Report on U.S. Experimental Activities

WPEC 2020

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WPEC, 11-15 May 2020, via Webex

Introduction

- **This update is based on presentations during the November 2019 CSEWG meeting.**
- **A link to full presentations:**

  https://indico.bnl.gov/event/6642/timetable/#20191104.detailed

- **Reports from different laboratories:**

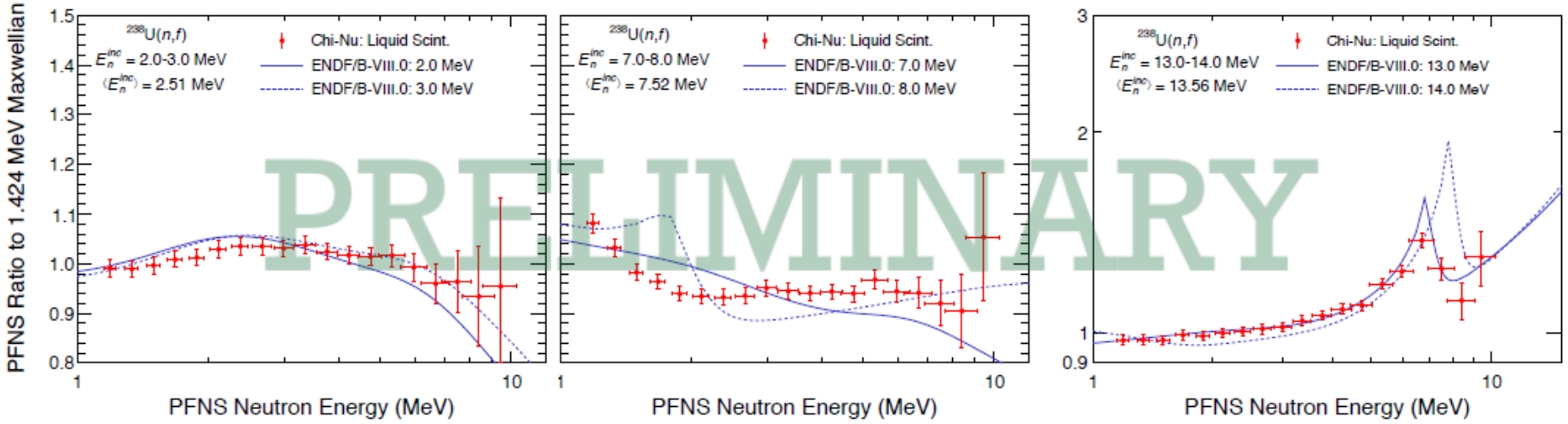
1. LENZ Measurement of the $^{16}O(n,\alpha)$ Reaction and a Chi-Nu Status Update. (LANL)
2. Measurement of the $^{35}Cl(n,p)^{35}S$ Reaction Cross Section at LANSCE. (LANL)
3. Recent Experimental Activities at LANSCE on Pt Capture Cross Sections. (LANL)
4. The SREFT (Spatially REsolving Fission Tracker) Time Projection Chamber. (LANL)
5. ORNL neutron cross section measurements for the US Nuclear Criticality Safety Program. (ORNL)
6. Experimental Activities at LBNL. (LBNL/UCB)
7. Nuclear data measurements carried at TUNL. (Duke University/TUNL)
8. Nuclear data measurement and analysis at RPI. (RPI)
9. Recent work on neutron standards data. (NIST)
10. Current status of EXFOR. (NNDC, BNL)
11. Measurements of branching ratios in U-238. (BNL)

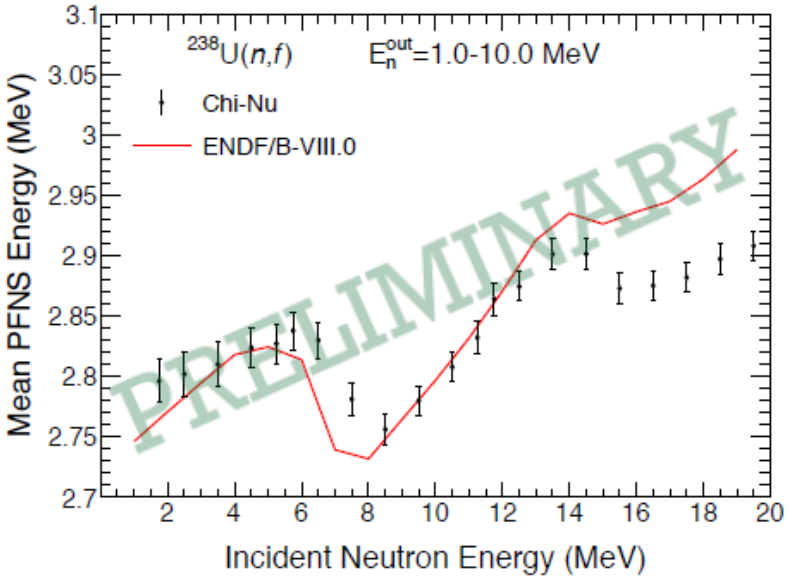
This report represents only part of the U.S. nuclear data activity.

Los Alamos National Laboratory

- **LENZ Measurement of the ^{16}O(n,al) Reaction and a Chi-Nu Status Update. (LANL)**
  - Preliminary ^{238}U PFNS Data
  - LENZ ^{16}O(n,α_0) cross section: preliminary

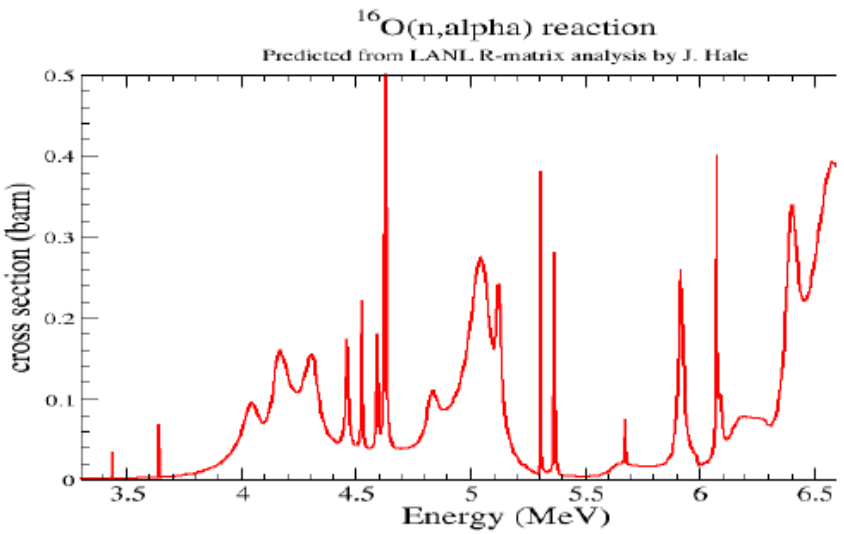
Status Update on the Chi-Nu PFNS Experiment: Analysis Improvements, ^{239}Pu Results, Prelim. ^{238}U Data

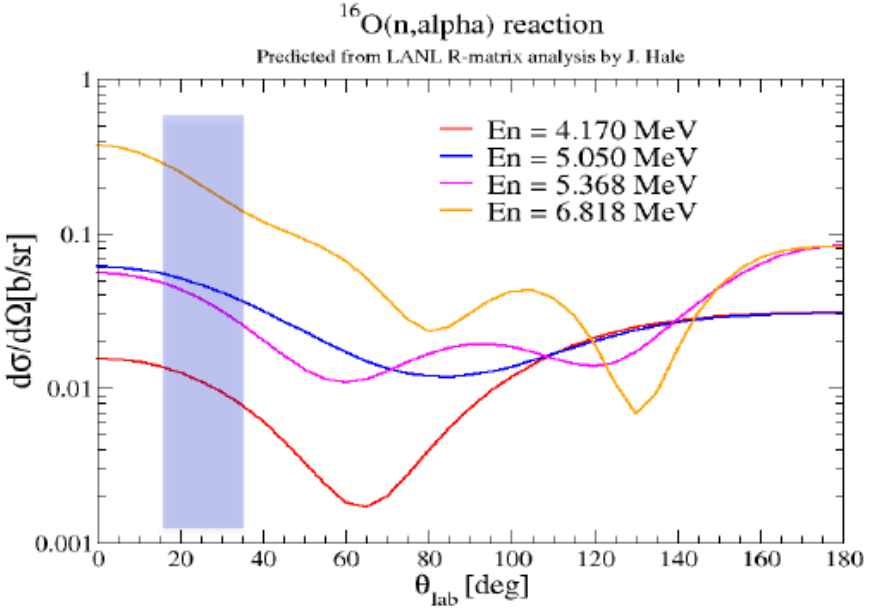


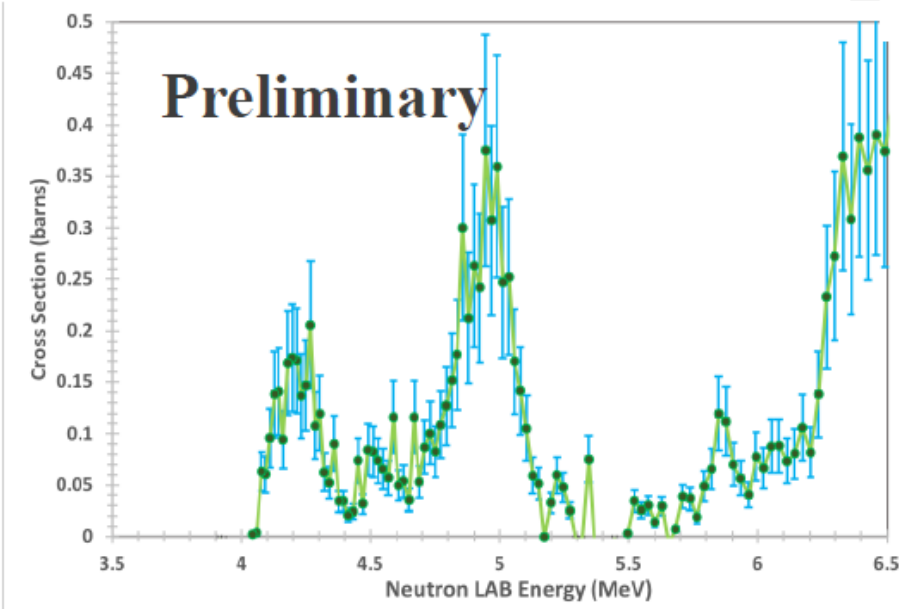


- Second-chance fission later than predicted?
- Signs of third-chance fission appear
- Pre-equilibrium also clearly seen
  - Begin later than predicted?
- Collect Li-glass data next year, complete analysis soon after

LENZ $^{16}O(n,\alpha_0)$ cross section: preliminary







- Currently 30 % uniform Uncertainty is applied to (n,α_0) cross sections, due to **on-going effort** of estimating corrections for angular distributions, beam-target overlap functions, absolute neutron flux normalization, etc.
- Double differential data can be used for direct R-matrix fit

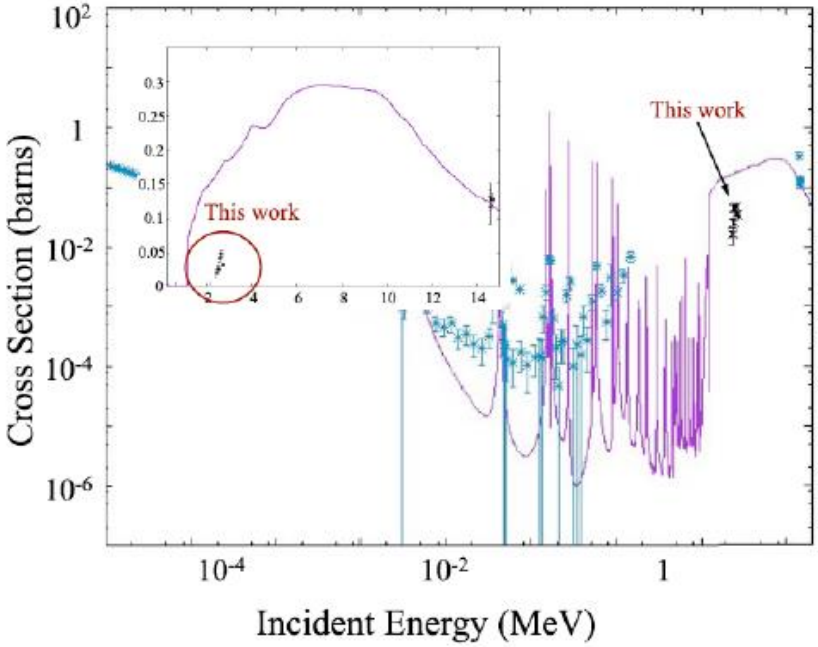
Los Alamos National Laboratory

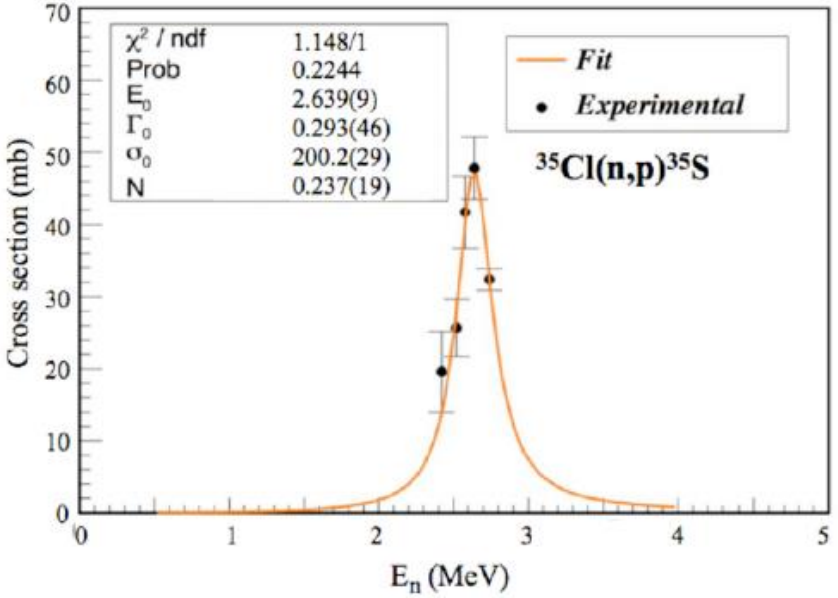
- **Measurement of the $^{35}Cl(n,p)^{35}S$ Reaction Cross Section at LANSCE. (LANL)**
  - Evidence of non-statistical properties at ~2.6 MeV ??
  - 350 and 450 ug/cm^2 NaCl (^{35}Cl enriched) targets evaporated on to 6um thick brass backing foils
  - Two flight paths: 15R (**15.2m**, forward angles) 15R (**14.2m**, forward and backward angles) and 90L (**8.1m**, backward angles)

Evidence of non-statistical properties at ~2.6 MeV

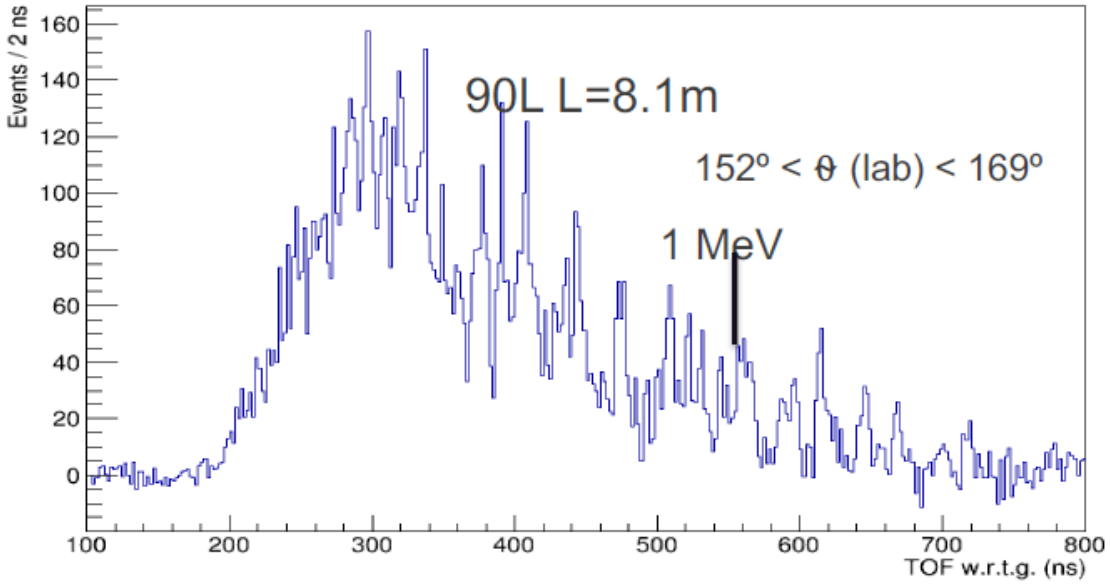
- Recent measurement of ^{35}Cl(n,p) and ^{35}Cl(n,a) at incident neutron energies between 2.42 and 2.74 MeV shows a hint of non-statistical behavior and a reduced cross-section relative to all data libraries.

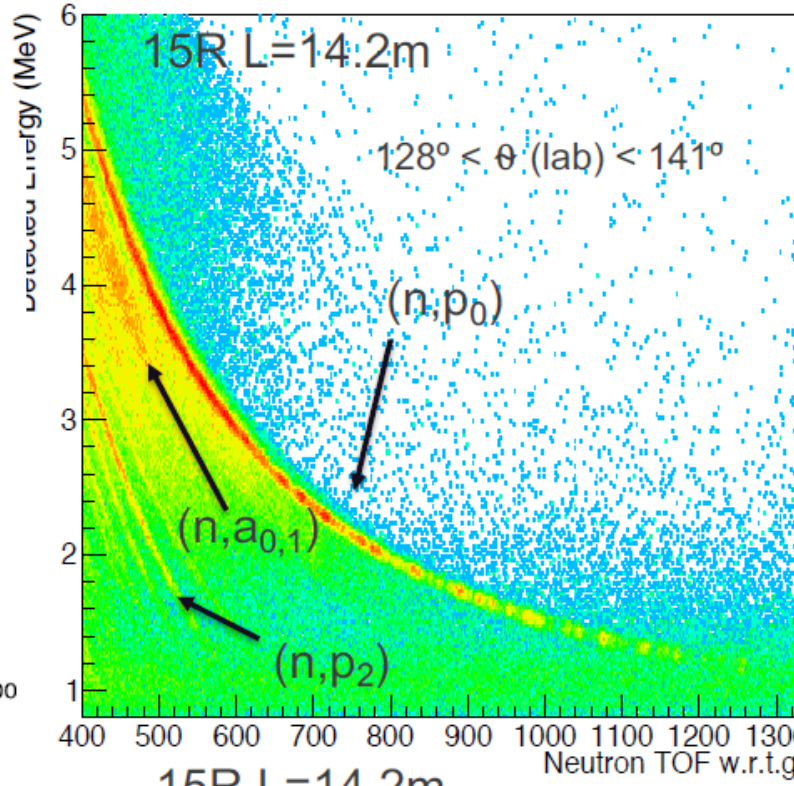
Batchelder et al. PRC99,044612(2019)



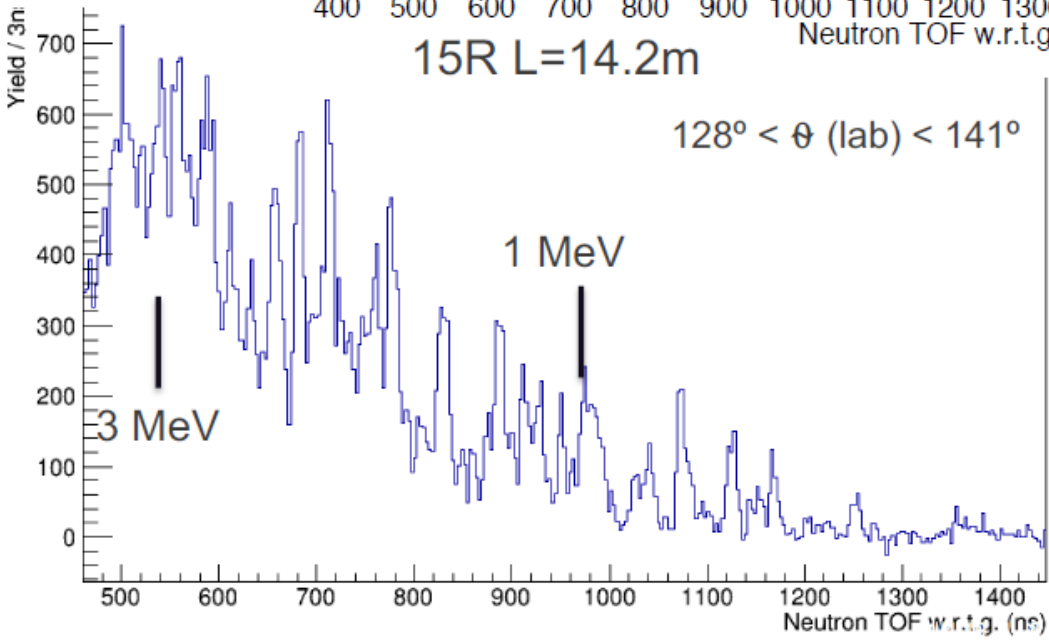


Measurement of $^{35}Cl(n,p)^{35}S_{gs}$

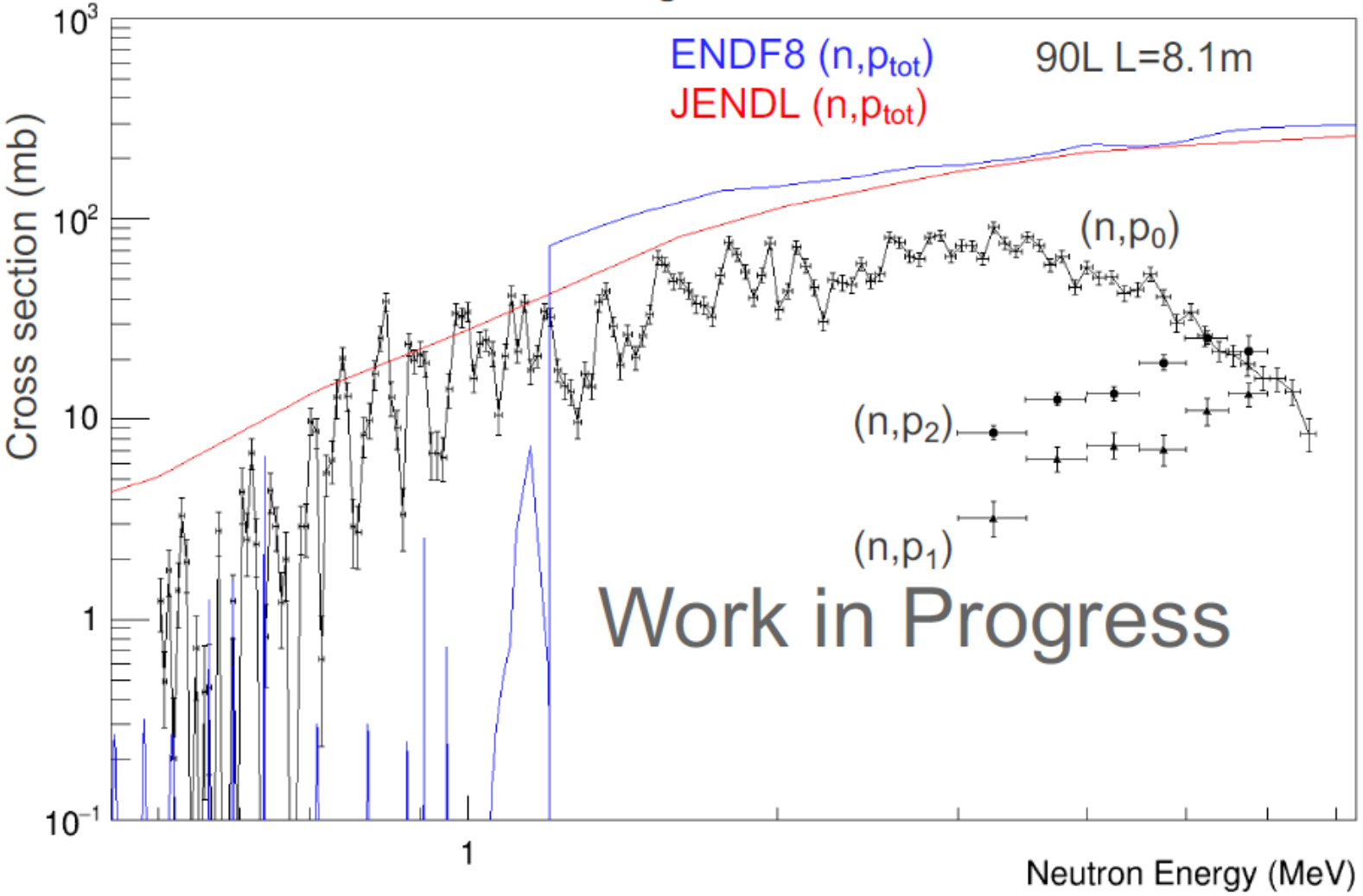




- Resonances observed at same energies for different flight path lengths
- Forward and backward angles



Measurement of $^{35}Cl(n,p)^{35}S_{gs}$



Assumption made here of an isotropic angular distribution, using only backward angle data from one detector at the 90L (8m) flight path.

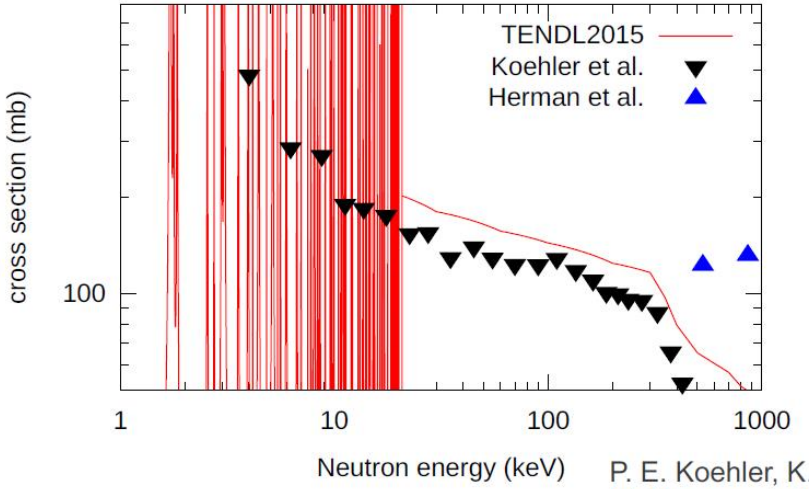
$152^\circ < \theta\ (\text{lab}) < 169^\circ$

Los Alamos National Laboratory

- **Recent Experimental Activities at LANSCE on Pt Capture Cross Sections. (LANL)**
  - Limited amount of data
  - Preliminary capture data presented

Current status of Pt(n,γ) data

- Pt+neutron data in ENDF is based on TENDL
- Experimental data is limited
- Example: ^{196}Pt



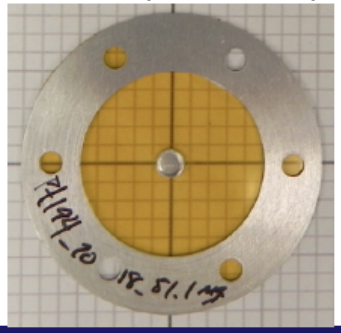
P. E. Koehler, K. H. Guber. PRC, 88:035802 (2013)
M. Herman, A. Marcinkowski. NPA, 357:1 (1981)

Samples

Samples and run times

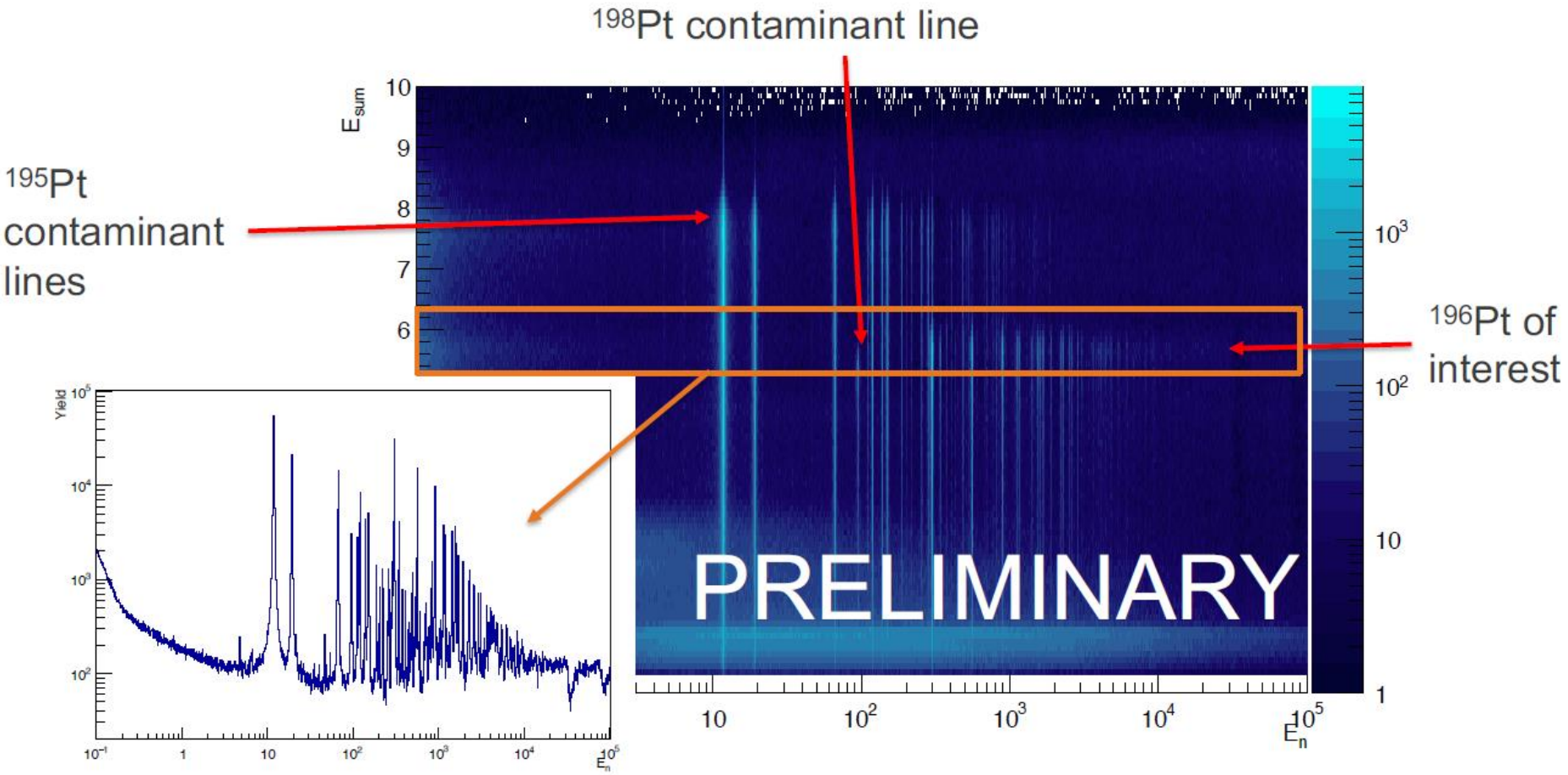
	Composition (%)					
	190	192	194	195	196	198
^{192}Pt	0.01	**56.93**	26.34	11.12	4.77	0.83
^{194}Pt	0.01	0.03	**96.45**	2.46	0.87	0.18
^{195}Pt	0.01	0.01	1.93	**96.63**	1.33	0.09
^{196}Pt	<0.01	0.01	1.45	3.55	**94.57**	0.42
^{198}Pt	<0.01	0.03	1.77	2.83	3.73	**91.63**
nat	0.01	0.78	32.86	33.78	25.21	7.38

All fabricated samples were purchased from NIDC, each had 4mm diameter and was mounted on Kapton tape



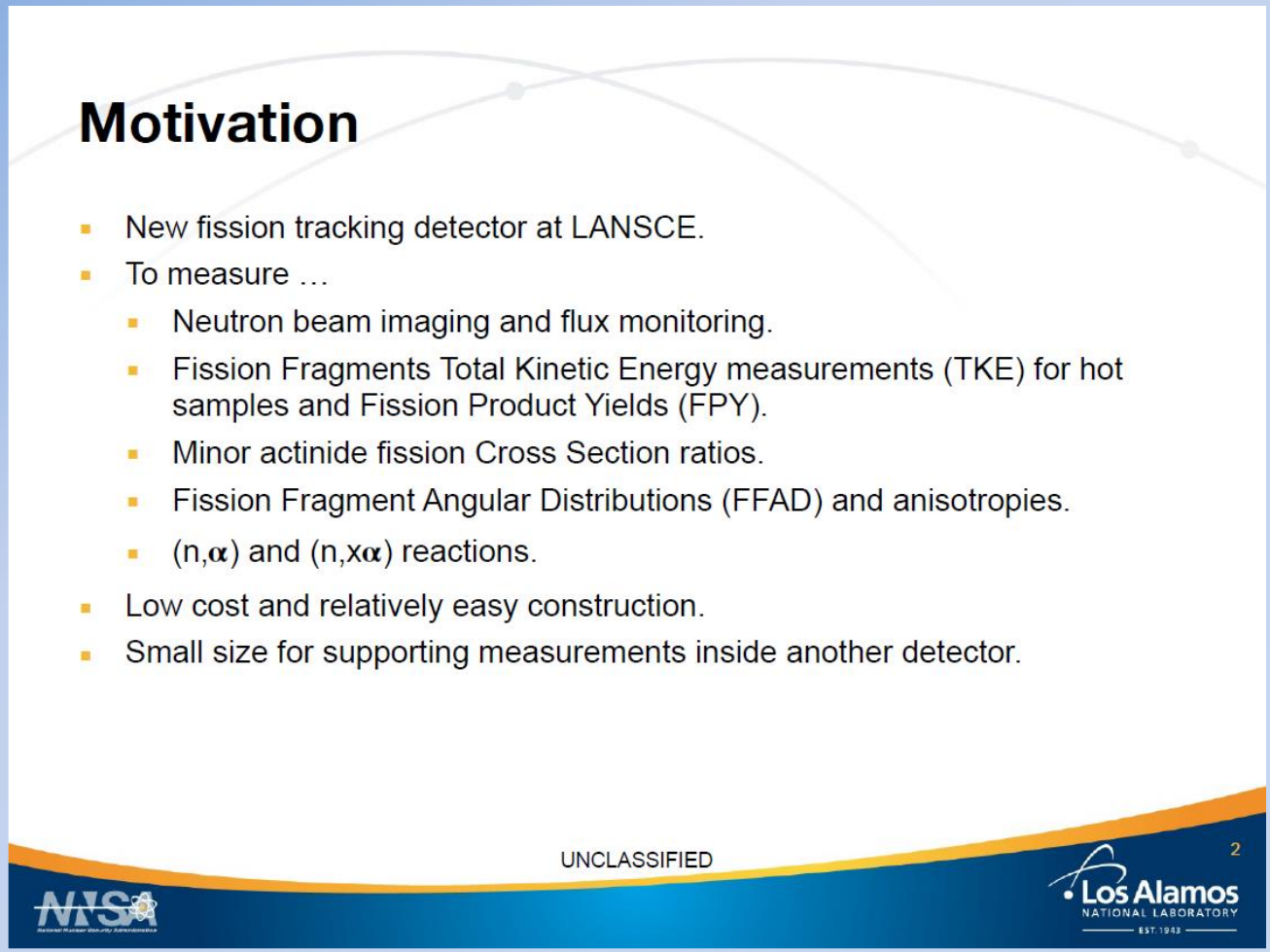
Sample	M/Y	Time (d)
194 50mg	10/18	4
194 10mg	10/18	1
195 50mg	10/18	4
195 10mg	10/18	1
196 50mg	10/18	1
196 10mg	10/18	1
195 50mg	9/19	1
192 20mg	9/19	3
196 50mg	9/19	4
196 10mg	919	1
198 57mg	9/19	4
198 10mg	9/19	1

Example data: ^{196}Pt (3.5% ^{195}Pt, 0.5% ^{198}Pt contamination)



Los Alamos National Laboratory

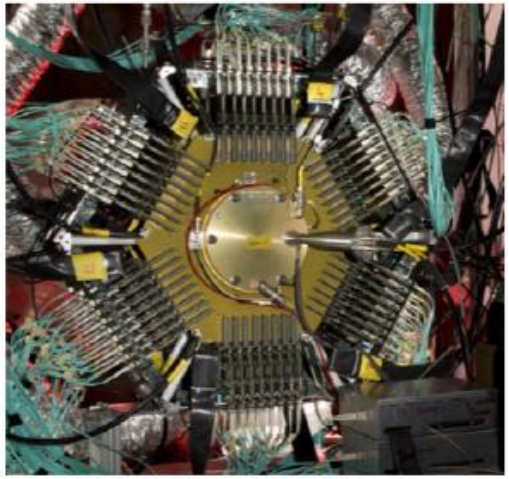
- **The SREFT (Spatially REsolving Fission Tracker) Time Projection Chamber. (LANL)**



Fission tracking detectors at LANSCE

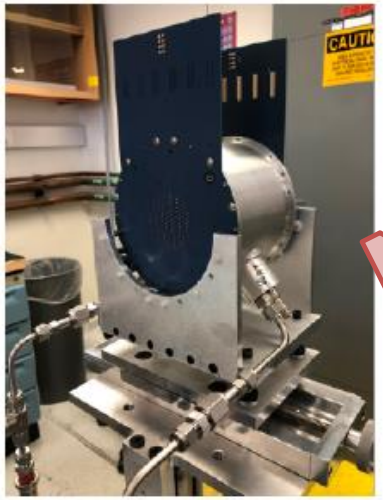
TPC*
(Time Projection Chamber)

- Very precise fission cross section ratios (unc. < 1%).
- ~3000 pads per anode = high number of channels needed.
- High power supply and cooling requirements.
- Custom DAQ system.



SREFT
(Spatially Resolving Fission Tracker)

- Minor actinide fission cross section ratios (unc. > 1%).
- 187 pads per anode => less channels needed.
- Limited cooling required and low power supply.
- Commercial DAQ system.



- Digitizers out of the beam

New

* NIFFTE Collaboration

Oak Ridge National Laboratory

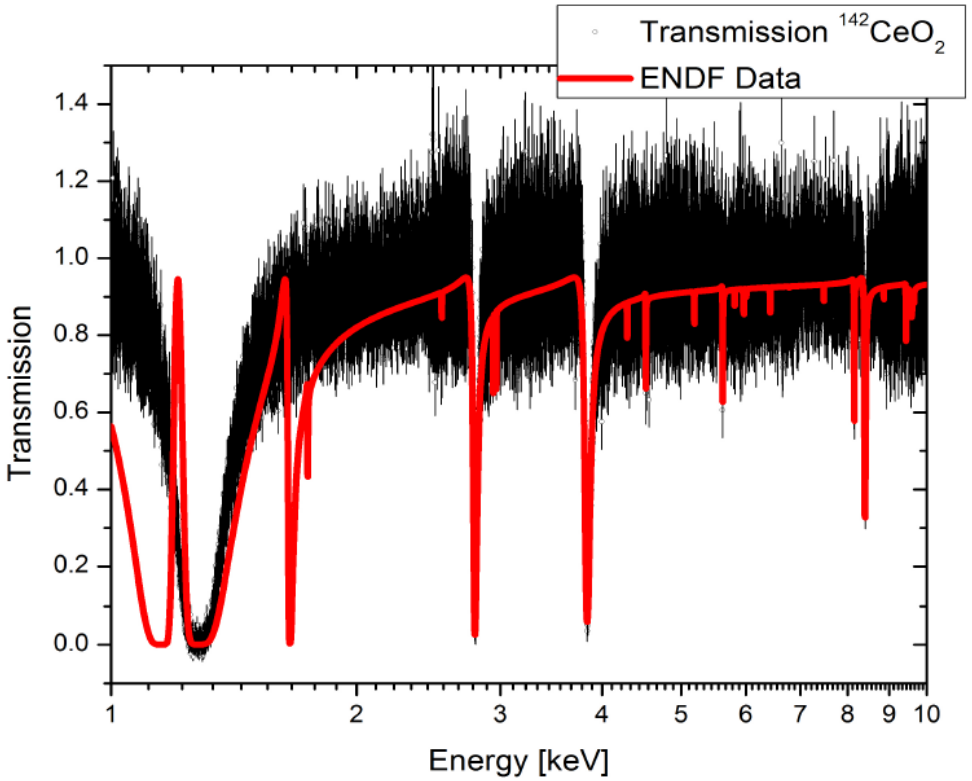
- **Transmission & Capture Measuring ^{142}Ce Resonance region**
  - Measurements at GELINA

142 Cerium sample preparation

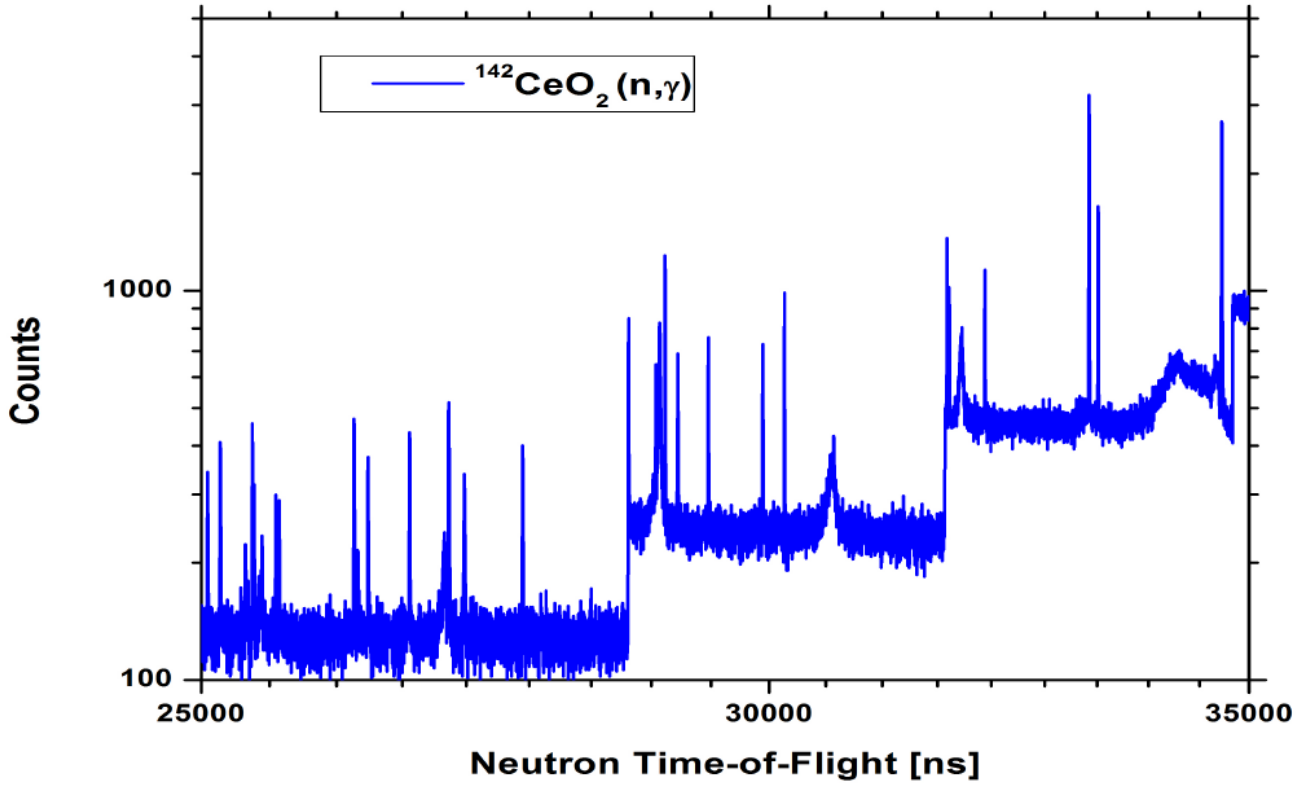
- Used cerium oxide, the inventory form from ORNL isotopes
- Oxides are hygroscopic, therefor the sample is sealed in an Al-can
- Oxide is heated to remove all moisture and pressed to a self-supporting disk

^{142}Ce Transmission detailed view misassigned resonances

- Used ENDF/B-VIII Ce resonance parameters
- Oxide sample requires to include **oxygen resonance parameter** in the resonance file to describe correctly the transmission.
- Not possible with ENDF/B-VIII, because it has only a pointwise cross section for oxygen.
- So used ORNL oxygen evaluation resonance parameter file from R. Sayer.



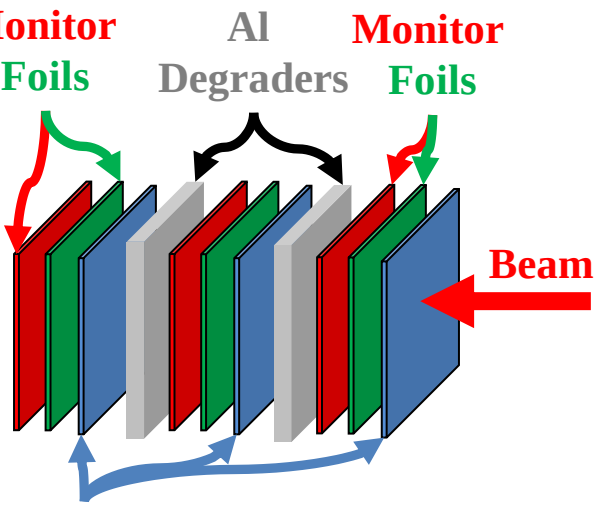
^{142}Ce capture 60m TOF spectrum



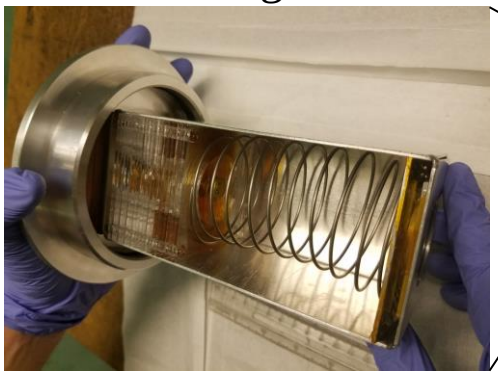
Cross Section measurements at LBNL and UC-Berkeley

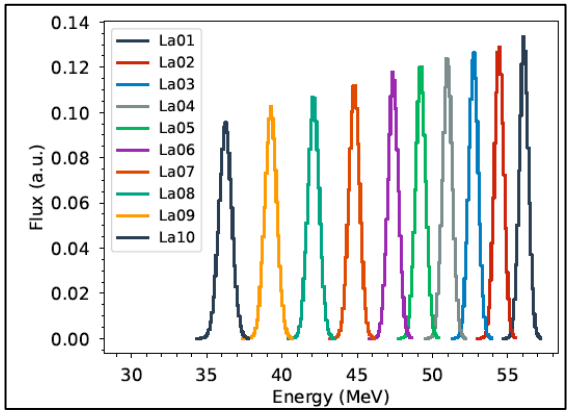
- **88-Inch cyclotron**
  - The DOE Isotope Program has recognized this and initiated a Tri-lab effort (BNL, LANL, LBNL) to measure important (p,x) cross sections from threshold to 200 MeV
  - As(p,x)^{72}Se,^{68}Ge in the energy range 40 -200 MeV
- **GENESIS array to measure the ^{238}U(n,n'γ), but it will also provide new insight into P(ν(A,Z)) for**
  - (n,f)
  - Neutrons from 16 MeV deuteron breakup
  - 10-20 EJ-309 scint. + Clovers and LEPS
  - Initial focus is ^{56}Fe(n,n'γ)

We can rapidly measure (p,D,α,x) cross sections using the stacked target technique*



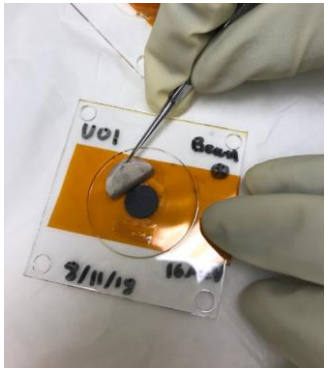
Stacked Target Holder



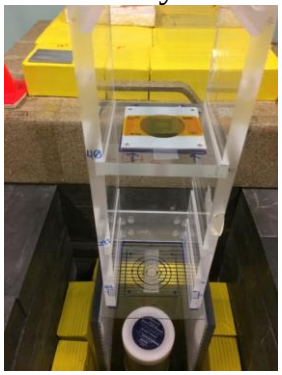


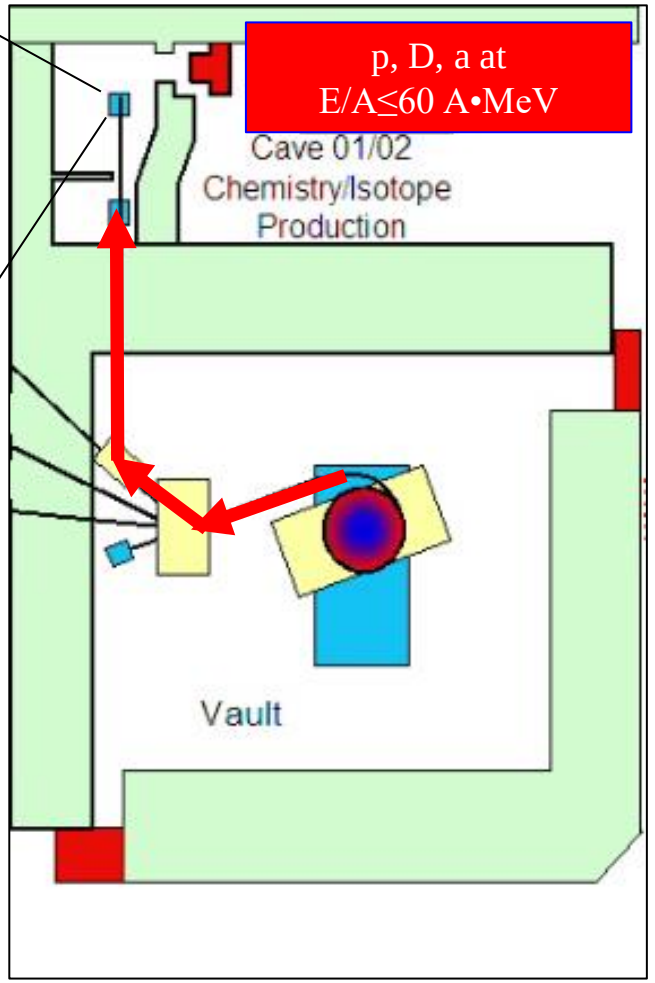
Energy from Activation Foil Variance Minimization

Pencil or overfill beams



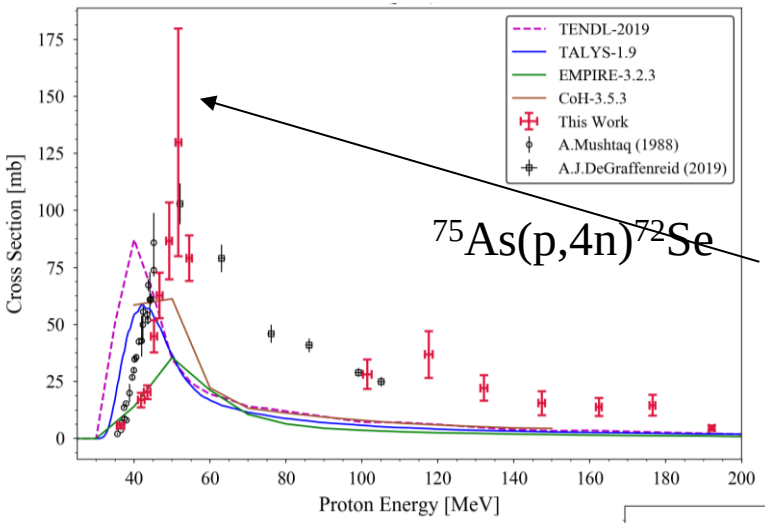
HPGe Assay



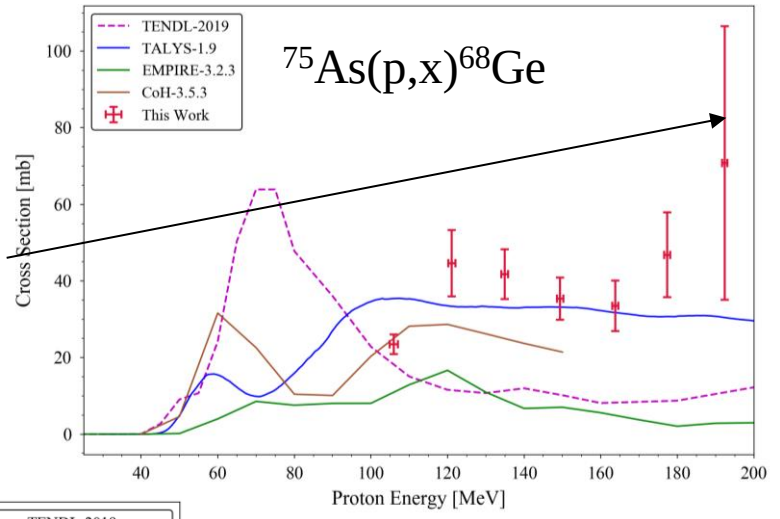


*S.A. Graves *et al.*, NIM B386 (2016) 44–53
https://doi.org/10.1016/j.nimb.2016.09.018

Our first joint effort with LANL-IPF and BNL-BLIP has centered on ^{75}As(p,x) with an emphasis on ^{68}Ge and ^{72}Se production (Morgan Fox)



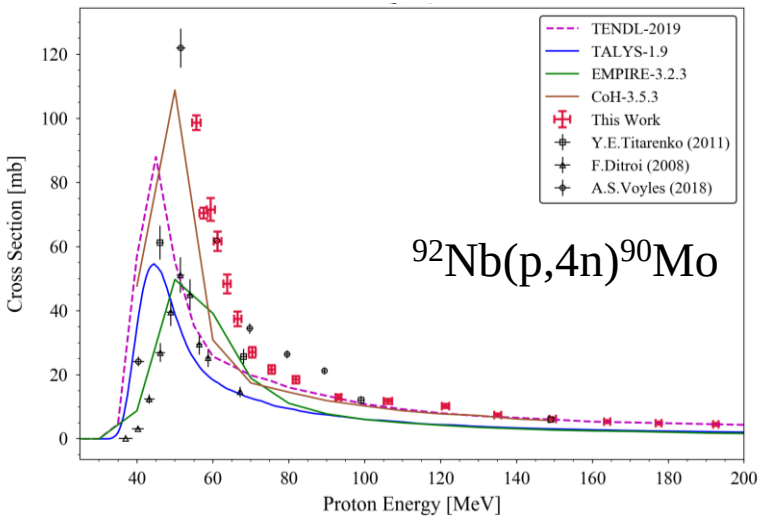
δσ Error bars should reduce by a factor of 3 after target mass measurement this week @ the McClellan reactor



Collaborators

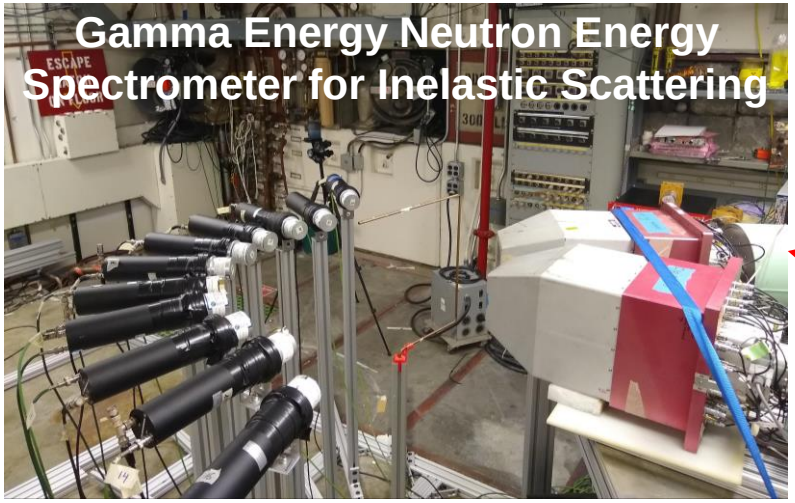
C. Cutler, D. Medvedev (BNL)

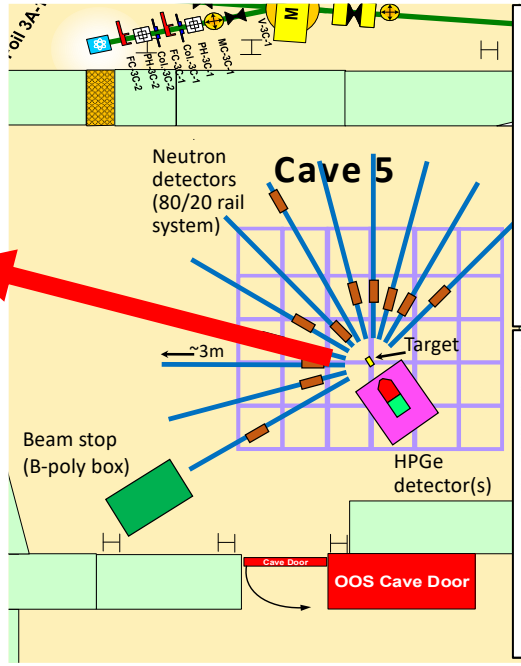
E. Birnbaum, F.M. Nortier, E. O'Brien, E. Vermeulen (LANL)

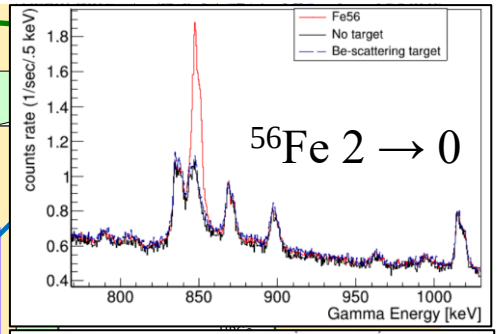


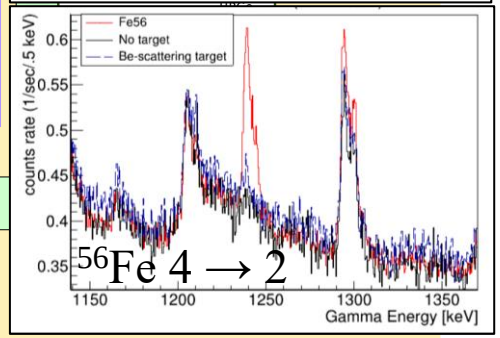
Next up, Sb (Catherine Apgar)

Example #4: We built the GENESIS array to measure the ^{238}U(n,n'γ), but it will also provide new insight into *P(ν(A,Z))* for (n,f)



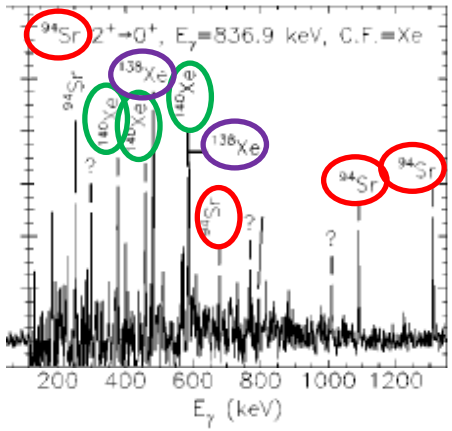


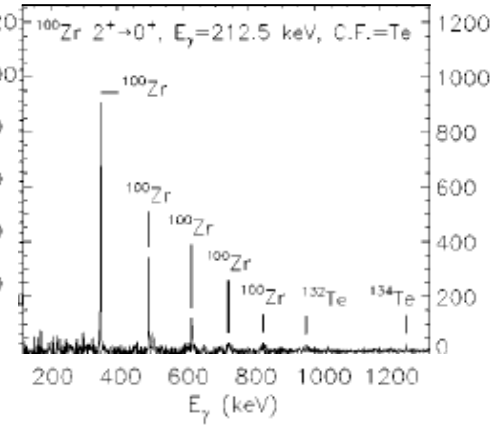




- Neutrons from 16 MeV deuteron breakup
- 10-20 EJ-309 scint. + Clovers and LEPS
- Initial focus is ^{56}Fe(n,n'γ) (D.L. Bleuel)
- Ph.D. student – Joey Gordon
- **^{238}U(n,fγ) data will provide insight into the A,Z,E,J$^{\pi}$ dependence of *P(ν)***

This is part of an interagency nuclear data effort initiated by DNN & DOE-NP





*W. Younes *et al.*, PRC 64, 054613 (2001)

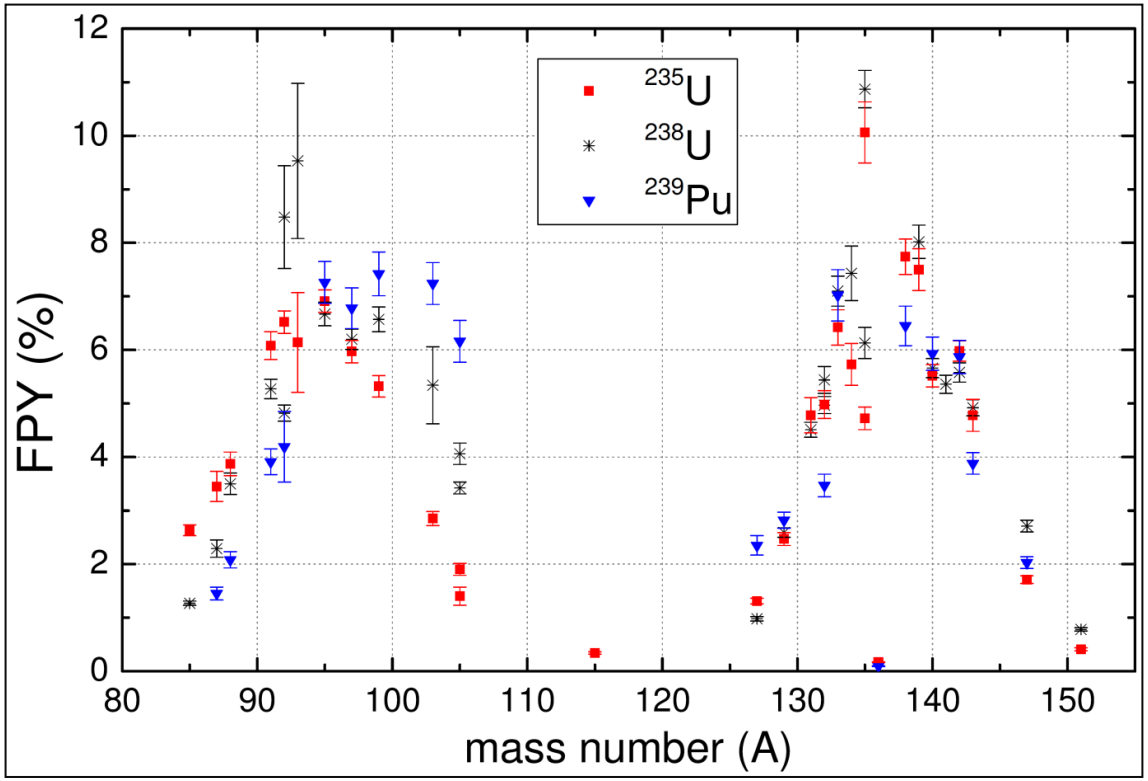
Nuclear data measurements at TUNL (Duke University/TUNL)

- **Fission product yield (photon induced)**
  - Move to short half-lives
  - Demonstrate a rabbit system
- **Medical Isotope production using (γ,x)**

γ-FPY @ 13 MeV results

TUNL

Product	FPY (%)		
	^{235}U	^{238}U	^{239}Pu
^{84}Br	1.77(13)	2.49(19)	
^{85}Kr^{m}	2.63(10)	1.27(4)	
^{87}Kr	3.45(28)	2.29(16)	1.45(12)
^{88}Kr	3.87(22)	2.92(17)	2.08(15)
^{91}Sr	6.08(26)	5.27(18)	3.91(24)
^{92}Sr	6.52(21)	4.82(15)	4.19(66)
^{92}Y		8.48(96)	
^{93}Y	6.14(93)	9.53(145)	
^{94}Y	6.84(37)	7.50(46)	4.71(33)
^{95}Zr	6.91(21)	6.67(22)	7.26(39)
^{97}Zr	5.97(21)	6.20(19)	6.78(38)
^{99}Mo	5.32(20)	6.57(22)	7.42(41)
^{104}Tc	2.37(14)	4.44(64)	1.96(14)
^{103}Ru	2.85(13)	5.34(72)	7.24(39)
^{105}Ru	1.90(11)	4.06(20)	6.16(39)
^{105}Rh	1.40(17)	3.42(11)	
^{115}Cd^{g}	0.34(2)		
^{128}Sn	1.22(16)	1.22(22)	1.18(16)
^{127}Sb	1.31(5)	0.98(4)	2.35(18)
^{129}Sb	2.47(12)	2.59(9)	2.82(15)
^{130}Sb	0.82(6)	1.61(11)	1.36(11)
^{131}Sb	1.59(13)	5.01(33)	
^{132}Te	4.98(26)	5.44(25)	3.47(21)
^{133}Te	4.10(42)	5.27(53)	4.03(43)
^{134}Te	5.37(39)	7.43(51)	
^{131}I	4.78(33)	4.51(14)	
^{133}I	6.42(33)	7.10(28)	7.02(48)
^{135}I	4.72(21)	6.13(29)	
^{135}Xe	6.38(20)	7.45(24)	
^{132}Cs		4.97(16)	
^{136}Cs[a]	0.17(1)		0.10(1)
^{138}Cs^{g}	7.74(33)		6.45(37)
^{139}Ba	7.50(39)	8.02(31)	
^{140}Ba	5.52(21)	5.66(18)	5.93(31)
^{141}Ba	4.43(27)		4.22(31)
^{142}La	5.98(19)	5.58(18)	5.87(31)
^{141}Ce		5.36(17)	
^{143}Ce	4.78(30)	4.92(15)	3.88(20)
^{146}Pr	4.86(39)		
^{147}Nd	1.71(7)	2.71(11)	2.03(11)
^{149}Nd	1.64(11)	2.82(10)	2.32(18)
^{151}Pm	0.41(3)	0.78(3)	



PHYSICAL REVIEW C **100**, 014608 (2019)

Fission product yield measurements using monoenergetic photon beams

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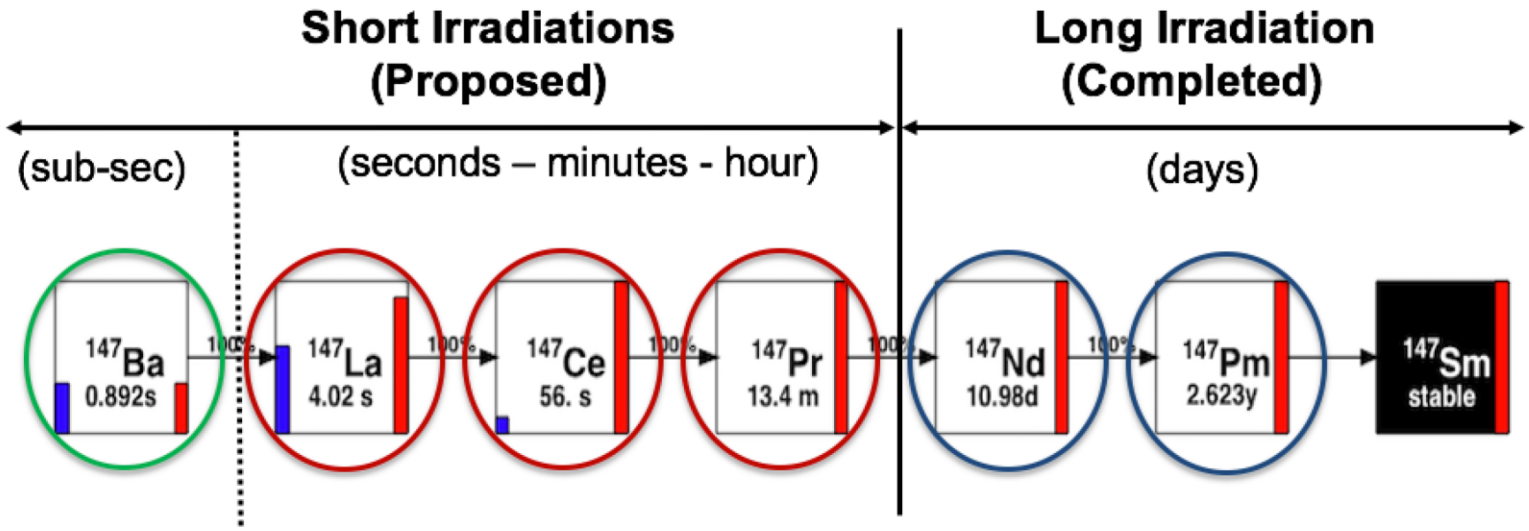
FPY measurements: moving up the decay chain



- Chain fission product yields $Y_{ch}(A,Z)$ – Completed at TUNL
- Cumulative fission product yields $Y_c(A,Z)$ – Proposed at TUNL
- Independent fission product yields $Y_i(A,Z)$ – Proposed at LBNL

Goal: Predicting independent and cumulative FPYs data simultaneously and consistently in the energy-dependent manner

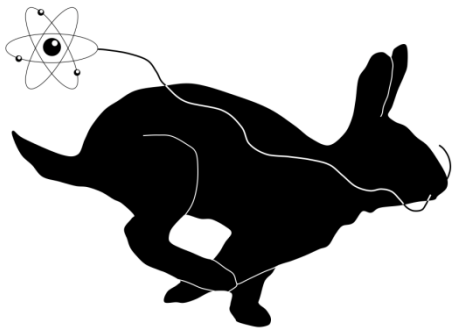
RABITTS

TUNL

Goal: measure fission product yields for ^{235}U, ^{238}U, and ^{239}Pu

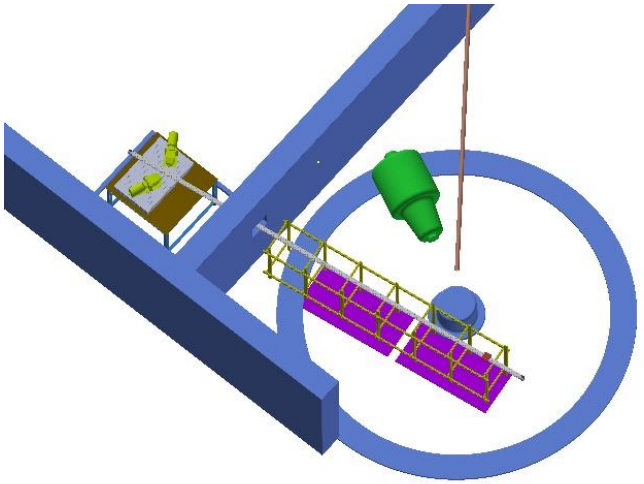
- Fission product $T_{1/2}$ from <1 s to 100 s
- Investigate dependence on neutron energy
- Construction began December 2018

RApid
Belt-driven
Irradiated
Target
Transfer
System



Fully automated system

- Moves between irradiation and counting positions
- 1 m track with 0.4 s transfer time
- 10 m track with 1 s transfer time
- User set irradiation, transfer, and counting time



Servomotor controls sample position

- Repeatability to ±33 μm
- Soft acceleration and deceleration

Data acquisition system

- Digital DAQ time stamps events to < μs precision

Very Short lived fission products

TUNL

Data on ^{235}U, ^{238}U, and ^{239}Pu

- 3 s irradiation time, 9 s counting time
- 6 hours beam on target

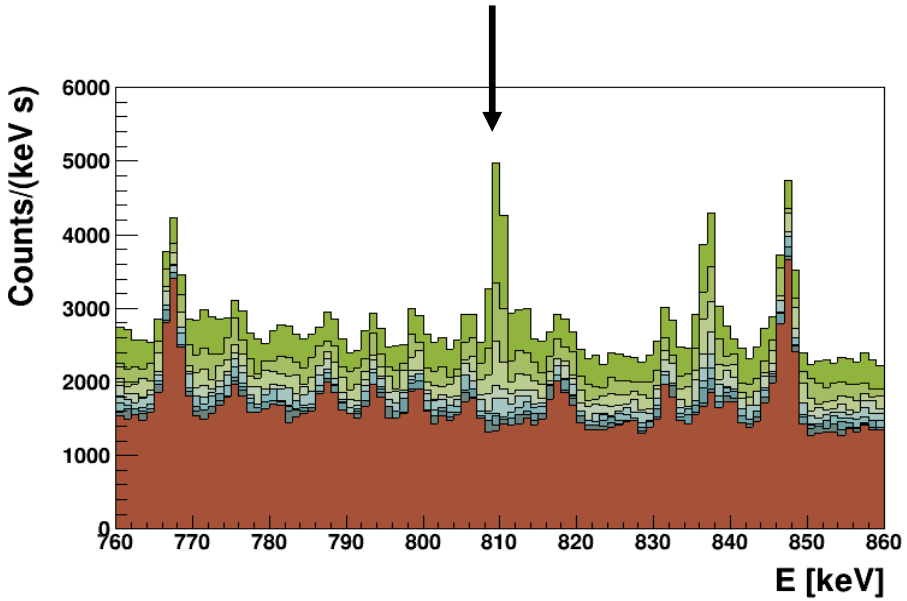
Applications:

- Advance fundamental understanding of the fission process
- Benchmark microscopic fission models
- Stockpile science
- Nuclear energy
- Nuclear forensics
- Antineutrino anomaly

^{96}Sr

E_γ = 809.4 keV

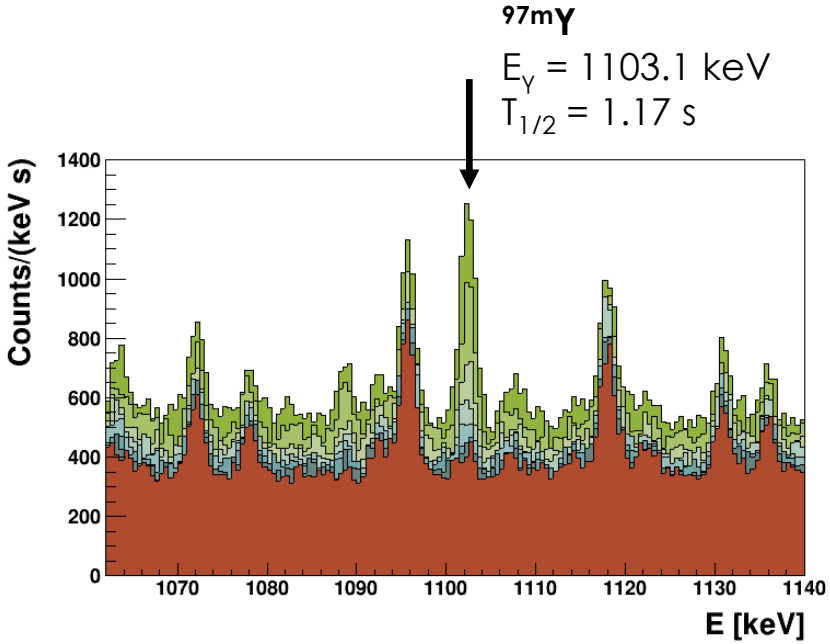
$T_{1/2}$ = 1.07 s



^{97m}Y

E_γ = 1103.1 keV

$T_{1/2}$ = 1.17 s



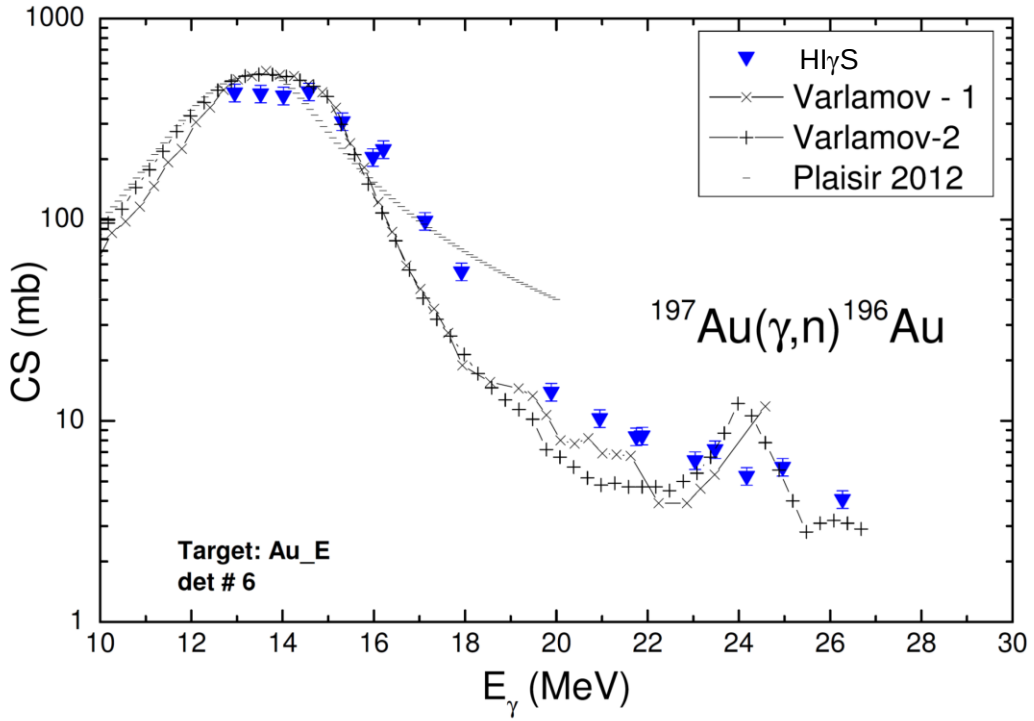
γ-ray intensity in 1 s intervals after irradiation

Medical Isotope Production

Cross section measurement: $^{197}Au(\gamma,n)^{196}Au$

TUNL

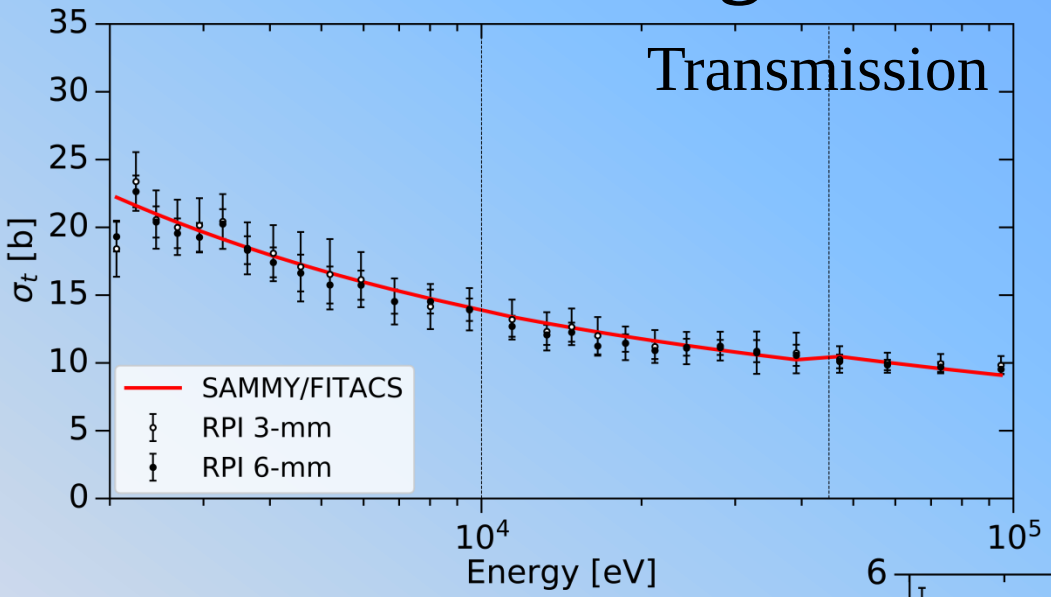
Preliminary data (14-27 MeV)

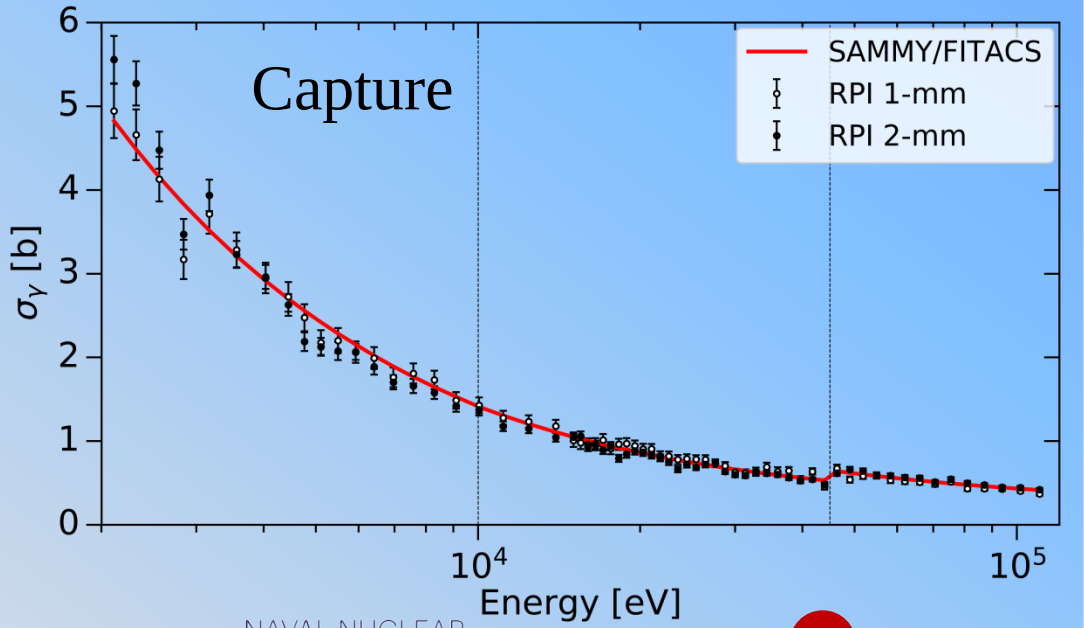


Nuclear data measurement and analysis at RPI

- ^{181}Ta transmission and capture
- KeV neutron scattering form Zr and Cu
- Neutron induced reactions for ^{235}U and ^{239}Pu

Multi-Region URR evaluation



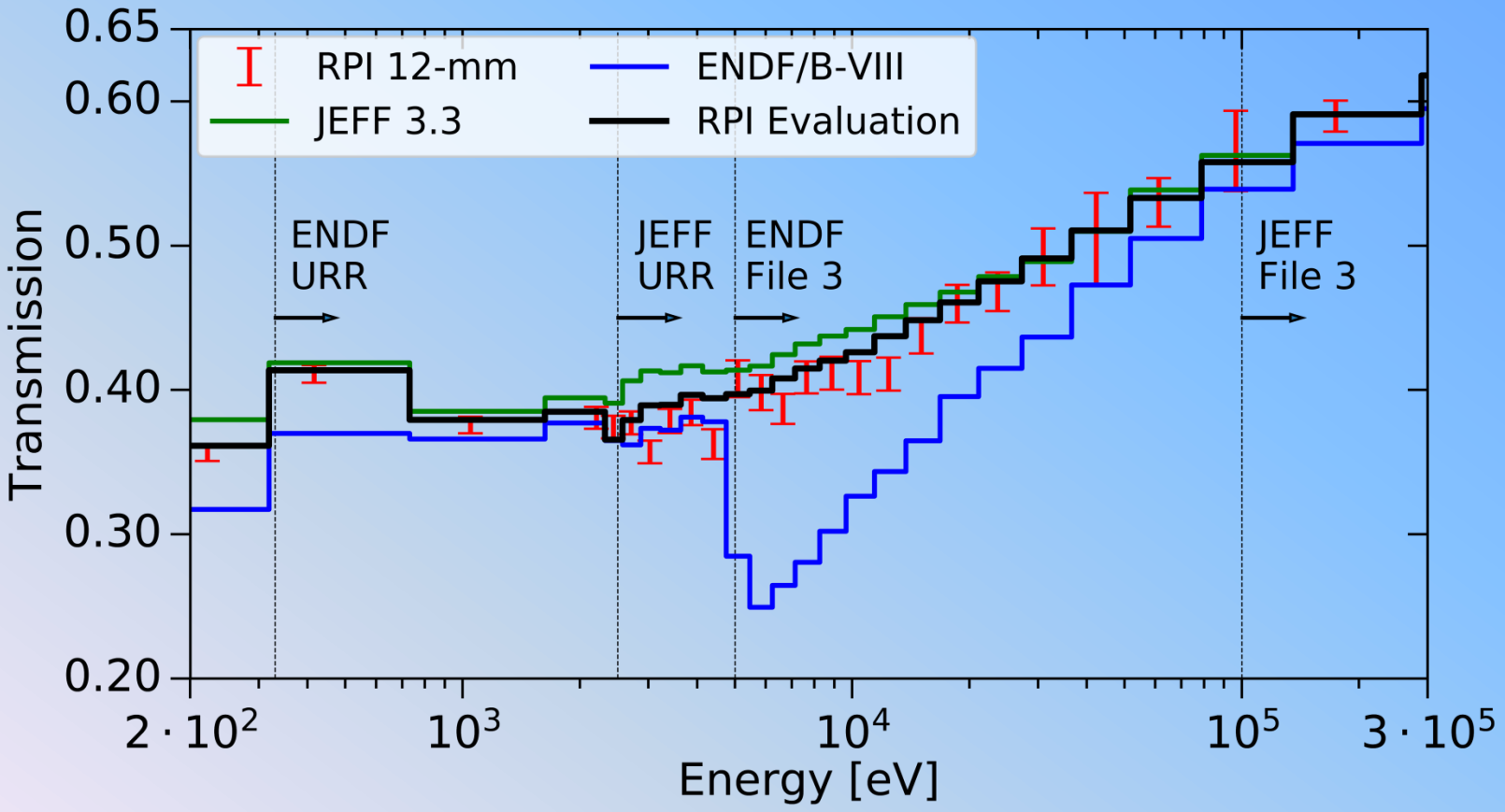


E-regions fit:

- 2-10 keV
- 10-45 keV
- 45-120 keV

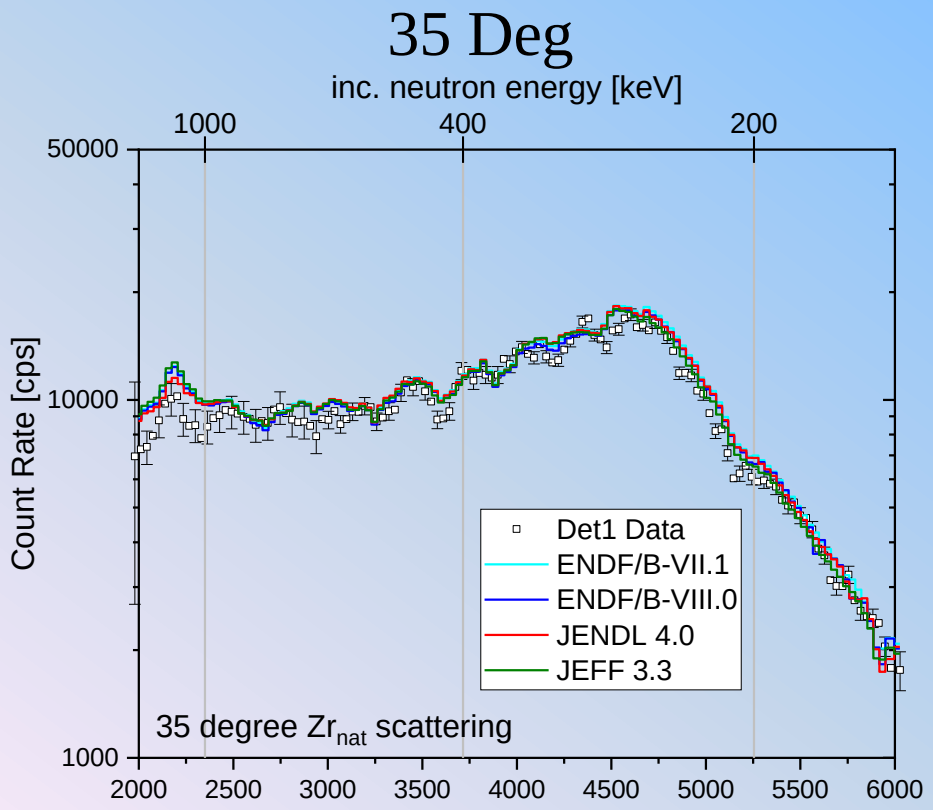
RPI Evaluation: Updated JEFF-3.3

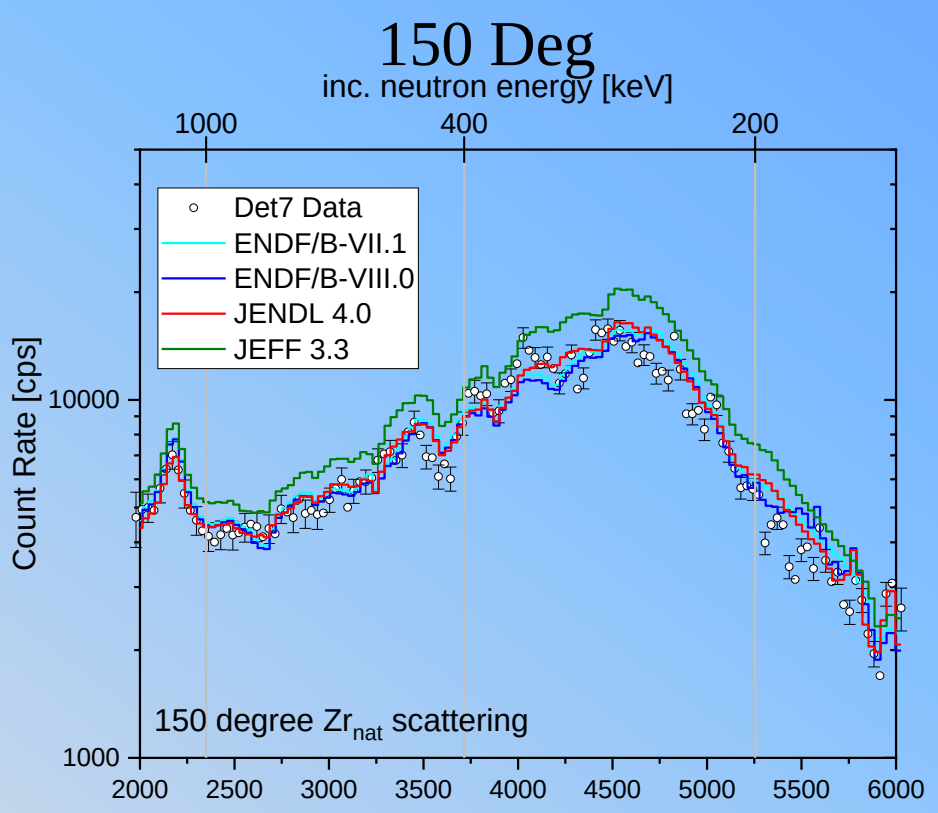
- Updated RRR and URR parameters
- Very sensitive to a_c, D and other $\langle Pars \rangle$
- Using the RPI evaluation we can improve agreement with measured data



Zirconium Scattering Conclusions

- Differences between evaluations between 0.1 – 1 MeV
- The extended RRR in ENDF/B-VIII and JENDL 4.0 better reproduces the experimental data





Rensselaer

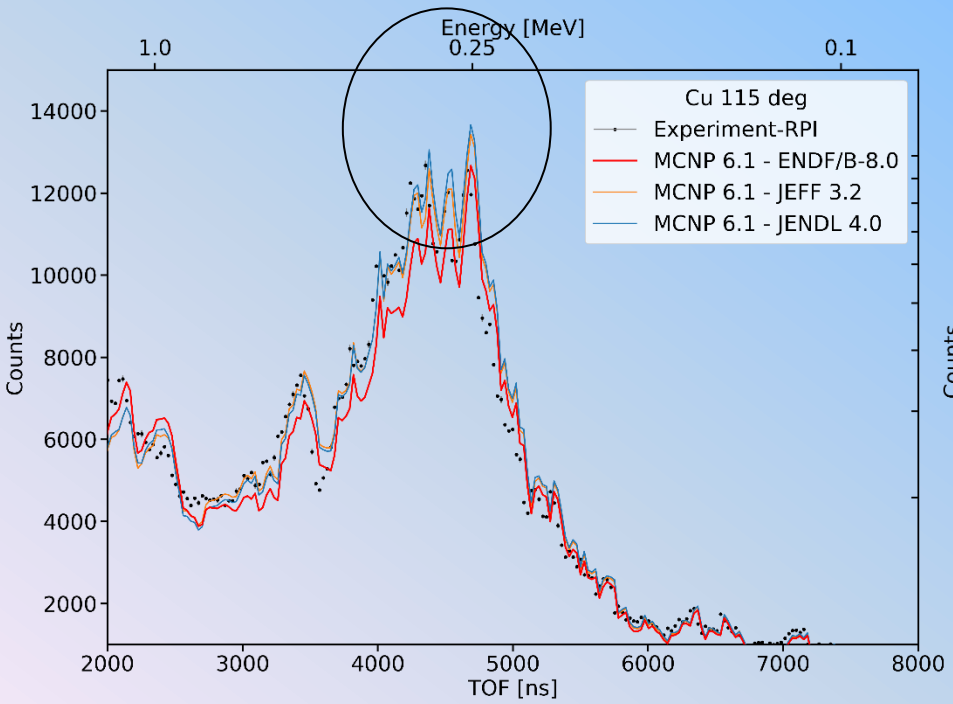
NCSP NUCLEAR CRITICALITY SAFETY PROGRAM

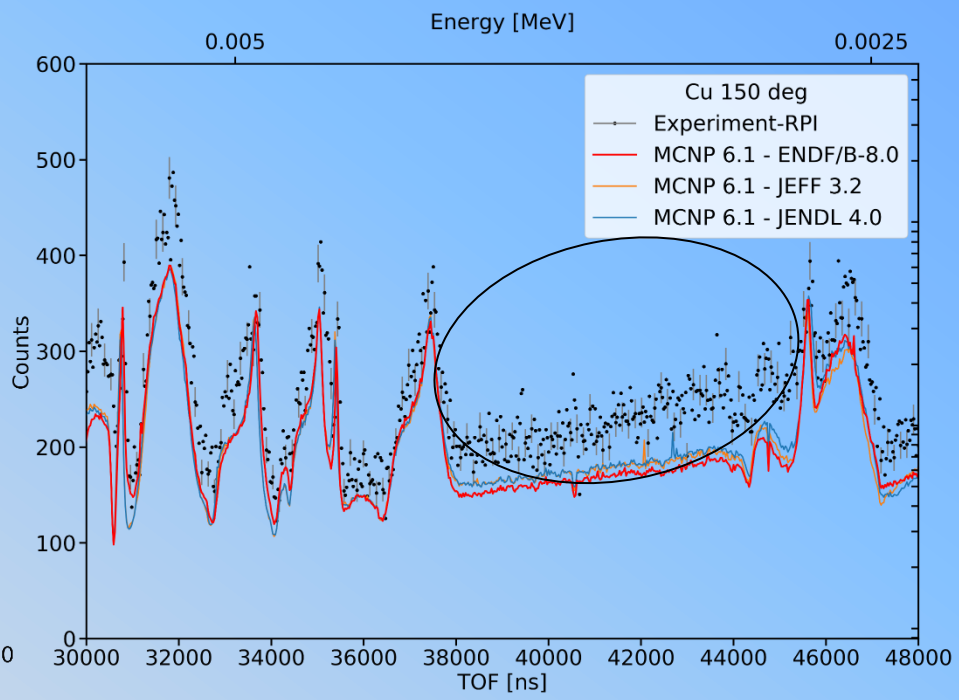
NAVAL NUCLEAR LABORATORY

linac The Gaerttner LINAC Center

Copper Scattering Closer Look

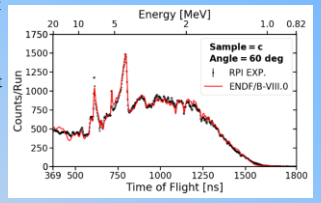
- Closer look shows some discrepancies between experiment and evaluations at the low and high keV energy range
  - Near 250 keV differences between evaluations at some angles
  - Near 3 keV the evaluations seem low at all angles

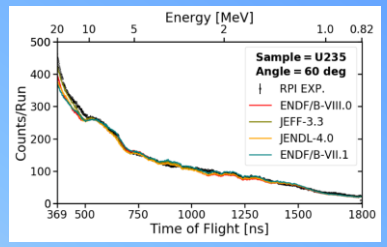


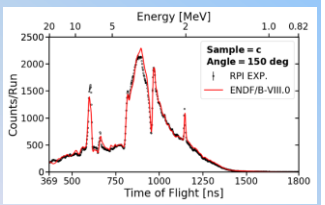


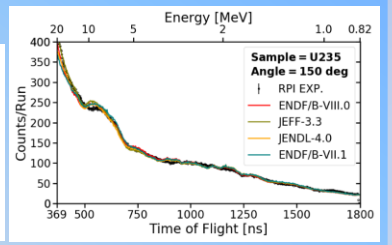
^{235}U results (full room simulation)

- Used one factor to normalize the simulation to experiment of both carbon and ^{235}U
- Carbon is in good agreement (some deviations at resonance peaks)
- For E<10 MeV ^{235}U show good agreement between experiment and simulation
- Both angles show differences between 4-8 MeV
- Below 10 MeV all evaluations are very similar.
- More angles are available



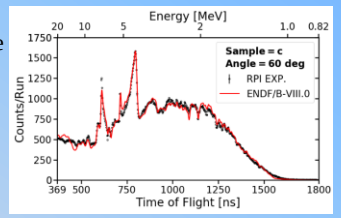


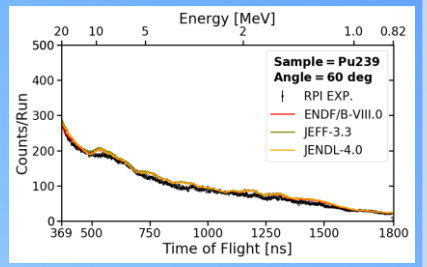


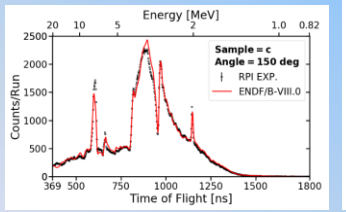


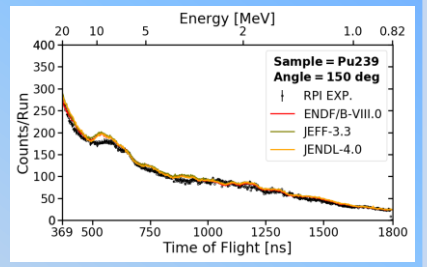
^{239}Pu results (full room simulation)

- The ^{239}Pu neutron emission yield is similar in shape to the ^{235}U yield
- The simulation is higher than the experimental data.
- Carfeul attention to the encapsulation of this sample









Recent work on neutron cross section standards at NIST

- **Update on all standard isotopes was given (see full talk on CSEWG web site)**

The Neutron Cross Section Standards

Reaction	Energy Range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV
^{6}Li(n,t)	0.0253 eV to 1 MeV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n,n)	10 eV to 1.8 MeV
Au(n,γ)	0.0253 eV, 0.2 to 2.5 MeV, 30 keV MACS
^{235}U(n,f)	0.0253 eV, 7.8-11 eV, 0.15 MeV to 200 MeV
^{238}U(n,f)	2 MeV to 200 MeV

Carlson's Summary

Summary-what is needed

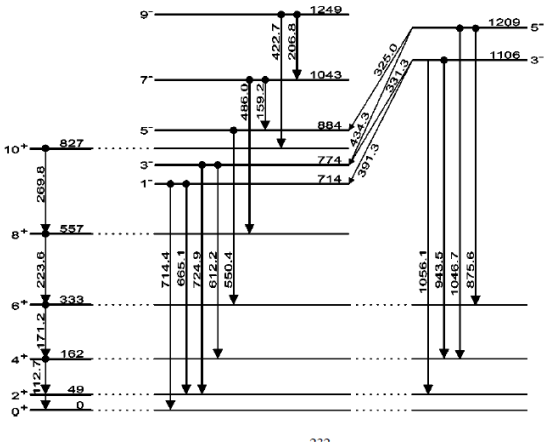
- Improved experimental work is necessary for all the standards
  - Especially the boron and lithium standards so the upper energy bound can be increased
    - Also for gold capture that has some of the largest uncertainties for the standards
- Extension of the hydrogen standard to about 150 MeV and possibly higher (work is underway by Hale and Paris)
  - It is now 20 MeV but there are cross section ratio data to much higher energies
  - Note that changes to a standard are not allowed for a given version but extensions are allowed
- Additional work beyond the ^{239}Pu(n,f) work of Neudecker for inspection of uncertainty sources for standards measurements.
- Further work on unrecognized sources of uncertainty
  - Inspection of data sets for unrecognized sources of uncertainty and correlations in data
- Consider improved evaluation techniques for the standard cross sections

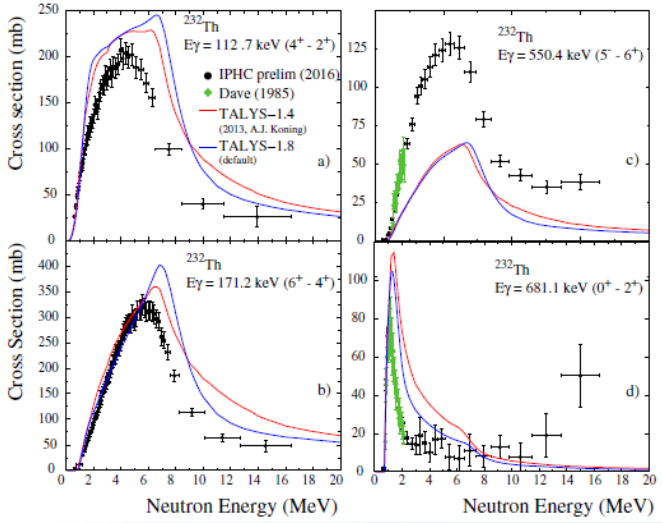
Measurements of branching ratios in U-238. (BNL)

- **Improving the double-differential $^{238}U(n,n'\gamma)$ cross section using neutron-gamma coincidences**

Motivation

Merger of nuclear structure and nuclear reaction physics





Branching ratios essential to determine cross section from off-yrast states

Maëlle Kerveno[1,]

EPJ Web of Conferences **146**, 11012 (2017)

Isn't ^{238}U well studied?

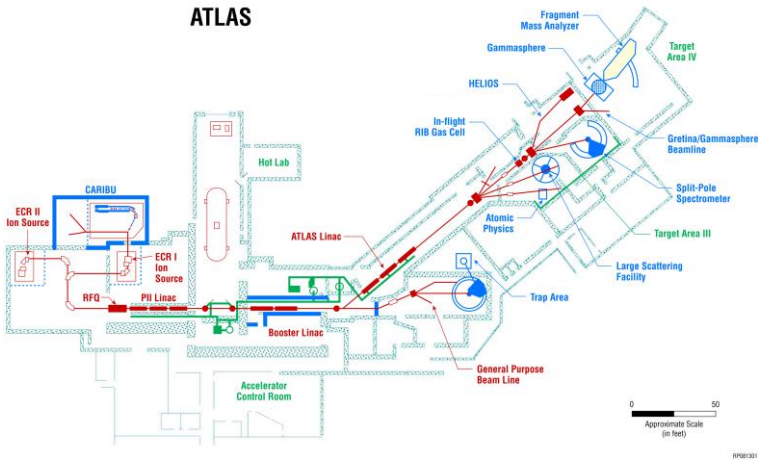
E_γ †	I_γ ‡	E_i(level)	J_i^π	E_f	J_f^π	Mult. §
324		1151	6^-	827.0	5^-	
329 e		2675.2	16^+	2346.4	14^+	
332		2502	15^+	2170	13^+	
333		2751	(17^-)	2418	(15^-)	
338.8 & 4		1415.2	14^+	1076.4	12^+	
346		2991	(16^+)	[illegible]	(14^+)	
347.5 & 4		2306.4	[illegible]	1958.9	15^-	
350		[illegible]	16^+	2333	14^+	
352		1318.0	8^-	966.4	7^-	
354 #	0.49	1414	2^+	1060.27	2^+	E2
355		2744	18^-	2389	16^-	
356		2712	(16^+)	2356	(14^+)	
356 e		3031.2	18^+	2675.2	16^+	
357.5 # 6	7.1 3	1037.24	2^+	680.17	1^-	
365		2867	17^+	2502	15^+	
368 e		2675.2	16^+	2306.4	17^-	
369		3120	(19^-)	2751	(17^-)	
372.9 & 4		1788.2	16^+	1415.2	14^+	
374.8 & 4		1150.4	9^-	775.7	10^+	
377		1528	10^-	1150.4	9^-	
377		3368	(18^+)	2991	(16^+)	
380 e		3411.2	20^+	3031.2	18^+	
382		3065	18^+	2683	16^+	
382.7 & 4		2689.0	19^-	2306.4	17^-	
383		3095	(18^+)	2712	(16^+)	
384		3128	20^-	2744	18^-	
387 e		2346.4	14^+	1958.9	15^-	
397.0 # 10	3.75 19	1128.8	(2^-)	732.06	3^-	
397		3264	19^+	2867	17^+	
399		1778	12^-	1378.6	11^-	
400 e		2048.7	12^+	1649.0	13^-	
400 e		3811.2	22^+	3411.2	20^+	
400.6 #	0.68	1530.1	2^+	1128.8	(2^-)	
401		3521	(21^-)	3120	(19^-)	
402.6 & 4		2190.9	18^+	1788.2	16^+	
405		3773	(20^+)	3368	(18^+)	

Only a handful of intensities reported

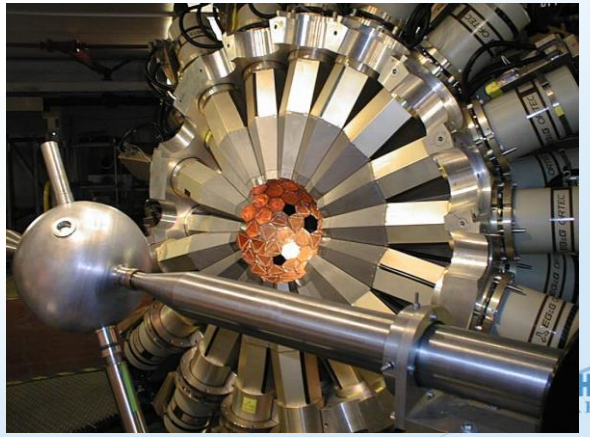
E. Browne, J.K. Tuli, Nucl. Data Sheets 127, 191 (2015)

BROOKHAVEN NATIONAL LABORATORY

Gammasphere at Argonne National Lab



100 HPGe detectors
Compton-suppressed
High coincidence efficiency



Preliminary Results

- Branching ratios for 22 levels in ^{238}U
- Cross checks between different beams
- Also will analyze neutron transfer, ^{237}U, ^{236}U

E_{level} (keV)	J_i^π	E_γ (keV)	BR
*680	1^-	634.6	100
		679.6	85(10)
731	3^-	583.0	91(7)
		686.4	100
826	5^-	519.0	65(4)
		678.0	100
*966	7^-	447.7	49(5)
		658.4	100
1150	9^-	183.6	21(2), 5.1(4)
		374.5	100, 25(2)
		632.2	100, 100
1378	11^-	302.5	24(5), 13(2)
		228.1	100, 5(7)
		602.5	100, 100
1649	13^-	233.3	16.8(9), 7.7(4)
		269.7	100, 46(2)
		572.2	100, 100
1959	15^-	309.5	96(5)7
		543.2	100
2306	17^-	347.0	100
		517.8	50(3)
2689	19^-	382.0	100
		497.9	32(1)
3104	21^-	414.4	100
		484.9	15(1)
3547	23^-	443.2	100
		479.4	11(1)

E_{level} (keV)	J_i^π	E_γ (keV)	BR
*950	2^-	218.0	43(17), 32(2)
		269.7	100, 74(29)
		904.7	100, 100
1028	4^-	295.5	100
		879.1	28(4)
1151	6^-	122.9	27(2), 100
		322.9	100, 100
		842.9	98(10), 27(2)
1318	8^-	167.0	100
		351.0	57(3)
1528	10^-	209.5	100
		376.7	9.6(7)
1778	12^-	249.5	100
		398.2	12.5(7)
1786	10^-	257.8	100
		636.4	29(7)
2048	12^-	261.5	100, 100
		270.5	17(1), 100
		669.7	16(2), 91(11)
2345	14^-	281.0	11(1), 79(10)
		297.2	100, 100
		697.4	100, 14(1)
2673	16^-	287.4	21(2)
		328.2	100

For more - see CSEWG web site

https://indico.bnl.gov/event/6642/timetable/#20191104.detailed

- **Measurements related to:**
  - Fission product yields
  - Internal Conversion Coefficients Precision Measurements
  - Decay Data Measurements for Applications