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Standard Test Method for Determination of Plutonium Isotopic Composition by Gamma-Ray Spectrometry¹

This standard is issued under the fixed designation C1030; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

~~1.1 This test method is applicable to the determination of isotopic abundances in isotopically homogeneous Pu-bearing materials. This test method may be applicable to other plutonium-bearing materials, some of which may require modifications to the described test method.~~

~~1.2 The procedure is applicable to sample sizes ranging from a few tenths of a gram up to the maximum sample weight allowed by criticality limits.~~

~~1.3 Because~~

~~1.1 This test method is applicable to the determination of isotopic abundances in isotopically homogeneous plutonium-bearing materials. This test method may be applicable to other plutonium-bearing materials, some of which may require modifications to the described test method.~~

~~1.2 The procedure is applicable to items containing plutonium masses ranging from a few tens of milligrams up to the maximum plutonium mass allowed by criticality limits.~~

~~1.3 Measurable gamma ray emissions from plutonium cover the energy range from approximately 30 keV to above 800 keV. K-X-ray emissions from plutonium and its daughters are found in the region around 100 keV. This test method has been applied to all portions of this broad spectrum of emissions.~~

~~1.4 The isotopic abundance of the ²⁴²Pu has no useful gamma-ray signature, its isotopic abundance is not determined. Isotopic correlation techniques may be used to estimate its relative abundance (Refs ~~Pu isotope is not directly determined because it has no useful gamma-ray signature. Isotopic correlation techniques may be used to estimate its relative abundance Refs (1, 2)-~~ and (2)).²~~

~~1.4 This~~ ~~1.5 This~~ test method has been demonstrated in routine use for isotopic abundances ranging from ~~9699 to 55%~~ ~~<50 %~~ ²³⁹Pu. This test method has also been employed for isotopic abundances outside this range.

~~1.5 The values stated in SI units are to be regarded as the standard.~~

~~1.6~~

~~1.6 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.~~

~~1.7 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.~~

2. Referenced Documents

2.1 *ASTM Standards:*³

C697 Test Methods for Chemical, Mass Spectrometric, and Spectrochemical Analysis of Nuclear-Grade Plutonium Dioxide Powders and Pellets

C698 Test Methods for Chemical, Mass Spectrometric, and Spectrochemical Analysis of Nuclear-Grade Mixed Oxides ((U, Pu)O₂)

C982 Guide for Selecting Components for Energy-Dispersive X-Ray Fluorescence (XRF) Systems

C1207 Test Method for Nondestructive Assay of Plutonium in Scrap and Waste by Passive Neutron Coincidence Counting

¹ This test method is under the jurisdiction of ASTM Committee C26 on Nuclear Fuel Cycle and is the direct responsibility of Subcommittee C26.10 on Non Destructive Assay.

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² The boldface numbers in parentheses refer to the list of references at the end of this standard.

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[C1316 Test Method for Nondestructive Assay of Nuclear Material in Scrap and Waste by Passive-Active Neutron Counting Using ²⁵²Cf Shuffler](#)

[C1458 Test Method for Nondestructive Assay of Plutonium, Tritium and ²⁴¹Am by Calorimetric Assay](#)

[C1493 Test Method for Non-Destructive Assay of Nuclear Material in Waste by Passive and Active Neutron Counting Using a Differential Die-Away System](#)

[C1500 Test Method for Nondestructive Assay of Plutonium by Passive Neutron Multiplicity Counting](#)

[E181 Test Methods for Detector Calibration and Analysis of Radionuclides](#)

[E267 Test Method for Uranium and Plutonium Concentrations and Isotopic Abundances](#)

2.2 *ANSI Standards:*

[ANSI N15.35 Guide to Preparing Calibration Material for Nondestructive Assay Systems that Count Passive Gamma Rays](#)⁴

[ANSI/IEEE Std 325-1996 IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors](#)

[ANSI N15.36 Measurement Control Program – Nondestructive Assay Measurement Control and Assurance](#)

3. Summary of Test Method

3.1 Relative intensities of gamma-rays from a plutonium sample are determined from a gamma-ray spectrum obtained with a high-resolution Ge detector.

3.1 The intensities of gamma-rays emitted from a plutonium-bearing item are determined from a gamma-ray spectrum obtained with a High-Purity Germanium (HPGe) detector. The method has also been used with CdTe detectors.

3.2 The atom ratio, $N^i/N_j N^k$, for isotopes i and j is related to the relative counting intensities, I_i and I_j , for the gamma-rays of energy k is related to the photopeak counting intensity, $C(E_j^i)$, for gamma ray j with energy E_i and E_j emitted from isotope i by:

$$(1) \quad N^i/N_j N^k = C(E_j^i)C(E_k) \cdot T_{1/2i}T_{1/2k} \cdot BR_{ik}BR_{ji} \cdot RE(E_i)RE(E_j)$$

$$(1) \quad N^i/N_j N^k = C(E_j^i)C(E_k) \cdot T_{1/2i}T_{1/2k} \cdot BR_{ik}BR_{ji} \cdot RE(E_i)RE(E_j)$$

$RE(E_i)$

where:

$\epsilon RE(E_j)$ = relative detection efficiency for a gamma-ray at energy E_j , $T^{1/2}$

$T_{1/2}^i$ = half-life, and half-life of isotope i , and

BR_{ji}^i = gamma-ray branching intensity (usually expressed as the gamma-ray emission probability per disintegration)-gamma-ray branching ratio or branching intensity (usually expressed as gamma-rays per disintegration) of gamma ray j from isotope i .

3.3 The conversion factors, C_{ij} , are computed from known half-lives and gamma-ray branching intensities.

3.4 The relative detection efficiency, ϵ , is a function of gamma-ray energy and results from the combined effects of detector response, attenuation due to absorbers and container walls, and self-absorption within the sample for gamma-rays of differing energies. The relative detection efficiencies are determined for each sample from the observed gamma spectrum.

3.3 The half lives $T_{1/2}$ and the branching ratios BR are known, published nuclear data. The photopeak counting intensity $C(E)$ is determined from the gamma ray spectrum of the measured item.

3.4 The relative detection efficiency, $RE(E)$, is a function of gamma-ray energy and arises from the combined effects of detector response, attenuation due to absorbers and container walls, and self-absorption within the measured item for gamma-rays of differing energies. The relative detection efficiencies are determined for each measured item from the observed gamma spectrum by considering a series of gamma rays from a single isotope. The quotient of the photopeak counting intensity for gamma ray j with energy E_j emitted from isotope i and the branching ratio of gamma ray j from isotope i is proportional to the relative detection efficiency at energy E_j . This quotient defines the shape of the relative efficiency as a function of energy.

$$(2) \quad C(E_j^i)BR_{ji} \propto N^i T_{1/2i} \cdot RE(E_j)$$

3.5 All factors in Eq 1 are either determined from the gamma ray spectrum of the measured item or are known, published nuclear constants. The absolute atom ratios are determined without recourse to standards or calibration by this so-called Intrinsic Calibration technique.

4. Significance and Use

4.1 The determination of plutonium isotopic composition by gamma-ray spectrometry is a nondestructive technique and when used with other nondestructive techniques, such as calorimetry (Test Method C1458) or neutron counting (Test Methods C1207, C1316, C1493, and C1500), can provide a wholly nondestructive plutonium assay necessary for material accountancy and safeguards needs.

4.2 Because gamma-ray spectrometry systems are typically automated, the routine use of the test method is fast, reliable, and is not labor intensive. The test method is nondestructive, requires no sample preparation, and does not create waste disposal problems.

⁴ Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, <http://www.ansi.org>.

4.3 This test method assumes that all plutonium in the measured item has the same isotopic distribution, often called isotopic homogeneity (see 7.2.4 and 7.2.5).

4.4 The ²⁴²Pu abundance is not measured by this test method and must be estimated from isotopic correlation techniques, stream averages, historical information, or other measurement techniques.

4.5 Americium-241 is a daughter product of ²⁴¹Pu. The ²⁴¹Am/²³⁹Pu atom ratio can also be determined by means of this test method (assuming a homogeneous isotopic distribution of plutonium and ²⁴¹Am). The determination of the ²⁴¹Am/²³⁹Pu atom ratio is necessary for the correct interpretation of a calorimetric heat measurement.

4.6 The isotopic composition of a given batch or item of plutonium is an attribute of that item and, once determined, can be used in subsequent inventory measurements to verify the identity of an item within the measurement uncertainties.

4.7 The method can also measure the ratio of other gamma-emitting isotopes to plutonium assuming they have the same spatial distribution as the plutonium in the item. Some of these “other” gamma-emitting isotopes include isotopes of uranium, neptunium, curium, cesium, and other fission products. The same methods of this standard can be used to measure the isotopic composition of uranium in items containing only uranium (3, 4, 5, 6).

5. Interferences

5.1 Because of the finite resolution of even the best quality HPGe detectors, the presence of other gamma-emitting sources must be assessed for their effects on the isotopic abundance determination.

5.1.1 The detector used for the spectral measurements shall be adequately shielded from other nearby plutonium sources. Background spectra shall be collected to ensure the effectiveness of detector shielding and to identify the background radiations.

5.1.2 If fission products are present in the item being measured, they will contribute additional gamma-ray spectral peaks. These peaks occur mainly in the 500 to 800-keV energy range and may affect the intensity determination of plutonium and americium peaks in this region. These high-energy gamma-rays from fission products also produce contributions to the Compton background below 500 keV that decrease the precision for peak intensity determination in this region.

5.1.3 For mixed plutonium-uranium oxide-bearing items, the appropriate corrections for the spectral peaks produced by uranium gamma emission shall be applied. The main interferences from uranium are listed in Table 1.

5.1.4 Other interference-producing nuclides can be routinely present in plutonium-bearing materials. The gamma rays from these nuclides must be assessed for their interference effects on the multiplets used for the plutonium isotopic analysis and the proper spectral corrections applied. Some of these interfering nuclides include: ²³⁷Np and its daughter ²³³Pa, ²⁴³Am and its daughter ²³⁹Np, ²³³U, and the Th decay chain daughters of ²³²U and ²³⁶Pu.

5.2 Count-rate and coincident-summing effects may also affect the isotopic abundance determination. This is especially important for items having high ²⁴¹Am concentrations. Random summing of the intense 59.5-keV ²⁴¹Am gamma ray with other intense gamma radiations produces spurious spectral peaks (7) that can interfere with the isotopic analysis. Thin (typically 0.5 to 2 mm) cadmium or tin (which is less toxic) absorbers should be placed on the front face of the detector to keep the height of the 59.5 keV gamma-ray peak equal to or less than the height of the most intense peaks in the 100-keV region.

<https://standards.iteh.ai/catalog/standards/sist/5fe47ad0-732d-4188-9209-ad7b5f6eff24/astm-c1030-10>

6. Apparatus

6.1 *Cooled High-Purity Germanium Detector, Preamplifier*—Cooling of the HPGe crystal may come from liquid nitrogen (LN₂) or from electric or electro-mechanical coolers that do not use LN₂. The configuration of the HPGe detector may be planar, semi-planar, or coaxial with the type, size and energy resolution of the detector chosen to accommodate the energy range of analysis for the desired measurements. Planar or semi-planar detectors with energy resolution (full-width at half maximum) at 122 keV better than 650 eV are best for analysis of spectra in the 60 to 450 keV region. Larger volume coaxial detectors with efficiencies (relative to a 3 × 3 NaI(Tl) at 1332 keV for a point source at a distance of 10 cm (ANSI/IEEE Std 325-1996)) of 25 to 100 % are used for analysis in the energy regions above 120 keV. Resolution of 2 keV or better at 1332 keV is preferred.

TABLE 1 Principal Gamma-Ray Interferences Due to from Uranium in (Mixed Pu₂U)O₂ Materials^A Materials

Energy (keV)	Branching Intensity Intensity- (% γ /disintegration) ₁ (%)	Isotope
143.77	40.7	²³⁶ U
143.76	10.96	²³⁵ U
163.36	4.85	²³⁶ U
163.33	5.08	²³⁵ U
185.72	56.1	²³⁶ U
185.715	57.2	²³⁵ U
202.42	4.07	²³⁶ U
202.11	1.08	²³⁵ U
205.31	4.87	²³⁶ U
205.311	5.01	²³⁵ U

^A Branching Intensity and Energy from Ref (17).

6.2 High Voltage Supply, Linear Amplifier, Analog-to-Digital Converter (ADC), Multichannel Pulse-Height Analyzer (MCA)—Systems containing these components compliant with Guide C982 may be used. A preferred and more convenient choice is an integrated digital spectroscopy system containing all components in a single unit with a high speed computer interface. Analysis of spectra in the 100 keV-region requires at least 4096 channels of data. Analysis in higher energy regions requires a minimum of 8192 channels of data with 16 384 data channels becoming more widely used.

6.3 High count rate applications require the use of pile-up rejection circuitry. Digital stabilization may be desirable for long count times under conditions of poor environmental control to ensure the quality of the spectral data. High quality digital spectroscopy systems fulfill all of these requirements and have been shown to have minimal degradation on plutonium isotopic composition measurement results at input counting rates as high as 100 kHz (8).

6.4 Because of the complexity of plutonium spectra, data reduction is usually performed by computer. Computerized analysis methods are well developed and have been highly automated with the development of various analysis software codes (8, 9, 10, 11, 12, 13, 14). Analysis software is commercially available as are all of the required data acquisition components.

7. Precautions

7.1 Safety Precautions—Plutonium-bearing materials are both radioactive and toxic. Use adequate laboratory facilities and safe operating procedures in handling items containing these materials. Follow all safe operating procedures and protocols specific to the facility or location where the measurements are being made.

7.2 Technical Precautions:

7.2.1 Preclude or rectify counting conditions that may produce spectral distortions. Use pulse pile-up rejection techniques if high count rates are encountered. Use absorbers when appropriate to reduce the intensity of the 59.5 keV gamma-ray of americium (see 5.2). Temperature and humidity fluctuations in the measurement environment may cause gain and zero-level shifts in the gamma-ray spectrum. Employ environmental controls or digital stabilization, or both, in this case. Failure to isolate the electronic components from other electrical equipment or the presence of noise in the AC power may also produce spectral distortions.

7.2.2 The decay of ²⁴¹Pu is shown in Fig. 1. The alpha decay branch proceeds through the daughter ²³⁷U which decays with a 6.75 day half-life to ²³⁷Np. It takes 67 days to reach 99.9 % of secular equilibrium for this branch of the decay. After secular equilibrium has been attained the strong gamma rays at 164.6, 208.0, 267.5, 332.4, 335.4, 368.6, and 370.9 keV from the decay of ²³⁷U may be used to directly determine ²⁴¹Pu. These major gamma rays from the decay of ²³⁷U also have an identical energy component from the beta decay branch of ²⁴¹Pu proceeding through ²⁴¹Am. The ²⁴¹Am component of these “co-energetic” peaks must be accounted for in the analysis. If secular equilibrium has not been reached, gamma rays (usually the 148.57-keV peak) from the direct decay of ²⁴¹Pu to ²³⁷U must be used to determine the ²⁴¹Pu isotopic fraction. At all times the gamma rays from the decay of ²³⁷U may be used to determine the relative efficiency.

7.2.3 The facility may place high-Z absorbers within the sealed, plutonium-bearing container to reduce external radiation exposure to the handler. As little as 1/16 in. (0.16 cm) of lead surrounding the plutonium will absorb the majority of the useful gamma rays in the 100 to 200-keV region and may invalidate the measurement, depending upon the energy range of the analysis.

7.2.4 The isotopic composition of all the plutonium in the item must be the same. The technique does not apply to nonuniform or heterogeneous mixtures of different isotopic composition. However, the physical distribution or chemical composition of the plutonium within the item may be non-uniform with no adverse effect on the results.

7.2.5 The ²⁴¹Am/²³⁹Pu atom ratio must be uniform in all the plutonium in the item, in order to obtain reliable specific power measurements to use in interpreting calorimetry results. Certain types of Pu materials with non-homogeneous Am-Pu distributions (salt residues) have been shown to be amenable to assay by this test method with slight modifications (15, 16). These materials

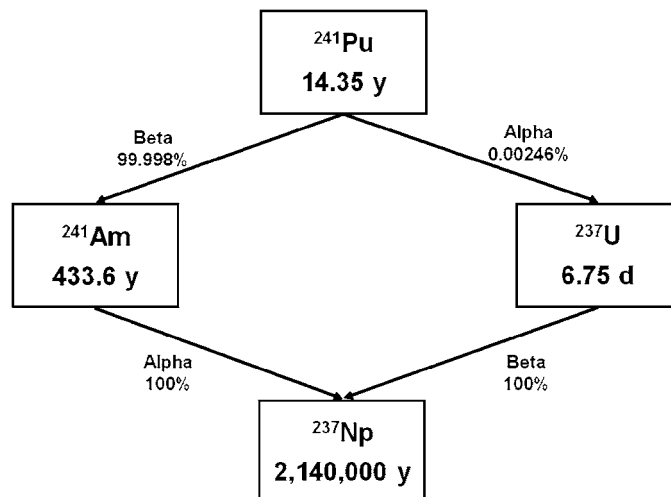


FIG. 1 The Decay of ²⁴¹Pu

have a low density salt matrix containing most of the americium while most of the plutonium is dispersed throughout this matrix as high density localizations or free metal shot.

7.2.6 Plutonium-bearing materials, especially those with strong (alpha, n) neutron emissions, should not be stored in the vicinity of the HPGe detector. High energy neutrons emitted by these materials can produce trapping centers in the HPGe crystal and severely degrade the resolution and peak shape of the detector. The use of N-type detectors, which are less susceptible to neutron damage, can prolong useful detector life.

8. Calibration, Standardization, and Measurement Control

8.1 *Apparatus*—The energy calibration of the spectrometry system can be adjusted using a gamma-ray-emitting check source or a plutonium-bearing item because the plutonium gamma-ray energies are well known. A listing of the principal gamma rays emitted from plutonium is given in Table 2. See also Test Methods E181 and Refs (17) and (18).

8.2 Reference Materials:

8.2.1 The expression relating atom ratios to detected peak intensities contains only fundamental constants (see 3.5) and does not depend upon reference standards. Reference standards can be used to identify biases in the values of measured results and as an aid in identifying possible spectral interferences.

8.2.2 Working reference materials with isotopic composition traceable to the National Measurement System may be used to verify the overall correct operation of the spectrometry system and data reduction techniques, and also as an aid in identifying interferences and biases. Working reference materials traceable to the National Measurement System should be prepared and validated by other analysis techniques (see Test Methods C697, C698, and E267).

8.3 Measurement Control:

8.3.1 A measurement control program (ANSI N15.36) shall be established in order to identify anomalous measurement results that may be due to instrument failure or operator (procedural) error. The measurement control program shall cover all phases of the plutonium isotopic measurement from the data collection through the calculation of the isotopic atom ratios.

8.3.2 Data collection procedures shall be standardized for each item type or measurement application. Control limits or ranges shall be established for the various data collection parameters such as: count time, count rate, system dead time, and counting geometry. To assure the quality of the collected data and analysis methods, the isotopic measurement control program would employ both internal and external checks discussed below.

8.3.3 Internal checks utilize parameters or measurement results from the spectral data of the item being assayed. An important internal check that provides a good indication of the overall hardware performance is the system resolution. System resolution should be monitored on a spectrum-to-spectrum basis using a strong, clean single peak in the spectrum. Another internal check is to monitor the position of certain spectral peaks to identify possible gain shifts. Monitoring the consistency of the isotopic ratios obtained from several peaks from the same isotope can identify possible interferences or inconsistent peak fitting results. For analysis methods that use fitting techniques, the statistical measures of goodness-of-fit, such as chi-square, can be used with suitable control limits for measurement control purposes.

8.3.4 External checks rely on a comparison of isotopic results among replicate gamma-ray spectral measurements or between the spectral measurement and another assay technique. The isotopic assay of working reference materials can be used to verify that the measurement system is still in control. Measurements of the same item on parallel instruments can also be used as a measurement control indicator. Other external techniques are: comparisons of the gamma-ray results from an item to destructive analysis results, participation in interlaboratory exchange programs, comparisons of the present data with historical or stream average data, and the reanalysis of items at random.

8.3.5 A successful measurement control program will employ a combination of internal and external techniques. Total reliance on an individual technique or check is not recommended. The simpler measurement checks, such as the monitoring of the system resolution, should probably be performed on a item-by-item or daily basis, while other more complex techniques could be performed less frequently.

8.3.6 The measurement control data provided by the internal and external checks can be used for constructing a data base for identifying and monitoring the random and systematic errors associated with the isotopic measurement system.

9. Procedure

9.1 Arrange the counting geometry to obtain the maximum count rate that does not produce any unwanted spectral distortions. The 59.5 keV peak from ²⁴¹Am usually produces a substantial contribution to the system dead time; its intensity can be reduced through the use of a Cd or Sn absorber (see 5.2).

9.2 Acquire the spectrum for the length of time necessary to achieve the desired level of statistical precision. The precision for an isotopic composition measurement depends on counting statistics and is a function of several parameters (see Section 11). Typical counting times may vary from 10 min to over 4 hr depending upon the purpose of the measurement and the plutonium mass in the measured item. Analysis may proceed directly upon the acquired data or the data may be stored on disk for analysis at a later time.

9.3 Analyze the spectral data. The procedural details of the analysis depend upon the specific software (8, 9, 10, 11, 12, 13, 14) used for the analysis.

9.4 The results of an isotopic measurement shall include an uncertainty assigned to each isotopic result. The uncertainties

TABLE 2 Energies and Gamma-Ray Branching Intensities^A of Prominent Pu and Am Spectral Peaks

NOTE 1—The Branching Intensity for ²⁴¹Pu–²³⁷U gamma rays includes the 2.45×10^{-5} branching fraction for the alpha decay of ²⁴¹Pu to ²³⁷U. See Fig. 2.

Isotope	Energy (keV)	Branching Intensity (γ/disintegration, %)	Isotope	Energy (keV)	Branching Intensity (γ/disintegration, %)
²⁴¹ Am	59.54	35.9			
²⁴¹ Am	59.54	35.9			
²⁴⁰ Am					
²⁴¹ Pu	125.29	4.08×10^{-5}			
²⁴¹ Pu	104.23	7.08×10^{-3}			
²⁴¹ Am	129.29	6.26×10^{-5}			
²⁴¹ Am	125.30	4.08×10^{-3}			
²³⁹ Pu	148.57	1.87×10^{-6}			
²³⁹ Pu	129.30	6.31×10^{-3}			
²⁴¹ Pu	152.68	9.37×10^{-6}			
²⁴¹ Pu	148.57	1.85×10^{-4}			
²³⁹ Pu	160.28	4.02×10^{-6}			
²³⁸ Pu	152.72	9.37×10^{-4}			
²⁴⁰ Pu	164.48 ^C	4.53×10^{-7}			
²⁴⁰ Pu	160.31	4.02×10^{-4}			
²⁴¹ Pu– ²³⁷ U		6.67×10^{-7}			
²⁴¹ Pu– ²³⁷ U	164.61	4.53×10^{-5}			
²⁴¹ Am	203.54	5.60×10^{-6}			
²⁴¹ Am	164.61	6.67×10^{-5}			
²³⁹ Pu	208.00 ^C	5.16×10^{-6}			
²³⁹ Pu	203.55	5.69×10^{-4}			
²⁴¹ Pu– ²³⁷ U		7.91×10^{-6}			
²⁴¹ Pu– ²³⁷ U	208.00	5.18×10^{-4}			
²⁴¹ Am	335.44 ^C	2.39×10^{-8}			
²⁴¹ Am	208.00	7.91×10^{-4}			
²⁴¹ Pu– ²³⁷ U		4.96×10^{-6}			
²⁴¹ Pu– ²³⁷ U	332.36	2.93×10^{-5}			
²⁴¹ Am	345.04	5.59×10^{-6}			
²⁴¹ Am	332.36	1.49×10^{-4}			
²⁴¹ Pu– ²³⁷ U			²³⁹ Pu		
²⁴¹ Pu– ²³⁷ U	368.64 ^C	1.05×10^{-8}	²⁴¹ Pu– ²³⁷ U	335.38	2.17×10^{-6}
²⁴¹ Pu– ²³⁷ U	368.64 ^C	1.05×10^{-8}	²⁴¹ Pu– ²³⁷ U	335.38	2.33×10^{-6}
²⁴¹ Am	375.04	1.57×10^{-5}			
²⁴¹ Am	335.38	4.96×10^{-4}			
²³⁹ Pu	413.71				
²³⁹ Pu	345.01	5.56×10^{-4}			
²³⁹ Pu	1.49×10^{-5}	1.55×10^{-3}			
²³⁹ Pu	375.05	1.55×10^{-3}			
²³⁹ Pu	375.05	1.55×10^{-3}			
²³⁹ Pu	642.48				
²³⁹ Pu	413.71	1.47×10^{-3}			
²⁴¹ Pu– ²³⁷ U	451.48	1.89×10^{-4}			
²³⁹ Pu	451.48	1.89×10^{-4}			
²⁴⁰ Pu	645.97	1.49×10^{-7}			
²⁴⁰ Pu	642.35	1.3×10^{-5}			
²³⁹ Pu	662.42	3.64×10^{-6}			
²³⁹ Pu	645.94	1.52×10^{-5}			
²⁴¹ Am	717.72	2.74×10^{-8}			
²⁴¹ Am	662.40	3.64×10^{-4}			
²³⁹ Pu					
²⁴¹ Pu					
Am	721.99	1.96×10^{-4}			
Am	772.01	1.96×10^{-4}			
²³⁸ Pu	766.39	2.2×10^{241} Am			
²³⁸ Pu	766.39	2.2×10^{-5}			

^A B Energies and branching intensities from Ref (157), except where noted.
^B Branching Intensity from "Handbook of Nuclear Data for Safeguards," INDC (NDS)-248, Nuclear Data Section, IAEA, Vienna, Austria, 1991.
^C Produced in decay of ²⁴¹Pu–²³⁷U and ²⁴¹Am, total intensity will be a function of the abundances of these two isotopes.

ascribed to the isotopic fractions and isotopic ratios shall be propagated from the statistical uncertainties of the measured peak areas and any uncertainties due to the peak area determination process. Some analysis procedures may also incorporate systematic measurement uncertainties into the final quoted uncertainty. It is incumbent upon the user to understand the components and contributions incorporated in the quoted uncertainty. The description of the included uncertainty components should be found in the user's manual for the software application used.