Gamma-Ray Intensities in the Thorium Active Deposit*

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The relative intensities of the gamma rays of the descendants of radiothorium have been studied by measuring the photoelectron spectra from thorium and platinum foils. The relative sensitivity of the arrangement at different energies was found by using other sources having gamma rays of known relative intensity. Comparison of the measured gamma-ray intensities with the measurements by others of internal conversion intensities allows internal conversion coefficients to be computed and the multipolarities of several transitions to be determined. An electric monopole transition was found in Po^{212}. The gamma-ray intensities are used to find the intensities of beta-ray branches. Gamma-ray intensities are compared with the known intensities of long-range alpha particles from Po^{212} and transition probabilities are estimated for some electromagnetic transitions between states of that nucleus. The level schemes of Po^{212} and Pb^{208} are discussed in the light of the information found here and of other recent information.

INTRODUCTION

In the decay of the active deposit of thorium states are excited in Bi^{212}, Po^{212}, Tl^{208}, and Pb^{208}. A simplified decay scheme is shown in Fig. 1. These nuclei are in a region close to the closing of both neutron and proton shells where calculations based on the shell model have had some success.[1] The radiations from the deposit have been the subject of extensive study for a half century,[2] but knowledge of the level schemes of the nuclei involved is far from complete. One particular lack has been the absence of quantitative knowledge of the intensities of the gamma rays emitted. We have measured the relative intensities of the gamma rays by the method of photoelectric conversion, and by comparison with previously published data have deduced new information about the excited states involved.

EXPERIMENTAL ARRANGEMENTS

The double-focusing beta-ray spectrometer used in this work was designed and built by Bartlett and Bainbridge.[3] The central orbit is of 30-cm radius and the magnet return flux is on the outside. A Geiger-Müller counter served as detector. The magnet current was supplied by automobile batteries and was controlled by a 150-turn Kohlrausch slide wire. The magnetic field was measured with a Rawson-Lush rotating-coil device[4] driven by a stable-frequency supply.

Thorium converter foils 8.3 and 29 mg/cm² thick and 4.0 mm wide were used for the principal part of the work; a platinum foil 22 mg/cm² thick and 6.4 mm wide was also used. With the acceptance solid angle set at 0.8%, counter slits 3.2 mm apart, and 4.0-mm-wide foil, the instrumental line width at half maximum was about 0.8%.

The source used for the photoelectron measurements was about 12 mC of radiothorium with its descendants, which include the nuclei of the thorium active deposit. The active material of the radiothorium source and of

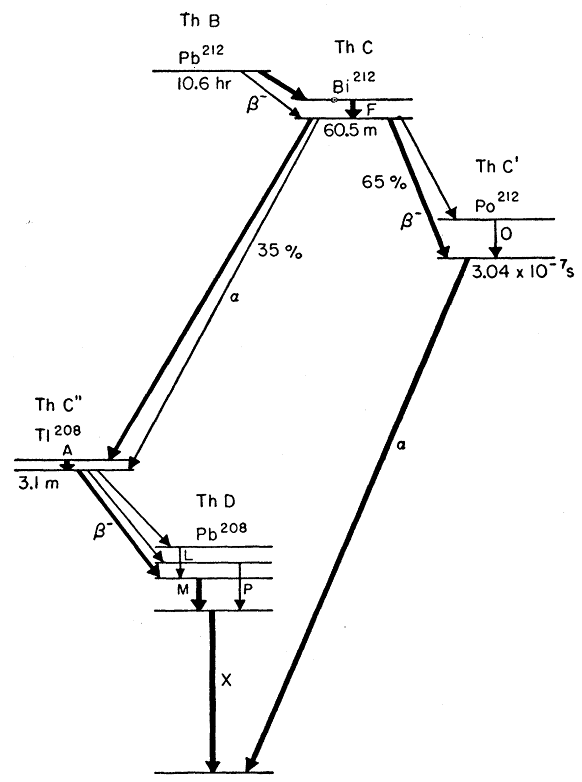

FIG. 1. A simplified decay scheme of the thorium active deposit. Only the most intense transitions are shown.

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[1] M. H. L. Pryce, Proc. Phys. Soc. (London) **A65**, 773, 962 (1952); I. Bergström and G. Andersson, Arkiv Fysik **12**, 415 (1957).
[2] An annotated bibliography is included in G. T. Emery, thesis, Harvard University, 1958 (unpublished).
[3] A. A. Bartlett and K. T. Bainbridge, Rev. Sci. Instr. **22**, 517 (1951).
[4] Manufactured by Rawson Electrical Instrument Company, Cambridge, Massachusetts.

the calibration sources was contained in cylinders of 0.080-inch inside diameter and 0.160-inch length. The outside diameter of the cylinders was 0.125 inch. They were held in an aluminum cup with 0.020-inch walls, which was in direct contact with the converter foil. The distance between the center of the source and the converter foil was then 0.083 inch.

GAMMA-RAY INTENSITIES

The calibration for efficiency of photoelectric conversion as a function of energy was made by using sources with gamma rays of different energy and known relative intensity. The sources selected were Na^{24} (1.368- and 2.754-Mev gamma rays), Na^{22} (annihilation radiation at 0.511 and a gamma ray at 1.277 Mev), and the 5.5-hour isomer of Hf^{180} (gamma rays at 216, 332, and 444 kev). The effects of the small alternative beta-decay branchings of Na^{24} and Na^{22} were considered. For Na^{24} the gamma rays have the same intensity within one-tenth percent. For Na^{22} small corrections were also included for annihilation in flight, three-quantum annihilation, and Doppler broadening of the annihilation line. The electron capture-to-positron ratio of Sherr and Miller[5] was used, since it has the smallest quoted error and a weighted mean of other values fell within that uncertainty. Our conclusion was that the annihilation radiation was (1.780 ± 0.012) times as intense as the 1.277-Mev gamma ray. The isomeric state in Hf^{180} has spin 9−,[6,7] and decays to the 8+ and 6+ levels of the ground-state rotational band, by 57- and 501-kev transitions, respectively. The 332- and 216-kev transitions are the 6+ to 4+ and 4+ to 2+ transitions, and thus occur once in each Hf^{180m} decay. The relative intensity of the 444-kev transition between the 8+ and 6+ levels depends on the branching from the isomeric state. The branching has been measured as 0.80 [6] and 0.85 [7]; we used the value 0.82 ± 0.05. Then corrections were made for the internal conversion of these low-energy transitions with the help of the tables of Sliv and Band[8] and of Rose[9]; the unscreened M-shell coefficients of Rose were multiplied by an empirical correction factor of 0.60 to account approximately for screening,[10] and conversion in further shells was assumed to be about $\frac{1}{4}$ that in the M shell. The final result for the relative intensities of the gamma rays at 216, 332, and 444 kev is 1.00, 1.15 ± 0.01, and 0.98 ± 0.05.

Since the same geometrical arrangement was used for the calibration runs as for the radiothorium, the complicated effects of the angular dependence of the photoelectric cross section and of electron scattering were automatically accounted for. Corrections were made for absorption in the cylinders containing the sources, and for absorption in the source materials. These corrections ranged from 2% to 28% for the calibration sources, which were in aluminum and copper cylinders, and from 6% to a factor of 2.47 for the radiothorium source, which was in an iridio-platinum cylinder. In making these corrections, account was taken of the different effective path length, due to the different angular distribution for photoelectron production and electron scattering, at different energies. A mean angle of traversal of the cylinder wall was estimated, and the effective path length was taken to be the wall thickness times the secant of that angle. The estimated secant was close to one at high energies and reached 1.26 at 216 kev.

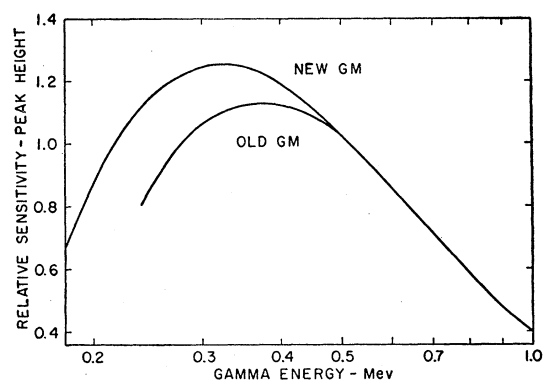

FIG. 2. Relative peak-height sensitivity for an 8.3 mg/cm² thorium converter as a function of energy. Curves for two different counter arrangements are shown.

The result of the calibration is a series of curves showing relative sensitivity as a function of energy for a particular converter foil and experimental arrangement. Two such curves, in which the line peak height is the measure of intensity, are shown in Fig. 2. The accuracy of the calibration is estimated to be about seven percent above 500 kev and about ten percent below 500 kev. This uncertainty includes that due to absorption in the calibration sources, but not that due to absorption in the radiothorium source. A more detailed account of the calibration procedure is given elsewhere.[11]

Two of the spectra taken are shown in Figs. 3 and 4. The results for relative gamma-ray intensities are given in Table I. A correction of $(1.8\pm0.5)\%$ has been subtracted from the measured intensity of the 511-kev

[5] R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954).

[6] G. Scharff-Goldhaber, M. McKeown, and J. W. Mihelich, Bull. Am. Phys. Soc. **1**, 206 (1956).

[7] V. S. Gvozdev, L. I. Rusinov, Yu. I. Filimonov, and Yu. L. Khazov, Nuclear Phys. **6**, 561 (1958).

[8] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICC K1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)], Part I; ibid, Report 58 ICC L1, Part II.

[9] M. E. Rose, *Internal Conversion Coefficients* (North Holland Publishing Company, Amsterdam, 1958). We wish to thank Dr. Rose for sending us some of his results before publication.

[10] P. J. Cressman and R. G. Wilkinson, Phys. Rev. **109**, 872 (1958); G. Backström, O. Bergman, and J. Burde, Nuclear Phys. **1**, 263 (1958); I. J. van Heerden, D. Reitman, and H. Schneider, Nuovo cimento **11**, 167 (1959).

[11] W. R. Kane, thesis, Harvard University, 1959 (unpublished); Technical Report No. 3–9 April, 1959 (unpublished).

gamma ray in Pb^{208} to remove the contribution of annihilation radiation. This radiation is due to the positrons produced in the walls of the source cylinder, mainly by the 2.615-Mev gamma ray in Pb^{208}.

INTERNAL CONVERSION DATA

Beginning in 1956 a comprehensive series of papers on the internal conversion spectrum of the thorium active deposit by a group in Leningrad including Krisyuk and Latyshev have appeared. The first papers were concerned with particular lines.[12,13] Work covering the whole spectrum appeared in three sections.[14,15] Discussions of individual level schemes followed.[16–19] The gamma-ray intensities found here may be combined with the internal conversion intensities of Krisyuk et al. to find conversion coefficients. Several internal conversion lines were compared experimentally to check the Leningrad results. The only discrepancy was in the intensity ratio of the A and A1 lines.[20] (The A line is due to $\dot{L}_I$ conversion of the 40-kev transition in Tl^{208} and the A1 line to K conversion of the 115-kev transition in Bi^{212}.) This had been reported as two-to-one[13] and, later, as eight-to-one.[15] We found the ratio to be five-to-one.[20a]

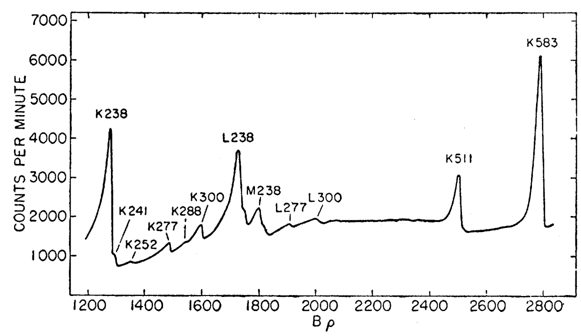

FIG. 3. Low-energy photoconversion spectrum of radiothorium source obtained with an 8.3-mg/cm² thorium converter. The magnetic rigidity ($B\rho$) is measured in gauss-cm.

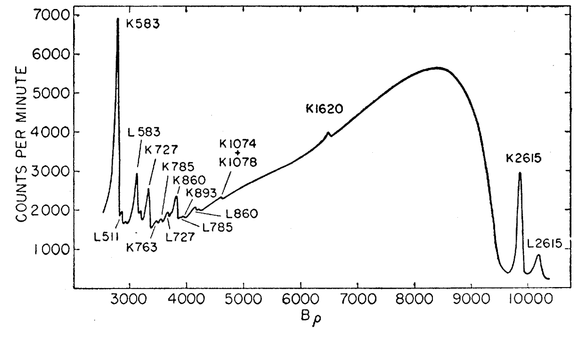

FIG. 4. High-energy photoconversion spectrum of radiothorium source obtained with a 29-mg/cm² thorium converter. The background reaching a peak near 8000 gauss-cm is due to Compton recoil electrons from the 2.615-Mev gamma ray of the Tl^{208} decay.

In computing the intensities in percent of decays for a particular nucleus, account must be taken of the branching ratio of Bi^{212}. We have used the value 0.354 for the ratio of alpha decays to total decays,[21] since the Leningrad group used that value (and also corrected

TABLE I. Relative intensity of gamma rays of the descendents of radiothorium.

Gamma name	Energy in kev	Nucleus	Intensity relative to gamma X
F	238	Bi^{212}	131 ±25
...	241	Em^{220}	14 ± 4
Fb	252	Pb^{208}	1.5± 0.7
G	277	Pb^{208}	6.9± 0.8
Ga	287	Tl^{208}	1.1± 0.4
H	300	Bi^{212}	10.0± 1.5
Ja2	328	Tl^{208}	0.5± 0.3
Jc5	452	Tl^{208}	0.4± 0.2
L	511	Pb^{208}	23.0± 2.0
M	583	Pb^{208}	86.4± 5.6
O	727	Po^{212}	18.5± 1.1
O2	763	Pb^{208}	1.9± 0.5
Oa	785	Po^{212}	2.7± 0.5
P	860	Pb^{208}	11.4± 1.2
Pa	893	Po^{212}	1.1± 0.6
Pa2a	953	Po^{212}	$\leqslant$1.3
R Ra	1074 1078	Po^{212}	1.8± 0.4
...	1350	Po^{212}	$\leqslant$0.6
S	1513	Po^{212}	$\leqslant$1.3
Sa	1620	Po^{212}	4.7± 0.6
...	1680	Po^{212}	$\leqslant$0.7
Sb	1800	Po^{212}	$\leqslant$0.7
...	2200	Po^{212}	$\leqslant$3.4
X	2614	Pb^{208}	100

[12] E. M. Krisyuk et al., Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **20**, 363 (1956) [translation: Bull. Acad. Sci. U.S.S.R. **20**, 322 (1956)]; E. M. Krisyuk et al., Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **20**, 883 (1956) [translation: Bull. Acad. Sci. U.S.S.R. **20**, 803 (1956)].

[13] E. M. Krisyuk, G. D. Latyshev, and A. G. Sergeev, Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **20**, 367 (1956) [translation: Bull. Acad. Sci. U.S.S.R. **20**, 335 (1956)].

[14] E. M. Krisyuk et al., Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **20**, 877 (1956) [translation: Bull. Acad. Sci. U.S.S.R. **20**, 797 (1956)]; V. D. Vorobev et al., Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **21**, 954 (1957) [translation: Bull. Acad. Sci. U.S.S.R. **21**, 956 (1957)].

[15] A. I. Zhernovoi et al., Zhur. Eksp. i Teoret. Fiz. **32**, 682 (1957) [translation: Soviet Phys.-JETP **5**, 563 (1958)].

[16] E. M. Krisyuk et al., Nuclear Phys. **4**, 579 (1957).

[17] E. M. Krisyuk et al., Zhur. Eksp. i Teoret. Fiz. **33**, 1144 (1957) [translation: Soviet Phys. JETP **6**(**33**)), 880 1958)].

[18] A. G. Sergeev et al., Zhur. Eksp. i Teoret. Fiz. **33**, 1140 (1957) [translation: Soviet Phys. JETP **6**(**33**), 878 (1958)].

[19] A. G. Sergeev et al., Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **22**, 785 (1958) [translation: Bull. Acad. Sci. U.S.S.R. **22**, 779 (1958)].

[20] The internal conversion lines have generally been referred to by the nomenclature introduced by C. D. Ellis, Nature **129**, 276 (1932); Proc. Roy. Soc. (London) **A138**, 318 (1932). Gamma rays are identified by the same letter, etc., as their most prominent internal conversion line.

[20a] *Note added in proof.*—The work of K. O. Nielsen, O. B. Nielsen, and M. A. Waggoner [Nuclear Phys. **2**, 476 (1956/57)] showed that, of the composite line due to L conversion of the 40-kev transition (lines A, Aa, and Ab) and K conversion of the 115-kev transition (line A1), (19±3) % of the total intensity was in coincidence with the 300-kev gamma ray in Bi^{212}, and thus was due to conversion of the 115-kev gamma ray. Their results imply a ratio of (3.8±0.7) for the intensities of the A and A1 lines.

[21] P. Marin, G. R. Bishop, and H. Halban, Proc. Phys. Soc. (London) **A66**, 608 (1953).

TABLE II. Comparison of the measured intensities of gamma rays in Po^{212} following the decay of Bi^{212} with earlier work. The intensities are given in percent of the decays of Bi^{212} to Po^{212}.

E_γ (Mev)	Itoh and Watase[a]	Curran et al.[a]	Latyshev[b]	Johansson[c]	Martin and Richardson[d]	Martin and Parry[e]	This work
0.727	8			18.5	5.7–8.3		10.1±0.6
0.785							1.5±0.3
0.83				16			⩽0.5
1.074 + 1.078				5.5		<2.2	1.0±0.2
1.34			2.0	4.5		<1.1	⩽0.3
1.513			2.0			<0.8	⩽0.7
1.620			5.5	7		1.9	2.6±0.4
1.680		8					⩽0.4
1.800	5.5		3.4	7		<0.55	⩽0.4
2.20			2.8			<0.27	⩽1.9

[a] See reference 25.
[b] See reference 26.
[c] See reference 27.
[d] See reference 24.
[e] See reference 31.

for the effect of the 60-minute half-life of Bi^{212}) in their series of papers on the individual nuclei.

POLONIUM-212

It has long been known that alpha particles (the "long range alphas") were emitted, in low intensity, from excited states at about 727, 1680, and 1800 kev in Po^{212}. The work of Lewis and Bowden[22] and that of Rytz[23] give the energies and intensities. Since the observed alpha transitions all lead to the 0+ ground state of Pb^{208}, these alpha-emitting levels must have either even spin and even parity or odd spin and odd parity. The strongest gamma ray in the beta decay of Bi^{212}, that of 727 kev, was shown by Martin and Richardson[24] to be of multipole order $E2$. The recent internal conversion measurements of Krisyuk and collaborators[18] imply states at 1513 and 1620 kev, as well as the alpha-emitting states.

There has been much confusion, however, about what gamma rays were emitted and in what intensity. A series of measurements on the Compton recoils produced by gamma rays of the thorium active deposit,[25–27] and on internal pair formation[28] implied several gamma rays in Po^{212} of energy greater than 727 kev and with intensity greater than or equal to two percent. A decomposition of the complex beta spectrum of Bi^{212} was attempted by Burde and Rozner[29]; their results also imply high-energy, high-intensity gamma rays. However, Fultz and Harding[30] found the average gamma-ray energy per decay to be 0.14±0.014 Mev, which is not consistent with high-energy, high-intensity gamma rays. And Martin and Parry,[31] in a more recent Compton recoil experiment, found only one high-energy gamma ray, at 1620 kev, and put low upper limits on the intensities of the others previously reported. Our results support and extend those of Martin and Parry, and give 0.155±0.024 for the average gamma energy per disintegration, in agreement with Fultz and Harding.

Table II compares our values for the intensity of Po^{212} gamma rays with earlier measurements. The line seen by Johansson at 0.83 Mev is probably the 0.860-Mev gamma in Pb^{208}. It may be worth noting that three of the gamma rays reported by earlier workers and not seen by Martin and Parry or by us, those of 1.34, 1.80, and 2.20 Mev, have energies similar to three of the strong gamma rays of the radium series, those of 1.38, 1.78, and 2.20 Mev, which occur in the decay of Bi^{214} to Po^{214}.

Our values for and limits on gamma-ray intensities may be compared with the internal conversion intensities of Krisyuk et al. to give conversion coefficients. The results are given in Table III, and the conversion coefficients are compared with the theoretical values of Sliv and Band in Fig. 5. The 727-kev transition is seen to be $E2$, in agreement with Martin and Richardson[24] and with the empirical rule that the first excited states of even-even nuclei are 2+.

The state at 1620 kev, from which come the 893- and 1620-kev transitions, must have spin 1+, since the 1620-kev transition is either $M1$ or $E3$, and the conversion coefficient of the 893-kev transition is consistent with $M1$ but not with $E1$. No alpha particles have been observed from this state. The state at 1513 kev, from which the 785- and 1513-kev transitions are supposed

[22] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. (London) **A145**, 235 (1934).
[23] A. Rytz, Compt. rend. Acad. Sci. U.R.S.S. **233**, 790 (1951).
[24] D. G. E. Martin and H. O. W. Richardson, Proc. Phys. Soc. (London) **A63**, 233 (1950).
[25] A. I. Alichanian and V. P. Dzelepov, Compt. rend. acad. sci. U.R.S.S. **20**, 115 (1938); S. C. Curran, P. I. Dee, and J. E. Strothers, Proc. Roy. Soc. (London) **A174**, 546 (1940); J. Itoh and Y. Watase, Proc. Phys.-Math. Soc. (Japan) **23**, 142 (1941).
[26] G. D. Latyshev and L. A. Kulchitsky, J. Phys. (U.S.S.R.) **4**, 515 (1941); G. D. Latyshev, Revs. Modern Phys. **19**, 132 (1947).
[27] A. Johansson, Arkiv Astron. mat. Fysik **34A**, No. 9 (1947).
[28] A. I. Alichanian and V. P. Dzelepov, Compt. rend. acad. sci. U.R.S.S. **20**, 113 (1938).
[29] J. Burde and B. Rozner, Phys. Rev. **107**, 532 (1957).
[30] S. C. Fultz and G. N. Harding, Can. J. Research **A26**, 313 (1948).
[31] D. G. E. Martin and G. Parry, Proc. Phys. Soc. (London) **A68**, 1177 (1955).

to come, offers some difficulties. The 785-kev transition is $M1$. The limit on the conversion coefficient of the 1513-kev transition indicates that it is $E4$, $E5$, $\cdots$, or $M2$, $M3$, $\cdots$. The unique spin implied by these considerations is 3+. It seems, however, unlikely that an $M3$ transition could compete with an $M1$ transition. If the 1513-kev transition had a single proton $M3$ transition probability, the 785-kev transition would be retarded by a factor of about 3×10^6 from the single proton $M1$ transition probability. A more likely prospect is that the spin of the 1513-kev state is 1+. Our limit on the conversion coefficient of the 1513-kev transition was found by taking the ratio of the internal conversion intensity of Krisyuk et al. less thirty percent, their estimated uncertainty, and our limit on the gamma-ray intensity. The resulting limit on the coefficient, 0.008, is not much above the theoretical $M1$ coefficient, 0.0062. We feel that our limit on the gamma intensity is sufficiently conservative. The true internal conversion intensity may lie somewhat outside the limits estimated by Krisyuk et al., or perhaps the transition shows an anomalous dipole conversion coefficient.

A level at 1680 kev is known from the long-range alphas. No gamma ray of this energy is seen, but a stopover transition of 953 kev goes to the first excited state. Our lower limit on the conversion coefficient rules out a pure $E1$ or $E2$ transition. Thus the state must either be 2+ or 5− or higher. Since excitation of high spin states by beta decay from the low spin (probably 1−) ground state of Bi^{212} is unlikely, the spin is almost certainly 2+. The limit on the conversion coefficient does not exclude an appreciable $E2$ component.

The case of the level at 1800 kev is especially interesting. K conversion electrons of an 1800-kev transition were seen by Krisyuk et al.,[14] and, earlier, by Ellis.[32] We found no gamma ray, however, and the conversion coefficient must be greater than 0.012. This eliminates

TABLE III. Electromagnetic transitions in Po^{212}. Intensities are given in percent of the decays of Bi^{212} to Po^{212}. ϵ_K is the K-conversion coefficient.

Gamma	E (kev)	$I_K(\%)^a$	$I_\gamma(\%)$	ϵ_K	Multipolarity
O	727	0.106	10.1±0.6	0.0105±0.0008	$E2$
Oa	785	0.051	1.5±0.3	0.034 ±0.008	$M1$
Pa	893	0.014	0.6±0.3	0.023 ±0.012	$M1$
Pa2a	953	0.010	⩽0.8	⩾0.009	$(M1+E2)$
R	1074	0.006}	1.0±0.2	⋯	$(E2)$
Ra	1078	0.014}		⋯	⋯
⋯	1350	⋯	⩽0.33	⋯	⋯
S	1513	0.008	⩽0.7	⩾0.008	?
Sa	1620	0.013	2.6±0.4	0.0050±0.0015	$M1$
⋯	1680	⋯	⩽0.4	⋯	⋯
Sb	1800	0.007	⩽0.4	⩾0.012	$E0$
⋯	2200	⋯	⩽0.27[b]	⋯	⋯

[a] See reference 18.
[b] See reference 31.

[32] C. D. Ellis, Proc. Roy. Soc. (London) **A143**, 350 (1934).

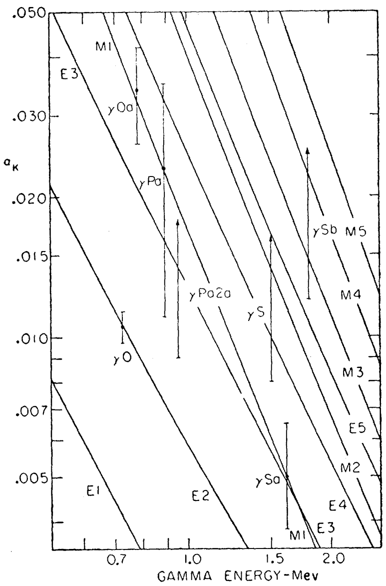

FIG. 5. Experimental internal conversion coefficients of electromagnetic transitions in Po^{212} following the decay of Bi^{212} compared to the theoretical values of Sliv and Band (reference 8).

all electric multipoles from one to five, inclusive, and since alphas are emitted from the level, the ground-state transition must have electric multipolarity. An $E6$ or higher multipole transition would be too slow to compete with the alpha decay from this level, so the transition must be electric monopole, and the state must be 0+. Krisyuk et al. found two internal conversion lines (R and Ra) which correspond to gamma rays of 1074 and 1078 kev in Po^{212}. The first fits as the stopover transition from the 1800-kev level. Since it goes from a 0+ to a 2+ state it must be $E2$, and the internal conversion intensity times the theoretical conversion coefficient gives a gamma intensity of $(1.2\pm0.4)\%$. This is consistent with the measured value, but it means that the gamma intensity of the 1078-kev transition must be small, less than about 0.5%. Thus the K-conversion coefficient of the 1078-kev transition must be greater than 0.018, and the transition cannot be $E1$ or $E2$. Its place in the level scheme remains unknown.

Figure 6 shows the level scheme of Krisyuk et al.,[18] with our transition intensities and spin assignments added. From the gamma-ray intensities one can find the amount of excitation of the various levels by the beta decays of Bi^{212} and the ft values for the partial spectra. These are shown in Table IV. The log ft values are all consistent with first forbidden transitions, as they must be if the spin assignments are correct.

For the excited states at 727, 1680, and 1800 kev, alpha emission is in competition with electromagnetic de-excitation. The ratio of transition probabilities for competing transitions is just the ratio of the transition intensities. Since the alpha intensities are known[22,23] and we have measured the gamma intensities, an estimate of the alpha transition probability allows an estimate of gamma transition probability to be made.

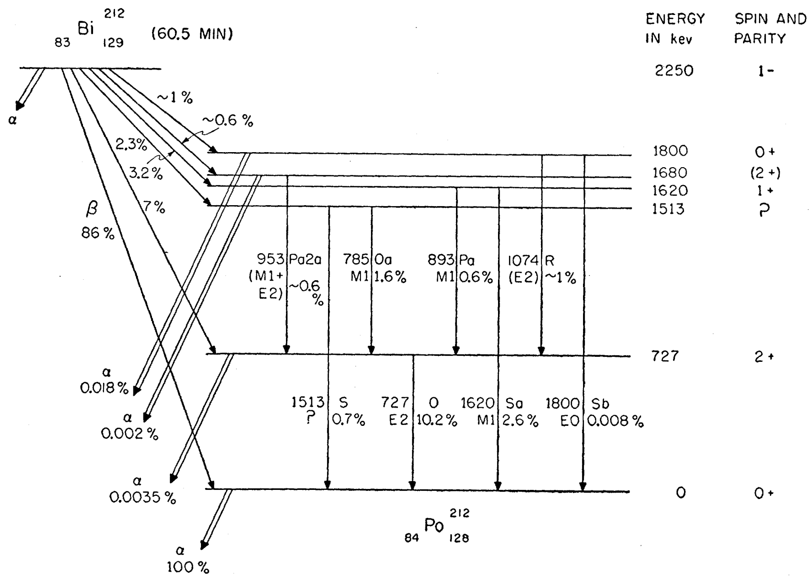

FIG. 6. Level scheme showing the states of Po^{212} excited in the beta decay of Bi^{212}. Bi^{212} also decays to states of Tl^{208} by alpha emission. Beta- and gamma-ray intensities are in percent of decays to Po^{212}.

We have used the semiempirical relation

$$\Lambda_\alpha^{(i)}/\Lambda_\alpha^{(0)}=(B_i/B_0)\exp[-C(Q_i^{-\frac{1}{2}}-Q_0^{-\frac{1}{2}})]$$

for the ratio of the alpha transition probability from an excited state to that from the ground state. The factor $\exp[-CQ^{-\frac{1}{2}}]$ gives the dominant dependence of the barrier penetration probability on Q, which is the disintegration energy corrected for the effects of the screening of the atomic electrons. We have used $C=297.8$, which describes the regularities of the even polonium isotopes of mass number 212 and above. The factor B includes the preformation factor; we have assumed, for the sake of this estimate, that the preformation factors and thus the factors B_i are the same for the states of Po^{212} under consideration. In the case of the spin 2 levels a correction has been made for the angular momentum dependence of the barrier penetration probability. The $L=2$ correction has been calculated for cases similar to these, and is always close to 0.60.[33]

The estimates of gamma-ray transition probabilities found by this method are used to find reduced transition probabilities, $B(E2)$.[34] These reduced transition probabilities may be compared with the "single proton" value, which is appropriate for two equivalent protons of large spin recoupling from a spin 2 state to a spin 0 state. The "single proton" value for polonium and for a nuclear radius of $1.2\times10^{-13}A^{\frac{1}{3}}$ cm is 0.0078 $e^2\times10^{-48}$ cm^4. We will quote all $B(E2)$ values in these units.

The $B(E2)$ value for the 727-kev transition is 0.08, ten times the "single proton" value. The limit on the intensity of an $E2$ component in the 953-kev gamma ray sets the limit $B(E2,953)\leq0.18$. The 1680-kev transition from the same level is not seen, and we find $B(E2,1680)\leq0.006$. For the stopover transition from the 1800-kev 0+ level, we find $B(E2,1074)=0.04$, about five times the nominal "single proton" estimate, but just the value to be expected for two protons recoupling from a spin 0 to a spin 2 state.

In a similar way we can estimate the transition probability for emission of a K electron in the 1800-kev $E0$ transition; it is $W_K=4\times10^9$ sec^{-1}. According to the discussion of $E0$ transitions by Church and Weneser[35]

$$W_K=|\rho|^2\Omega,$$

where Ω is a function of the energy and the electron wave functions, and ρ is the strength parameter, a measure of the overlap between the initial and final wave functions. Ω is about 1.6×10^{12} sec^{-1} for 1800 kev and polonium, so $|\rho|=0.05$. A similar estimate for the well-known 1.416-Mev $E0$ transition in Po^{214} gives $|\rho|=0.05$. The lifetime of that state has recently been directly measured by Tutter,[36] and his measurement yields $|\rho|=0.03$.

TABLE IV. Beta transitions from Bi^{212} to Po^{212}. The branch intensities are derived from the gamma-ray intensities.

Energy of excited state (Mev)	Maximum energy of betas (Mev)	Intensity in percent	log ft
0	2.25	86	7.3
0.727	1.52	7	7.7
1.513	0.74	~2	~7.1
1.620	0.63	~3.2	~6.6
1.680	0.57	<1.2	>7.0
1.800	0.45	~1.2	~6.7

[33] I. Perlman and J. O. Rasmussen, in *Encyclopedia of Physics*, edited by S. Flügge (Springer-Verlag, Berlin, Vienna, 1957), Vol. 32, 149.

[34] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, 101 (1953).

[35] E. L. Church and J. Weneser, Phys. Rev. **103**, 1035 (1956).

[36] M. Tutter, Z. Physik **155**, 368 (1959).

There are several similarities between the level schemes of Po^{212} and Po^{214}, of which we will comment on two.[37] In each case the four lowest alpha-emitting levels show the spin sequence 0+, 2+, 2+, 0+, and the ratios of the energies of the second 2+ and 0+ states to the first 2+ state are almost the same. The first two levels from which no alphas are known are, in Po^{212} at 1513 and 1620 kev, and in Po^{214} at 1729 and 1764 kev. In each case the lower state decays mostly to the first excited state, while the higher one decays mostly in a direct transition to the ground state. A diagram comparing the known levels of Po^{212} with these lower levels of Po^{214} is shown in Fig. 7.

LEAD-208

The principal features of the level scheme of Pb^{208} were established by the work of Elliott and collaborators,[38–40] who measured internal conversion coefficients and directional correlations. The angular correlation work was almost completely confirmed by Wood and Jastram.[41] Table V shows our results for the gamma-ray intensities, the internal conversion intensities of Krisyuk et al.,[17] and the resulting conversion coefficients and multipolarities. The conclusions, with one exception, are consistent with the previous work. The discrepancy is in the amount of multipole mixing in the 511-kev gamma ray, gamma L. Elliott et al. originally reported the intensity ratio of $E2$ to $M1$ as 1.7 ± 0.3,[38] and later [40] as 1.0 ± 0.4. Wood and Jastram found the ratio to be 0.04 ± 0.02. Our value of the gamma-ray intensity, when combined with the internal conversion data of the Leningrad group, gives a conversion coefficient indicating nearly pure $M1$; the ratio of $E2$ to $M1$ intensities is 0.18 ± 0.15.

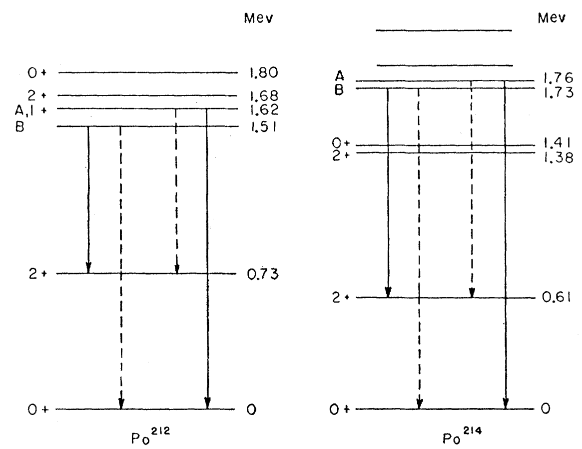

FIG. 7. Comparison of the levels of Po^{212} and Po^{214} excited in the decays of Bi^{212} and Bi^{214}. Alphas are emitted from the levels which are identified as 0+ and 2+. No alphas are known from the levels labelled A and B. In each case the de-excitation of level A takes place mostly to the ground state, while the de-excitation of level B takes place mostly to the first excited (2+) state.

TABLE V. Electromagnetic transitions in Pb^{208}. The intensities are given in percent of Tl^{208} decays. ϵ_K is the K-conversion coefficient.

Gamma	E (kev)	$I_K(\%)$[a]	$I_\gamma(\%)$	ϵ_K	Multi-polarity
Ec	211	0.15	...	...	($M1$)
Ed	233	0.13	...	...	($M1$)
Fb	252	0.37	1.5 ± 0.7	0.25 ± 0.15	($M1$)
G	277	2.4	6.9 ± 1.2	0.35 ± 0.06	$M1$
Jc7	486	0.01	...	...	($E2$)
L	511	1.7	23.0 ± 2.0	0.074 ± 0.007	$M1+E2$
M	583	...	86.4 ± 5.6	0.0156[b]	$E2$
O2	763	0.058	1.9 ± 0.5	0.031 ± 0.008	$M1$
P	860	0.27	11.4 ± 1.2	0.024 ± 0.003	$M1$
X	2614	0.17	(100)	(0.0017)[a–c]	$E3$

[a] See reference 17.
[b] See reference 38.
[c] A. I. Alichanian and S. J. Nikitin, Phys. Rev. 53, 767 (1938).

The level scheme is shown in Fig. 8. Our values for the gamma-ray intensities may be used to derive the intensities of the beta-ray branches. From these, values of log ft may be found. The results are shown in Table VI. The method gives an intensity of ($0.2\pm6.8\%$) for the 2.38-Mev branch; Elliott et al.[40] found it to be about 0.03%, and their value has been used in computing log ft for that branch. The transitions to the four

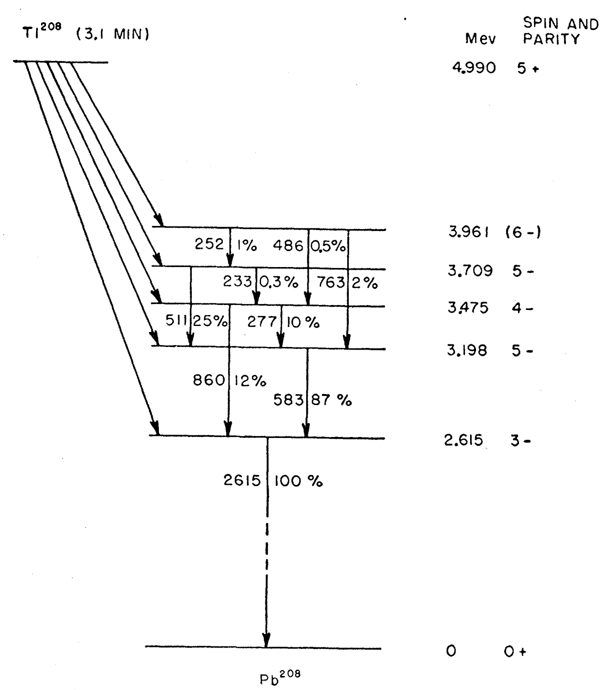

FIG. 8. Level scheme showing the decay of Tl^{208} to Pb^{208}.

[37] We consider the level scheme given by D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. 30, 794 (1958).
[38] L. G. Elliott et al., Phys. Rev. 93, 356 (1954); 94, 795(A) (1954).
[39] L. G. Elliott et al., Proc. Roy. Soc. (Canada) 48, 12A (1954).
[40] L. G. Elliott et al. (private communication to Nuclear Data Sheets, 1958).
[41] G. T. Wood and P. S. Jastram, Phys. Rev. 100, 1237(A) (1955).

TABLE VI. Beta transitions from thallium-208 to lead-208. The branch intensities are derived from the gamma-ray intensities.

Energy of excited state (Mev)	Maximum energy of betas (Mev)	Intensity in percent	log ft
2.62	2.38	~0.03[a]	9.3
3.20	1.80	51.3	5.6
3.48	1.52	20.6	5.7
3.71	1.28	24.3	5.4
3.96	1.03	3.6	5.8

[a] See reference 40.

higher levels all have log ft between 5 and 6. Several first forbidden decays of thallium and lead isotopes have similar values, but it had been thought[42] that all such favored transitions had no spin change. At least one of these transitions has unit spin change.

THALLIUM-208

The conversion coefficients deduced by direct comparison with the data of Krisyuk et al.[19] are consistent with the usual $M1$ assignment[43] for the 288-, 328-, and 453-kev transitions in Tl^{208}, but the uncertainties are of the order of 50%. The ratio of the intensities of the 288- and 328-kev gamma rays was measured more accurately; that result was compared with the internal conversion intensities and the excitation of the level by alpha decay to give $\epsilon_K(288) = 0.34 \pm 0.13$ and $\epsilon_K(328) = 0.25 \pm 0.10$. The theoretical values for magnetic dipole transitions are 0.36 and 0.26.[8]

BISMUTH-212

The conversion coefficients deduced for the 238- and 300-kev transitions in Bi^{212} are 0.61 ± 0.15 and 0.30 ± 0.08. Both transitions must be almost pure $M1$ because of K/L and $L_{I}:L_{II}:L_{III}$ internal conversion ratios.[16,44,45] The theoretical values for $M1$ transitions are 0.71 and 0.38.[8]

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[44] E. Sokolowski, K. Edwardson, and K. Siegbahn, Nuclear Phys. **1**, 160 (1956).
[45] A. G. Sergeev et al., Nuclear Phys. **9**, 498 (1959); Zhur. Eksp. i Teoret. Fiz. **35**, 348 (1958) [translation: Soviet Phys.-JETP **35**(8), 242 (1959)].