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γ-ray and internal-conversion intensity studies of transitions in the decay of ^{228}Th[†]

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High resolution intensity studies have been made of the 115, 239, and 300 keV transitions in ^{212}Bi, the 252, 277, 511, 583, 722, 763, and 860 keV transitions in ^{208}Pb, the 288, and 453 keV transitions in ^{208}Tl, and the 727 and 785 keV transitions in ^{212}Po, using carefully intensity-calibrated Ge(Li) and Si(Li) detectors. Twenty-four K-, L-, and M-shell internal-conversion coefficients were derived from the data and multipole mixing parameters $|\delta|$ and mixing percentages were deduced.

[RADIOACTIVITY ^{228}Th; Measured I_γ, I_e; deduced $\alpha_{K,L,M}$ and $|\delta|$ for transitions in ^{212}Bi, ^{208}Pb, ^{208}Tl, and ^{212}Po.]

Recent successful attempts to describe nuclei in the region of doubly magic ^{208}Pb with shell model calculations[1-7] have stimulated further experimental investigation of the properties of the level schemes and electromagnetic transitions of nuclei in this region. Recently, for example, multipole mixing ratios were measured using γ-γ directional correlation techniques in five transitions in ^{208}Pb and were compared with those calculated on the basis of the particle-hole model.[8] It was during the interpretation of the data of Ref. 8 that it was discovered that much of the existing internal-conversion data in the region were in serious conflict and the present investigation was initiated. References to early (and also to more recent) decay scheme work in ^{208}Pb are given in Ref. 8. Also, a proposed decay scheme is given which contains several changes based on the γ-γ directional correlation results of Ref. 8 as well as on the preliminary values of internal-conversion coefficients reported in this paper.

Many previous studies have been made of the γ-ray spectra of the daughters of ^{228}Th,[9-14] while Ref. 13 concerns mainly the decay scheme of ^{208}Tl. Prior to the γ-γ directional correlation measurements presented in Refs. 8 and 12, multipole mixing ratios $|\delta|$ were deduced from the available internal conversion studies[15-23] and, as pointed out by Jagam and Murty[12] and by Wolfson,[18] for example, there were many seriously conflicting results. Generally, directional correlation measurements are far more effective for the evaluation of multipole mixing ratios while in addition, they are sensitive to the sign of δ. However, in some of the transitions in ^{208}Pb discussed in Refs. 8 and 12, accurate internal-conversion data were needed in order to select spin sequences as well as to choose one of the two possible solutions of δ allowed by the experimental correlation coefficients; hence, the present work was undertaken.

The γ-ray intensities were measured with a large true-coaxial Ge(Li) detector of 17% efficiency at 1.33 MeV. The relative efficiency was carefully calibrated using two different calibration γ-ray sources. The first was an absolutely calibrated source of ^{226}Ra which has many well studied γ rays which range in energy from 53.24 keV to 2447.63 keV. The second was a National Bureau of Standards standard reference source containing ^{109}Cd, ^{57}Co, ^{139}Ce, ^{203}Hg, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{60}Co, and ^{88}Y. The absolute γ ray emission rates were determined at NBS and were supplied with the sources. The two independent relative efficiency measurements were found to be in excellent agreement. In addition to the precision γ-ray intensity measurements, an extensive set of Ge(Li)-Ge(Li) coincidence measurements was also made using a 17% and a 10% efficiency Ge(Li) detector. We shall not discuss these results except to say that they were in agreement with the most recent, as well as earlier, decay scheme studies and in particular support the γ-ray coincidence relationships in ^{208}Tl given in Ref. 13 and those given in Refs. 8, 9, and 11 for ^{208}Pb. No significant new features of any of the decay schemes in the daughters of ^{228}Th were discovered in our coincidence studies. Conversion electron-γ coincidence studies using an Si(Li) detector and a 7.62 cm × 7.62 cm NaI(Tl) scintillation detector were also made and an approximate conversion coefficient for the 722 keV transition in ^{208}Pb was measured. Isolation of the 722 keV line by coincidence observation is necessary because this line is completely masked by the K-shell line of the 727 keV transition in ^{212} Po. The results were not of high quality; however, a definite assignment of $M1+E2$ was possible for the 722 keV transition in ^{208}Pb.

The relative internal-conversion-electron intensity studies were made with an 80 mm^2 Si(Li) detector in which the first stage field effect transistor as well as the detector were maintained at approximately 77 °K. The source strength was chosen at about 1 μCi so that the rate of all pulses due to β^-, internal conversion IC-electrons, and α particles was low compared with the pulse pileup limitations of the circuitry. The amplifier gain was set so that pulses due to the α particles were larger than the upper end of the pulse-height range of the multichannel pulse-height analyzer and hence were ignored by the analyzer. The source was electrodeposited on a 5.1 μm Pt foil which resulted in Pt x rays appearing in the lower end of the electron spectrum. The Si(Li) spectrometer was intensity calibrated with the well-known internal-conversion lines in ^{192}Ir and ^{182}Ta. In addition several sources of ^{133}Ba of varied thickness were used in order to interpret the tails on the low energy electron lines. The K-shell and L- and M-shell line intensities of the 81 keV transition relative to the 356 keV K-shell line in ^{133}Cs are well known and were very helpful in the interpretation of the tail of the K-shell line of the 239 keV transition in ^{212}Bi. Three long counting experiments were made consisting of 48, 56, and 73 h, respectively. In addition, many other runs were made in which only the data from a few important lines were analyzed, for example the 511 keV K-shell line. A typical spectrum is shown in Fig. 1. The relative γ-ray and internal-conversion intensities are given in Table I. The major part of the quoted errors in these data was due to the uncertainties in fitting the peaks and integrating the areas under the

TABLE I. Experimental internal-conversion-electron intensities, γ-ray intensities, conversion coefficients, and implied multipole mixing.

Nuclide	E_γ (shell)	I_{e^-}	I_γ	ICC	Multipolarity
^{212}Bi	115.1 (L)	64(13)	1.9(2)	$(4.3 \pm 1.3)\times 10^{-1}$	$E2$
^{212}Bi	238.6 (K)	6584(988)	139(4)	$(6.1 \pm 1.1)\times 10^{1}$	$M1+E2$ [a]
^{212}Bi	238.6 (L)	1221(120)	139(4)	$(1.13 \pm 0.15)\times 10^{-1}$	$M1+E2$ [a]
^{212}Bi	238.6 (M)	266(40)	139(4)	$(2.5 \pm 0.5)\times 10^{-2}$	$M1+E2$ [a]
^{208}Pb	252.0 (K)	30(10)	0.62(4)	$(6.2 \pm 2.5)\times 10^{-1}$	$M1$(<48% $E2$)
^{208}Pb	277.3 (K)	185(17)	6.1(2)	$(3.91 \pm 0.48)\times 10^{-1}$	$M1$
^{208}Pb	277.3 (L)	31(3)	6.1(2)	$(6.5 \pm 0.9)\times 10^{-2}$	$M1+E2$
^{208}Pb	277.3 (M)	7.7(12)	6.1(2)	$(1.5 \pm 0.3)\times 10^{-2}$	$M1+E2$
^{208}Tl	288.2 (K)	16.4(25)	0.97(5)	$(2.18 \pm 0.43)\times 10^{-1}$	$M1+E2$
^{212}Bi	300.0 (K)	212(21)	8.8(3)	$(3.11 \pm 0.42)\times 10^{-1}$	$M1+25\%$ $E2$
^{212}Bi	300.0 (L)	42(4)	8.8(3)	$(6.1 \pm 0.8)\times 10^{-2}$	$M1+E2$
^{212}Bi	300.0 (M)	9(3)	8.8(3)	$(1.3 \pm 0.4)\times 10^{-2}$	$M1+E2$
^{208}Tl	453.0 (K)	7.3(14)	1.10(6)	$(8.6 \pm 2.2)\times 10^{-2}$	$M1+28\%$ $E2$
^{208}Pb	510.7 (K)	140(7)	22.8(7)	$(7.91 \pm 0.64)\times 10^{-2}$	$M1$(<21% $E2$)
^{208}Pb	510.7 (M)	5.2(11)	22.8(7)	$(3.0 \pm 0.6)\times 10^{-3}$	$M1+E2$
^{208}Pb	583.1 (K)	100	85	1.516×10^{-2}	$E2$ [b]
^{208}Pb	583.1 (L)	26.6(19)	85	$(4.0 \pm 0.3)\times 10^{-3}$	$E2$
^{208}Pb	583.1 (M)	5.8(9)	85	$(8.8 \pm 1.3)\times 10^{-4}$	$E2$
^{208}Pb	722.0 (K)	~0.8	0.27(2)	$\sim 4\times 10^{-2}$	$M1+E2$
^{212}Po	727.0 (K)	14.4(10)	21.0(8)	$(8.84 \pm 1.04)\times 10^{-3}$	$E2$
^{212}Po	727.0 (L)	3.7(6)	21.0(8)	$(2.3 \pm 0.4)\times 10^{-3}$	$E2$
^{208}Pb	763.2 (K)	4.6(3)	1.82(9)	$(3.25 \pm 0.40)\times 10^{-2}$	$M1+18\%$ $E2$
^{212}Po	785.0 (K)	8.3(8)	3.26(16)	$(3.3 \pm 0.5)\times 10^{-2}$	$M1+2\%$ $E2$
^{208}Pb	860 (K)	23.8(10)	13.9(6)	$(2.21 \pm 0.31)\times 10^{-2}$	$M1+$ (small $E2$)

[a] Probably pure $M1$ with penetration effects.
[b] Pure $E2$ transition used to normalize all other line intensities.

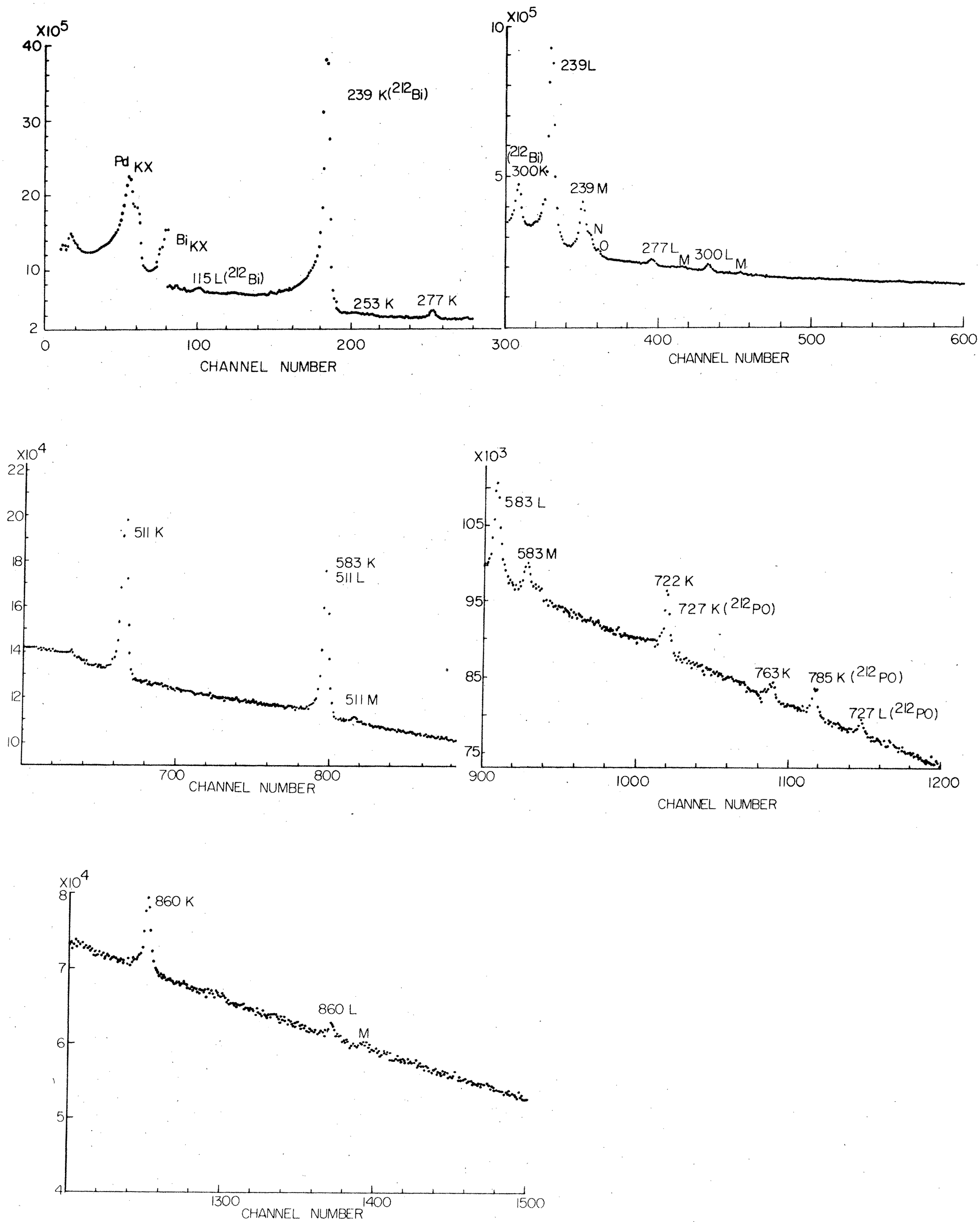

FIG. 1. Typical electron spectrum from the decay of ^{228}Th. The Pt x-rays come from external conversion in the Pt foil backing.

TABLE II. Experimental shell ratios and the implied multipole mixing.

E_γ	Shells	Ratio	Multipolarity	$\lvert\delta\rvert$
238.6	K/L	5.4 ± 0.5	$M1 + 6\%\ E2$	$0.3 \pm ^{0.2}_{0.3}$ [a]
238.6	K/M	24.8 ± 3.2	$M1 + (<14\%\ E2)$	$0.0 \pm ^{0.4}_{0.0}$ [a]
238.6	$K/(N+0)$	66 ± 6	$M1 + 12\%\ E2$	$0.4 \pm ^{0.2}_{0.4}$ [a]
277.3	K/L	6.0 ± 0.8	$M1 + (<13\%\ E2)$	$0.0 \pm ^{0.4}_{0.0}$
277.3	K/M	24 ± 5	$M1 + 5\%\ E2$	$0.2 \pm ^{0.4}_{0.2}$
300.0	K/L	5.1 ± 0.7	$M1 + 15\%\ E2$	$0.4 \pm ^{0.3}_{0.4}$
300.0	K/M	23.6 ± 4.5	$M1 + 6\%\ E2$	$0.2 \pm ^{0.4}_{0.2}$
583.1	K/L	3.8 ± 0.3	$E2$	∞
727.0	K/L	3.9 ± 0.9	$E2$	∞

[a] All are actually consistent with the expected pure $M1$.

peaks. The errors in the shell ratios of the 239 keV transition were smaller than the internal conversion coefficients because the tails could be treated equivalently; hence, these ratios rather than the conversion coefficients were used to deduce $|\delta|$.

The internal-conversion coefficients were derived from the data by internally normalizing all of the intensities to that of the 583.1 keV K line which is a pure $E2$ transition. The conversion coefficient of transition x is then given by

$$\alpha(x) = \frac{I_{e^-}(x) I_\gamma(583)}{I_\gamma(x) I_{e^-}(583)} \alpha_K(583) . \qquad (1)$$

The use of the 583.1 keV line minimizes the error in the energy dependence of the relative efficiencies of the detectors because it is in the middle of the range of interest; however, this does present a problem because the L lines of the 510.7 keV transition fall right under the 583.1 K peak. Fortunately the accurate, high resolution studies of this line by Wolfson[18] enables us to accurately correct the intensity for the 510.7 L-line intensities. A further consistency check on this procedure was the agreement obtained between the present value and theory for the α_K of the 727.0 keV pure $E2$ transition in ^{212}Po.

Much of the earlier internal-conversion data[15-23] were in serious conflict as discussed in Refs. 12 and 18 and the multipole mixing ratios deduced were also in conflict with some of those measured in γ-γ directional correlation experiments.[8, 12] The results given in Tables I and II appear internally consistent and in addition, those in ^{208}Pb are in agreement with the directional correlation data of Ref. 8. The other data reported here should be very useful in the interpretation of directional correlation data in ^{112}Bi, ^{208}Tl, and ^{212}Po. It should be pointed out here that the particle-hole model of True, Ma, and Pinkston[1] can be extended to these nuclei[2] and experimental studies similar to those given in Refs. 8 and 12 in ^{208}Pb will be very valuable in evaluating these extensions. The present data will be useful in the interpretation of such results.

At first glance one is tempted to suspect a small but non-negligible systematic error in the present data because the most probable values of the conversion coefficients and ratios of the 238.6 keV transition in ^{212}Bi all imply a multipolarity ($M1$ + small $E2$) rather than the pure $M1$ multipolarity expected. It is believed[23] that this transition occurs between the (0^-) state at 238.62 keV in ^{212}Bi and the (1^-) ground state. In addition, the high quality L-subshell ratio data reported in Ref. 23, from four independent investigations, were in agreement with a pure $M1$ multipolarity. We have reinterpreted the subshell data by averaging the four independent sets of data using the mean square deviation as the error. We find $L_1/L_2 = 9.41 \pm 0.13$ which is to be compared with 9.55 for a pure $M1$ transition. The implied multipolarity is $M1 + (1.5 \pm 1.4)\%\ E2$. Also, we find $L_1/L_3 = 130 \pm 4$, which is to be compared with the theoretical values 138.7 for a pure $M1$ transition and 0.5523 for a pure $E2$ transition. The implied multipolarity in this case is $M1 + (6.3 \pm 3.0)\%\ E2$, which is consistent with the small $E2$ mixtures observed in the present data. One could conclude that the spin assignments of the ground state or of the 238.62 keV level in ^{212}Bi should be reconsidered. Far more probably, the L-subshell data is sensitive enough to expose the fact that the ICC calculations are only first order approximations.

An important question settled by the present results is that concerning the multipole mixing ratio of the 510.7 keV transition. The $\gamma\gamma(\theta)$ experiments of both Refs. 8 and 12 allow for $|\delta| \simeq 0.7$ or $|\delta| \simeq 0.05$. The larger value would be in serious disagreement with the prediction of $|\delta| \simeq 0.02$ of the particle-hole model[8] in that vastly different configuration mixing is necessary to achieve such a large $|\delta|$ in this case. The present data indicate that $|\delta| < 0.5$ which favors the smaller value. Earlier internal-conversion data yield several values from $|\delta| + 0.2$ to $|\delta| + 1.7$.

Another important question which the present data help clarify is the multipole mixing ratio of the 277 keV transition. The value $\delta(277) = 4.8 \pm 0.4$ given in Ref. 12 is in disagreement with the value $\delta(277) = 0.008 \pm 0.011$ given in Ref. 8 which agrees well with that predicted by the particular-hole model.[8] The present values α_K, K/L, and K/M support the smaller value and remove this possible serious disagreement with the model.

Finally the assignment of the spin and parity (6^-) to the 3920 keV level in ^{208}Pb is strongly supported by the present approximate value of $\alpha_K(722)$ which implies a multipolarity of $M1+E2$. In addition, the parity of the 3961 keV level in ^{208}Pb was not a settled issue and the present value of $\alpha_K(763)$ implies a multipolarity $M1+18\%\ E2$ which fixes the parity of this level as (−) and selects the value $J^\pi=(5^-)$ of the two values (5^-) or (6^+) consistent with reaction data. A more complete discussion of how these conversion coefficients are useful in the selection of spin assignments and solutions of δ from $\gamma\gamma(\theta)$ data in ^{208}Pb can be found in Ref. (8).

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