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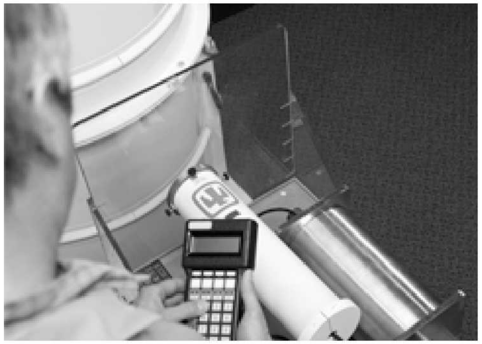

Plutonium gamma spectroscopy training

Revision 02

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Discussion topics

- Presentation conventions
- General information
  - Plutonium related half-lives
  - Typical plutonium isotopic mass & activity percentages
  - Plutonium decay heat generation
  - Plutonium spontaneous fission neutron production rates
  - Plutonium (alpha, neutron) production rates
  - Useful plutonium emissions for analysis
  - Plutonium gamma spectroscopy notes

Discussion topics

- Plutonium isotopic determinations
- Plutonium age determinations
- Neutron &/or alpha reactions of interest
- Plutonium activity/mass determinations

Presentation conventions

- Pu-241 (14.35 y) -> U-237 (6.8 d) equilibrium is assumed throughout the presentation.
  - 90% Pu-241 -> U-237 equilibrium occurs at 22.5 days.
- The U-237 yields listed in this presentation include the 2.45E-03% branch from its parent nuclide, Pu-241, per ICRP Publication 107.
  - Pu-241 (14.35 y) 99.998% -> Am-241 (433.2 y) -> Np-237 (2.14E+06 y)
  - Pu-241 (14.35 y) 0.00245% -> U-237 (6.8 d) -> Np-237 (2.14E+06 y)
- Decay chains are represented in this presentation utilizing a "+" symbol.
  - Np-237+ represents Np-237 in equilibrium with Pa-233.
  - Pu-241+ represents Pu-241 in equilibrium with U-237.
  - Th-228+ represents Th-228 in equilibrium with its decay products.
- "**Bolded**" gamma emissions listed in this presentation can generally be treated as interference free.

Plutonium related half-lives

Nuclide	Half Life
Pu-238	87.7 y
Pu-239	24,110 y
Pu-240	6,564 y
Pu-241	14.35 y
Pu-242	375,000 y
Am-241	432.2 y
U-237	6.75 d
Np-237	2,144,000 y
Pa-233	27.0 d

Typical plutonium type mass & activity percentages

Initial Mass Percentages

Nuclides	Low-burnup Pu (Mass %)	High-burnup Pu (Mass %)	Heat source Pu (Mass %)
Pu-238	0.010%	1.500%	83.890%
Pu-239	93.771%	58.100%	13.800%
Pu-240	5.999%	24.100%	1.900%
Pu-241	0.200%	11.400%	0.320%
Pu-242	0.020%	4.900%	0.090%
Am-241	0.000%	0.000%	0.000%

Decay Corrected Mass Percentages at 20 Years

Nuclides	Low-burnup Pu (Mass %)	High-burnup Pu (Mass %)	Heat source Pu (Mass %)
Pu-238	0.009%	1.286%	81.652%
Pu-239	93.783%	58.319%	15.723%
Pu-240	5.991%	24.154%	2.161%
Pu-241	0.076%	4.357%	0.139%
Pu-242	0.020%	4.921%	0.103%
Am-241	0.122%	6.962%	0.222%

Initial Activity Percentages

Nuclides	Low-burnup Pu (Activity %)	High-burnup Pu (Activity %)	Heat source Pu (Activity %)
Pu-238	0.611%	2.118%	97.664%
Pu-239	20.759%	0.297%	0.058%
Pu-240	4.858%	0.451%	0.029%
Pu-241	73.772%	97.133%	2.248%
Pu-242	0.000%	0.002%	0.000%
Am-241	0.000%	0.000%	0.000%

Decay Corrected Activity Percentages at 20 Years

Nuclides	Low-burnup Pu (Activity %)	High-burnup Pu (Activity %)	Heat source Pu (Activity %)
Pu-238	0.937%	4.358%	98.828%
Pu-239	37.260%	0.716%	0.069%
Pu-240	8.706%	1.084%	0.035%
Pu-241	50.421%	89.110%	1.014%
Pu-242	0.001%	0.004%	0.000%
Am-241	2.675%	4.727%	0.054%

- A plutonium production reactor irradiates U-238 for a short time, then processes it to chemically remove the plutonium isotopes.
- The longer the exposure time in the reactor (higher burnup), the more Pu-238, Pu-240, Pu-241, & Pu-242 are produced relative to Pu-239.
- Pu-241 increases more rapidly than Pu-240 as burnup increases.
- Following chemical separation, Am-241 builds-in from the decay of Pu-241 (14.4 y half-life).

Plutonium decay heat generation

Initial Mass Percentages

Nuclides	Decay Heat (Watts/kg)	Low-burnup Pu (Mass %)	High-burnup Pu (Mass %)	Heat source Pu (Mass %)	Low-burnup Pu (Watts/kg)	High-burnup Pu (Watts/kg)	Heat source Pu (Watts/kg)
Pu-238	567.16	0.010%	1.500%	83.890%	0.06	8.51	475.79
Pu-239	1.92	93.771%	58.100%	13.800%	1.80	1.12	0.27
Pu-240	7.06	5.999%	24.100%	1.900%	0.42	1.70	0.13
Pu-241	3.29	0.200%	11.400%	0.320%	0.01	0.38	0.01
Pu-242	0.12	0.020%	4.900%	0.090%	0.00	0.01	0.00
Am-241	114.71	0.000%	0.000%	0.000%	0.00	0.00	0.00
					2.3	11.7	476.2

Decay Corrected Mass Percentages at 20 Years

Nuclides	Decay Heat (Watts/kg)	Low-burnup Pu (Mass %)	High-burnup Pu (Mass %)	Heat source Pu (Mass %)	Low-burnup Pu (Watts/kg)	High-burnup Pu (Watts/kg)	Heat source Pu (Watts/kg)
Pu-238	567.16	0.009%	1.286%	81.652%	0.05	7.30	463.10
Pu-239	1.92	93.783%	58.319%	15.723%	1.80	1.12	0.30
Pu-240	7.06	5.991%	24.154%	2.161%	0.42	1.71	0.15
Pu-241	3.29	0.076%	4.357%	0.139%	0.00	0.14	0.00
Pu-242	0.12	0.020%	4.921%	0.103%	0.00	0.01	0.00
Am-241	114.71	0.122%	6.962%	0.222%	0.14	7.99	0.25
					2.4	18.3	463.8

Plutonium spontaneous fission neutron production rates

Initial Mass Percentages

Nuclides	Spont Fission Yield (n/s-kg)	Low-burnup Pu (Mass %)	High-burnup Pu (Mass %)	Heat source Pu (Mass %)	Low-burnup Pu (n/s-kg)	High-burnup Pu (n/s-kg)	Heat source Pu (n/s-kg)
Pu-238	2.59E+06	0.010%	1.500%	83.890%	259	38850	2172751
Pu-239	2.18E+01	93.771%	58.100%	13.800%	20	13	3
Pu-240	1.02E+06	5.999%	24.100%	1.900%	61190	245820	19380
Pu-241	5.00E+01	0.200%	11.400%	0.320%	0	6	0
Pu-242	1.72E+06	0.020%	4.900%	0.090%	344	84280	1548
Am-241	1.18E+03	0.000%	0.000%	0.000%	0	0	0
					61813	368968	2193682

Decay Corrected Mass Percentages at 20 Years

Nuclides	Spont Fission Yield (n/s-kg)	Low-burnup Pu (Mass %)	High-burnup Pu (Mass %)	Heat source Pu (Mass %)	Low-burnup Pu (n/s-kg)	High-burnup Pu (n/s-kg)	Heat source Pu (n/s-kg)
Pu-238	2.59E+06	0.009%	1.286%	81.652%	221	33314	2114792
Pu-239	2.18E+01	93.783%	58.319%	15.723%	20	13	3
Pu-240	1.02E+06	5.991%	24.154%	2.161%	61104	246369	22047
Pu-241	5.00E+01	0.076%	4.357%	0.139%	0	2	0
Pu-242	1.72E+06	0.020%	4.921%	0.103%	344	84644	1765
Am-241	1.18E+03	0.122%	6.962%	0.222%	1	82	3
					61691	364424	2138609

Plutonium (alpha, neutron) production rates

- The following (alpha, neutron) reactions increase plutonium neutron outputs by producing single neutrons that are not correlated with time.
- Thick-target yields from (alpha, neutron) reactions (PANDA manual: Table 11-5)

Target	Pu Avg
Li	1.13
Be	65
B	17.5
C	0.078
O	0.059
F	5.9
Na	1.1
Mg	0.89
Al	0.41
Si	0.076
Cl	0.07

Neutrons per E6 α

Plutonium gamma spectroscopy notes

- When reporting Am-241 mass fractions, the convention is to report the mass fraction of Am-241 relative to the total amount of plutonium mass present (Am-241 mass/total Pu mass).

- Pu-236 is present in trace quantities in Pu.
  - Pu-236 (2.9 y) -> U-232 (72.0 y) -> Th-228 (1.9 y)
  - Both Pu-236 & U-232 are not readily detectable by gamma spectroscopy.
  - However, Th-228 decay product gamma emissions can be detected in some aged plutonium spectra.

Plutonium gamma spectroscopy notes

- When the measured Pu-239/Pu-240 mass ratio is less than 5, do not simply use the measured Pu-240/(Pu-239+Pu-240) mass fraction to estimate the Pu-240 mass fraction in the plutonium.

  - To better estimate the Pu-240 mass fraction, corrections should be made for the contributions from other Pu isotopes (Pu-238, Pu-241, Pu-242) present.

  - Correlations are commonly used to account for Pu-242 since it is essentially undetectable by gamma spectroscopy. See PANDA 2007 Addendum Chapter 2 for more information.

Plutonium gamma spectroscopy notes

- Plutonium is a dense, high Z material & therefore very good at self-attenuating its gamma emissions. Therefore, high yield, low energy gamma emissions may be significantly reduced or not detected.
- For a given energy, when radioactive materials reach infinite thickness, the outer layers of the dense radioactive material essentially shield all gamma emissions from inner layers of the dense radioactive material.
  - This eliminates the ability to perform accurate activity &/or mass estimates unless additional information is known about the sample geometry &/or composition. However, it may be possible to provide surface area estimates from gamma spectra.

Nuclide	Gamma Energy (keV)	Density (g/cc)	1% Transmission Thickness (mm)	0.1% Transmission Thickness (mm)
Pu-239	129.3	19.65	0.62	0.94
Pu-239	413.7	19.65	8.4	12.6

Infinite thickness = The thickness needed to reduce transmission to 0.1% or approximately 7 mean free paths.

Plutonium gamma spectroscopy notes

- For unshielded plutonium samples, consider the use of graded shielding (Cd-Cu or Sn-Cu) to eliminate/reduce Am-241 59.5 keV gamma emissions in the spectrum.
  - May allow closer sample to detector distances to be used (reducing detection limits & increasing higher energy emission count rates).
  - Reduces “coincidence” summing with other photon emissions.
  - For portable gamma spectroscopy systems, I have used graded shield thicknesses between 30 to 60 mil of Cd or Sn in conjunction with 15 to 30 mil of Cu.

Plutonium gamma spectroscopy notes

- To improve the accuracy of plutonium isotopic determinations, consider the following options:

  - **Move the sample closer to the detector (within reason)**

  - If large amounts of Am-241 are present, use graded shielding to reduce random summing from Am-241.

  - NOTE: If high dead times & large amounts of Am-241 are present, then random sum peaks from Am-241 (59.5 keV with 99.0 & 103.0 keV) can complicate assessment of the 160.3 keV Pu-240 peak area commonly used for plutonium isotopic determinations.

Useful plutonium emissions for analysis

Nuclide	Energy (keV)	Yield (gps/dps)
Pu-239	**129.3**	**6.310E-05**
Pu-239	**203.6**	**5.690E-06**
Pu-239	**255.4**	**8.000E-07**
Pu-239	**345.0**	**6.060E-06**
Pu-239	**375.1**	**1.554E-05**
Pu-239	**413.7**	**1.466E-05**
Pu-239	**451.5**	**1.894E-06**
Pu-239	640.0	8.700E-08
Pu-239	**645.9**	**1.520E-07**
Pu-239	**658.9**	**9.700E-08**
Pu-239	**718.0**	**2.800E-08**
Pu-239	769.3	1.190E-07

Nuclide	Energy (keV)	Yield (gps/dps)
Am-241	**59.5**	**3.590E-01**
Am-241	125.3	4.080E-05
Am-241	208.0	7.910E-06
Am-241	**419.3**	**2.870E-07**
Am-241	**662.4**	**3.640E-06**
Am-241	**722.0**	**1.960E-06**

Nuclide	Energy (keV)	Yield (gps/dps)
Pu-241+	**148.6**	**1.855E-06**
Pu-241+	208.0	5.194E-06

Nuclide	Energy (keV)	Yield (gps/dps)
Pu-240	160.3	4.020E-06
Pu-240	642.4	1.300E-07

Nuclide	Energy (keV)	Yield (gps/dps)
Np-237+	**300.3**	**6.620E-02**
Np-237+	312.2	3.860E-01
Np-237+	340.8	4.470E-02

Nuclide	Energy (keV)	Yield (gps/dps)
Pu-238	**152.7**	**9.370E-06**
Pu-238	201.0	3.900E-08
Pu-238	742.8	5.200E-08
Pu-238	766.4	2.200E-07
Pu-238	786.3	3.250E-08
Pu-238	851.7	1.250E-08
Pu-238	**1001.0**	**9.900E-09**

Nuclide	Energy (keV)	Yield (gps/dps)
Th-228+	**238.6**	**4.330E-01**
Th-228+	**583.2**	**3.036E-01**
Th-228+	727.3	6.579E-02
Th-228+	860.6	4.465E-02
Th-228+	**2614.5**	**3.564E-01**

Plutonium isotopics overview

- Above the 100 keV region, there are four primary regions of interest for assessing plutonium isotopics
  - 160 keV
  - 208 keV
  - 332/336 keV
  - 640 keV

- Above the 100 keV region, only two regions of interest can be used for direct measurement of both Pu-239 & Pu-240
  - 160 keV
  - 640 keV
  - NOTE: Both regions of interest have interferences which complicate assessment

- For assessment at or below the 100 keV region, see PANDA Manual Chapter 8.3 for additional information

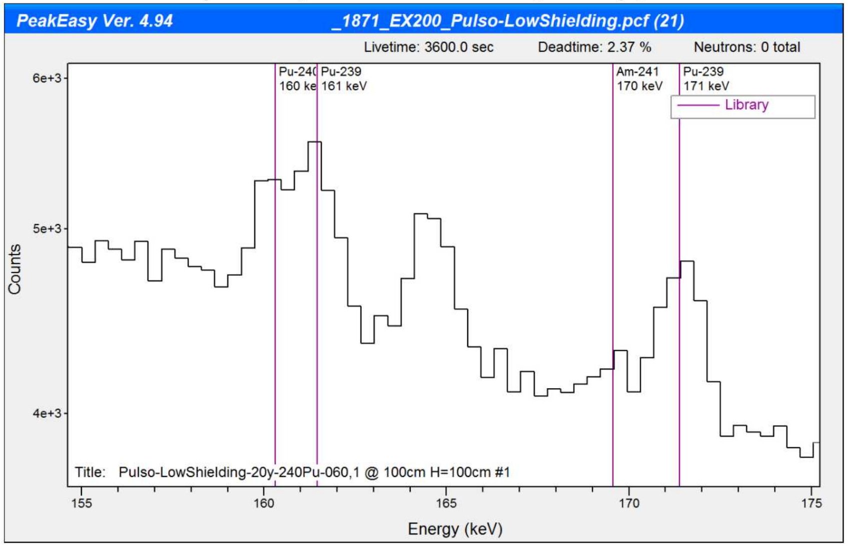
Example spectra

- So what do these regions of interest look like?

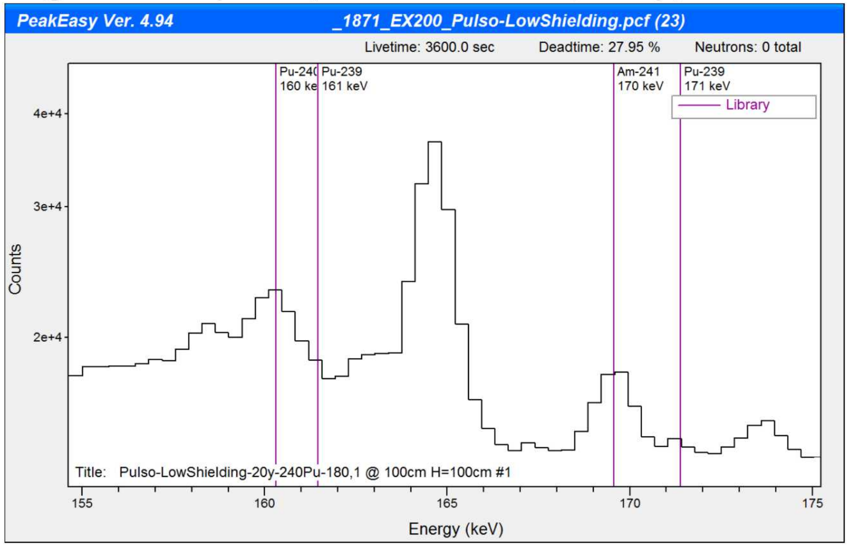
- Example spectra
  - 20 year old, low-burnup plutonium (6.0% Pu-240)
  - 20 year old, high-burnup plutonium (18.0% Pu-240)

160 keV region of interest

Low-burnup Pu (6.0% Pu-240, 20 y)



High-burnup Pu (18.0% Pu-240, 20 y)



Energy (keV)	Phot/Decay	Nuclide
160.0	6.54E-08	Pu-241
160.2	6.20E-08	Pu-239
160.3	4.02E-06	Pu-240
161.5	1.23E-06	Pu-239

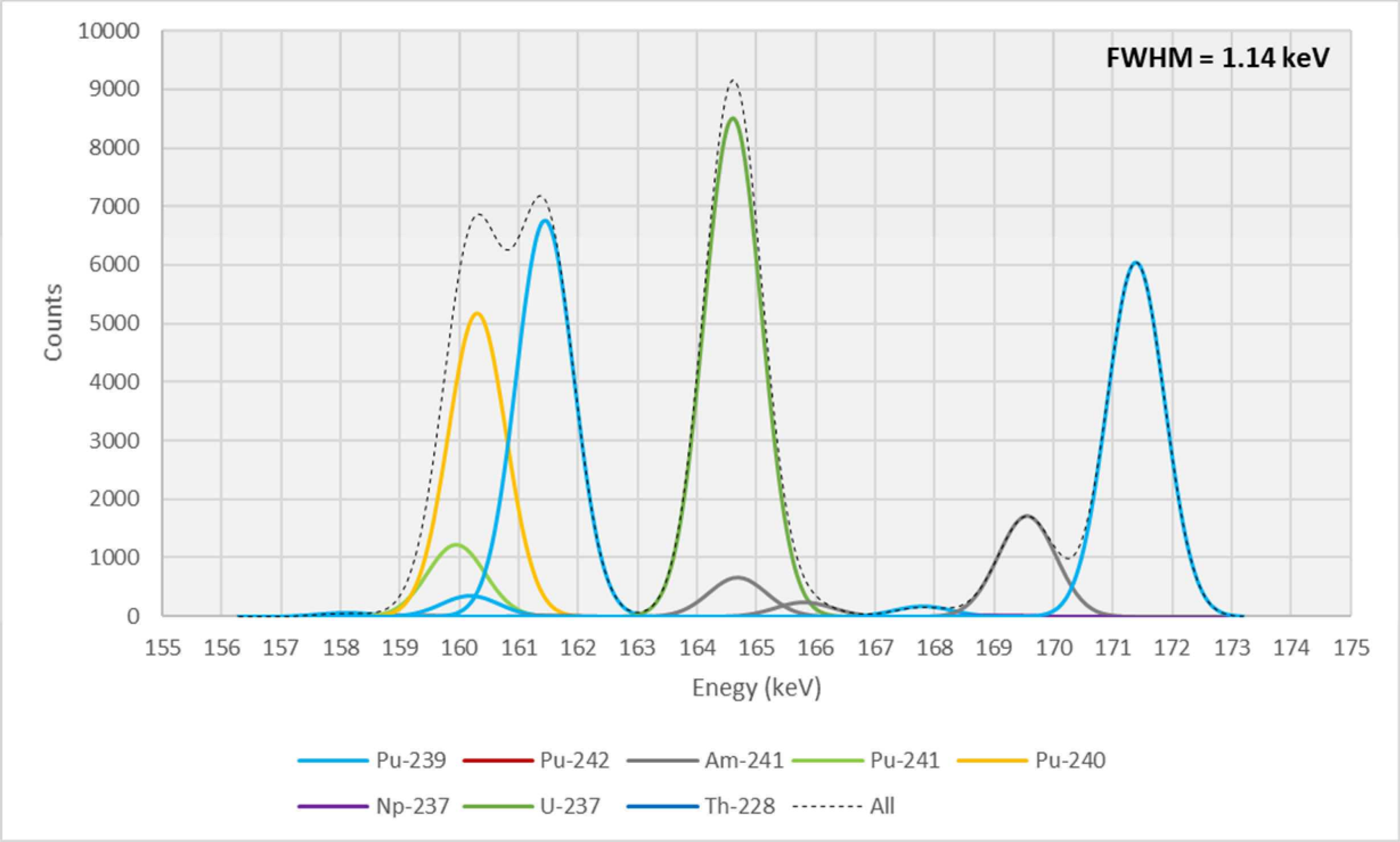
Energy (keV)	Phot/Decay	Nuclide
164.6	4.56E-07	U-237
164.7	6.67E-07	Am-241
169.6	**1.73E-06**	**Am-241**
171.4	**1.10E-06**	**Pu-239**

- Pu-240 160.3 keV emission has strong interferences from Pu-241 at 160.0 keV & Pu-239 at 160.2 keV.
- If high dead times & large amounts of Am-241 present, then random sum peaks from Am-241 (59.5 keV with 99.0 & 103.0 keV) can further complicate assessment.
- NOTE: Evidence of random summing in high-burnup Pu (18.0% Pu-240, 20 y) spectrum.

160 keV region of interest

Low-burnup Pu (6.0% Pu-240, 20 y)

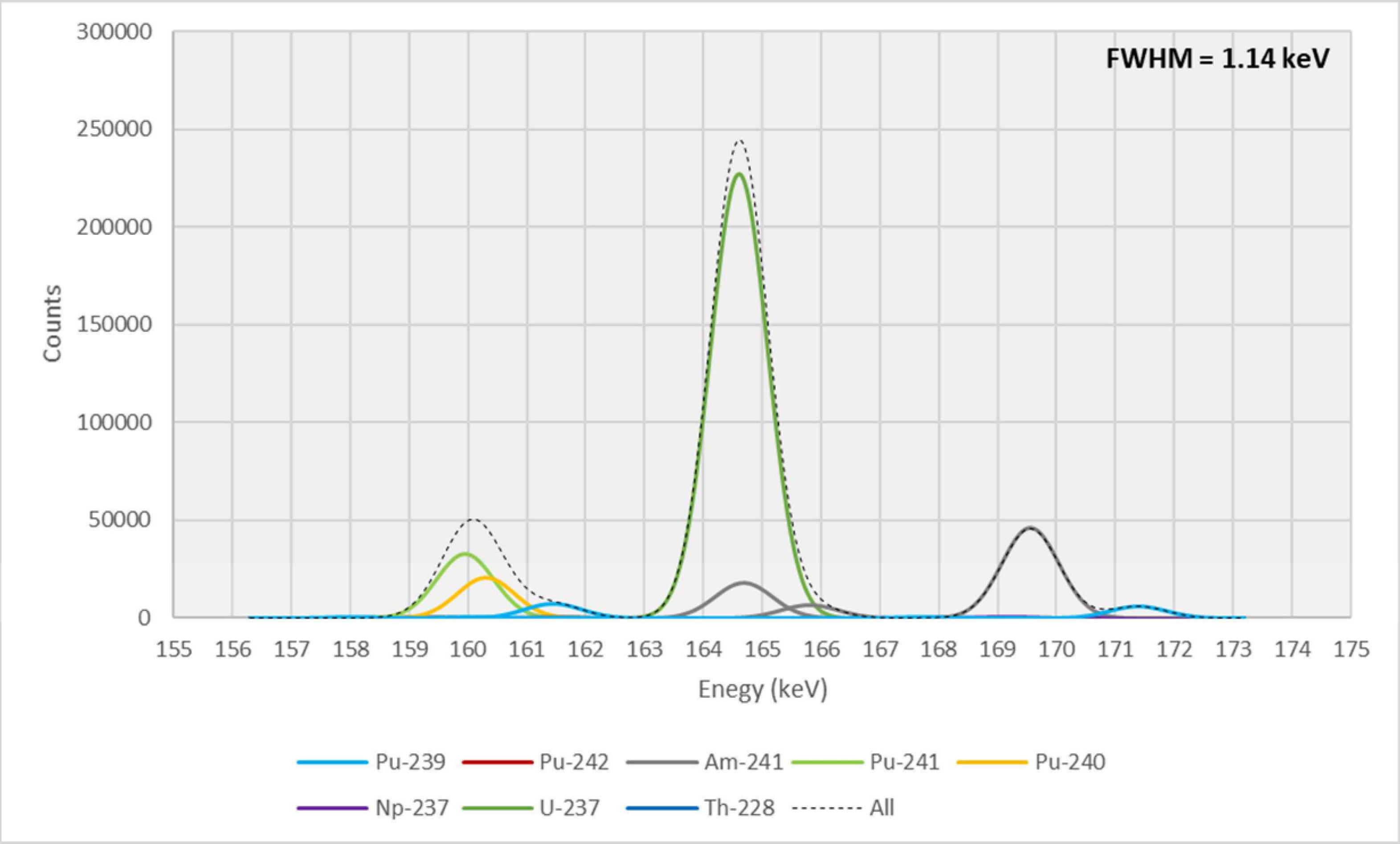
- Example of Pu-240 160.3 keV emission interferences



160 keV region of interest

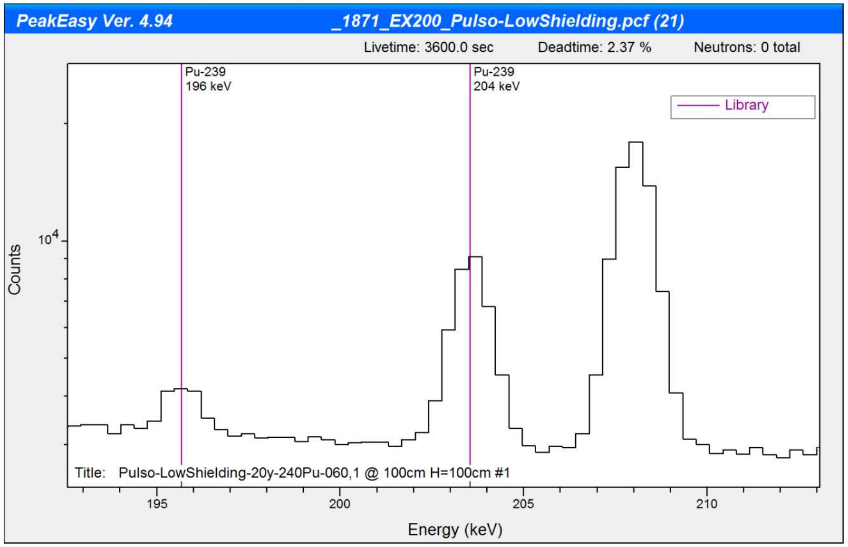
High-burnup Pu (18.0% Pu-240, 20 y)

- Example of Pu-240 160.3 keV emission interferences

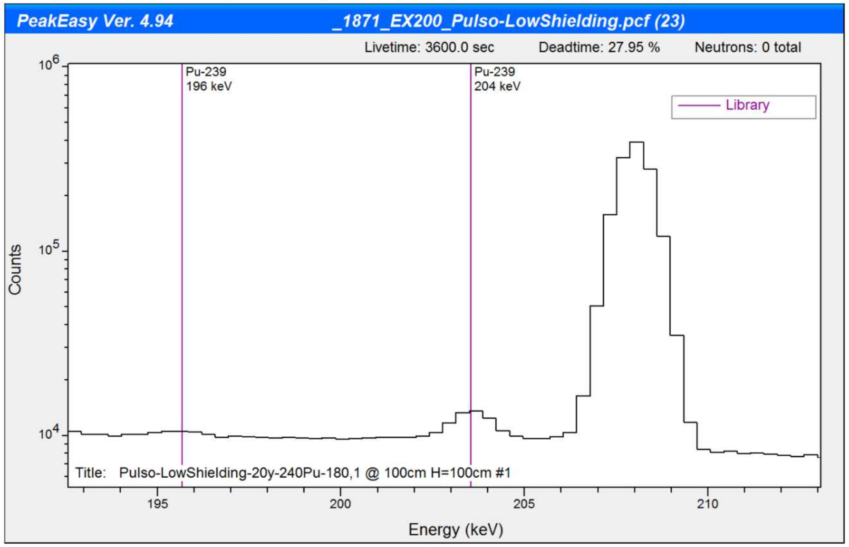


208 keV region of interest

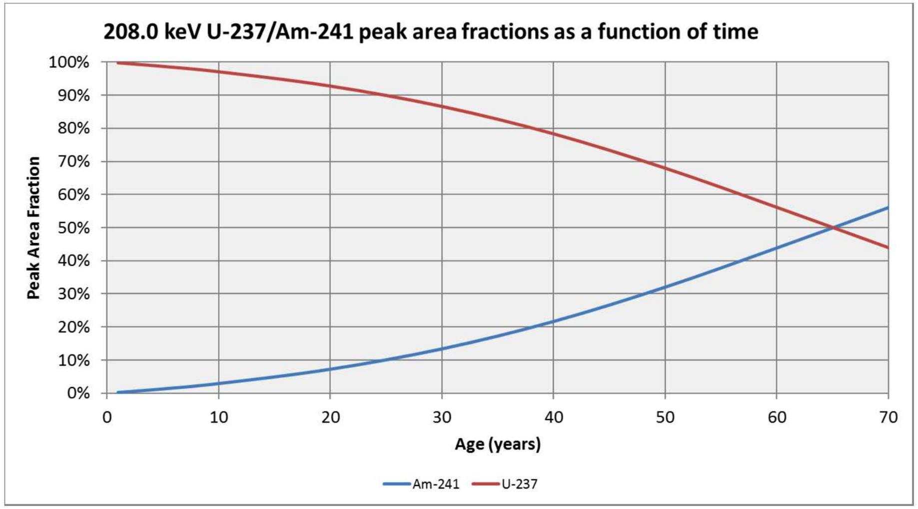
Low-burnup Pu (6.0% Pu-240, 20 y)



High-burnup Pu (18.0% Pu-240, 20 y)

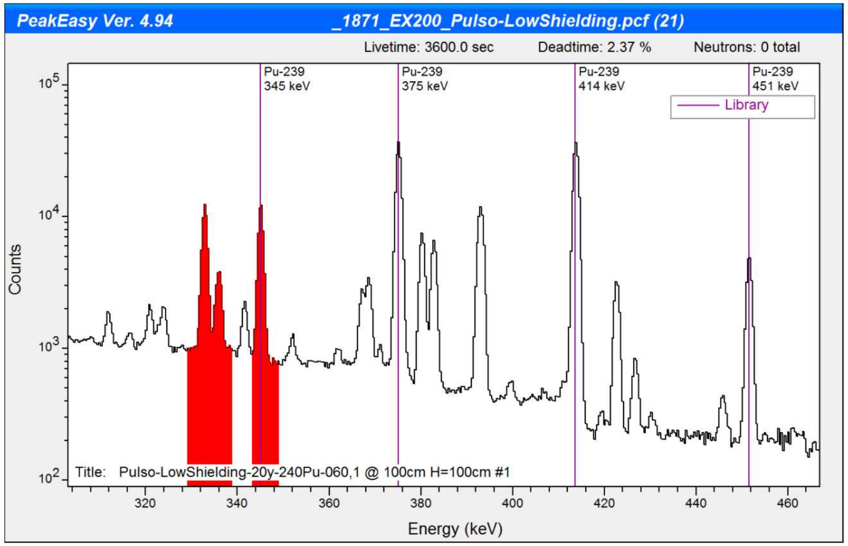


Energy (keV)	Phot/Decay	Nuclide
195.7	**1.07E-06**	**Pu-239**
203.6	**5.69E-06**	**Pu-239**
208.0	5.19E-06	U-237
208.0	7.91E-06	Am-241



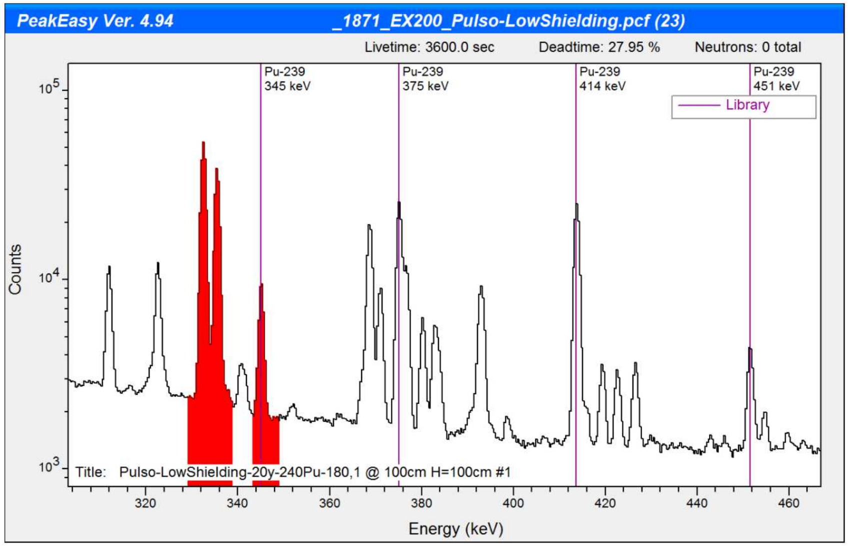
332/336 keV region of interest

Low-burnup Pu (6.0% Pu-240, 20 y)



Energy (keV)	Phot/Decay	Nuclide
332.4	1.49E-06	Am-241
332.4	2.94E-07	U-237
332.8	4.94E-06	Pu-239

High-burnup Pu (18.0% Pu-240, 20 y)



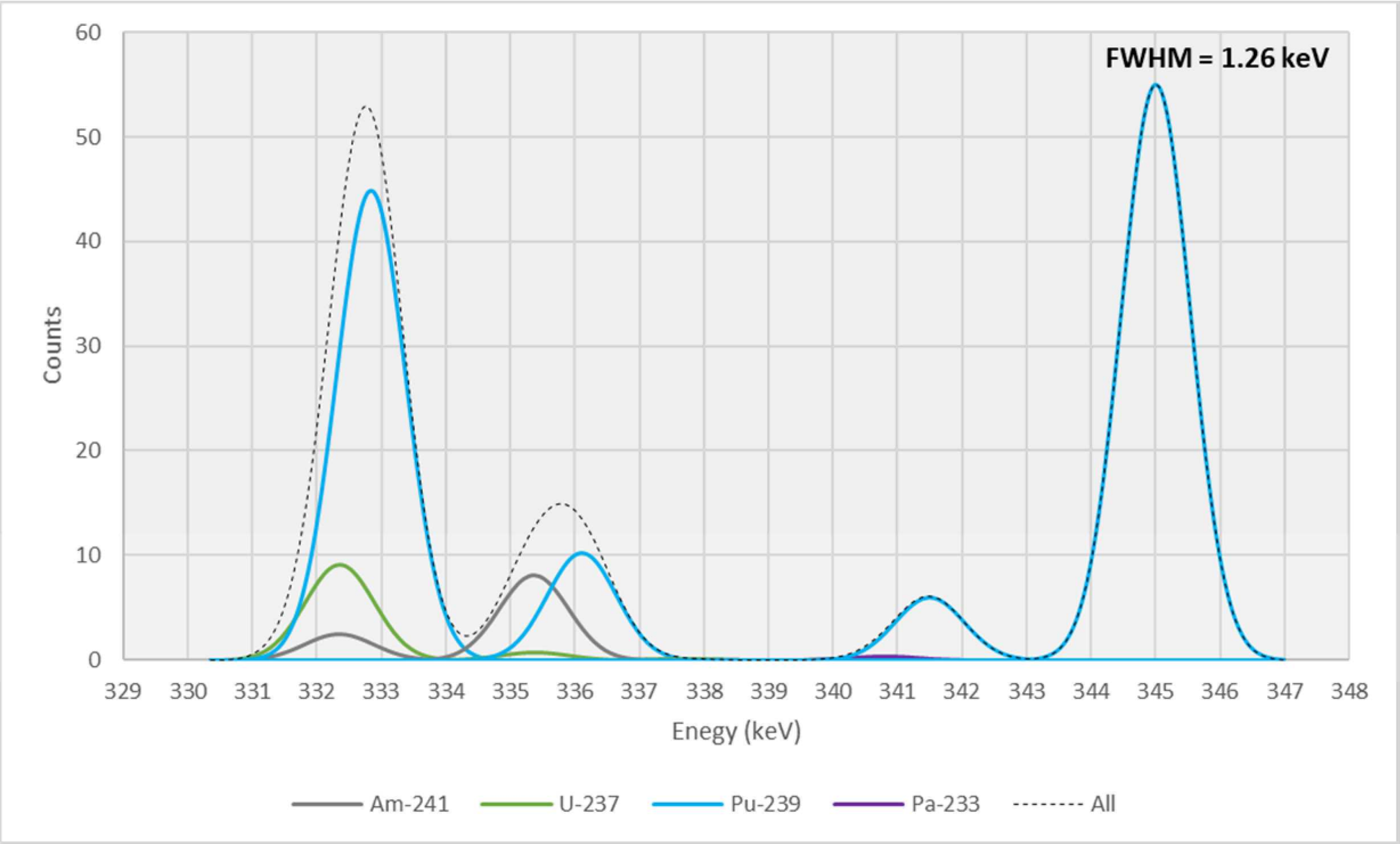
Energy (keV)	Phot/Decay	Nuclide
335.4	4.96E-06	Am-241
335.4	2.33E-08	U-237
336.1	1.12E-06	Pu-239
345.0	**6.06E-06**	**Pu-239**

- The 345.0 keV emission from Pu-239 is interference free.
- If good counting statistics, it is possible to strip the Pu-239 contribution from 332 & 336 keV complexes & solve for the Pu-241/U-237 & Am-241 peak areas to determine the time since chemical separation.

332/336 keV region of interest

Low-burnup Pu (6.0% Pu-240, 20 y)

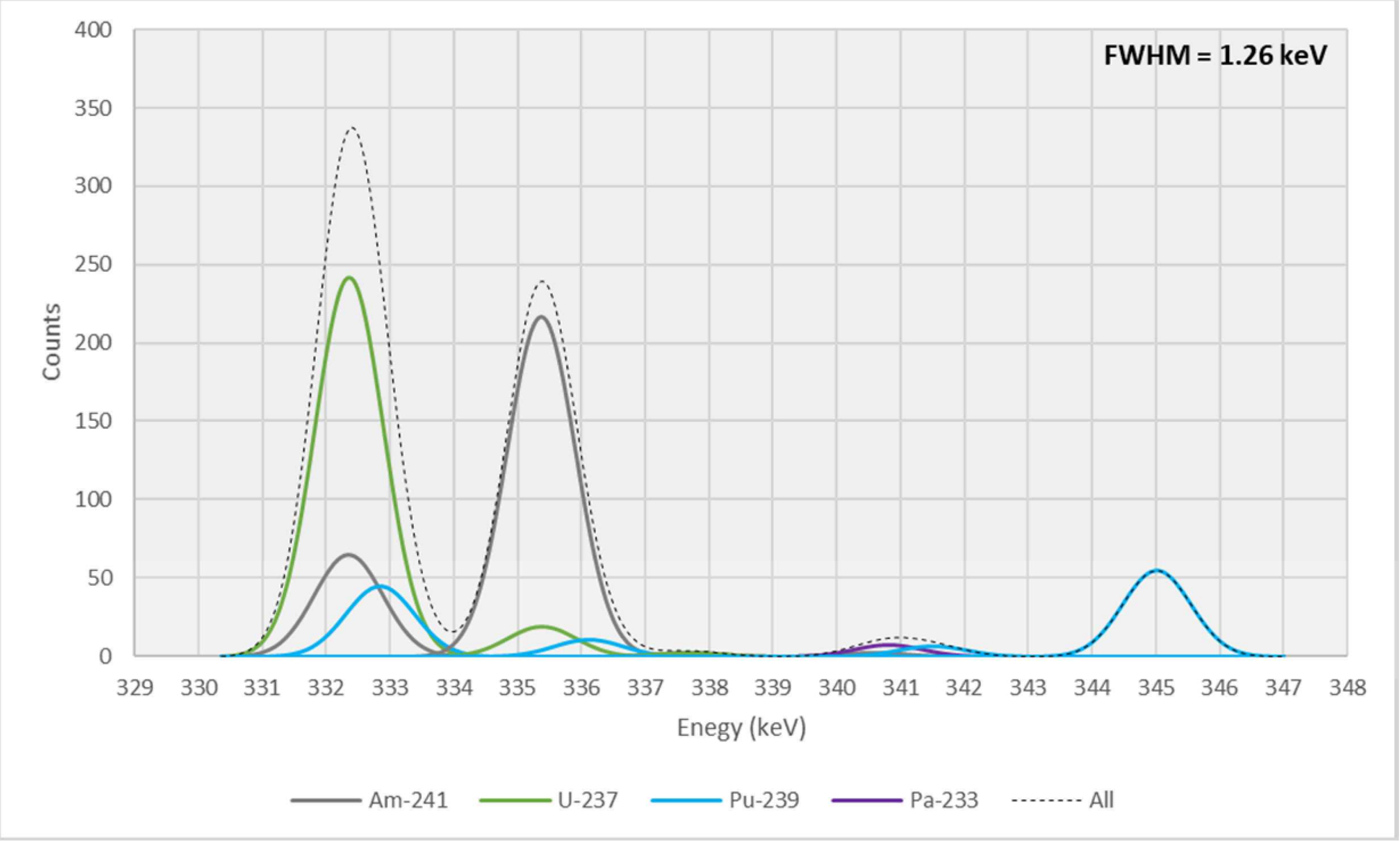
- Example of 332/336 keV ROI interferences



332/336 keV region of interest

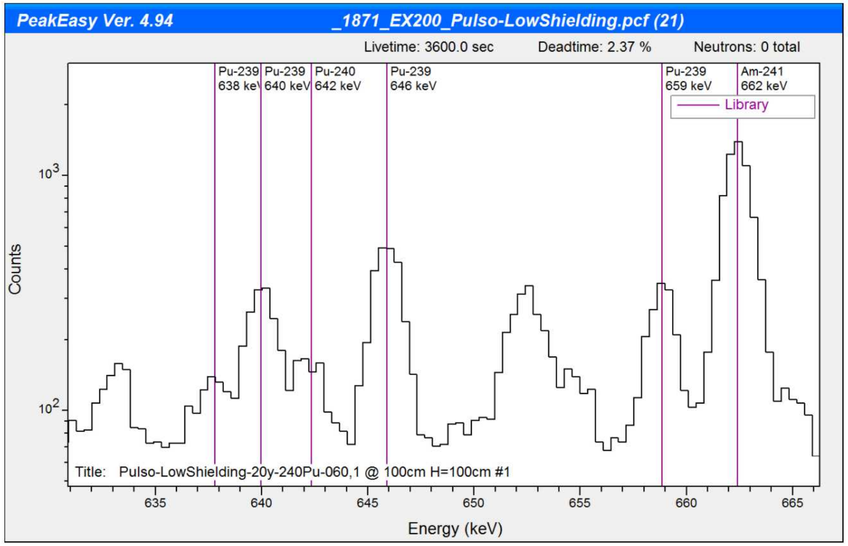
High-burnup Pu (18.0% Pu-240, 20 y)

- Example of 332/336 keV ROI interferences



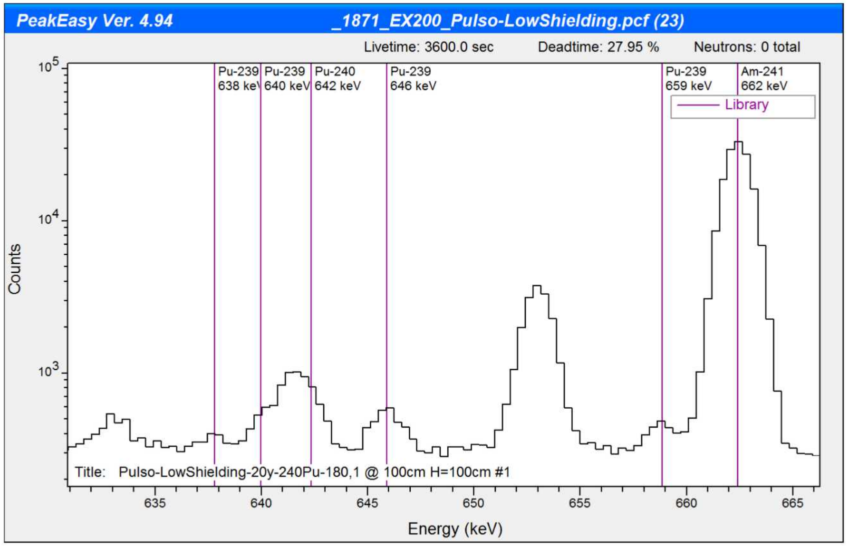
640 keV region of interest

Low-burnup Pu (6.0% Pu-240, 20 y)



Energy (keV)	Phot/Decay	Nuclide
637.8	**2.56E-08**	**Pu-239**
640.0	8.70E-08	Pu-239
641.5	7.10E-08	Am-241
642.4	1.30E-07	Pu-240
645.9	**1.52E-07**	**Pu-239**

High-burnup Pu (18.0% Pu-240, 20 y)



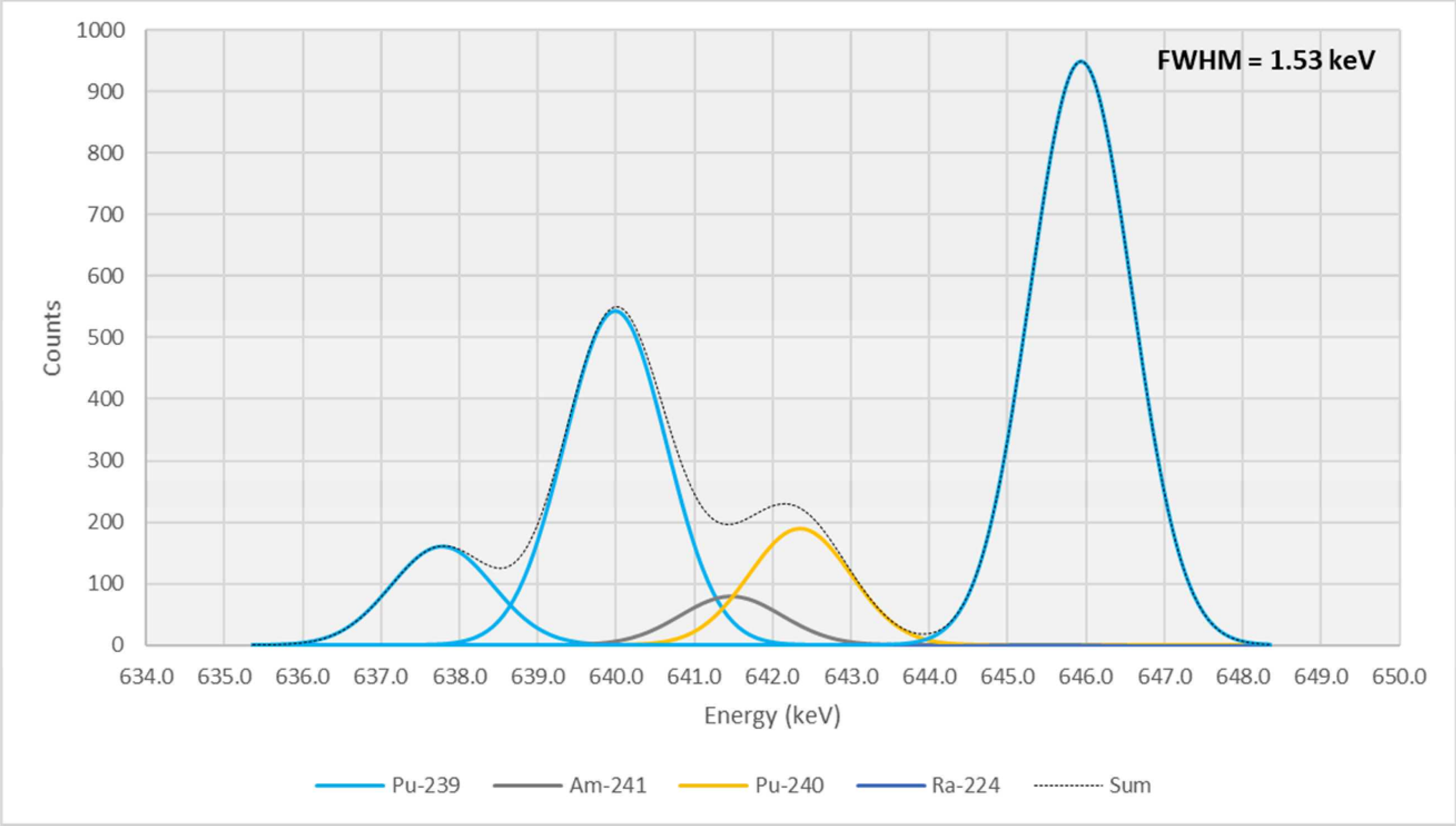
Energy (keV)	Phot/Decay	Nuclide
653.0	3.77E-07	Am-241
658.9	**9.70E-08**	**Pu-239**
662.4	**3.64E-06**	**Am-241**
722.0	**1.96E-06**	**Am-241**

- For high burn-up &/or aged samples, the Pu-240 642.4 keV emission has interference from Am-241 at 641.5 keV.

640 keV region of interest

Low-burnup Pu (6.0% Pu-240, 20 y)

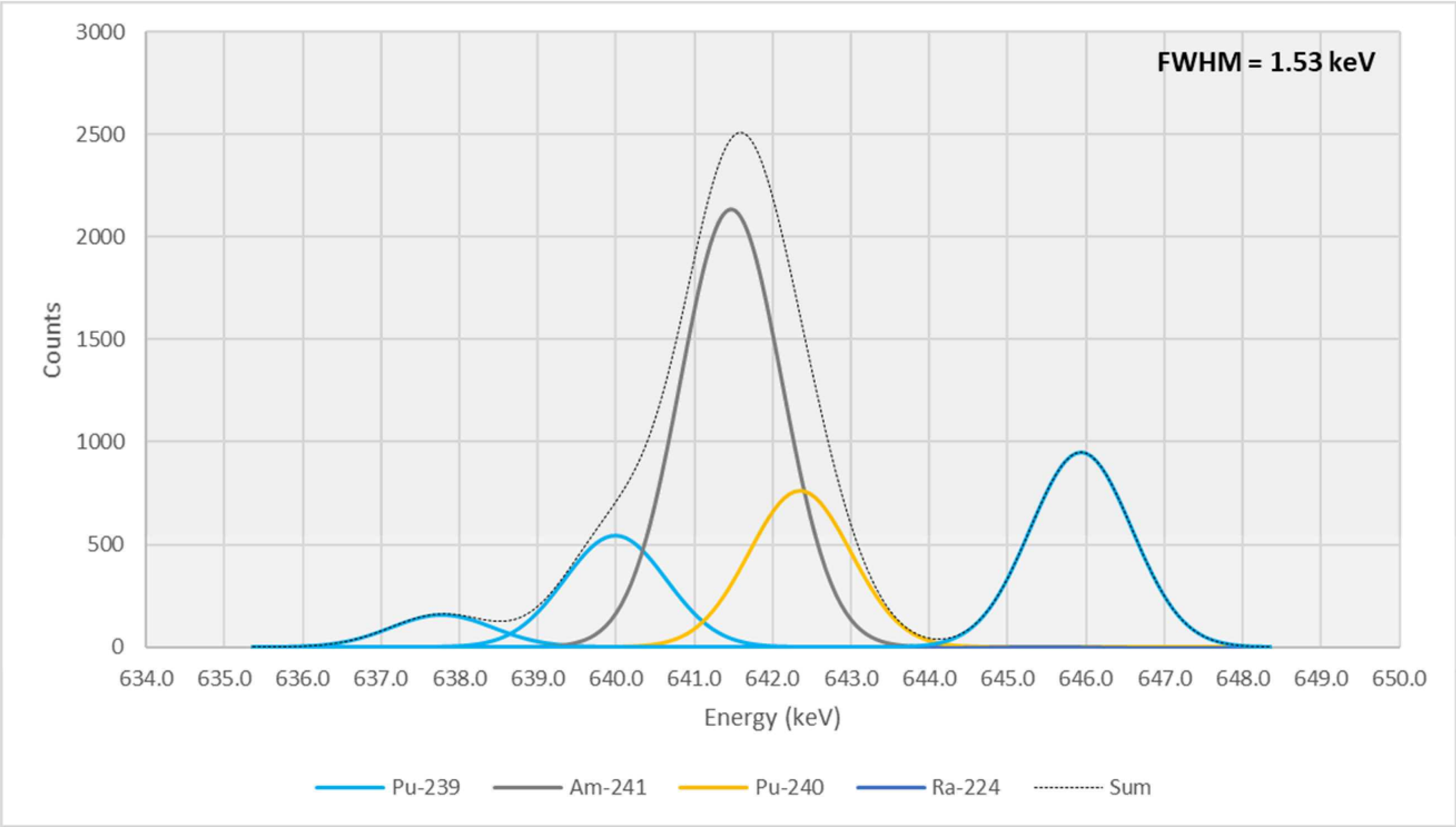
- Example of Pu-240 642.4 keV emission interference



640 keV region of interest

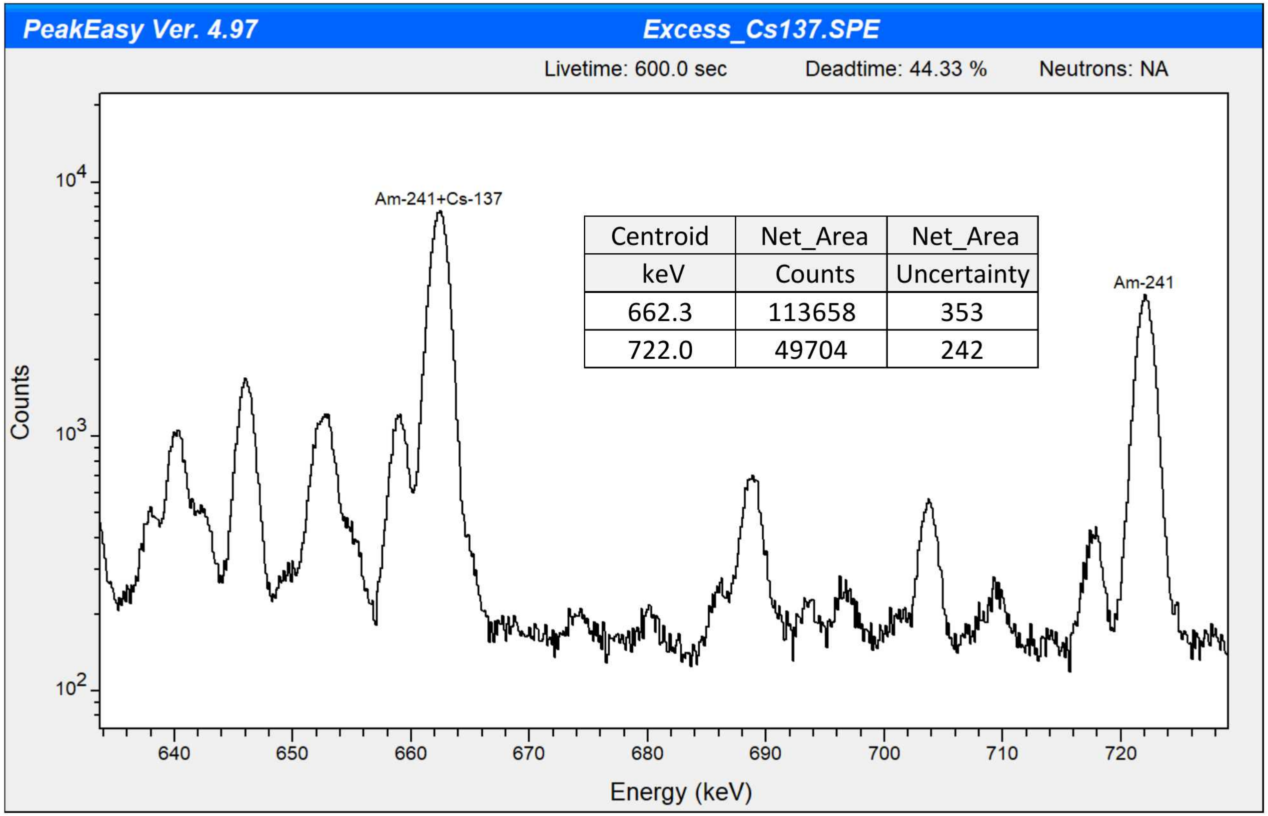
High-burnup Pu (18.0% Pu-240, 20 y)

- Example of Pu-240 642.4 keV emission interference



640 keV region of interest

- Additional note
  - If the 662.4 keV peak area exceeds the 722.0 keV peak area by more than a factor of 2, the material has likely been irradiated & Cs-137 (661.7 keV) is likely present.



Centroid keV	Net_Area Counts	Net_Area Uncertainty
662.3	113658	353
722.0	49704	242

Plutonium isotopics overview

- Accurate assessment of plutonium burn-up is difficult due to interferences affecting Pu-240 peak area determinations.

  - Pu/U isotopic software programs such as LANL Fixed-Energy Response-Function Analysis with Multiple Efficiency (FRAM) & LLNL Multi-Group Analysis (MGA) are available.

  - These Pu/U isotopic software programs use relative efficiency curves (discussed later) as the fundamental analysis method.

Plutonium isotopics overview

- The PeakEasy Library "Plutonium" folder contains useful reference spectra as a function of burn-up, shielding, & detector resolution.

- The SNL_GS-Pu-PredictivePlotter.xlsb EXCEL application is useful for visualization of peak interferences in plutonium gamma spectrum ROIs used for plutonium isotopic & age determinations.

  - Generates predictive plots based on the entered plutonium material type, age, & the detector FWHM.

Plutonium isotopics overview

- EX13_MultiplePuSpectra_FxOfAge-Burnup.pcf contains over 100 synthetic ORTEC Detective EX200 spectra, generated using GADRAS 18.6.5, for lightly shielded plutonium as a function of burn-up & age.

- For a more detailed overview of assessing plutonium isotopics, see “Cliffnotes for Plutonium Isotopics” (aka Cliffnotes_Isotopics-Pu_Updated_2015-06-09_FINAL.docx).

Plutonium isotopics overview

- Visual plutonium isotopics practice
  - Pu-GammaSpec\01_Visual_PuIsotopics
  - NOTE: The visual plutonium isotopics practice spectra are roughly 20 years old which allows comparison to the examples provided.

Material age determinations

- Gamma spectroscopy can be a useful technique for age determinations (chronology) of materials.

- The age can be determined using gamma spectroscopy results for suitable parent/decay product nuclides in conjunction with decay/in-growth calculations.

Material age determinations

- For material age determinations, it is generally assumed that no decay product activity is present immediately following chemical separation (aka, 100% chemical separation).

    - When all of the decay product activity is not removed during the chemical separation process, the age calculated will appear to be longer than it actually is resulting in an age estimate that is biased high.

Material age determinations

- Equation: Assuming decay product nuclide activity is equal to 0 at the time of chemical separation.

$$A_D = B * A_{PO} * (\lambda_D/(\lambda_D-\lambda_P)) * (EXP(-\lambda_P * t) - EXP(-\lambda_D * t))$$

A_D is the decay product nuclide activity

A_{PO} is the initial parent nuclide activity

λ is the decay constant in days^{-1}

t is the decay time in days

B is the branching fraction

Plutonium age determinations

- The time since chemical separation can be estimated by examining the decay of Pu-241 into Am-241/U-237.
    - Pu-241 (14.35 y) 99.998% -> Am-241 (433.2 y) -> Np-237 (2.14E+06 y)
    - Pu-241 (14.35 y) 0.00245% -> U-237 (6.8 d) -> Np-237 (2.14E+06 y)
- Although there are many Am-241 gamma emissions that can be used, there are limited “useable” Pu-241 &/or U-237 gamma emissions.

Nuclide	Energy (keV)	Yield (gps/dps)
U-237	208.0	5.19E-06
Pu-241	**148.6**	**1.86E-06**
U-237	332.4	2.94E-07

- Regardless of what gamma emissions are used, interference corrections for Pu-241/U-237 &/or Am-241 are necessary.

Plutonium age determinations

- Accordingly, the time since chemical separation can be estimated using closely spaced Am-241/Pu-239 peak pairs & the Pu-241/Am-241 activity ratio as follows.
  - Estimate the Pu-239/Am-241 activity ratio, using one of the following regions containing closely spaced Am-241/Pu-239 peak pairs.

Nuclide	Energy (keV)	Yield (gps/dps)
Pu-239	124.5	6.81E-07
Pu-239	125.2	5.63E-07
Am-241	125.3	4.08E-05
Pu-239	**129.3**	**6.31E-05**

Nuclide	Energy (keV)	Yield (gps/dps)
Pu-239	**658.9**	**9.70E-08**
Am-241	**662.4**	**3.64E-06**

Nuclide	Energy (keV)	Yield (gps/dps)
Pu-239	**718.0**	**2.80E-08**
Am-241	**722.0**	**1.96E-06**

Nuclide	Energy (keV)	Yield (gps/dps)
Am-241	**419.3**	**2.87E-07**
Pu-239	**413.7**	**1.47E-05**

  - The 659/662, 718/722, & 414/419 keV regions are interference free.
  - To estimate the Am-241 125.3 keV peak area, the 125 keV Pu-239 peak area contribution must be stripped using the 129.3 keV Pu-239 peak.
  - If the Am-241 662.4 keV emission is being used, check Am-241 662.4 & 722.0 keV peak area ratios for reasonableness to determine if Cs-137 is present.

Plutonium age determinations

- The 208 keV region of interest can be utilized to determine the Pu-241/Am-241 activity ratio as follows:
  - Using the Pu-239 203.6 keV peak, strip the Am-241 contribution from the 208.0 keV peak using the previously estimated Pu-239/Am-241 activity ratio & determine the U-237 (Pu-241) peak area.

Nuclide	Energy (keV)	Yield (gps/dps)
Pu-239	**203.6**	**5.69E-06**
U-237	208.0	5.19E-06
Am-241	208.0	7.91E-06

  - Determine the Pu-241/Am-241 activity ratio & solve for time using decay/in-growth calculations.

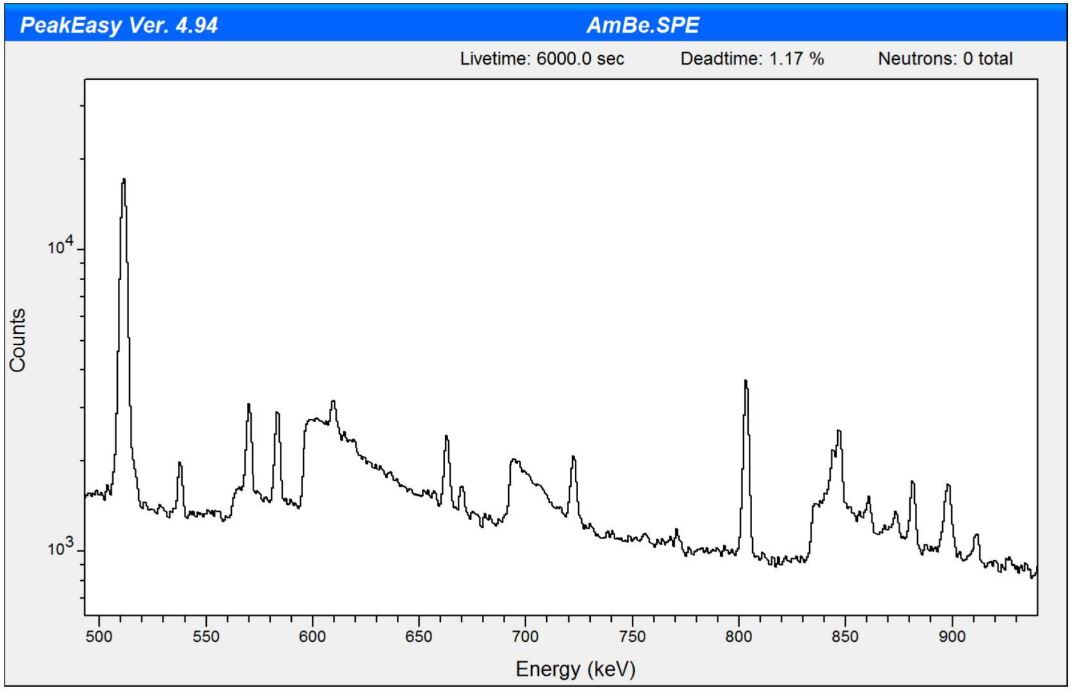
- Other regions can be used to determine time since chemical separation.
  - 332/336/345 keV region of interest.
  - 144/146/149 keV region of interest.

Plutonium age determinations

- Plutonium age determination practice
  - Pu-GammaSpec\02_Age

Neutron &/or alpha reactions of interest

HPGe (Ge-70=20.5% 3.2 barns, Ge-72=27.4% 0.98 barns, Ge-74=36.5% 0.24 barns)			
Ge-72(n,n'g)	n-scatter (prompt)	691.0	NA
Ge-74(n,n'g)	n-scatter (prompt)	595.8	NA
Ge-70(n,g)Ge-71m	Ge-71m (20.4 ms)	198.4	9.10E-01
Ge-74(n,g)Ge-75m	Ge-75m (47.7 s)	139.7	3.88E-01



"Ski-slope" or "saw tooth" structure from fast neutron inelastic scatter interactions on Ge.

Neutron &/or alpha reactions of interest

Fe(n,g) reactions: Fe-56=91.8%, 2.55E+00 barns			
Fe-56(n,g)	n-capture (prompt)	7631.1	2.85E-01
Fe-56(n,g)	n-capture (prompt)	7645.5	2.41E-01
Fe-56(n,g)	n-capture (prompt)	352.8	1.17E-01
Fe(n,n'g) reactions			
Fe(n,n'g)	n-scatter (prompt)	846.8	1.00E+00
Fe(n,n'g)	n-scatter (prompt)	1238.3	1.05E-01
Fe(n,n'g)	n-scatter (prompt)	1408.2	6.90E-02

Al(n,g) reactions: Al-27=100.0%, 2.30E-01 barns			
Al-27(n,g)Al-28	Al-28 (2.3 m)	1779.1	1.00E+00
Al-27(n,g)	n-capture (prompt)	7723.9	2.74E-01
Al(n,n'g) reactions			
Al(n,n'g)	n-scatter (prompt)	1014.4	1.00E+00
Al(n,n'g)	n-scatter (prompt)	843.8	6.00E-01
Al(n,n'g)	n-scatter (prompt)	2211.8	5.20E-01

Neutron &/or alpha reactions of interest

Cu(n,g) reactions: Cu-63=69.2%, 3.79E+00 barns			
Cu-63(n,g)	n-capture (prompt)	7914.5	3.08E-01
Cu-63(n,g)	n-capture (prompt)	7636.6	1.57E-01
Cu-63(n,g)	n-capture (prompt)	7306.2	8.90E-02
Cu(n,n'g) reactions			
Cu(n,n'g)	n-scatter (prompt)	962.0	1.00E+00
Cu(n,n'g)	n-scatter (prompt)	669.7	4.60E-01

Cd(n,g) reactions: Cd-113=12.2%, 2.45E+03 barns			
Cd-113(n,g)	n-capture (prompt)	558.6	7.27E-01
Cd-113(n,g)	n-capture (prompt)	651.3	1.39E-01

H-1=100.0%			
H-1(n,g)	3.32E-01 barns	2223.3	1.00E+00

O-16/17=99.6%/0.04%			
O-18(α,ng)Ne-21	α-n (81 ps)	2438.0	NA
O-17(α,ng)Ne-20	α-n (730 fs)	1633.6	NA
O-18(α,ng)Ne-21	α-n (52 fs)	1395.0	NA
O-18(α,ng)Ne-21	α-n (81 ps)	2790.0	NA

Neutron &/or alpha reactions of interest

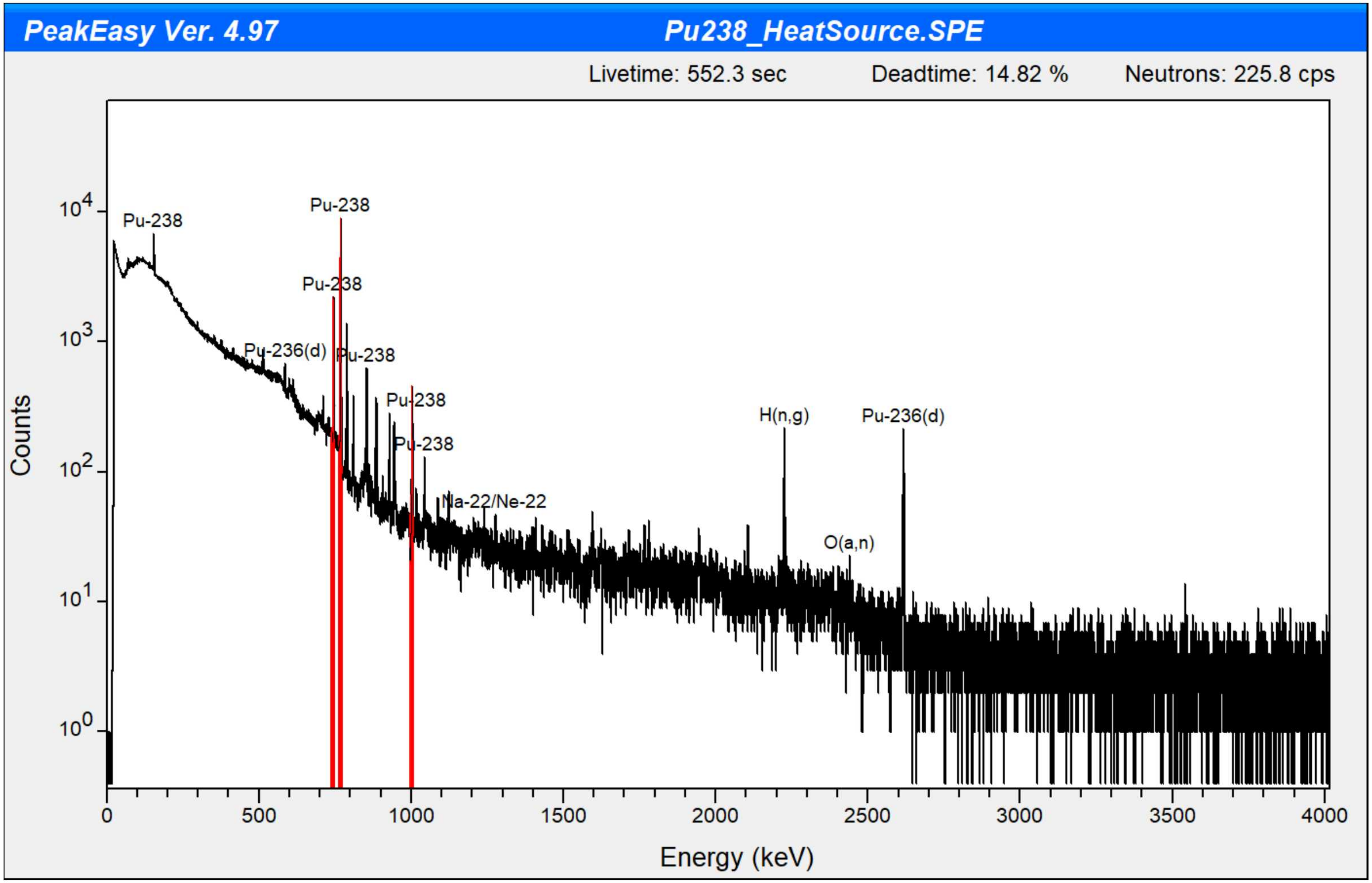
N-14=99.6%			
N-14(n,g)	7.47E-02 barns	5269.2	2.97E-01
N-14(n,g)	n-capture (prompt)	1884.8	2.16E-01
N-14(n,g)	n-capture (prompt)	5298.0	2.10E-01
N-14(n,g)	n-capture (prompt)	10829.2	1.41E-01
N-14(α,pg)O-17	α-p (179.2 ps)	870.9	NA

Cl-35=75.8%			
Cl-35(n,g)	3.32E+01 barns	1950.9	2.17E-01
Cl-35(n,g)	n-capture (prompt)	6110.9	2.00E-01
Cl-35(n,g)	n-capture (prompt)	1164.7	1.99E-01

Miscellaneous reactions			
Li-7(α,α'g)Li-7	DB Triangle (73 fs)	477.6	1.00E+00
B-10(n,αg)Li-7	DB Square (73 fs)	477.6	1.00E+00
Be-9(α,ng)C-12	DB (42 fs)	4438.9	5.90E-01
F-19(α,ng)Na-22	Na-22 (2.6 y half-life)	1274.5	9.99E-01
F-19(α,pg)Ne-22	α-p (3.6 ps)	1274.3	NA
Al-27(α,pg)Si-30	α-p (215 fs)	2236.0	NA

NOTES: DB = Doppler broadened; The 870.9 keV peak has been observed in spectra from alpha-emitting nuclides in the chemical forms of nitrate, carbonate, or oxide.

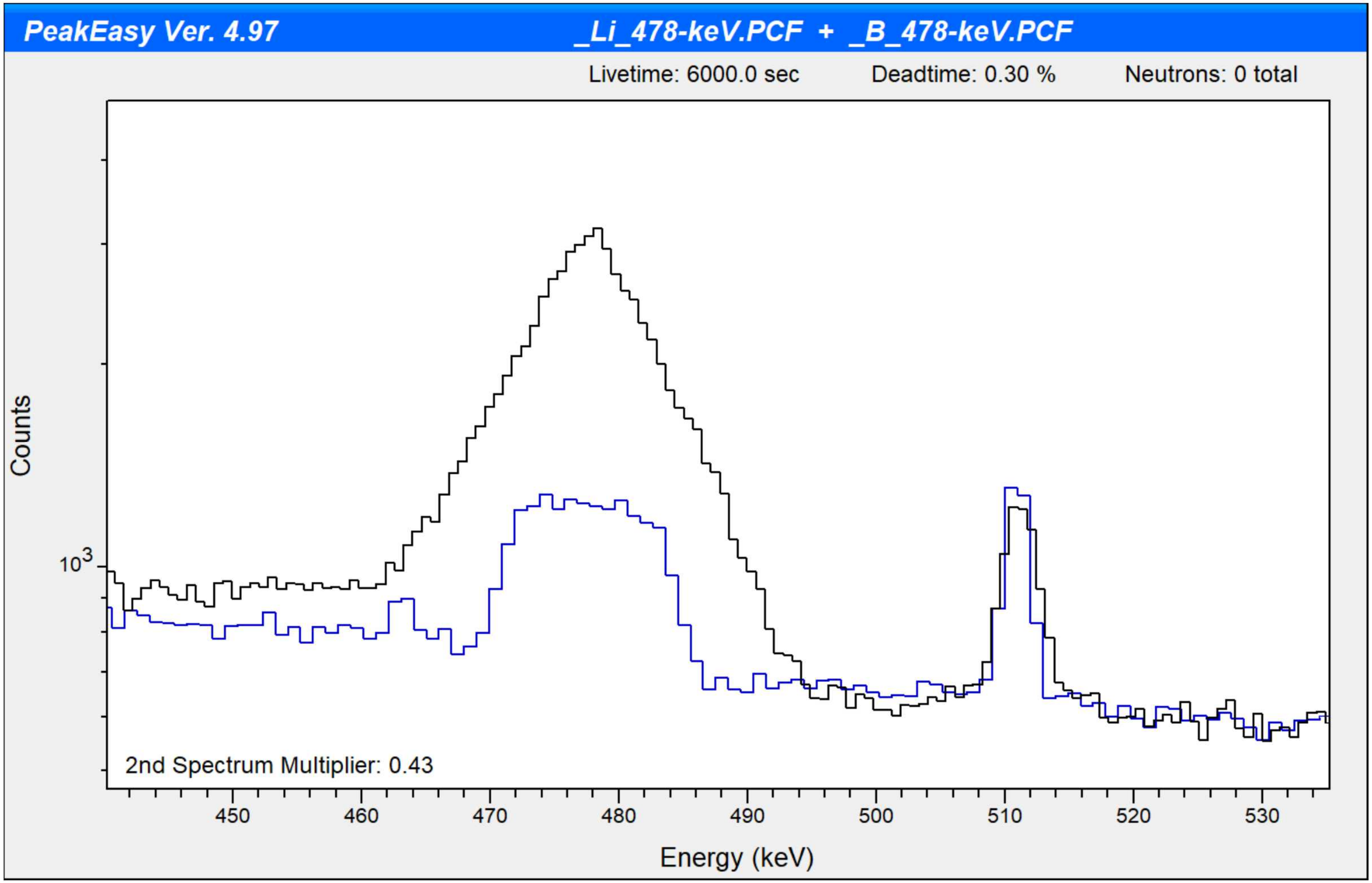
Neutron &/or alpha reactions of interest



Pu-238 heat source spectrum

H-1(n,g); O-18(α,ng)Ne-21; F-19(α,ng)Na-22/F-19(α,pg)Ne-22

Neutron &/or alpha reactions of interest



Li-7(α,α'g)Li-7 = Doppler broadened triangle

B-10(n,αg)Li-7 = Doppler broadened square

Neutron &/or alpha reactions of interest

- Plutonium reactions of interest practice
  - Pu-GammaSpec\03_RxsOfInterest

Plutonium activity/mass determinations

- Plutonium activity/mass practice problems
  - Pu-GammaSpec\06B_Activity-Mass_J9005404
  - Pu-GammaSpec\06C_25x25x25cmBox

- Relative plutonium activity/mass practice problem
  - Pu-GammaSpec\05_Eff-RelativeMOX

- The Pu-239 gamma emissions at 129.3, 203.6, 255.4, 345.0, 375.1, 413.7, 451.5, 645.9, 658.9, & 718.0 keV are recommended for differential attenuation analysis &/or relative efficiency curve generation since these emissions are generally interference free.

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