Analysis of Gamma Ray Emissions From Fission Product Contributors to the Antineutrino Spectrum

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Reactor Antineutrino Anomaly (RAA)

- Name given to an apparent bump in the energy spectrum of antineutrinos from reactors, around 5 MeV energy

Reactor Neutrino[1]

- From one fission, about 7 antineutrinos are produced.
- A 1 GW thermal reactor emits approximately 1E+20 antineutrinos per second
- A reactor produces over 1000 fission fragment nuclides, each of which beta decays.

Modeling the Reactor Neutrino Spectrum

Dwyer and Langford[2]

- Ab-initio summation method with nuclear data from ENDF/B-VII.1
- RAA : spectral bump is shown at Antineutrino energy at 5 to 7 MeV (Positron energy at 4 to 6 MeV)
- Claim: resulting from strengths of eight beta decay branches in the tabulated nuclear data.

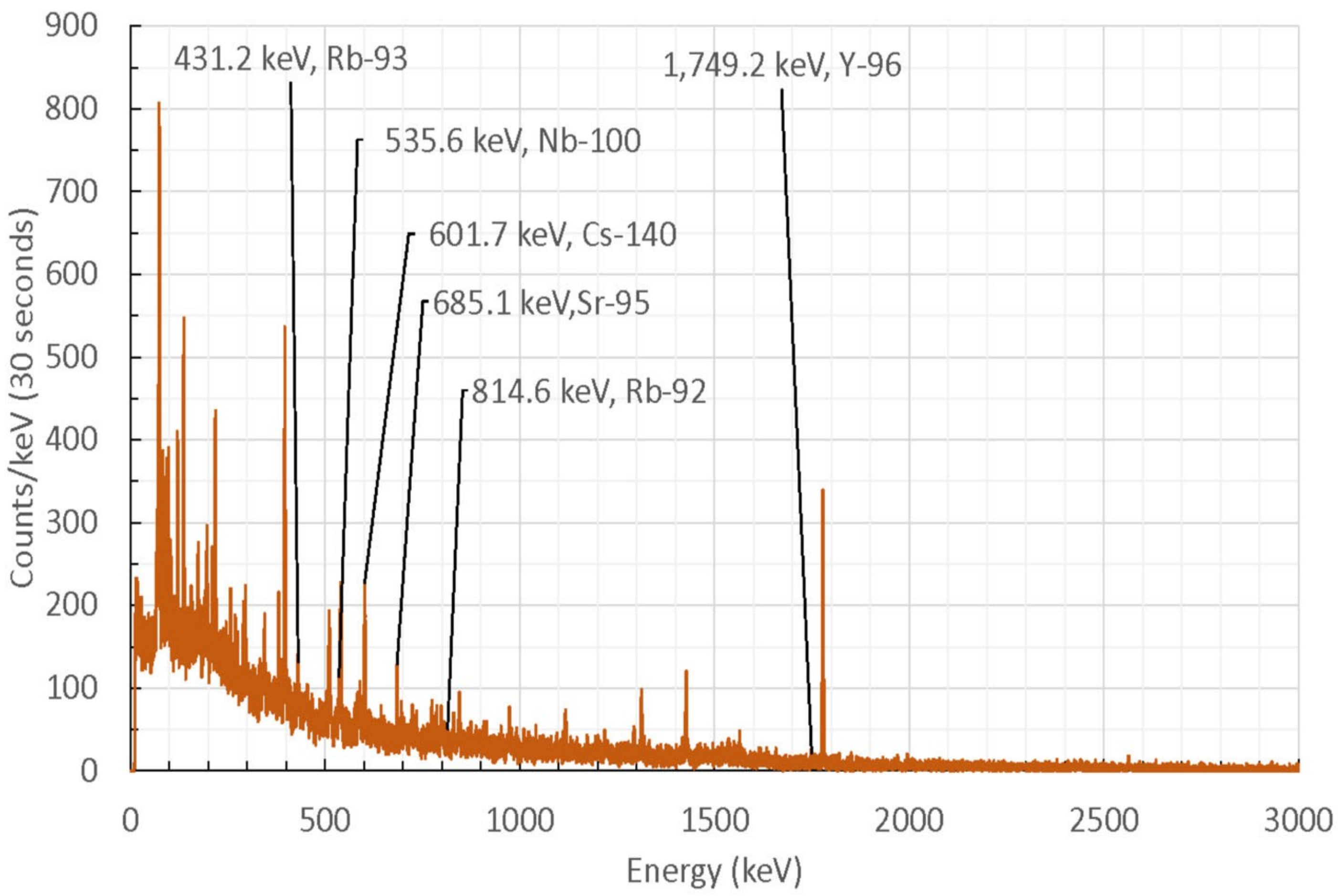
93-Rb	(432.61 keV, 5.84 s)	100-Nb	(535.67 keV, 1.5 s)	140-Cs	(602.25 keV, 63.7 s)
95-Sr	(685.6 keV, 23.9 s)	92-Rb	(814.98 keV, 4.48 s)	96-Y	(1750.4 keV, 5.34 s)
142-Cs	(359.60 keV, 1.68 s)	97-Y	(1103 keV, 1.7 s)		

- The tabulated Cumulative Fission Yields of these nuclides can be checked by their gamma ray emissions!

[1]Hayes and et al, 2012, *Reactor Antineutrino Flux & the Anomaly*, Applied Antineutrino Physics workshop
[2]Dwyer, Daniel A, and Thomas Langford, 2015, "Spectral Structure of Electron Antineutrinos from Nuclear Reactors“, *Physical Review Letters* 114

^{235}U Sample Irradiation at ORNL HFIR NAA Facility*

- Natural Uranium nitrate ICP calibration solution
- 252.72 nano gram
- Irradiate for 30 seconds using PT-2, HFIR*, at NAA*
- “Rabbit” transit time = 20 seconds
- 142-Cs and 97-Y have decayed away
    - Exploring alternate way to measure these
- Gamma ray emission is measured for 30 seconds using ORNL P-type high purity germanium detector



*Oak Ridge National Laboratory (ORNL)
*High Flux Isotope Reactor (HFIR)
*Neutron Activation Analysis facility (NAA)

Expected Gamma Ray Rates

Expected net count

$$\lambda\, N\, f\, \varepsilon\, t_c \left(\frac{5.2E + 8}{10E + 10}\right)$$

- Must solve Bateman equations for nuclides produced during irradiation (N)
  - Utilized RadICal[1]
  - Outputs gamma rays / second emission rate from each product nuclide
- Efficiency (ε) of ORNL HPGe – GEANT4 simulated
- Emission probability (*f*) for selected gamma ray line
- Decay constant (λ)

Uncertainty in expected net count[2]

$$\frac{dc}{c} = \sqrt{\left(\frac{dN}{N}\right)^2 + \left(\frac{df}{f}\right)^2 + \left(\frac{d\lambda}{\lambda}\right)^2 + \left(\frac{d\epsilon}{\epsilon}\right)^2}$$

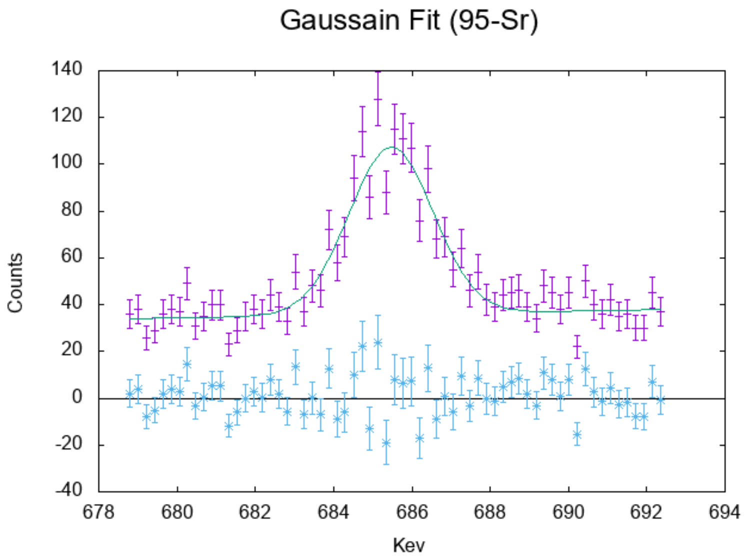
- C and dC are expected count and its uncertainty
- N and dN are the number of nuclides fission produced and its uncertainty
- *f* and d*f* are the gamma ray emission probability and its uncertainty
- λ and dλare the decay constant and its uncertainty
- ε and dε are the GEANT4 simulated efficiency of ORNL HPGe detector and its uncertainty.

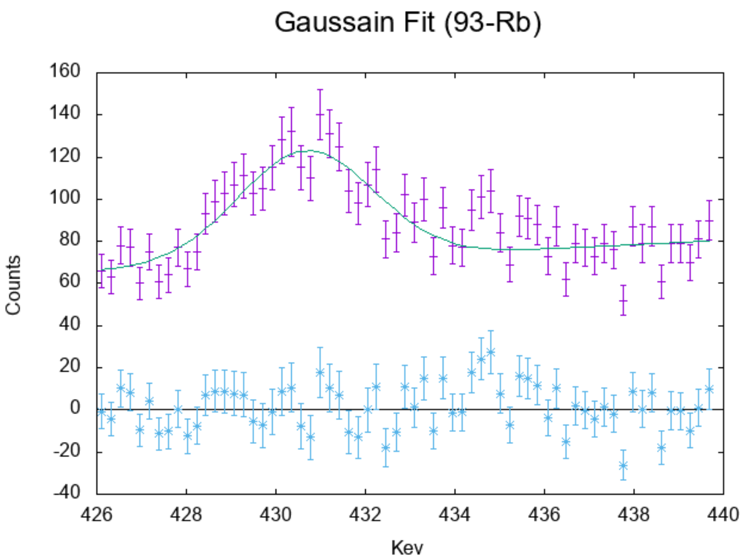
[1]Robins,J. and et al, *RadICalc: a program for estimating radiation intensity of radionuclide mixtures*, J Radioanal Nucl Chem (2015) 303:1955–1960

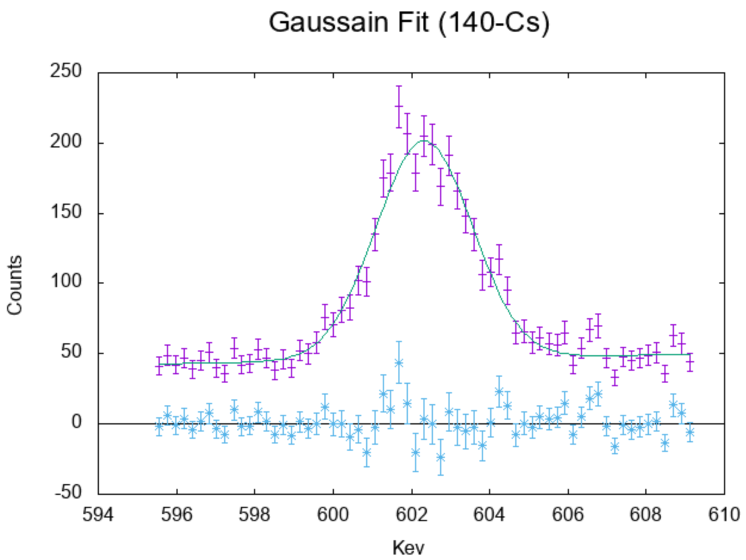
[2]Taylor, John Robert. 1982. *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements.* Mill Valley: University Science Books.

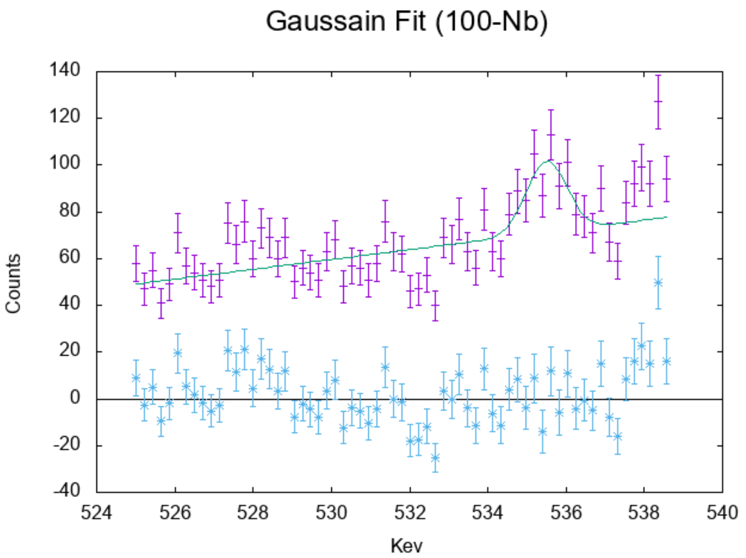
Analysis of Observed Gamma Ray Peaks

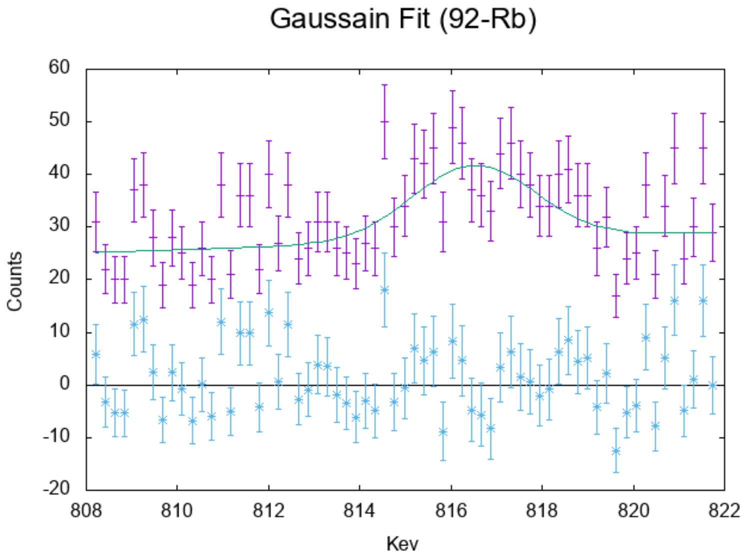
Nonlinear Peak Fitting (GNUPLOT)

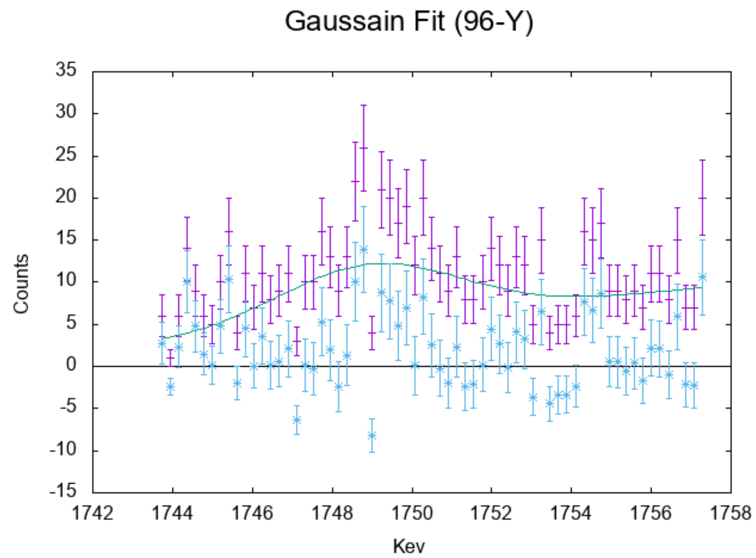












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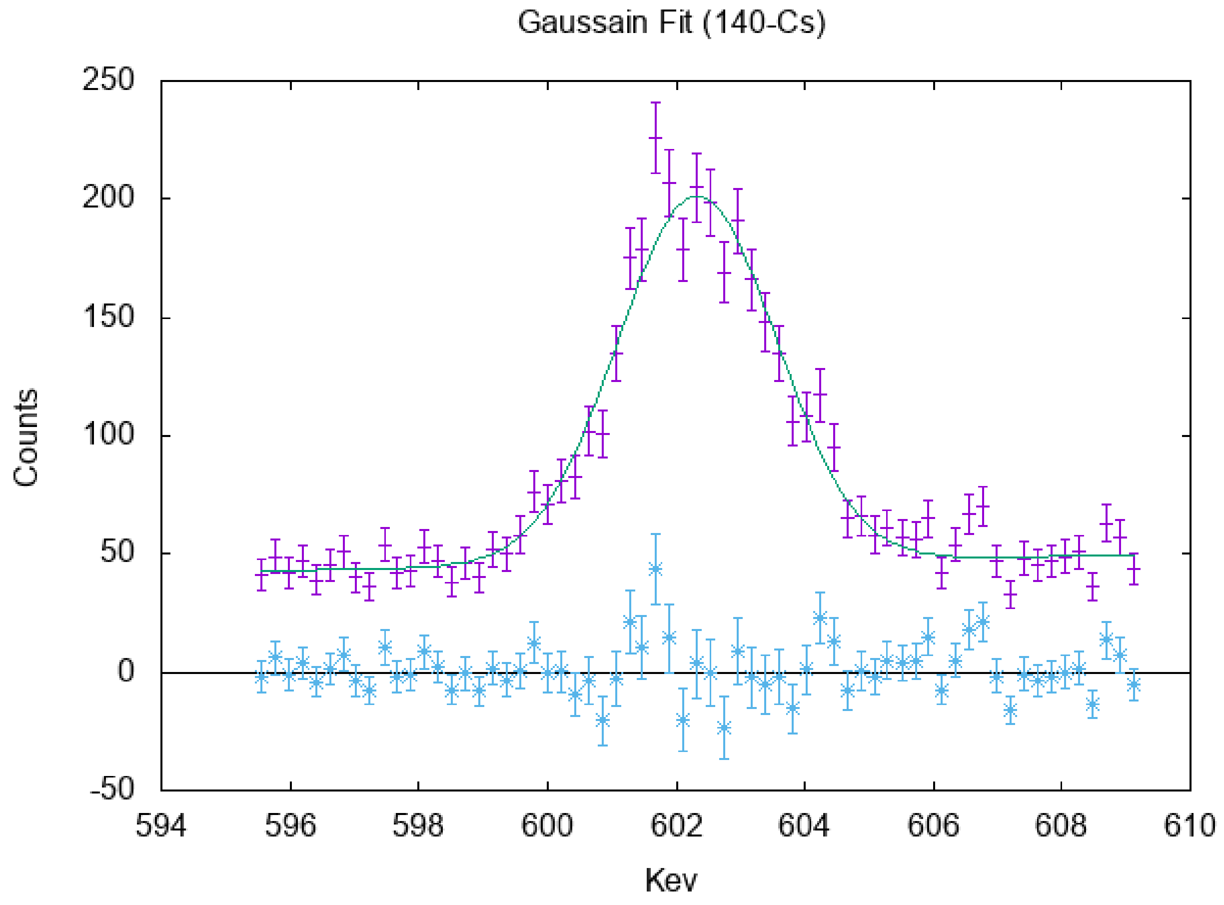

Nonlinear fitting (gnuplot)

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After 8 iterations the fit converged.
final sum of squares of residuals : 83.2073
rel. change during last iteration : 0

degrees of freedom    (FIT_NDF)                        : 60
rms of residuals      (FIT_STDFIT) = sqrt(WSSR/ndf)    : 1.17762
variance of residuals (reduced chisquare) = WSSR/ndf   : 1.38679
p-value of the Chisq distribution (FIT_P)              : 0.0253908

Final set of parameters            Asymptotic Standard Error
=======================            ==========================
amp1            = 479.356          +/- 18.06        (3.768%)
mu1             = 602.32           +/- 0.04786      (0.007946%)
fwhm1           = 2.89969          +/- 0.1085       (3.741%)
a1              = 0.508822         +/- 0.2612       (51.34%)
b1              = -260.269         +/- 157.3        (60.43%)

correlation matrix of the fit parameters:
                amp1   mu1    fwhm1  a1     b1
amp1            1.000
mu1             0.018  1.000
fwhm1           0.455 -0.207  1.000
a1             -0.022 -0.231  0.041  1.000
b1              0.018  0.231 -0.045 -1.000  1.000
```

Fitted net count

Gaussian (assumption)

- Amplitude (amp1, 479)
- mean (mu1, 602)
- FWHM (fwhm1, 2.9)

Uncertainty

Asymptotic standard error

- Amplitude (amp1, +/- 18)
- Mean (mu1, +/- 0.05)
- FWHM (fwhm1, +/- 0.1)

Alternate Analysis Method: Manual Peak Sum

Summation method: a peak profile is not assumed.

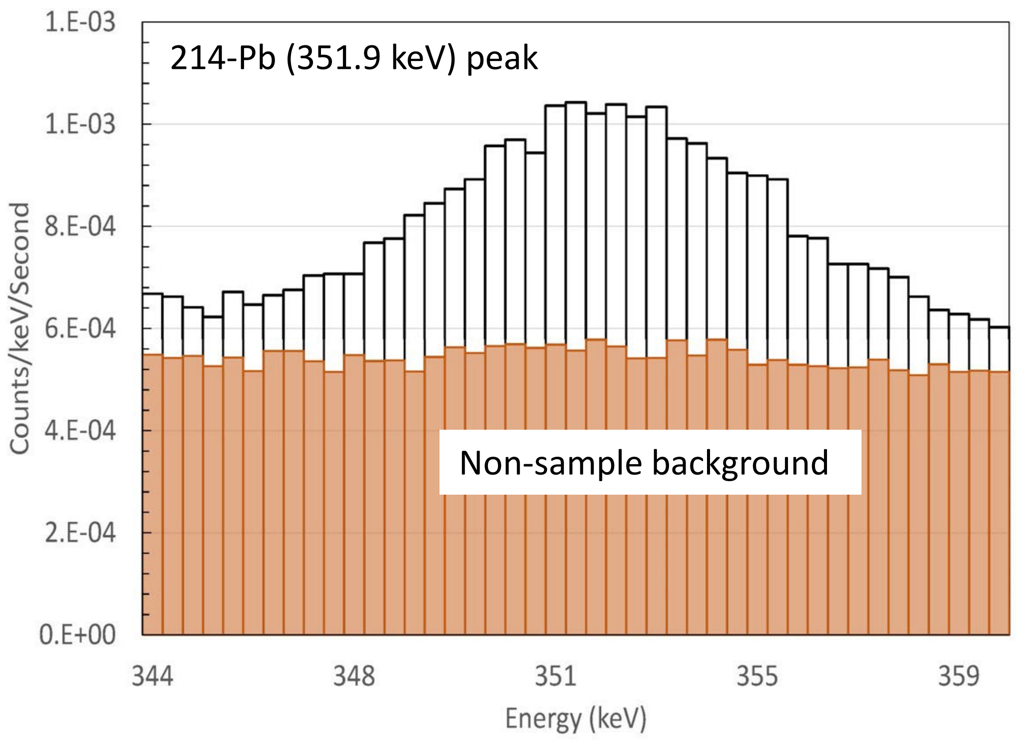
Net count

- Subtract gross non-sample peak count from sample peak
- Subtract continuum ($\bar{B}'$) using trapezoid formula

$$N' = \sum_{n}(C' - D') - \underbrace{\frac{n}{2P}\left(\sum_{P_l}(C' - D') + \sum_{P_r}(C' - D')\right)}_{\bar{B}'}$$

Due to non-sample background

$$\sigma^{2\prime} = \frac{\bar{G}\prime}{t_s} + \Sigma_n\left(\frac{D\prime}{t_s} + \frac{D\prime}{t_b}\right) + \left(\frac{1}{t_s}\right)\left(\frac{n}{2p}\right)\bar{B}' + \left(\frac{n}{2p}\right)^2\left(\Sigma_{P_l}\left(\frac{D\prime}{t_s} + \frac{D\prime}{t_b}\right) + \Sigma_{P_r}\left(\frac{D\prime}{t_s} + \frac{D\prime}{t_b}\right)\right)$$



- Peak centroid: 352.8 keV
- FWHM: 2.1 keV
- Peak width search range: 3xFWHM using 3 channel averaged count
- Peak base width = 346.6 to 360 keV

Predicted and Measured Fission Daughter Counts

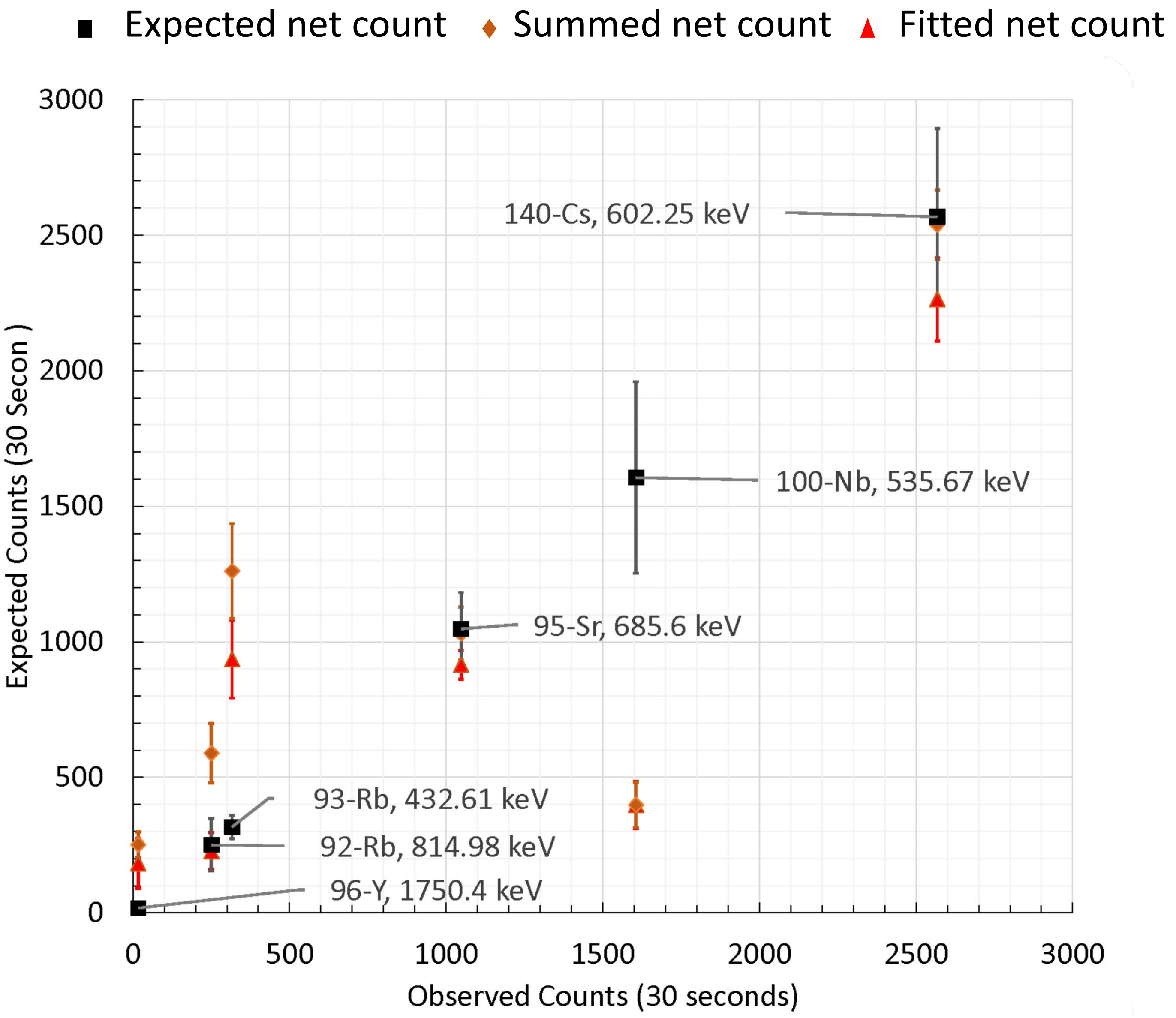
95-Sr, 140-Cs, 92-Rb and 96-Y
- Measured rates within 2σ of expected rate

93-Rb (low) and 100-Nb (high)
- Measured rates are not within 2σ expected rate
- Partial support for Dwyer & Langford proposed explanation of RAA

Follow Up

1) Errors in tabulated fission yields? Or in RadICalc?
- RadICal uses ENDF* VII, and Fitted and summed use ENDF VIII

2) Better understanding about the systematic and random errors in RadICal and analysis methods used.
3) Refine the calculation models
3) Further study is planned using more irradiations with larger samples at ORNL.



*Evaluated Nuclear Data File (ENDF)