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National Uranium Resource Evaluation

HIGH RESOLUTION GAMMA-RAY SPECTROSCOPY APPLIED TO BULK SAMPLE ANALYSIS

**Field Engineering
Corporation**

Grand Junction Operations
Grand Junction, CO 81502

January 1980

PREPARED FOR U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Resource Applications
Grand Junction Office, Colorado

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INTRODUCTION

On approximately January 1, 1975 an R&D project was begun to introduce state-of-the-art techniques into potassium, uranium, and thorium gamma-ray spectroscopy.¹ The central elements of this system are a high resolution Ge(Li) detector and a multichannel analyzer with a sufficient number of channels to utilize the full resolving capability of the detector. The first major phase of this project included the assembly of the system, construction of a low background shield, determination of system parameters, and formulations of a near-term analysis scheme. This phase has been completed and it is the purpose of this report to document that work.

The Ge(Li) spectrometer system and its use for bulk sample potassium, uranium, and thorium analysis have been well characterized by the study reported here. The near-term analysis scheme permits the direct assay of uranium, in addition to the conventional equivalent uranium assay provided by sodium iodide spectrometers. This represents a significant improvement for BFEC in laboratory radiometric assay methods because the direct assay for uranium is independent of the uranium/radium disequilibrium condition.

¹K. L. Kosanke, R&D Project No. 5001, "Sample Assay Using a Ge(Li) Detector," September, 1975.

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A. Ge(Li) Gamma-Ray Spectrometer

This section of the report will discuss only the configuration and operation of the new Ge(Li) spectrometer. The present NaI KUT system will not be discussed in the main text of this report but is discussed as part of a general discussion of KUT spectrometry as applied to bulk samples in Appendix A.

1. System Configuration and Specifications

A block diagram of the present Ge(Li) spectrometer is shown in Figure 1. Equipment model numbers, along with pertinent specifications or operational parameters are tabulated below:

Ge(Li) detector: Princeton Gamma-Tech
Resolution: 1.68 keV (FWHM) @ 1.33 MeV
 3.16 keV (FWHM) @ 1.33 MeV
 0.67 keV (FWHM) @ 0.12 MeV
Efficiency: 16.3% (relative to 3 inch x 3 inch NaI(Tl) at 25 cm)
Peak/Compton Ratio: 48:1 @ 1.33 MeV
Preamplifier: PGT-RG-11C

High Voltage Supply: Power Designs (AEC-5000)
Amplifier: Princeton Gamma-Tech
 Shaping, 2 μ sec
 Restorer, low
 Output, DC-Unipolar-93 ohm

Multichannel Analyzer: ORTEC (6240)
 4096 channels

Computer: Digital Equipment (PDP-11/10)
 16K core

Hard Copy Terminal: Digital Equipment (Decwriter II)
Plotter: Hewlett-Packard (7004B X-Y)

When count-rate information is required it is generated using a single channel analyzer and scaler.

2. Low Background Shield

In order to allow low-level counting, a low background shield was constructed. The shield was constructed using 2 inch by 4 inch by 8 inch lead bricks in a pattern chosen to eliminate cracks through the walls. Wall thicknesses are 6 inches on the top and sides and 4 inches on the bottom. In addition, the shield was graded on the inside using 1/4 inch copper sheets to reduce fluoresced Pb X-rays by a factor of ~ 50 . Relatively thick copper sheets were chosen instead of thinner sheets of cadmium and copper because of cost and delivery time considerations. With the complete shield, the background was reduced by a factor of about 200 at 100 keV and a factor of about 15 at 2500 keV. Reductions in the background continuum and background peaks are listed in Tables 1 and 2.

(Does not show LN_2 level monitor.)

FIGURE 1. Block Diagram of Present Ge(Li) Gamma Spectrometer

TABLE 1
Reduction of Background Continuum in Ge(Li) Shielding Cave

Energy (keV)	Background Continuum Recorded		Fractional Background Reduction (out of cave/in cave)
	Out of Cave (cpm/keV)	In Cave (cpm/keV)	
100	39.2 (.13)	0.19 (.008)	206 (9)
200	17.5 (.08)	0.19 (.008)	92 (4)
500	2.4 (.03)	0.055 (.004)	44 (3)
1000	0.75 (.02)	0.014 (.002)	54 (8)
1500	0.18 (.009)	0.008 (.002)	22 (6)
2000	0.07 (.005)	0.003 (.001)	23 (8)
2500	0.03 (.003)	0.002 (.001)	15 (8)

Notes: 1. () indicates 1 σ uncertainty.
2. Counts were taken for a time of 20,000 seconds.

TABLE 2
Reduction of Background Peaks in Ge(Li) Shielding Cave

Energy (keV)	Decay chain of origin	Background Peaks Recorded		Fractional Background Reduction (out of cave/in cave)
		Out of cave (cpm)	In cave (cpm)	
186.2	²³⁵ U	----	0.29 (.08)	---
239.0	²³² Th	20.2 (1.2)	0.22 (.05)	92 (34)
351.9	²³⁸ U	17.7 (.4)	---	---
510.5	β^+ ann.	8.5 (.5)	0.88 (.08)	10 (1)
582.8	²³² Th	8.8 (.3)	---	---
608.9	²³⁸ U	18.5 (.4)	0.25 (.04)	74 (12)
910.6	²³² Th	7.0 (.3)	---	---
968.3	²³² Th	4.1 (.2)	---	---
1119.6	²³⁸ U	5.1 (.2)	---	---
1237.3	²³⁸ U	2.2 (.1)	---	---
1460.0	⁴⁰ K	44.7 (.4)	0.06 (.02)	745 (250)
1591.9	²⁶¹⁴ DE	1.3 (.1)	---	---
1728.7	²³⁸ U	0.97 (.08)	---	---
1763.8	²³⁸ U	5.0 (.1)	0.06 (.02)	83 (27)
2102.9	²⁶¹⁴ SE	1.1 (.1)	---	---
2203.5	²³⁸ U	1.3 (.1)	---	---
2614.0	²³² Th	7.1 (.2)	0.02 (.01)	355 (180)

Notes: 1. () indicates 1 σ statistical uncertainty.
2. Runs were made for a time of 20,000 seconds.
3. The presence of the peak at 186 keV for the run inside the shield suggests possible contamination.

Access to the shield is gained through the top, which is made of two halves, each on rollers. The Ge(Li) detector is mounted up through the bottom of the shield and is mechanically isolated from the shield with foam rubber. When a sample changer is added to the system, samples will enter through one of the sides of the shield. In order to limit the possibility of contamination of the shield it has been fitted with a plastic liner.

3. Background Variations Due to Radon

The main contribution to the background within the low background shield is from atmospherically borne radon and its daughter activities. At present no provision has been made for eliminating these activities from the volume within the shield. An experiment was run to estimate the maximum error that might be introduced as a result of neglecting background corrections. A series of 36 background counts was taken for 20,000 seconds over three weekends. The maximum background rate from all sources recorded during any of these intervals corresponded to <0.5 ppm U_3O_8 . Accordingly, at this stage of the development, no correction for background will be made. When routine counting of bulk samples begins, a background correction will be made.

4. Energy Linearity of the System

The linearity of the system was determined in two ways: using a ramp pulser; and using gamma lines of well known energy. The ramp pulser (Berkeley Nucleonics Model No. GL3) was used to determine if any local non-linearities existed; none were found and the results are shown in Figure 2. Overall linearity was established using the prominent ^{214}Pb and ^{214}Bi lines in the uranium decay chain. A 20,000-second count was made using a 500 ppm uranium ore standard. Gamma-ray peak centroids were located using the ORTEC Peak Find software package. A least squares fit of a quadratic function to these data gives the energy calibration equation:

$$\text{Energy (keV)} = 2.8195 + 0.6580 (\text{Channel No.}) + 0.0000 \times 10^{-7} (\text{Channel No.})^2.$$

5. System Stability

The stability of the system was determined in two tests. The first test determined the short term stability and consisted of a series of twenty-six 8,000-second counts of a thorium standard, run consecutively over a weekend. The second test determined the long term stability and consisted of a series of twenty-two 4,000-second counts of ore samples containing uranium and thorium in varying concentrations. These samples were run at random times during the working day over a period of nine days. From the results generated during each counting period, the position of the centroid of the 2614.6 keV peak of ^{208}Tl was recorded. In no case did the centroid position fall more than one-half channel from the mean channel number (~ 3975) in either test.² The results of these tests are shown graphically in Figures 3a and 3b.

²The slight change in gain between the two tests was the result of a slight modification to the system.

FIGURE 2. Linearity of Ortec MCA Model 6240 Using a Berkeley Nucleonics Ramp Pulser Model GL 3

FIGURE 3a. Short Term Stability of the Ortec 6240 MCA

FIGURE 3b. Long Term Stability of the Ortec 6240 MCA

It is suspected that the periodic nature of the data shown in Figure 3a is a reflection of daily temperature and/or voltage fluctuations.

6. Absolute Gamma Efficiency

Absolute gamma efficiency curves were prepared for point sources in two positions and for bulk samples in both large and small cans in contact with the detector. Point source efficiencies were determined for the 1st and 15th positions on the source holder prepared for the Ge(Li) detector. These positions correspond to approximate contact with and to a 7-inch separation from the detector along its axis. These efficiencies were determined using absolute counting sources of ^{241}Am , ^{133}Ba , ^{137}Cs , ^{57}Co , ^{60}Co , ^{54}Mn , ^{203}Hg , ^{22}Na , and ^{88}Y prepared by Amersham, Inc., with strengths of 10 μCi with absolute uncertainties of 2-5 percent, and sources of ^{241}Am , ^{57}Co , ^{137}Cs , ^{54}Mn , and ^{22}Na prepared by Isotope Products with strengths of 1 μCi with uncertainties of 2-4 percent. In addition, relative counting sources of ^{56}Co , ^{226}Ra , and ^{228}Th were used to extend the range of the efficiency determination.

Absolute efficiencies for bulk samples along the axis of the detector were determined on contact with the detector in both the large and small can geometry. Can dimensions are 4-1/8-inch diameter x 2-1/4-inch thick for the large cans and 1-7/8-inch diameter x 1/2-inch thick for the small cans. The large and small cans were loaded with 0.051 ± 0.01 percent and 1.01 ± 0.01 percent uranium, respectively, and allowed to come to radon equilibrium. The source material was supplied by the New Brunswick Laboratory operated by the Energy Research and Development Administration (ERDA) and had a reported radium-to uranium-weight ratio of 3.44×10^{-7} . Absolute counting efficiencies were determined using the absolute gamma intensities reported for the ^{238}U chain in equilibrium. (Appendix B of this report is a listing of absolute gamma intensities for peaks in the ^{238}U , ^{235}U , and ^{232}Th decay chains.) The result for each of the configurations discussed is presented in Figure 4.

7. Live Time Clock Errors

Because of the intent to make quantitative measurements with the Ge(Li) spectrometer, it was necessary to determine the accuracy of live time corrections made by the MCA as a function of count rate. This was done by counting an ^{88}Y source in a fixed geometry and varying the total count rate using a ^{228}Th source placed at various distances from the detector. In every instance, the gross count rate >50 keV and the count rate in the 1836 keV peak of ^{88}Y were recorded. These results were plotted and a curve fit to the data. The curve was extrapolated back to zero count rate and set equal to zero percent relative live time clock error at that point, by definition. These results are shown in Figure 5.

In addition to the gross count rate scale, scales for approximate percent uranium as U_3O_8 and approximate percent analyzer dead time are included. Five of the data points are shown with error bars for the 2 (95 percent) confidence level to give a feeling for the typical uncertainty in the data points. Because of the importance of live time

FIGURE 4. Absolute Efficiency of the 16.3 Percent Ge(Li) Spectrometer as a Function of Energy

FIGURE 5. Live Time Clock Errors in Ortec 6240 MCA

corrections, additional data should be collected to reduce the uncertainty in the shape of the curve if it were not for the following considerations: in this case the live time corrections are relatively small; this MCA will soon be replaced with a new system; at high count rates the curve's shape and direction are those expected (based on the MCA's algorithm for live time correction); and at this preliminary stage of the evaluation of the Ge(Li) analysis scheme, the ultimate in precision is not necessary. For perspective, it should be pointed out that the maximum live time clock error expected for ore samples in the range from zero to 1.5×10^4 ppm U_3O_8 is only ± 0.5 percent.

B. Library of Ge(Li) Spectra

A collection of gamma spectra for bulk samples was recorded using the Ge(Li) spectrometer. The principal purpose was not to demonstrate the power of this high resolution instrument but rather to serve as an aid in understanding the present Ge(Li) analysis scheme and to help in the identification of gamma transitions observed during routine analysis.

The first two spectra (equilibrium uranium ore shown in Figure 6 and radium-rich uranium ore shown in Figure 7) are particularly significant. An examination of these two spectra will reveal almost no difference, yet the first is in equilibrium and by definition has a fractional disequilibrium coefficient³ of 1.00 while the second is grossly out of equilibrium and has a fractional disequilibrium coefficient of 7.6×10^{-3} . The reason for this is that almost all the peaks present in either spectrum result from the decay of nuclei below radium in the decay chain, primarily ^{214}Pb and ^{214}Bi , and therefore cannot be used to indicate the presence of uranium. Figure 10 offers a comparison of the low-energy portions of these spectra. It is this low-energy region where the differences are most noticeable. For example, the 63 and 93 keV peaks from the decay of ^{234}Th (^{238}U chain) and the 143, 163 and 205 keV peaks from the decay of ^{235}U are absent in the radium rich, or depleted uranium, spectrum. Also, the 186 keV peak is reduced relative to the ^{214}Pb peaks due to the absence of its ^{235}U component. The third spectrum, radium depleted uranium ore shown in Figure 8, has a fractional disequilibrium coefficient of $>10^3$ and exhibits a marked difference from the equilibrium uranium spectrum due to the complete absence of the normally prominent ^{214}Bi lines.

Spectra of equilibrium thorium ore and potassium as K_2CO_3 shown in Figures 9 and 11 respectively, were included to complete the KUT picture. Figure 10 is a presentation of the low-energy portions of Figures 6 through 9 and is the portion of the spectrum in which the greatest differences can be seen.

³Fractional disequilibrium coefficient is defined here to be the ratio of actual cU_3O_8 to radiometrically determined gU_3O_8 based on the 1765 keV line of ^{214}Bi . See Appendix C for definitions of the several U_3O_8 prefixes.

FIGURE 6. Ge(Li) Spectrum of Equilibrium Uranium Ore

FIGURE 7. Ge(Li) Spectrum of Radium Rich (Depleted Uranium) Uranium Ore Sample

FIGURE 8. Ge(Li) Spectrum of Radium Depleted Uranium Ore Sample

FIGURE 9. Ge(Li) Spectrum of Equilibrium Thorium Ore Sample

LOG OF COUNTS (ARBITRARY UNITS)

FIGURE 10. Comparison of Low Energy Portions of Figures 6 through 9

FIGURE 11. Ge(Li) Spectrum of ^{40}K as K_2CO_3

C. Ge(Li) Scheme for the "Near Term"

Analysis Scheme Description

The first phase of the BFEC Ge(Li) spectrometer project⁴ included the development of a preliminary "near term" analysis scheme for computing, among other things, the direct uranium content of bulk samples. As with the NaI(Tl) KUT system, it remains necessary to allow canned bulk samples to come to radon equilibrium ⁵(> 20 days). However, improved precision and a direct uranium determination will result from the Ge(Li) analysis scheme.

Conventional KUT concentrations will be calculated using the equations below:

$$\%K = \frac{S_K [R_{1461} - (0.0423)R_{2614}]}{W} \quad (1)$$

$$\text{ppm } gU_3O_8 = \frac{S_{gU_3O_8} R_{1764}}{W} \quad (2)$$

$$\text{ppm } ThO_2 = \frac{S_{ThO_2} R_{2614}}{W} \quad (3)$$

where,

- S = (Concentration) (Weight/Count Rate) for a standard sample,
- R = Count rate of the signature peak (1461, 1764, 2614 keV), live time corrected with Compton background and background contributions to the peaks from sources within the shield subtracted,
- W = Sample weight.

The fraction 0.0423 of the 2614 keV intensity from ²⁰⁸Tl must be subtracted from the potassium signature at 1461 keV to correct for an interfering thorium series peak at 1459 keV.⁶

In effect, the improved precision in these concentrations results from an elimination of interferences from other peaks that would have fallen in the NaI (Tl) KUT windows and from the ability to eliminate the Compton background by subtraction. See Appendix A for a more complete discussion of these points.

⁴K. L. Kosanke, R&D Project No. 5001, "Sample Analysis Using a Ge(Li) Detector," Sept., 1975.

⁵If the sample is counted twice (e.g. one and three days after canning) it is not necessary to wait for equilibrium and in addition, a relative emanation coefficient can be found for the sample.

⁶Private communication from R. Murri, Bendix Field Engineering Corporation.

The direct U_3O_8 determination is based on the calculation of the fractional disequilibrium for the sample, defined earlier in this report as the ratio U_3O_8/gU_3O_8 . Accordingly,

$$\text{Concentration } U_3O_8 = (\text{Fractional disequilibrium}) \times (\text{Concentration } gU_3O_8). \quad (4)$$

The calculation of the fractional disequilibrium is based on the intensity of 186 keV peak⁷, R_{186} . Because of its rather low energy it is necessary to correct the observed intensity for self-absorption in the sample. This is done by first plotting as a function of energy the observed count rates in the 242⁸, 295, and 352 keV peaks from ^{214}Pb in the sample, each divided by their count rate in the uranium standard sample.

$$A_E = \text{Sample } R_E / \text{Standard } R_E \quad (5)$$

Next, these three points are fit to a straight line using a least squares technique that weights the points 1:2:3 for the 242, 295, and 352 ratios, respectively. These weight factors approximate the statistical confidence in their relative count rates. It is assumed that a straight line closely approximates the self-absorption curve over this limited energy span, particularly when only three points of limited statistical precision are used. The A_E curve is then extrapolated back to 186 keV and the value of A_{186} is read from the graph. Additional studies indicate that the precision of the self-absorption correction improves if a quadratic fit is performed to these three points along with two additional points from the 609 and 1120 keV intensities of ^{214}Bi . Finally, the self-absorption corrected count rate of the 186 keV peak, normalized to the uranium standard concentration, is found by dividing the observed peak count rate by A_{186} .

$$\text{Self-absorption corrected } R_{186} = \text{Sample } R_{186} / A_{186} \quad (6)$$

As mentioned in an earlier note the 186 keV peak can contain a component from ^{228}Ac in the ^{232}Th decay chain. This component is subtracted from the 186 peak using the observed count rate for the 239 keV peak of ^{212}Pb , also in the ^{232}Th chain.

$$\text{Thorium corrected } R_{186} = (\text{Self-absorption corrected } R_{186}) - (R_{186} \text{ from } ^{228}Ac) \quad (7)$$

$$R_{186} \text{ from } ^{228}Ac = (\text{Sample } R_{239} / A_{239}) (2.4 \times 10^{-3}) \quad (8)$$

and,

$$2.4 \times 10^{-3} = 0.105/44.6 = \text{Absolute } I_{186} \text{ from } ^{228}Ac / \text{Absolute } I_{239} \text{ from } ^{212}Pb$$

⁷Contributions to the 186 keV peak come from up to 10 transitions in the ^{235}U , ^{238}U , and ^{232}Th decay chains. The major components are from ^{235}U , ^{226}Ra , and ^{228}Ac with absolute intensities (I_E) in their decay chains of 56 percent, 3.5 percent, and 0.105 percent, respectively.

⁸It is necessary to correct the 242 keV peak in the sample spectrum for a contribution from ^{224}Ra in the ^{232}Th decay chain. This is done by subtracting from the 242 keV peak, 0.0830 times the count rate of the 239 keV peak of ^{212}Pb , also in the ^{232}Th decay chain.

Note, I_E is an intensity taken from a decay scheme. Any difference in self-absorption or detection efficiency between 186 and 239 keV is assumed negligibly small.

This thorium corrected 186 peak count rate still contains components from transitions in the decay of both ^{226}Ra and ^{235}U . Because the sample has been held long enough for members in the chain below ^{226}Ra to come into equilibrium, it is a simple matter to subtract the ^{226}Ra component from the 186 keV peak count rate.

$$\text{Radium corrected } R_{186} = (\text{Thorium corrected } R_{186}) - (R_{186} \text{ from } ^{226}\text{Ra}), \quad (9)$$

where

$$R_{186} \text{ from } ^{226}\text{Ra} = (\text{Uranium standard } R_{186}) \times (\text{Fraction of 186 events from } ^{226}\text{Ra in the standard}),$$

$$\text{Uranium standard } R_{186} = 5.02 \text{ cps},$$

$$\text{Fraction of events from } ^{226}\text{Ra} =$$

$$\frac{(\text{Absolute } I_{186} \text{ from } ^{226}\text{Ra})}{(\text{Absolute } I_{186} \text{ from } ^{226}\text{Ra}) + (\text{Effective } I_{186} \text{ from } ^{235}\text{U})}$$

$$\text{Absolute } I_{186} \text{ from } ^{226}\text{Ra} = 3.9\%,$$

$$\text{Effective } I_{186} \text{ from } ^{235}\text{U} = (\text{Absolute } I_{186} \text{ from } ^{235}\text{U}) \times (\text{Ratio of decay rates of } ^{235}\text{U} : ^{238}\text{U}), \quad (10)$$

$$\text{Absolute } I_{186} \text{ from } ^{235}\text{U} = 56\%,$$

$$\text{Ratio of decay rates of } ^{235}\text{U} : ^{238}\text{U} = \frac{N_{235} \lambda_{235}}{N_{238} \lambda_{238}}$$

where

$$N_{235}/N_{238} = \text{Abundance ratio of } ^{235}\text{U} : ^{238}\text{U} = 0.72/99.3, \text{ assuming natural abundances}$$

and

$$\begin{aligned} \lambda_{235}/\lambda_{238} &= \text{Ratio of decay constants } ^{235}\text{U} : ^{238}\text{U} \\ &= 4.5 \times 10^{+9} / 7.1 \times 10^{+8}. \end{aligned}$$

By substitution equation (10) becomes

$$\text{Effective } I_{186} \text{ from } ^{235}\text{U} = 2.5\%$$

and equation (9) becomes

$$\text{Radium corrected } R_{186} = (\text{Thorium corrected } R_{186}) - 3.06 \text{ cps.} \quad (11)$$

The radium corrected 186 count rate is just the count rate resulting from ^{235}U in the sample, normalized to the uranium standard concentration. Then, assuming a constant $^{235}\text{U}/^{238}\text{U}$ ratio, the fractional disequilibrium coefficient will equal the radium corrected 186 count rate divided by the expected 186 count rate from ^{235}U .

$$\text{Fractional disequilibrium} = \frac{(\text{Radium corrected } R_{186})}{(\text{Expected } R_{186} \text{ from } ^{235}\text{U})}$$

where

$$\begin{aligned} \text{Expected } R_{186} \text{ from } ^{235}\text{U} &= (\text{Uranium standard } R_{186}) \times \\ &(\text{Fraction of 186 keV events from } ^{235}\text{U} \text{ in the standard}) = 1.96 \text{ cps.} \end{aligned}$$

By substitution equation (4) becomes

$$\begin{aligned} \text{Concentration}^9 \text{ rU}_3\text{O}_8 &= (\text{Radium corrected } R_{186} \div 1.96 \text{ cps}) \\ &\times (\text{Concentration gU}_3\text{O}_8). \end{aligned} \quad (12)$$

2. Example Using Analysis Scheme

Sample number 125050 weighing 609 grams was counted for 4,000 seconds and spectral peak areas determined using the ORTEC "Peak Find" program. The results for the peaks used in this analysis scheme are listed in the table below.

Peak Energy	Peak Intensity	% Uncertainty
186 keV	2.02 cps	-
239 keV	0.19 cps	-
242 keV	0.72 cps	-
295 keV	1.56 cps	-
352 keV	2.58 cps	-
1461 keV	0.166 cps	4.5
1764 keV	0.279 cps	3.0
2614 keV	0.0102 cps	17.1

First, using equations 1 through 3 from the previous section, concentrations of K, gU_3O_8 , and ThO_2 are calculated.

$$\%K = \frac{S_K R_{1461}}{W} \quad (1)$$

where S_K = (concentration) x weight/count rate) for the potassium standard and was empirically found to equal 8.50×10^3 percent·grams·(cps)⁻¹.

⁹Here rU_3O_8 is meant to express U_3O_8 concentrations as determined using the 186 keV peak from ^{235}U . See Appendix C for a complete listing of U_3O_8 prefixes and definitions.

By substitution,

$$\%K = \frac{(8.50 \times 10^3) (0.166)}{609} = 2.32\%$$

The uncertainty in potassium concentration is reported as twice the statistical uncertainty in the 1461 keV peak area.

$$\begin{aligned}\text{Uncertainty in K} &= 2(1461 \text{ uncertainty}) (\text{K concentration}) \\ &= 2(0.045) (2.32\%) = 0.21\%\end{aligned}$$

The potassium concentration was reported as 2.3 ± 0.2 percent K. Similarly, for gU_3O_8 and ThO_2 , concentrations were reported as 96 ± 6 ppm gU_3O_8 and 8 ± 3 ppm ThO_2 .

The determination of rU_3O_8 based on ^{235}U gamma transitions is more complicated and begins with establishing the sample self-absorption in the region of the 186 keV transition. It is this peak that is used for the determination of the sample's fractional disequilibrium. As indicated in the previous section, before the sample's self-absorption can be found using the 242, 245, and 352 keV peaks, the 242 keV peak must be corrected for a ^{224}Ra component:

$$\begin{aligned}\text{corrected } R_{242} &= R_{242} - (0.083 R_{239}) \text{ cps} \\ &= 0.72 - (0.017) \text{ cps} \\ &= 0.70 \text{ cps.}\end{aligned}$$

Using equation (5), the ratios (A_g) for the 242, 295, and 352 keV peaks were determined and are:

Peak Energy (keV)	Sample Intensity (cps)	Standard Intensity (cps)	Ratio	Weighting Factor
242	0.70 ± 0.02	4.96 ± 0.02	0.141 ± 0.002	1
295	1.56 ± 0.02	10.63 ± 0.03	0.147 ± 0.002	2
352	2.58 ± 0.03	17.82 ± 0.04	0.145 ± 0.002	3

Note, uncertainties are at the 1σ (67 percent) confidence level.

These data points were then fit to a straight line using a weighted least-squares technique. While this was done numerically it is also shown graphically for illustration in Figure 12.

Before completing the example calculation for rU_3O_8 concentration, it will be instructive to discuss the interpretation of the graph in more detail. If the sample had the same self-absorption and the same concentration as the standard, all the A_g ratios would equal one, to within statistical limits. In this instance the slope and intercept should be nearly zero and one, respectively. If the sample had the same self-

Calculated:

Slope = 1.83×10^{-5}

Intercept = 0.139

Average deviation = 1.2%

$A_{186} = 0.1425$

FIGURE 12. Graphic Presentation of Numerically Generated Weighted Least Squares Fit of the Ratios A_E

absorption as the standard, but had either greater or lesser U_{308} concentration, all the A_E ratios would be equal and either greater or less than one, respectively. In the case of Figure 12 the A_E ratios are each approximately 0.14, thus the sample must have about one-sixth the ^{214}Pb concentration of the standard. A comparison of 1764 keV peak intensities does indeed suggest a ^{214}Pb concentration of 1/6.21 that of the standard. Because of the generally exponential dependence of self-absorption on gamma energy, if the sample self-absorption is greater or less than the standard it must be expected that the slope of the A_E ratios will be positive or negative, respectively. In the case of Figure 12 the curve has a slight positive slope, indicating the sample is slightly more self-absorbing than the standard.

Returning to the example calculation, after the slope and intercept are found, the A_{186} ratio is calculated to be 0.1425. By substitution into equation (6)

$$\text{Self-absorption corrected } R_{186} = \frac{R_{186}}{A_{186}} = \frac{2.02}{0.142} \text{ cps} = 14.2 \text{ cps.}$$

This is the count rate that would be expected if the sample were at the standard concentration with the same self-absorption as the standard. The next step is to calculate and subtract the 186 keV component from ^{228}Ac in the ^{232}Th decay chain. By substitution into equation (8),

$$\begin{aligned} R_{186} \text{ from } ^{228}Ac &= \frac{(\text{Sample } R_{239}) (2.4 \times 10^{-3})}{A_{239}} \\ &= \frac{(0.19) (2.4 \times 10^{-3})}{0.143} = 3.2 \times 10^{-3} \text{ cps.} \end{aligned}$$

Thus,

$$\text{Thorium corrected } R_{186} = (14.2 - 3.2 \times 10^{-3}) \text{ cps} = 14.2 \text{ cps.}$$

The 186 keV component for ^{228}Ac is negligible. The final correction to the 186 keV peak is to subtract the equilibrium contribution from ^{226}Ra , which, as found in the last section, is 3.06 cps.

Thus,

$$\text{Radium corrected } R_{186} = (14.2 - 3.06) \text{ cps} = 11.1 \text{ cps}$$

and,

$$\begin{aligned} \text{Fractional disequilibrium} &= \frac{\text{Radium corrected } R_{186}}{\text{Expected } R_{186} \text{ from } ^{235}U} \\ &= \frac{11.1}{1.96} = 5.66 \end{aligned}$$

From equation (4),

$$\begin{aligned}\text{Concentration } rU_3O_8 &= (\text{Fractional disequilibrium}) \times \\ &\quad (\text{Concentration } gU_3O_8) \\ &= (5.66) (96 \text{ ppm}) = 544 \text{ ppm}.\end{aligned}$$

A chemical determination of U_3O_8 concentration had been made for this sample previously and was reported to be 510 ± 50 ppm cU_3O_8 .

3. Preliminary Results Using Analysis Scheme

Several of the numerical values used to calculate rU_3O_8 concentration were determined empirically at other labs and often contain significant uncertainties. The result could be systematic error in U_3O_8 concentration reported when using this scheme and it may be necessary to add a correction factor to equation (12). This factor will be determined empirically through a comparison of radiometrically and chemically determined U_3O_8 concentrations.

At this early stage of development of the Ge(Li) technique, errors reported for percent K, ppm gU_3O_8 , and ppm ThO_2 are twice the statistical values, i.e.

$$\text{Reported error} = 2 (N_p + 2N_b)^{1/2}$$

where

N_p is the net number of counts in the peak

N_b is the number of counts in the background under the peak.

While it is known that these error limits are too generous and will be reduced, they should not be lowered to just one times the statistical error because of unresolved uncertainties, such as uncertainties in reported standard concentrations, uncertainties in counting geometries from one can to the next, and uncertainties in self-absorption at even the higher energies used in determining percent K, ppm gU_3O_8 , and ppm ThO_2 . Similarly, at this early stage of development, it is felt no error limits can be presented for reported rU_3O_8 concentration.

Table 3 presents a comparison between chemically and radiometrically determined U_3O_8 concentrations for small can samples. Each sample was counted for 4,000 seconds. It should be assumed the same precision would result for the normal large can samples either with one-fourth the uranium concentration or for counting one-fourth the time.

TABLE 3

Comparison of Chemical and Radiometric U_3O_8 Assays. The Radiometric Assay Utilizes the 186 keV Intensity from the Decay of ^{235}U .

<u>U_3O_8 Concentration (ppm)</u>		
<u>Sample No.</u>	<u>Chemical</u>	<u>Radiometric</u>
12800	590	570
12281	1400	1000
12282	1000	1010
12283	430	490
12284	1590	1500
12285	4250	4260
12286	7700	8550
12287	640	740
12288	1270	1260
12289	2270	2300
12290	4640	4560

D. Conclusions and Recommendations

A high resolution Ge(Li) gamma-ray spectrometer has been installed and made operational for use in routine bulk sample analysis by the BFEC geochemical analysis department. The Ge(Li) spectrometer provides bulk sample analyses for potassium, uranium, and thorium that are superior to those obtained by the BFEC sodium iodide spectrometer.

The "near term" analysis scheme permits a direct assay for uranium that corrects for bulk sample self-absorption effects and is independent of the uranium/radium disequilibrium condition of the sample.

A more complete analysis scheme should be developed that fully utilizes the gamma-ray data provided by the Ge(Li) spectrometer and that more properly accounts for the sample self-absorption effect. Such a scheme has been devised under a BFEC subcontract to Nuclear Environmental Services/SAI. A report describing this scheme and its evaluation has been placed on open-file by the DOE/Grand Junction.¹⁰ This new analysis scheme should be implemented on the BFEC Ge(Li) spectrometer at the earliest date.

¹⁰J. E. Cline, "Development of New and Improved Data Reduction Techniques for Radiometric Assay of Bulk Uranium Ore Samples", Science Applications Inc., GJBX-124(78), 1977.

APPENDIX A

DESCRIPTION OF GAMMA SPECTROMETRY AS APPLIED TO LABORATORY BULK SAMPLE ANALYSIS

1) General Discussion

Gamma-ray photons emitted from nuclei undergoing decay have discrete energies characteristic of the nuclear species from which they were emitted. For example, when ^{235}U nuclei decay, gamma photons with 27 different characteristic energies can be emitted; the most frequent being 185.71 keV photons which are emitted in 56 percent of the decays.

For a bulk sample, some fraction of the gamma photons emitted from decaying nuclei contained in the sample are absorbed in the sample itself and are, in effect, totally lost to an observer of the bulk sample. This is a result of interactions between photons and atomic electrons in which all of the photon's energy is lost to the electron (photoelectric effect). This is an energy dependent phenomenon affecting low-energy photons most strongly and has the effect of changing the energy distribution of photons emanating from the bulk sample. For example, if 100 gamma photons were emitted from decaying nuclei in a sample, 50 of which possessed 100 keV of energy and 50 of which possessed 10 MeV of energy, it is quite possible, considering only the photoelectric effect, that the final distribution of photons might be 5 and 49 for 100 keV and 10 MeV, respectively.

An additional fraction of the gamma photons emitted by decaying nuclei do emanate from the bulk sample but no longer have energies characteristic of the nucleus from which they originated. This is a result of interaction with atomic electrons in which only a portion of the energy of the incident photon is lost to the electron (Compton scattering). This also is an energy dependent phenomenon and has the effect of further changing the energy distribution of "characteristic" photons emanating from the bulk sample. Accordingly, gamma photons emanating from a bulk sample can be divided into two categories: first are those which have not Compton scattered within the sample and have energies characteristic of the emitting nuclei, but have an altered energy distribution as a result of photoelectric interaction; second are those which have Compton scattered and have a continuous spectrum of energies from zero to near the maximum energy of the nuclear gamma photons. There is a less important third category of photons, those resulting from positron annihilation following pair production. These have the characteristic energy of 511.01 keV and only occur for gammas with energies >1022 keV.

The question to ask at this point is, can an analysis of the gamma photons emanating from a bulk sample yield quantitative information on the radioactive components of the sample? The answer is an unqualified yes if we know enough about the bulk sample, and fortunately, only a slightly qualified yes, if we do not. If the sample size, density, approximate spatial distribution of radionuclides, and approximate distribution of atomic numbers for the components of the sample are known, then it is possible to correct for all the distortions of the initial flux of gamma photons emitted from decaying nuclei in the sample. Once the initial gamma flux is reconstructed on paper, it

is a simple matter to determine quantitatively the radioactive constituents of a sample. The method is essentially one of counting up the number of photons emitted with characteristic energies for each of the nuclei being sought and multiplying by proportionality constants. Fortunately, even though this amount of detailed information about the sample is not generally known, the ranges of values found in practice are not extremely broad. Accordingly, techniques involving the comparison of the gamma flux from a typical (standard) bulk sample and the gamma flux from an unknown sample in the laboratory can be expected to yield results with relatively good precision.

The discussion above was idealized to the extent that no mention was made of the mechanism for detecting the gamma photons emanating from the sample. The ability to quantitatively assay the radioactive components of a bulk sample, knowing the emitted gamma flux, would be of little value if additional uncertainties were introduced in the detection process. Gamma photons undergo the same interactions in the detection process as they did in the bulk sample (photoelectric, Compton, and pair production). The effect of these competing interactions is indeed to distort the observed gamma flux. Fortunately, a great deal is known about the detectors used and this distortion can be corrected either theoretically by calculation or empirically by comparison with standard samples of known concentrations. Thus, in practice the answer to the question about the ability to perform quantitative analysis of bulk samples remains only a slightly qualified yes.

It is worth noting further that the accuracy of the assay is improved if only those gamma photons are considered which are detected as still possessing the full energy they had when they were initially emitted from the nucleus (these are the characteristic energies mentioned earlier). These gamma photons will not have interacted in the bulk sample and will have interacted in the detector to deposit their full energy generating photopeaks. With this simpler and more direct transport mechanism it is not necessary to consider a collection of mechanisms which can start with gamma photons with different initial energies, which interact in the bulk sample or detector to lose a portion of their energy and finally be detected as photons of the same energy. The result of using only photopeak (full energy) intensities in the assay technique is greater precision as a result of fewer uncertainties than those associated with more complicated mechanisms. This theme will be taken up again in Section 3 of this Appendix when mentioning one of the proposed new methods for KUT spectrographic analysis.

2) Description of the NaI(Tl) KUT Spectrometer and Analysis Schemes

The KUT gamma spectrometer presently in use in the Analytical Laboratory is shown as a block diagram in Figure A-1. The gamma detection system employs a NaI(Tl) crystal. Pulses from the detector are amplified and presented to the input of a 512 channel analyzer which sorts the pulses according to amplitude (gamma energy). After 2,400 seconds the data stored in the MCA is dumped to DEC 11/20 computer storage. At this point the data is transferred to magnetic tape in order to be processed on the CDC-3100.

FIGURE A-1. Block Diagram of Geochemical Analytical Laboratory KUT Spectrometer

There are three regions (windows) in the energy spectrum that respond to the characteristic gamma photons of potassium, uranium, and thorium.¹¹ These regions are shown in Figure A-2. It is the count rates recorded in these regions that are used to calculate percent K, ppm SU_3O_8 , and ppm ThO_2 . These calculations now proceed as follows¹²:

$$\text{Th(ppm)} = \frac{S_{\text{Th}} R_{\text{Th}}}{W} \times 10^4, \quad (1)$$

$$\text{sU(ppm)} = \frac{S_{\text{U}} (R_{\text{U}} - R_{\text{U,Th}})}{W} \times 10^4, \quad (2)$$

$$\%K = \frac{S_{\text{K}} (R_{\text{K}} - R_{\text{K,Th}} - R_{\text{K,U}})}{W} \quad (3)$$

where

Th(ppm) , sU(ppm) , and $\text{K(\%)}$ are the concentrations of thorium, uranium, and potassium,

S_{Th} , S_{U} , and S_{K} are the calibration coefficients for Th, U, and K,

R_{Th} , R_{U} , and R_{K} are the net count rates recorded in the Th, U and K windows.

$R_{\text{U,Th}}$, $R_{\text{K,Th}}$, and $R_{\text{K,U}}$ are the cross count rates recorded in the U window from Th, in the K window from Th, and in the K window from U, respectively, and are defined below. W is the weight of the sample.

The calibration coefficients are determined from standards:

$$S_{\text{Th}} = \frac{\text{Th(\%)}_{\text{std}} W_{\text{Th std}}}{R_{\text{Th std}}}, \quad (4)$$

$$S_{\text{U}} = \frac{\text{U(\%)}_{\text{std}} W_{\text{U std}}}{R_{\text{U std}}}, \quad (5)$$

$$S_{\text{K}} = \frac{\text{K(\%)}_{\text{std}} W_{\text{K std}}}{R_{\text{K std}}}. \quad (6)$$

¹¹In the case of uranium and thorium, it is actually gamma radiation from daughters that are detected. The ^{214}Bi 1765 keV line is used for uranium and the ^{208}Tl 2614 keV line is used for thorium. The assumption of secular equilibrium is implicit.

¹²Described in "Handbook of Analytical Procedures," RMO-3008, February 6, 1970.

FIGURE A-2. KUT Data Showing Window Placements. Data Collected in the Laboratory Using a Collection of ^{40}K , ^{226}Ra , and ^{228}Th Sources

The cross count rates are

$$R_{U,Th} = \frac{S_{Th} R_{Th}}{K_{U,Th}}, \quad (7)$$

$$R_{K,Th} = \frac{S_{Th} R_{Th}}{K_{K,Th}}, \quad (8)$$

$$R_{K,U} = \frac{S_U}{K_{K,U}} (R_U - R_{U,Th}), \quad (9)$$

where $K_{U,Th}$, $K_{K,U}$, and $K_{K,Th}$ are count conversion factors.

The count conversion factors are determined from standards:

$$K_{U,Th} = \frac{Th(\%)_{std} W_{Th std}}{R_{U,Th std} - (P_{Th,U} W_{Th std}/S_U)}, \quad (10)$$

$$K_{K,Th} = \frac{Th(\%)_{std} W_{Th std}}{R_{K,Th std} - (P_{Th,U} W_{Th std}/K_{K,U})}, \quad (11)$$

$$K_{K,U} = \frac{U(\%)_{std} W_{U std}}{R_{K,U std}}, \quad (12)$$

where $P_{Th,U}$ is the percent U in the Th standard.

These equations are quite involved; yet they still possess the basic deficiency of not correcting for uranium peaks entering partially into the thorium window, as shown in Table A-1. What is needed is a $R_{Th,U}$ term subtracted from R_{Th} in equation (1). This deficiency has been corrected through the implementation of the analysis program KOSNAI.

The complexity of the preceding equations arises directly from the broad window method used to collect data with the present KUT system. The data recorded in the windows comes from three principal sources (see Table A-1): first is a contribution from photopeaks falling in the window from the decay of nuclei for which the window was meant to detect; second is a contribution from photopeaks falling partially in the window from the decay of other

TABLE A-1

Some of the Prominent KUT Photo Peaks Falling at Least
Partially in the KUT Windows^(1, 2)

Window	Energy (keV)	Source	Decay Chain	Relative Photo-Peak Intensity ⁽³⁾	
T	2614	208 Tl	Th	6.4	← { Thorium Signature Peak
H	2448	214 Bi	U	1.6	
O	2204	214 Bi	U	5.3	
R	2119	214 Bi	U	1.3	
I	{ Sample	{ Photo Peaks	{ U and	-	
U	{ Compton	{ >2070 keV	{ Th		
M	{ Detector	{ Photo Peaks	{ U and	-	
	{ Compton	{ >2300 keV	{ Th		
	2204	214 Bi	U	5.3	
	2119	214 Bi	U	1.3	
	2103	2614 S.E.	U	-	
	1848	214 Bi	U	2.3	
U	1765	214 Bi	U	16.7	← { Uranium Signature Peak
R	1730	214 Bi	U	3.2	
A	1661	214 Bi	U	1.2	
N	1631	228 Ac	Th	0.98	
I	1588	228 Ac	Th	2.3	
U	1580	228 Ac	Th	0.45	
M	{ Sample	{ Photo Peaks	{ U and	-	
	{ Compton	{ >1495 keV	{ Th		
	{ Detector	{ Photo Peaks	{ U and	-	
	{ Compton	{ >1715 keV	{ Th		
	1661	214 Bi	U	1.2	
	1631	228 Ac	Th	0.98	
	1588	228 Ac	Th	2.3	
P	1580	228 Ac	Th	0.45	
O	1509	214 Bi	U	2.2	
T	1502	228 Ac	Th	0.35	
A	1496	228 Ac	Th	0.62	
S	1461	40 K	K	0.47	← { Potassium Signature Peak
S	1459	228 Ac	Th	0.59	
I	1408	214 Bi	U	2.6	
U	1378	214 Bi	U	4.3	
M	{ Sample	{ Photo Peaks	{ K, U and	-	
	{ Compton	{ >1225 keV	{ Th		
	{ Detector	{ Photo Peaks	{ K, U and	-	
	{ Compton	{ >1440 keV	{ Th		

Note: (1) Contributions in windows due to pile-up are neglected.
(2) Because of the inherently poor resolution (~9 percent) of NaI detectors, window contributions will occur from outside the window settings.

	Window	Fringe
K	1360-1560	1240-1700
U	1660-2300	1510-2505
T	2300-3000	2095-3270

(3) Assumes concentrations of 5 percent K, 500 ppm U, and 100 ppm Th.

radionuclides present in the the sample ¹³; third, and usually largest, is a contribution from Compton scattered photons. In the analysis of the data, it is necessary to subtract out the latter two contributions. The problem with this is not the extra mathematics but the additional uncertainties (errors) that can result.

3) Brief Description of the Ge(Li) Technique

As a result of the Ge(Li) gamma spectrometer developmental project it is possible to use only photopeak data in the determination of KUT concentrations. This is achieved by the use of a high resolution Ge(Li) detection system (50 times greater resolution than the present NaI system) in conjunction with a larger multichannel analyzer. See Figure A-3 for a graphic comparison of NaI(Tl) and Ge(Li) spectrometer resolution. Table A-2 identifies the many peaks observed in the Ge(Li) spectrum. As a result of the higher resolution of the spectrometer, interfering photopeaks are eliminated (the second contribution discussed above for the present KUT system). Similarly, as a result of higher resolution, the Compton continuum (the third contribution above) can be accounted for by the ability to accurately establish the background under the photopeaks. Accordingly, the equations for calculating KUT concentrations are simply:

$$\text{ThO}_2(\text{ppm}) = \frac{S_{\text{ThO}_2} R_{2614}}{W} \quad (1)$$

$$\text{gU}_3\text{O}_8(\text{ppm}) = \frac{S_{\text{gU}_3\text{O}_8} R_{1765}}{W} \quad (2)$$

$$K(\%) = \frac{S_K R_{1461}}{W} \quad (3)$$

The symbols were defined previously for equations (1), (2), and (3). Here a distinction has been made in the uranium concentration, with $\text{gU}_3\text{O}_8(\text{ppm})$ taken to mean uranium concentration as determined using the ²¹⁴Bi 1765 keV line. The reason for this is that this technique can be used to determine ²³⁵U and/or ²³⁸U directly¹⁴, requiring no assumption of secular equilibrium. Equation (3) assumes there is no interference from the 1459 keV intensity of ²⁰⁸Tl.

¹³For example, four uranium and six thorium photopeaks fall at least partially in the potassium window.

¹⁴For a more complete discussion of this technique, see Ken Kosanke, "Sample Assay Using a Ge(Li) Detector," R&D Project #5001, September, 1975. Also, see the main text of this report.

Comparison of NaI & Ge(Li) Detector Resolution

A-9

FIGURE A-3. Comparison of NaI and Ge(Li) Detector Resolution

TABLE A-2

Peak Identification for Figure A-3

Data Point	Energy (keV)	Source Nuclide	Decay Chain	Data Point	Energy (keV)	Source Nuclide	Decay Chain
(1)	<100	X-rays		(23)	1079	$^{212}_{\text{Bi}}$	$^{232}_{\text{Th}}$
(2)	144	$^{235}_{\text{U}}$	$^{235}_{\text{U}}$	(24)	1120	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(3)	186	$^{235}_{\text{U}}$	$^{235}_{\text{U}}$	(25)	1156	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
	186	$^{226}_{\text{Ra}}$	$^{238}_{\text{U}}$	(26)	1208	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(4)	239	$^{212}_{\text{Pb}}$	$^{232}_{\text{Th}}$	(27)	1238	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
	242	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$	(28)	1254	1765S.E.	$^{238}_{\text{U}}$
(5)	270	$^{228}_{\text{Ac}}$	$^{232}_{\text{Th}}$	(29)	1281	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
	277	$^{208}_{\text{Tl}}$	$^{232}_{\text{Th}}$	(30)	1378	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(6)	295	$^{214}_{\text{Pb}}$	$^{238}_{\text{U}}$	(31)	1408	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(7)	352	$^{214}_{\text{Pb}}$	$^{238}_{\text{U}}$	(32)	1461	$^{40}_{\text{K}}$	$^{40}_{\text{K}}$
(8)	463	$^{228}_{\text{Ac}}$	$^{232}_{\text{Th}}$	(33)	1509	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(9)	511	$^{208}_{\text{Tl}}$	$^{232}_{\text{Th}}$	(34)	1539	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(10)	583	$^{208}_{\text{Tl}}$	$^{232}_{\text{Th}}$	(35)	1543	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(11)	609	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$	(36)	1588	$^{228}_{\text{Ac}}$	$^{232}_{\text{Th}}$
(12)	665	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$	(37)	1592	2614D.E.	$^{232}_{\text{Th}}$
(13)	727	$^{212}_{\text{Bi}}$	$^{232}_{\text{Th}}$	(38)	1631	$^{228}_{\text{Ac}}$	$^{238}_{\text{U}}$
(14)	769	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$	(39)	1661	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(15)	772	$^{228}_{\text{Ac}}$	$^{232}_{\text{Th}}$	(40)	1730	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(16)	795	$^{228}_{\text{Ac}}$	$^{238}_{\text{U}}$	(41)	1765	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(17)	806	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$	(42)	1848	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(18)	836	$^{228}_{\text{Ac}}$	$^{232}_{\text{Th}}$	(43)	2103	2614S.E.	$^{232}_{\text{Th}}$
(19)	860	$^{208}_{\text{Tl}}$	$^{232}_{\text{Th}}$	(44)	2119	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(20)	911	$^{228}_{\text{Ac}}$	$^{232}_{\text{Th}}$	(45)	2204	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(21)	935	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$	(46)	2448	$^{214}_{\text{Bi}}$	$^{238}_{\text{U}}$
(22)	1001	$^{234\text{m}}_{\text{Pa}}$	$^{238}_{\text{U}}$	(47)	2614	$^{208}_{\text{Tl}}$	$^{232}_{\text{Th}}$

APPENDIX B

LISTING OF GAMMA TRANSITIONS IN THE ^{238}U , ^{235}U , and ^{232}Th DECAY CHAINS

From "High-Resolution Gamma Ray Spectrometry for Laboratory Analysis of the Uranium and Thorium Decay Series" by A. R. Smith and H. A. Wollenberg, contained in The Natural Radiation Environment II. NTIS conf-720805-P-1.

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APPENDIX I: GENERAL COMMENTS

The Ge(Li) γ -ray spectrometer can now resolve many of the closely spaced γ -lines from the natural radioactive heavy-element series (U-238, U-235, Th-232), providing information useful for disequilibrium determinations as well as for the usual "total" U and Th assays. Thus a detailed listing of γ -ray energies and intensities from these families is of increased practical significance. The compilations given here include experimental data available up to the date of this symposium. General references consulted include Lederer et al. (1967), Way (1965-68; 1966-68; 1968-72), and Nuclear Data Group (1969-72). Specific references have been consulted in cases where new data had been reported since 1966. Such references are included in each section of this appendix, keyed to the isotopes studied.

The γ -rays within each family are ordered by energy; energies are given in keV; absolute intensities are given in numbers of photons emitted per 100 decays of the longest-lived parent; and identification, as belonging to the decaying nuclide.

Energy values assigned by different experimenters are frequently in agreement to within 0.1 keV, except for some of the weaker γ -lines. On the other hand, intensity values reported by different experimenters often disagree by 5-10%, even for the most intense γ -lines, with correspondingly greater disagreements for the weaker lines. Although energy calibration of Ge(Li) spectrometers can be reliably accomplished with these sources, it is questionable whether absolute efficiency calibrations can be similarly established until the discrepancies are resolved.

The detailed lists given here call attention to the problem of observing weak γ -lines that have energies lower than strong γ -lines. The Ge(Li) detector response gives a spectral shape in which the total absorption peak stands above the level of its lower-energy continuum by a factor varying between 10- and 100-fold, depending on γ -ray energy and region of interest in the continuum. Weak γ -lines 100 times less intense than a strong higher-energy γ -line should be easily measurable; γ -lines as much as 1000-10000 times weaker than the strong line can be observed in favorable cases.

APPENDIX Ia: U-238 DECAY SERIES

The ratio U-235/U-238 is (nearly) constant in nature; it follows that both decay series will always appear in the same proportions under equilibrium conditions. We include U-235 series γ -rays along with U-238 γ -rays for this reason, in proportion calculated from: U-235/U-238 ratio of 0.00711 on a weight basis; U-238 half life of 4.51×10^9 years; and, U-235 half life of 7.13×10^8 years (Hyde et al., 1964). Intensities of U-235 series γ -rays in this list are 0.0450 times the intensities listed for this series in Appendix Ib. Note that U-235 series members are all odd-mass isotopes, while U-238 series members are all even-mass isotopes; this is a simple way to distinguish between the two families.

In the U-238 series, γ -rays listed for Ra-226 are derived primarily from the detailed list of Ra-226 in equilibrium with its daughters (Lingeman et al., 1969). We have assigned the γ -rays from this list to specific daughter nuclides, but all γ -rays not known to belong to particular nuclides have been assigned to Bi-214. All strong γ -lines are correctly assigned; it is only some of the weak ones which are inferentially assigned.

ISOTOPE REFERENCES

U-238	Lederer 1967
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U-234	Lederer 1967
Pa-234	Borggreen 1968, Gunnink 1971, Wapstra 1967
Pa-234M	Gunnink 1971, Wapstra 1967
Th-234	Foucher 1962, Foucher 1965
Th-230	Lederer 1967
Ra-226	Gunnink 1969, Lederer 1967, Lingeman 1969,
Rn-222	Lingeman 1969
At-218	Lederer 1967
Po-218	Lederer 1967
Po-214	Lederer 1967
Po-210	Lederer 1967
Bi-214	Gunnink 1969, Lingeman 1969
Bi-210	Lederer 1967
Pb-214	Gunnink 1969, Lingeman 1969
Pb-210	Lederer 1967, Lingeman 1969
Tl-210	Lederer 1967, Lingeman 1969
Tl-206	Lederer 1967
Hg-206	Wolf 1968

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Pa-231	25.54	1.21E-04	Fr-223	49.80	2.34E-02
Pa-231	27.35	1.26E-02	Th-227	50.20	3.86E-01
Pa-231	29.95	1.24E-04	Th-227	50.70	7.11E-04
Pa-231	31.00	1.21E-05			
Pa-231	31.54	9.45E-06	Pa-231	50.98	1.89E-06
Pa-234	34.30	4.74E-06	Th-227	51.20	unknown
Pa-231	35.82	2.16E-05	Pa-231	52.74	1.15E-04
Pa-231	38.20	2.01E-04	Pb-214	53.23	2.20E+00
Pa-231	39.57	1.89E-06	U-234	53.30	1.18E-01
Pa-231	39.97	1.62E-05	Th-227	54.20	unknown
Th-227	40.10	unknown	Pa-231	54.61	1.09E-04
Th-227	42.20	3.55E-03	Th-227	56.10	8.88E-05
Pa-231	42.48	8.10E-06	Pa-231	56.76	8.10E-06
Th-231	42.81	2.43E-03	Pa-231	57.19	5.26E-05
Pa-231	43.05	9.45E-06	Pa-234	58.20	7.11E-06
Pa-234	43.40	3.32E-04	Th-231	58.55	1.89E-02
Th-227	43.50	1.07E-02	Th-227	59.60	4.00E-04
Th-227	43.80	2.22E-03	Pa-231	60.50	9.45E-06
Th-227	44.10	3.11E-04	Th-227	61.50	unknown
Pa-231	44.16	8.10E-05	Th-227	62.00	unknown
Th-227	44.30	5.77E-04	Th-227	62.50	1.11E-02
Pa-234	45.19	2.37E-05	Th-227	62.70	4.00E-04
Pa-231	46.37	2.81E-04	Th-234	62.80	6.70E-03
Pb-210	46.52	4.10E+00	Th-234	63.30	5.69E+00
Th-227	48.30	unknown	Pa-234	63.40	6.64E 03
Th-227	48.50	2.00E-03	Pa-231	63.67	6.75E-05
Th-227	49.80	8.88E-03	Th-227	64.50	1.24E-03

*Decaying isotope

[†] Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Pb-211	65.40	1.80E-03	Fr-223	100.00	5.85E-04
Th-227	66.20	2.66E-04	Th-227	100.40	3.55E-03
Th-227	66.40	3.11E-04	Pa-231	100.92	4.32E-05
Pa-234	67.10	9.48E-05	Th-231	102.29	1.71E-02
Th-230	67.80	3.81E-01	Th-227	102.50	unknown
Th-227	68.70	8.88E-05	Pa-231	102.60	2.70E-05
Th-227	68.80	1.24E-03	Pa-234	103.41	3.08E-03
Th-227	69.80	4.00E-04	U-235	104.82	2.05E-02
Pa-234	69.90	5.45E-04	U-235	105.61	4.09E-02
Ac-227	70.00	7.02E-04	Ac-227	106.50	5.85E-05
Pa-231	70.50	9.45E-06	Ra-223	106.80	9.90E-04
Pa-231	71.90	2.70E-06	Th-231	107.60	3.06E-03
Pa-231	72.50	5.40E-06	Th-227	108.00	3.11E-04
Th-231	72.76	9.90E-03	Th-231	108.44	5.89E-02
Th-227	72.90	3.55E-04	Th-227	109.60	2.66E-04
Th-227	73.70	7.55E-04	Th-230	110.00	6.45E-05
Pa-231	74.18	3.37E-05	Th-227	110.60	8.88E-05
Th-227	75.30	4.00E-04	Ra-223	110.80	2.52E-03
Pa-231	77.36	9.18E-05	Th-231	111.54	2.45E-03
Pa-234	79.69	3.08E-04	Th-231	112.48	8.73E-04
Th-227	79.70	7.99E-02	Th-227	112.60	3.55E-04
Tl-210	80.00	unknown	Th-227	113.10	2.40E-02
Fr-223	80.00	7.60E-03	Th-234	115.00	4.22E-01
Th-231	81.21	3.35E-02	Th-231	116.83	9.00E-04
Th-231	82.06	1.53E-02	Th-227	117.00	7.11E-03
Th-231	84.20	2.52E-01	Th-227	117.50	5.33E-04
Ac-227	85.60	1.58E-03	U-234	120.90	4.13E-02
Th-227	89.90	unknown	Ac-227	121.50	2.34E-04
Th-231	89.93	3.78E-02	Ra-223	122.30	5.98E-02
U-235	89.96	1.10E-01	Th-227	123.60	3.55E-04
Th-231	92.27	1.71E-02	Th-227	124.40	8.88E-05
Th-234	92.30	3.15E+00	Pa-231	124.60	6.75E-06
Th-234	92.80	3.55E+00	Th-227	124.70	1.33E-04
Th-231	92.94	2.97E-03	Th-231	124.95	2.40E-03
U-235	93.35	1.80E-01	Pa-234	125.20	2.13E-03
Th-227	94.00	6.00E-02	Rn-219	130.70	4.68E-03
Th-227	95.00	unknown	Pa-234	131.00	4.74E-02
Pb-211	95.00	5.98E-04	Ac-227	133.50	1.17E-04
Th-231	95.85	2.52E-02	Th-231	134.03	9.81E-04
Th-227	96.10	2.00E-03	Th-227	134.20	1.33E-04
Pa-231	96.88	1.19E-04	Pa-234	134.37	3.55E-04
Tl-210	97.00	8.40E-04	Th-231	135.69	3.23E-03
Th-231	99.27	5.31E-03	Th-234	136.00	3.35E-02
Ac-227	99.50	1.17E-03	Fr-223	136.00	2.34E-04
Th-227	99.50	unknown	Th-231	136.80	1.35E-04
Pa-234	99.67	1.26E-02	Pb-214	137.45	6.00E-02
Th-227	99.70	unknown	Pa-234	139.97	1.97E-03

*Decaying isotope

[†] Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Th-227	140.50	1.42E-03	Pa-234	193.40	1.90E-03
U-235	140.75	9.36E-03	U-235	194.94	2.77E-02
Th-227	141.20	2.89E-03	Pb-214	196.30	5.00E-02
Pb-214	141.30	4.00E-02	Pa-234	196.40	1.18E-03
Th-230	142.00	4.51E-02	Th-227	197.60	4.44E-04
U-235	143.77	4.81E-01	Pa-231	199.00	8.10E-06
Ra-223	144.19	1.41E-01	Pa-234	199.70	2.37E-03
Pa-234	144.35	7.11E-04	Th-227	200.50	2.22E-04
Pa-231	144.50	1.62E-05	Pa-234	200.60	2.37E-03
Th-231	145.13	2.52E-04	Th-227	201.80	9.77E-04
Th-231	145.96	1.26E-03	U-235	202.10	4.81E-02
Ac-227	147.00	3.51E-04	Th-227	202.50	2.66E-04
Th-227	149.80	7.99E-04	Pa-234	202.90	2.84E-03
Pa-234	150.20	4.74E-04	Th-227	204.20	1.02E-02
Pa-234	152.46	1.42E-02	Fr-223	205.00	4.68E-04
Ra-223	154.18	2.35E-01	Th-227	205.20	7.55E-03
Th-234	155.00	2.68E-02	U-235	205.33	2.19E-01
Ra-223	158.62	3.42E-02	Pb-214	205.59	1.50E-02
Pa-234	159.10	1.18E-03	Th-230	206.00	3.22E-06
Ac-227	160.00	8.19E-04	Th-227	206.10	1.15E-02
Th-227	162.20	2.66E-04	Th-227	206.40	1.78E-04
Th-231	163.16	6.25E-03	Th-227	210.60	5.60E-02
U-235	163.37	2.18E-01	Th-227	212.60	3.78E-03
Th-234	167.00	2.68E-02	Th-227	212.70	7.55E-04
Th-227	168.20	6.22E-04	U-235	215.35	1.24E-03
Fr-223	170.00	1.40E-04	Th-227	218.80	2.44E-03
Th-227	170.10	1.33E-04	Th-227	219.00	2.00E-03
Pa-234	170.77	1.18E-03	Pa-234	219.60	4.74E-04
Th-227	171.40	unknown	Rn-219	222.00	1.26E-03
Ac-227	172.00	2.34E-04	Th-227	224.70	6.66E-04
Th-227	173.40	4.89E-04	Pa-234	226.15	1.52E-02
Th-227	175.80	7.99E-04	Pa-234	227.00	1.42E-02
Ra-223	176.00	9.45E-04	Th-227	230.40	unknown
Ra-223	177.30	9.45E-04	U-235	233.54	1.24E-03
Ra-223	179.60	6.75E-03	Fr-223	234.00	2.11E-03
Pa-234M	182.50	1.66E-03	Th-227	234.90	2.58E-02
U-235	182.57	1.62E-02	Th-230	235.00	3.22E-06
Th-234	184.00	1.34E-02	Th-227	236.00	5.11E-01
Th-230	184.00	9.03E-03	Pb-214	238.40	1.50E-02
Th-227	184.70	1.20E-03	U-235	240.93	2.88E-03
U-235	185.72	2.52E+00	Pb-214	241.92	7.60E+00
Pa-234	185.95	4.03E-03	Pa-231	242.20	1.08E-05
Ra-226	186.00	3.90E+00	Pa-231	243.00	4.59E-05
Ac-227	190.00	2.92E-05	Pa-234	245.00	2.37E-03
Fr-223	190.00	unknown	Pa-231	245.40	9.45E-06
Ra-223	193.00	4.50E-04	Pa-231	246.00	1.35E-06
			Th-227	246.40	5.33E-04

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
U-235	246.88	2.34E-03	U-235	291.63	9.00E-04
Pa-234	248.80	5.92E-03	Th-227	292.30	2.44E-03
Th-227	249.60	3.11E-04	Rn-219	294.00	2.65E-03
Th-227	250.20	1.24E-02	Pa-234	294.90	4.80E-03
Th-227	250.40	3.11E-03	Pb-214	295.22	1.89E+01
Ra-223	251.70	2.56E-03	Tl-210	296.00	1.68E-02
Th-227	252.50	4.89E-03	Th-227	296.60	1.73E-02
Th-230	253.00	1.10E-02	Pb-214	298.76	2.00E-02
Th-227	254.70	4.04E-02	Pa-231	299.94	3.05E-03
Ra-223	255.00	2.25E-03	Th-227	300.00	8.39E-02
Pa-231	255.78	1.36E-04	Th-227	300.30	1.24E-02
Th-227	256.20	2.80E-01	Pa-231	302.52	3.16E-03
Th-230	257.00	5.16E-04	Bi-214	303.00	8.00E-02
Pa-234M	258.23	7.30E-02	Th-227	304.40	6.00E-02
Pa-231	258.40	3.10E-06	Hg-206	305.00	7.20E-07
Pb-214	258.82	8.00E-01	Pb-214	305.40	3.00E-02
Ra-226	260.00	7.00E-03	Th-227	308.50	6.66E-04
Pa-231	260.14	2.34E-04	Pa-231	310.00	1.89E-06
Th-227	262.70	4.44E-03	Th-227	312.60	2.31E-02
Th-227	267.00	unknown	Pa-231	312.88	1.28E-04
Th-227	267.90	unknown	Pb-211	313.60	5.98E-04
Ra-223	269.41	6.12E-01	Pb-214	314.20	8.00E-02
Th-227	270.50	unknown	Th-227	314.80	2.40E-02
Th-227	270.70	1.42E-03	Th-227	314.80	1.11E-03
Rn-219	271.20	4.47E-01	Th-227	318.80	2.66E-04
Pa-234	271.85	2.37E-03	Th-227	319.20	7.99E-04
Pa-234	272.00	7.11E-04	Fr-223	320.00	4.68E-04
Th-227	273.00	2.18E-02	Ra-223	323.88	1.62E-01
Pa-231	273.08	7.83E-05	Pb-214	324.30	2.00E-02
Bi-214	273.50	8.00E-02	Th-227	325.20	2.22E-04
Pb-214	274.80	7.00E-01	Th-227	326.20	8.88E-05
U-235	275.34	1.21E-03	Pa-231	327.02	4.05E-05
Pa-231	276.99	9.04E-05	Ra-223	328.50	7.29E-03
Th-227	279.70	4.00E-03	Pa-231	329.89	1.75E-03
Th-227	281.00	unknown	Th-227	329.90	1.29E-01
Bi-214	281.10	6.00E-02	Ra-223	333.80	5.58E-03
Th-227	281.40	6.66E-03	Bi-214	334.30	6.00E-02
Pa-231	283.56	2.12E-03	Th-227	334.40	5.11E-02
Th-227	284.30	1.11E-03	Ra-223	338.30	1.17E-01
Th-227	285.60	2.44E-03	Bi-214	338.50	4.00E-02
Th-227	286.20	7.33E-02	Th-227	339.80	unknown
Pa-231	286.55	1.21E-05	Pa-231	340.61	2.23E-04
Bi-214	286.90	3.00E-02	Th-227	342.50	8.44E-03
Ra-223	288.40	6.61E-03	Pb-211	342.70	8.98E-04
Th-227	289.60	1.78E-04	Ra-223	342.90	9.45E-03
Fr-223	290.00	3.51E-04	U-235	345.89	1.35E-03

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Th-227	346.30	3.55E-04	Bi-214	426.50	1.00E-01
Ra-223	346.80	7.65E-03	Pb-211	426.90	8.20E-02
Th-227	348.50	2.66E-04	Pb-211	429.10	3.89E-04
Fr-223	350.00	5.85E-05	Ra-223	432.00	1.35E-03
Th-227	350.50	3.55E-04	Th-227	432.50	1.78E-04
Bi-211	351.10	5.98E-01	Pa-231	435.10	4.45E-06
Pb-214	351.99	3.63E+01	Pa-231	437.90	5.53E-06
Th-227	352.60	4.00E-04	Pa-231	438.70	2.02E-06
Pa-231	354.38	1.28E-04	Bi-214	440.40	3.00E-02
Pa-231	356.96	2.34E-04	Ra-223	444.92	5.71E-02
Pa-231	359.25	1.21E-05	Pa-234M	451.00	3.50E-03
Tl-210	360.00	8.40E-04	Pa-234	453.90	2.10E-03
Ra-223	361.50	2.25E-03	Bi-214	455.00	2.80E-01
Th-227	362.50	1.78E-04	Pa-234	458.20	2.20E-03
Pa-231	363.74	9.99E-06	U-234	460.00	1.18E-05
Th-227	369.40	1.78E-04	Pb-214	462.10	1.70E-01
Pa-234	369.50	4.80E-03	Pa-234	468.30	1.96E-03
Th-227	370.90	8.88E-05	Pb-214	470.60	1.00E-02
Ra-223	371.50	2.43E-02	Bi-214	474.60	7.00E-02
Pa-234	371.90	2.30E-03	Pa-234	475.90	1.73E-03
Pa-231	374.90	6.21E-06	Tl-210	480.00	4.20E-04
Th-227	375.10	4.44E-05	Pb-214	480.50	3.40E-01
Ra-223	376.00	5.40E-04	Pa-231	486.70	2.43E-06
Pa-231	379.09	6.61E-05	Pb-214	487.25	3.30E-01
Tl-210	380.00	6.30E-04	Ra-223	488.00	6.75E-04
Th-227	382.40	2.66E-04	Pa-231	491.00	6.75E-07
Ra-223	382.50	6.75E-04	Pa-231	501.60	8.10E-07
Th-227	383.60	8.88E-05	Pb-211	503.60	3.59E-05
Pa-231	384.70	5.53E-06	Pa-231	509.00	4.05E-07
Bi-214	386.80	3.10E-01	U-234	510.00	1.18E-05
Pa-231	387.00	6.75E-07	Rn-222	511.00	1.00E-01
U-235	387.81	5.40E-04	Pb-214	511.00	3.00E-02
Bi-214	388.80	3.70E-01	Pa-231	516.20	1.75E-06
Pa-231	391.50	9.18E-06	Rn-219	516.50	9.90E-04
Th-227	392.40	4.00E-04	Ra-223	527.00	3.15E-03
Ra-223	393.50	4.95E-04	Pb-214	533.80	1.70E-01
Pa-231	395.50	3.51E-06	Pa-231	535.20	6.75E-07
Bi-214	396.30	3.00E-02	Bi-214	536.60	4.00E-02
Pa-231	398.10	1.26E-05	Pb-214	538.70	5.00E-03
Rn-219	401.80	2.92E-01	Bi-214	543.50	1.00E-01
Th-227	402.50	1.78E-04	Pa-234	544.00	3.50E-03
Pb-211	404.80	1.77E-01	Pb-214	544.00	6.00E-02
Bi-214	405.90	1.50E-01	Pa-231	546.60	8.10E-07
Pa-231	407.71	4.86E-05	Bi-214	546.80	3.00E-02
Pa-231	410.50	2.56E-06	Pa-234	569.29	2.02E-02
Th-227	415.20	4.44E-05	Po-211	569.60	7.20E-05
Ra-226	420.00	2.00E-04	Pa-231	572.10	6.75E-07

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Bi-214	572.60	6.00E-02	Tl-210	798.20	3.00E-02
U-234	580.00	7.08E-06	Po-214	799.00	1.40E-02
Pb-214	580.30	3.60E-01	Po-210	803.00	1.10E-03
Ra-223	598.50	4.18E-03	Pa-234	805.80	7.60E-03
Ra-223	609.00	2.83E-03	Bi-214	806.20	1.10E+00
Pb-211	609.30	1.50E-03	Pa-234	808.40	2.87E-03
Bi-214	609.37	4.28E+01	Bi-214	815.00	4.00E-02
Ra-226	610.00	2.00E-04	Pa-234	819.10	2.30E-03
Bi-214	615.80	9.00E-02	Bi-214	821.20	1.60E-01
Ra-223	632.00	1.35E-03	Pa-234M	825.00	6.00E-03
Bi-214	633.60	5.00E-02	Bi-214	826.00	1.30E-01
Bi-214	639.00	3.00E-02	Pa-234M	831.30	7.40E-03
Bi-214	649.40	5.00E-02	Pb-211	831.80	1.44E-01
Hg-206	652.00	1.00E-07	Bi-214	832.00	3.00E-02
Pa-234	654.30	2.16E-03	Bi-214	839.20	5.90E-01
Bi-214	665.60	1.40E+00	Pa-234M	851.66	7.40E-03
Tl-210	670.00	4.20E-04	Tl-210	860.00	1.47E-03
Pb-211	675.20	5.98E-04	Pb-211	865.20	4.19E-04
Rn-219	677.00	2.70E-04	Pa-234	866.50	1.20E-03
Bi-214	683.30	8.00E-02	Pa-234	876.10	4.00E-03
Pa-234	691.30	9.00E-03	Pa-234	880.50	1.96E-02
Bi-214	693.30	3.00E-02	Pa-234	883.24	1.97E-02
Bi-214	698.40	7.00E-02	Pa-234	887.39	6.30E-03
Pa-234	699.00	6.00E-03	Pb-211	897.30	1.38E-02
Pa-234	701.10	7.00E-03	Po-211	897.30	7.63E-05
Bi-214	703.10	4.70E-01	Tl-207	897.30	7.18E-03
Pb-211	704.30	2.21E-02	Pa-234	898.67	4.50E-03
Pa-234	706.00	7.00E-03	Pb-214	904.10	5.90E-01
Bi-214	710.80	6.00E-02	Bi-214	904.10	7.00E-02
Bi-214	719.90	3.80E-01	Tl-210	910.00	6.30E-04
Bi-214	727.00	5.00E-02	Pa-234	921.77	1.25E-02
Pa-234	733.39	1.06E-02	Pa-234	925.07	1.36E-02
Bi-214	734.30	3.00E-02	Pa-234	926.68	1.91E-02
Pa-234	739.70	1.10E-02	Bi-214	934.00	3.10E+00
Pa-234M	742.79	9.50E-02	Pa-234	936.70	7.50E-04
Bi-214	753.00	1.10E-01	Pa-234	941.50	2.40E-03
Pa-234M	766.39	3.13E-01	Pa-234	946.07	3.55E-02
Pb-211	766.40	2.93E-02	Bi-214	964.10	3.70E-01
Pb-214	768.40	8.00E-02	Pa-234	965.70	5.65E-04
Bi-214	768.40	4.80E+00	Pa-234	980.50	4.20E-03
Fr-223	780.00	4.68E-04	Pa-234	984.10	2.70E-03
Pa-234	781.50	7.00E-03	Pa-234	994.90	7.48E-03
Pb-214	785.95	8.60E-01	Pa-234M	1001.10	8.28E-01
Bi-214	786.10	2.90E-01	Pb-211	1014.10	8.98E-04
Pa-234M	786.30	5.50E-02	Pa-234	1028.70	5.54E-04
Pa-234	796.40	6.65E-03	Bi-214	1032.50	7.00E-02
			Pa-234	1041.70	9.58E-04

*Decaying isotope

[†] Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Pa-234	1044.30	7.46E-04	Pa-234M	1510.32	1.30E-02
Bi-214	1052.00	3.30E-01	Pa-234M	1527.25	2.18E-03
Tl-210	1060.00	2.52E-03	Bi-214	1538.70	5.30E-01
Pa-234	1061.86	2.40E-03	Tl-210	1540.00	4.20E-04
Bi-214	1070.00	2.60E-01	Bi-214	1543.30	3.40E-01
Pb-211	1080.00	4.79E-04	Pa-234	1548.24	1.40E-03
Pa-234	1083.70	1.60E-03	Pa-234M	1553.80	8.20E-03
Bi-214	1104.00	1.60E-01	Pa-234	1558.90	7.00E-04
Pb-211	1109.10	4.85E-03	Pa-234M	1570.80	1.05E-03
Tl-210	1110.00	1.47E-03	Bi-214	1583.30	7.30E-01
Bi-214	1120.40	1.50E+01	Tl-210	1590.00	4.20E-04
Pa-234	1122.00	6.53E-04	Pa-234	1593.20	2.65E-03
Pa-234M	1125.10	4.70E-03	Pa-234M	1593.20	3.40E-04
Bi-214	1133.80	2.50E-01	Bi-214	1594.80	3.00E-01
Pa-234	1151.10	3.90E-04	Bi-214	1599.50	3.40E-01
Bi-214	1155.30	1.70E+00	Pa-234	1638.10	3.80E-04
Bi-214	1172.90	3.00E-02	Tl-210	1650.00	4.20E-04
Pa-234M	1193.76	1.34E-03	Pa-234	1654.10	3.30E-04
Pb-211	1195.50	4.79E-04	Bi-214	1661.40	1.16E+00
Bi-214	1207.80	4.70E-01	Pa-234	1668.40	1.20E-03
Tl-210	1210.00	3.57E-03	Bi-214	1684.10	2.40E-01
Pa-234	1220.10	8.75E-04	Pa-234	1685.80	2.97E-04
Pa-234M	1237.26	4.90E-03	Pa-234	1694.30	1.28E-03
Bi-214	1238.20	6.10E+00	Pa-234	1716.50	1.94E-04
Pb-211	1270.00	4.79E-04	Bi-214	1729.80	3.20E+00
Bi-214	1281.00	1.50E+00	Pa-234M	1737.91	2.12E-02
Pa-234	1292.70	8.60E-04	Pa-234	1750.20	1.61E-04
Bi-214	1303.80	1.10E-01	Pa-234M	1760.05	1.44E-03
Tl-210	1310.00	4.41E-03	Bi-214	1764.60	1.67E+01
Bi-214	1317.10	7.00E-02	Pa-234M	1765.80	7.60E-03
Pa-234	1320.50	2.90E-04	Bi-214	1782.10	1.50E-02
Pa-234	1352.90	2.24E-03	Pa-234M	1796.70	5.70E-04
Bi-214	1377.70	4.30E+00	Pa-234M	1809.25	3.70E-03
Bi-214	1385.40	8.00E-01	Pa-234	1819.80	8.55E-04
Pa-234M	1393.50	3.70E-03	Pa-234M	1831.48	1.75E-02
Bi-214	1401.60	1.50E+00	Bi-214	1838.60	3.70E-01
Bi-214	1408.00	2.60E+00	Bi-214	1847.60	2.30E+00
Tl-210	1410.00	1.05E-03	Pa-234	1863.00	1.15E-02
Pa-234M	1413.90	2.31E-03	Pa-234M	1867.48	9.15E-03
Bi-214	1415.70	3.00E-02	Bi-214	1873.40	2.20E-01
Pa-234M	1434.27	9.00E-03	Pa-234	1874.77	7.80E-03
Pa-234	1445.80	4.00E-04	Pa-234M	1877.00	1.93E-03
Bi-214	1447.00	3.00E-02	Bi-214	1890.40	1.00E-01
Pa-234	1452.60	9.50E-04	Pa-234	1890.50	2.00E-04
Bi-214	1479.20	5.00E-02	Pa-234M	1893.65	2.13E-03
Tl-210	1490.00	4.20E-04	Bi-214	1896.70	1.80E-01
Bi-214	1509.30	2.20E+00	Pa-234M	1911.21	6.10E-03

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Pa-234	1925.78	5.70E-04	Bi-214	2699.50	5.00E-03
Bi-214	1936.60	5.00E-02	Bi-214	2719.40	1.50E-03
Pa-234M	1937.06	2.87E-03	Bi-214	2770.30	2.60E-02
Pa-234M	1969.04	4.00E-04	Bi-214	2786.10	5.00E-03
Bi-214	1994.70	5.00E-03	Bi-214	2827.60	2.10E-03
Tl-210	2010.00	1.47E-03	Bi-214	2880.70	8.00E-03
Bi-214	2011.00	3.70E-02	Bi-214	2893.70	6.00E-03
Bi-214	2016.00	1.60E-02	Bi-214	2918.00	1.50E-03
Pa-234	2022.50	1.87E-04	Bi-214	2922.20	1.60E-02
Pa-234	2041.00	8.97E-05	Bi-214	2940.00	1.50E-03
Bi-214	2053.20	7.00E-02	Bi-214	2963.00	1.00E-03
Pa-234	2065.50	8.00E-05	Bi-214	2979.00	1.40E-02
Bi-214	2084.20	1.00E-02	Bi-214	2988.70	1.00E-03
Bi-214	2089.70	5.00E-02	Bi-214	3000.10	1.00E-02
Tl-210	2090.00	1.05E-03	Bi-214	3054.00	2.10E-02
Bi-214	2110.40	1.00E-01	Bi-214	3081.70	5.00E-03
Bi-214	2118.70	1.30E+00	Bi-214	3142.50	1.00E-03
Pa-234	2136.40	8.25E-05	Bi-214	3162.20	5.00E-04
Bi-214	2147.70	1.20E-02	Bi-214	3182.80	5.00E-04
Bi-214	2192.50	7.00E-02			
Bi-214	2204.30	5.30E+00			
Bi-214	2260.00	5.00E-03			
Bi-214	2266.40	1.50E-02			
Tl-210	2280.00	6.30E-04			
Bi-214	2293.70	3.30E-01			
Bi-214	2312.50	9.00E-03			
Bi-214	2331.70	2.10E-02			
Bi-214	2377.20	6.00E-03			
Tl-210	2380.00	1.68E-03			
Bi-214	2423.70	6.00E-03			
Tl-210	2430.00	1.89E-03			
Bi-214	2448.00	1.65E+00			
Bi-214	2479.00	1.60E-02			
Bi-214	2505.60	7.00E-03			
Bi-214	2695.10	3.10E-02			

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

APPENDIX Ib: U-235 DECAY SERIES

The U-235 decay series members are listed in terms of this uranium isotope alone in equilibrium with all its daughters. This situation is never observed in nature, where the U-235/U-238 ratio is found to be constant to within 1-3%, at a "normal" value of 0.00711 on a weight basis. For equilibrium series studies, a properly aged Ac-227 source could provide the correct assemblage of all its daughter γ -rays. Addition of the right proportion of isotopically separated U-235 could then provide a synthetic equilibrium sample of all major U-235 series γ -rays, for a period that is short compared to the 22-year half life of Ac-227.

ISOTOPE	REFERENCES
U-235	Gunnink 1971
Pa-231	Lange 1969, De Pinho 1970
Th-231	Gunnink 1971
Ac-227	Polak 1966
Th-227	Davidson 1968, Hesselink 1972
Ra-223	Davidson 1970, Krien 1970
Fr-223	Lederer 1967
Rn-219	Davidson 1970, Krien 1970
Po-215	Lederer 1967
Po-211	Lederer 1967
Bi-211	Gorodetzky 1968, Hamilton 1968
Pb-211	Gorodetzky 1968, Hamilton 1968
Tl-207	Lederer 1967

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Pa-231	25.54	2.70E-03	Pa-231	54.61	2.43E-03
Pa-231	27.35	2.79E-01	Th-227	56.10	1.97E-03
Pa-231	29.95	2.76E-03	Pa-231	56.76	1.80E-04
Pa-231	31.00	2.70E-04	Pa-231	57.19	1.17E-03
Pa-231	31.54	2.10E-04	Th-231	58.55	4.20E-01
Pa-231	35.82	4.80E-04	Th-227	59.60	8.88E-03
Pa-231	38.20	4.47E-03	Pa-231	60.50	2.10E-04
Pa-231	39.57	4.20E-05	Th-227	61.50	unknown
Pa-231	39.97	3.60E-04	Th-227	62.00	unknown
Th-227	40.10	unknown	Th-227	62.50	2.47E-01
Th-227	42.20	7.90E-02	Th-227	62.70	8.88E-03
Pa-231	42.48	1.80E-04	Pa-231	63.67	1.50E-03
Th-231	42.81	5.40E-02	Th-227	64.50	2.76E-02
Pa-231	43.05	2.10E-04	Pb-211	65.40	3.99E-02
Th-227	43.50	2.37E-01	Th-227	66.20	5.92E-03
Th-227	43.80	4.94E-02	Th-227	66.40	6.91E-03
Th-227	44.10	6.91E-03	Th-227	68.70	1.97E-03
Pa-231	44.16	1.80E-03	Th-227	68.80	2.76E-02
Th-227	44.30	1.28E-02	Th-227	69.80	8.88E-03
Pa-231	46.37	6.24E-03	Ac-227	70.00	1.56E-02
Th-227	48.30	unknown	Pa-231	70.50	2.10E-04
Th-227	48.50	4.44E-02	Pa-231	71.90	6.00E-05
Th-227	49.80	1.97E-01	Pa-231	72.50	1.20E-04
Fr-223	49.80	5.20E-01	Th-231	72.76	2.20E-01
Th-227	50.20	8.59E+00	Th-227	72.90	7.90E-03
Th-227	50.70	1.58E-02	Th-227	73.70	1.68E-02
Pa-231	50.98	4.20E-05	Pa-231	74.18	7.50E-04
Th-227	51.20	unknown	Th-227	75.30	8.88E-03
Pa-231	52.74	2.55E-03	Pa-231	77.36	2.04E-03
Th-227	54.20	unknown	Th-227	79.70	1.78E+00

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Fr-223	80.00	1.69E-01	Th-227	124.40	1.97E-03
Th-231	81.21	7.44E-01	Pa-231	124.60	1.50E-04
Th-231	82.06	3.41E-01	Th-227	124.70	2.96E-03
Th-231	84.20	5.60E+00	Th-231	124.95	5.34E-02
Ac-227	85.60	3.51E-02	Rn-219	130.70	1.04E-01
Th-227	89.90	unknown	Ac-227	133.50	2.60E-03
Th-231	89.93	8.40E-01	Th-231	134.03	2.18E-02
U-235	89.96	2.45E+00	Th-227	134.20	2.96E-03
Th-231	92.27	3.80E-01	Th-231	135.69	7.17E-02
Th-231	92.94	6.60E-02	Fr-223	136.00	5.20E-03
U-235	93.35	4.00E+00	Th-231	136.80	3.00E-03
Th-227	94.00	1.33E+00	Th-227	140.50	3.16E-02
Th-227	95.00	unknown	U-235	140.75	2.08E-01
Pb-211	95.00	1.33E-02	Th-227	141.20	6.42E-02
Th-231	95.85	5.60E-01	U-235	143.77	1.07E+01
Th-227	96.10	4.44E-02	Ra-223	144.19	3.13E+00
Pa-231	96.88	2.64E-03	Pa-231	144.50	3.60E-04
Th-231	99.27	1.18E-01	Th-231	145.13	5.60E-03
Ac-227	99.50	2.60E-02	Th-231	145.96	2.80E-02
Th-227	99.50	unknown	Ac-227	147.00	7.80E-03
Th-227	99.70	unknown	Th-227	149.80	1.78E-02
Fr-223	100.00	1.30E-02	Ra-223	154.18	5.23E+00
Th-227	100.40	7.90E-02	Ra-223	158.62	7.60E-01
Pa-231	100.92	9.60E-04	Ac-227	160.00	1.82E-02
Th-231	102.29	3.80E-01	Th-227	162.20	5.92E-03
Th-227	102.50	unknown	Th-231	163.16	1.39E-01
Pa-231	102.60	6.00E-04	U-235	163.37	4.85E+00
U-235	104.82	4.56E-01	Th-227	168.20	1.38E-02
U-235	105.61	9.10E-01	Fr-223	170.00	3.12E-03
Ac-227	106.50	1.30E-03	Th-227	170.10	2.96E-03
Ra-223	106.80	2.20E-02	Th-227	171.40	unknown
Th-231	107.60	6.80E-02	Ac-227	172.00	5.20E-03
Th-227	108.00	6.91E-03	Th-227	173.40	1.09E-02
Th-231	108.44	1.31E+00	Th-227	175.80	1.78E-02
Th-227	109.60	5.92E-03	Ra-223	176.00	2.10E-02
Th-227	110.60	1.97E-03	Ra-223	177.30	2.10E-02
Ra-223	110.80	5.60E-02	Ra-223	179.60	1.50E-01
Th-231	111.54	5.45E-02	U-235	182.57	3.60E-01
Th-231	112.48	1.94E-02	Th-227	184.70	2.66E-02
Th-227	112.60	7.90E-03	U-235	185.72	5.61E+01
Th-227	113.10	5.33E-01	Ac-227	190.00	6.50E-04
Th-231	116.83	2.00E-02	Fr-223	190.00	unknown
Th-227	117.00	1.58E-01	Ra-223	193.00	1.00E-02
Th-227	117.50	1.18E-02	U-235	194.94	6.15E-01
Ac-227	121.50	5.20E-03	Th-227	197.60	9.87E-03
Ra-223	122.30	1.33E+00	Pa-231	199.00	1.80E-04
Th-227	123.60	7.90E-03	Th-227	200.50	4.93E-03

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Th-227	201.80	2.17E-02	Th-227	273.00	4.84E-01
U-235	202.10	1.07E+00	Pa-231	273.08	1.74E-03
Th-227	202.50	5.92E-03	U-235	275.34	2.69E-02
Th-227	204.20	2.27E-01	Pa-231	276.99	2.01E-03
Fr-223	205.00	1.04E-02	Th-227	279.70	8.88E-02
Th-227	205.20	1.68E-01	Th-227	281.00	unknown
U-235	205.33	4.87E+00	Th-227	281.40	1.48E-01
Th-227	206.10	2.57E-01	Pa-231	283.56	4.71E-02
Th-227	206.40	3.95E-03	Th-227	284.30	2.47E-02
Th-227	210.60	1.24E+00	Th-227	285.60	5.43E-02
Th-227	212.60	8.39E-02	Th-227	286.20	1.63E+00
Th-227	212.70	1.68E-02	Pa-231	286.55	2.70E-04
U-235	215.35	2.75E-02	Ra-223	288.40	1.47E-01
Th-227	218.20	5.43E-02	Th-227	289.60	3.95E-03
Th-227	219.00	4.44E-02	Fr-223	290.00	7.80E-03
Rn-219	222.00	2.80E-02	U-235	291.63	2.00E-02
Th-227	224.70	1.48E-02	Th-227	292.30	5.43E-02
Th-227	230.40	unknown	Rn-219	294.00	5.90E-02
U-235	233.54	2.75E-02	Th-227	296.60	3.85E-01
Fr-223	234.00	4.68E-02	Pa-231	299.94	6.78E-02
Th-227	234.90	5.72E-01	Th-227	300.00	1.87E+00
Th-227	236.00	1.14E+01	Th-227	300.30	2.76E-01
U-235	240.93	6.40E-02	Pa-231	302.52	7.02E-02
Pa-231	242.20	2.40E-04	Th-227	304.40	1.33E+00
Pa-231	243.00	1.02E-03	Th-227	308.50	1.48E-02
Pa-231	245.40	2.10E-04	Pa-231	310.00	4.20E-05
Pa-231	246.00	3.00E-05	Th-227	312.60	5.13E-01
Th-227	246.40	1.18E-02	Pa-231	312.88	2.85E-03
U-235	246.88	5.20E-02	Pb-211	313.60	1.33E-02
Th-227	249.60	6.91E-03	Th-227	314.80	5.33E-01
Th-227	250.20	2.76E-01	Th-227	314.80	2.47E-02
Th-227	250.40	6.91E-02	Th-227	318.80	5.92E-03
Ra-223	251.70	5.70E-02	Th-227	319.20	1.78E-02
Th-227	252.50	1.09E-01	Fr-223	320.00	1.04E-02
Th-227	254.70	8.98E-01	Ra-223	323.88	3.60E+00
Ra-223	255.00	5.00E-02	Th-227	325.20	4.93E-03
Pa-231	255.78	3.03E-03	Th-227	326.20	1.97E-03
Th-227	256.20	6.22E+00	Pa-231	327.02	9.00E-04
Pa-231	258.40	6.90E-05	Ra-223	328.50	1.62E-01
Pa-231	260.14	5.19E-03	Pa-231	329.89	3.90E-02
Th-227	262.70	9.87E-02	Th-227	329.90	2.86E+00
Th-227	267.00	unknown	Ra-223	333.80	1.24E-01
Th-227	267.90	unknown	Th-227	334.40	1.14E+00
Ra-223	269.41	1.36E+01	Ra-223	338.30	2.59E+00
Th-227	270.50	unknown	Th-227	339.80	unknown
Th-227	270.70	3.16E-02	Pa-231	340.61	4.95E-03
Rn-219	271.20	9.93E+00	Th-227	342.50	1.88E-01

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Pb-211	342.70	2.00E-02	Pa-231	438.70	4.50E-05
Ra-223	342.90	2.10E-01	Ra-223	444.92	1.27E+00
U-235	345.89	3.00E-02	Pa-231	486.70	5.40E-05
Th-227	346.30	7.90E-03	Ra-223	488.00	1.50E-02
Ra-223	346.80	1.70E-01	Pa-231	491.00	1.50E-05
Th-227	348.50	5.92E-03	Pa-231	501.60	1.80E-05
Fr-223	350.00	1.30E-03	Pb-211	503.60	7.98E-04
Th-227	350.50	7.90E-03	Pa-231	509.00	9.00E-06
Bi-211	351.10	1.33E+01	Pa-231	516.20	3.90E-05
Th-227	352.60	8.88E-03	Rn-219	516.50	2.20E-02
Pa-231	354.38	2.85E-03	Ra-223	527.00	7.00E-02
Pa-231	356.96	5.19E-03	Pa-231	535.20	1.50E-05
Pa-231	359.25	2.70E-04	Pa-231	546.60	1.80E-05
Ra-223	361.50	5.00E-02	Po-211	569.60	1.60E-03
Th-227	362.50	3.95E-03	Pa-231	572.10	1.50E-05
Pa-231	363.74	2.22E-04	Ra-223	598.50	9.30E-02
Th-227	369.40	3.95E-03	Ra-223	609.00	6.30E-02
Th-227	370.90	1.97E-03	Pb-211	609.30	3.33E-02
Ra-223	371.50	5.40E-01	Ra-223	632.00	3.00E-02
Pa-231	374.90	1.38E-04	Pb-211	675.20	1.33E-02
Th-227	375.10	9.87E-04	Rn-219	677.00	6.00E-03
Ra-223	376.00	1.20E-02	Pb-211	704.30	4.92E-01
Pa-231	379.09	1.47E-03	Pb-211	766.40	6.52E-02
Th-227	382.40	5.92E-03	Fr-223	780.00	1.04E-02
Ra-223	382.50	1.50E-02	Pb-211	831.80	3.21E+00
Th-227	383.60	1.97E-03	Pb-211	865.20	9.31E-03
Pa-231	384.70	1.23E-04	Pb-211	897.30	3.06E-01
Pa-231	387.00	1.50E-05	Po-211	897.30	1.70E-03
U-235	387.81	1.20E-02	Tl-207	897.30	1.59E-01
Pa-231	391.50	2.04E-04	Pb-211	1014.10	2.00E-02
Th-227	392.40	8.88E-03	Pb-211	1080.00	1.06E-02
Ra-223	393.50	1.10E-02	Pb-211	1109.10	1.08E-01
Pa-231	395.50	7.80E-05	Pb-211	1195.50	1.06E-02
Pa-231	398.10	2.79E-04	Pb-211	1270.00	1.06E-02
Rn-219	401.80	6.48E+00			
Th-227	402.50	3.95E-03			
Pb-211	404.80	3.94E+00			
Pa-231	407.71	1.08E-03			
Pa-231	410.50	5.70E-05			
Th-227	415.20	9.87E-04			
Pb-211	426.90	1.82E+00			
Pb-211	429.10	8.64E-03			
Ra-223	432.00	3.00E-02			
Th-227	432.50	3.95E-03			
Pa-231	435.10	9.90E-05			
Pa-231	437.90	1.23E-04			

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

APPENDIX 1c: TH-232 DECAY SERIES

The Th-232 decay series members are listed for the equilibrium condition. The absolute intensities given here and in Appendix 1a are appropriate to a Th/U ratio of 3.2 to 1, as a consequence of the U-238 and Th-232 half lives. This is a "normal" ratio for natural materials; in effect, these two lists can be used in direct combination for estimation of Ge(Li) spectrometer response from normal materials.

Experimental data has been converted to the given absolute intensities by use of the following normalizations: all Ac-228 γ -ray intensities are normalized to 30.0% abundance for the 911 keV line; the Bi-212 decay branching is 36.0% to Tl-208 and 64.0% to Po-212.

ISOTOPE	REFERENCES
Th-232	Lederer 1967
Th-228	Lederer 1967, Gunnink 1972
Ac-228	Arnoux 1969, Dalmasso 1971, Ythier 1969
Ra-228	Lederer 1967
Ra-224	Gunnink 1969, Lederer 1967
Rn-220	Lederer 1967
Po-216	Lederer 1967
Po-212	Lederer 1967
Bi-212	Gunnink 1969, Gunnink 1972
Pb-212	Gunnink 1969, Gunnink 1972
Tl-208	Gunnink 1969, Gunnink 1972, Pakkanen 1969

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Bi-212	39.87	1.10E+00	Ac-228	209.40	4.71E+00
Th-228	84.40	1.60E+01	Tl-208	211.50	6.12E-02
Ac-228	99.50	1.41E+00	Th-228	217.00	2.70E-01
Pb-212	115.16	6.05E-01	Ac-228	224.00	6.90E-02
Ac-228	129.10	3.03E+00	Ac-228	231.80	6.00E-02
Th-228	132.00	2.60E-01	Tl-208	233.50	1.19E-01
Ac-228	141.00	5.10E-02	Pb-212	238.63	4.46E+01
Bi-212	144.00	1.01E-02	Ra-224	240.98	3.70E+00
Ac-228	145.90	2.28E-01	Tl-208	252.60	2.52E-01
Ac-228	154.20	1.02E+00	Ac-228	257.30	3.30E-02
Bi-212	164.00	4.68E-03	Ac-228	263.60	6.00E-02
Th-228	169.00	9.00E-02	Ac-228	270.30	3.90E+00
Ac-228	174.10	3.30E-02	Tl-208	277.36	2.34E+00
Pb-212	176.63	5.22E-02	Ac-228	279.00	2.40E-01
Ac-228	184.60	1.05E-01	Ac-228	282.00	7.50E-02
Ac-228	191.50	1.26E-01	Bi-212	288.07	3.42E-01
Ac-228	199.50	3.63E-01	Ra-224	290.00	9.00E-03
Ac-228	204.10	1.77E-01	Bi-212	295.10	2.41E-02
Th-228	205.00	3.00E-02	Pb-212	300.11	3.42E+00

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Ac-228	321.70	2.61E-01	Ra-224	650.00	6.00E-03
Bi-212	327.96	1.40E-01	Ac-228	651.30	1.05E-01
Ac-228	328.00	3.48E+00	Ac-228	660.40	2.70E-02
Ac-228	332.40	4.89E-01	Ac-228	666.30	4.80E-02
Ac-228	338.40	1.24E+01	Ac-228	674.60	1.05E-01
Ac-228	340.90	4.35E-01	Ac-228	677.30	8.70E-02
Ac-228	357.00	2.04E-02	Ac-228	687.90	7.80E-02
Ac-228	372.20	9.00E-03	Ac-228	701.50	2.04E-01
Ac-228	377.80	3.30E-02	Ac-228	707.30	1.62E-01
Ac-228	388.80	1.50E-02	Tl-208	722.30	9.72E-02
Ac-228	396.80	3.36E-02	Ac-228	727.00	8.25E-01
Ac-228	398.60	3.78E-02	Bi-212	727.27	6.66E+00
Ac-228	409.40	2.31E+00	Ac-228	737.60	4.20E-02
Ra-224	410.00	4.00E-03	Ac-228	755.20	1.14E+00
Pb-212	415.20	1.80E-02	Tl-208	763.30	6.05E-01
Ac-228	416.10	1.80E-02	Ac-228	772.10	1.68E+00
Ac-228	419.40	2.70E-02	Ac-228	782.00	5.64E-01
Bi-212	433.50	1.26E-02	Bi-212	785.46	1.11E+00
Ac-228	440.30	1.50E-01	Ac-228	794.80	5.01E+00
Ac-228	449.00	5.70E-02	Ac-228	816.70	3.60E-02
Bi-212	452.83	3.74E-01	Tl-208	821.10	3.24E-02
Ac-228	463.00	4.80E+00	Ac-228	824.80	6.00E-02
Ac-228	471.30	3.60E-02	Ac-228	830.40	6.39E-01
Bi-212	473.50	4.68E-02	Ac-228	835.60	1.88E+00
Ac-228	474.60	3.00E-02	Ac-228	840.20	1.02E+00
Ac-228	478.20	2.49E-01	Ac-228	853.50	1.50E-02
Tl-208	486.00	1.80E-02	Tl-208	860.47	4.32E+00
Bi-212	493.20	1.80E-02	Ac-228	870.40	6.00E-02
Ac-228	503.70	2.22E-01	Ac-228	873.80	8.70E-02
Ac-228	509.60	5.10E-01	Ac-228	887.10	2.10E-02
Tl-208	510.72	8.10E+00	Bi-212	893.35	3.67E-01
Ac-228	515.30	4.50E-02	Ac-228	904.20	9.00E-01
Ac-228	520.00	8.10E-02	Ac-228	911.10	3.00E+01
Ac-228	523.00	1.26E-01	Ac-228	919.00	2.85E-02
Ac-228	540.40	3.00E-02	Ac-228	921.80	2.10E-02
Rn-220	542.00	7.00E-02	Tl-208	927.70	4.68E-02
Ac-228	546.30	2.28E-01	Ac-228	931.00	1.50E-02
Ac-228	555.20	5.10E-02	Ac-228	944.10	1.11E-01
Ac-228	562.30	1.02E+00	Ac-228	948.00	1.26E-01
Ac-228	570.70	1.92E-01	Bi-212	952.10	1.76E-01
Ac-228	572.10	1.68E-01	Ac-228	958.50	3.27E-01
Tl-208	583.14	3.10E+01	Ac-228	964.60	5.64E+00
Ac-228	615.90	9.00E-02	Ac-228	968.90	1.81E+01
Ac-228	620.30	9.90E-02	Ac-228	975.90	5.40E-02
Ac-228	629.20	4.80E-02	Ac-228	979.60	2.40E-02
Ac-228	640.20	6.60E-02	Tl-208	982.80	7.20E-02
			Ac-228	988.10	1.98E-01

*Decaying isotope

[†]Absolute intensity per 100 decays of the longest lived parent

ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]	ISOTOPE*	γ -ENERGY (keV)	INTENSITY (%) [†]
Tl-208	1004.00	3.60E-03	Bi-212	1620.62	1.51E+00
Ac-228	1016.70	2.55E-02	Ac-228	1624.70	3.30E-01
Ac-228	1019.70	2.55E-02	Ac-228	1630.40	2.02E+00
Ac-228	1033.10	2.34E-01	Ac-228	1638.00	5.61E-01
Ac-228	1053.50	3.30E-02	Tl-208	1643.00	3.60E-03
Ac-228	1065.10	1.53E-01	Ac-228	1666.40	2.16E-01
Bi-212	1074.00	1.58E-02	Ac-228	1677.60	6.90E-02
Bi-212	1078.80	5.36E-01	Bi-212	1679.50	6.84E-02
Tl-208	1093.90	1.37E-01	Ac-228	1685.90	1.08E-01
Ac-228	1095.70	1.38E-01	Ac-228	1702.30	6.90E-02
Ac-228	1103.40	1.80E-02	Ac-228	1706.50	1.35E-02
Ac-228	1110.60	3.60E-01	Ac-228	1713.00	6.00E-03
Ac-228	1117.80	6.30E-02	Ac-228	1724.30	3.30E-02
Ac-228	1135.60	1.26E-02	Ac-228	1738.30	2.01E-02
Ac-228	1142.70	1.05E-02	Ac-228	1741.10	1.59E-02
Ac-228	1153.60	1.65E-01	Ac-228	1750.80	9.60E-03
Ac-228	1164.60	7.80E-02	Ac-228	1757.90	4.50E-02
Ac-228	1175.30	3.00E-02	Ac-228	1784.40	9.90E-03
Ac-228	1217.10	2.70E-02	Bi-212	1800.00	3.60E-03
Ac-228	1247.10	5.85E-01	Bi-212	1806.00	1.12E-01
Ac-228	1249.70	6.00E-02	Ac-228	1823.30	5.25E-02
Ac-228	1276.80	2.10E-02	Ac-228	1835.60	4.80E-02
Tl-208	1282.70	1.80E-02	Ac-228	1842.30	5.25E-02
Ac-228	1287.50	1.23E-01	Ac-228	1871.10	2.70E-02
Ac-228	1309.50	2.16E-02	Ac-228	1887.40	1.14E-01
Ac-228	1316.10	2.19E-02	Ac-228	1907.80	1.20E-02
Ac-228	1348.40	1.35E-02	Ac-228	1930.20	2.55E-02
Ac-228	1358.50	3.00E-02	Ac-228	1952.60	7.50E-02
Ac-228	1374.30	1.71E-02	Ac-228	1965.70	2.55E-02
Tl-208	1384.00	7.20E-03	Tl-208	2614.47	3.60E+01
Ac-228	1415.70	2.70E-02			
Ac-228	1430.90	3.30E-02			
Ac-228	1451.50	1.89E-02			
Ac-228	1459.20	1.08E+00			
Ac-228	1469.60	2.10E-02			
Ac-228	1480.40	2.10E-02			
Ac-228	1495.80	1.09E+00			
Ac-228	1501.50	6.00E-01			
Bi-212	1512.75	3.13E-01			
Ac-228	1528.80	6.90E-02			
Ac-228	1537.70	5.10E-02			
Ac-228	1548.40	4.50E-02			
Ac-228	1556.90	2.10E-01			
Ac-228	1573.10	5.70E-02			
Ac-228	1580.20	7.35E-01			
Ac-228	1587.90	3.84E+00			
Ac-228	1609.30	1.20E-02			

*Decaying isotope

[†] Absolute intensity per 100 decays of the longest lived parent

REFERENCES FOR APPENDIX I

- ARNOUX, M. and A. GIZON. 1969. *Compt. Rend.*, B269, 317.
- BORGGREEN, J., D. DAVIES, N. J. S. HANSEN, J. PEDERSON, and H. L. NIELSEN. 1968. *Nucl. Phys.*, 118:261.
- DALMASSO, J. and H. MARIA. 1971. *Compt. Rend.*, B272, 905.
- DAVIDSON, W. F. and R. D. CONNOR. 1968. *Nucl. Phys.*, 116:342.
- DAVIDSON, W. F. and R. D. CONNOR. 1970. *Nucl. Phys.*, 149:363.
- DAVIDSON, W. F. and R. D. CONNOR. 1970. *Nucl. Phys.*, 149:385.
- FOUCHER, R., J. MERINIS, A. DE PINHO, and M. VALADARES. 1962. *Compt. Rend.*, B255, 1916.
- FOUCHER, R., J. M. LAGRANGE, O. RAHMOUNI, and H. SERGOLLE. 1965. *J. Phys. (Paris)*, 26:430.
- GORODETSKY, S., F. A. BECK, T. BYRSKI, and A. KNIPPER. 1968. *Nucl. Phys.*, 117:208.
- GUNNINK, R., J. B. NIDAY, R. P. ANDERSON, and R. A. MEYER. 1969. Lawrence Livermore Laboratory report UCID-15439.
- GUNNINK, R. and J. F. TINNEY. 1971. Lawrence Livermore Laboratory report UCRL-51086.
- GUNNINK, R. 1972. Private communication.
- HAMILTON, W. D. and K. E. DAVIES. 1968. *Nucl. Phys.*, 114:577.
- HESSELINK, W. H. A., A. H. WAPSTRA, J. G. KROMME, E. J. HAIGHTON, M. VAN HAMPEN, W. HUTJES, and K. E. M. DIJKMAN. 1972. *Nucl. Phys.*, 191:283.
- HYDE, E. K., I. PERLMAN, and G. T. SEABORG. 1964. *The Nuclear Properties of the Heavy Elements, Volume II*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.
- KRIEN, K., C. GUNTHER, J. D. BOWMAN, and B. KLEMME. 1970. *Nucl. Phys.*, 141:75.
- KRIEN, K., M. J. CANTY, and P. HERZOG. 1970. *Nucl. Phys.*, 157:456.
- LANGE, R. C. and G. R. HAGEE. 1969. *Nucl. Phys.*, 124:412.
- LEDERER, C. M., J. M. HOLLANDER, and I. PERLMAN. 1967. *Table of Isotopes*, Sixth Edition. New York, N.Y.: John Wiley and Sons, Inc.
- LINGEMAN, E. W. A., J. KONIJN, P. POLAK, and A. H. WAPSTRA. 1969. *Nucl. Phys.*, 133:630.
- NUCLEAR DATA GROUP. 1969-72. *Nuclear Data Sheets, Section B, Vols. 3-8*. New York: Academic Press.

PAKKANEN, A., J. KANTELE,, and P. SOUMINEN. 1969. *Z. Physik.*, 218:273.

DE PINHO, A. G., E. F. DA SILVEIRA, and N. L. DA COSTA. 1970. *Phys. Rev. C*2, 572.

POLAK, R., A. H. WAPSTRA, and C. YTHIER. 1966. Private Communication in Nuclear Data, 1-5, K. Way, Editor. New York: Academic Press.

WAPSTRA, A. H. 1967. *Nucl. Phys.*, 97:641.

WAY, K. Editor. 1965-68. Nuclear Data, Section A. Vols. 1-4. New York: Academic Press.

WAY, K., Editor. 1966-68. Nuclear Data, Section B, Vols. 1-2. New York: Academic Press.

WAY, K., Editor. 1968-72. Nuclear Data Tables, Section A, Vols. 5-10. New York: Academic Press.

WOLF, G. K. 1968. *Nucl. Phys.*, 116:387.

YTHIER, C., J. DALMASSO, G. ARDISSON, H. MARIA, and H. FOREST. 1969. *Compt. Rend. B*269, 785.

APPENDIX C

LISTING AND DEFINITIONS OF U_3O_8 PREFIXES

- 1) cU_3O_8 chemically determined using colorimetric technique
- 2) fU_3O_8 chemically determined using fluorimetric technique
- 3) vU_3O_8 chemically determined using volumetric technique
- 4) xU_3O_8 determined using x-ray fluorescence technique
- 5) nU_3O_8 radiometrically determined using neutron activation technique
- 6) sU_3O_8 radiometrically determined using NaI(Tl) KUT technique
- 7) gU_3O_8 radiometrically determined using Ge(Li) KUT technique
- 8) rU_3O_8 radiometrically determined using Ge(Li) direct ^{235}U technique
- 9) eU_3O_8 radiometrically determined using total gamma technique