Neutron-Deficient Isotopes of Thallium*

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The activities of the K-capturing isotopes of $Tl^{198-202}$ have been investigated. Using 180° beta-ray spectrographs, more than 150 conversion lines have been observed. A new isomer of 1.9-hr half-life has been found and assigned to mass number 198. There are three gamma rays of 282.4, 260.7 (isomeric), and 48.7 kev associated with this activity. No thallium isomers, other than Tl^{198m}, or mercury isomers, other than the already known Hg^{199m}, were found. The first excited states in Hg^{200} and Hg^{202} were found to be 2+ states. The level schemes of Hg^{198} and Hg^{200} are complex.

INTRODUCTION

THE present work is concerned mainly with an investigation of thallium activities in an attempt to understand why isomers which might be expected to exist in thallium and mercury have not been observed. (Thallium has 81 protons and for this reason isomerism might be expected, as in gold where isomers exist in all odd-A isotopes. For the odd-odd isotopes, the odd neutron is also close to the magic number 126. Thus for these isotopes there exist several possibilities of coupling between the odd neutron and the odd proton which could give rise to high spins and which could therefore result in isomerism.)

Thus far thallium activities have been investigated mainly by two groups of workers. The Berkeley[1] group has produced a number of thallium activities by bombarding gold with alpha particles, and has identified three activities of 1.8-hr, 7-hr, and 27-hr half-lives which they attribute to Tl^{198}, Tl^{199}, and Tl^{200}, respectively. The Indiana group[2,3] has been concerned mainly with spectrometer investigations of the complex spectra of Tl^{199} and Tl^{200}. Other workers[4] from different laboratories have investigated the 3-day activity of Tl^{201} and the 12-day activity of Tl^{202}, but beta-ray spectrometer data are lacking. Very recently Sugarman[4] has produced all the thallium activities mentioned above by bombarding mercury with negative pions.

We have used 11.5-Mev deuterons to produce the neutron-deficient isotopes of thallium. As a result of either or both (d,n) and $(d,2n)$ reactions from Hg^{198} (10 percent), Hg^{200} (23 percent), Hg^{201} (13 percent), and Hg^{202} (30 percent) present in ordinary mercury, we obtained good yields of all thallium activities from $A=198$ to $A=202$. The mercury was usually in the form of powdered $HgCl_2$, and the active thallium was separated using ether extractions of $TlBr_3$. The thallium activities were analyzed using 180° beta-ray spectrographs of approximately 0.2 percent resolution and with an energy range up to energies of about 850 kev.

THALLIUM 198. ISOMERIC STATE

K, L, M, and N conversion lines corresponding to gamma-ray energies of 282.4 and 260.7 kev, and decaying with a half-life of about 1.9 hr, were found. The exceptionally low value of 0.61 for the K/L ratio of the 260.7-kev transition indicates that it is associated with an isomeric transition. Another gamma ray with an energy of 48.7 kev, decaying with a half-life of approximately 2 hr, was also found. Since no other short-lived activities appear to be present, we believe that all three gamma rays belong to the same activity.

Careful energy measurements of the conversion lines of the 282- and 261-kev gamma rays showed that they were definitely converted in thallium.

Orth *et al.*[1] also observed a 1.8-hr activity when gold was bombarded with alpha particles. Their excitation curves showed that the 1.8-hr activity should be attributed to mass number 198. In order to assign this activity to a definite mass number, we have also made activation experiments as a function of the incident deuteron energy. To summarize these experiments briefly, we found that the ratio of the intensity of the 1.8-hr lines to the 6.5-hr lines of Tl^{199} changes from a value of 1.0 (arbitrary units) at 11.5 Mev to 0.76 at 10.0 Mev. The falling off in intensity of the 1.8-hr lines is attributed to a more rapid falling off of the $(d,2n)$ cross section with decreasing deuteron energy than that of the (d,n) cross section. Since Tl^{198} is the only activity produced by a $(d,2n)$ reaction alone, this would mean that the 1.8-hr activity belongs to mass number 198 in agreement with the Berkeley experiments.[1] This conclusion is also supported by the fact that Wilkinson[3] did not observe the 1.8-hr activity when gold was bombarded with 20-Mev alpha particles. Since the threshold for the $(\alpha,3n)$ reaction is higher than 20 Mev, one would not expect Tl^{198} to be produced in those experiments from Au^{197}.

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† On leave of absence from the Nobel Institute of Physics, Stockholm, Sweden. Assistance in part from Svenska Atomkommittén is gratefully acknowledged.
[1] Orth, Marquez, Heiman, and Templeton, Phys. Rev. **75**, 1100 (1949); H. M. Neuman and I. Perlman, Phys. Rev. **78**, 191 (1950).
[2] H. I. Israel and R. G. Wilkinson, Phys. Rev. **83**, 1051 (1951).
[3] R. G. Wilkinson (private communication, 1953).
[4] R. S. Krishnan and E. A. Nahum, Proc. Cambridge Phil. Soc. **36**, 490 (1940); K. Fajans and A. F. Voigt, Phys. Rev. **58**, 177 (1940); **60**, 619 (1941); W. Maurer and W. Ramm, Z. Physik **119**, 602 (1942); H. C. Martin and B. C. Diven, Phys. Rev. **86**, 565 (1952); N. Sugarman and A. Haber, Phys. Rev. **92**, 730 (1953).

It is difficult on the basis of the experimental evidence to make a definite statement regarding the multipole nature of the isomeric transition. Some tentative suggestions can be made by comparing theoretical and experimental values of the mean-life, K/L and L_I/L_{III} ratios shown in Table I.

On the basis of K/L and L_I/L_{III} ratios alone, there seems little doubt that the isomeric transition is largely either $M3$ or $M4$. Unfortunately there is considerable uncertainty in the theoretical values of these ratios for the higher electric multipoles.

On the basis of lifetimes alone, the transition is in accord with purely $M4$ radiation. However, since the isomeric transition occurs in an odd-odd nucleus there is some basis for believing that the theoretical $M4$ lifetime may be even longer than is given in Table I. There is also a considerable spread in the theoretical lifetimes of the electric multipole radiations.

Assuming that the 261- and 282-kev gamma rays are in cascade, and provided that the multipolarity of two gamma rays are known, it is possible to calculate the intensity ratio of the corresponding K-conversion lines. The predicted cascade intensities are in this case most sensitive to a change in the multipolarity of the 282-kev gamma ray. As can be seen from Table II it is to be concluded that the 282-kev transition is unlikely to be either a pure $E2$, $E1$, or $M1$ transition, but is more probably a mixture of $M1$ and $E2$ multipole transitions.

TABLE I. Data pertinent to the assignment of multipolarity of the isomeric transition of 260.7 kev in Tl^{198m}.

Multipole	K/L	L_I/L_{III}	T_γ theory[a] (sec)	T_γ exptl. (sec)
	0.6 (obs)	1.33 (obs)		1×10^4 (obs)
$M3$	3.1[b]	1.25[c]	7×10^{-1}	1.6×10^5
$M4$	1.2[d]	0.7[c]	9×10^5 [b]	5.0×10^5
$M5$	0.6[b]	0.4[c]	1×10^{12}	1.4×10^6
$E3$	0.8[b]	0.1?	4×10^{-3}	1.7×10^4
$E4$	0.2[b]	?	5×10^3	3.2×10^4
$E5$	0.1?	?	6×10^9	6.2×10^4

[a] V. F. Weisskopf, Phys. Rev. 83, 1073 (1951).
[b] M. Goldhaber and A. W. Sunyar, Phys. Rev. 83, 90 (1951).
[c] N. Tralli and I. S. Lowen, Phys. Rev. 76, 1541 (1949).
[d] W. L. Bendel, thesis, University of Illinois, 1953 (unpublished); I. Bergström *et al.*, Arkiv. Fysik (to be published).

Tl^{198} consists of 81 protons and 117 neutrons. Thus both the odd proton and the odd neutron are close to filled shells. According to the shell model the odd proton would be expected to be either $s_{1/2}$, $d_{3/2}$, $(d_{5/2})$, or $h_{11/2}$. The corresponding possible assignments for the odd neutron are expected to be either $p_{1/2}$, $f_{5/2}$, or $i_{13/2}$. It is therefore evident that an isomer in Tl^{198} might be associated with quite an abnormally high spin state.

THALLIUM 198. GROUND STATE

There is a large number of gamma rays in the thallium activities with half-lives of about 5 or 6.5 hr. Only the strongest gamma rays could be definitely assigned to either one of these half-lives. Associated with the 5-hr half-life are gamma rays of the following energies: 195, 284, 402, 411.1, and 675 kev. The latter two gamma rays are almost certainly identical with those found in the decay of Au^{198}. The K/L and $(L_I+L_{II})/L_{III}$ ratios of the 411-kev gamma ray are in good agreement with those found for the 411-kev gamma ray in the beta decay of Au^{198}. We therefore assign the 5-hr activity to the ground state of Tl^{198}.

TABLE II. Expected ratios of the K-conversion lines of the 261- to 282-kev transitions of Tl^{198m} for different multipole assignments.

Multipolarity of 282-kev transition / Multipolarity of 261-kev transition	$E1$	$E2$	$M1$
$M3$	12.0	4.8	1.07
$M4$	12.4	4.9	1.10
$M5$	12.5	5.0	1.12
$E3$	5.5	2.2	0.49
$E4$	8.5	3.4	0.77
$E5$	10.8	4.3	0.97

(Experimental ratio $K_{261}/K_{282}=1.45$)

In the activation experiments mentioned previously, when the deuteron bombarding energy was decreased from 11.5 to 10.0 Mev, it was found that the intensity of the isomeric lines decreased relatively to those of the ground state activity. However, the intensity ratio of the 5-hr lines (Tl^{198} ground state) to the 6.5-hr lines (Tl^{199} ground state) remained approximately constant. This might be understood if, of the total reduced activations at the lower energy, the fraction reaching the isomeric state were to decrease in comparison with those reaching the ground state of Tl^{198}. This explanation might be possible in view of the fact that the isomeric state probably has a spin considerably higher than that of the ground state.

Because the spin of the Tl^{204} ground state is very probably $2-$,[5] and also because the K-capture decays of Tl^{202} and Tl^{200} are consistent with $2-$ assignments, it would seem plausible that the ground state of Tl^{198} would also be $2-$. Assuming shell structure and Nordheim's rule, such a state could arise consistently in several ways for Tl^{198}.

Since the 411- and 1086-kev levels of Hg^{198} are both known to be $2+$, a $2-$ assignment to the 5-hr Tl^{198} ground state would determine the K capture to the Hg^{198} levels as first forbidden. If we use the theoretical curves for $\log f_k$,[6] the maximum K-capture energy release would then be $\sim$2 Mev, and the branching to the 411- and 1086-kev levels would be approximately 1:0.8.

Experimentally it was found that the intensity ratio of the gamma rays from the 411- and 1086-kev levels was of the order 10:1. This might indicate that the

[5] Lidofsky, Macklin, and Wu, Phys. Rev. 87, 204, 391 (1952); E. der Mateosian and A. Smith, Phys. Rev. 88, 1186 (1952).
[6] King, Dismuke, and Way, Oak Ridge National Laboratory Report ORNL-1450 (unpublished).

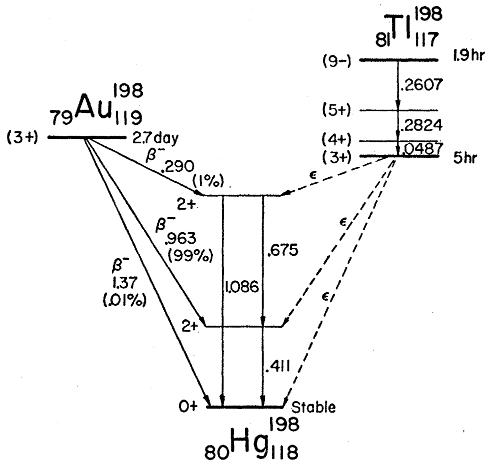

FIG. 1. Proposed decay scheme of Tl^{198} and Tl^{198m}.

411-kev level is fed from several other levels in addition to the 1086-kev level, and the presence of other observed gamma rays lends some support to this viewpoint. It seems more probable, however, that the K-capture transitions are not first forbidden and that the Tl^{198} ground state is not 2−.

It has recently been shown that the 2.7-day Au^{198} decays to the ground state of Hg^{198} with a beta ray of a high $\log(ft)$-value equal to 11.35.[7] A 3+ assignment for Au^{198} is therefore probable, and a similar assignment for the Tl^{198} ground state could arise from a coupling of an $h_{11/2}$ proton and an $f_{5/2}$ neutron. The 5-hr K-capture transitions would then be allowed, and for a $\log ft$-value of 5.5 the energy release to the 411-kev state would be approximately 900 kev. For an energy release of about 225 kev to the 1086-kev state, a similar $\log ft$-value would be associated with an approximately 10 percent branch. This is in excellent agreement with our experimental intensities of the 411- and 675-kev gamma rays.

A possible decay scheme of the isomeric and ground state of Tl^{198} activities is shown in Fig. 1. Very tentative level assignments are given.

THALLIUM 199. GROUND STATE

In the radioactive thallium there is a large number of conversion lines with a half-life of about 6.5 hr. The strongest lines correspond to gamma rays of 50.0, 158.4, 208.1, 247.2, 333.6, 454.6, and 491.3 kev. From the fact that the three lowest energy gamma rays are also found in the decay of Au^{199}, we conclude that the 6.5-hr activity belongs to mass number 199. These gamma-ray identifications are in excellent agreement with those of Wilkinson.[3]

The energy accuracy is estimated to be about 0.1 percent. Intercombinations of the gamma rays fit within this accuracy into the decay scheme presented in Fig. 2. This scheme is also consistent with that suggested by Wilkinson[3] and based on coincidence measurements. He showed that both the 247- and 334-kev gamma rays coincide with the 158-kev gamma ray.

From earlier work[8] on the beta decay of Au^{199} it has been suggested that the 158- and 208-kev levels are $f_{5/2}$ and $p_{3/2}$, respectively. Tentative assignments of the 455- and 491-kev levels can also be given, by considering the multipolarity of the gamma rays emitted.

No L_{III} conversion has been observed for the 247-, 455-, and 491-kev gamma rays. In all three gamma rays the L_I and L_{II} lines are observed and in the case of the 247-kev gamma ray, $L_I:L_{II}$ is about 10. This indicates that the 247-, 455-, and 491-kev gamma rays are due to magnetic dipole transitions. Unfortunately the L line of the 334-kev gamma rays was obscured by a 5-hr K line. Wilkinson,[3] however, did not have this disturbing activity in his experiments and his value of $K/L=1.8$ for the 334-kev transition indicates an $E2$ transition. It is therefore suggested that the 491-kev level is $\frac{1}{2}-$ and that the 455-kev level is a $\frac{1}{2}-$ or $\frac{3}{2}-$level.

It is interesting to speculate on the possibility that the 455- and 491-kev levels arise from a coupling of the 158- and 208-kev one-particle levels with the 411-kev 2+ excitation of the even-even core of Hg^{198}. The separation of the 455- and 491-kev levels is much the same as that of the 158- and 208-kev levels and the proposed spins of the 455- and 491-kev levels could arise from combinations of the 2+ and $p_{3/2}$ levels and of the 2+ and $f_{5/2}$ levels, respectively.

The most probable shell structure assignment for the ground state of Tl^{199} is $s_{1/2}$. As in the case of the ground state of Tl^{198}, K capture could then take place to a number of Hg^{199} levels with comparable intensity. For a maximum energy release to the Hg^{199} ground state of about 1 Mev, the $\log ft$-values of the four partial K-capture transitions of Fig. 2 would be of the order of 6.2, consistent with the first forbidden transition required by the decay scheme.

The suggested decay scheme also agrees with other experimental data. It is consistent, for example in our experiments, with the nonappearance of the isomeric transition in Hg^{199}. A K-capture transition from the

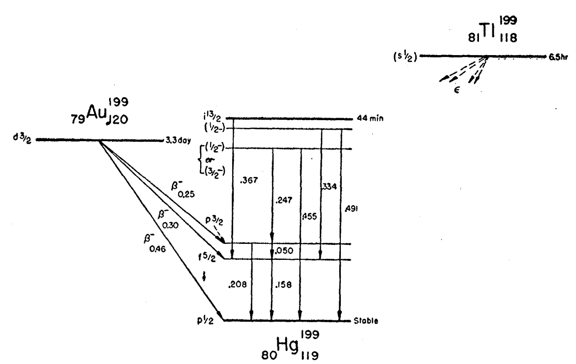

FIG. 2. Proposed decay scheme of Tl^{199}.

[7] L. G. Elliott and J. L. Wolfson, Phys. Rev. 82, 333 (1951).

[8] P. M. Sherk and R. D. Hill, Phys. Rev. 83, 1097 (1951).

ground state of Tl^{199} to the isomeric state of Hg^{199} is energetically possible but is strongly forbidden by the large spin change to the $i_{13/2}$ level. For the same reason it is evident that the most probable transition from the isomeric state is that to the $f_{5/2}$ level, the other transitions being more forbidden. Hole[9] also observed only the 158-kev gamma ray in addition to the isomeric gamma ray. If the 455- and 247-kev gamma rays are both emitted from the same level and are both $M1$ transitions their intensity ratio should be $(455/247)^2 = 6.2$. This should be compared with the experimental value 3.4. (This value has been obtained by using the experimental ratio of the K-conversion lines and the theoretical K-conversion coefficients of Rose *et al.*) In the same way the $M1$ transition from the 491-kev level to the ground state would be about 250 times stronger than an $M1$ transition to the 455-kev level. Undoubtedly for this reason, the corresponding 36-kev gamma ray between these levels has not been observed.

THALLIUM 200. GROUND STATE

The conversion spectrum decaying with 27-hr half-life is very complex. This activity has been assigned to mass number 200.[1] We have found conversion lines corresponding to gamma rays of 252, 289, 367.8, 579, 629, and 829 kev. Gamma rays of energies 116, 660, and 786 kev probably also belong to this activity. There are certainly still weaker gamma rays associated with the 27-hr activity. Many of these gamma rays have been observed by Wilkinson[2,3] who further lists gamma rays of 1210 kev, 1360 kev, and probably also 1520 kev. Butement and Shillito[10] using a scintillation spectrometer have reported gamma rays of energies 390 and 1130 kev in the beta decay of Au^{200}.

The energy of the most intense 367.8-kev gamma ray is considered to be absolutely known with an accuracy of better than 1:1000 since its L_{I} line was measured as

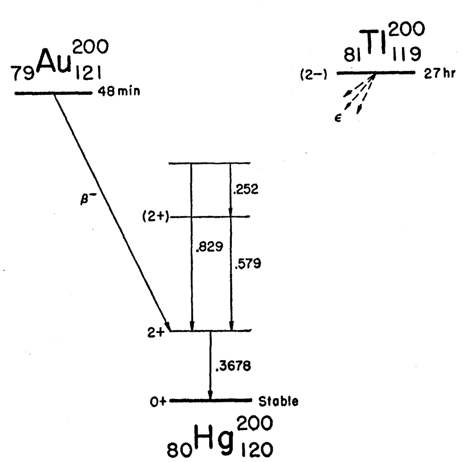

FIG. 3. Proposed decay scheme of Tl^{200}.

[9] N. Hole, Arkiv Mat. Astron. Fysik **36**, (No. 2) (1948).

[10] F. D. S. Butement and R. Shillito, Proc. Phys. Soc. (London) **A65**, 945 (1952).

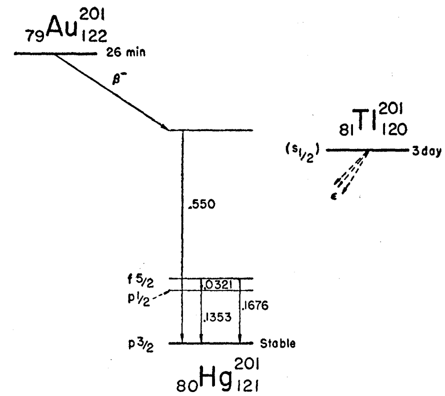

FIG. 4. Proposed decay scheme of Tl^{201}.

a close doublet with the L_{I} line of the 364.18-kev gamma ray of I^{131}. Active iodine was added to the thallium source so that both L_{I} lines appeared on the same film.

Wilkinson[3] showed that all the strong gamma rays are in coincidence with the 368-kev gamma ray. Thus the 368-kev excited state is very probably the first excited state. Our values of $K/L=2.0$ and $(L_{\text{I}}+L_{\text{II}})/L_{\text{III}}=3.0$ indicate that the 368-kev gamma ray corresponds to an $E2$ transition. Thus, in agreement with the extensive investigations of even-even nuclei,[11] the first excited state in the even-even nucleus Hg^{200} is a 2+ state. The decay scheme in Fig. 3 is very incomplete and indicates only some of the more obvious features. For example, the energy sum of the 252- and 579-kev transitions agrees within our experimental error with the 829-kev transition, and the 579-kev transition from K/L ratio and L_{I} intensity is predominantly an $M1$ radiation.

THALLIUM 201. GROUND STATE

Neuman and Perlman[1] have reported a gamma ray of 210 kev associated with the decay of the 3-day activity of Tl^{201}. We were not able to observe this gamma ray but found conversion lines corresponding to gamma rays of 30.5, 32.1, 135.3, and 167.6 kev which decayed with a half-life of approximately 3 days.

For the two low-energy gamma rays we observed only L_{I} component lines. This indicates that these two transitions probably are of the $M1$ type. In the case of the 135- and 168-kev gamma rays the L_{I} and L_{II} lines could be well resolved and in both cases their $L_{\text{I}}:L_{\text{II}}$ intensity ratios were about 10. For $M1$ transitions of these energies Gellman *et al.*[12] give a theoretical $L_{\text{I}}:L_{\text{II}}$ value of about 11.

Since the 32.1-kev transition is probably a link between the 135.3 and 167.6-kev transitions, a possible decay scheme is as shown in Fig. 4. The level from which the 30.5-kev gamma ray is emitted is uncertain,

[11] G. Scharff-Goldhaber, Phys. Rev. **90**, 487 (1953); P. Preiswerk and P. Stahelin, Helv. Phys. Acta **24**, 623 (1952); A. H. Wapstra, Physica **18**, 799 (1952); F. Asaro and I. Perlman, Phys. Rev. **87**, 799 (1952).

[12] Gellman, Griffith, and Stanley, Phys. Rev. **85**, 944 (1952).

TABLE III. Energies (in kev) and spin assignments of the first excited states in even-Hg isotopes.

	Hg^{196}	Hg^{198}	Hg^{200}	Hg^{202}
1st excited level	426(2+)	411(2+)	368(2+)	439(2+)
2nd excited level		1086(2+)	947(2+)	

and there is no *a priori* reason that the order of the 32.1- and 135.3-kev γ rays should not be reversed. The decay of the 26-min Au^{201} measured by Butement and Shillito[10] is also included in the figure. Since we did not observe the 550-kev gamma ray, it is possible that the ground state of Tl^{201} lies below the 550-kev excited level in Hg^{201}.

We have also looked for an $i_{13/2}$ isomeric state in Hg^{201} (and Hg^{203}). The energy separations of the $f_{5/2}$ and $p_{1/2}$ levels from the $i_{13/2}$ levels in the odd-A isomers of Hg are smooth curves when plotted as a function of the odd neutron number.[13] Extrapolating these curves to higher neutron numbers, one might expect to find $M4$ isomers in Hg^{201} and Hg^{203} associated with the half-lives of approximately 10 and 1 min arising from transitions of energies of approximately 600 and 850 kev, respectively. In order to check this, enriched isotope samples of Hg^{200}, Hg^{202}, and Hg^{204} were irradiated with gamma rays from the 20-Mev betatron. By measuring the activity of Hg^{199m} produced in a (γ,n) reaction, we were able to calculate the activities of the expected $M4$ transitions in Hg^{201} and Hg^{203}. No such activity, even 100–1000 times weaker than the expected, was observed. One possible explanation of the absence of isomerism of the expected type is that the $i_{13/2}$ level has moved energetically so high that another underlying level of intermediate spin has destroyed the metastability of the $i_{13/2}$ level. It would, however, still seem worthwhile searching for shorter-lived isomers in Hg^{201}, Hg^{203}, and Hg^{205}.

THALLIUM 202. GROUND STATE

In agreement with earlier observations,[4] only one gamma ray has been observed in the decay of the 12-day Tl^{202}. Since the K line was measured as a close doublet with the L_I line of the 364.18-kev gamma ray in I^{131}, the energy of 439.1 kev for this gamma ray should be absolutely known with an accuracy of better than 1:1000. The K/L ratio$=2.6$ and the $(L_I+L_{II})/L_{III}$ ratio$=3.5$, strongly suggesting an $E2$ transition. Since no other gamma ray was observed, we believe that the 439-kev gamma ray is emitted from the lowest level in Hg^{202}. That this level should be a 2+ level is in agreement with the systematics of even-even nuclei.[11] The proposed decay scheme is shown in Fig. 5.

TABLE IV. Energies (in kev) and level assignments of low-lying states in the odd-A Hg isotopes. (g.s.$=$ground state.)

Nucleus Level	$Hg^{193\,a}$	$Hg^{195\,b,c}$	Hg^{197}	Hg^{199}	Hg^{201}
$p_{1/2}$			g.s.	g.s.	135
$p_{3/2}$	g.s.	g.s.		208	g.s.
$f_{5/2}$	37	36	134	158	168
$i_{13/2}$	138	158	299	525	very high

[a] J. W. Mihelich *et al.*, Phys. Rev. **91**, 498 (1953).
[b] Gopalakrishnan, de Shalit, and Mihelich, Phys. Rev. **89**, 908 (1953).
[c] Huber, Joly, Scherrer, and Verster, Helv. Phys. Acta **25**, 621 (1952).

SYSTEMATICS OF NUCLEAR LEVELS IN MERCURY

Even A

As pointed out by Goldhaber and Sunyar (reference b, Table I), G. Scharff-Goldhaber,[11] and others,[11] the first excited states in even-even nuclei are predominantly 2+ levels. The energies of these levels also show a regular energy dependence with A.[11] A summary of data pertaining to mercury is shown in Table III. The energies are given in kev and are followed by the spin assignments in parentheses.

ODD A

Energy level trends in odd-A nuclei have been pointed out in connection with the study of isomers.[13] The energy levels, assignments and separations of the odd-A isotopes, many of them tentative, are collected in Table IV.

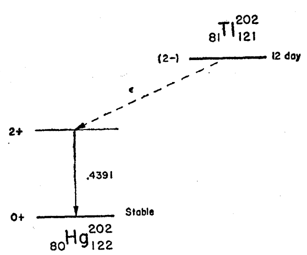

FIG. 5. Proposed decay scheme of Tl^{202}.

It is apparent from Table IV that the $i_{13/2}$ and $f_{5/2}$ levels vary energetically in a systematic manner. However, the behavior of the $p_{1/2}$ and $p_{3/2}$ levels is rather capricious. It would seem somewhat anomalous that the $\frac{3}{2}$ state at one stage ($A=193$, 195) should be lowest, should later ($A=197$, 199) concede to the $\frac{1}{2}$ state as lowest state, and then return again to be the ground state at $A=201$. It is possible also that the unexpected interchange of the $p_{3/2}-p_{1/2}$ spin-orbit doublet for $A=199$ is associated with this irregular behavior of the spin-$\frac{3}{2}$ ground state.

The present work on the thallium activities remains somewhat incomplete. There are for example many weak conversion lines which we have been unable to classify. These lines are listed below, arranged in order of increasing energy (in kev): (No Auger lines are listed. Abbreviations: ew$=$extremely weak, vw$=$very weak, w$=$weak.) 36.9, 37.6 ew 5–27 hr; 81.4, 82.9, 83.8, 99.7 w 27 hr?; 132.6 ew <27 hr, 137.1 vw 27 hr?; 165.1, 188.7 ew ?; 195.9 w ?; 201.5 ew ?; 226.0 w 27 hr?,

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

271.7 ew 27 hr; 293.5, 299.6, 303.8 w 27 hr?; 332.6, 333.6 ew ?; 392.4 w ?; 414 ew ?; 458 vw 6 hr; 465, 473, 480 ew 6 hr?; 503, 508, 513 w 6 hr?; 582, 604, 618, 640 ew ?; 667, 687 w ?.

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Note added in proof:—M. C. Michel (thesis, University of California, 1953) has recently made a time-of-flight analysis of the thallium isotopes. Independently he assigns the 1.8-hr activity to $A=198$ and also observes the 5.3-hr activity of Tl^{198} which is reported in our work.

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Large-Angle Scattering of Co^{60} Gamma Rays*†

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Measurements of the scattering of Co^{60} gamma rays from lead, tin, copper, and aluminum have been made at a mean angle of 135°. In addition to Compton scattering and annihilation radiation, some higher energy components are present. Elastic scattering was observed in each of these scatterers and the cross section for this process has been measured. Results are shown to be consistant with recent theoretical calculations on Rayleigh and Thomson scattering.

INTRODUCTION

INVESTIGATION of the large-angle scattering of gamma rays permits the measurement of scattering events other than Compton scattering. This is of low energy and can be discriminated against. Investigations of this type were made by Chao[1] and Gray and Tarrant[2] in a study of the scattering of ThC″ gamma-rays from lead and other scatterers, and first showed the presence of annihilation radiation from positrons produced in the scatterer.

Pollard and Alburger[3] employed this method in 1948 in an attempt to measure nuclear resonance scattering of Na^{24} gamma rays in magnesium. Their results showed no marked excess in intensity of gamma rays scattered from magnesium over those scattered from aluminum. However, measurements on scattering from magnesium, aluminum, lead, and mercury showed, in each case, an unidentified component of hard radiation having an absorption coefficient characteristic of the unmodified incident beam.

Moon[4] and Storruste[5] have made similar measurements on scattering from lead, copper, and aluminum. Moon has attempted to explain the results of Pollard and Alburger on the basis of interference between coherent scattering by bound electrons (Rayleigh scattering) and Thomson scattering from the nucleus. In addition, he has confirmed the calculations of Franz[6] on Rayleigh scattering at a mean angle of 115° and at an energy of 0.41 Mev, and Storruste has extended his measurements to other angles in the region from 60° to 150°.

More recently, Wilson[7] has measured this elastic scattering from lead at various angles in the energy regions near 1.3 Mev and 2.6 Mev in an attempt to find evidence of Delbrück scattering (potential scattering by virtual pair formation in the field of the nucleus).

With this background in mind, an investigation was undertaken of large-angle scattering of Co^{60} gamma rays, with particular attention paid to the elastic scattering. Knowledge of the cross sections for this process, and their dependence on the atomic number of the scatterer, would be useful in the interpretation of existing calculations on Rayleigh scattering and might provide additional evidence for the existence of Delbrück scattering or resonance scattering.

THEORY

In addition to Compton scattering and annihilation radiation, other scattering events are possible in the energy region of 1.3 Mev by the processes of bremsstrahlung, Thomson scattering, Rayleigh scattering,

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[1] C. Y. Chao, Phys. Rev. **36**, 1519 (1930).
[2] L. H. Gray and G. T. P. Tarrant, Proc. Roy. Soc. (London) **136**, 662 (1932).
[3] E. C. Pollard and D. E. Alburger, Phys. Rev. **74**, 926 (1948).
[4] P. B. Moon, Proc. Phys. Soc. (London) **A63**, 1189 (1950).
[5] A. Storruste, Proc. Phys. Soc. (London) **A63**, 1197 (1950).
[6] W. Franz, Z. Physik **98**, 314 (1935).
[7] R. R. Wilson, Phys. Rev. **90**, 720 (1953).