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On the nature of the 17 μs isomer of the ^{133}Sb valence nucleus

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Abstract. The decay of the 17 μs isomer of ^{133}Sb was re-investigated experimentally. It was produced by thermal neutron induced fission of ^{241}Pu. Its detection is based on time correlation between fission fragments selected by the LOHENGRIN spectrometer at ILL (Grenoble), and the γ-rays, and conversion electrons from the isomer. The interpretation of the level scheme is based on shell model calculations, where empirical two-body matrix elements were employed. The good agreement between theory and experiment suggests that the isomer is the $21/2^+$ member of the 2p-1h $\pi g_{7/2}\nu(f_{7/2}h^{-1}_{11/2})$ configuration.

PACS. 21.10.Tg Lifetimes – 23.20.Lv Gamma transition level energies – 25.85.Ec Neutron-induced fission – 21.60.Cs Shell model – 27.60.+j $90 \leq A \leq 149$

The nucleus ^{133}Sb consists of the doubly magic ^{132}Sn core and one valence proton. Due to its particularly simple structure it plays an essential role for testing the nuclear shell model. The information concerning this nucleus comes from β^- decay studies of the ^{133}Sn fission fragment (FF) [1,2]. It has been found that the single-proton states are below 3 MeV excitation, while the three quasiparticle excitations start above 4 MeV. This work was supplemented by the observation of two isomers of half-lives of 3 and 16 μs, respectively. However, the experimental study of [3] is not sufficient to unambiguously identify the nature of the isomers and the levels they feed above 4.3 MeV, and additional information is still necessary. For this purpose, we have re-investigated the decay of the isomers and measured the conversion electrons of the low energy transitions of their decay scheme. A microscopic shell calculation was also performed to understand the nature of the states above 4 MeV excitation.

The FF of the A=133 mass chain were produced by thermal neutron induced fission of ^{241}Pu. The spectrometer LOHENGRIN at ILL has been used to separate the FF of ionic charge q=23 recoiling from a thin target of about 400 μg cm^{-2}. The FF are detected by a ΔE gas-detector of 13 cm length, and subsequently stopped in a mylar window of 12 μm thickness. The γ-rays de-exciting the isomeric states are detected by two large volume Ge detectors and the conversion electrons are detected by two cooled Si(Li) detectors covering a total area of 2×6 cm^2 and located 7 mm behind the mylar window. The gas pressure of the ionization chamber was tuned to stop the FF at about 3 μm from the outer surface of the mylar window to minimize electron absorption and to have a good energy resolution. The ion transport time through the LOHENGRIN spectrometer is about 2.2 μs, which limits the observation of isomers in ^{133}Sb to half-lives longer than ~ 0.7 μs. Events were stored on a disk each time a Si(Li) or a Ge detector was fired within a time range of 40 μs after the detection of a FF.

The γ-rays of 162.5, 1510.5 and 2791.0 keV seen in the present work are the same as those already observed in [3]. The decay curves of the 162.5 and 1510.5 keV γ lines in Fig. 1 show an unique half-life $T_{1/2}$=16.8(0.5) μs, in good agreement with the previous value of 16.0(1.5) μs. However, the short component of 3.0(1.5) μs previously observed in the time spectrum of the 162.5 keV γ-ray [3] is not present in our measurement. This difference may be due to the poor stastistics, bad background substraction or (and) the presence of a contaminating mass in the previous study. In conclusion, the 3 μs isomer does not exist or is much more weakly produced in the fission of ^{241}Pu than in the fission of ^{235}U, which is much less probable.

As the 61.5 Kev γ-ray transition was not observed with our large volume Ge detectors, the conversion coefficients of the 61.5 and 162.5 keV transitions were deduced from the Si(Li) spectrum in coincidence with the 1510.5 keV γ-ray shown in Fig. 2. In the isomer decay, the sum of the delayed photon and electron intensity must be conserved for each cascading transition. Consequently, the experimental ratio of the K-conversion intensities have to satisfy the relation :

$$\frac{K(61.5)}{K(161.5)} = \frac{\alpha_K(61.5)}{\alpha_T(61.5)} \, \frac{\alpha_T(162.5)}{\alpha_K(162.5)}$$

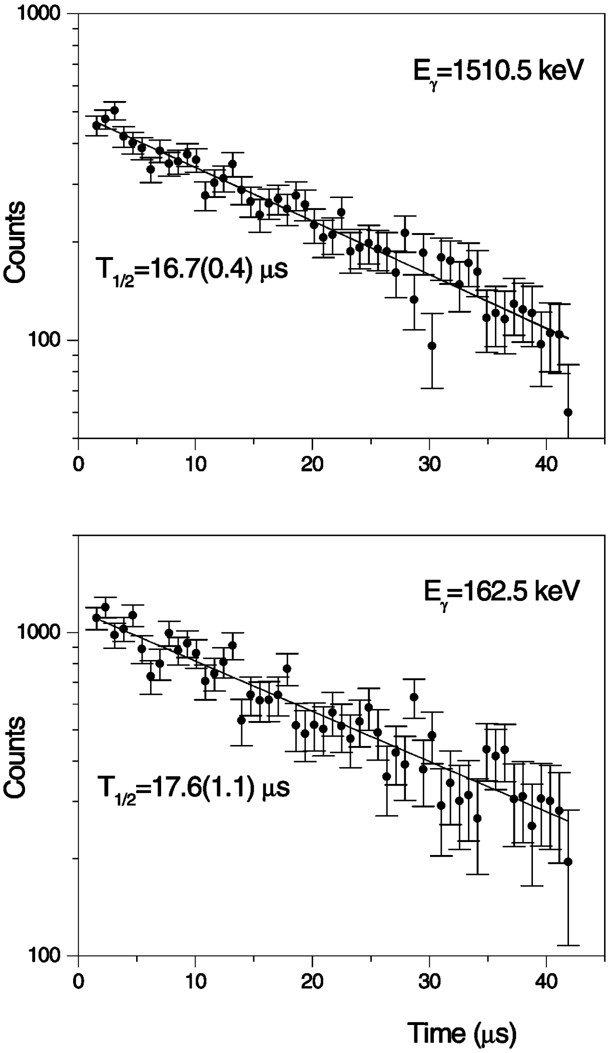

Fig. 1. Half-life spectra of the 1510.5 and 162.5 keV γ-rays

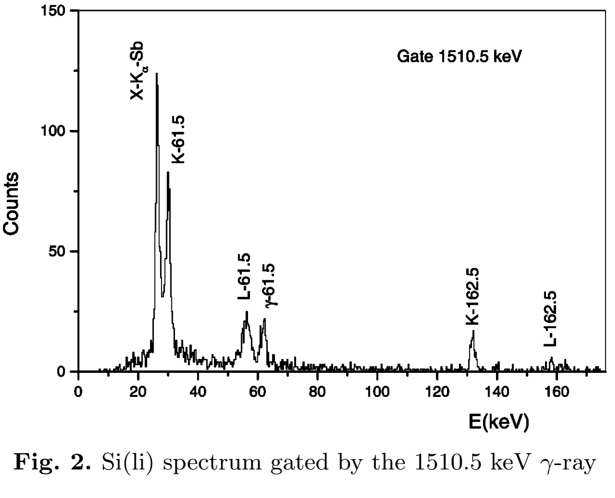

Fig. 2. Si(li) spectrum gated by the 1510.5 keV γ-ray

where α_K and the α_T are the tabulated K and total conversion coefficients respectively. One can now try to find a combination of multipolarities satisfying the experimental ratio. This method is very precise, and the measured experimental ratio K(61.5)/K(162.5)=5.0(0.3) agrees with the calculated value of 4.8, where both the 61.5 and 162.5 keV transitions are assumed to have an M1 multipolarity. Moreover, the X-ray intensity corrected for the fluorescence yield of the two K-lines observed shows that there is no room for an additional unobserved transition of energy higher than 30 keV, the value of the K electron binding energy of Sb. The inspection of another electron spectrum performed with a lower threshold excludes any possible transition with energy higher than 20 keV. The γ spectrum in coincidence with the 1510.5 keV gate shows that the maximum relative intensity of a possible cross-over from the 4526 keV to the 4302 keV level is ~5 %.

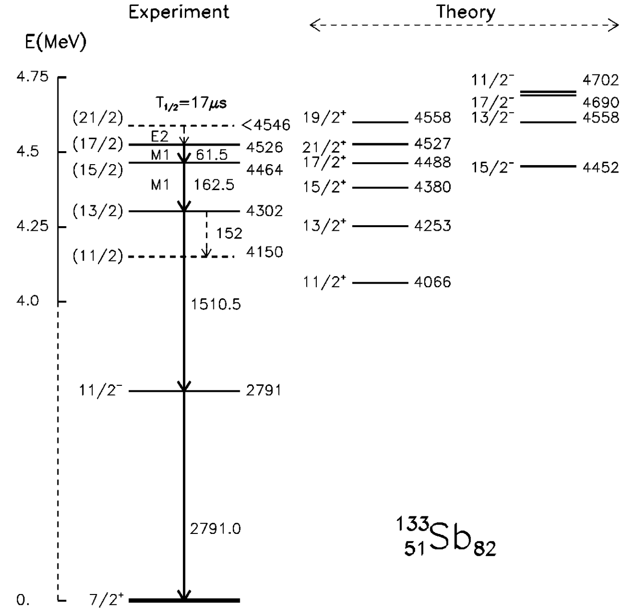

Fig. 3. Proposed level scheme of ^{133m}Sb. The computed yrast excitations above 4 MeV are shown on the right. The relative order of the experimental 61.5 and 162.5 keV was chosen to have the best agreement with theory

The level scheme of the 17 μs isomer of ^{133}Sb is shown in Fig. 3. It differs from the previous one by the fact that i) the 3 μs isomer was not observed, and ii) the 61.5 and 162.5 keV transition multipolarities were measured unambiguously for the first time. The absence of any cross-over transition to the ground state requires that the spin of the 4302 keV level must be at least 13/2 and that the higher levels should have the same parity. However, all this information is still not sufficient to deduce the nature of the isomer and the levels above 4 MeV. To elucidate this problem we have computed the yrast states expected in this energy region with spin $I \geq 11/2$. Above the single-proton states, the lowest 2p - 1h states are expected to have the $\pi g_{7/2}\nu(f_{7/2}d_{3/2}^{-1})$ configuration for negative parity levels, and the $\pi g_{7/2}\nu(f_{7/2}h_{11/2}^{-1})$ configuration for positive parity levels. In this calculation the residual interaction was expanded in three two body interactions between the valence orbitals $\pi g_{7/2}$, $\nu f_{7/2}$, and $\nu d_{3/2}^{-1}$ or $\nu h_{11/2}^{-1}$. These two body matrix elements are taken from experiment, in the even mass neighbouring nuclei : ^{132}Sn for $\nu(f_{7/2}d^{-1}_{3/2})$ and $\nu(f_{7/2}h^{-1}_{11/2})$, and ^{132}Sb for $\pi g_{7/2}\nu d^{-1}_{3/2}$ [4]. The ^{134}Sb nucleus is almost unknown, and for the $\pi g_{7/2}\nu f_{7/2}$ interaction we have used an estimation from the well-known ^{210}Bi as proposed Bhattacharyya et al. [5]. Moreover, as no valuable experimental information can be obtained for the $\pi g_{7/2}\nu h^{-1}_{11/2}$ multiplet of ^{132}Sb, we have used the theoretical calculation results of Andreozzi et al. [6], which reproduce also very precisely the low energy $\pi g_{7/2}\nu d^{-1}_{3/2}$ multiplet in this nucleus. The single-particle energies are also taken from experiment. However, we think that the experimental energy difference $\epsilon h^{-1}_{11/2} - \epsilon d^{-1}_{3/2}$=241.8 keV, measured for ^{131}Sn is very likely uncorrect. We have used in this calculation a more realistic value of 110 keV, which will be discussed in a forthcoming publication. The experimental mass data in the vicinity of ^{132}Sn used in the calculation are from [7,8].

Figure 3 shows that there is a good agreement between the experiment and the calculated positive parity states of the $\pi g_{7/2}\nu(f_{7/2}h^{-1}_{11/2})$ configuration when the spin and parity I^{π}=13/2$^+$ are assigned to the 4302 keV state. The theoretical calculation presented in Fig. 3 shows that the 21/2$^+$ state has a lower energy than the 19/2$^+$ state, and this 21/2$^+$ state can only decay to 17/2$^+$ by a low energy E2 transition. This 21/2$^+$ state should be a good candidate for the isomeric state in ^{133}Sb. A conclusion of the same nature was also proposed by Isakov et al. [9]. However, in this case, the two body interactions were not taken from experiment but were computed and the calculated states are ∼300 keV too high in energy.

The fact that the isomeric transition was not observed in this work requires that its energy should be lower than 20 keV. A mean root square deviation of 47 keV is obtained between the experiment and theory for the four states 13/2$^+$, 15/2$^+$, 17/2$^+$, and 21/2$^+$ of the $\pi g_{7/2}\nu(f_{7/2}h^{-1}_{11/2})$ configuration. However, considering that the computed states are all systematically tow low, one suspects the existence of a possible downward shift of about ∼ 47 keV of the computed absolute energies. Note that this shift is compatible with the errors in the mass data [7,8] used in the calculation. After the correction of the shift, the mean root square deviation between experiment and theory is 19 keV.

The isomeric E2 transition probability is almost independent of its energy below 20 keV, and corresponds to a value B(E2) = 9 e^2 fm^4. A rough estimation of the B(E2) value was computed assuming that the leading term comes from the $< \pi g_{7/2}\|M(E2)\|\pi g_{7/2} >$ reduced matrix element, while the $< \nu(f_{7/2}h^{-1}_{11/2})_J\|M(E2)\|\nu(f_{7/2}h^{-1}_{11/2})_{J'} >$ ones are very likely small because they take place between p - h states, and were neglected in the calculation. With the theoretical quadrupole moment Q(7/2)=-30.1 e fm^2 proposed in [9] as ingredient, a value B(E2)=6 e^2 fm^4 was deduced. As expected, this estimation takes into account ∼65 % of the experimental value.

A weak intensity γ-ray transition of 152 keV was observed in coincidence with the K-61.5 keV electron transition. This line, observed at the limit of our detection system, may correspond to the 13/2$^+$→11/2$^+$ transition expected from the theory and in competition with the strong 1510.5 keV E1 transition for the decay of the 4302 keV level. The measured experimental branching ratio is $I_\gamma(1510.5)/I_\gamma(152)$=20(10). It is important to verify whether or not this value is reasonable. Along the cascade of M1 transitions de-exciting the 21/2$^+$ isomeric level, the B(M1) values are expected to decrease when the spin decreases. This effect is a consequence of the increasing complexity of the wave function as the spin decreases : the 21/2$^+$ state corresponds to the coupling of the $\pi g_{7/2}$ proton with the $\nu(f_{7/2}h^{-1}_{11/2})_J$ neutrons coupled to 3 J=7-9 states, while for the 11/2$^+$ state all the 8 levels of the neutron configuration are involved. It is difficult to compute very reliably these B(M1) values, but the use of the B(M1)=0.45 W.u. and B(M1)=0.25 W.u., estimated by Isakov [9] for the 17/2$^+$→15/2$^+$ and 15/2$^+$→13/2$^+$ transitions, helps us to get via extrapolation a B(M1)∼ 0.1 W.u. for the next 13/2$^+$→11/2$^+$ transition. With these values one deduces a high hindrance factor H_w∼5 10^4 W.u. for the 1510.5 keV transition, compatible with a 2p - 1h →1 p nature of the E1 transition. The decay pattern of the 4302 keV state, with a strong E1 branch to the $\pi h_{11/2}$ state and a very weak branch to the 11/2$^+$ 2p - 1h state, justifies a posteriory the spin proposed for the 4302 keV level.

In our investigation, we have shown that very likely there is only one isomer of 17 μs half-life in ^{133}Sb and we have determined the multipolarity of the low energy transitions of 61.5 and 162.5 keV. The nature of the isomerism in this nucleus has been clarified through a comparison with theory. The good agreement between theory and experiment demonstrates that the empirical two body interactions used in the calculation are relevant for the future more extensive calculations for nuclei around ^{132}Sn.

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