Nuclear Data measurements at the RPI Gaerttner LINAC Center and EXFOR reporting

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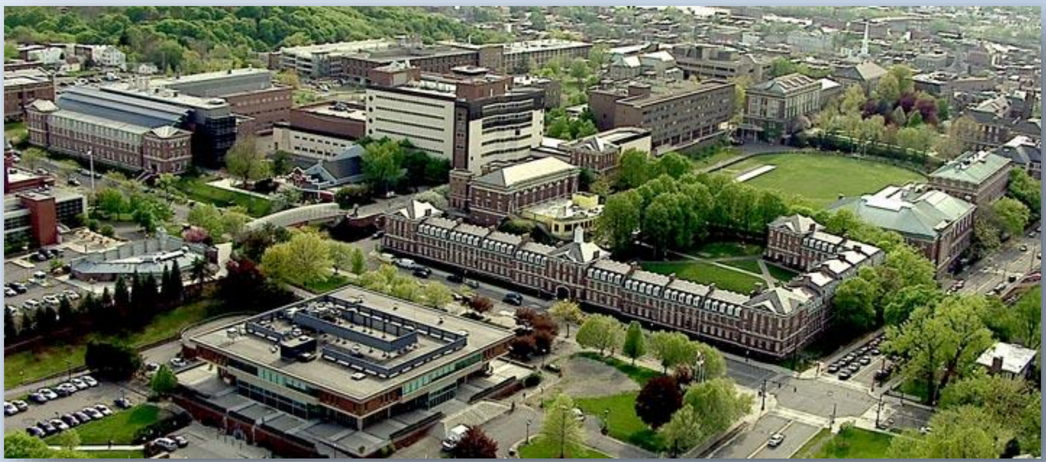

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Outline

- Asked to discuss the Resolved Resonance Region
- Types of differential measurements
  - Transmission → total cross section
  - Yield → capture, fission, scattering, self-indication
- Quasi-Differential
  - Will not discuss

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History and background

- RPI has been measuring nuclear data since the RPI LINAC started operation in December 1961.

- About 128 entries in EXFOR
  - First one - 1962, a capture measurement on Fe-56:
    - J.E. Russell, R.W. Hockenbury, R.C. Block, “Neutron Capture Cross Section Experiments”, R.P.I. annual progress report, No.62, p.10, 1962, EXFOR 11724.
    - Last entry in 2019.

- Current capabilities:
  - Transmission (0.001 eV - 20 MeV)
  - Capture (0.01 eV - 500 keV)
  - Scattering (2 keV - 20 MeV)
  - Fission (0.01 eV - 2 keV, 0.5 MeV - 20 MeV)
  - LSDS fission, (n,alpha) 0.1 eV - 100 keV
  - Other (fission fragment yields, prompt fission neutrons)

Resonance measurements at RPI

- Data Included transmission and capture, recently also fission.
- Capture measured with the RPI multiplicity detector (~4π NaI+$^{10}B_4C$ liner), C_6D_6 detector array and the lead slowing down spectrometer.
- Data reduced to transmission (T), capture yield (Y_γ), or fission yield (Y_f)
- Multiple sample thicknesses are usually measured
- SAMMY fits are used to extract resonance parameters using both transmission and capture of multiple sample thicknesses.
- After the results are submitted for publication to a journal or a thesis, the data are sent to EXFOR

Transmission

1. Dead time correction is applied to all raw data sets.
2. Since data are taken for many cycles, the files are summed.
3. Background is fitted to an analytical function, uncertainty includes the fitted parameters, covariance, and χ^2 scaling.
4. Transmission and associated error (statistical) are calculated.

$$T_i = \frac{\left(C_i^s - K_s B_i - B_s\right)}{\left(C_i^o - K_o B_i - B_o\right)}$$

- C_i^s, C_i^o are the count rates of the sample and open measurements, respectively,
- B_i is the time-dependent background count rate,
- B_s, B_o are the steady state background counting rates for the sample and open measurements, respectively,
- K_s, $K_o \approx 1$ are background normalization factors for the sample and open measurements, respectively.

- Transmission normalization is not used at RPI.
- Recently covariance was also calculated (will be discussed in the context of URR)

Capture

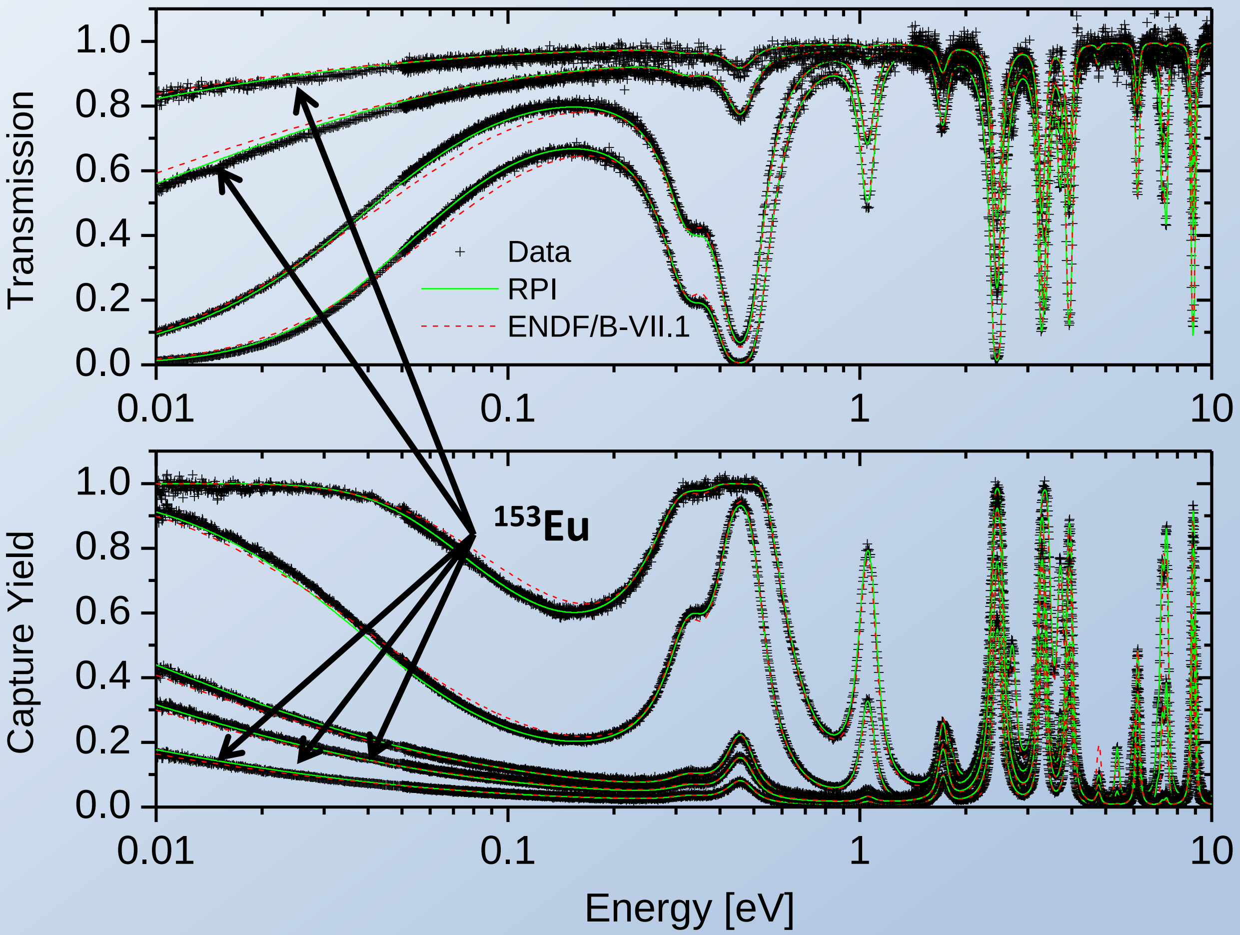
- Dead time correction is used on all raw data
- Since data are taken for many cycles, the files are summed.
  - Flux shape is a separate measurement using a boron sample
- Capture yield is calculated as:

$$Y_i = \frac{C_i - B_i}{\phi_i \eta}$$

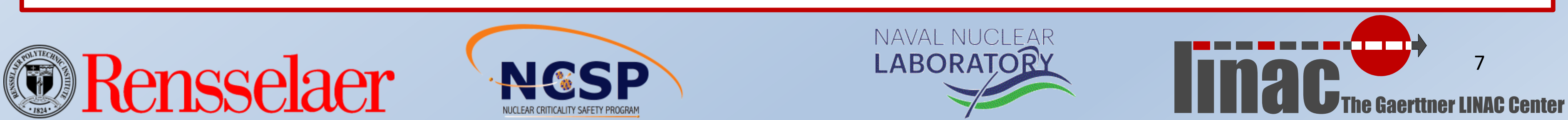
  - C_i dead-time-corrected and monitor-normalized counting rate of the sample measurement
  - B_i dead-time-corrected and monitor-normalized background counting rate
  - η product of the flux normalization factor and efficiency
  - ϕ_i background-subtracted, and monitor-normalized neutron flux shape
- In some EXFOR entries Y_γ/N is wrongly reported as σ_γ, this is a thin sample approximation which is not accurate for all cases:

$$Y_\gamma = (1 - e^{-N\sigma_t})\frac{\sigma_\gamma}{\sigma_t} \rightarrow \text{for } N\sigma_t \ll 1 \rightarrow Y_\gamma \approx N\sigma_t$$

Example: ^{153,nat}Eu low energy



G. Leinweber, D. P. Barry, J. A. Burke, M. J. Rapp, R. C. Block, Y. Danon, J. A. Geuther and F.J. Saglime III, "**Europium resonance parameters from neutron capture and transmission measurements in the energy range 0.01–200 eV**", Ann. Nucl. Energy, vol. 69, pp. 74 - 89, 2014.



Submitting data to EXFOR

- Publish the data in a paper or report (thesis).
- Follow the templates suggested in INDC(NDS)-0647, "**EXFOR Data in Resonance Region and Spectrometer's Response Function**".

  https://www-nds.iaea.org/index-meeting-crp/CM-RF-2013/

- Provide additional data not in the paper:
  - TOF bin configuration.
  - Energy resolution (SAMMY example).
  - Data for all samples.
  - Covariance if available.
  - Additional facility details (moderator type and temperature, neutron intensity…).

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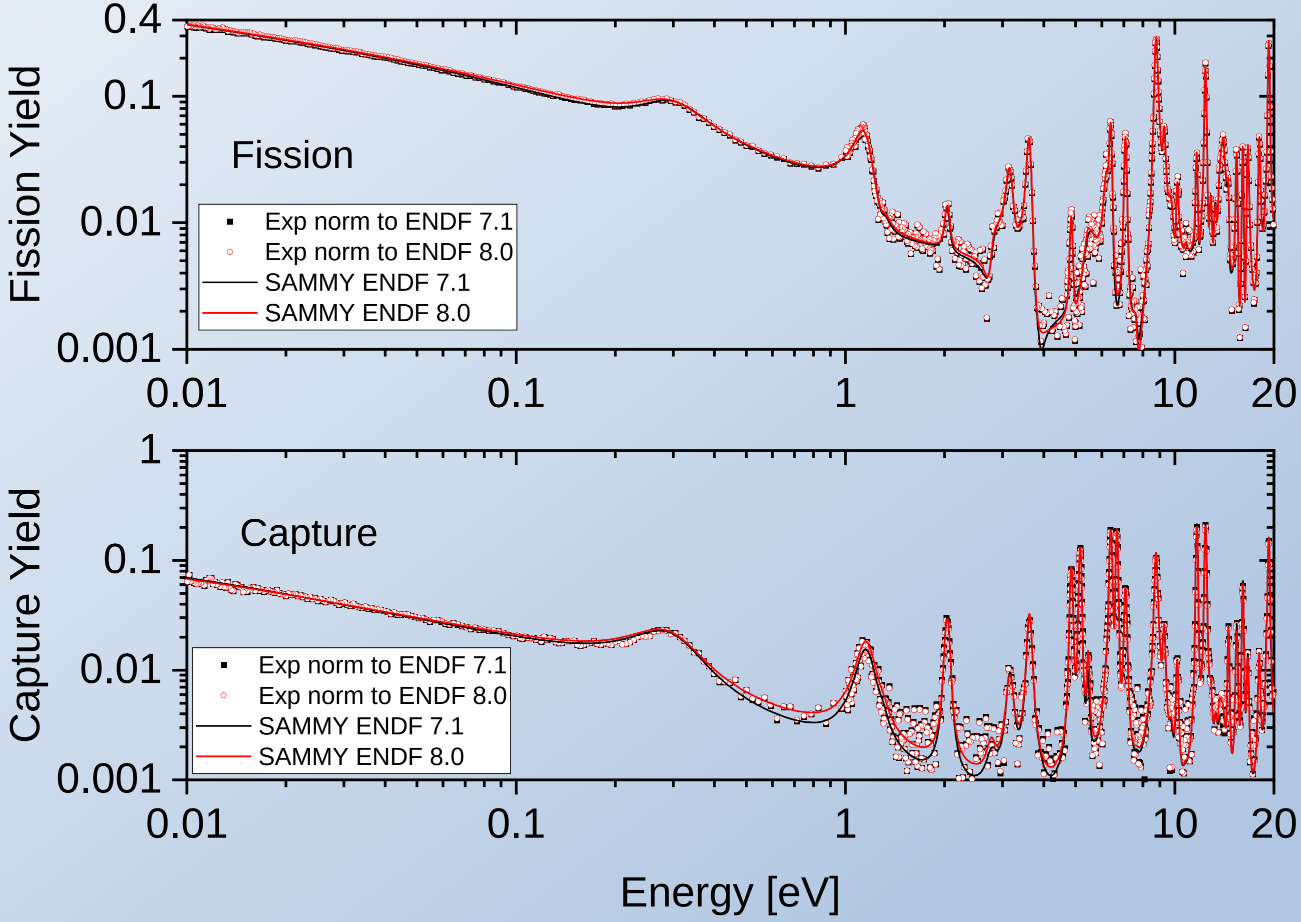
Example: Simultaneous measurement of ^{235}U Capture and Fission Yield



Y. Danon, D. Williams, R. Bahran, E. Blain, B. McDermott, D. Barry, G. Leinweber, R. Block and M. Rapp, "**Simultaneous Measurement of ^{235}U Fission and Capture Cross Sections From 0.01 eV to 3 keV Using a Gamma Multiplicity Detector**", Nuclear Science and Engineering, vol. 187, no. 3, pp. 291-301, 2017.

Example: ^{235}U capture template

A EXPERIMENT DESCRIPTION

Parameter	Value	Ref.
1. **Main Reference**	Simultaneous Measurement of U-235 Fission and Capture Cross Sections From 0.01 eV to 3 keV Using a Gamma Multiplicity Detector	[1]
2. **Facility**	RPI	
3. **Neutron Production**		
Neutron production beam	Electron	
Average beam energy	53 MeV	
Average beam current	8.0 ± 0.5 μA	
Pulse width	500 ± 50 ns FWHM	
Repetition rate (pulse/sec)	25	
Nominal beam power	53 MeV x 8 us = 424 W	
Primary neutron production target	Tantalum	
Neutron source position in moderator	Enhanced Thermal Target	
4. **Moderator**		
Material	Water, polyethylene, and graphite	[2]
Dimension (thickness, height x widthxdepth,...)	Integral; see references	[2]
Mass (g)	Unspecified	
Temperature (K)	293	
Target nominal neutron production intensity (n/sec)	$\approx 6 \times 10^{11}$	
Moderator-room decoupler (Cd, B, ...)	N/A	
5. **Other experimental details**		
Measurement type	**Capture yield**	
Method (total energy, total absorption, ...)	Total absorption	
Effective flight path length (m)	25.446 ± 0.006	
Flight path angle with respect to moderator surface	90 (perpendicular to surface)	
Neutron beam dimensions at sample position (diameter mm)	50.4	
Neutron beam profile	Circular	
Overlap suppression	None	
Other fixed beam filters	0.125 cm Pb	
6. **Detector**		
Type	16-segment multiplicity w/ 16 PMTs	[1]
Material	NaI (Tl activated)	
Surface Dimensions (mm x mm. diameter in mm, ...)	Annular, 305 mm outer diameter, 89 mm inner diameter with an inner annular 99.4 wt % B-10 liner	
Detector(s) angle with respect to neutron beam line	90 deg. Detector is outside the neutron beam	
Detector(s) solid angle	0.9430 of 4π	
Thickness (mm)	108	
Distance from samples (mm)	19	
7. **Sample**		
Type (metal, powder, liquid, crystal)	U metal disks	[1]
Chemical composition	U metal 93.33 ± 0.03 wt% U-235	
Sample composition (at/b)	0.00054 ± 0.00002	
Isotopic composition (weight percent):	U-234 1.087 ± 0.016 U-235 93.334 ± 0.034 U-236 0.1266 ± 0.0018 U-238 5.452 ± 0.021	
Sample Temperature (K)	293	
Detector(s) solid angle	0.9430 of 4π	
Sample mass (g)	2.4	
Geometrical shape	9 disks	
Surface dimension (diam. mm x thickness mm)	12.7 x 0.11 (nominal per disk)	
Nominal thickness (mm)	0.11	
Containment description	0.8 mm thick aluminum contai	
Additional comment	Each disk was wrapped is 0.075 aluminum	
8. **Response/Resolution function**		
Dead time correction	<3%, DT=1.125 μs	
Background subtraction	<3% Empty aluminum sample holder	
Flux determination (reference reaction, ...)	^{10}B (n, $\alpha\gamma$) ^{7}Li	
Normalization	11.7-eV and 13.4-eV resonances in U-235	[1]
Detector efficiency	Not Applicable	
Self-shielding	Not Applicable	
Time-of-flight binning	0 eV $< E <$ 0.1 eV 104.8576 μs 0.1 eV $\leq E <$ 1 eV 52.4288 μs 1 eV $\leq E <$ 4.7 eV 3.2768 μs 4.7 eV $\leq E <$ 2500 eV 0.8192 μs	
9. **Data Reduction Procedure**		
Pulse width (SAMMY input file)	0.5 μs	[3]
Additional specifications (SAMMY)	DO NOT SHIFT ENERGY for exponential tail on resolution broadening; i.e., time zero at pulse centroid	
Yield normalization	ENDF/B-VIII.0 (see ref. for details)	[1]

Resolution

B References

[1] Y. Danon, D. Williams, R. Bahran, E. Blain, B. McDermott, D. Barry, G. Leinweber, R. Block, and M. Rapp. Simultaneous measurement of ^{235}U fission and capture cross sections from 0.01 eV to 3 keV using a gamma multiplicity detector. *Nuclear Science and Engineering*, 187(3):291–301, 2017.

[2] Y. Danon, RC Block, and RE Slovacek. Design and construction of a thermal neutron target for the rpi linac. *Nucl. Instrum. Methods Phys. Res., Sect. A*, 352(3):596–604, 1995.

[3] N. M. LARSON. Updated users' guide for sammy: Multilevel R-Matrix fits to neutron data using Bayes' equation. *ORNL/TM-9179/R8 ENDF-364/R2, Oak Ridge National Laboratory*, 2008.

^{235}U capture template - continue

C DATA FORMAT

Column	Content	Comments	Unit
1	Energy		eV
2	Observable	Capture yield	unit-less
3	Uncertainty	(1σ)Total uncertainty: counting statistics, background subtraction, and normalization as described in reference 1	unit-less

Energy	Y-cap	Uncertainty
0.01005	0.064	0.006
0.01016	0.074	0.006
0.01028	0.064	0.006
0.01040	0.065	0.005
0.01052	0.063	0.005
0.01065	0.061	0.005
0.01077	0.061	0.005
0.01090	0.063	0.005
0.01103	0.062	0.005
0.01117	0.064	0.005
0.01130	0.059	0.005
0.01144	0.065	0.005
0.01158	0.066	0.004
0.01172	0.069	0.004
0.01187	0.068	0.004
0.01202	0.061	0.004
0.01217	0.064	0.004
0.01233	0.060	0.004
0.01248	0.061	0.004
0.01264	0.058	0.004
0.01281	0.063	0.004
0.01297	0.057	0.004
0.01314	0.056	0.004
0.01332	0.063	0.004
0.01349	0.058	0.003
0.01367	0.054	0.003
0.01386	0.053	0.003
0.01405	0.060	0.003
0.01424	0.059	0.003
0.01443	0.057	0.003
0.01463	0.057	0.003
0.01484	0.051	0.003
0.01505	0.055	0.003
0.01526	0.052	0.003
0.01548	0.055	0.003
0.01570	0.055	0.003
0.01592	0.057	0.003
0.01616	0.053	0.003
0.01639	0.056	0.003

The EXFOR entry for ^{235}U capture

```
ENTRY          14518   20190303   20190819   20190809         1450
SUBENT      14518001   20190303   20190819   20190809         1450
BIB               10         63
TITLE      Simultaneous Measurement of 235U Fission and Capture
           Cross Sections From 0.01 eV to 3 keV Using a Gamma
           Multiplicity Detector
AUTHOR     (Y.Danon,D.Williams,R.Bahran,E.Blain,B.Mcdermott,
           D.Barry,G.Leinweber,R.Block,M.Rapp)
INSTITUTE  (1USARPI,1USAKAP)
REFERENCE  (J,NSE,187,291,2017)
FACILITY   (LINAC,1USARPI) measurement was conducted at Rensselaer
           Polytechnic Institute using the electron linear
           accelerator at the Gaerttner LINAC Center.
DETECTOR   (NAICR)A 16-segment NaI(Tl) gamma-multiplicity
           detector located at the 25-m experimental station was
           used for the measurement. The overall dimensions of
           segmented detector were diameter 30.5 cm and length
           30.5 cm. A 5.08-cm-diameter collimated neutron beam
           passed into the center of the detector through on-axis
           cylindrical hole with diameter of 8.9 cm. There was a
           1.0-cm-thick annular B4C liner enriched to 99.5 at. %
           in 10B between the central beam path and the NaI(Tl)
           segments to minimize low-energy neutrons scattering
           from the sample and then interacting with the
           detector segments.
ANALYSIS   Fission and capture reactions were measured
           simultaneously using segmented high-efficiency gamma
           multiplicity NaI(Tl) detector. The multiplicity of
           fission gamas peaks at multiplicity 8 to 10 is higher
           than the multiplicity of capture gamma cascade, which
           peaks at multiplicity 3 to 4. Total deposited gamma
           energy was used to separate fission from capture
           reactions. The gamma multiplicity was used to improve
           the separation. This method enabled capture and fission
           yield measurements up to neutron energy of 3 keV.
ERR-ANALYS (ERR-T) Total uncertainty, which include
                   - counting statistics
                   - normalization values
                   - correction for false capture
            The overall uncertainty is dominated by the
            normalization uncertainty
COMMENT    Subentry 2  reaction 235U(n,f) from RPI files
                 U-235 Thermal Fission normalized to ENDF 7.1.tex
                 U-235 Thermal Fission normalized to ENDF 8.tex
                 Sample thickness 0.00054 +- 0.00002 at/b
                 Repetition rate 25 Hz
                 Pulse width (500+-50)ns
            Subentry 3  reaction 235U(n,f) from RPI files
                 U-235 Epi Fission normalized to ENDF 7.1.tex
                 U-235 Epi Fission normalized to ENDF 8.tex
                 Sample thickness 0.00436 +-0.00002 at/b
                 Repetition rate 225 Hz
HISTORY    (20190303C) Compiled by S.H.
ENDBIB            63
NOCOMMON           0          0
ENDSUBENT         66
SUBENT      14518004   20190303   20190819   20190809         1450
BIB                9         38
```

Resolution ???
Missing information

```
REACTION   1(92-U-235(N,G)92-U-236,,RYL)
            EXFOR U-235 Thermal Capture normalized to ENDF 7.1.tex
           2(92-U-235(N,G)92-U-236,,RYL)
            EXFOR U-235 Thermal Capture normalized to ENDF 8.tex
COMMENT     Data combined from RPI files
STATUS      (TABLE) Data shown in figs. 6-10 of the reference
                    sent by author (Y.D.)
ANALYSIS   1Yield normalization to ENDF/B-VII.1
           2Yield normalization to ENDF/B-VIII.0
INC-SOURCE (PHOTO)Neutrons were produced through a (gamma,n)
            reaction when electrons from the RPI 60-MeV electron
            linac interact with a tantalum target,
            Nominal beam energy                 53 MeV
            Nominal beam power                 424 W
            Neutron target            Enhanced thermal target
            Moderator material  Water, polyethylene and graphite
            Moderator temperature              293 K
METHOD      (TOF)
            Repetition rate                      25 Hz
            Pulse width                      (500+-50) ns
            Flight path                  (25.446+-0.006)m
SAMPLE      (92-U-234,ENR=0.01087)
            (92-U-235,ENR=0.93334)
            (92-U-236,ENR=0.001266)
            (92-U-238,ENR=0.05452)
             Chemical composition   U metal 93.33+-0.03 wt% U-235
            Atomic density (at/b)            0.00054+-0.00002
            Sample mass                          2.4 g
                  9 disks, each with
                  Diameter              12.7  mm
                  Nominal thickness      0.11 mm
                  Temperature           293 K
            Containment  0.8 mm thick aluminum container
                         Each disk was wrapped in 0.076 mm of
                         aluminum foil
MONITOR     (5-B-10(N,A)3-LI-7,,SIG,G)
            Normalized to 11.7-eV and 13.4-eV resonances in U-235
ERR-ANALYS (ERR-1) Systematic uncertainty in normalization
ENDBIB              38
COMMON               2          3
ERR-1       THICKNESS
PER-CENT    ATOMS/B
2.          0.00054
ENDCOMMON            3
DATA                 5       1179
EN          DATA       1ERR-T      1DATA       2ERR-T      2
EV          NO-DIM     NO-DIM      NO-DIM      NO-DIM
    0.01005      0.064      0.006      0.064      0.006
    0.01016      0.074      0.006      0.074      0.006
    0.01028      0.065      0.006      0.064      0.006
    0.01040      0.065      0.006      0.065      0.005
    0.01052      0.063      0.006      0.063      0.005
    0.01065      0.061      0.005      0.061      0.005
```

Two different normalizations

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Resolution function (E< 2 keV)

- Use the resolution functions built into SAMMY with parameters provided by the user.
- Use ^{238}U (ENDF) as a reference for energies and resonance parameters.
- **Transmission**
  - Thermal - use the RPI resolution function in SAMMY
  - Epi-thermal – use a Gaussian + exponential tail (variable with E)
- **Capture**
  - Thermal - Gaussian + exponential tail (constant with E)
  - Epi thermal - Gaussian + exponential tail (constant with E)

SAMMY Gaussian + tail

- SAMMY has a form for Gaussian and exponential

$$f_{GE}(E) = \frac{1}{\Delta_E \Delta_G \pi} \int_{E-\Delta E_S}^{\infty} dE'' \exp\left\{-\frac{\left(E'' - (E - \Delta E_S)\right)}{\Delta_E}\right\} \times \int_{-\infty}^{+\infty} dE' \exp\left\{-\frac{(E' - E'')^2}{\Delta_G^2}\right\} f(E')$$

- Δ_G – Gaussian width (moderator (ΔL) + channel width (Δt_c) + burst width (Δt_G) + other E dist (Δ_c))

$$\Delta_G^2 = \Delta_{all}^2 = \frac{2}{3} E^2 \left(\frac{\Delta L}{L}\right)^2 + \frac{2}{m} E^3 \frac{2}{3} \left(\frac{\Delta t_c}{L}\right)^2 + \frac{2}{m} E^3 \frac{1}{\ln 2} \left(\frac{\Delta t_G}{L}\right)^2 + \Delta_C^2 \quad ,$$

- Δ_E – exponential width (moderator + detector)

$$\Delta t_E = D_1 E + D_0 + D_2 \ln(E) \qquad \Delta_E = \frac{2E^{3/2}}{L(m/2)^{1/2}} \Delta t_E$$

- ΔE_S – shift center (use shift)

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Example: SAMMY Gaussian + exponential resolution parameters

	Thermal Capture	Epi-Thermal Capture	Epi-Thermal Transmission
DELTAL Uncertainty in flight path length	0.0055	0.0055	0.0055
DELTAG Burst width	0.0254	0.0254	0.0254
DELTAE Exponential tail	0.06*	0.06*	0
DELTE:**DELE0**	0	0	0.18650
DELTE:**DELE1**	0	0	1.2687e-6
DELTE:**DELE2**	0	0	0.02069

*EXPONENTIAL FOLDING width is energy dependent
DO NOT SHIFT ENERGY for exponential tail

Example: RPI resolution function
Thermal Region Transmission

- Complicated function with many parameters (Enhanced thermal target + detector)

$$I_2(t) = A_0 \left\{ \frac{(t+\tau)^2}{2!\Lambda^3} e^{-(t+\tau)/\Lambda} + A_1 \left[A_2 e^{-A_3(t+t_0)} + A_4 e^{-A_5(t+t_0)} \right] X(t) + \sum_{i=1}^{5} B_{2i-1} e^{-B_{2i}(t+t_0)} \right\} ,$$

$$\Lambda(E) = \Lambda_0 + \Lambda_1 \ln(E) + \Lambda_2 [\ln(E)]^2 + \Lambda_3 E^{\Lambda_4}$$

$$\tau(E) = \tau_1 e^{-\tau_2 E} + \tau_3 e^{-\tau_4 E} + \tau_5 + \tau_6 E^{\tau_7}$$

$$A_i(E) = \{ a_{i1} e^{-a_{i2} E} + a_{i2} e^{-a_{i4} E} + a_{i5} + a_{i6} E^{a_{i7}} \} \alpha_i$$

Param	Value	Param	Value	Param	Value	Param	Value
τ_1	320.94	Λ_0	679.98	a_1	-000078	A_0	935.91
τ_2	0.02426	Λ_1	-226.21	a_2	0.02407	A_1	-69.068
τ_3	318.46	Λ_2	21.09	a_3	-0.00063	A_2	0.005
τ_4	0.02922			a_4	3.53	A_3	0.39485
τ_5	235.71			a_5	0.000112	A_4	0.0075

Conclusions

- Reporting to EXFOR usually follows a journal or thesis publication with extensive experimental details.
- Any additional relevant information such as energy resolution should be also in EXFOR
- Reported values in the RRR are usually transmission and capture yield and their associated uncertainties.
- Resonance parameter analysis results are also available and can be reported to EXFOR.