result, it is inferred that fission results only from reactions in which a compound nucleus is formed from the carbon particle and the gold nucleus. This observation is in contrast to those in the uranium-plus-carbon system, in which, at higher bombarding energies ($\geqslant 90$ Mev), there is incomplete momentum transfer in some of the reactions that lead to fission.[23]

The slight increase in fragment kinetic-energy release with increasing bombarding energy is attributed to an increase in the average number of neutrons evaporated prior to fission. Thus, the fissioning nuclei produced in the higher energy bombardments have higher values of the quantity $Z^2/A^{\frac{1}{3}}$ and would be expected, on the basis of Terrell's correlation of kinetic energy release with $Z^2/A^{\frac{1}{3}}$,[35] to yield higher kinetic energies.

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Disintegration of Te^{119}

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The disintegration of Te^{119} has been studied with the help of magnetic spectrometers and scintillation counters. Two half-lives are observed—one of 4.7 ± 0.3 days and one of $\sim$16 hours. These represent the decay from two isomeric states. The isomeric transition is not observed because of the strong competition from the decay to states of Sb^{119}. The 4.7-day disintegration occurs by electron capture and exhibits gamma rays of the following energies: 0.153, 0.270, 0.930, 1.10, 1.22, and 2.12 Mev. The following coincidences are observed: (2.12, 0.270), (1.22, 0.930, 0.153), (1.10, 0.270). The $K/(L+M)$ ratio for the line at 0.153 Mev is 7.85 and for the line at 0.270 Mev is 5.77. The 16-hour isomer exhibits positrons of end-point energy 0.627 Mev; and two gamma rays of energy 1.76 and 0.645 Mev. A disintegration scheme is given.

INTRODUCTION

THE disintegration of Te^{119} has, up to the present, been the subject of very little definitive study. Lindner and Perlman,[1] in studying the spallation products of antimony, showed that Te^{119} decayed with one half-life of 16 hours and a second of 4.5 days indicating that two isomeric states were involved. They showed that the 4.5-day Te activity is the parent of the 39-hour Sb^{119}. Beyond this very little information was obtained. The Nuclear Data Sheets[2] quote Dropesky and Fink, in unpublished work, as having established that there are no strong positrons with the 16-hour activity and that the 4.5-day activity has associated with it a gamma ray of 0.56 Mev. In view of the small amount of information on this radioactive nucleus and since it lies in the region of isomeric states involving the $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ configurations, the present writers undertook an investigation of Te^{119}.

PREPARATION OF SOURCES

In order to prepare Te^{119}, tin was bombarded by 22-Mev alpha particles in the Indiana University cyclotron. In most cases tin metal was used containing, of course, all the stable isotopes of tin. Certain confirmatory ex-experiments were performed by bombarding separated SnO_2 (92.60% Sn^{116}) obtained from the Stable Isotopes Division of the Oak Ridge National Laboratory. Since the yield was much better when metallic tin was bombarded, this was the usual target. Of the many possible radioactive tellurium isotopes that can be obtained from (α,n) and $(\alpha,2n)$ reactions on ordinary tin, most have long lives and well-known spectra. Interference from these was slight and could be corrected for. The 6-day Te^{118} with its 3.5-min Sb^{118} daughter is the only tellurium isotope that could be troublesome.

Metallic targets were treated by cutting off a thin layer (1–5 mils) on a milling machine and dissolving the tin metal in 12N HCl. The resultant solution was diluted to 3N in HCl and Te and Sb carriers added. Tellurium metal was precipitated by the usual procedure of adding SO_2 and hydrazine hydrochloride. The Te metal was centrifuged, washed and redissolved in dilute HNO_3. More Sb carrier was added and the cycle was repeated. The sources were prepared by evaporation of the nitrate. Sources made from the oxide were prepared by fusing with KHF_2, diluting and allowing the tellurium to deposit electrochemically on copper. The tellurium was then dissolved and further purified by the SO_2 method. In cases in which sources were to be used

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[1] M. Lindner and I. Perlman, Phys. Rev. **73**, 1124 (1948); **78**, 499 (1950).

[2] *Nuclear Data Sheets*, edited by C. L. McGinnis (Publications Office, National Academy of Sciences, National Research Council, Washington, D. C.).

in a permanent field spectrometer, tellurium was electroplated onto a thin copper wire from an HF solution.

APPARATUS

Various types of apparatus were used to study the radiations from Te^{119}. The gamma rays and their relative intensities were measured with the help of a NaI(Tl) scintillation spectrometer. The NaI(Tl) crystal measured 3 inches by 3 inches and was used in connection with a 5-inch Dumont Type 6364 photomultiplier tube. The crystal had been previously calibrated for intensity measurement for the particular geometrical arrangement used.[3] The pulse-height distribution was displayed on a 100-channel analyzer.

A magnetic lens spectrometer was used to measure the positron distribution and the energies and intensities of internal conversion electrons. A permanent field photographic recording magnetic spectrograph was employed to measure the lower energy internal conversion lines.

Finally, coincidences between gamma rays and between positrons and gamma rays were investigated with the help of various types of coincidence counting arrangements. For gamma-gamma coincidence measurements, two $1\frac{1}{2}$-inch by $1\frac{1}{2}$-inch NaI(Tl) crystals were used. Positrons were measured with the help of an anthracene crystal. Two types of coincidence circuits were used. The first was a standard "fast-slow" coincidence circuit of resolving time $\tau = 0.1$ μsec which could be used either to record coincidences between two single-channel scintillation spectrometers or to display, on a 100-channel analyzer, the spectrum in coincidence with a given gamma ray (or positron group) selected by a single-channel analyzer.

The second type of coincidence circuit was constructed using two RCA 6810-A fourteen dynode tubes. The pulse which was fed to the fast coincidence circuit was taken from the anode, put through a limiter, clipped, and then into a fast coincidence circuit. The pulses for which energy selection was desired were taken from the seventh dynode, passed through a linear amplifier and single-channel pulse-height analyzer into a triple coincidence circuit, into which the pulses from the fast coincidence circuit were also fed. If the 100-channel analyzer was to be used to display a spectrum which is in coincidence with a given gamma ray, the analyzer was placed in one leg of the slow coincidence circuit. A single-channel analyzer, in the other leg of the slow system, was set on the gamma ray of interest. The gate of the 100-channel analyzer was then opened by a coincidence pulse which resulted from the output of the fast coincidence circuit and the slow pulse from the single-channel analyzer.[4] The resolving time of this circuit was approximately $\tau = 15$ mμsec.

[3] See A. C. G. Mitchell, C. B. Creager, and C. W. Kocher, Phys. Rev. **111**, 1343 (1958).

[4] See, for example, R. E. Bell, R. L. Graham, and H. E. Petch, Can. J. Phys. **30**, 35 (1952).

TABLE I. Energies, relative intensities, and half-lives of gamma rays of Te^{119}.

Energies from internal conversion lines		Scintillation spectrometer		
Energy of gamma rays (kev)	Half-life	Energy of gamma ray (kev)	Relative intensity	Half-life
153.0±0.1	5.3 days	155	112	
270.6±0.1	4.38 days	270	54	
...	...	511 (ann. rad.)	...	
645 ±1	15±2 hr	645	(20)	15 ±1 hr
...	...	930	22	...
...	...	1100	21	
1221 ±1	4.6 days	1220	100	4.8±0.2 days
...	...	1760	(1)	18.5±1 hr
...	...	2120	7	4.5±0.3 days

THE EXPERIMENTS

The Gamma Rays

The energies of the various gamma rays were measured with the help of a permanent field photographic recording magnetic spectrograph, a magnetic lens spectrometer and a scintillation spectrometer using a 100-channel analyzer. The half-lives of the lines were determined from the data of the magnetic lens and the scintillation spectrometer. Finally, the relative intensities of the gamma rays were determined with the help of the scintillation spectrometer. The results of the investigation are shown in Table I. The results given there were obtained when ordinary metallic tin was bombarded by alpha particles so that lines owing to other long-lived tellurium activities were present. These served as checks on the energy calibration of the permanent field and the magnetic lens spectrometers. The relative intensities were taken early enough in the run so that the lines arising from long-lived activities made a negligible contribution.

It will be seen at once that two of the lines—those at 0.645 and 1.76 Mev—have a half-life of 15–20 hours. The remainder have a half-life of approximately 5 days. As far as these experiments are able to ascertain there seems to be no growth or decay of one system from the other. This implies at once that the lifetimes of the isomeric states involved are governed to a large extent by their several transition probabilities to states of Sb^{119} rather than by the gamma-ray lifetime for isomeric transitions in Te^{119}. A similar situation exists to a greater or less extent in several Te isomers.[5] In Table I, the intensities of the 0.645 Mev and 1.76 Mev are shown relative to each other, while the lines of the long half-life are shown relative to the line at 1.22 Mev. Figures 1(a) and 1(b) show a scintillation spectrum taken shortly after bombardment. The line at 2.1 Mev has also been seen in measurements of photoelectrons from a uranium radiator in a magnetic lens spectrometer showing that this line as seen on a scintillation spectrometer is not caused by pileup.

The Particle Spectrum

As mentioned earlier, the particle spectrum was investigated in a magnetic lens. In addition to internal

[5] T. Alvager and G. Oelsner, Arkiv Fysik **12**, 319 (1957).

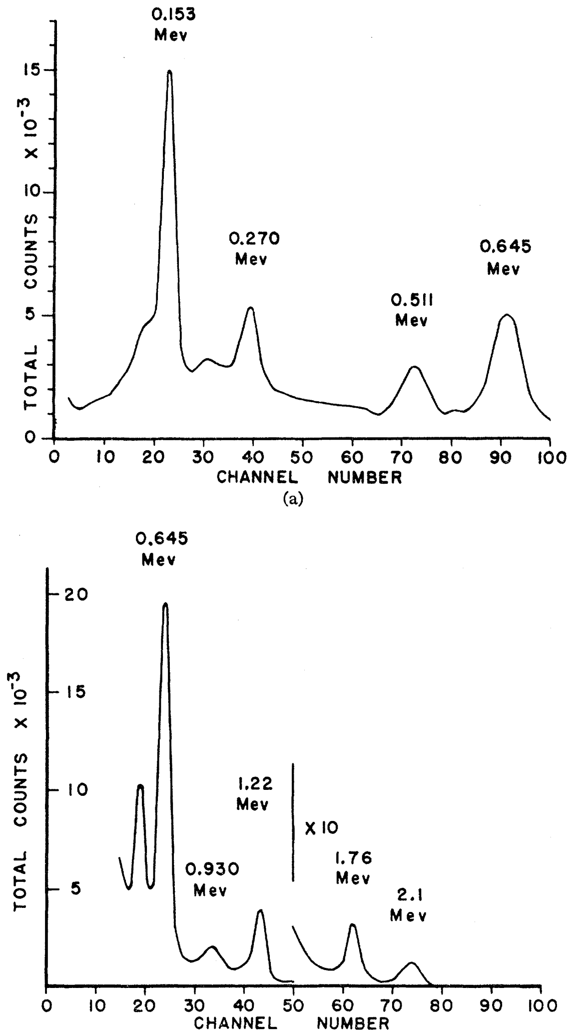

FIG. 1. (a) Scintillation spectrum of Te^{119} up to 0.700 Mev. (b) Scintillation spectrum of Te^{119} from 0.500 Mev to 2.1 Mev.

conversion lines, two positron groups were found. Of these, the higher energy group showed a half-life of 5.6 days and an end-point energy of 2.7 Mev. A low-energy group, end-point energy 0.627 Mev, was also seen.

The high-energy group shows a log $ft=7.9$, and the end-point energy is much too high to be in agreement with the beta-ray systematics for Te^{119}. If this group is ascribed to the 3.5-min Sb^{118} in equilibrium with its parent Te^{118}, formed by an $(\alpha,2n)$ reaction, the end-point energy and log ft value (5.6) are in reasonable agreement with previous information on Sb^{118}. Experiments to be described below show that this is indeed the case.

In addition to the high-energy positron group, one of lower energy was also found. The analysis of this group was carried out in the usual manner after correcting for the contributions from the high-energy long-lived group. The positrons of this group exhibited a half-life of approximately 13 hours. This value was obtained after corrections for the long-lived group and is not considered to be very accurate. A Fermi plot is shown in Fig. 2. The end-point energy of this spectrum is 0.627 ± 0.002 Mev.

Since the half-lives of Te^{119} ($5d$) and Te^{118} ($6d$) lie so near together, experiments were designed to disentangle these two activities. In the first place, the use of the enriched SnO_2 (92.6% Sn^{116}) covered with enough nickel foil to cut down the energy of the alpha-particle beam below the threshold for the $(\alpha,2n)$ reaction yielded activities of too low intensities to work with. It was therefore decided to irradiate metallic tin, mill off five portions each approximately 0.001 inch thick and measure these on an anthracene scintillation counter. The ratio of the number of positrons at 900 kev to that at 250 kev was studied as a function of the depth below the surface. At the same time a check on the relative intensities of the 1.22- and 0.153-Mev gamma rays was made. The results are shown in Table II.

It will be seen from the table that the intensity of the high-energy positron group decreases rapidly with respect to the low-energy group as a function of depth below the surface, indicating that it is produced by an $(\alpha,2n)$ reaction. The relative intensities of the two gamma rays are the same within the limit of error for the activity produced on the surface and that produced at a depth of about 0.004 inch.

Coincidence Measurements

Many gamma-gamma coincidence experiments were carried out using one or more types of the coincidence counting apparatus described above. We consider first the gamma rays from the 5-day isomer.

If the single-channel analyzer in one arm of the coincidence circuit were set on the gamma ray at 2.12 Mev and those gamma rays in coincidence with this were displayed on the 100-channel analyzer, it was found

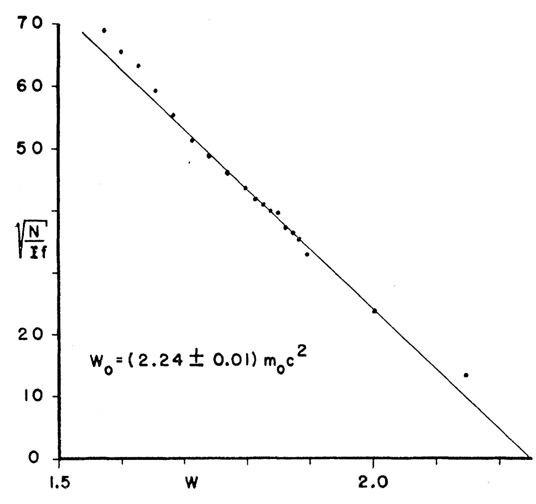

FIG. 2. Fermi plot of positrons from Te^{119} (short life).

that only the line at 0.270 Mev was in coincidence. Figure 3 shows the coincidence spectrum up to 0.4 Mev.

Figure 4 shows the result of setting the single-channel analyzer on the peak of the line at 1.22 Mev and displaying the coincidence spectrum from 0.7 Mev to 1.2 Mev. It will be seen that there is a line at 0.930 Mev in coincidence with that at 1.22 Mev. Figure 5 shows that portion of the low-energy region which is in coincidence with the 1.22-Mev line. It will be seen that the line at 0.153 Mev is in strong coincidence with that at 1.22 Mev. Supplementary experiments have shown that the weak peak at 0.270 Mev arises from two factors—a small contribution from the coincidences between Compton electrons of the 2.12-Mev line and the 0.270-Mev line and a larger contribution from the high-energy tail of the 1.10-Mev line in coincidence with that at 0.270-Mev. If the setting of the single-channel analyzer was moved to the low-energy side of the 1.22-Mev line and placed at an energy corresponding to 1.1 Mev, the coincidence line at 0.270 Mev was observed to increase markedly and that at 0.153 Mev to decrease. The above coincidences were confirmed by setting the single-channel analyzer on the various low-energy lines and observing the high-energy lines in coincidence with them. The results of the coincidence experiments are given in Table III.

In regard to the radiations from the shorter lived isomer it was found that the 1.76-Mev and the 0.645-Mev gamma rays were not in coincidence. Positron-gamma coincidence experiments performed with a source which had been prepared in such a way that the $(\alpha,2n)$ process had a very small yield showed no coincidences between positrons of the 0.627-Mev group and either the 0.645-Mev, 1.76-Mev or the 0.153-Mev gamma ray.

TABLE II. Relative intensities of positrons and gamma rays as a function of depth below surface.

	Approximate depth below surface (mils)	Ratios 900-kev β^+/250-kev β^+	Relative intensities of gamma rays 1.22 Mev	0.153 Mev
Cut 1	0	0.237	100	103
Cut 2	1	0.195		
Cut 3	2	0.162		
Cut 4	3	0.132		
Cut 5	4	0.093	100	111

TABLE III. Results of coincidence experiments on the 5-day isomer.

Gamma ray (Mev)	In coincidence with gamma rays (Mev)
2.12	0.270
1.22	0.930, 0.153
1.10	0.270

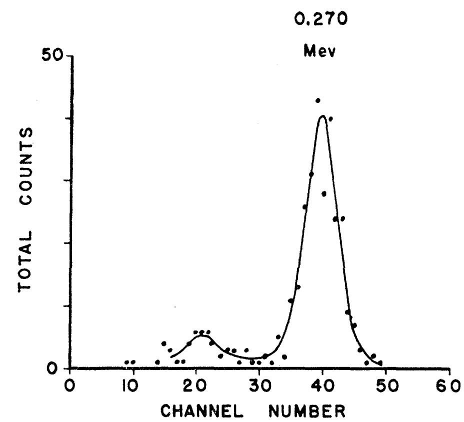

FIG. 3. Gamma rays in coincidence with gamma ray at 2.1 Mev.

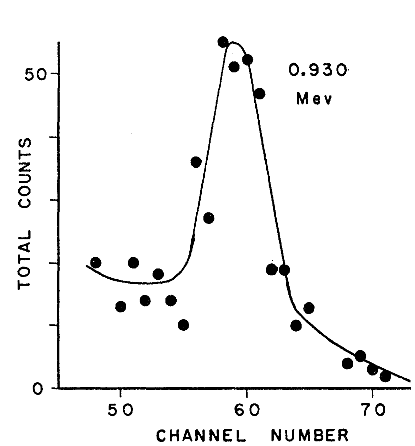

FIG. 4. Gamma rays in coincidence with the gamma ray at 1.22 Mev (region 0.7 to 1.2 Mev).

Internal Conversion Coefficient of the 0.645-Mev Gamma Ray

The internal conversion coefficient of the 0.645-Mev line of the short-lived isomer was measured by a comparison method as follows. The number of internal conversion electrons of the 0.645-Mev line and those from a standard Cs^{137} line were measured in the magnetic lens spectrometer. The intensities of the respective gamma rays were then measured on a calibrated scintillation counter.[3] The value of the internal conversion coefficient for the 0.645-Mev line is $\alpha_{tot}=4\times10^{-3}$ $(\pm10\%)$. This is to be compared with theoretical values of $\alpha_2(K+L)=3.9\times10^{-3}$ and $\beta_1(K+L)=4.9\times10^{-3}$. The experiments are not good enough to differentiate between α_2 and β_1 but it is clear that this line cannot have either an $E3$ or $M3$ character. Since the 0.645-Mev gamma ray is of $M1$ or $E2$ character, the state from which it comes must be of short life compared to the resolving time (10^{-7} sec) used in the positron-gamma experiments. The lack of coincidence between positrons and the 0.645-Mev line cannot be accounted for by a long-lived state.

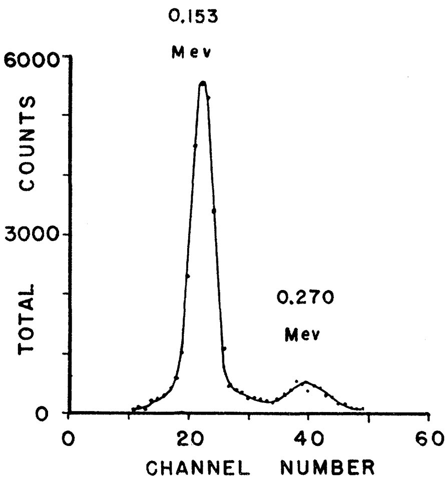

FIG. 5. Gamma rays in coincidence with the gamma ray at 1.22 Mev (low-energy region).

DISCUSSION OF RESULTS

From the information obtained in these experiments it is possible to give a reasonable description of the decay of the long-lived state together with an energy level diagram for the product nucleus and also to infer the disintegration characteristics of the short-lived state.

Consider the long-lived state. From the data given in Table I for the various lines associated with this decay, a value for the half-life of 4.7±0.3 days is calculated. From the relative intensities of the gamma rays and the results of the coincidence experiments a tentative energy level scheme for Sb^{119} can be drawn and is shown in Fig. 6. From the disintegration scheme and the relative intensities of the gamma rays the relative probability per disintegration of exciting the various levels can be calculated. These are shown on the diagram. It will be seen at once that the level at 1.37 Mev has the highest probability of being populated and that the ground state and first excited levels are very weakly populated.

The product nucleus $_{51}Sb^{119}$ has one proton outside a closed shell. Sb^{121} has a ground-state configuration $\frac{5}{2}+$ and Sb^{123}, $\frac{7}{2}+$. The $\frac{7}{2}+$ and $\frac{5}{2}+$ states lie close together. For Sb^{119} the level order would presumably be[6] $\frac{5}{2}+$, $\frac{7}{2}+$, $\frac{3}{2}+$, $\frac{1}{2}+$. The present experiments are not detailed enough to give definite information on these predictions. Nevertheless, the following considerations suggest that the level assignment for the first three states may be correct. Nainan[7] has found that the half-life of the

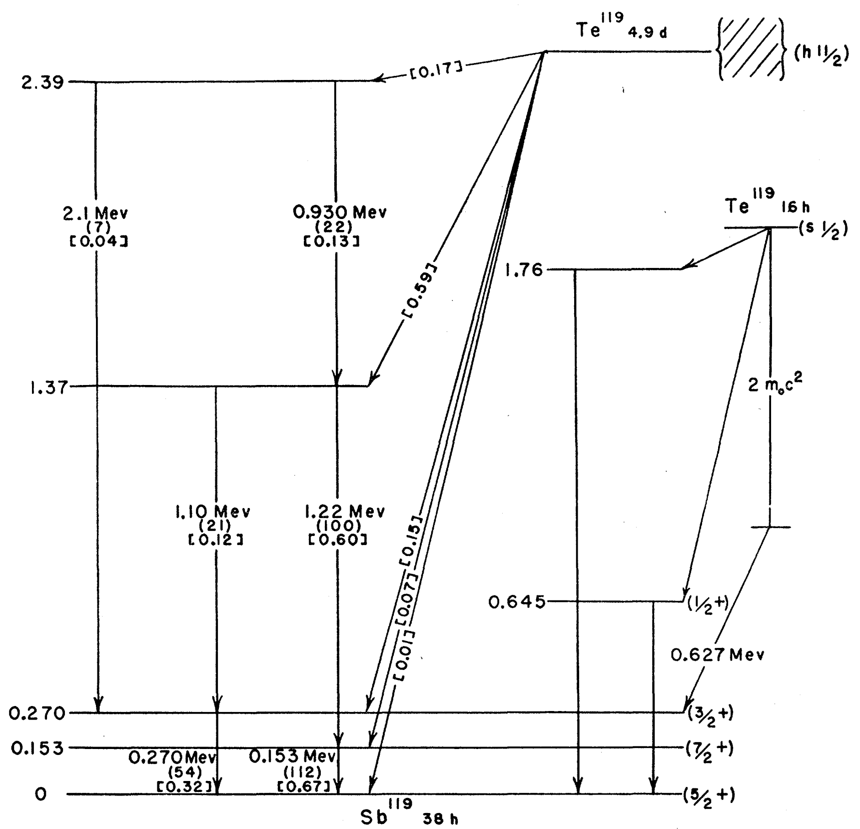

FIG. 6. Tentative decay scheme for Te^{119}. For the 5-day activity the relative intensities of the gamma rays are given in parentheses, with the intensity of the 1.22-Mev gamma ray=100. The fraction per disintegration is given in square brackets.

[6] J. H. D. Jensen, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955), p. 415 ff.
[7] T. D. Nainan, Bull. Am. Phys. Soc. 5, 239 (1960).

state at 0.153 Mev is 0.84×10^{-9} sec which is in agreement with an $M1(10\%)+E2(90\%)$ mixture for the 0.153-Mev transition. The present authors have measured the $K/(L+M)$ ratio for this line and obtain $K/(L+M)=7.85$. This is to be compared with theoretical values of $M1=8.35$ and $E2=3.48$. Thus it would appear that the 0.153-Mev line is a mixture of $M1$ and $E2$ which would agree with a transition $\frac{7}{2}+$ to $\frac{5}{2}+$. The $K/(L+M)$ ratio for the line at 0.270 Mev has also been measured in these experiments and has been found to be 5.77, which is to be compared with theoretical values of $M1=5.32$ and $E2=4.16$. Such an $M1+E2$ mixture would be in agreement with a transition $\frac{3}{2}+$ to $\frac{5}{2}+$. However, $K/(L+M)$ ratios are not very sensitive functions of the multipole order in this region and it will be necessary to carry out directional correlation experiments to make a final decision. Such experiments are in progress in this laboratory.

As mentioned in the foregoing, the radiations from the 16 hour activity consist of a positron group of 0.627-Mev end-point energy, a strong gamma ray of energy 0.645 Mev and a weak one of 1.76 Mev, none of which are in coincidence. These radiations were found in both the experiments using ordinary metallic tin and those using SnO_2 enriched in Sn^{116}. Since both the 5-day and the 16-hr activities decay independently and since no growth of the one from the other has been found suggests that the probability of transition from the two Te states to Sb is considerably greater than that of the isomeric transition in Te and in addition that the 0.645-Mev and 1.76-Mev gamma rays are in Sb^{119}.

By using figures for the ratio of the relative number of internal conversion electrons of the 0.645-Mev line to the number of positrons of the low-energy group measured in the magnetic lens, the figures for the internal conversion coefficient and the relative intensity of the two gamma rays, it is possible to obtain a rough set of values for the relative transitions from the 16-hr state. These are shown in Table IV. Using these figures the value of log ft for the positron transition is 6.9 and for the transition to the 0.645-Mev state is 5.2. It would appear, therefore, that the transition to the 0.645-Mev state is allowed and that the positrons are once forbidden or l forbidden.

TABLE IV. Relative intensities of transitions from the 16-hr state.

Radiation	Relative intensity	Percent of disintegration
0.645-Mev γ	100	0.90
1.76-Mev γ	5	0.05
Positrons	5	0.05

The systematics of the isomers of Te suggest[8] that the $h_{11/2}$ state lies considerably higher than the $s_{1/2}$ ground state and that the $d_{3/2}$ state lies close to the $h_{11/2}$ state, insuring a transition of long life—possibly around 200 days. Such a long half-life could not compete with the 5-day electron capture and hence the gamma ray arising from the isomeric transition would be extremely weak. The weak positron group from the 16-hr state having a log $ft=6.9$ would be consistent with a transition to a $\frac{3}{2}+$ state but not to a $\frac{5}{2}+$ ground state. Actually the measured half-life of the state at 0.270 kev appears to be somewhat shorter than the other states associated with the 5-day decay, which could be accounted for by a contribution from the weak 16-hr positron activity. The allowed nature of the transition to the state at 0.645 Mev would suggest that this state is the $\frac{1}{2}+$ state of Sb^{119}. The suggested features of the decay of the 16-hr state are incorporated into Fig. 6. If this scheme is correct the $s_{1/2}$ state of Te would lie 1.92 Mev above the ground state of Sb^{119} and the $h_{11/2}$ at greater than 2.39 Mev. This would give an $h_{11/2}$-$s_{1/2}$ energy difference of 400–500 kev.

ACKNOWLEDGMENTS

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[8] M. Goldhaber and R. D. Hill, Revs. Modern Phys. 24, 179 (1952).