experimental verification is called for. In particular, a possible microsecond component in the intensity decrease of the 4297 keV transition should be verified.

In contrast to the 3 μs isomer, the existence of the 16 μs isomer in ^{133}Sb is well documented [2]. It is evident from our data that the entire 2792-1510-162-61 keV cascade, populated in the decay of the 16 μs isomer [2], receives also a prompt feeding from fission. In particular, the 61.3 keV transition has some prompt component, because of a weak coincidences with rhodium lines is seen in Fig. 1(f). Therefore, the 4525.6 keV level most likely does not correspond to any isomer, in contrast to suggestions of Ref. [2]. Let us note that this observation is consistent with the $M1$ character assigned in Ref. [2] to the 61.7 keV transition. We conclude therefore, that the 16 μs isomer must be located above the 4525.6 keV level.

The lowest-lying excitations known in the doubly magic ^{132}Sn nucleus are of $\nu f_{7/2} h_{11/2}^{-1}$ and $\nu f_{7/2} d_{3/2}^{-1}$, particle-hole type, as well as 3^- octupole state. Most of the $\nu f_{7/2} h_{11/2}^{-1}$ states are known in the 4–5 MeV range in ^{132}Sn. Their excitation energies provide $\nu f_{7/2} h_{11/2}^{-1}$ two-body interactions for use in shell-model calculations. In Ref. [8], they were used together with empirical $\pi g_{7/2} \nu h_{11/2}^{-1}$ and $\pi g_{7/2} \nu f_{7/2}$ interactions to calculate $\pi g_{7/2}^{n} \nu f_{7/2} h_{11/2}^{-1}$ energies in the two- and three-proton $N = 82$ nuclei ^{134}Te and ^{135}I. Excellent agreement with experimental data was obtained in both nuclei.

A calculation for the one-proton, $N = 82$ nucleus ^{133}Sb using the same two-body interactions gave energies for $\pi g_{7/2} \nu f_{7/2} h_{11/2}^{-1}$ states. The near-yrast part of this multiplet is shown in Fig. 4. An important feature of the calculated results is that the $21/2^+$ multiplet member lies below the $19/2^+$ levels and can decay only by a $\sim$30 keV, $21/2^+ \rightarrow 17/2^+ E2$ transition with a half-life of the order of 10 μs. A comparison of the calculations to the experimentally observed levels, marked by thick lines in Fig. 4, thus provides strong support for the placement of the 16 μs isomeric state

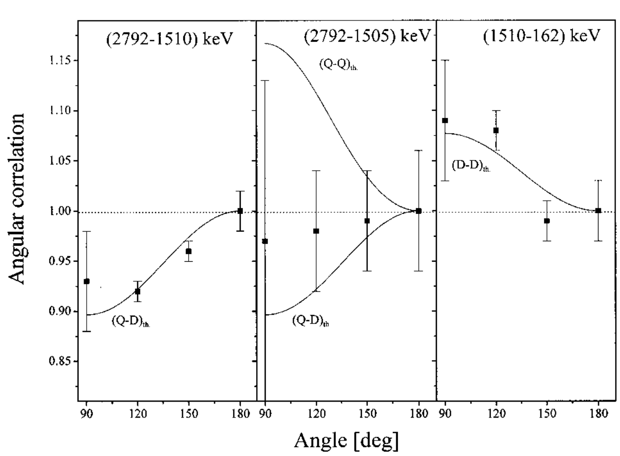

FIG. 3. Angular correlations between γ rays in ^{133}Sb.

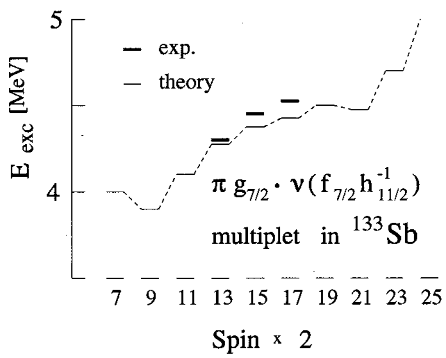

FIG. 4. Comparison of the experimental data to shell-model calculations for core-excited states in ^{133}Sb.

at about 4560 keV. Most likely this is the expected $21/2^+$ isomer of $\pi g_{7/2}\nu f_{7/2}h_{11/2}^{-1}$ character.

It is interesting to ask about other members of the $\pi g_{7/2}$ $\otimes$core multiplet. The $19/2^+$ level should decay to the $17/2^+$ level at 4526 keV. In the present data we could not identify such level. The $11/2^+$ member of the multiplet, predicted at 4.1 MeV is also not observed, despite the fact that the corresponding 2^+ level at 4042 keV in ^{132}Sn core is clearly seen in our prompt-γ data. In β^- decay of ^{133}Sn [7], two levels were found around 4 MeV, which may belong to the $(\pi g_{7/2}\otimes 2^+)_j$ multiplet, though nothing is known about their spins. In the present analysis these levels are not seen.

The 4297.0, 4359.7, and 4625.0 keV levels in ^{133}Sb probably correspond to the coupling of the $g_{7/2}$ proton to the negative parity 3^-, 4^-, and 5^- excitations in ^{132}Sn core. What we observe in the present data, are most likely only the yrast members, resulting from this coupling.

In summary, high-energy excited levels in ^{133}Sb were observed up to 4.7 MeV. Spins and parities were assigned to some of these levels based on angular correlations and linear polarization measurement. Coincidence data allowed to resolve some ambiguities concerning the order of excited levels in ^{133}Sb, as reported in previous studies and to propose new positions for (still not identified) two isomeric levels proposed previously. Shell-model calculations describe the observed yrast excitations as the result of coupling of the $\nu(f_{7/2}h_{11/2})$ core excitations to the valence proton in the $\pi g_{7/2}$ orbital. One of the isomers, with a half-life of $T_{1/2}=16\ \mu$s is interpreted as the $21/2^+$ member of the $\pi g_{7/2}\otimes\nu(f_{7/2}h_{11/2})$ multiplet, which appears below the $19/2^+$ member and decays via an unobserved, low energy, $E2$ transition to the $17/2^+$ member of the multiplet. The newly identified 4297.0 keV level, most likely corresponds to the octupole excitation in the core.

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