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Decays of ^{134}Sn and 0^- ^{134}Sb

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The first measurements of γ rays following the decays of ^{134}Sn and the 0^- isomer of ^{134}Sb are reported. The decay schemes have been constructed using the γ-ray data in combination with results from delayed neutron spectroscopy. Both decays are dominated by the first forbidden ground-state β transitions. All observed levels can be interpreted in terms of the shell model. The energy of the $(\nu h_{9/2}\pi h_{11/2})1^+$ state in ^{134}Sb was found to be 3.85 MeV, implying a n-p interaction energy which is less than that of the g orbitals in very neutron-rich isotopes of In.

Apart from the ^{208}Pb region, the nuclei near ^{132}Sn offer the only possibility for studies of a double shell closure in heavy nuclei. The fact that the nuclei in the ^{132}Sn region are far away from the line of β stability makes the experimental work difficult. At present only about one half of the single-particle states in this region have been located, and some of these are known only as β-decaying states. The spectroscopic information on excited proton-neutron states in the doubly odd nuclei neighboring ^{132}Sn is reasonably detailed only in the case of ^{132}Sb which has been studied by Kerek *et al.*[1] and more recently by Stone, Faller, and Walters.[2] The levels of ^{130}In, ^{132}In, and ^{134}Sb are known only from their β decays.[3-5] The levels of these doubly odd valence nuclei are important, because they provide our only source of first-hand knowledge on details of the n-p interaction in complex nuclei. The current work was initiated to search for the excited states of ^{134}Sb, where both protons and neutrons are single valence particles in otherwise unfilled shells. One particular goal of the experiment was to identify the $(\nu h_{9/2}\pi h_{11/2})1^+$ level which is the only state within the simplest configuration space which can be populated by an allowed β transition from the ground state of ^{134}Sn. The results discussed here also include new information on the lowest-lying low spin states of ^{134}Te. A detailed report on the structure of ^{134}Te will be published separately.

The main motivation for the current experiments was to obtain nuclear structure data for ^{134}Sb and the low spin levels of ^{134}Te. A secondary objective, also of considerable interest, has been to provide sufficient decay scheme information to enable the evaluation of the total β-decay energies of ^{134}Sn and ^{134}Sb using $\beta\gamma$-coincidence data. This is a part of an ongoing precision study[5] of Q_β values of nuclides in the ^{132}Sn region. The numbers quoted later stem from this study and are preliminary in nature.

The experiments were performed using samples of mass-separated fission products from the OSIRIS (Refs. 6 and 7) on-line facility located in Studsvik. The combined target and ion source of the facility has recently[7] been upgraded, which has resulted in strongly improved production yields for short-lived fission product nuclei. Common practices for studies of the radiation following the decays of short-lived β emitters have been described previously, see, e.g., Ref. 8. In the present experiments on $A=134$, the γ-ray spectra were dominated by the radiation following the decay of 10 s ^{134}Sb due to its high fission yield and high γ-ray branching. Two sets of relatively weak γ rays, see Fig. 1, having half-lives of 1.2 and 0.75 s were found to follow the decays of ^{134}Sn and a low spin isomer[3] of ^{134}Sb, respectively. The identification relies to some extent on the difference in the release of the elements Sn and Sb from the fission target. Atoms of Sb have a considerably longer average delay time in the target. The relative intensity of the Sb fraction of a collected sample therefore shows a stronger dependence on the target temperature, which can be used to determine the origin of γ rays or other radiations.

The decay of ^{134}Sn was almost unknown before the experiments reported here. The existing data consists of a delayed neutron spectrum recorded[9] at our laboratory some time ago, and a somewhat approximate value[10] of $(17\pm13)\%$ for the delayed neutron branching. The de-

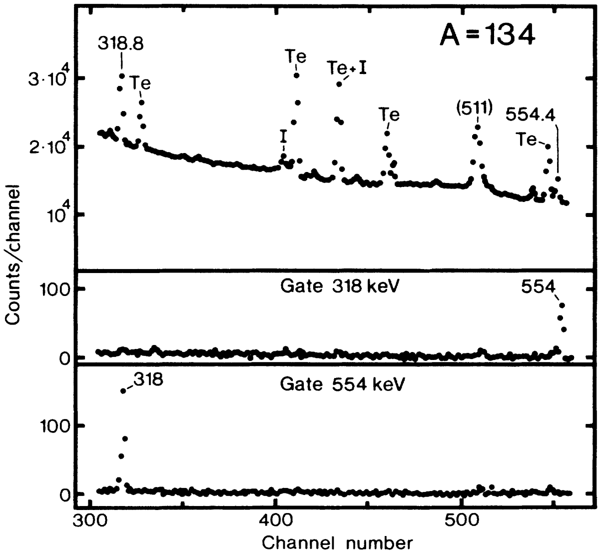

FIG. 1. The top panel shows a portion of a γ-ray spectrum recorded as the first group in a multispectrum scaling experiment with a group time of 1 s. The two γ rays labeled with the energies are due to ^{134}Sn, and are in coincidence as seen in the two lower panels which show data from the $\gamma\gamma$-coincidence experiment. Most of the γ rays visible in the figure are transitions in other $A=134$ isobars as indicated in the top panel.

layed neutron spectrum is important as a complement to our β- and γ-ray spectroscopic data, as discussed later, and it is therefore reproduced here, see Fig. 2.

The low spin isomer of ^{134}Sb has previously only been observed[3] as a short-lived component of the β spectrum of the neutron rich $A=134$ isobars. It is now clear that this nuclide has a very strong β transition to the ground state of ^{134}Te, which results in a rather weak feeding of the excited states. The absolute intensities of the γ rays in ^{134}Te were determined through a dual multispectrum scaling experiment using both β- and γ-ray detectors. The high intensity of the β particles from the 0.75 s ^{134}Sb decay precluded a determination of the absolute intensities of γ rays from ^{134}Sn in this way. We have therefore chosen to give relative intensities for the ^{134}Sn γ rays listed in Table I. A conversion to an absolute scale can be attempted by using the (poorly) known[10] delayed neutron branching of ^{134}Sn combined with the observed intensities of the 1096 and 2755 keV γ rays from ^{133}Sb in our spectra obtained for mass 134. This procedure suggests that the most intense γ ray of ^{134}Sn, at 872.19 keV, has an intensity of about $(6\pm3)\%/d$. The intensity scale of the ^{134}Sb γ rays as given in Table II has been normalized by using a value of $(57\pm6)\%/d$ for the 706 keV transition in the decay of 10 s ^{134}Sb. This transition was used for the calibration of the detectors in the dual multispectrum experiment.

The low spin decay chain studied here is illustrated in Fig. 3. The first forbidden transition to the ground state dominates the decay of both ^{134}Sn and ^{134}Sb. These transitions are discussed in more detail later in the paper. The lowest-lying levels of ^{134}Sb are the members of the $\nu f_{7/2}\pi g_{7/2}$ multiplet. In cases where both particles have the same character, i.e., both are particles or both are holes, the n-p interaction tends to produce a stronger binding and hence a lower energy of the multiplet members at the extremes of the allowed range of spins. In the work of Kerek *et al.*[3] the two isomers of ^{134}Sb were taken to be the 0$^-$ and 7$^-$ members of the multiplet.

The argument in favor of a 0$^-$ assignment of the ground state of ^{134}Sb, rather than 1$^-$ as in the analogous case of ^{210}Bi, was the absence of observed β-particle population of the 2$^+$ level in ^{134}Te. The considerably more detailed information now at hand supports the assumption of a 0$^-$ ground state of ^{134}Sb, but we have no firm experimental evidence for this. The β-particle feeding of the ^{134}Sb ground state in the decay of ^{134}Sn is strong, with a logft value very similar to the value of 5.4 observed[11] for

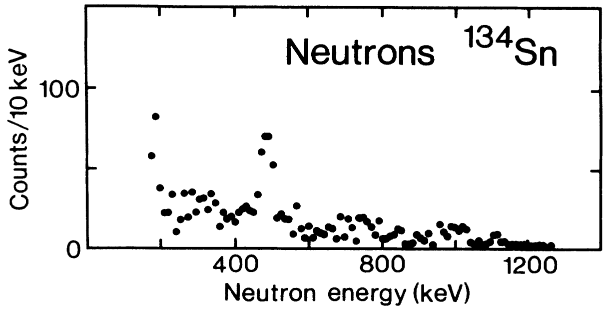

FIG. 2. Before the present experiments, ^{134}Sn was only known as a delayed neutron precursor. The figure shows a pulse height spectrum of neutrons from the $A=134$ isobars obtained (Ref. 9) using a ^{3}He proportional counter. The neutron peak near 480 keV follows the decay of ^{134}Sn. The intensity of this transition is about 20% of the total spectrum. The peak may represent a major part of the ^{134}Sn neutron intensity as the contributions to the spectrum by ^{134}Sb and short-lived contaminants are not well known. The high points at low energies are caused by pulse pileup from γ-ray interactions in the counter.

TABLE I. γ rays following the decay of ^{134}Sn ($T_{1/2}=1.20\pm0.10$ s)

Energy[a] (keV)	Relative intensity[b]	Coincidence relations
52.80[c] 20	2.1 6	
317.78 20	52 3	555
554.43 20	29 2	318
872.19 20	100 5	none
921.5[c] 5	9 3	
962.22[d] 20	23.8 15	none
1117.3[c] 5	8 3	
1325.6[c] 7	4 2	

[a] In our notation 317.78 20 = 317.78 ± 0.20, etc.

[b] The discussion given in the text suggests that intensities in units of %/decay can be obtained by multiplication with a factor of 0.06.

[c] Possibly due to ^{134}Sb.

[d] Transition in ^{133}Sb following neutron emission.

TABLE II. γ rays following the decay of the low spin isomer of ^{134}Sb ($T_{1/2}=0.75\pm0.07$ s). Only the strongest lines are included for the regin $E_\gamma > 3$ Mev.

Energy[a] (keV)	Intensity (%/d)	Coincidence relations
52.80[b] 20	0.03 1	
166.93 20	0.12 2	2464
921.5[b] 5	0.08 2	
1117.3[b] 5	0.08 2	
1185.6 5	0.06 2	
1279.01 10	1.1 5	
1325.6[b] 5	0.018 5	
1352.14 20	0.93 5	1279
1654.57 20	0.26 2	1279
1710.2 4	0.03 1	
2464.29 30	0.29 2	167
2631.47 30	0.96 7	none
2934.0 10	0.013 4	
3630.4 6	0.04 1	
3660.2 6	0.06 2	
4103.2 7	0.06 2	
5645.0 10	0.09 2	
6279.6 10	0.07 2	
6450.9 10	0.12 2	
6624.0 10	0.07 2	
6686.7 10	0.14 3	
6733.2 15	0.04 1	
6820.4 15	0.06 2	

[a] See footnote a of Table I.

[b] Possibly due to ^{134}Sn.

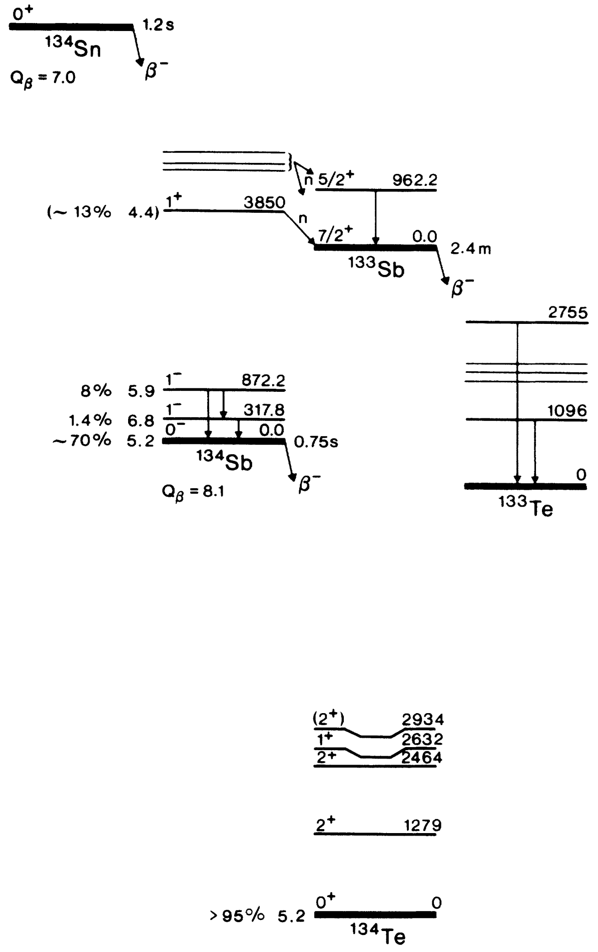

FIG. 3. An illustration, drawn to scale, of the low spin decay chain studied here. The γ transitions in ^{133}Te were used for the deduction of β intensities feeding the low-lying levels of ^{134}Sb, as discussed in the text. The intensity of the β transition to the 3850 keV level was deduced by assuming a log*ft* of 4.4. All excited states of ^{134}Sb and ^{134}Te shown here have half lives less than one ns. A more detailed level scheme of ^{134}Te is given in Fig. 4.

the $\nu f_{7/2}\rightarrow\pi g_{7/2}$ transition in the decay of ^{133}Sn. On the basis of empirical data, this observation, in analogy with the situation at ^{210}Bi, strongly favors $J^\pi=0^-$ for the ^{134}Sb ground state. It can be remarked, that in terms of the shell model, the ground-state β transitions following the decays of ^{134}Sn and ^{134}Sb both have the character $\nu f_{7/2}\rightarrow\pi g_{7/2}$ which is reflected by the observed log*ft* values.

The shell model should provide a very good description of the states formed by the two valence particles in ^{134}Sb. At low-excitation energies we expect a substantial β-particle population only of the low spin members of the $\nu f_{7/2}\pi g_{7/2}$ and $\nu f_{7/2}\pi d_{5/2}$ multiplets. Adopting the ground state as the 0^- member of the former multiplet, it is natural to accept the 317.8 keV level as the corresponding 1^- state. The level at 872.2 keV can then hardly be interpreted as other than the 1^- state having the lowest spin of the $\nu f_{7/2}\pi d_{5/2}$ multiplet; see Fig. 3. The log*ft* value for the β transition feeding this latter level is in good agreement with that[11] of the corresponding single-particle transition in the decay of ^{133}Sn.

The γ-ray decay of the 872.2 keV level populates both of the observed lower-lying levels. The transitions are both of the type $d_{5/2}\rightarrow g_{7/2}$. They are consequently *l*-forbidden and cannot be induced by the bare magnetic moment operator, but do proceed through higher-order magnetic effects. Under the general assumption that the transitions are induced by an operator having the properties of a tensor of rank one, the angular momentum geometry would, for perfectly pure configurations, imply that

$$B(M1;1\rightarrow 0)=\tfrac{14}{3}B(M1;1\rightarrow 1)\,.$$

Even very small configuration admixtures, adding allowed $M1$ strength, could change this ratio considerably. Experimentally, we find the transition probabilities to the two final states to be approximately equal, indicating that some mixing indeed occurs.

The position of the 1^+ state formed by the spin-orbit partners $\nu h_{9/2}$ and $\pi h_{11/2}$ is of considerable interest. The *n*-*p* interaction is particularly effective in these cases due to the good overlap of the orbitals. The interaction energy in light and medium nuclei may reach a strength comparable to that of the pairing interaction. Federman and Pittel have discussed[12] the importance of the interaction between spin-orbit partners and have shown that the interaction strength can be sufficient to cause the onset of ground-state deformation in nuclei. On the experimental side, one can get information on the strength of the *p*-*n* interaction simply by comparing the energy of the 1^+ level with zero-order estimate of the level multiplet energy obtained by adding the quasiparticle or single-particle energies of the spin-orbit partners as observed in the adjacent odd-mass nuclei. A good example is the $\nu g_{7/2}$ and $\pi g_{9/2}$ pair which is well known in the ^{132}Sn region. These *g* orbitals show an interaction energy of about 1 MeV as has been observed[13] in the heaviest In isotopes approaching $N=82$. In the case of the *h* orbitals of interest here, the $\pi h_{11/2}$ level is known[14] at 2792 keV in ^{133}Sb. The $\nu h_{9/2}$ state has not been identified with certainty in ^{133}Sn. The available systematics of energy levels along $N=83$ indicates that the excitation energy should be about 1.3 MeV. It is not unlikely that the position of this level is defined by the 1485 keV γ ray observed to follow the decay of ^{133}In in experiments[5,15] at the OSIRIS and ISOLDE facilities. For the sake of definiteness we use this latter value, arriving at an estimate of 4277 keV for the energy of the $\nu h_{9/2}\pi h_{11/2}$ multiplet. The neutron binding energy of ^{134}Sb, as deduced from the total decay energies recently measured[5] at our laboratory, is 3.37 MeV with an uncertainty of about 0.10 MeV. These numbers suggest that the 1^+ level quite likely is situated above the neutron binding energy. We have not been able to identify any γ rays possibly following the decay of the level. On the other hand, a strong peak is seen at 0.48 MeV in the delayed neutron spectrum, Fig. 2. It is tempting to ascribe this peak to a *d*-wave neutron transition from the 1^+ level to the ^{133}Sb ground state. One can get an idea of the transition intensity by estimating the intensity of the β-particle feeding of the 1^+ level. The allowed β transitions in the region near ^{132}Sn are usually quite fast, having logft values of about 4.4. By assuming this value also for the ^{134}Sn decay, the intensity feeding the 1^+ level is deduced to be about 13%/d. This number is quite compatible with the intensity of the peak in the neutron spectrum and with the total delayed neutron branching[10] of about 17%. (The unknown intensity of the delayed neutrons feeding the ^{133}Sb ground state from higher-lying levels of ^{134}Sb is expected to be a few times higher than the feeding of about 1.4% observed here for the 962 keV level.)

The conclusion is that the $(\nu h_{9/2}\pi h_{11/2})1^+$ state in all likelihood can be identified at an energy near 3850 keV (see Fig. 3), implying a n-p interaction energy of about 0.43 MeV. Despite the uncertainties involved in the derivation of this value, it is clear that the interaction energy of the h-orbital particle pair is only about half as much as that of the g-orbital hole pair mentioned above. According to Federman and Pittel,[12] this reduction is expected and can be traced to the higher number of states available in the higher shells.

As a curiosity one may mention that the h orbitals discussed above are observed as pure hole states in ^{207}Tl and ^{207}Pb. In this case one would thus have the unique opportunity to determine the n-p interaction energy for a specific pair of spin-orbit partners at both extremes of the same major shells, in the case that the pertinent 1^+ state is identified in ^{206}Tl.

Very few excited states are known in ^{134}Te. The work of Kerek *et al.*[3] revealed the most strongly populated levels in the decay of the high spin isomer of ^{134}Sb. Additional information on γ-transition probabilities has subsequently been obtained,[16] but no additional levels are reported. Theoretical calculations (see Refs. 3 and 16) have shown that the low-lying levels can be well understood in terms of two protons mainly occupying the $g_{7/2}$ and $d_{5/2}$ orbitals.

The levels receiving the main population in the decay of the low spin isomer of ^{134}Te are shown in Figs. 3 and 4. For the β transition to the ground state, the analogy with the $\nu f_{7/2} \rightarrow \pi g_{7/2}$ decay of ^{133}Sn has been discussed above. Drawing further on the similarity with the ^{133}Sn decay, we expect the β transition to the 2631.5 keV level to have the same nature as the $\nu f_{7/2} \rightarrow \pi d_{5/2}$ transition on grounds of the observed logft value. This excited state should thus be the 1^+ level of the $g_{7/2}d_{5/2}$ proton multiplet expected at about 2.5 MeV. The corresponding 2^+ level, expected[3] at a slightly lower excitation energy, is identified at 2464.3 keV. Assuming $M1$ multipolarities, the γ-ray branching from the proposed 1^+ level shows a $B(M1)$ for the 166.9 keV transition, within the level multiplet, which is about 70 times higher than the $B(M1)$ to the first 2^+ level. This is reasonable due to the l-forbidden nature of the latter transition and gives further credibility to the proposed shell model interpretation. The logft value of the β transition feeding the 2464.3 keV level (see Fig. 4), is also reasonable for a first forbidden unique transition in nuclei near closed shells.

A level at 2933.6 keV is tentatively identified as the 2^+ state of the $d^2_{5/2}$ multiplet. The observed β-particle population of the level, and its subsequent γ-ray decay are compatible with a 2^+ assignment. The identification is not as reliable as for the lower-lying levels because states of more complex nature can be expected at energies above about 3 MeV.

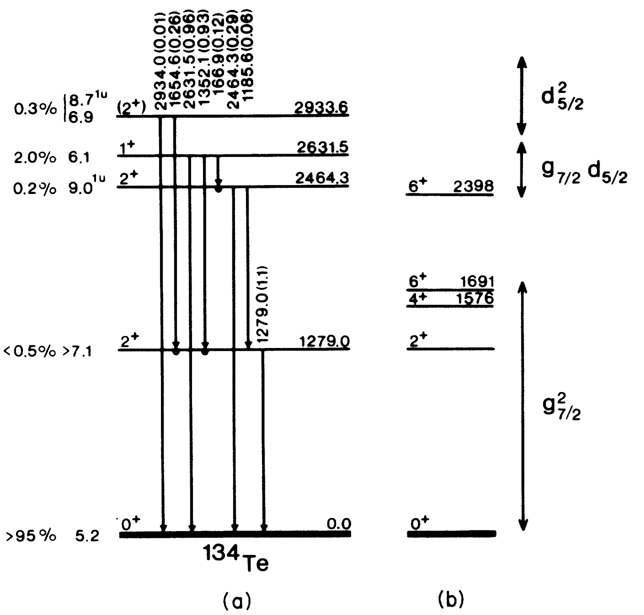

FIG. 4. The low-lying low spin levels of ^{134}Te observed in the current work are shown together with levels of higher spins found by Kerek *et al.* (Ref. 3). The regions of excitation energy where specific two-proton states are expected are indicated to the right.

We did not find any evidences for 0^+ levels in the range 2.7–3.2 MeV. Any γ rays from such levels to the 2^+ state must be weaker than 0.05%/d or they would have been seen in the $\gamma\gamma$-coincidence spectra. We also expect to have observed any $E0$ transition stronger than 0.1%/d at energies greater than 2 MeV in the dual *MSS* experiment described earlier in the paper.

The ground-state to ground-state $\Delta J = 0$, yes transitions in the decay chain studied here connect states with well-defined shell model configurations. Similar transitions are known among light nuclei and in the lead region. The current data is thus filling in a considerable gap in the nuclear systematics, where previous information consisted of Kerek's early study[3] of ^{134}Sb and of data[17] for the ^{96}Y$\rightarrow$ ^{96}Zr decay, involving a final nucleus with doubly closed subshells. First forbidden β transitions are generally difficult to interpret since as many as six different operators may contribute incoherently to the decay rate. In cases where the initial and final states both have $J = 0$ only two operators are effective, which simplifies the situation, especially if the connected states can be accurately described by the shell model. It is then possible to use the experimental data for extraction of the effects due to first forbidden resonances or non-nucleonic effects such as meson exchange currents; see, e.g., Refs. 17–20. Such an analysis is beyond the scope of the present paper which is mainly intended as a presentation of experimental results.

An evaluation of the β-transition rates in terms of logft values is given in Table III. The main uncertainty in the decay rate of the ^{134}Sn$\rightarrow$ ^{134}Sb ground-state transition

TABLE III. Decay rates of β transitions with the character $\nu f_{7/2} \rightarrow \pi g_{7/2}$ in the ^{132}Sn region.

Parent nucleus	Energy of final state	logft value	Contributions to the uncertainty %β	$T_{1/2}$	Q_β
^{134}Sn	≈ 0	5.20(16)	0.15	0.04	0.03
^{134}Sb	0	5.15(5)	0.01	0.04	0.02
^{133}Sn	0	5.43(5)	0.03[a]	0.04	0.02

[a] The β-particle feeding of the ground state was taken to be $(85 \pm 5)\%/d$. See Ref. 11.

stems from the transition intensity, which is strongly dependent on the delayed neutron branching given by Ref. 10. Any improvement in the precision of this number will probably have to be based on methods where ^{134}Sn is separated from ^{134}Sb. Other uncertainties arise from the half-life determinations and the total decay energies. The latter are accurate[5] to within about 0.10 MeV.

The data shown in Table III also includes an evaluation of the decay rate of the basic $\nu f_{7/2} \rightarrow \pi g_{7/2}$ transition[11] of ^{133}Sn. It is obvious from the table that the ^{134}Sn and ^{134}Sb transitions may well have identical transition rates, and that the existing data points to a significant difference between the logft values of ^{133}Sn and ^{134}Sb. It is possible that the transition moments are somewhat different between the pure single-particle case and the situation when ΔJ is restricted to zero. The data of Table III suggests however that difference in transition rate may approach a factor of 2, which is substantial as also the single-particle rate of ^{133}Sn is expected[11] to be dominated by one of the $\Delta J = 0$ moments. Further experiments are being planned to improve the precision in the decay rates of Table III.

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