Radiations from Sb^{122}†

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The radiations from Sb^{122} were investigated by use of a magnetic solenoid spectrometer, a coincidence scintillation spectrometer, and a proportional counter spectrometer. Three β^--groups are present with end-points 1970±5, 1400±10 740±20 kev. The highest energy β-groups exhibits an α-shape and the two lower β-groups have allowed Kurie plots. Gamma-ray investigations showed that four gamma rays of energies 566±4, 686±4, 1137±6 and 1260±6 kev could be associated with the decay of Sb^{122}. Coincidence techniques related the 1150-kev γ-ray with the K-capture side and also showed that the 566 and 686-kev γ-rays are in cascade. The ratio of $(K+L)$ capture relative to total β^--emission was found to be 3.1 percent. The ratio of K-capture to the excited state of Sn^{122} and K-capture to the ground state was found to be 1:2.1. The intensities of all radiations are listed and the ft-values for various transitions calculated. An upper limit of 10^{-3} is placed on the positron emission.

INTRODUCTION

THE first studies on the radiations of Sb^{122} in this laboratory were made in 1950.[1] The shape of the highest energy β^- group from Sb^{122} was investigated first. It showed a unique first-forbidden shape of the type of transition of $\Delta I=2$, yes, which assigns the spin and parity of the ground state of Sb^{122} as 2^-. Further work with a magnetic coincidence spectrometer isolated the second group of β^-transition and revealed that the upper energy of this transition is 1.45 Mev and that the shape of the spectrum is indistinguishable from an allowed one. However, subsequent β and γ angular correlation experiments showed a definite anisotropic distribution[2] which furnished further information on the possible spin and parity assignments of the first excited state of Te^{122}. The spectra of the two highest-energy β groups and the β-γ angular correlation of Rb^{86} and I^{126} were investigated at that same period and a general similarity was observed among these three isotopes (Rb^{86}, Sb^{122}, and I^{126}). The general conclusions concerning the assignments of the spin and parity of the energy levels in Sb^{122} and Te^{122} were at that time in substantial agreement with Glaubman's results from γ-γ angular correlation.[3] The shapes of the two highest β spectra were also in good accord with his results. Lately, however, several more gamma rays were reported in Sb^{122}. Further, the analysis of the composite β spectrum led to conclusions which were quite different from those previously obtained.[4,5] In view of these differences, it seemed highly desirable to have the radiations of Sb^{122} systematically reinvestigated. The reinvestigation was performed with the magnetic solenoidal β spectrometer, the proportional counter spectrometer, and the selective coincidence spectrometer.

PREPARATION OF THE SOURCE

Sb^{122} was produced from the reaction $Sb^{121}(n,\gamma)Sb^{122}$ by bombarding enriched Sb^{121} with slow neutrons in the Brookhaven pile for a period of three days. The enriched Sb had an abundance ratio of Sb^{121} to Sb^{123} equal to 99.4 percent to 0.6 percent and was procured from the Stable Isotope Research and Production Division of Oak Ridge National Laboratories. The presence of the small amount of Sb^{123} in the bombarded sample contaminated the source with the 60-day Sb^{124} isotope which was produced by the reaction $Sb^{123}(n,\gamma)Sb^{124}$. The number of disintegrations of Sb^{124}, present at the time the experiment was carried out, was less than 0.4 percent of the number of disintegrations of Sb^{122}. This estimate was made using the intensity ratio of the 1.71-gamma line of Sb^{124} and the 566-kev gamma line of Sb^{122}.

β^- RADIATIONS

The first measurement of the β^- spectrum of Sb^{122} in this laboratory was made in 1950 by using a magnetic solenoidal spectrometer and the magnetic coincidence spectrometer. The results were briefly reported by Macklin, Lidofsky, and Wu.[1] Recently, the total β^- spectrum, in particular the conversion electrons of the 566-kev gamma line, was again investigated. The Kurie plot of the highest-energy portion reveals an α shape. Consequently, the α correction factor $(\frac{1}{2}K^2L_0+\frac{3}{4}L_1)^{\frac{1}{2}}$ was applied to each point on the curve and another plot was made of these corrected values [Fig. 1(a)]. The points in the higher-energy region fall on a straight line that crosses the energy axis at 1970 kev. Therefore, the highest energy β^- group in Sb^{122} has an end point of 1970±5 kev and an α shape. The analysis of the total β^- spectrum was continued after subtracting the highest-energy β^- group from the composite spectrum.

A Kurie plot of the remainder was made and is shown in Fig. 1(b). The high-energy points fall on a straight line which crosses the energy axis at 1400±10 kev and there-

† This work was partially supported by the U. S. Atomic Energy Commission.

[1] C. S. Wu, Proceedings of the International Conference on Nuclear Physics, Chicago (unpublished), p. 158; Macklin, Lidofsky, and Wu, Phys. Rev. 82, 334 (1951).
[2] I. Shaknov, Phys. Rev. 92, 33 (1951).
[3] M. J. Glaubman, Ph.D. thesis, University of Illinois, Urbana, Illinois (unpublished); M. J. Glaubman and F. R. Metzger, Phys. Rev. 87, 203 (1952).
[4] Cork, Brice, Hickman, and Schmid, Phys. Rev. 93, 1059 (1954).
[5] J. Moreau, Compt. rend. 18, 1130 (1954).

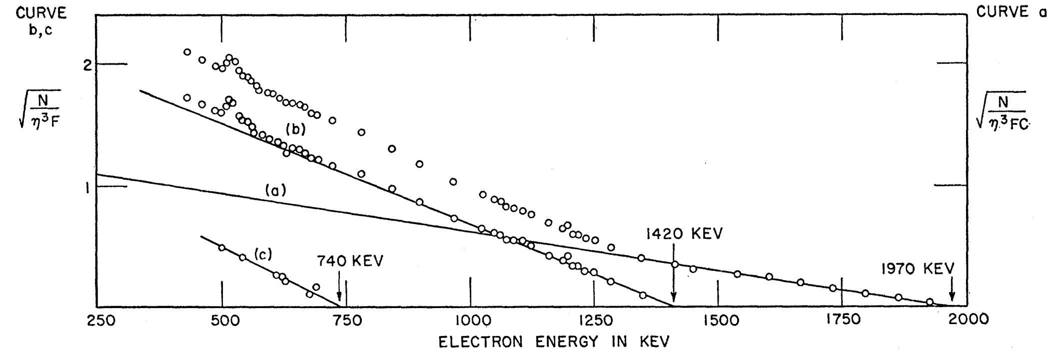

FIG. 1. (a) Corrected Kurie plot showing a high energy β^- group with endpoint energy of 1970±5 kev. (b) Kurie plot of remaining β^- groups obtained after subtraction of highest energy group from the composite spectrum, showing a second β^- group with endpoint energy of 1400±10 kev. (c) Kurie plot for the lowest-energy β^- group with endpoint of 740±20 kev.

fore yields a second β^- group with a linear Kurie plot and end point of 1400±10 kev. Repeated application of the above procedure gave the third and lowest energy β^- group with a linear Kurie plot and an end point of 740±20 kev [Fig. 1(c)].

The relative intensities of the β^- transitions are determined by comparing the areas under the three component β^- spectra shown in Fig. 2. The ratio of intensities for the 740±20, 1400±10, and 1970±5 kev transitions are 6.3:61.1:29.1 respectively. However, it is felt that the intensity ratio of the 740-kev group to the 1400-kev group is probably higher than the true ratio as there are always some extra low-energy electrons due to the self-absorption effect and the scattering effect in the source.

INTERNAL CONVERSION

The only gamma ray which is converted to any observable extent is the 566-kev gamma line. Figure 3 shows the internal conversion electron spectrum for this line. The energy of the peak is 534 kev and since the K-binding energy of tellurium is 31.8 kev this gives the energy of the gamma ray as 566 kev. The $K/(L+M)$ ratio obtained by a comparison of the areas under the peaks is 5.3±0.5. The value of α_K obtained is $(\alpha_K)_{566} = 5.2\times10^{-3}$. The theoretical value of α_K found in the tables of Rose *et al.*[6] for electric quadrupole radiation is 5.0×10^{-3}. The agreement is very good. Since the value of α_K/α_L is quite insensitive to the parameter Z^2/E for values of $Z^2/E\sim5$, no conclusions can be made regarding the multipole order of the radiation from this ratio. It might be mentioned, however, that the magnitude of the experimental result is of the correct order.

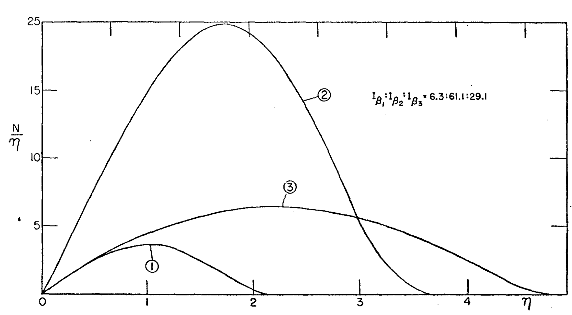

FIG. 2 The three component β^- spectra.

EXTERNAL CONVERSION

A precise energy determination of the gamma rays was made by measuring the energy of the photoelectric lines from an 11.5-mg/cm² thick lead radiator in a

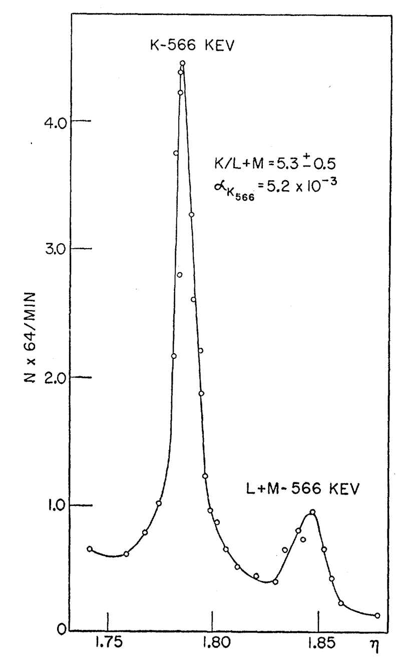

FIG. 3. Internal conversion electron spectrum for the 566-kev gamma ray of Sb^{122}.

[6] Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report ORNL-1023 (unpublished).

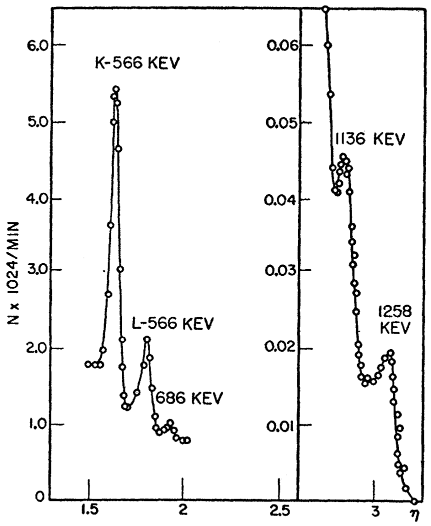

FIG. 4. External conversion electron spectrum showing the presence of four gamma radiations in the decay of Sb^{122} at energies 566±4, 686±4, 1258±6, 1137±6 kev.

magnetic spectrometer. The electron spectrum shown in Fig. 4 reveals the presence of four gamma radiations. After correction of peak energies for the K or L binding energies of lead is made, the radiations correspond to energies of 566±4, 686±4, 1258±6, and 1137±6 kev.

Gamma-Ray Spectrum

(a) *Single Spectrum Analysis*

The spectrum of photons emitted in the decay processes was investigated with a single channel scintillation spectrometer. The resolution is 9 percent for the 661 kev line of Cs^{137}. Repeated checking assured that the apparatus was stable and that the gamma-ray energies could be measured with about 3 percent accuracy.

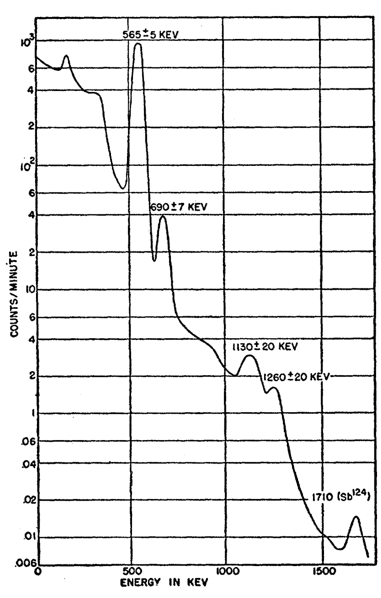

FIG. 5. Single gamma-ray spectrum of Sb^{122} obtained by using a single-channel scintillation spectrometer.

The relative efficiency of the spectrometer for detecting radiations of different energies was determined by a method outlined previously.[7] A plot of relative efficiency *versus* energy was made on log-log graph paper and yields a smooth curve.

The single spectrum is shown in Fig. 5. Four gamma rays belonging to Sb^{122} are identified at the energies 565±5, 693±7, 1130±11, and 1260±13 kev. A peak in the very low energy region due to the x-rays of Sn^{122} and Te^{122} is also present. Further investigation showed that no other gamma rays could be associated with Sb^{122}.[8] The peak at 1.71 Mev has been previously reported in the decay scheme of Sb^{124}. The presence of this isotope was justified earlier in this paper. After suitable corrections were made for background, Compton radiations from higher-energy gamma rays, and variations in the detecting efficiency with energy, the relative intensities of the gamma rays were determined with an accuracy of about 10 percent and are listed in Table I. The possibility of the 1150- and the 1260-kev radiations arising from the summation of the 565- and 693-kev gamma rays was eliminated by the usual absorption methods.

TABLE I. Relative intensity of the gamma radiations.

γ radiation	Single-channel analyzer	Coincidence spectrometer
566 kev	100	100
686 kev	5.1	5.3
1258 kev	0.99	
1137 kev	1.10	

(b) *Coincidence Measurements*

The assignment of the various gamma radiations and the x-rays in the decay scheme was done with the selective coincidence spectrometer (Fig. 6). The instrument consists of two crystals each mounted on a Dumont K-1186 photomultiplier tube. The phototubes are horizontally placed head on and the source is mounted between them. The system of crystals, tubes and source is enclosed in a $\frac{1}{16}$-in. thick aluminum light tight shield. Provision is made for varying the source distance. The crystals used for detecting gamma rays are $1\frac{1}{2}$ in.$\times 1\frac{1}{2}$ in. NaI and the crystal used for detecting the x-ray is a $1\frac{1}{2}$ in.$\times\frac{1}{8}$ in. NaI. All three crystals are permanently sealed in aluminum containers with glass windows. The housing for the x-ray crystal has a 1-mil thick aluminum foil window. Electrons are absorbed

[7] Koerts, Macklin, Farrelly, van Lieshout, and Wu, Phys. Rev. **98**, 1230 (1955).

[8] The authors wish to express their appreciation to Dr. J. Mihelich of Brookhaven National Laboratory for communicating the results of his investigation of the gamma rays in Sb^{122}.

in a polystyrene slab. The use of the thin aluminum and the polystyrene slab minimizes the absorption of the low-energy gamma radiation.

A detailed description of the performance of the spectrometer and the methods employed for the energy calibration and efficiency determination have been given in an earlier paper.[7] Briefly, its function is to select radiation of a particular energy which has been detected in one of the phototubes and then to display on a multichannel pulse height analyzer all the radiations detected in the second phototube which are in coincidence with this selected one. The coincidence mechanism employs a combination of fast and slow coincidences.

The gamma-gamma coincidence spectra found are shown in Fig. 7(a), (b). The spectrum (a) was obtained when selection of the 565-kev gamma was made and shows that the 693-kev gamma ray is in coincidence with it. The spectrum (b) was obtained by selecting the 693-kev gamma ray and serves not only as a check on (a) but also to confirm the absence of any other coincident events. Selection of the 1150-kev gamma ray showed that no radiation with energy greater than 100 kev could be in coincidence with this gamma ray. Furthermore, proportional counter investigations of the Sn x-rays resulting from K-capture transitions showed that these x-rays were relatively abundant and are in fact about 10 times as intense as the Te x-rays. Thus it seemed logical to extend the coincidence investigation to the K-capture side. The spectrum of radiation in coincidence with the Sn x-rays, Fig. 7(c), confirms the above suspicion and definitely establishes that the 1150-kev gamma is in the K-capture branch.

The relative intensity of the 563-kev to the 693-kev radiation was calculated from the coincidence data in accordance with the procedure developed in reference 7. The results are listed in Table I and agree well with those determined from the analysis of the single-channel spectrum.

Determination of the Relative Intensity of the Electron Capture Process

The electron capture transitions of Sb^{122} should lead both to an excited and to the ground state of the Sn^{122} nucleus with the emission of Sn x-rays. Since the x-rays are close in energy to the Ba K x-rays which arise from the internal conversion of the 661-kev gamma radiation of Cs^{137}, a particularly useful type of comparison method may be employed to determine the intensity ratio of K-capture to the 563-kev gamma-transition. The method involves a measurement of the x-rays of Sn and Ba with a proportional counter (Fig. 8) and a measurement of the 563-kev gamma line of Sb^{122} and the 661-kev gamma line of Cs^{137} with a single-channel scintillation spectrometer. The same sources must be used in both cases.

The details of the method, along with a discussion of the various correction factors which are employed, are given in reference 7. The intensity of K-capture transitions relative to the intensity of the 563-kev gamma radiations as determined according to the above procedure is 4.1 percent. By multiplying this ratio by the factor $I_{563}/(I_{\beta 1}+I_{\beta 2}+I_{\beta 3})$, one gets for the ratio of K-capture to β^- emission the value 2.8 percent. If one

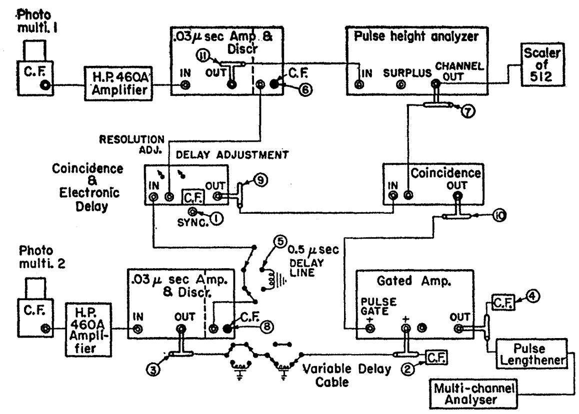

Fig. 6. Block diagram of the selective coincidence spectrometer.

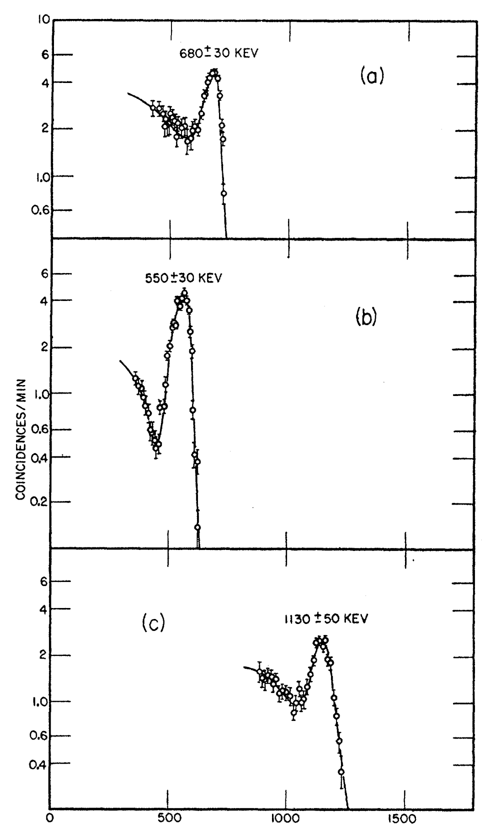

FIG. 7. (a) Gamma radiations in coincidence with the 566-kev gamma ray. (b) Gamma radiation in coincidence with the 686-kev gamma ray. (c) Gamma radiation in coincidence with the Sn^{122} x-ray.

then uses the value of 1.12 for the ratio of total capture to K-capture, one obtains $(K+L)$ capture/$\beta^- = 3.1$ percent.

Ratio of K_1 to K_2 Capture

The branching ratio for K-capture to the excited and to the ground states of Sn can be calculated from the results of the coincidence measurements. The formula used is

$$f = N_{1150,\ \text{x-ray coinc}} / (N_{\text{x-ray singles}} \times \epsilon_{1150}),$$

where f is the fraction of total K-capture going to the excited state; ϵ_{1150} is the value of the detection efficiency of the coincidence spectrometer for the 1150-kev gamma ray. The latter was determined to be 3.8×10^{-4}. Substitution of the coincidence data into the above formula gives a value 1/2.7 for f. Therefore, the ratio of K-capture to the excited state to that for the ground state is about 1.0:1.7.

It is also possible to make another independent estimate of this branching ratio from the single spectrum in conjunction with the information obtained from the proportional counter investigations. This gives for the ratio of K-capture to the excited state to that to the ground state a value of 1:2.4, which agrees within statistics with the value found from the coincidence data.

ESTIMATE OF THE POSITRON INTENSITY

An estimate of the energy available to the ground state of the Sn^{122} nucleus for K-capture may be obtained from a graph of decay energy *versus* mass number for neighboring isotopes (Fig. 9). The systematics show that this energy is large enough for positron emission to occur. Investigation of the positron spectrum showed that the intensity is so weak that only an upper limit could be placed on it. This limit was determined using the magnetic solenoid spectrometer with a separating baffle. The results give a value of 1.0×10^{-3} for an upper limit on the intensity of the positrons relative to the intensity of negatrons. This is in agreement with theoretical predictions.

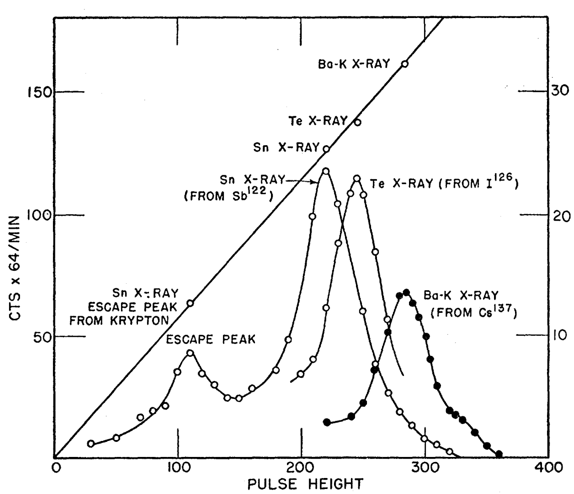

FIG. 8. Proportional counter measurements of the Sn and Ba K x-rays.

DISCUSSION

On the basis of the results of the present investigation. a proposed decay scheme is given for Sb^{122} (Fig. 10), The intensities of the various radiations together with the calculated ft-values for the transitions are listed in Table II.

The ratio of the intensities of the two highest negatron groups β_2/β_3 was obtained from the Kurie analysis of the total negatron spectrum. As was previously mentioned, the ratio β_1/β_2, is considered to be high because of scattering, etc. It is felt that the value of this ratio as determined from the relative intensities of the gamma radiations by scintillation techniques is correct to within 10 percent and constitutes a more reliable estimate.

Since the results of the investigations of the shape of the β^- spectra indicate a 2^- state for Sb^{122} and furthermore since Sn is an even-even nucleus, it can be concluded that any positron transitions to the ground state of Sn would be unique forbidden. With this knowledge, it is interesting to calculate roughly the expected upper limit for positron emission. Letting $\log ft = 8.5 \pm 0.2$ for a unique forbidden transition and choosing 1.7–2.0 Mev as the energy available for the transition (see Fig. 9), one can use the Davisson graph to calculate the partial half-life of the β^+ transition to the ground state. The theoretical upper limit on the fraction of decay going by positron emission is the ratio $\tau_{\text{total}}/\tau_{\beta^+}$, which is 0.1 percent–0.01 percent. This is consistent with the experimental findings.

The intensity of the K x-rays relative to the 566-kev γ ray as determined by the comparison method is known with a high degree of accuracy since good corrections for the proportional counter are known. The L-capture correction was taken to be 12 percent but

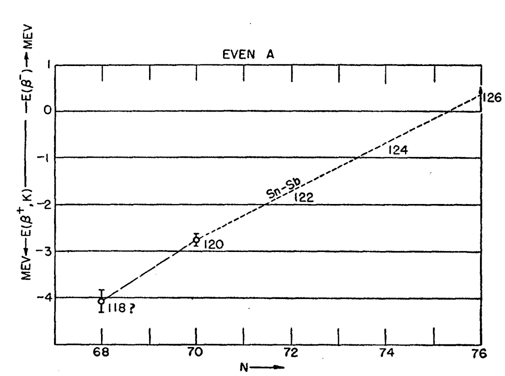

FIG. 9. Graph of decay energy versus mass number for neighboring isotopes of Sb^{122} [taken from K. Way and M. Wood, Phys. Rev. 94, 119 (1954)].

TABLE II. Intensities of the radiations emitted in the decay of Sb^{122} along with the calculated *ft*-values for the various transitions.

Radiation	Abundance (%)	Logf_0t	Logf_1t
$\beta_1^- = 740\pm20$ kev	4.0 ± 0.5	7.68	
$\beta_2^- = 1400\pm10$ kev	62.9 ± 2.0	7.59	
$\beta_3^- = 1970\pm 5$ kev	30.0 ± 1.0		8.50
β^+	less than 0.1		
$EC_1 = 0.25$–0.85 Mev	1.1 ± 0.1	6.66–7.72	
$EC_2 = 1.4$–2.0 Mev	2.0 ± 0.3		7.95–8.57
$\gamma_1 = 566\pm4$ kev	66.4 ± 6.6		
$\gamma_2 = 686\pm4$ kev	3.4 ± 0.4		
$\gamma_3 = 1258\pm6$ kev	0.66 ± 0.12		
$\gamma_4 = 1137\pm6$ kev	0.73 ± 0.10		

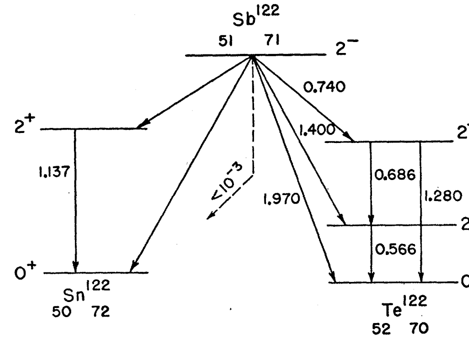

FIG. 10. Decay scheme proposed for Sb^{122}.

this value may be slightly questionable since it applies only to allowed transitions.

The relative intensities of γ_1, γ_2, γ_3, and γ_4 were obtained from the single spectrum using crystal efficiencies which are known to be accurate to about 10 percent. The intensity ratio of γ_1 to γ_2 was independently verified by the coincidence data (Table I). The branching ratio for *K*-capture to the two states in Sn^{122} has been calculated from the x-ray coincidence data and from the singles spectrum.[9,10]

The absolute branching ratios were obtained from the relative intensities and are listed in Table II together with the *ft* values for the various transitions.

CONCLUSION[10]

There now seems to be conclusive evidence that the highest-energy β^- group has an α shape, thereby establishing a spin and parity of 2^- for the ground state of Sb^{122}. The transitions to the excited states of Te^{122}, are of the type $2^- \rightarrow 2^+$ and the *ft* values are compatible with the mean value of log*ft*7.5 ± 0.5. The possibility of a 4^+ level for the second excited state of Te is not feasible since this would require a much lower intensity for the cross-over transition. Gamma-gamma angular correlation results also support this assignment.

The 1150-kev gamma ray is definitely associated with the *K*-capture branch. This high energy for the first excited state of Sn agrees well with the systematics and should in fact be expected in light of the closed shell proton state for the Sn^{122} nucleus.

The *ft* values for electron capture to the first excited state of Sn^{122} are compatible with a $2^- \rightarrow 2^+$ type transition although only a range of *ft* values has been estimated so that the evidence is not completely conclusive.

The choice of the $h_{11/2}$ state for the 71st neutron is the only posibility in order to obtain a negative parity. The two reasonable choices for the 51st proton are the $d_{5/2}$ or the $g_{7/2}$ state and the necessity for spin 2 rules out the possibility of the $d_{5/2}$ state.

It is interesting to note that the even-even isotopes of Te and Xe in this mass region seem to possess at least a second 2^+ state at an excitation energy slightly larger than twice that of the first excited 2^+ state.[11]

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Dr. J. Mihelich of Brookhaven National Laboratory for his investigations of the low-intensity conversion lines in the β spectrum, and Mr. Raymond Gold for his assistance in obtaining the data.

[9] The average of these two independent measurements was taken for the value of the ratio.

[10] Conclusions on the radiations of Sb^{122} by Glaubman are in good agreement with that of this paper. M. J. Glaubman, Phys. Rev. **98**, 1172(A) (1955); Farrelly, Koerts, Benczer, van Lieshout, and Wu, Phys. Rev. **98**, 1172(A) (1955).

[11] See reference 7; G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).