Radiations of Te^{127} and Te^{127m}†

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The radiations of Te^{127} and Te^{127m} have been examined by beta-ray spectrometry and gamma-ray scintillation spectrometry. Te^{127} (9.35±0.10 hr) decays predominantly (99%) by a beta transition of end-point energy 695±10 kev to the ground state of I^{127}. The remaining 1.0±0.2% of the decay is accompanied by gamma rays of energies 58.5±1, 145±2, 203±3, 215±4, 360±4, and 418±2 kev. By means of gamma-gamma coincidence measurements, these gamma rays have been fitted into a consistent decay scheme which involves levels in I^{127} at 58.5, 203, and 418 kev. Te^{127m} (105±2 days), which decays predominantly by the well-known 89-kev isomeric transition, also has a 1.5±0.5% beta branch which populates the 58.5-kev level in I^{127} and another beta branch of total intensity ~0.013% which is accompanied by a gamma ray of energy 665±5 kev. Plausible spin and parity assignments for the excited levels of I^{127} are discussed.

INTRODUCTION

THE nuclide Te^{127} is known to exist in two isomeric states.[1] The upper state, for which half-lives of 90 days[1] and 115 days[2] have been reported, decays by isomeric transition to a beta-emitting ground state of half-life 9.3 hours.[1] From conversion electron measurements[2–5] the isomeric transition energy has been found to be 88.5 kev and the multipolarity $M4$.

Until the past year, the only radiation measurements reported on the ground state were those obtained by the absorber method; they indicated a beta energy of 0.7 Mev, with no gamma radiation.[6] Recently, the ground-state radiations have been examined by beta- and gamma-scintillation spectrometry. The investigators[7] report a single beta-ray group of energy 683±10 kev and no gamma radiation.

Since, however, other investigators[8,9] have found a series of excited states of I^{127} populated by electron-capture decay of Xe^{127}, which is presumed to have a $d_{3/2}$ ground-state configuration,[10,11] and since the Te^{127}, with a ground-state configuration presumed to be $d_{3/2}$,[12] would be expected to decay in part by beta transitions to some of the same I^{127} excited states, it appeared worthwhile to re-examine the Te^{127} radiations with particular attention to possible low-intensity beta and gamma transitions. This paper reports the results of such an examination.

EXPERIMENTAL TECHNIQUES

Two types of Te^{127} sources were used in this study. The first type was obtained by milking from Sb^{127} which had been isolated from fission products. In the preparation of these sources, the fission-product mixture was allowed to stand about 90 hours after the end of the uranium irradiation to allow for decay of Sb^{129}, the remaining fission-product antimony was isolated, and the Te^{127} was separated from it after a growth period of the order of 10–15 hours. Since the Sb^{127} has a 93-hour half-life, several successive Te^{127} sources could be obtained from a single batch of the parent material. The second series of sources consisted of a Te^{127m}–Te^{127} equilibrium mixture produced by a three-month neutron irradiation[13] of electromagnetically enriched Te^{126}.[14] These n,γ sources were radiochemically purified after irradiation, but were slightly contaminated with Te^{123m}, Te^{125m}, and Te^{129m} from neutron capture in the small amounts of other tellurium isotopes remaining in the enriched Te^{126}.

Beta counting for measurement of half-life and absolute source strength was carried out with methane-flow beta proportional counters. The beta-ray spectrum was measured with a short-lens beta-ray spectrometer set for a momentum resolution of 2.2%. Conversion lines were examined with a 141-gauss, 180° beta-ray spectrograph of energy resolution approximately 0.2% and upper energy limit ~500 kev. Gamma rays were studied with NaI(Tl) scintillation spectrometers used in conjunction with a 100-channel pulse-height analyzer and coincidence circuitry.

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

[13] The neutron irradiation was carried out at the Materials Testing Reactor, operated by Phillips Petroleum Company, Atomic Energy Division, Idaho Falls, Idaho.
[14] The enriched Te^{126} was obtained from the Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee. The isotopic composition reported was: 122, 0.1%; 124, 0.6%; 125, 0.7%; 126, 95.4%; 128, 2.6%; 130, 0.5%.

MEASUREMENTS AND RESULTS

Half-Lives

The Te^{127} and Te^{127m} half-lives were measured by beta counting a source derived from fission-product antimony as described in the preceding section. The only radioactive tellurium contaminant, Te^{125m}, was calculated to constitute less than one atom percent of the Te^{127m} obtained at separation time. The half-life of the Te^{127m}, measured over a span of 13 months, was 105±2 days. The half-life of the ground-state Te^{127}, taken from the first week of decay of the same sample, was 9.35±0.10 hours.

Beta Spectra

The beta-ray spectrum of Te^{127} was measured with the use of a fission-product source of thickness ~2 mg/cm². Within the limits imposed by spectrometer resolution and source thickness, no conversion lines were observed, and the spectrum appeared to consist of a single beta group of maximum energy 695±10 kev.

A more careful search for conversion lines was made by examining a $Te^{127m}-Te^{127}$ source in the 180° beta-ray spectrograph. Two exposures were made, the first long enough to produce considerable beta-continuum blackening of the low-energy portion of the film, and the second long enough to produce darkening out to the 400-kev region. No conversion lines other than those associated with the Te^{123m}, Te^{125m}, Te^{127m}, and Te^{129m} isomeric transitions were observed.

Gamma Spectra

Examination of the Te^{127} fission-product source by scintillation spectrometry revealed a weak gamma spectrum with photo-peaks at 418±2, 360±4, 208±5, and 58.5±1 kev, together with the K x-ray of iodine. Scintillation measurements of this source taken under identical conditions at intervals of about 10 hours showed that all parts of the gamma spectrum decayed with the Te^{127} half-life. Examination of the $Te^{127m}-Te^{127}$ source showed, in addition to the Te^{127} gamma spectrum, photopeaks at 89±2, 159±4, 580±15, and 665±5 kev, and about a 12-fold enhancement of the 58.5-kev peak. Typical scintillation spectra of the two types of sources, measured through 16 mils of copper absorber to suppress x-rays, are plotted in Fig. 1.

The intensities of the gamma rays from Te^{127} were determined by two absolute measurements on a single fission-product source. First, the disintegration rate was measured by beta counting under conditions of known counting efficiency; then, the intensities of the photopeaks were measured in a scintillator arrangement, the detection efficiency of which had previously been calibrated with a series of gamma emitters of known disintegration rates. The 418-kev gamma ray, which was the most abundant, was found to occur in 0.8 ±0.1% of the beta disintegrations. Measurements of the abundances of the gamma rays of lower energy were subject to somewhat greater error because of the combined effects of the Compton background from the 418-kev gamma ray and the bremsstrahlung from the relatively intense beta radiation of the source. The shape of the Compton background was estimated by measuring the 412-kev gamma-ray "spectrum" of a Au^{198} source of similar size and in similar geometry.

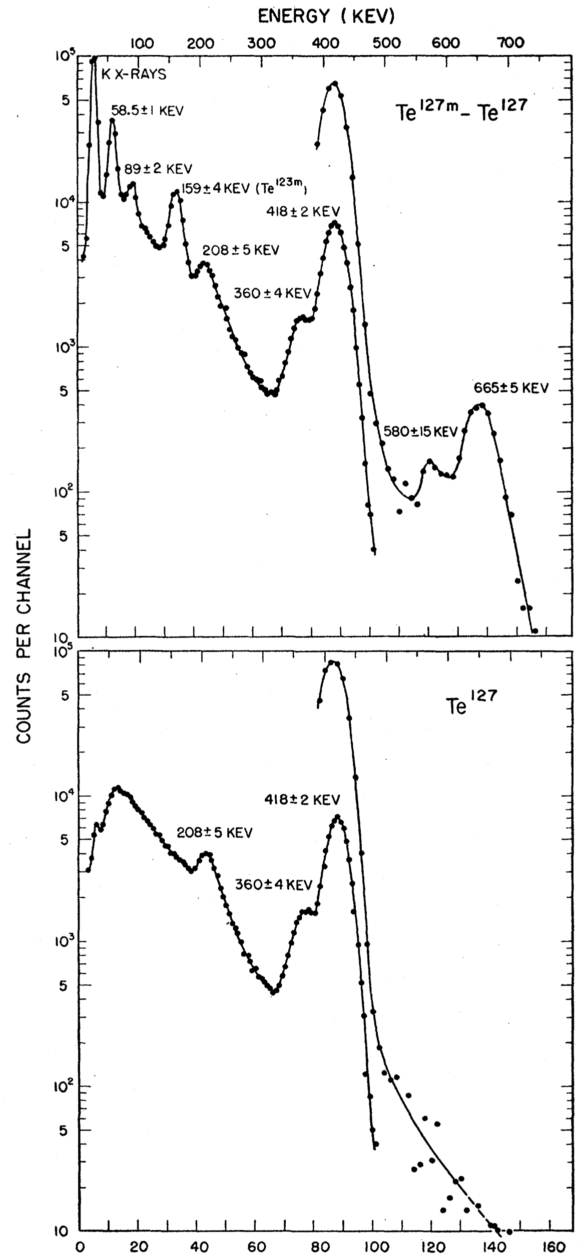

FIG. 1. Gamma scintillation spectra of $Te^{127m}-Te^{127}$ and Te^{127} sources, measured with a $1\frac{1}{2}$ inch×$1\frac{1}{2}$ inch NaI(Tl) crystal through 16 mils of copper absorber. The partial spectra of the >400-kev region represent longer counts taken to emphasize weak high-energy gamma rays.

From the spectrum remaining after subtraction of the aforementioned Compton spectrum, with proper correction for the slight difference in energies, the bremsstrahlung background was taken out empirically in such a way as to leave reasonable peak-to-valley ratios in the remaining spectrum.

The relative intensities of the gamma rays from $Te^{127m}-Te^{127}$ were measured with the same calibrated scintillator arrangement, with the 418-kev gamma ray used as the intensity reference standard. The results of the gamma intensity and energy measurements on the Te^{127} and $Te^{127m}-Te^{127}$ sources are summarized in Table I. The 208-kev photopeak is listed both singly, as observed in the singles spectrum, and as the 203–215-kev doublet which is believed to constitute its actual composition. In addition, an intensity is cited for a 145-kev gamma ray which was not clearly observable in the singles spectra. Both these pieces of information are based on gamma-gamma coincidence work to be described in the next section.

The gamma rays of 580 and 159 kev are listed separately at the end of the table because they are believed to be due to impurities. The energy of the gamma ray following electron capture decay of Te^{121} (which would have been in equilibrium with any Te^{121m} produced in the n,γ sample) has been reported as 575 kev. The energy of the gamma ray following the 89-kev isomeric transition of Te^{123m} has been reported as 159 kev. The similarity of the Te^{121m} and Te^{123m} half-lives to the half-life of Te^{127m} made an identification based on decay rates uncertain.

Coincidence Measurements

The positions of the excited levels of I^{127} produced by Te^{127} decay, together with upper limits for the intensities of beta branches leading to two of these levels, were deduced from a series of gamma-gamma coincidence measurements on $Te^{127m}-Te^{127}$ sources. In order to minimize the possibility of false coincidences resulting from registration in one crystal of Compton-scattered gammas from the other, the gate and analyzer crystals were placed in the same quadrant and shielded by $\frac{1}{8}$ inch of lead in such a manner that they could "see" the source but not one another.

The coincidence spectrum with the 360-kev photopeak used as the source of gate pulses showed photopeaks at 28±2 kev and 59±2 kev; there was no evidence for gammas of higher energy. The 28-kev peak is evidently produced by iodine x-rays from internal conversion of some of the 58-kev transitions. Because of partial absorption of the lower energy radiations by the crystal housing materials, the ratio of the observed intensities of the 28- and 59-kev peaks is considerably lower than their true intensity ratio.

The coincidence spectrum with the 58-kev peak used as the source of gate pulses showed photopeaks at 155±10, 208±10, and 365±10 kev. Within the limits imposed by counting statistics, the 155-kev peak appeared to be too broad to have been produced by a single gamma ray. It was interpreted as probably consisting of the summed effect of the photopeak of a 145-kev gamma ray and the Compton peak from the 360-kev gamma ray.

A third set of coincidence measurements was conducted to elucidate the gamma transitions involved in the 208-kev photopeak. With the gate channel set to cover the 175–240-kev region, the coincidence spectrum showed a weak peak at 145±10 kev and a strong peak at 208±5 kev, with no indication of any photopeaks above the latter. A coincidence peak at 58 kev, which would be expected on the basis of the preceding coincidence experiment, was too weak to be distinguishable above background.

The absence of the 418-kev peak in any of the coincidence spectra suggests that the corresponding gamma transition goes directly to the ground state of I^{127}. The low intensities of the 580- and 665-kev gamma rays precluded definite conclusions as to their presence or absence in the coincidence spectra. Since the Te^{127m} is about 785 kev above the ground state of I^{127}, it is energetically possible for both gammas to represent transitions to the 58-kev level.

Levels in I^{127} at 56–57 and 200–203 kev, with a weak transition between them of 145 kev, have been proposed by Bergström[8] and by Mathur[9] from Xe^{127} decay studies. The postulate of these same two levels, plus another at 418 kev, provides a level scheme which is consistent with the results of the present work. In terms of this scheme, the 360-kev and 145-kev gamma rays represent transitions to the 58-kev level from levels at 418 and 203 kev, respectively, and the 208-kev photopeak is produced by gamma transitions from the 418-kev level to the 203-kev level and the 203-kev level to the ground state. Neither of the aforementioned investigators found any 418-kev gamma radiation from Xe^{127} decay, but both found evidence for an I^{127} level at about 370 kev which decayed to the 203-kev level and to the ground state. In Te^{127} decay, on the other hand, the absence of definite indications of a

TABLE I. Gamma rays from Te^{127} and $Te^{127m}-Te^{127}$ sources.

Energy (kev)	Relative intensity[a] Te^{127}	$Te^{127m}-Te^{127}$
665 ±5	<0.06	1.7±0.3
418 ±2	100	100
360 ±4	15 ±3	15 ±3
208 {203±3, 215±4}	11 ±2	11 ±2
145 ±2	0.8±0.2	0.8±0.2
89 ±2	<1	13 ±3
58.5±1	5.6±1.4	72 ±18
580 ±15(Te^{121m})	<0.2	(0.6±0.2)
159 ±4(Te^{123m})	<1	(39 ±7)

[a] Absolute intensity: $(418\gamma)/(\text{total } \beta) = 0.008 \pm 0.001$.

170-kev peak in the gross gamma-scintillation spectrum shows that the 370-kev level in I^{127} is not populated to an extent comparable with the 418-kev level, though the data do not exclude the possibility of a small contribution from the corresponding 370- and 170-kev gamma rays. An upper limit to this contribution was estimated on the basis of the coincidence data. In the Te^{127} coincidence spectrum gated by the 208-kev photopeak [Fig. 2(c)], the intensities of the gamma rays corresponding to the 145-, possible 170-, and 208-kev peaks are approximately in the ratio $1:\lesssim 0.4:13$; with the total internal conversion coefficients taken as 0.4, 0.23, and 0.14, respectively (an estimate based on a compromise between $E2$ and $M1$ multipolarity assignments), the relative numbers of transitions are then in the ratio $1:\lesssim 0.35:11$. From these intensity figures it may be calculated that the 203-kev level decays ~15 percent via the 145–58 cascade and ~85 percent by direct transition to the ground state, and that the 170-kev transitions are $\lesssim 0.063$ as abundant as the 215-kev transitions. The 215-kev transitions, in turn, cannot contribute more than $\sim 1/1.85 = 0.54$ of the 208-kev photopeak in the singles spectrum (Fig. 1), and thus the 170-kev transitions are $\lesssim 0.043$ as abundant as the 418-kev gamma rays. From the Xe^{127} gamma scintillation spectra shown in the paper of Mathur,[9] the relative gamma-peak areas indicate that $\sim\frac{2}{3}$ of the 370-kev states decay by way of 170-kev transitions; this figure, taken in conjunction with the datum $(170\text{ trans})/(418\gamma) \lesssim 0.043$ and with the measured intensity ratio $(418\gamma)/(\text{total }\beta) = 0.008 \pm 0.001$ for Te^{127}, indicates that not more than about 0.05 percent of the Te^{127} beta disintegrations populate the 370-kev state of I^{127}. Similarly, if $\frac{1}{3}$ of the 370-kev states decay directly to the ground state, the corresponding gamma rays cannot contribute more than about 12 percent to the observed "360-kev" radiation.

The relative contributions of the 203- and 215-kev gamma rays to the 208-kev peak could not be determined exactly. In principle, the calculation could be made from the data given above, together with gamma intensities from the coincidence spectrum gated by the 58-kev gammas; in practice, this gate channel contained such a large component of radiation from bremsstrahlung and from Compton-scattered radiation that the coincidence spectrum derived from it had only qualitative significance. Another coincidence experiment, in which the 208-kev peak was used as the gate, and in which the gate counting rate was compared with the counting rate of the 208-kev peak in the coincidence spectrum under conditions where the effective counting efficiencies of both scintillation crystals were known, showed that the major part of the gammas of the 208-kev peak were in coincidence. In terms of the level scheme proposed, this means that the 203-kev level is fed mainly by gamma transitions from the 418-kev level.

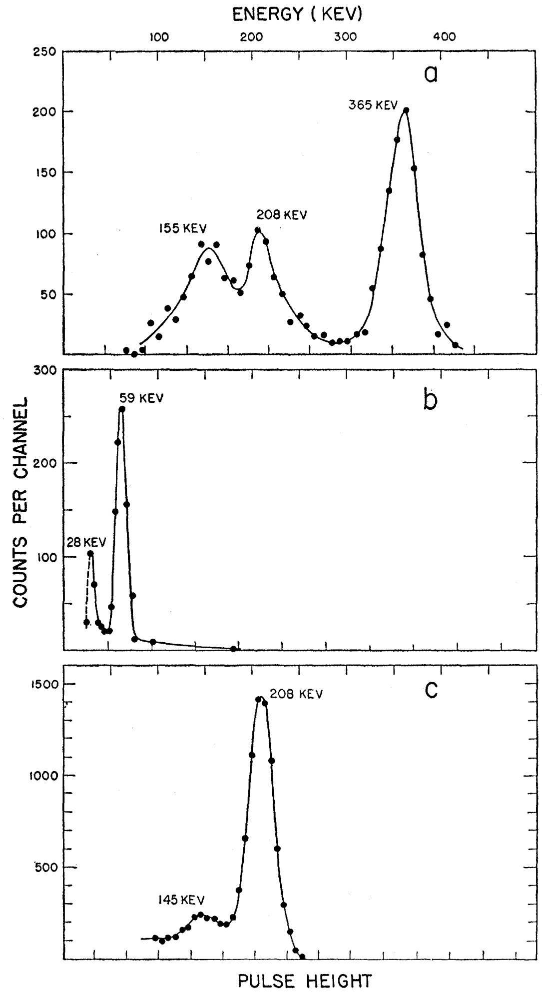

FIG. 2. Gamma-coincidence spectra obtained with the gate channel set to accept pulses from photopeaks at (a) 58 kev; (b) 360 kev; (c) 208 kev.

Intensities of Beta Branches

The fraction of the Te^{127} beta disintegrations leading to the 418-kev level was calculated from the measured ratio of 418-kev gammas to total betas by taking into account the three paths by which this level is depopulated. With the assumptions that the 215-kev gammas contributed half of the 208-kev peak and that the 360-kev gammas contributed all of the 360-kev peak, and with the total internal conversion coefficients of the 418-, 360-, and 215-kev gamma rays assumed to be 0.017, 0.025, and 0.14, respectively, the fraction of 418-kev levels decaying by emission of 418-kev gammas was found to be 0.8. The fraction of the Te^{127} beta disintegrations leading to the 418-kev state is then $0.008/0.8 = 0.01$, which leads to a $\log f_0 t = 6.1$ for the beta transition.

If it is assumed, in the limiting case, that all of the observed "208-kev" gammas represent transitions from the 203-kev level to the ground state, i.e., that the

203-kev level is fed only by beta decay, the fraction of Te^{127} beta transitions leading to this level is $\sim$0.0012, and $\log f_0 t = 7.8$. Since as mentioned in the previous section, the gamma-gamma coincidence results indicated that the 203-kev level is populated mainly from the 418-kev level, the true beta branching to the former is probably several-fold smaller and $\log f_0 t > 7.8$.

The observation that the relative intensity of the 58-kev gamma ray is more than tenfold greater in the $Te^{127m}-Te^{127}$ spectrum than in the Te^{127} spectrum led to the conclusion that the 58-kev level is fed by a direct beta branch from Te^{127m}. The fraction of the Te^{127m} decaying by way of this branch was derived from the data of Table I and the total internal conversion coefficient of the 58-kev transition. The latter number was not measured directly, but was estimated from the Te^{127} gamma intensity data by comparison of the intensity of the 58-kev gamma with the sum of the intensities of the 145- and 360-kev transitions, by one of which it is always preceded. By this approach, $(1+\alpha)_{58} \approx (15\times 1.025 + 0.8\times 1.4)/5.6 \simeq 2.95$. The fraction F of the Te^{127m} decaying by way of beta transitions to the 58-kev level was then obtained from the following expression:

$$F=\left\{\frac{1}{\left(\dfrac{N_{418\gamma}}{N_\beta}\right)_0 (1+\alpha)_{58}\left[\left(\dfrac{N_{58\gamma}}{N_{418\gamma}}\right)_m-\left(\dfrac{N_{58\gamma}}{N_{418\gamma}}\right)_0\right]}+1\right\}^{-1},$$

where the subscripts 0 and m refer to Te^{127} and $Te^{127m}-Te^{127}$, respectively; substitution of the appropriate data gave

$$F\approx\left\{\frac{1}{0.008\times 2.95[0.72-0.06]}+1\right\}^{-1}\simeq 0.015.$$

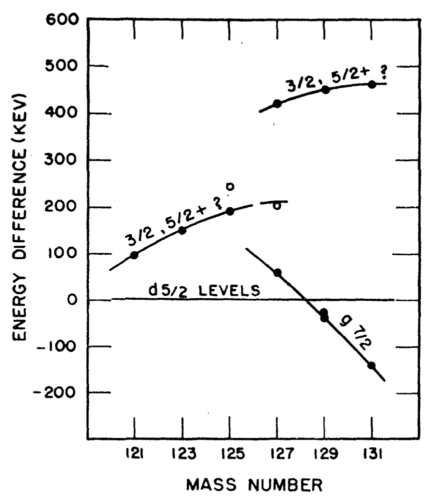

FIG. 3. Level spacings of iodine isotopes as a function of mass number.

The corresponding $\log f_0 t$ value was 9.7, which suggests a $\Delta j = 2$ (yes) transition. Calculation of the comparative half-life in terms of the function given by Davidson[15] for first-forbidden unique transitions, *viz.*, $f_1 t$, where $f_1/f_0 = a(Z)(W_0^2-1)+b(Z)(W_0-1)$, gave a $\log f_1 t = 9.0$, in good agreement with the corresponding values of 8.60, 8.96, and 8.85 for the odd-A beta emitters Sn^{123m}, Sn^{125m}, and Cs^{137}, respectively.

Similar calculations were made for the Te^{127m} beta branch presumed to precede the 665-kev gamma ray. The fraction of Te^{127m} decays which lead to production of this gamma ray is 1.3×10^{-4}. With the assumption that the 665-kev gamma represents a transition to the ground state, $\log f_0 t$ and $\log f_1 t$ were 11.2 and 9.4, respectively; for the assumption that the gamma transition terminates at the 58-kev level, the corresponding numbers were 10.3 and 8.2, respectively.

The calculated beta branching ratios from the foregoing discussion are summarized in Table II.

Level Assignments

Of the three lowest excited states of I^{127} shown to be produced in the decay of Te^{127m} and Te^{127}, only the first, at 58.5 kev, can be characterized as to spin and parity with any degree of certainty. Its direct production by beta decay of Te^{127m} with $\log f_1 t = 9.0$ leads to an assignment of $7/2^+$ (with the configuration of Te^{127m} taken as $h_{11/2}$); from the crossover of ground states from $d_{5/2}$ in I^{125} and I^{127} to $g_{7/2}$ in I^{129} and I^{131}, it may be concluded that the state is $g_{7/2}$. The $d_{5/2}-g_{7/2}$ level spacing as a function of iodine mass number, for the cases where the levels can be assigned with reasonable confidence, is shown in Fig. 3.

TABLE II. Beta transitions of Te^{127} and Te^{127m}.

Beta energy (kev)	Percent branch	$\log f_0 t$	Spin and parity change
Te^{127}:			
695±10	99%	5.45	$\Delta j=1$, no
492	<0.12%	>7.8	
325	<0.05%	>7.5	
277	~1.0%	6.1	($\Delta j=1$, no)
Te^{127m}:			
726	1.5%	9.7	$\Delta j=2$, yes
119	0.013%	11.2	($\Delta j=2$, yes)?

The $\log f_0 t = 6.1$ for the Te^{127} beta branch to the 418-kev state of I^{127} is somewhat large for an allowed transition but is probably too small for a first-forbidden transition. If it is considered to be of the allowed type, the spin and parity possibilities for the 418-kev level are $5/2^+$, $3/2^+$, and $1/2^+$. The occurrence of gamma transitions from this level to the 58-kev level eliminates the likelihood of $1/2^+$, leaving $5/2^+$ and $3/2^+$ as the best possibilities.

The 203-kev level may be characterized as probably

[15] J. P. Davidson, Jr., Phys. Rev. **82**, 48 (1951).

$3/2^+$ or $5/2^+$ by the following argument: the gamma ray intensity data of Mathur[9] and the conversion electron intensity data of Bergström[8] indicate than an appreciable fraction of the Xe^{127} electron capture decay goes directly to this level, limiting it to $5/2^+$, $3/2^+$, or $1/2^+$. Direct gamma transitions from this level to the 58-kev level eliminate the choice of $1/2^+$. Either of the remaining choices is consistent with the gamma intensity data from Te^{127}, but both create problems in the interpretation of the beta decay in that the $\log f_0t > 7.8$ deduced for possible direct beta decay from the Te^{127} ground state to the 203-kev level of I^{127} is apparently too high for the allowed transition expected. The source of this anomaly may lie in the influence of the nuclear core, as discussed by de-Shalit and Goldhaber.[16] Their explanation of the core effect may be applied by postulating that the apparent forbiddenness of the beta transition is due to a difference in population of the $h_{11/2}$ neutron orbitals in the initial and final states involved. First of all, the ground-state neutron configurations of Te^{127}, I^{127}, and Xe^{127} may plausibly be assigned as $h_{11/2}{}^{10}\,d_{3/2}{}^1$, $h_{11/2}{}^{10}\,d_{3/2}{}^0$, and $h_{11/2}{}^8\,d_{3/2}{}^1$, respectively. The proton states are presumed to be made up of configurations involving $g_{7/2}$ and $d_{5/2}$ orbitals and need not be specified in detail for purposes of the argument. If now the 203-kev state of I^{127} has a neutron configuration $h_{11/2}{}^8\,d_{3/2}{}^2$, electron capture decay of Xe^{127} could proceed normally to this state whereas beta decay from Te^{127} should be impeded by the necessity for transferring two neutrons from h orbitals to d orbitals. A further result, for which the experimental evidence is lacking, is that the decay of Xe^{127} to the ground state of I^{127} should be suppressed.

In the same way, characterization of the neutron configurations of the 370-kev and 418-kev states of

[16] A. de-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).

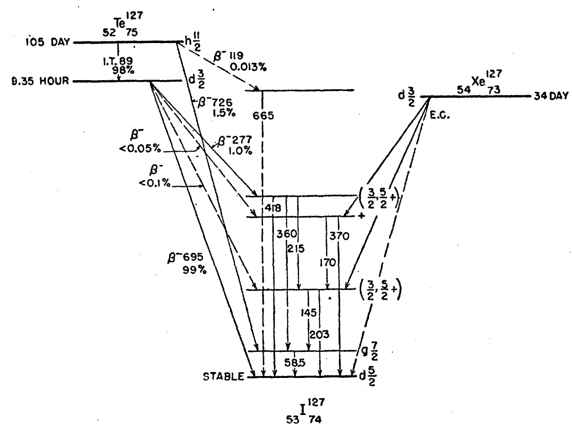

FIG. 4. Energy levels of I^{127} from decay of $Te^{127m}-Te^{127}$ and Xe^{127}.

I^{127} as $h_{11/2}{}^8\,d_{3/2}{}^2$ and $h_{11/2}{}^{10}\,d_{3/2}{}^0$, respectively, could account for apparent forbiddenness of Te^{127} beta decay to the former and of Xe^{127} electron-capture decay to the latter.

It is of interest to compare the spacings of the proposed levels of I^{127} with those of the probably analogous levels of some of the other odd-A iodine isotopes, as deduced from published material on the gamma spectra of the corresponding radioactive tellurium or xenon isotopes. The energy differences, plotted with reference to the $d_{5/2}$ level, are shown in Fig. 3. Although insufficient information is available to characterize the excited states, it is noteworthy that the energy spacings deduced for "comparable" levels appear to be a smooth function of iodine mass number.

A decay scheme which is consistent with the present work and with the published information on Xe^{127} decay is outlined in Fig. 4.