Decay of ^{112,113,114}Te and ^{115}Te^{g+m}

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The decay of the two new isotopes ^{112}Te ($T_{1/2} = 2.0 \pm 0.2$ min) and ^{113}Te ($T_{1/2} = 1.6 \pm 0.2$ min) is investigated, together with the decay of the ^{114}Te ($T_{1/2} = 15.2 \pm 0.7$ min) and the two isomers in ^{115}Te ($T_{1/2} = 5.7 \pm 0.2$ min and 6.7 ± 0.4 min). Decay schemes are proposed and compared to previously available data and theoretical calculations. Some systematic trends are discussed.

RADIOACTIVITY ^{112,113,114}Te, ^{115}Te^{g+m} [from $^{(112),(114)}$Sn (^{3}He, xn)]; measured $T_{1/2}$, E_γ, $\gamma\gamma$-coin, $\gamma\gamma\Delta t$; deduced logft; ^{112,113,114,115}Sb deduced levels, J, π. Isotope separated sources.

I. INTRODUCTION

The nuclear structure of the neutron-deficient Sb isotopes was not studied very extensively before. Bassani *et al.*[1] performed (^{3}He,d) measurements on the stable tin isotopes from which they obtained some information on low-lying levels in ^{113,115}Sb. Gil *et al.*[2] and Kamermans, Jongsma, and Verheul[3] studied ^{112,114}Sb with ($p,n\gamma$) in-beam techniques. The decay of ^{115}Te was studied by several authors.[4-6] Recently, Charvet *et al.*[6] reported the existence of a β-unstable isomeric state in ^{115}Te. Some data on the decay of ^{113,114}Te are available.[7,8]

We investigated the decay of $^{112-115}$Te with pure sources, obtained by isotope separation. This way of source production made it possible to assign two newly found activities uniquely to the isotopes ^{112,113}Te. 4096×4096 γ-γ coincidence measurements were performed. In ^{114}Sb, the half-lives of some low-lying excited states were measured. An anti-Compton system was used as a level spectrometer.

II. EXPERIMENTAL PROCEDURES

A. Source production

The tellurium sources were produced by irradiating natural tin foils with 25–40 MeV ^{3}He particles from the AVF cyclotron of the Vrije Universiteit. The foils were transported with a rabbit system towards the ion source of a mass separator where they arrive 30 sec after the end of the irradiation. By choosing an adequate warming-up time of the irradiated target in the ion source just Te activities evaporate out of the foil. In this way not only a mass separation but also an element separation is performed.[9-11] For coincidence experiments and calibration purposes also sources produced on targets enriched in ^{112}Sn or ^{114}Sn were used. The sources were produced by the reactions tabulated in Table I.

B. Single γ ray spectroscopy

Singles measurements were performed with 70–75 cm^3 Ge(Li) detectors at a resolution of about 2.4 keV at the 1332 keV ^{60}Co γ ray. For the detection of γ rays below 100 keV a Röntgen detector with a resolution of 220 eV at 5.9 keV was employed.

Due to the large contamination in sources produced with (^{3}He,xn) reactions far from β stability, the isotope separated sources are obviously most suitable for assignment of the γ rays. This is illustrated in Fig. 1 with a part of the γ ray spectrum of ^{112}Te, produced by the ^{112}Sn(^{3}He, $3n$)^{112}Te reaction; the spectra measured with the anti-

TABLE I. Reactions used for the production of the sources.

Enriched targets (No isotope separation)	Natural targets (Isotope separation)
^{112}Sn(^{3}He, $3n$)^{112}Te at 35 MeV	$^{(112)}$Sn(^{3}He, $3n$)^{112}Te at 40 MeV
^{112}Sn(^{3}He, $2n$)^{113}Te at 25 MeV	$^{(112)}$Sn(^{3}He, $2n$)^{113}Te at 30 MeV
^{114}Sn(^{3}He, $3n$)^{114}Te at 35 MeV	$^{(114)}$Sn(^{3}He, $3n$)^{114}Te at 40 MeV
^{114}Sn(^{3}He, $2n$)^{115}Te at 25 MeV	$^{(116)}$Sn(^{3}He, $4n$)^{115}Te at 40 MeV

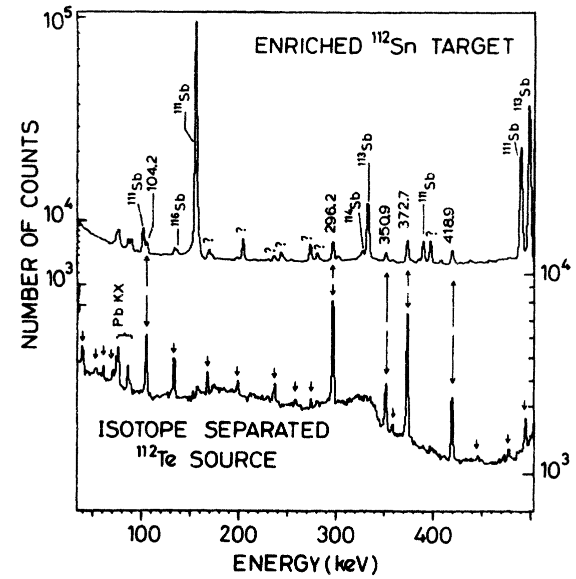

FIG. 1. Part of the γ ray spectrum of ^{112}Te, measured on sources produced on enriched targets and on isotope separated sources. The ^{112}Te γ rays are denoted by arrows. Only the most intense ^{112}Te γ rays are visible in the upper spectrum.

Compton system after irradiation of an enriched ^{112}Sn target, and measured on an isotope separated source, are given. Only intense γ rays from the decay of ^{112}Te are visible in the upper spectrum.

Separate measurements of the intensity of the annihilation radiation $\gamma\pm$ were performed. To determine these intensities, appropriate corrections for the geometry and coincident summation were applied.[10]

C. Coincidence spectroscopy

Ge(Li)-Ge(Li) coincidence measurements were performed 4096×4096 at resolving times of 50–90 nsec. In the case of ^{114}Te, where low energy transitions play an important role, separate experiments with low-energy detectors were done. The time difference between two pulses which were recorded as a coincidence was also measured for this isotope. The coincidence data were stored 4096×4096 (×4096) in the ND 50/50 memory under software control of a PDP 8/L computer and afterwards dumped on a magnetic tape at a CDC 1700 computer which is used for the data analysis.

The anti-Compton system was used as a level spectrometer.[12]

III. EXPERIMENTAL RESULTS

A. Discovery of the new isotopes ^{112,113}Te

The production of pure Te sources with the isotope separator offered the possibility to assign two newly found activities uniquely to the isotopes ^{112}Te and ^{113}Te.[9,10] This is illustrated in Figs. 2 and 3. The decay curves of the γ rays from the Sb daughter isotopes show a complete growth for the isotope separated sources, so there is no Sb

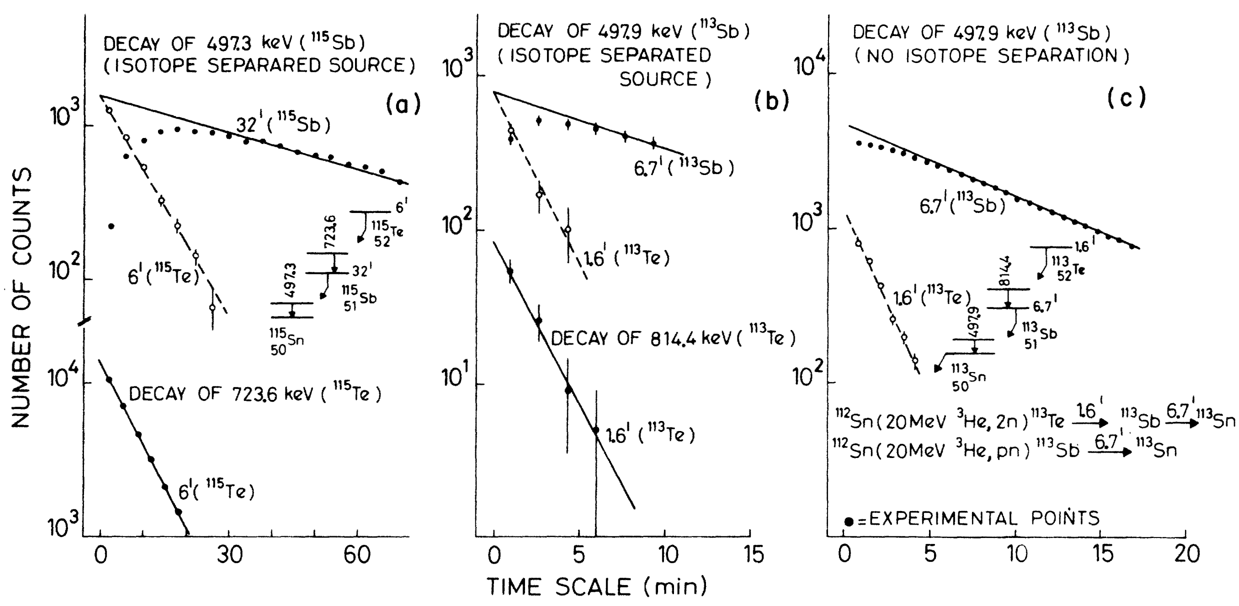

FIG. 2. (a)–(c) The discovery of ^{113}Te (see text). The experimental points are given by closed circles. Open circles denote the growth as determined by computer analysis.

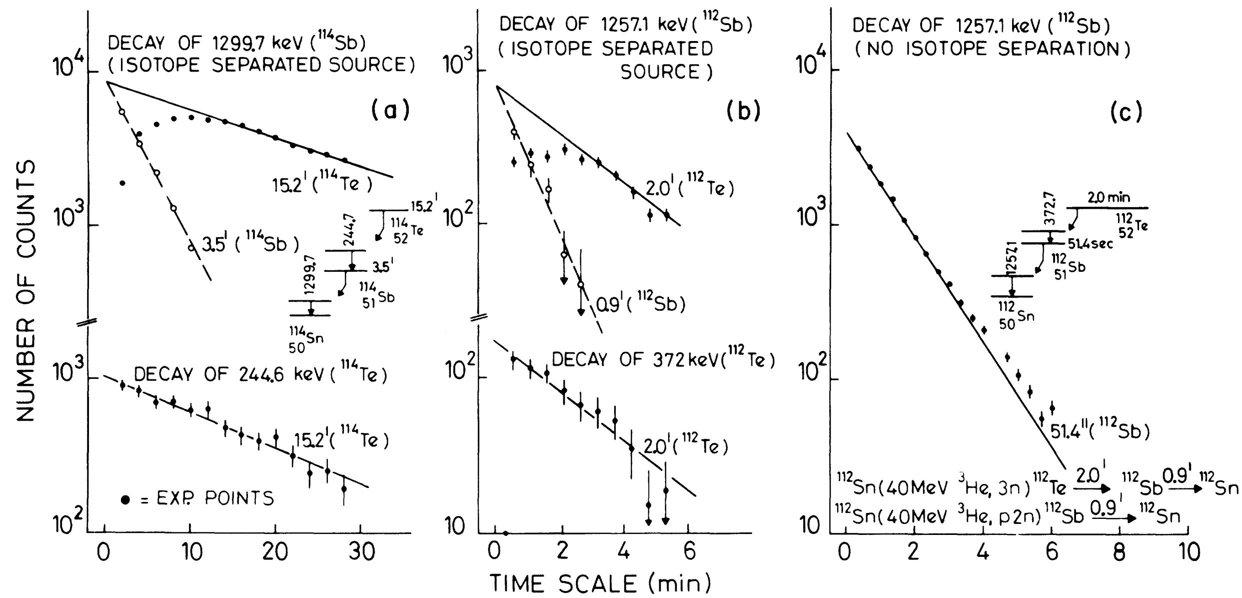

FIG. 3. (a)–(c) The discovery of ^{112}Te (see text). The experimental points are given by closed circles. Open circles denote the growth as determined by computer analysis.

in the source at time zero (the end of the separation). For comparison, the decay curves of the Sb and Te γ rays are given for $A = 115, 114$ [Figs. 2(a) and 3(a)]. Figures 2(c) and 3(c) show the decay of the Sb daughter isotope when no isotope separation was applied. It appears that most of the Sb activity was directly produced in the (^{3}He,*pn*) and (^{3}He,*p*2*n*) reactions. Only 25% of ^{113}Sb and <5% of ^{112}Sb is produced by decay of ^{113}Te and ^{112}Te, respectively. The half-lives of the new isotopes are 1.6 ± 0.2 min (^{113}Te) and 2.0 ± 0.2 min (^{112}Te). We reported this before.[9-11] Recently, Charvet, Chery, and Duffait.[7] also assigned a 2.0 min half-life to the decay of ^{113}Te, produced with the ^{112}Sn$(\alpha, 3n)$ reaction. The assignment was based on the fact that no growth was observed when the sources were produced with the ^{112}Sn(d,n) reaction. However, this does not exclude the possibility of an isomeric state in ^{113}Sb definitely.

B. Singles measurements

Many new γ rays could be assigned to the decay of the several isotopes. Detailed lists of the γ rays, their energies, relative intensities, and decay times, and the γ ray spectra are given elsewhere.[10] In Table II a survey is given of the numbers of assigned γ rays obtained from this work, the half-lives, and the percentage of the total observed γ ray intensity which could be placed in the decay scheme. Moreover, for each isotope the energy and relative intensity of the most intense γ rays and the β^+ annihilation radiation are given in the last two columns.

C. Coincidence data

A large number of sources (^{115}Te: 40, ^{114}Te: 20, ^{113}Te: 73, ^{112}Te: 49) were measured to gather about 3×10^6 coincident events per experiment. Because of the occurrence of important contaminating activities only (a sometimes very small) part of these coincidences are due to the decay of the isotope of interest. To analyze the data, gates were set for all dominant peaks and coincidences with the background were subtracted. Spectra and lists of the observed coincidence relations are given elsewhere.[10] In the decay schemes coincidences are marked by dots.

In Fig. 4 the time spectra of the coincidences with some low-energy γ transitions from the decay of ^{114}Te are given together with the prompt time spectra which were obtained from the coindences with the Compton background at these energies. The energies of the gating γ rays are 45.86, 54.61, 83.80, and 90.28 keV. The prompt spectra show a full width at half maximum of ~7 nsec and slopes of ~2 nsec. It appears that the time spectra of the high-energy (>100 keV) coincidences with the 90.28 keV γ ray and the coincidences with the 83.80 keV are mainly prompt. The time spectra of the coincidences with the 45.86 and 54.61 keV γ rays and the low-energy (<100 keV) part of the coincidences with the 90.28 keV γ ray obviously show a delayed component, corresponding with $T_{1/2} = 24 \pm 5$ nsec.

TABLE II. Survey of some experimental results.

Isotope	Number of observed γ rays	Half-life (min)	Part of the total observed γ ray intensity placed in decay scheme (%)	Strongest γ rays $E\gamma \pm \Delta E\gamma$	$I\gamma \pm \Delta I\gamma$
^{112}Te	36	2.0 ± 0.2	60	296.2 ± 0.2	86 ± 8
				350.9 ± 0.2	36 ± 3
				372.7 ± 0.2	100
				418.9 ± 0.2	57 ± 5
				511 $\gamma^{\pm}$	1800 ± 700
^{113}Te	39	1.6 ± 0.2	85	511 $\gamma^{\pm}$	780 ± 200
				644.8 ± 0.2	29 ± 3
				814.4 ± 0.3	100
				1018.1 ± 0.4	59 ± 6
				1181.0 ± 0.4	56 ± 6
^{114}Te	50	15.2 ± 0.7	90	83.80 ± 0.02	200 ± 40
				90.28 ± 0.02	300 ± 50
				244.62 ± 0.05	100
				511 $\gamma^{\pm}$	2400 ± 400
				726.6 ± 0.2	129 ± 16
				1897.3 ± 0.5	112 ± 13
^{115}Te^{g+m}	85	5.7 ± 0.2	97	511 $\gamma^{\pm}$	405 ± 25
		6.7 ± 0.4		656.9 ± 0.1	21.3 ± 0.6
				723.6 ± 0.1	100
				1098.7 ± 0.1	54 ± 3
				1326.9 ± 0.1	71 ± 4
				1380.6 ± 0.1	72 ± 4

IV. DECAY SCHEMES

The decay schemes are given in the Figs. 5–8, together with the most relevant information from reaction studies. In these figures, spins and parities for the levels are only included if the number of possible values for J^π can be restricted to one or two. New levels in the daughter nuclei were only proposed if they could be based on manifest and unambiguous coincidence relations. The energy and J^π values of levels which were already known from previous decay work, are underlined in Figs. 5–8. Levels and their deexciting γ rays are dashed when they are based on just one γ ray and if no further evidence for their existence was obtained from reaction experiments. The following remarks about the decay schemes of the separate isotopes should be made.

A. ^{112}Te

From the present data it is not possible to construct a more complete decay scheme than that given in Fig. 5. The Q_{EC} value of 3.8 MeV was estimated from the mass formulas given by Garvey *et al.*[13] As the normalization gives large problems, the given intensities just denote the branching per level. In spite of these problems, caused by unknown conversion coefficients and rather many unplaced transitions, it is very probable that the logft values for the levels at 38.6, 372.7, and 715.0 keV are <5.8, and therefore we assigned $J^\pi = (1^+)$ to these levels.

B. ^{113}Te

From the intensity of the annihilation radiation it appears that there should be direct ground state feeding. This was confirmed by the results of the level spectrometer experiment.[10] Together with the allowed feeding of the $\frac{7}{2}^+$ state at 814.4 keV this yields as possibilities for the ^{113}Te ground state $J^\pi = \frac{5}{2}^+, \frac{7}{2}^+$. From the systematics in the odd Te isotopes and the Sn isotopes with the same neutron numbers we conclude to $J^\pi = (\frac{7}{2}^+)$.

C. ^{114}Te

The decay scheme could be constructed by combining the data from the ^{114}Te decay and the results of the ^{114}Sn$(p, n\gamma)^{114}$Sb work of Kamermans.[3] The 90.28 and 45.86 keV transitions are also observed in the decay of a 220 μsec isomeric state at 495 keV which is probably 8^-; the 54.60 keV transition was not observed in this decay. Therefore, the decay scheme which was presented earlier by us[10] cannot be right concerning the placing of these particular γ rays. From a coincidence experiment

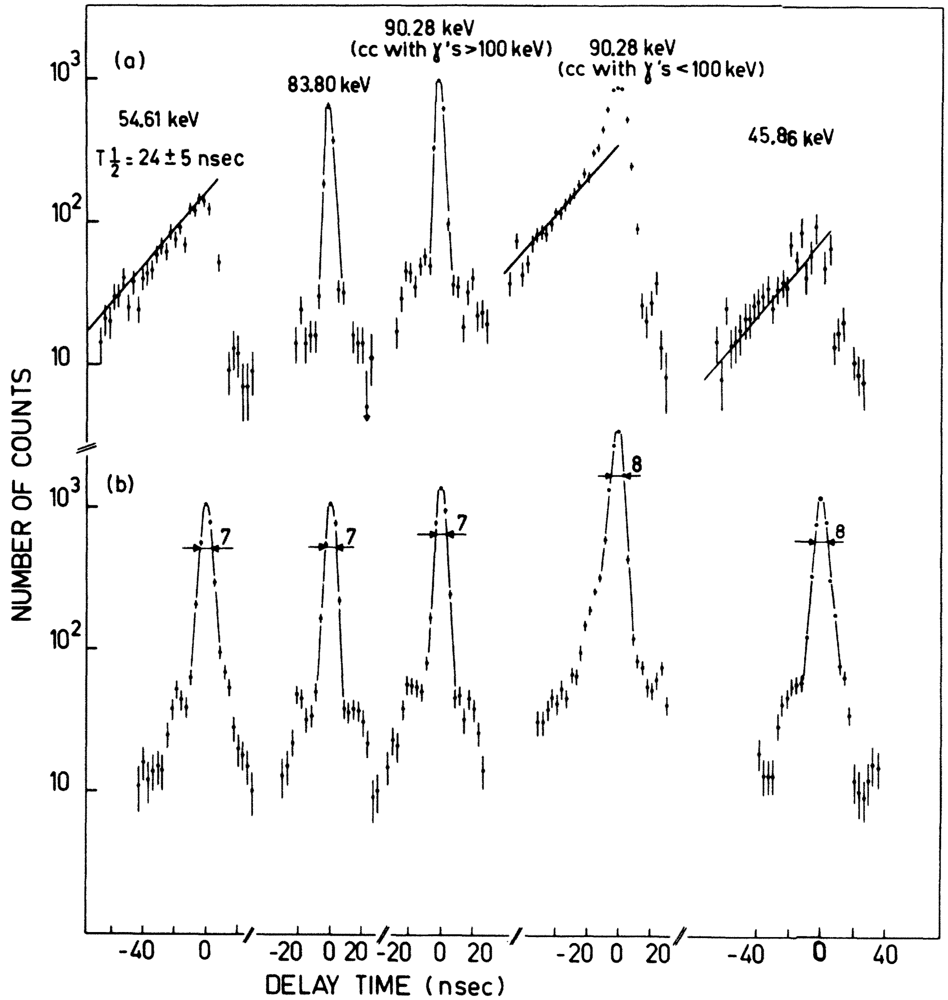

FIG. 4. (a) Time spectra of the coincidences with some low-energy γ transitions from the decay of ^{114}Te. The energies of the gating γ rays are given above the spectra. (b) The corresponding prompt time spectra.

with two low-energy photon detectors, it turned out that the 45.86 and 54.60 keV γ rays are not coincident with each other and that both are coincident with the 90.28 keV γ ray. It is impossible to assign the observed 24 nsec half-life (cf. Fig. 4) to one of the levels in Fig. 7.

As no conversion electrons were measured, a precise normalization of the decay scheme is not possible, and therefore only branching ratios per level are given. The logft value of the β transition to the 1897.2 keV state is <5.8, so $J^{\pi} = (1^+)$ can be assigned to this level. The other spin assignments were deduced from the in-beam experiments by Kamermans,[3] except for the ground state which is known to be 3^+ from its β decay.[10]

D. ^{115}Te

Recently, Charvet *et al.*[6] found two β-unstable states in ^{115}Te, viz., a $\frac{1}{2}^+$ state with $T_{1/2} = 7.5 \pm 0.3$ min and a $\frac{7}{2}^+$ state with $T_{1/2} = 6.0 \pm 0.2$ min. They unsuccessfully tried to measure the conversion electrons of the $M3$ transition between the isomers and give an upper limit of 20 keV for its energy. They conclude from this and from the half-lives involved that this branching is probably very small. The existence of two β-unstable states in ^{115}Te was confirmed by our experiments. From the decay scheme, it follows that the first two excited states in ^{115}Sb both are directly fed by β decay. Because of the spin difference between these states[1] it is impossible that both states are directly fed from one ^{115}Te state. Moreover, there is a significant difference between the half-lives of the γ rays deexciting these states. We found half-lives of 6.7 ± 0.4 and 5.7 ± 0.2 min, respectively.

The somewhat larger values of Charvet *et al.*[6] might be explained from the occurrence of contaminating activities, as they applied no isotope

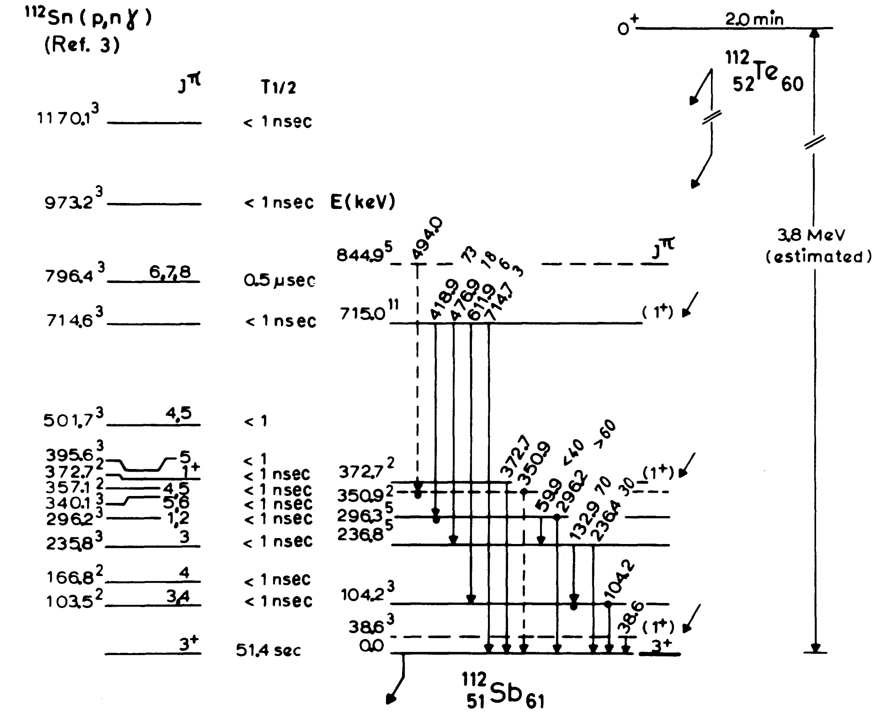

FIG. 5. The decay scheme of ^{112}Te.

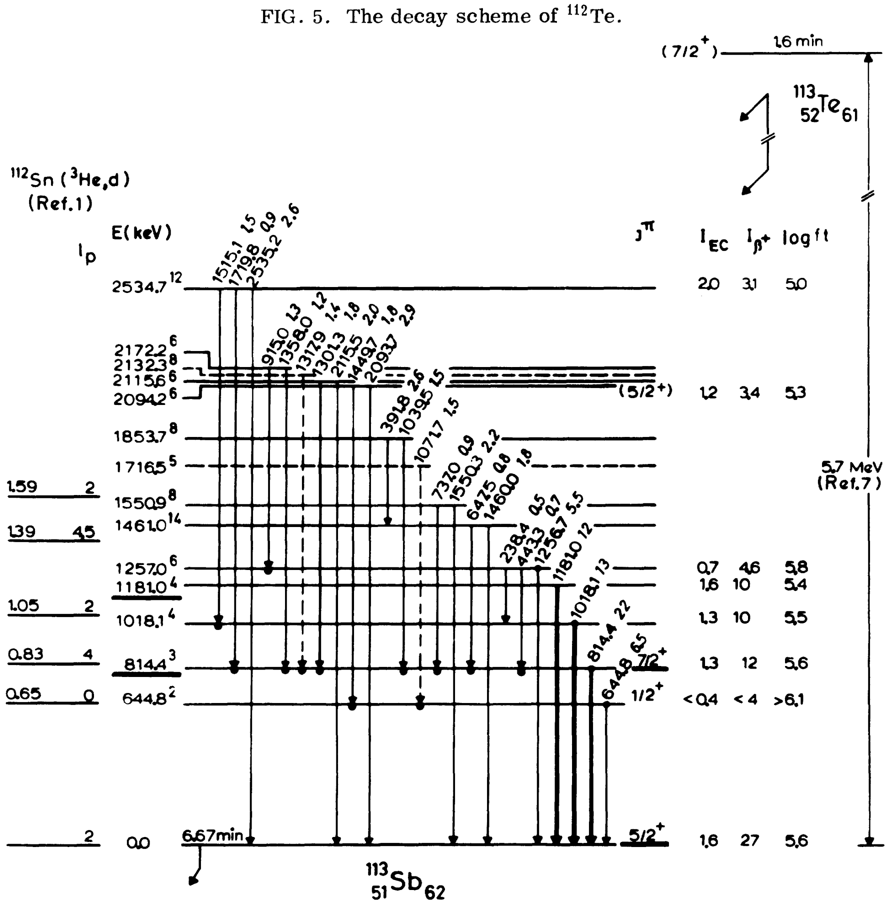

FIG. 6. The decay scheme of ^{113}Te.

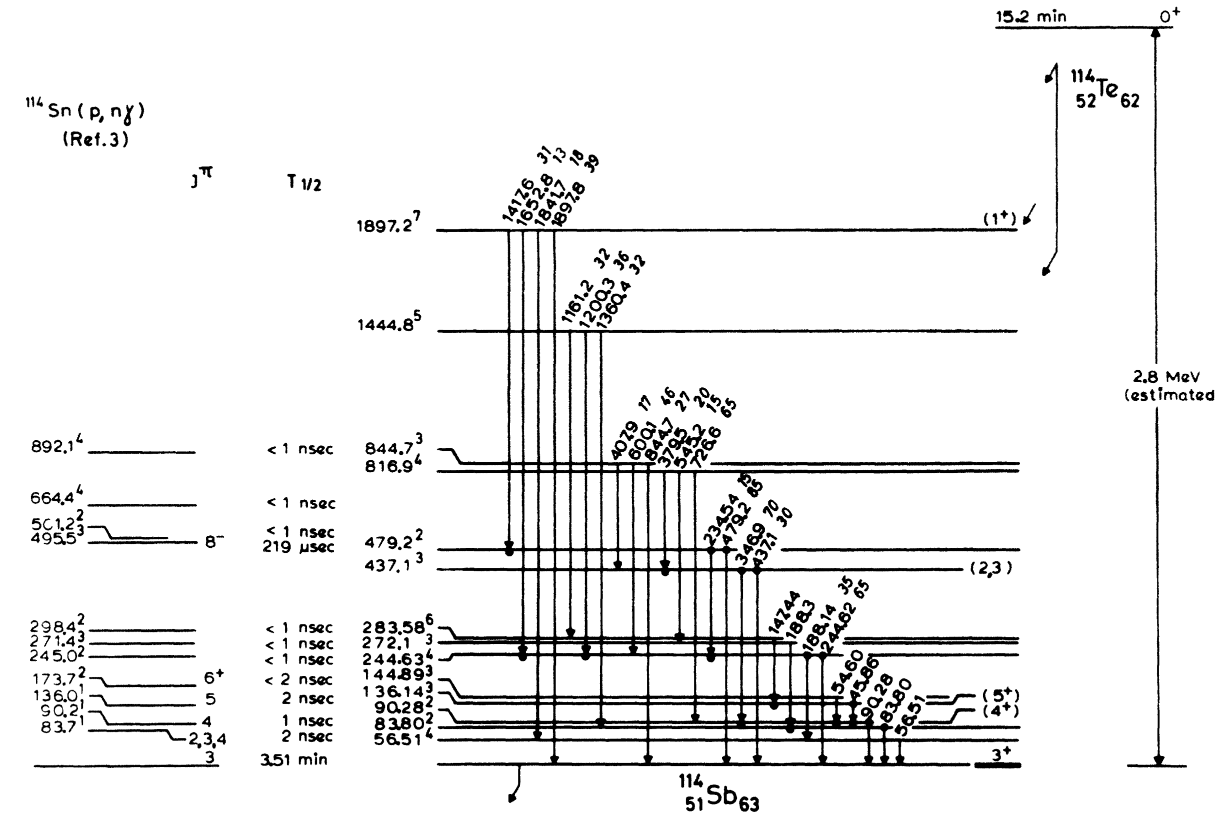

FIG. 7. The decay scheme of ^{114}Te.

separation. Burmistrov and Shilin[5] also studied the decay of ^{115}Te. Their sources were produced with the ^{112}Sn(α,n) reaction at 18 MeV. The $\frac{1}{2}^+$ state in ^{115}Te is produced about twice as strongly by them if compared with our experiments. From a detailed comparison of the relative γ ray intensities in both experiments and from the half-lives of the γ rays we conclude for seven levels in ^{115}Sb that they are fed by β decay of the $\frac{1}{2}^+$ state and for nine levels that they are fed by β decay of the $\frac{7}{2}^+$ state. For six levels, it could not be deduced from which state they are fed. Three of them, however, at 1300.4, 2104.4, and 2215.1 keV are incorporated in the decay schemes, as they are fed by γ decay from levels which could be ascribed to the decay of one of the isomers. We could not deduce unambiguously in which ratio these levels are fed from the ^{115}Te states, and therefore no intensities are given. From our coincidence measurements, it is suggested that three more states occur in ^{115}Sb. They are located at 1953.9, 2130.7, and 2378.1 keV. The normalization was performed assuming that there is no internal transition between the isomers in ^{115}Te.[6]

V. DISCUSSION

A. Odd Sb nuclei ^{113,115}Sb

For the description of the odd antimonies most authors use a semimicroscopic model.[14-19] The level schemes of ^{113,115}Sb were calculated in such a model by de Pinho, Jeronymo, and Goldman[15] and Goldstein *et al.*[19] In Fig. 9 the results of Goldstein and de Pinho are compared with the experimental level schemes. In this calculation the diagonalization space was truncated by considering only the $2d_{3/2}$, $3s_{1/2}$, $1g_{7/2}$, and $2d_{5/2}$ shell model states and quadrupole phonon states. The single-particle energies, the vibrational energies, and the coupling strength are taken as parameters, and only levels within the area 0–2 MeV are given. It is difficult to make a detailed comparison as for only a few levels J^{π} could be determined definitely, but the number of levels in the mentioned area is about the same as being found experimentally. As no theoretical data are available, branching ratios cannot be compared.

From the (^{3}He,d) work of Conjeaud *et al.*[1] it appeared that the wave functions of the lowest-lying

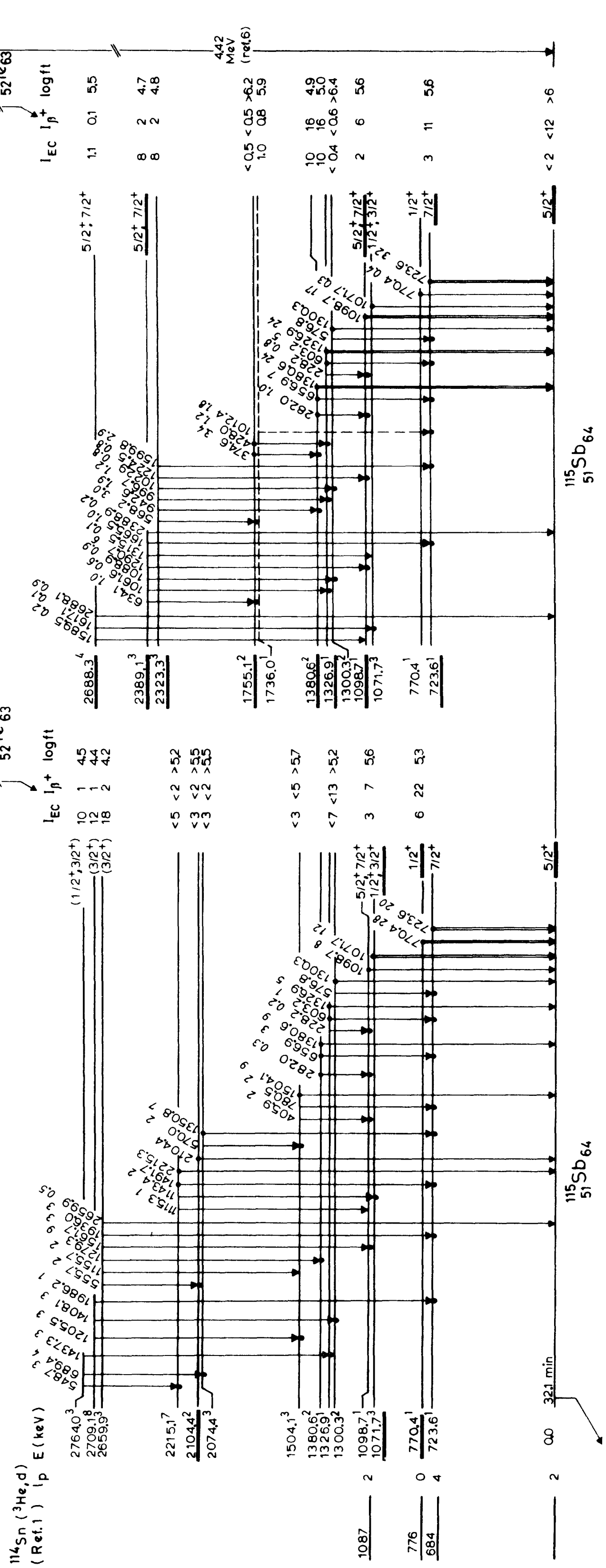

FIG. 8. The decay schemes of ^{115g}Te and ^{115m}Te.

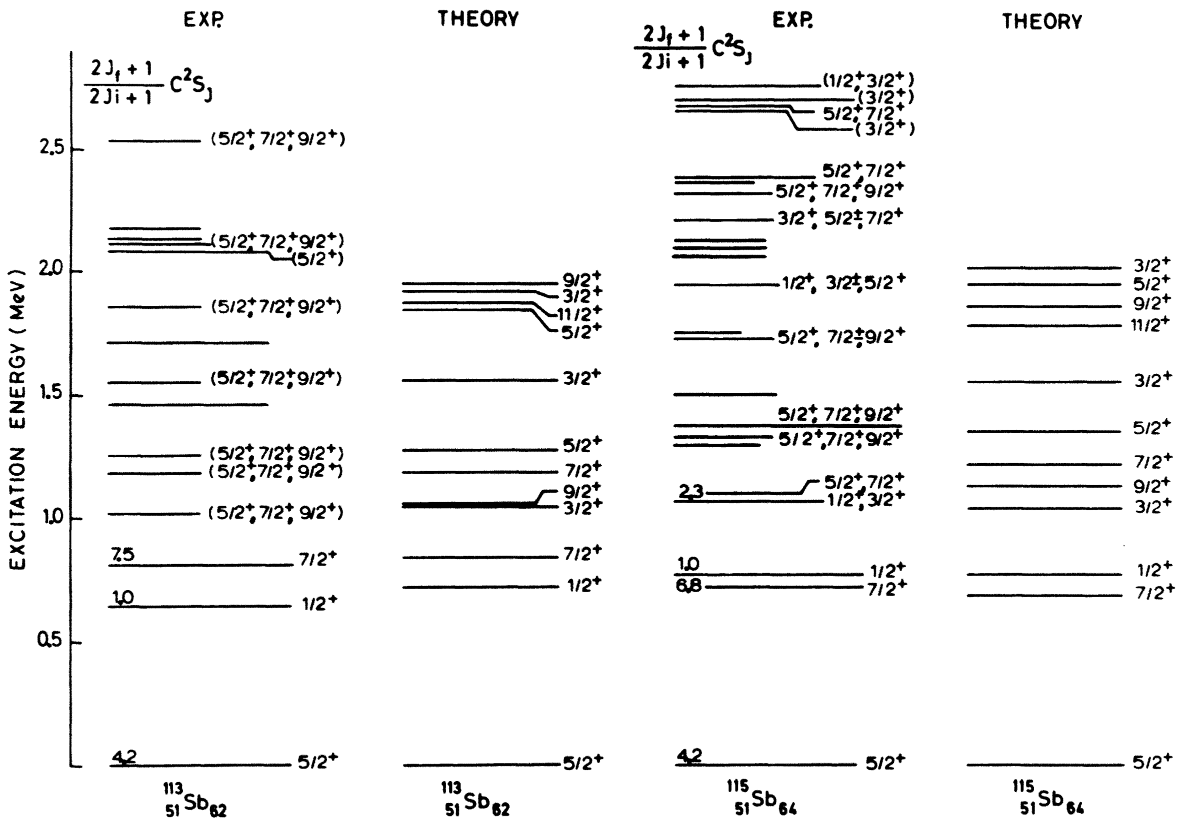

FIG. 9. Comparison of the experimental level schemes of ^{113,115}Sb with the theoretical results of Goldstein and de Pinho (Ref. 19). Above the levels the spectroscopic factors deduced from (^{3}He,d) reactions (Ref. 1) are given.

$\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ states in the odd antimonies contain large single-particle components. Especially for the first $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states large spectroscopic factors were found (cf., Fig. 9). The wave functions of the odd Te ground states are expected to contain large single-particle components too. It is interesting to compare the logft values for the transitions between these states (see Table III). It appears that the logft values for the $\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$ transitions are significantly larger than for the $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ transitions. This might be caused by the single-particle component in the wave functions as the $3s_{1/2} \rightarrow 2d_{3/2}$ transition is l forbidden. The occurrence of such a selection rule might also explain the large logft values for the $\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$ transitions in the decay of the odd antimonies[10] and, e.g., the $\frac{3}{2}^- \rightarrow \frac{5}{2}^-$ transitions in the decay of the odd Ga isotopes. From this point of view, it is surprising that in the decay of ^{113}Te a large ground state feeding was observed (logft = 5.6) as the value of the corresponding $\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$ transition in the decay of ^{113}Sb is >6.7.[10] The fact that ft values are usually considerably larger than the single-particle estimates may be understood from an admixture of many small complex components in the wave functions, as has been discussed by Fujita, Futami, and Ikeda,[21] and therefore does not invalidate the above considerations.

TABLE III. Logft values from the decay of neutron-deficient odd Te ground states ($J^\pi = \frac{7}{2}^+$ or $\frac{1}{2}^+$).

Isotope	Transition $J^i \rightarrow J^f$ $\frac{7}{2}^+ \rightarrow \frac{7}{2}^+$	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$	$\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$
^{113}Sb	5.6	5.6		
^{115}Sb	5.6	>6	5.3	5.7
^{117}Sb			5.5 [a]	>6.4 [a]
^{119}Sb			5.5 [a]	6.4 [a]
^{121}Sb			6.0 [b]	6.7 [b]

[a] Data taken from Ref. 5.
[b] Data taken from Ref. 20.

B. Odd-odd Sb nuclei ^{112,114}Sb

In their decay work Singh *et al.*[22] propose an isomeric state in ^{114}Sb, which should be β unstable with a half-life of 8 min and $J^\pi = (8^-)$. According to them, such a state arises from the coupling of a $2d_{5/2}$ proton to an $1h_{11/2}$ neutron. Although we intensively searched for it and reproduced the experiments of Singh *et al.*,[22] the existence of such a state was not confirmed. This has been discussed in detail elsewhere.[10] Moreover, recent in-beam measurements of Kamermans[3] showed the existence of γ-unstable 8^- isomers in ^{112,114}Sb with half-lives in the μsec region.

It is striking that in ^{114}Sb the branching of the (4^+) and (5^+) states at 90.28 and 136.14 keV to the 3^+ ground state was not observed and therefore is very small. This can be explained if the ground state wave function has a large $|[2d_{5/2}(p), 3s_{1/2}(n)]^{3+}\rangle$ component and the wave functions of the 4^+ and 5^+ states contain important $|[2d_{5/2}(p), 1g_{7/2}(n)]^{4+ \text{ or } 5+}\rangle$ components. This is expected on very simple grounds, and confirmed by recent calculations of van Gunsteren *et al.*[23] The states of the $|2d_{5/2}(p), 1g_{7/2}(n)\rangle$ multiplet will prefer to decay within the multiplet, if possible, rather than through a $\Delta l = 4$ transition to the $|2d_{5/2}(p), 3s_{1/2}(n)\rangle$ states.

C. Te nuclei

In Fig. 10 the half-lives of the ground states of the neutron-deficient Te isotopes are plotted vs the mass number. As can be expected, the experimental points are located on two curves, for the odd and even nuclei, which show a very smooth behavior. The half-lives of the newly found isotopes ^{112}Te and ^{113}Te, fit excellently in this picture.

Just as in the odd Sn isotopes with two protons less the crossing of the $\frac{1}{2}^+$ and $\frac{7}{2}^+$ "single-neutron" states occurs near $N = 63$. This explains the observed isomerism in $^{115}_{52}\mathrm{Te}_{63}$, just as in $^{113}_{50}\mathrm{Sn}_{63}$; apparently, the two extra protons do not disturb this feature. There is no reason for the assumption made by several authors[4,5] that from the systematics in the heavier Te isotopes it follows that ^{115}Te has a $\frac{1}{2}^+$ ground state.

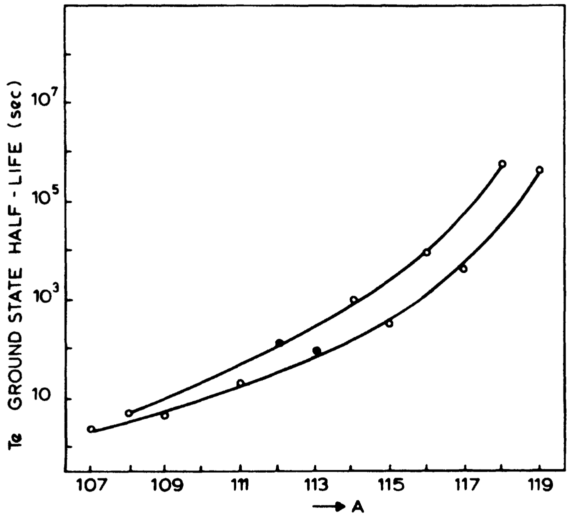

FIG. 10. The ground state half-lives of the neutron-deficient Te isotopes plotted versus the mass number. From this picture, the half-life of the unknown isotope ^{110}Te is estimated to be about 20 sec.

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