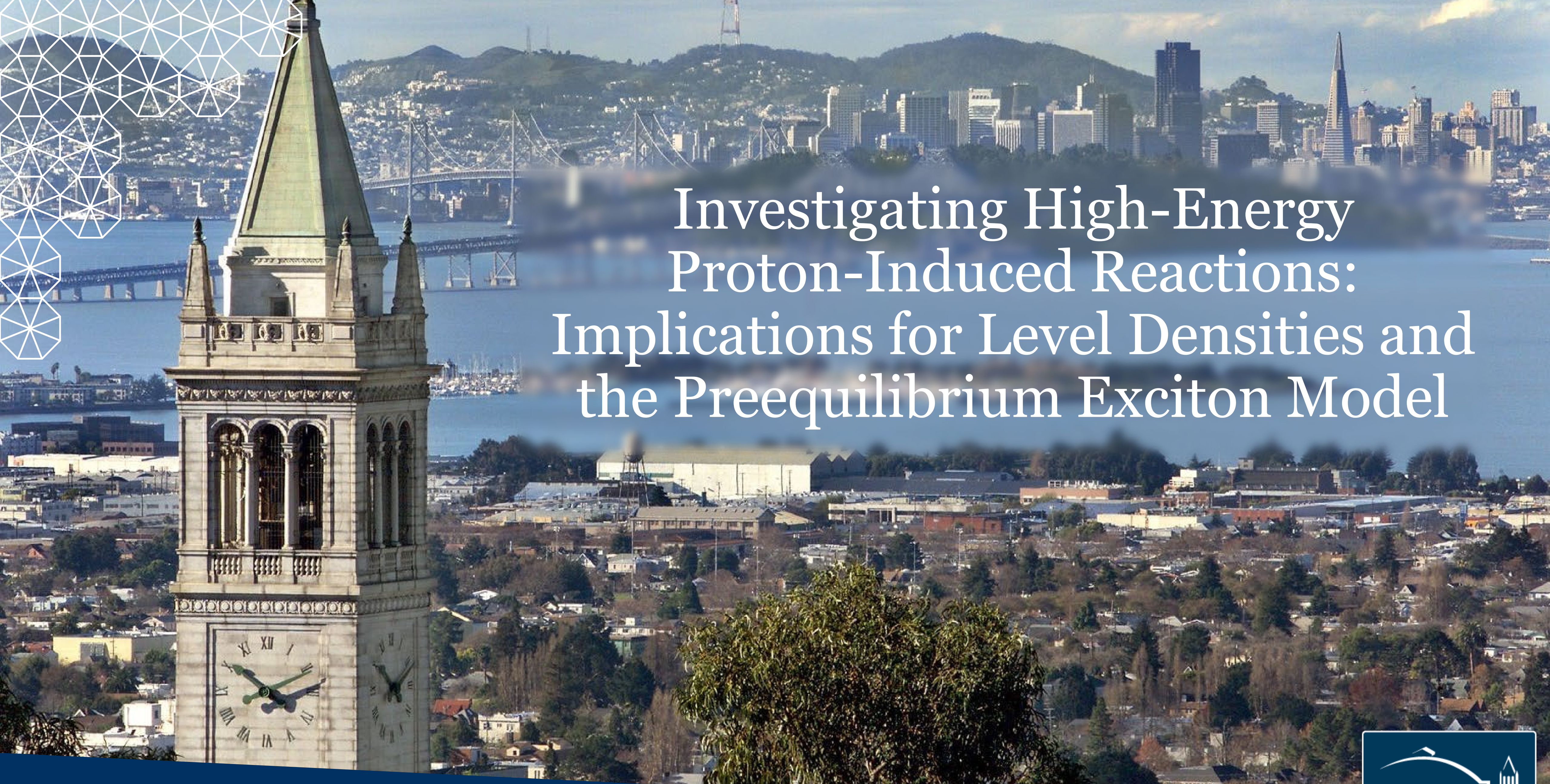
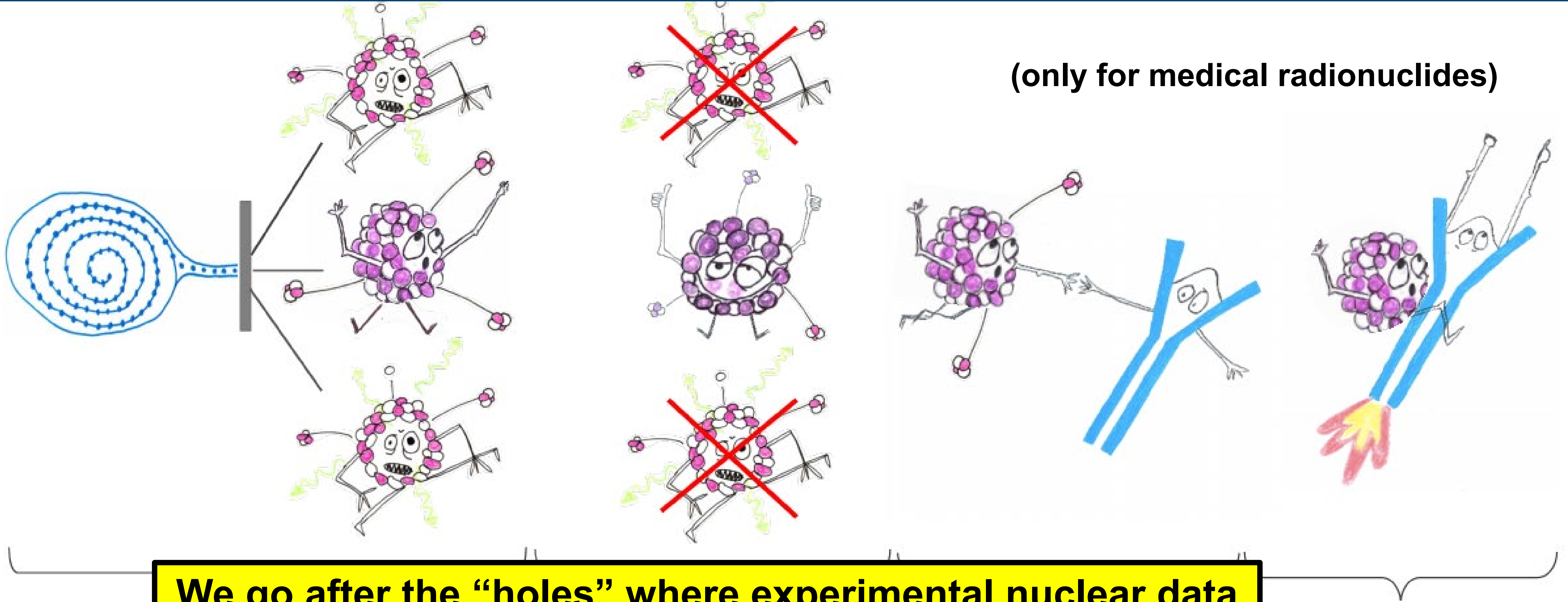


Investigating High-Energy Proton-Induced Reactions: Implications for Level Densities and the Preequilibrium Exciton Model

https://avoyles.github.io/
http://nucleardata.berkeley.edu

Andrew S. Voyles | 13 June 2023 | 16th Varenna Conference

Isotope Production (in a nutshell)



(only for medical radionuclides)

We go after the "holes" where experimental nuclear data do not exist by performing *targeted measurements* where there is a community-identified need!

Needs:

1

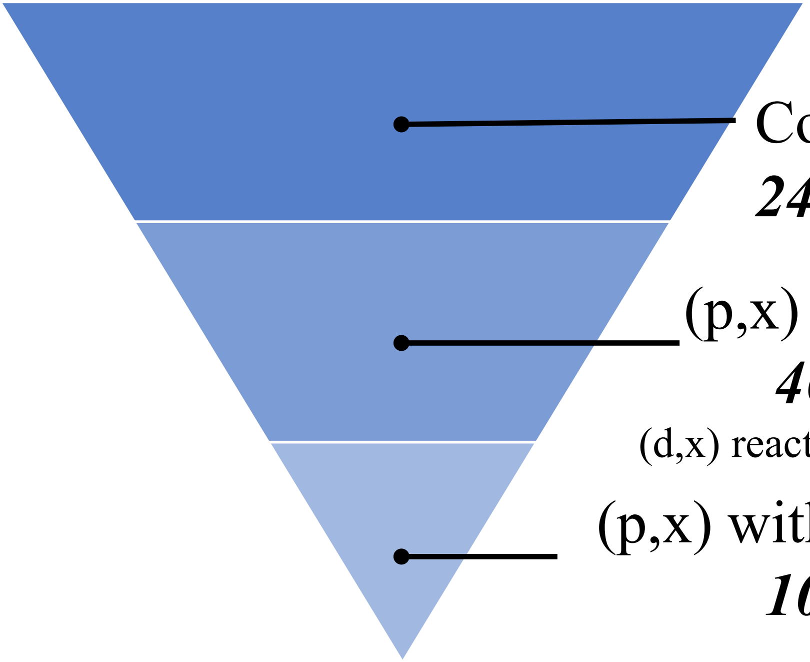
Tr

Cross sections

Decay data

4)Delivery

The Nuclear Data Pipeline



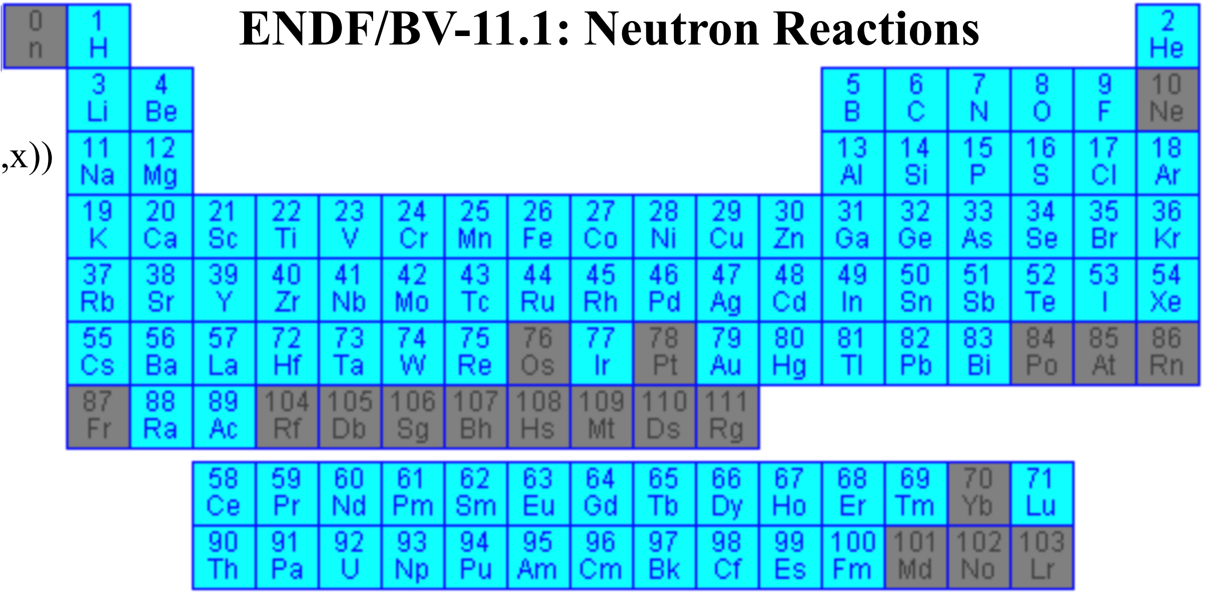
Compilation (EXFOR)
24 000 datasets (46% for (n,x))

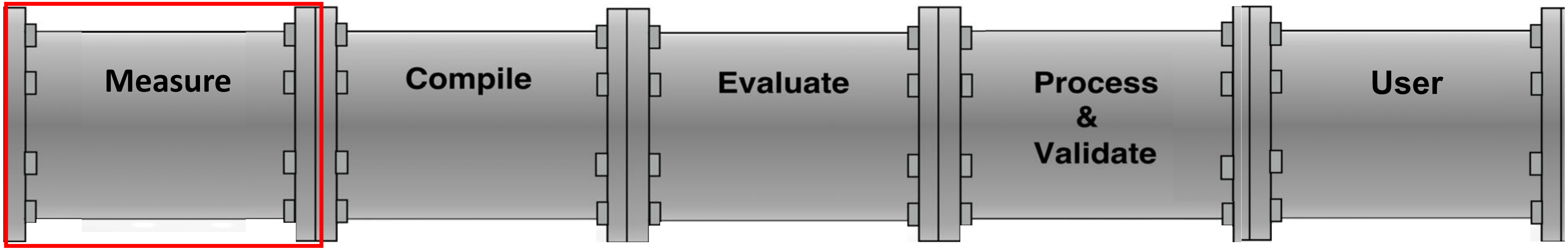
(p,x) reactions - 20%
4600 datasets

(d,x) reactions ***2000*** datasets – 9%

(p,x) with $E_p > 100$ MeV
10 datasets

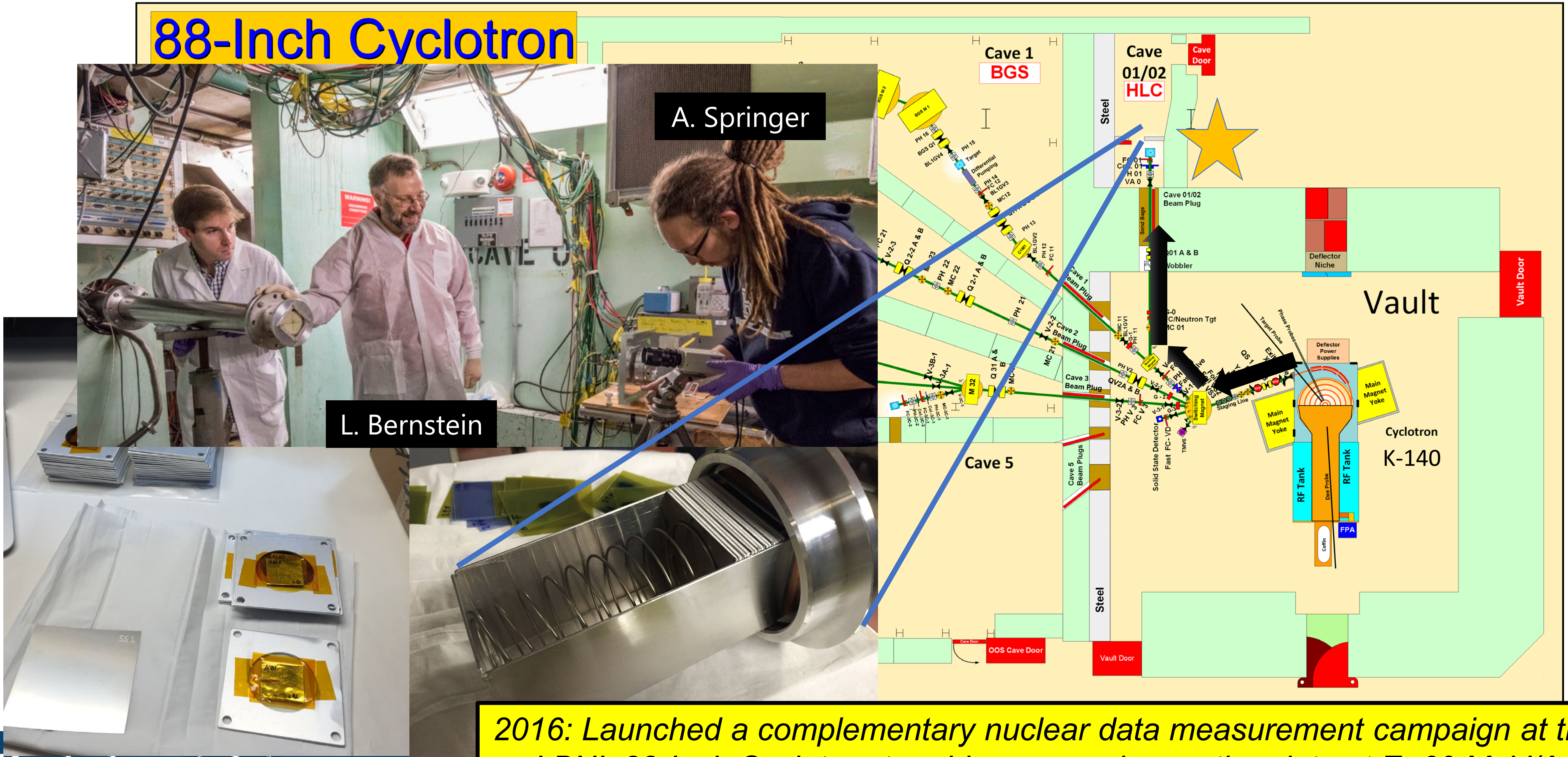
ENDF/BV-11.1: Neutron Reactions





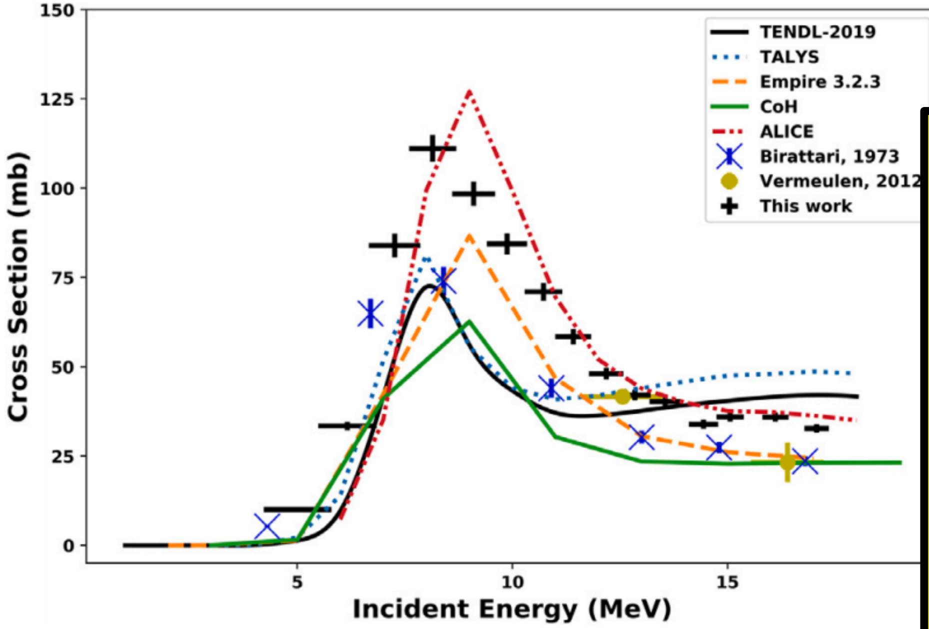
D.A. Brown, Nuclear Data Sheets, 148:1–142, 2018.
A.J. Koning, Nuclear Physics A, 744:15–76, 2004.

Stacked-Target Cross Section Measurements



2016: *Launched a complementary nuclear data measurement campaign at the LBNL 88-Inch Cyclotron to address gaps in reaction data at E<60 MeV/A*

A Few Recent Highlights…

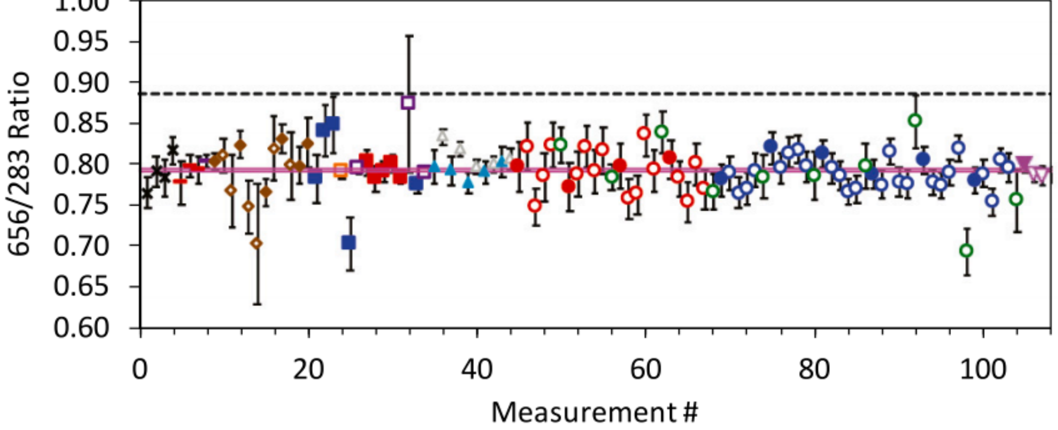


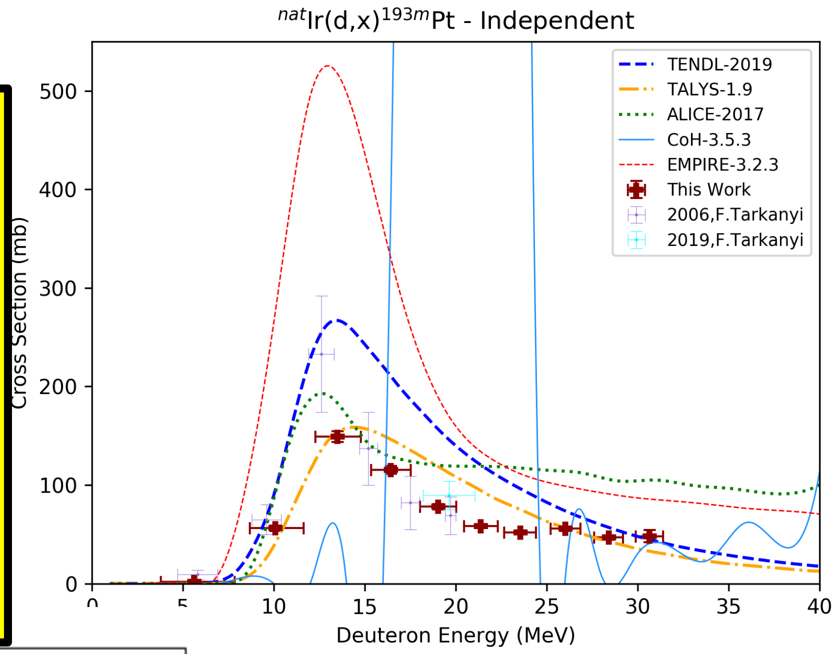
Gd(p,x)^{160}Tb & the "Tb Quartet"

Resolving γ intensity discrepancies

D.L. Bleuel, et al., Applied Radiation and Isotopes, 170 (2021) 109625

M.S. Basunia, et al., Physical Review C, 101 (2020) 064619



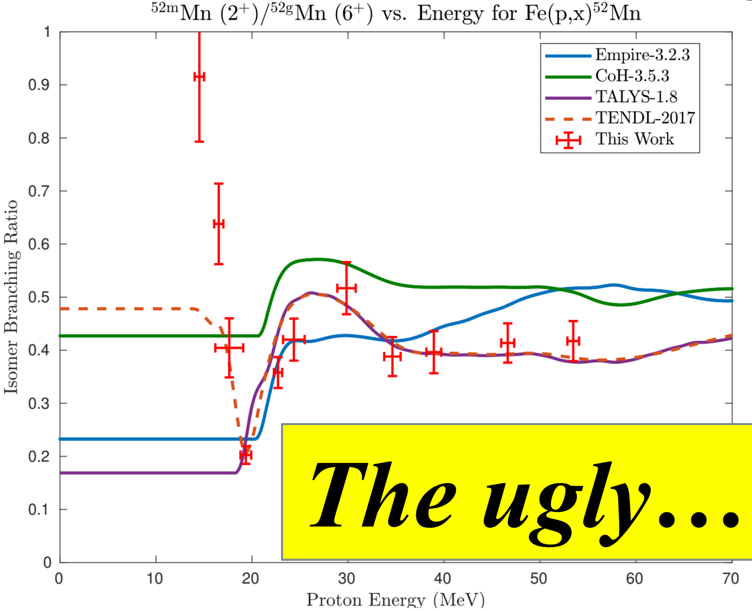


Ir(d,x)^{193m}Pt for targeted Meitner-Auger therapy

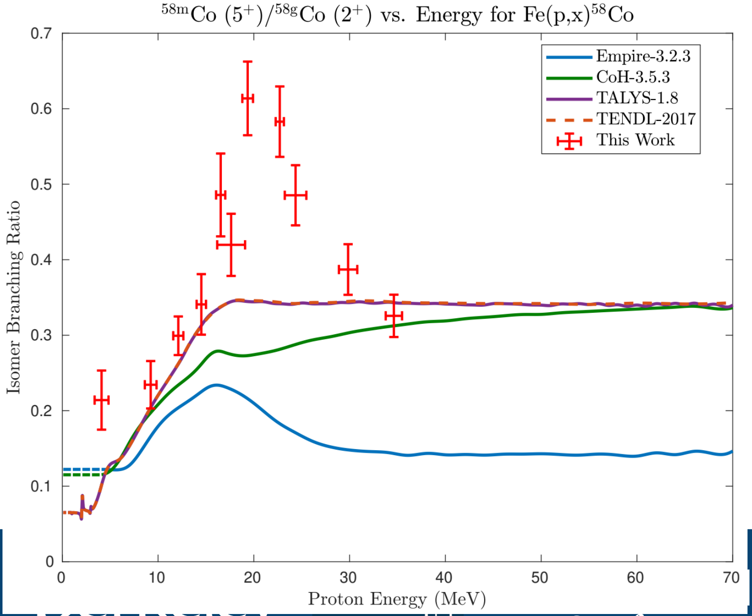
Forthcoming: 4 pathways for ^{225}Ac

R.K. Chapman, Applied Radiation and Isotopes, 171 (2021) 109647.
H.L.O. Ekeberg, *Nuclear Excitation Functions For Medical Isotope Production: Targeted Radionuclide Therapy via NatIr(d, x)193mPt*. MS thesis, U. Oslo. 2020.

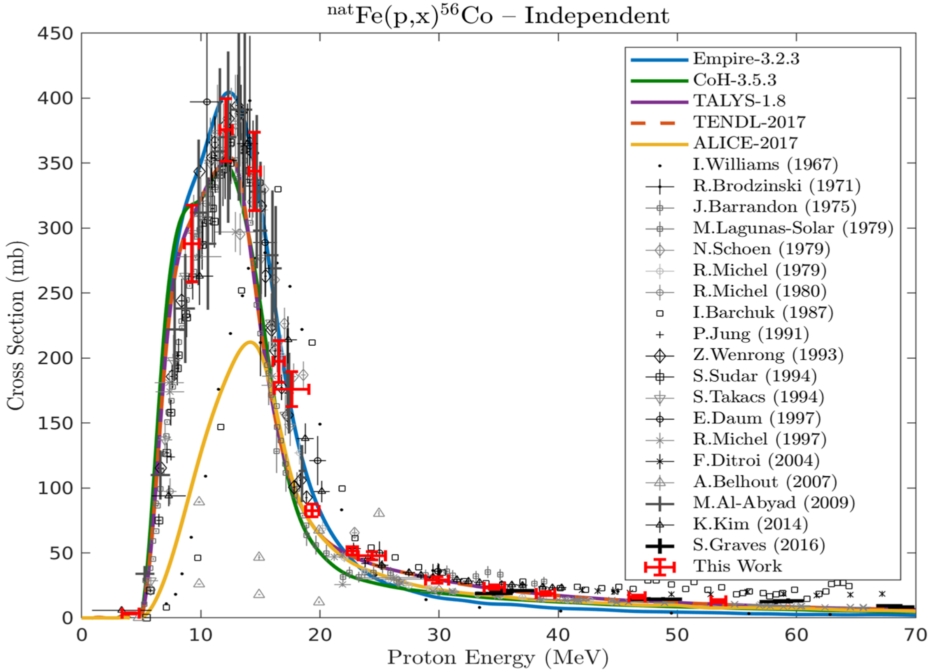
What If No Experimental Data Exist?

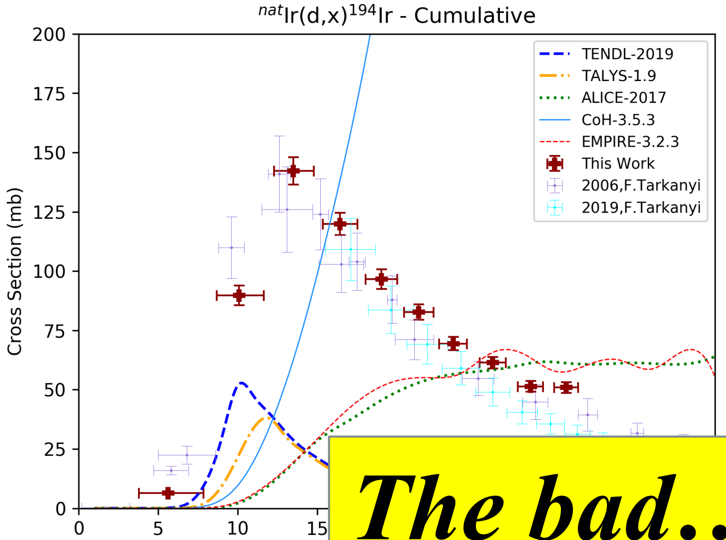


The ugly…

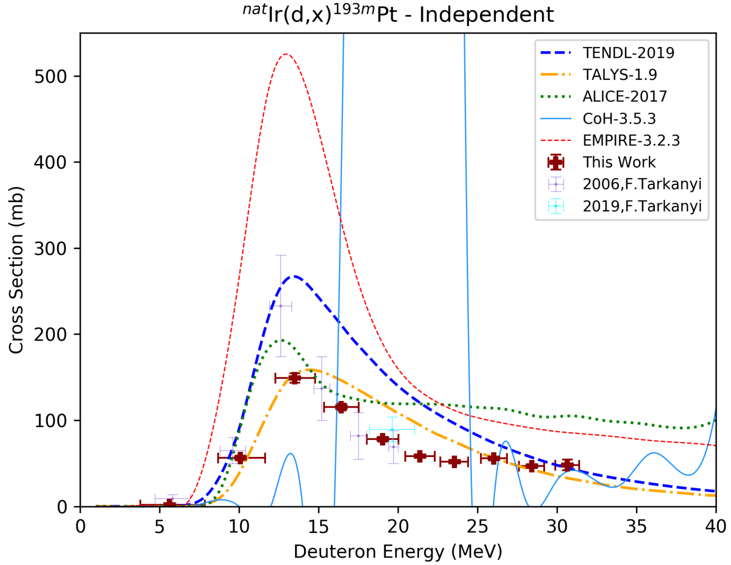


The good…





The bad…



16th Varenna Conference, 13 June 2023

A.S. Voyles, EPJ A, 57 (2021) 94
H.L.O. Ekeberg, M.S. Thesis 2020

Current nuclear data needs for applications
Phys. Rev. Res. 4, 021001 (2022)

Isotope Production Research

A Tri-lab collaboration has been formed between LBNL, LANL, and BNL to measure (p,x) reactions relevant to isotope production from threshold to 200 MeV *for primary isotopes of interest and their impurities*.

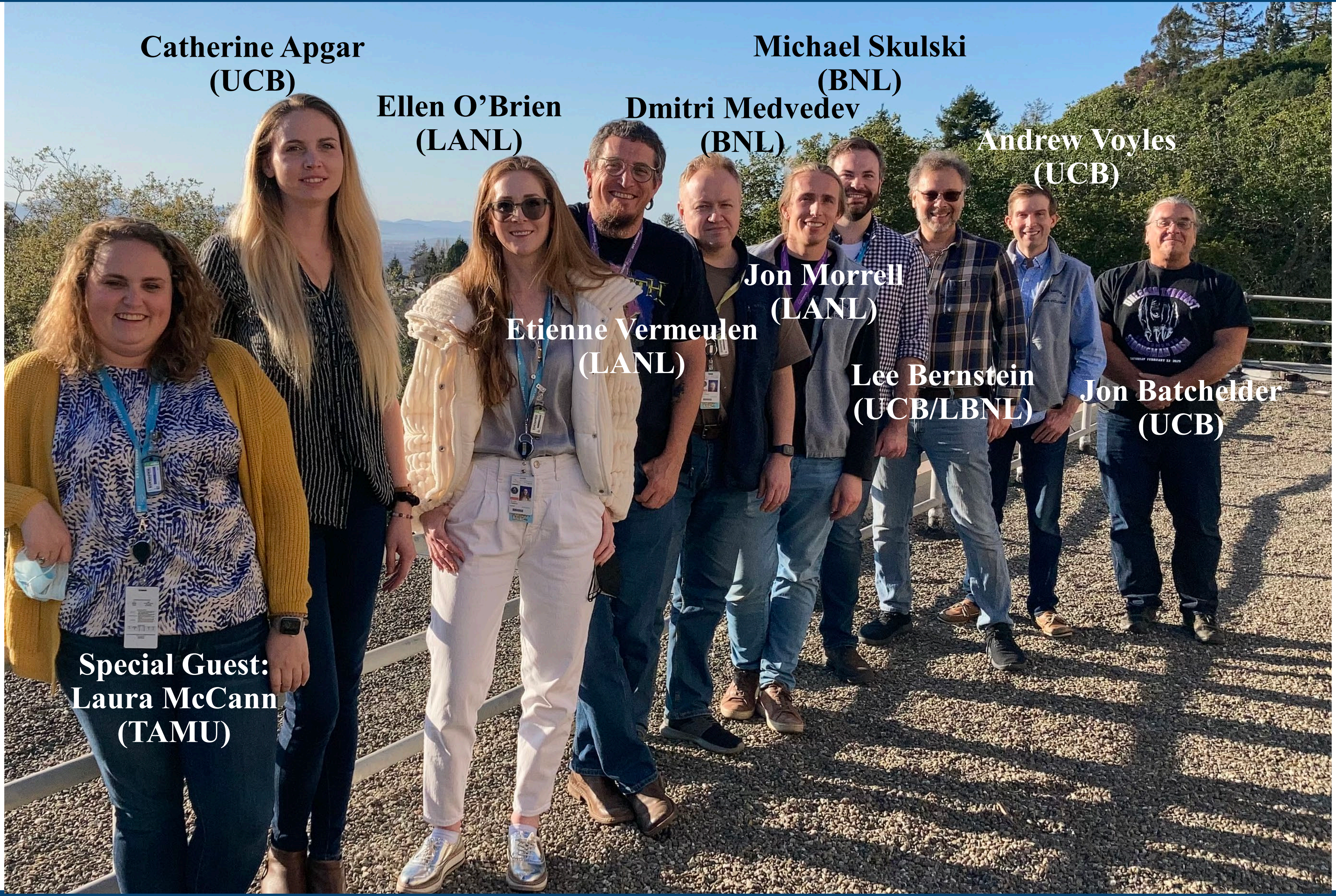
LBNL 88-Inch Cyclotron
$E_{p,max}$ = 60 MeV

LANL IPF
$E_{p,max}$ = 100 MeV

BNL BLIP
$E_{p,max}$ = 200 MeV

The unique strength of this group is its access to all the different irradiations facilities and expertise

The Tri-Lab Effort in Nuclear Data



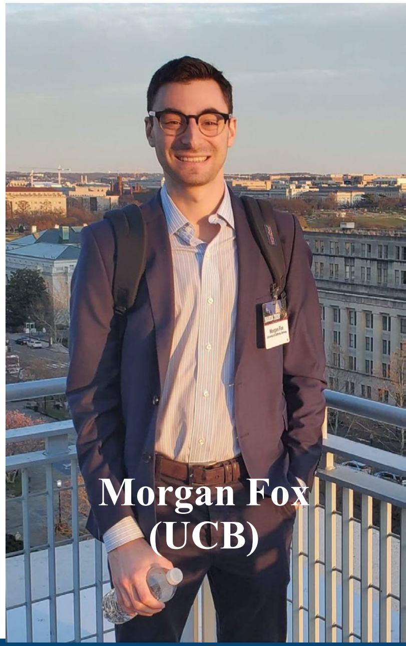
Not Pictured:

Eva Birnbaum (LANL)

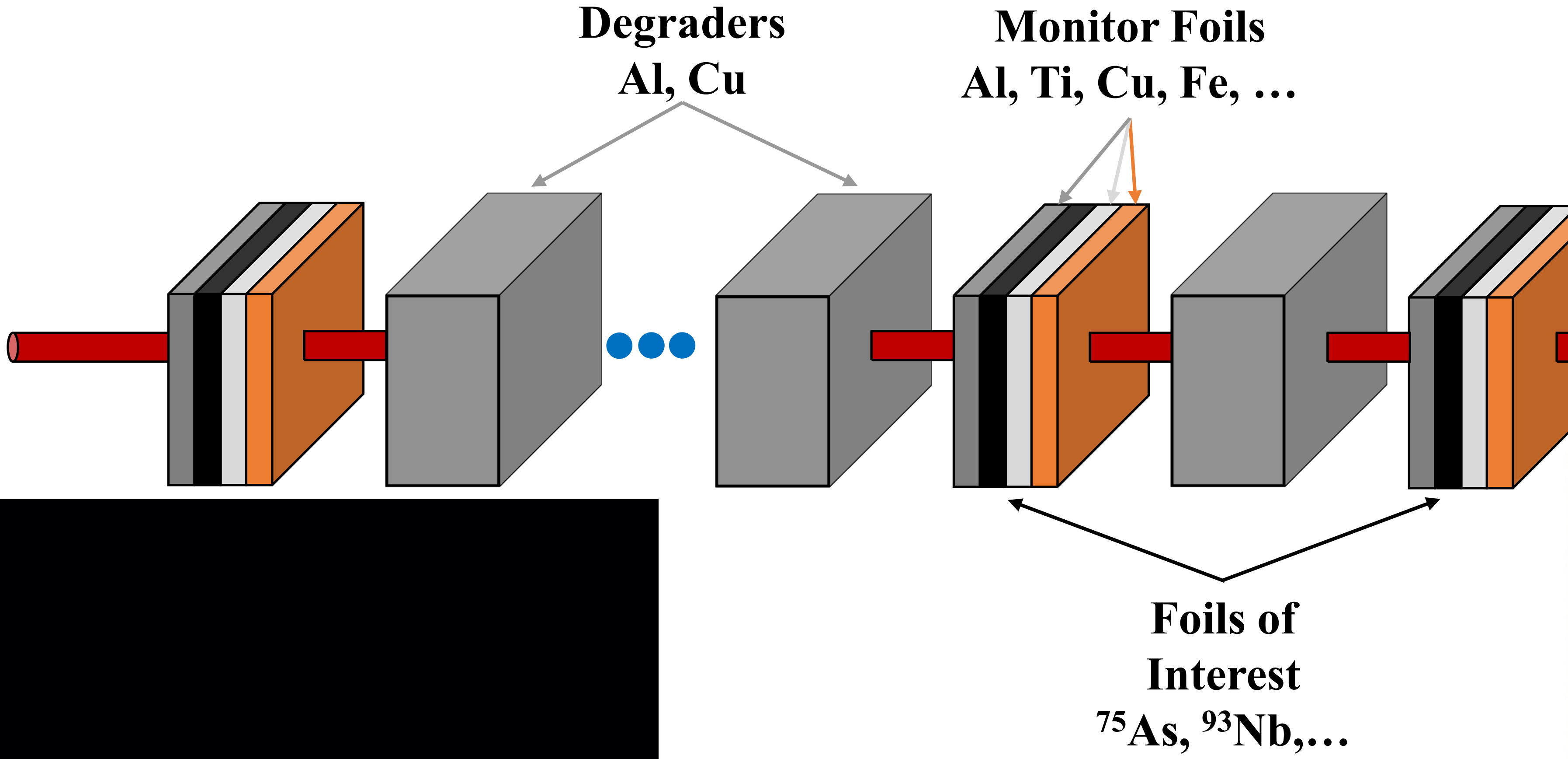
Cathy Cutler (BNL)

Amanda Lewis (UCB)

Arjan Koning (IAEA)



Stacked-Target Experimental Method

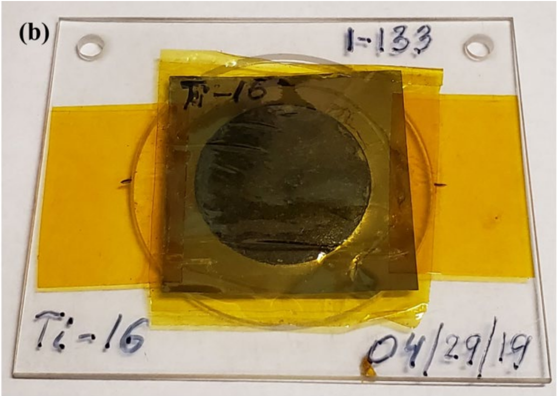


Degraders
Al, Cu

Monitor Foils
Al, Ti, Cu, Fe, …

H^+
Beam

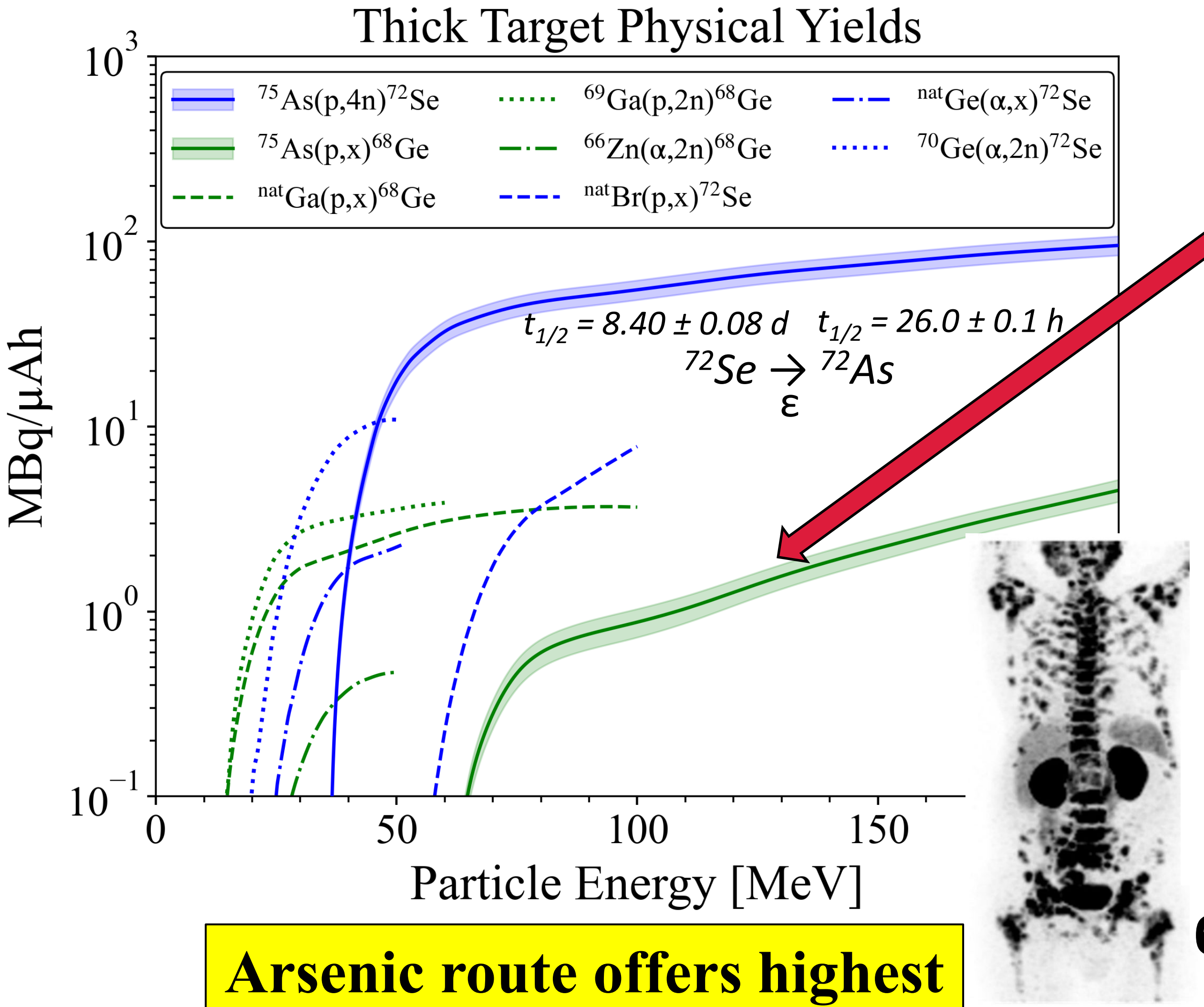
Foils of Interest
^{75}As, ^{93}Nb,…

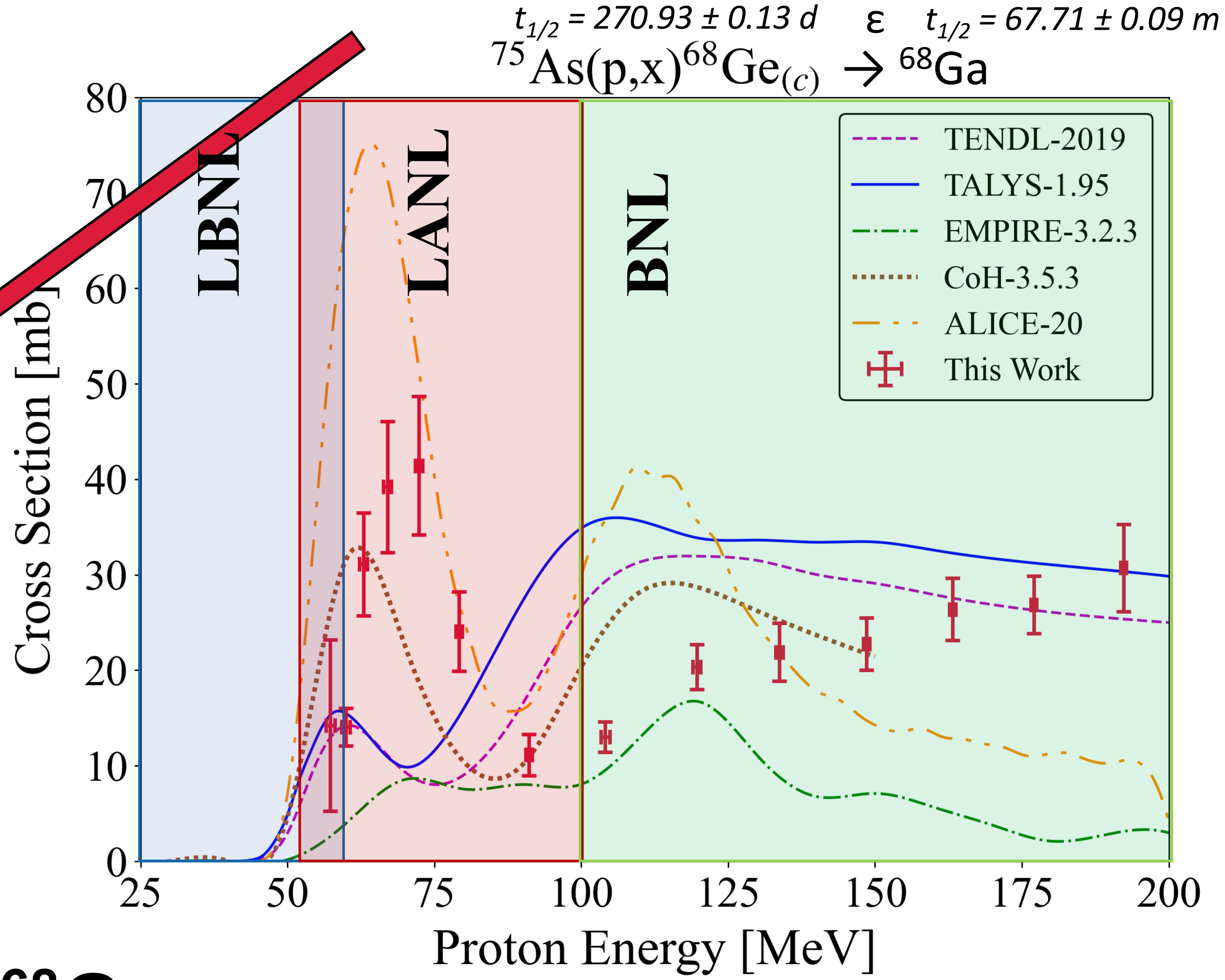


Check out Curie! (and help improve it!)
https://jtmorrell.github.io/curie/build/html/index.html

A.S. Voyles *et al.*, *NIM B 429 (2018) & EPJ A 57:94 (2021)*
J.T. Morrell et al., EPJ A 56:13 (2020)
M. B. Fox *et al.*, *PRC, 103(3):034601 (2021) & PRC 104, 064615 (2021)*

^{72}Se and ^{68}Ge Production





^{68}Ga

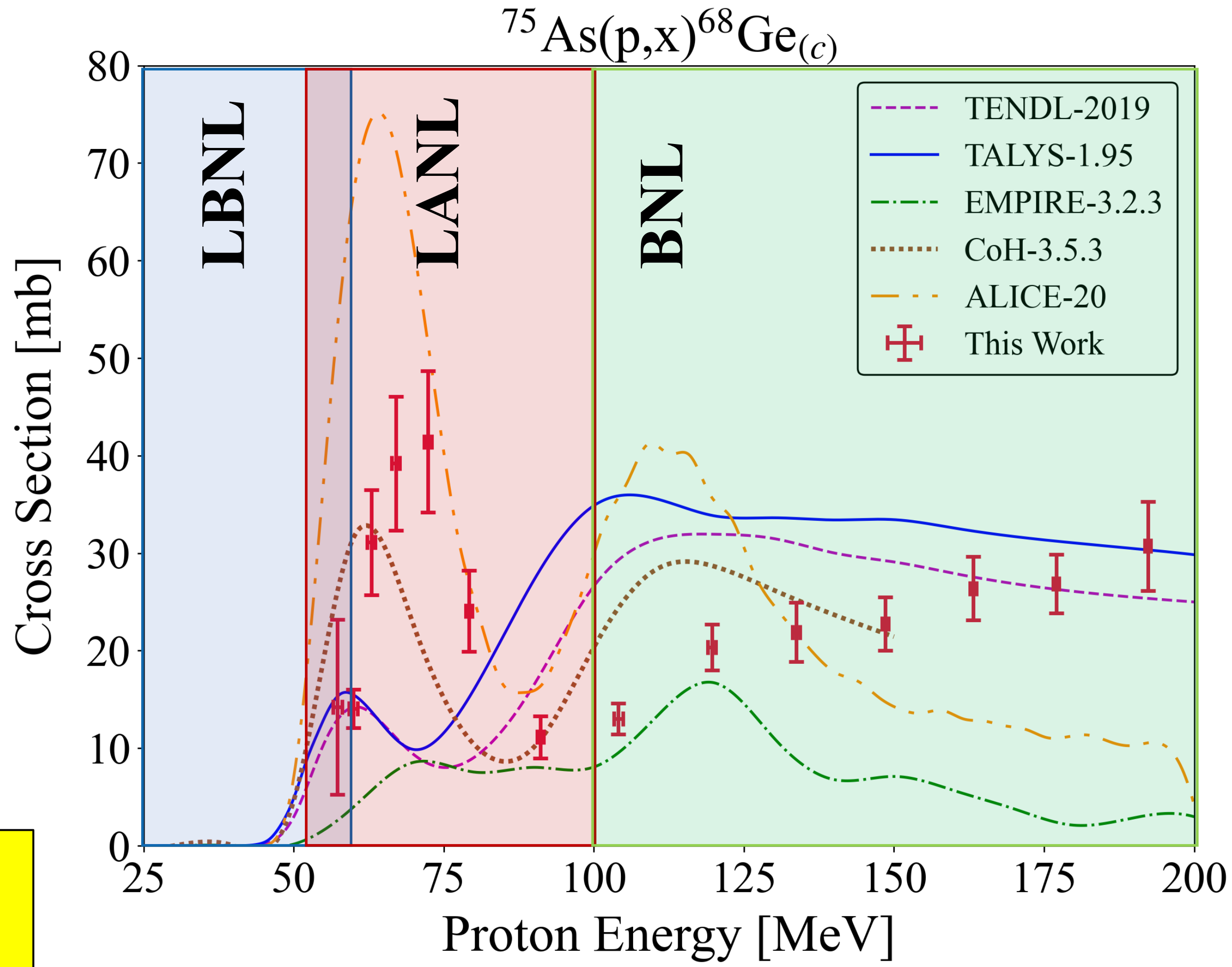
Arsenic route offers highest yield and purity for ^{72}Se

PRC 104, 064615 (2021)
J.Nuc.Med 57.12 (2016)

Nuclear Data Contributions – Medical and Models

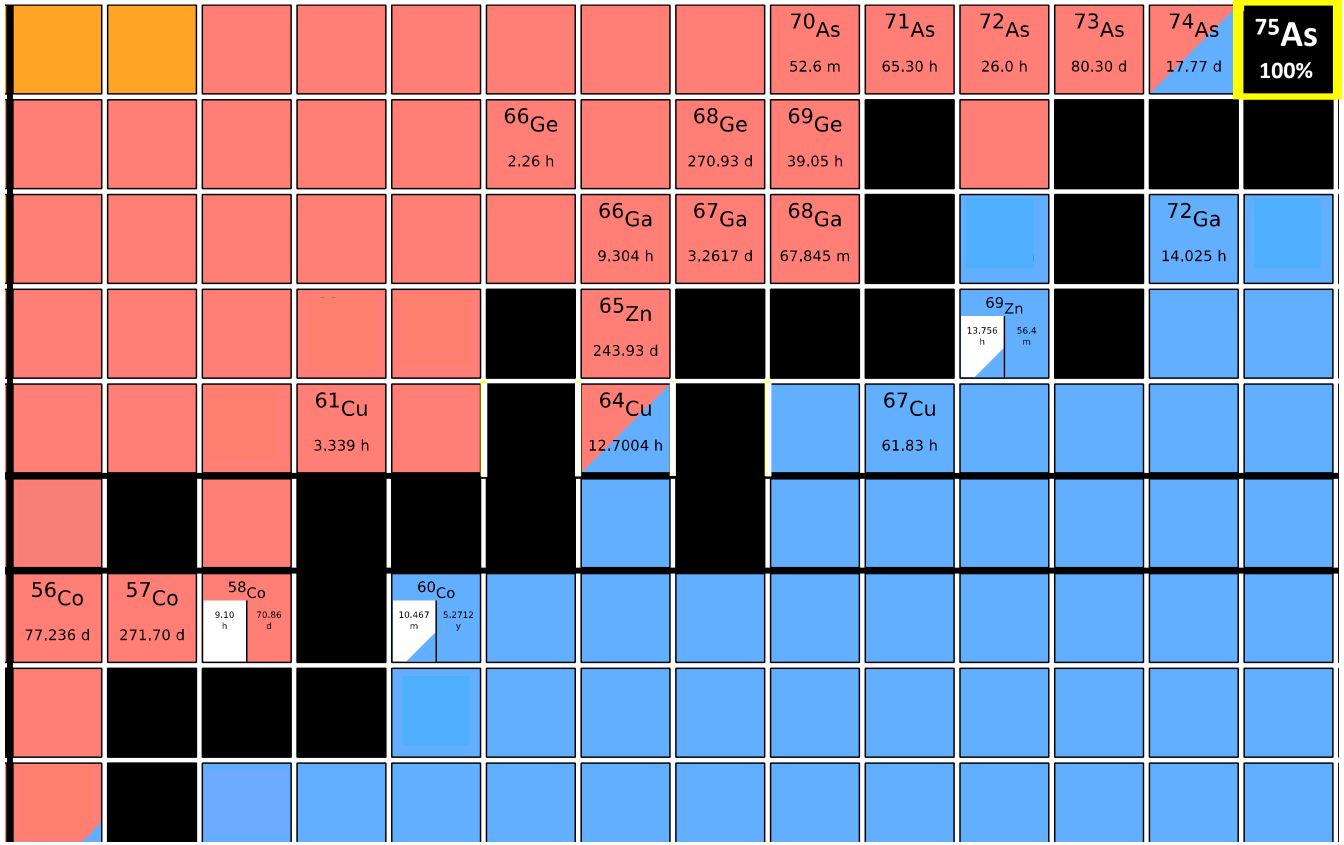
- These data add direct value for isotope production
- But we are also a nuclear data group
  - This is a large & self-consistent contribution of scarce data!
  - A valuable opportunity to study high-energy reaction modeling and evaluation

How do we improve modeling for high-energy proton-induced reactions?



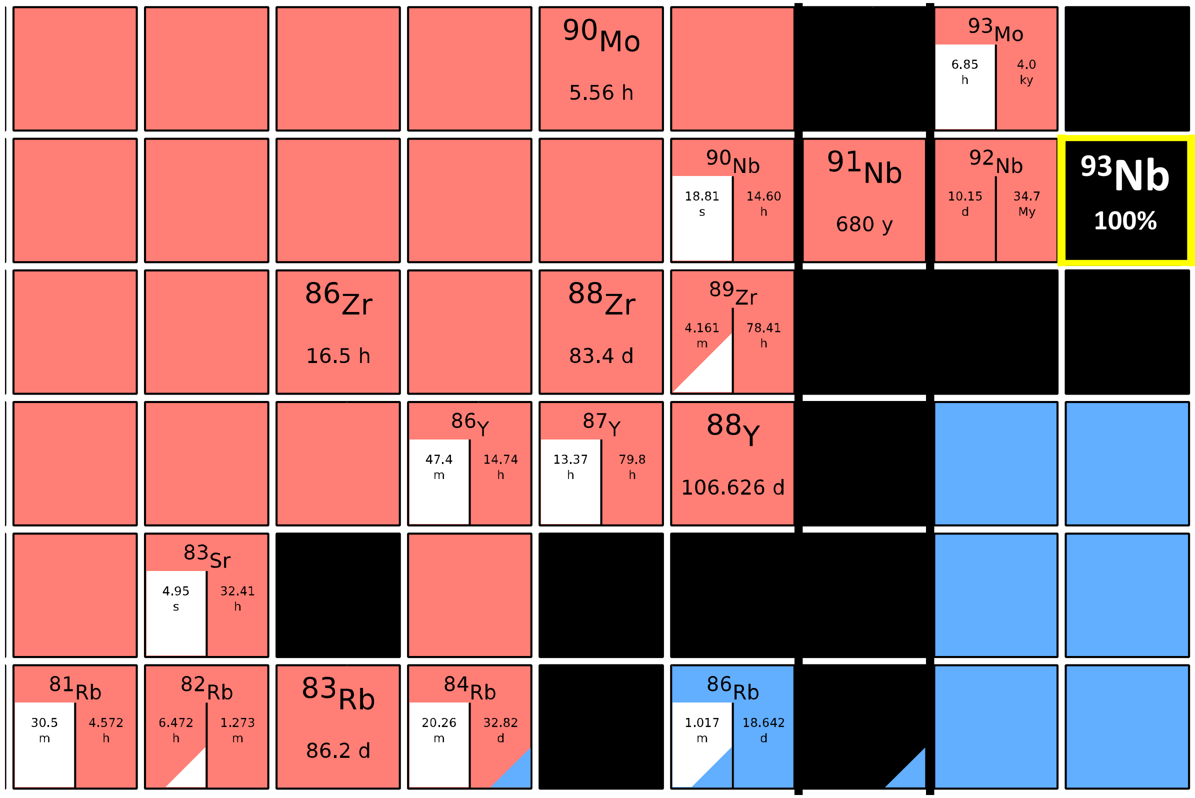
PRC 104, 064615 (2021)

Our first experiments involved the ^{93}Nb(p,4n) monitor channel and improving production of the ^{72}Se/^{72}As and ^{68}Ge/^{68}Ga generators



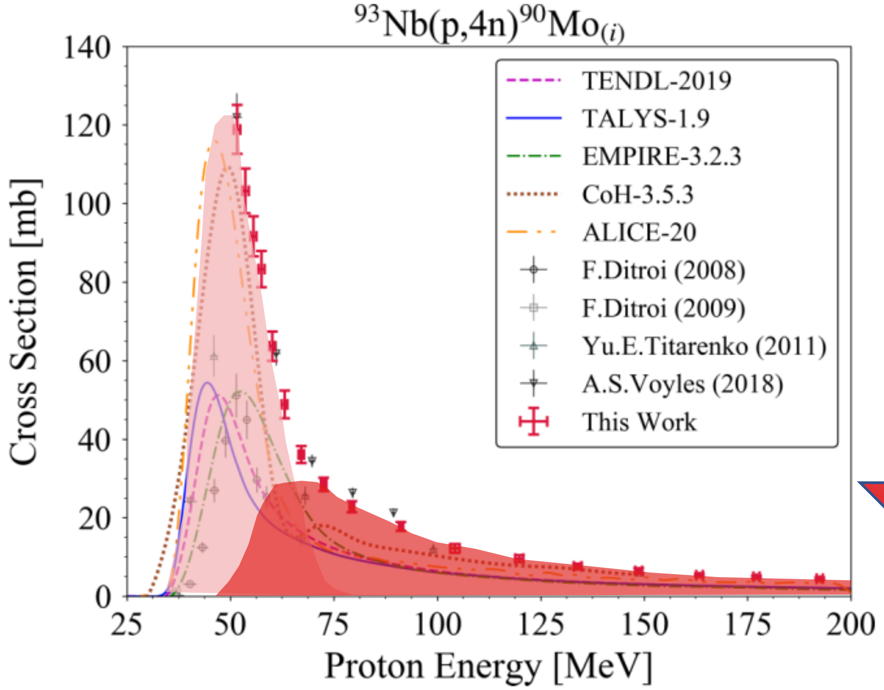
21 excitation functions for ^{75}As(p,x)

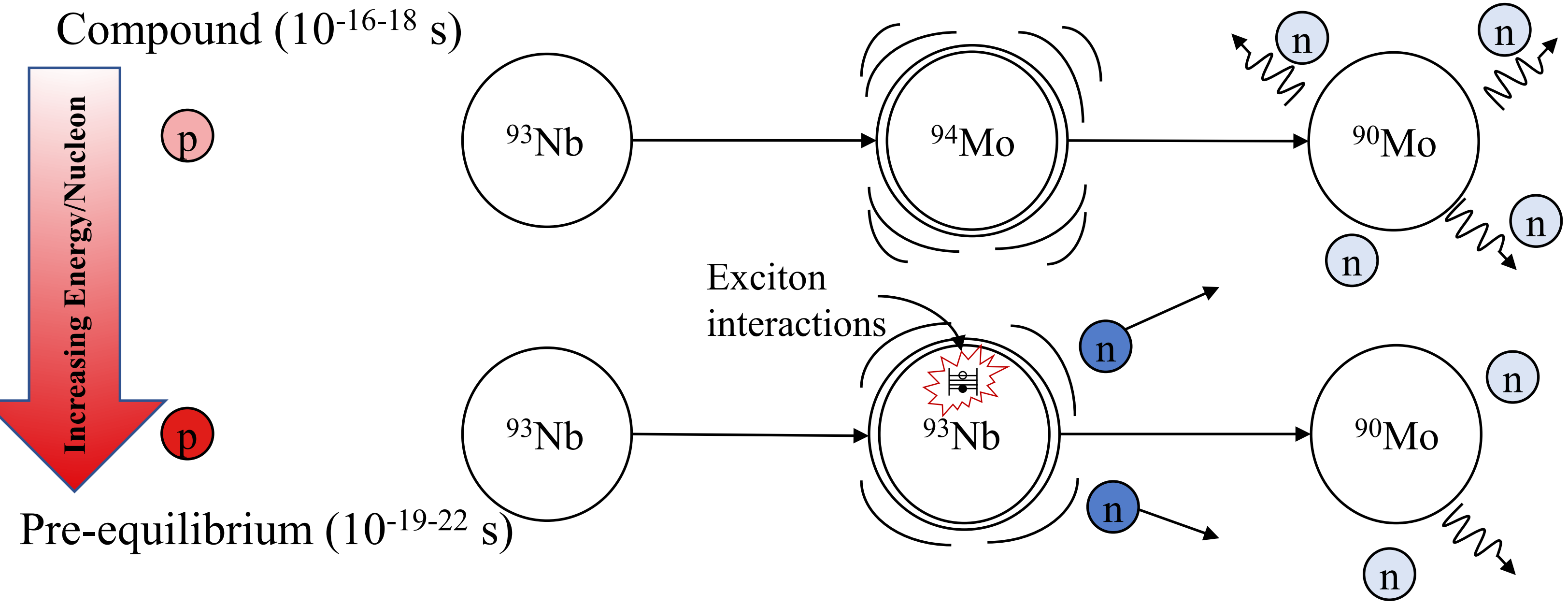
23 excitation functions for ^{93}Nb(p,x)



Impact Beyond "Better Fitting Lines"

- The goal is not surface level improvements in χ^2
  - The reflection of physics adjustments made and the process are vitally important pieces
- This is the start to an evaluation approach and the comments we make are substantial because they immediately become a basis for these regimes

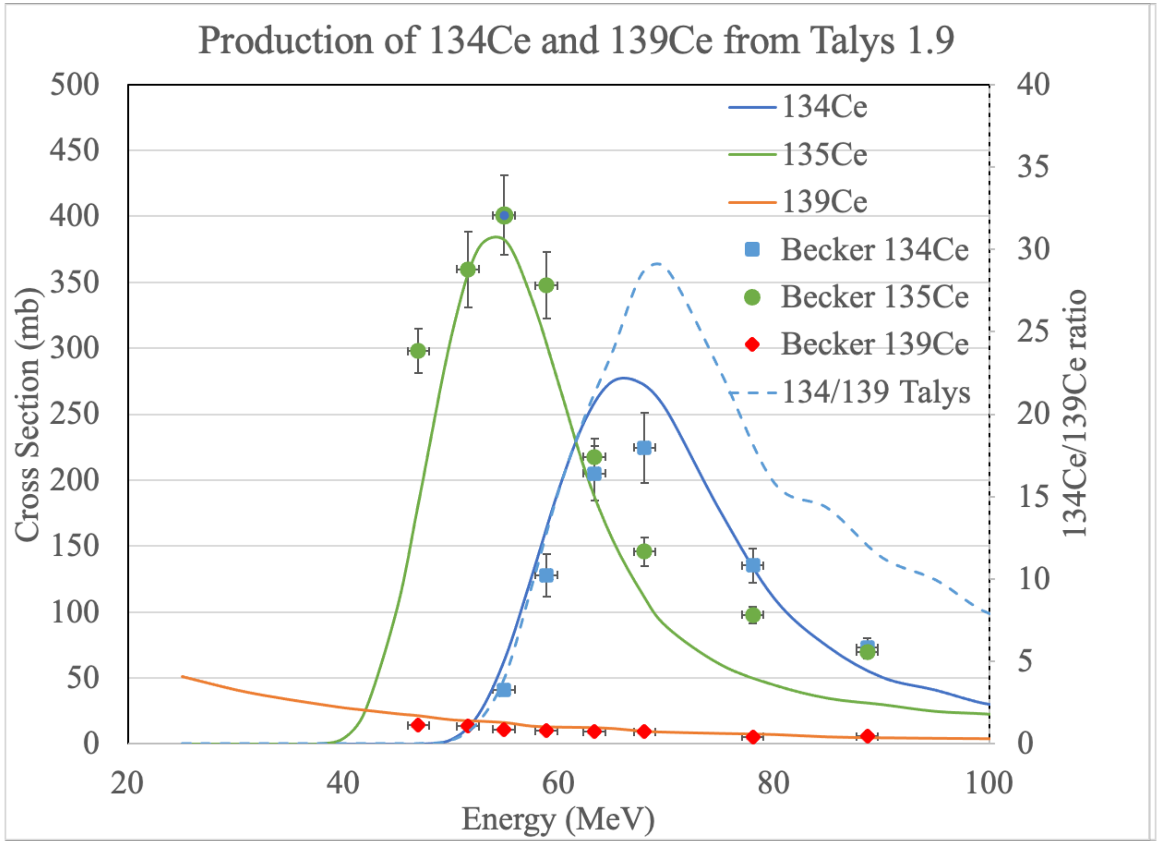



Compound (10^{-16-18} s)

Pre-equilibrium (10^{-19-22} s)

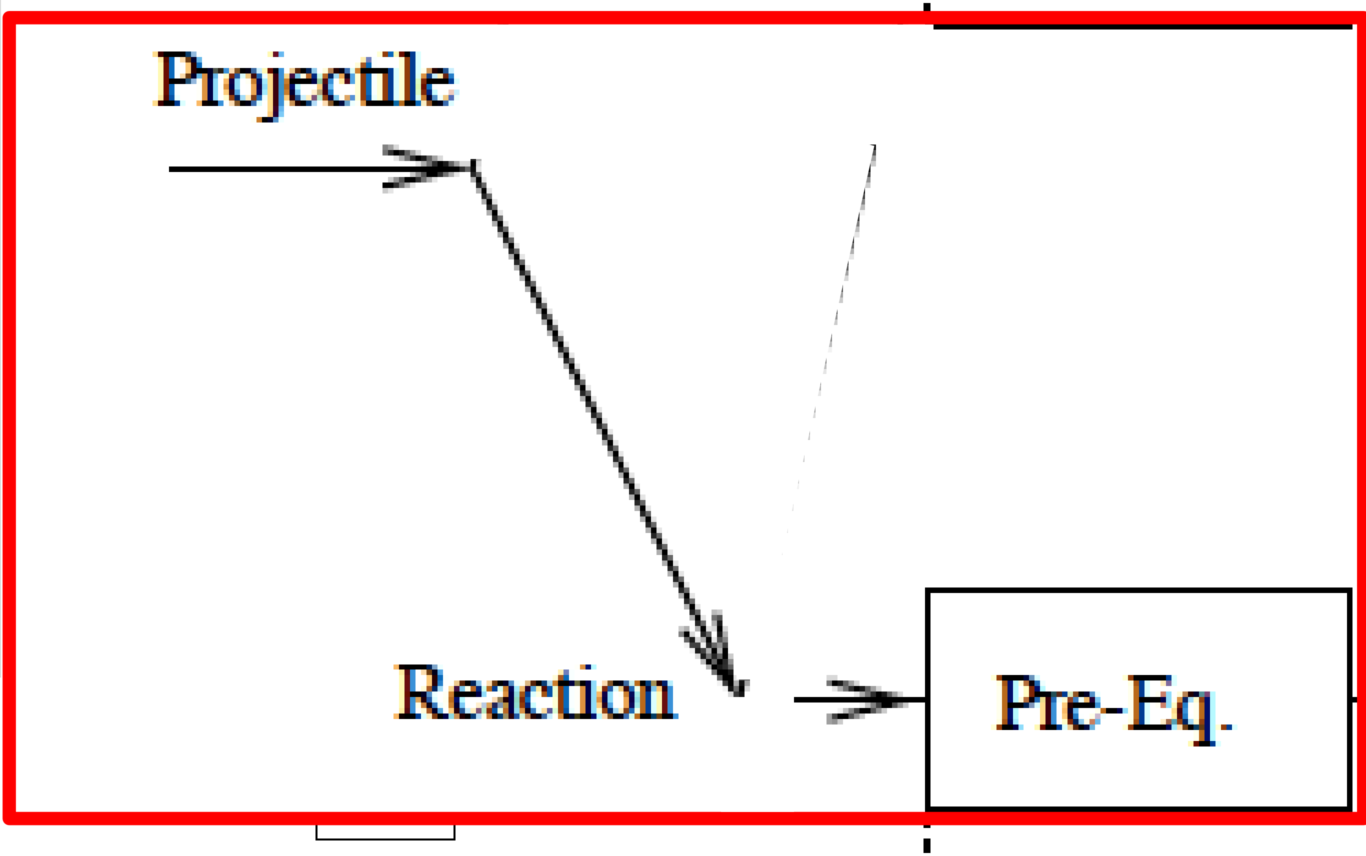
M. B. Fox *et al., PRC, 103(3):034601, 2021*

The TREND experimental effort* seeks an improvement in the ability of reaction modeling to optimize radioisotope production



More data are needed to obtain the correct set of reaction parameters

*But there are literally **thousands** of other parameters that can be adjusted!*



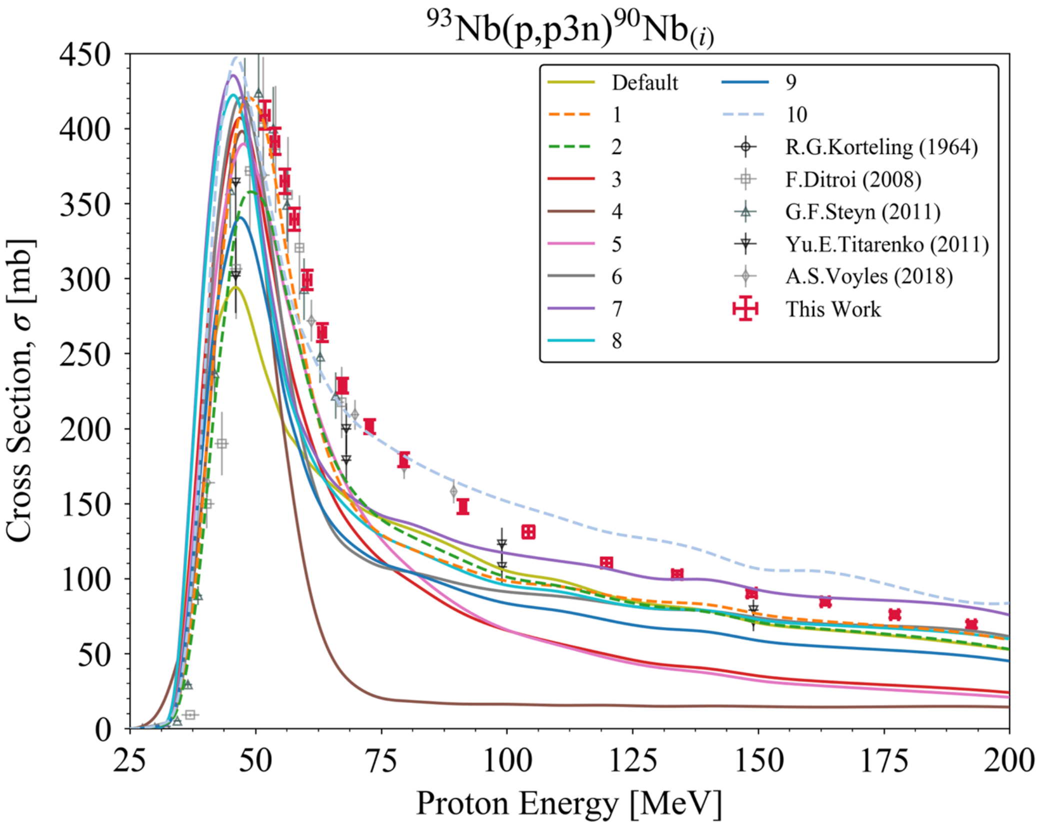
*M. B. Fox *et al.*, *PRC, 103(3):034601, 2021 & PRC 104, 064615 (2021)*

What Happens if We Don’t Do the Right Thing?

- Consider 10 different models, with arbitrary choices of which simplistic or complex parameters are adjusted, to reproduce similar improvements over the default prediction...

M. Fox, PRC 103(3):034601, 2021

What Happens if We Don’t Do the Right Thing?



Models 1, 2, 10 perform best over default

with arbitrary cl

ted, to reproduce

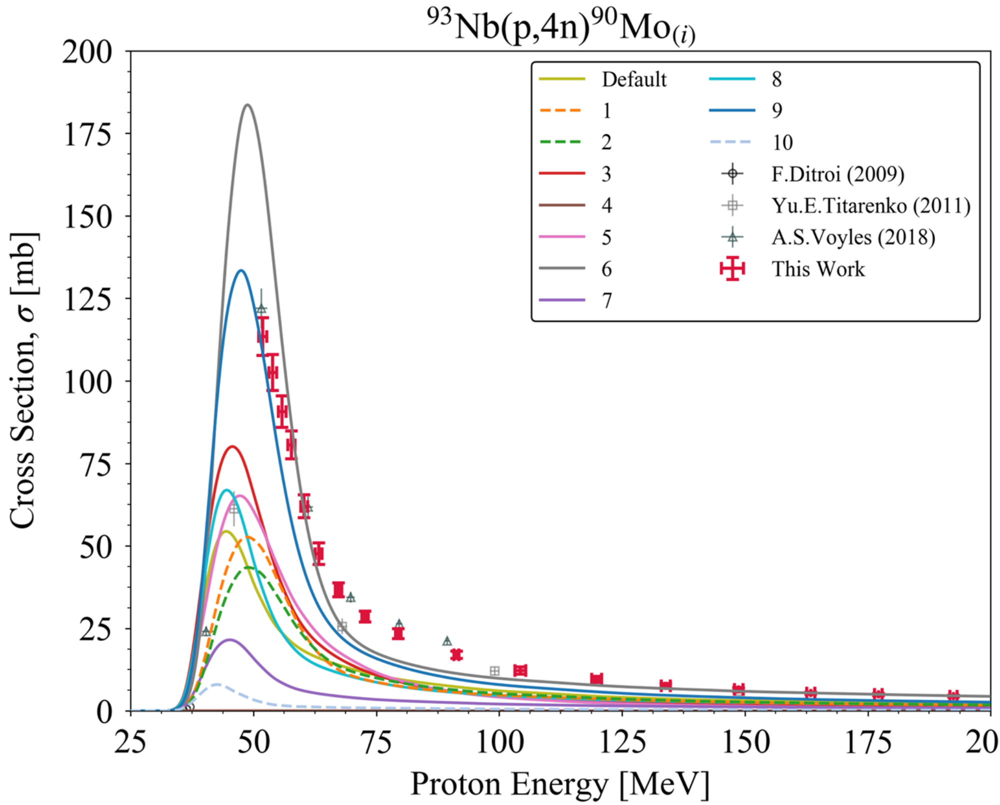
, what parameter

ble

ength

onstant, M2shift, M2l

w1adjust, v1adjust

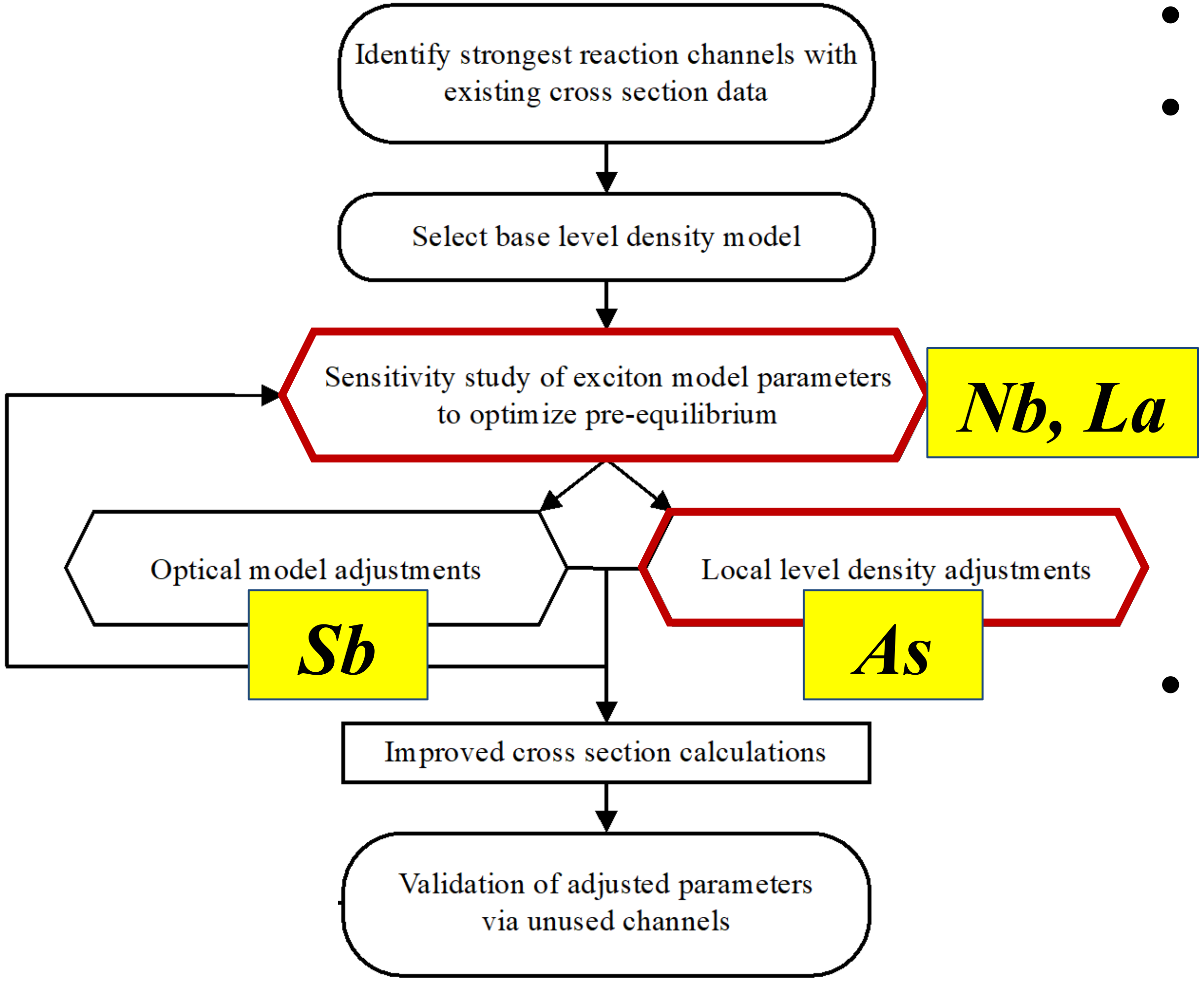


Models 1, 2, 10 perform extremely poorly

Single-channel optimizations lead to non-unique, non-physical solutions!

M. Fox, PRC 103(3):034601, 2021

TREND results were used to develop a new data evaluation methodology for high-energy (p,x) reactions


Identify strongest reaction channels with existing cross section data

Select base level density model

Sensitivity study of exciton model parameters to optimize pre-equilibrium

Nb, La

Optical model adjustments

Sb

Local level density adjustments

As

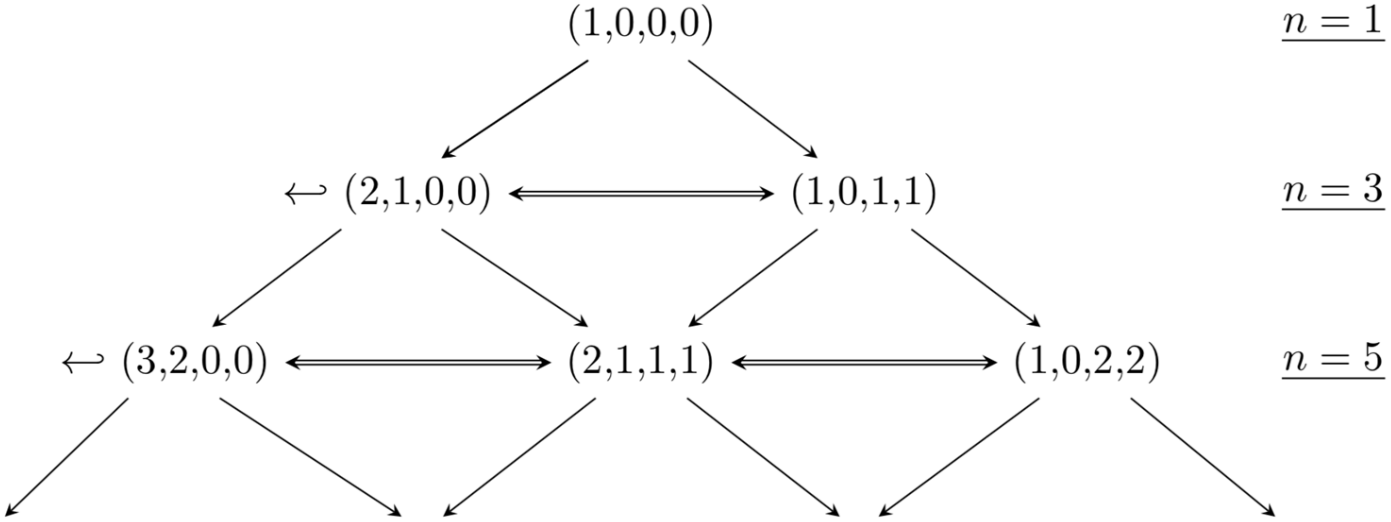
Improved cross section calculations

Validation of adjusted parameters via unused channels

- Based in TALYS code
- We established a collaboration with the TALYS lead developer, Dr. Arjan Koning (Head of the IAEA Nuclear Data Section)
- Emphasis placed on pre-equilibrium parameter adjustments to match the strongest-fed channels
- The modeling is validated via comparison to nonelastic, cumulative channels (same product formed by several exit channels)

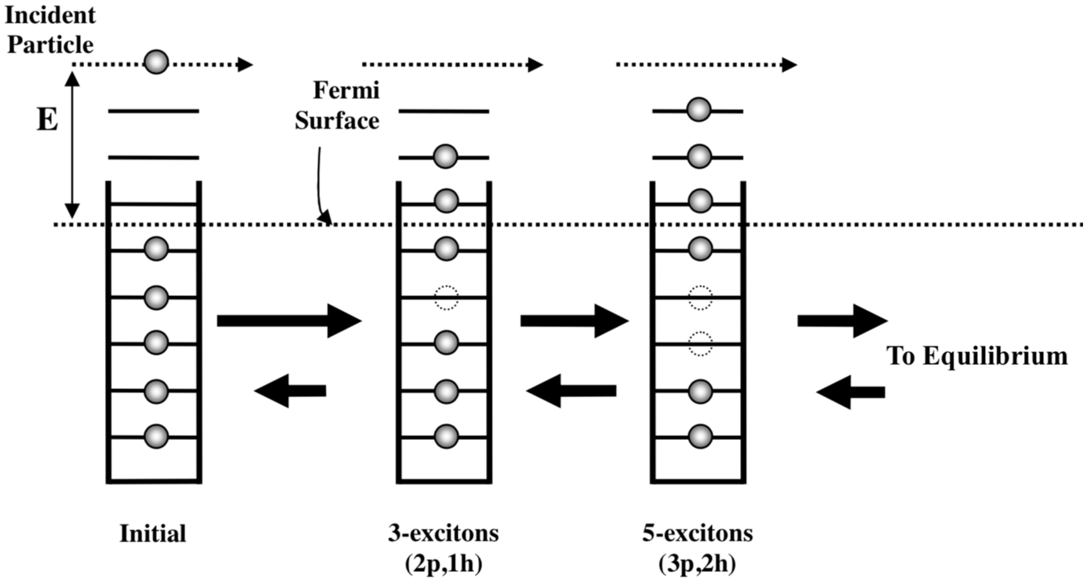

Morgan Fox

Methodology provides insight into pre-equilibrium reaction dynamics and a host of nuclear data properties relevant to accurate modeling



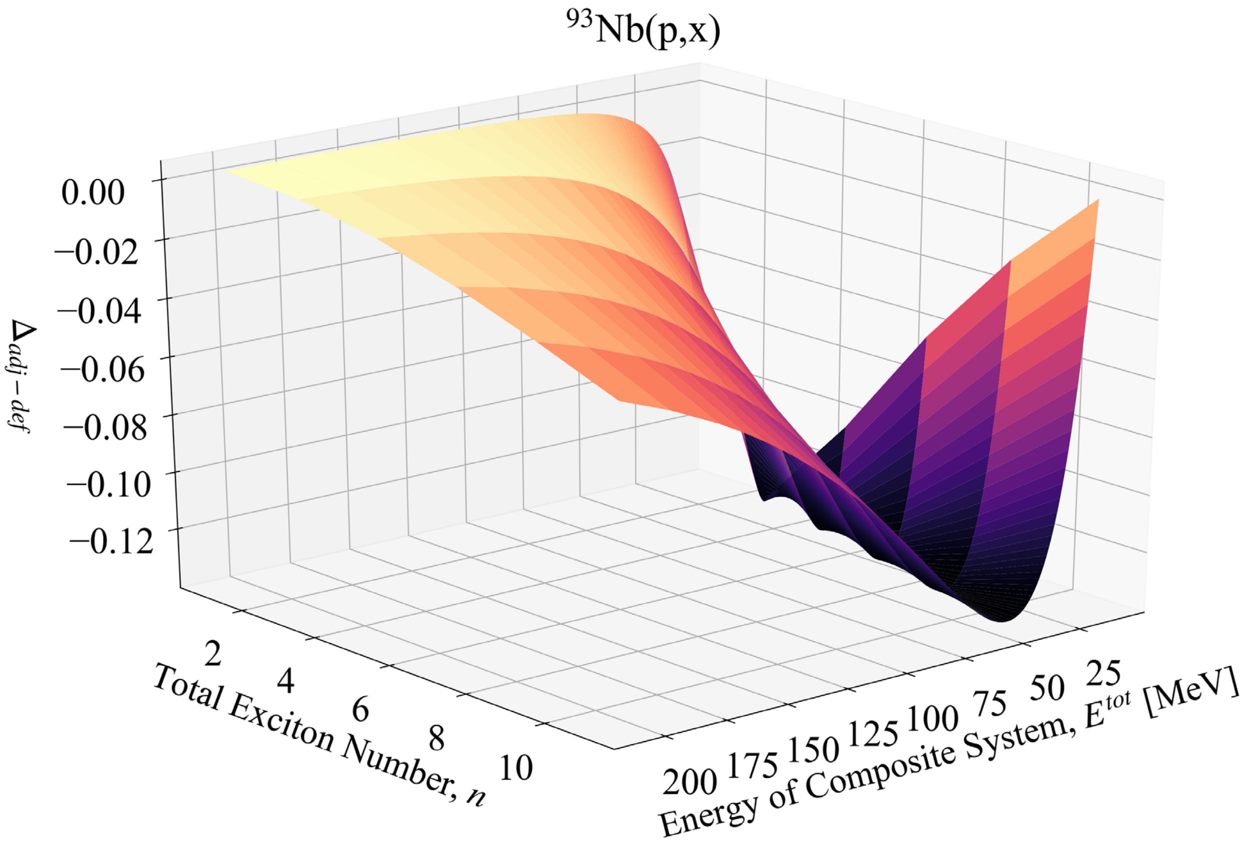
$$M^2 = \frac{\overset{M2constant}{C_1} A_p}{A^3}\left[7.48\overset{M2limit}{C_2} + \frac{4.62\times10^5}{\left(\frac{E^{\mathrm{tot}}}{nA_p} + 10.7\underset{M2shift}{C_3}\right)^3}\right]$$

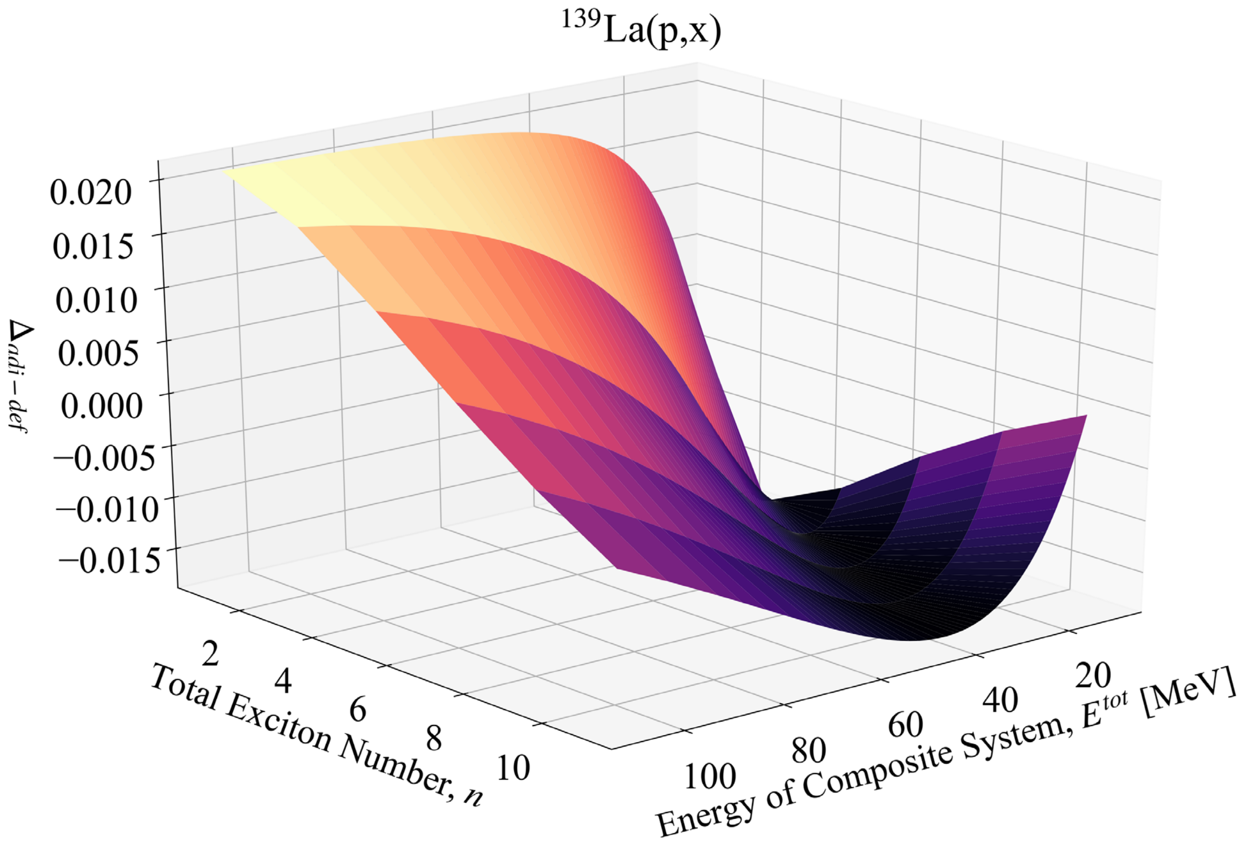
$$\Delta_{\text{adj-def}} = \frac{M^2(E^{\mathrm{tot}},n)_{\mathrm{adj}}}{M^2(E^{\mathrm{tot}},n)_{\mathrm{adj,max}}} - \frac{M^2(E^{\mathrm{tot}},n)_{\mathrm{def}}}{M^2(E^{\mathrm{tot}},n)_{\mathrm{def,max}}}$$



Exciton strength parameters are key for modeling pre-equilibrium emission!

Analyzing a Trend in Exciton Adjustments





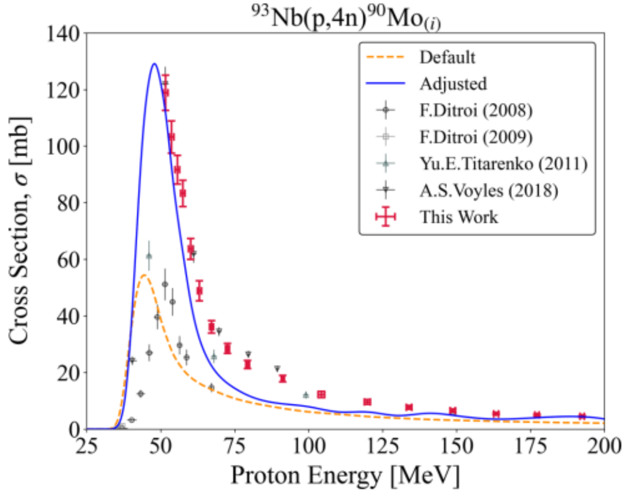
Significant differences are consistently seen in the energy region where we transition from the compound to pre-compound models!

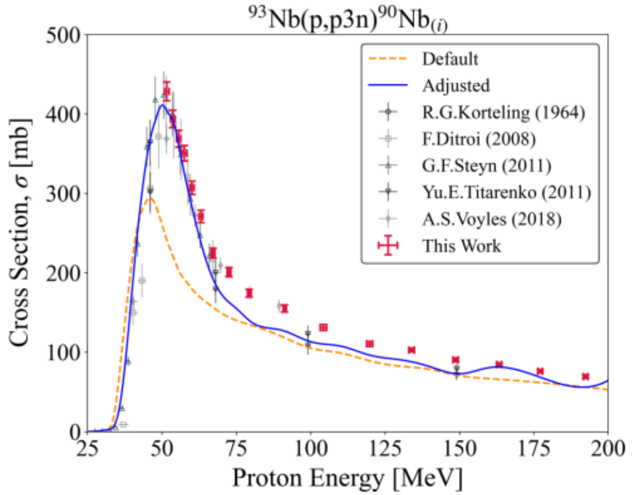
*M. B. Fox *et al.*, *PRC, 103(3):034601, 2021* & *PRC 104, 064615 (2021)*

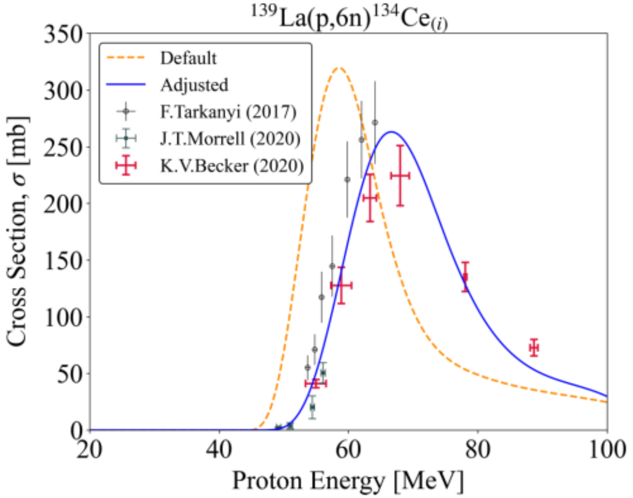
Evaluation Procedure applied to ^{93}Nb(p,x), ^{139}La(p,x)

- Exciton model adjustments in this mass region have led to significant improvements in pre-equilibrium, with global χ^2 improvements up to 40x
- However, the base level density (**ldmodel 4**, Goriely HFB + Skyrme) needed to be changed (**ldmodel 5**, Hilaire HFB + Skyrme) for most Nb, Mo products

All is not well in the state of Denmark w.r.t. level density!



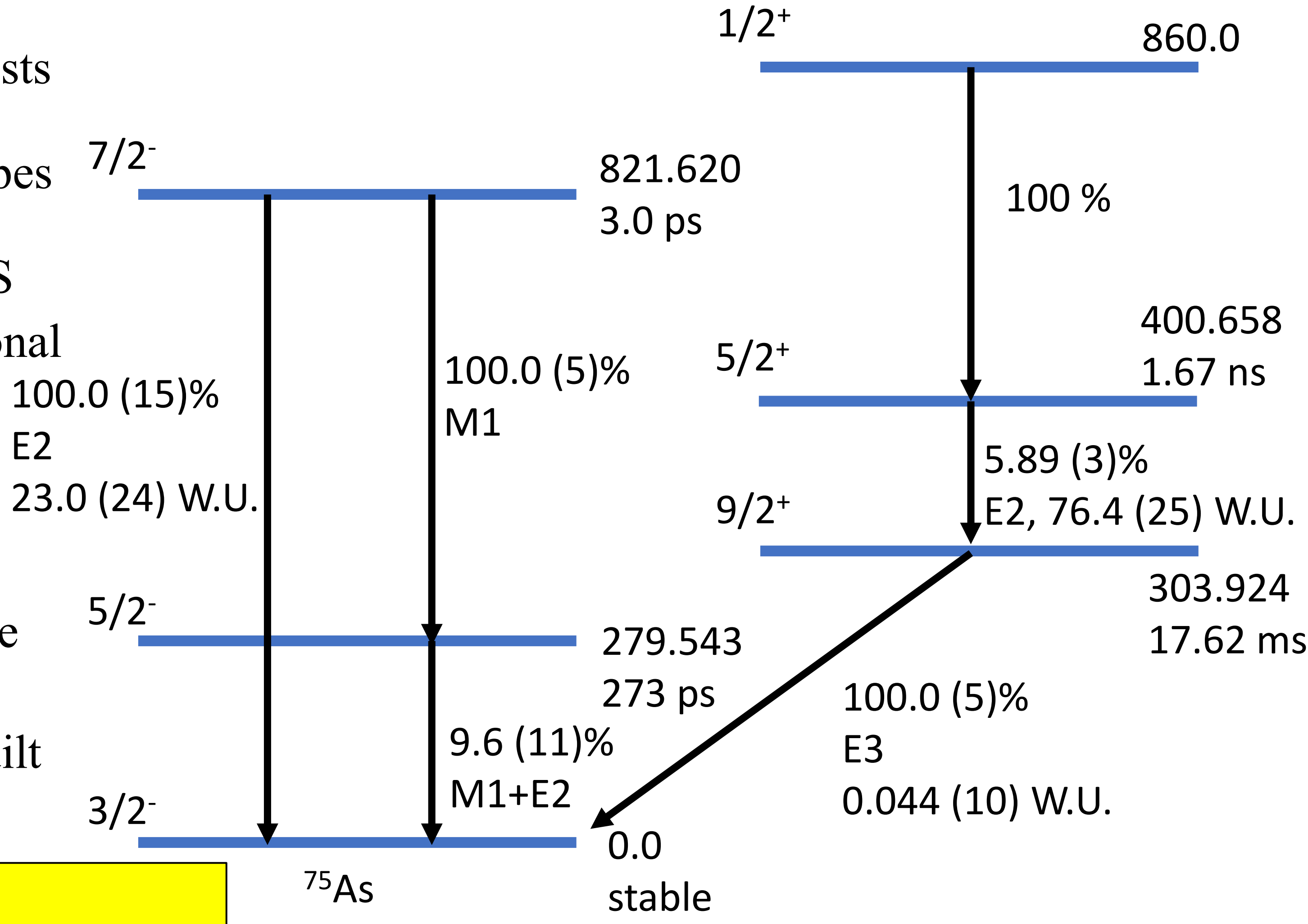




*M. B. Fox *et al.*, *PRC, 103(3):034601, 2021 & PRC 104, 064615 (2021)*

Level Density Adjustments in ^{75}As(p,x)

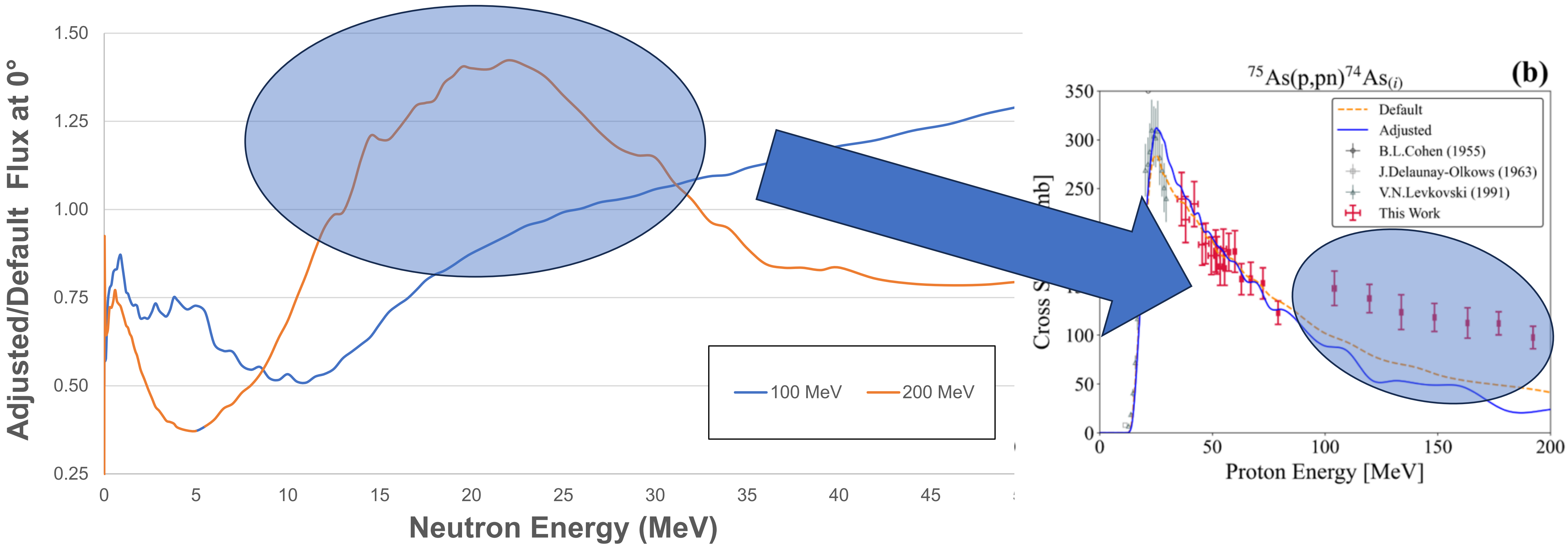
- RIPL-3 suggests an oblate deformation of β_2= -0.25
- Nilsson diagram systematics for neutron-rich isotopes near A=60-80 indicate prolate, ENDF lists β_2= 0.314(6)
- TALYS lacks deformation coupling for As isotopes and does a spherical OMP calculation via ECIS
- 3-level apparent rotational band added to TALYS
- Neighboring ^{76,74}Se, ^{76,74}Ge demonstrate vibrational character, have vibrational coupling schemes in TALYS for CC
- ^{241}Am is only odd-Z nucleus with vibrational deformation in TALYS
- Since TALYS ECIS is unsuited for purely vibrational coupling schemes in odd-Z nuclei, we were forced to use weak-coupling model and modeled ^{75}As as soft vibrational, with a weak vibrational band (based on ^{241}Am formatting) built on top of the G.S. rotational band



TALYS also lacks isospin….

*M. B. Fox *et al., PRC, 103(3):034601, 2021 & PRC 104, 064615 (2021)*

What are the effects of these changes on the neutron flux look like behind a thick target at BNL-BLIP or LANL-IPF?



There is a sizable neutron flux behind all thick target stacks at these Isotope Production facilities!

Level Density Adjustments in ^{75}As(p,x)

- Like with Nb/La, we see a clear need to transition to a new level density model as we get far from target
  - Effect is more prominent in As, as we produce isotopes further from stability
  - More pronounced for (p,xn) channels
  - This does NOT imply that one ldmodel is better than others – ***none work globally for high E_x!***

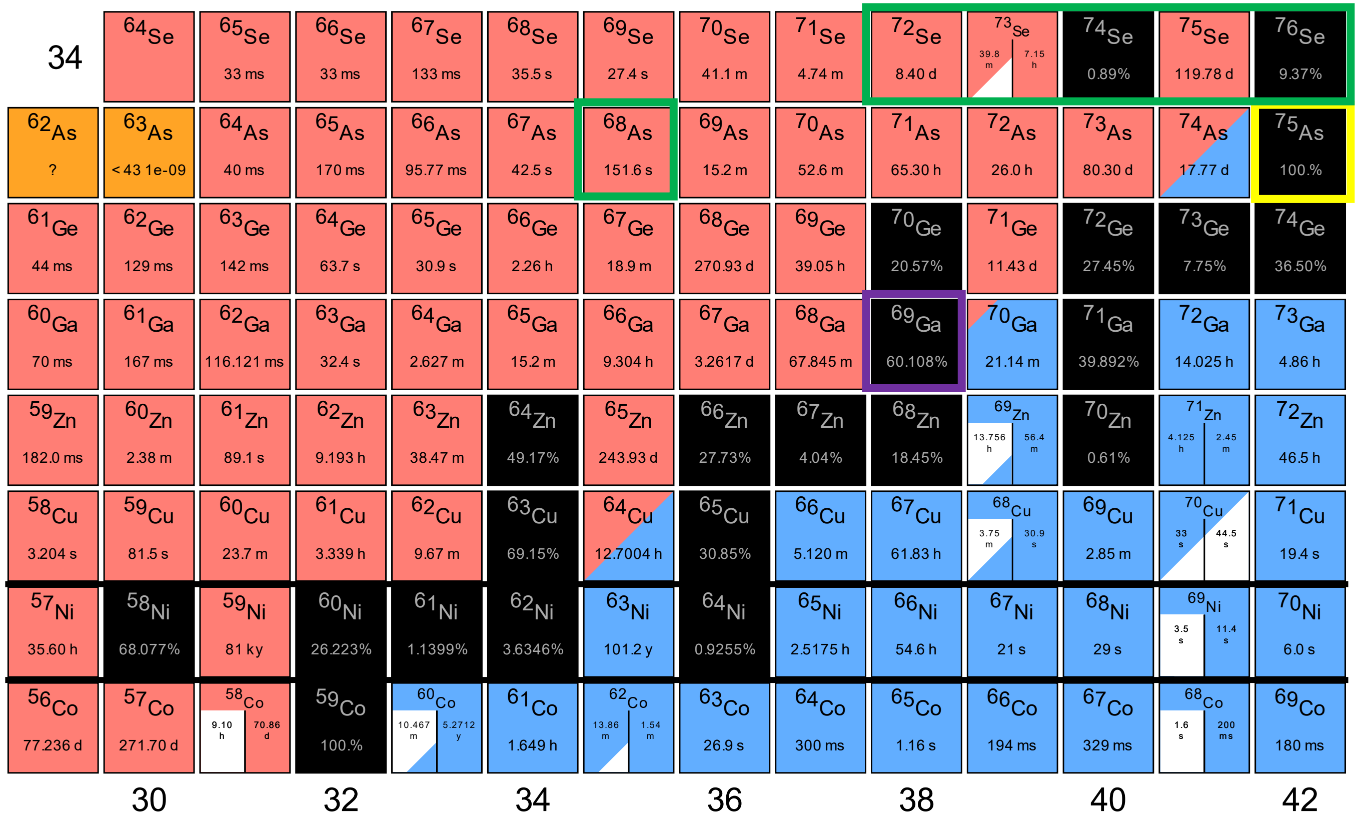
This is a problem!

A new Gogny + QRPA "ldmodel 7"?

🟩 → **ldmodel 4**, Goriely HFB + Skyrme

🟪 → **ldmodel 5**, Hilaire HFB + Skyrme

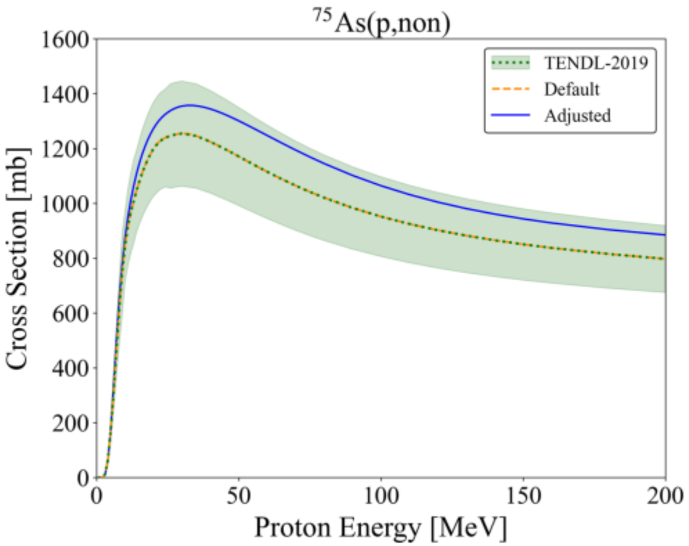
All others → **ldmodel 6**, Temperature-Dependent HFB + Gogny

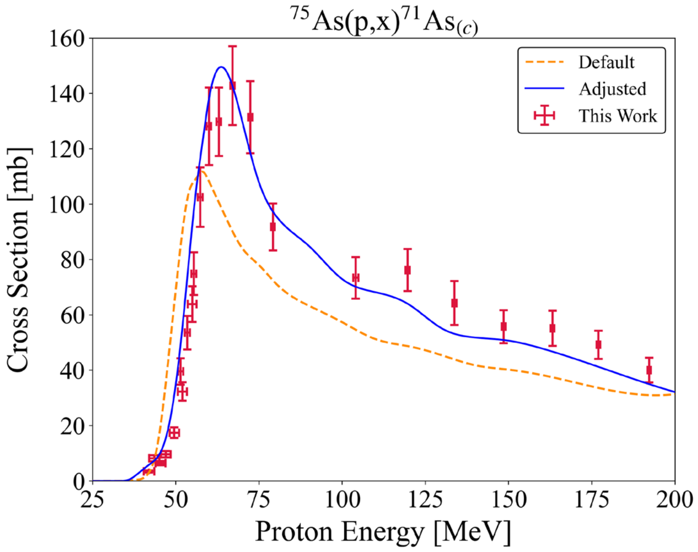


34		^{64}Se	^{65}Se 33 ms	^{66}Se 33 ms	^{67}Se 133 ms	^{68}Se 35.5 s	^{69}Se 27.4 s	^{70}Se 41.1 m	^{71}Se 4.74 m	^{72}Se 8.40 d	^{73}Se 39.8 m 7.15 h	^{74}Se 0.89%	^{75}Se 119.78 d	^{76}Se 9.37%
	^{62}As ?	^{63}As < 43 1e-09	^{64}As 40 ms	^{65}As 170 ms	^{66}As 95.77 ms	^{67}As 42.5 s	^{68}As 151.6 s	^{69}As 15.2 m	^{70}As 52.6 m	^{71}As 65.30 h	^{72}As 26.0 h	^{73}As 80.30 d	^{74}As 17.77 d	^{75}As 100.%
32	^{61}Ge 44 ms	^{62}Ge 129 ms	^{63}Ge 142 ms	^{64}Ge 63.7 s	^{65}Ge 30.9 s	^{66}Ge 2.26 h	^{67}Ge 18.9 m	^{68}Ge 270.93 d	^{69}Ge 39.05 h	^{70}Ge 20.57%	^{71}Ge 11.43 d	^{72}Ge 27.45%	^{73}Ge 7.75%	^{74}Ge 36.50%
	^{60}Ga 70 ms	^{61}Ga 167 ms	^{62}Ga 116.121 ms	^{63}Ga 32.4 s	^{64}Ga 2.627 m	^{65}Ga 15.2 m	^{66}Ga 9.304 h	^{67}Ga 3.2617 d	^{68}Ga 67.845 m	^{69}Ga 60.108%	^{70}Ga 21.14 m	^{71}Ga 39.892%	^{72}Ga 14.025 h	^{73}Ga 4.86 h
30	^{59}Zn 182.0 ms	^{60}Zn 2.38 m	^{61}Zn 89.1 s	^{62}Zn 9.193 h	^{63}Zn 38.47 m	^{64}Zn 49.17%	^{65}Zn 243.93 d	^{66}Zn 27.73%	^{67}Zn 4.04%	^{68}Zn 18.45%	^{69}Zn 13.756 h 56.4 m	^{70}Zn 0.61%	^{71}Zn 4.125 h 2.45 m	^{72}Zn 46.5 h
	^{58}Cu 3.204 s	^{59}Cu 81.5 s	^{60}Cu 23.7 m	^{61}Cu 3.339 h	^{62}Cu 9.67 m	^{63}Cu 69.15%	^{64}Cu 12.7004 h	^{65}Cu 30.85%	^{66}Cu 5.120 m	^{67}Cu 61.83 h	^{68}Cu 3.75 m 30.9 s	^{69}Cu 2.85 m	^{70}Cu 33 s 44.5 s	^{71}Cu 19.4 s
28	^{57}Ni 35.60 h	^{58}Ni 68.077%	^{59}Ni 81 ky	^{60}Ni 26.223%	^{61}Ni 1.1399%	^{62}Ni 3.6346%	^{63}Ni 101.2 y	^{64}Ni 0.9255%	^{65}Ni 2.5175 h	^{66}Ni 54.6 h	^{67}Ni 21 s	^{68}Ni 29 s	^{69}Ni 3.5 s 11.4 s	^{70}Ni 6.0 s
	^{56}Co 77.236 d	^{57}Co 271.70 d	^{58}Co 9.10 h 70.86 d	^{59}Co 100.%	^{60}Co 10.467 m 5.2712 y	^{61}Co 1.649 h	^{62}Co 13.86 m 1.54 m	^{63}Co 26.9 s	^{64}Co 300 ms	^{65}Co 1.16 s	^{66}Co 194 ms	^{67}Co 329 ms	^{68}Co 1.6 s 200 ms	^{69}Co 180 ms
		30		32		34		36		38		40		42

*M. B. Fox *et al.*, *PRC, 103(3):034601, 2021 & PRC 104, 064615 (2021)*

Level Density Adjustments in ^{75}As(p,x)





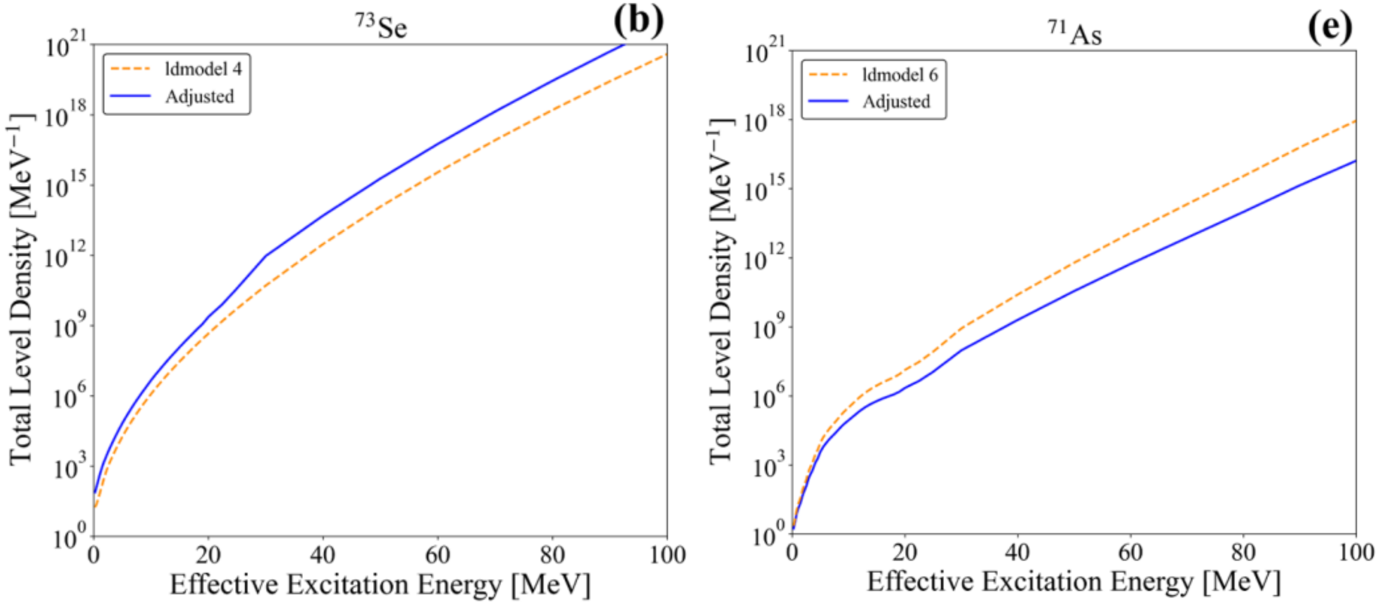
$$\rho(E_x, J, \pi) = \exp(c\sqrt{E_x - \delta})\rho_{\text{mic}}(E_x - \delta, J, \pi)$$

ctable

34 73 0.24
33 74 0.3
33 73 0.75
33 71 −0.4
32 69 0.285
31 67 −0.45

ptable

34 73 −0.65
34 72 0.14
33 73 −1.85
32 69 −0.25
31 67 5.5



We see global χ^2 improvements of ~3, but need more discrete level data and level density measurements!

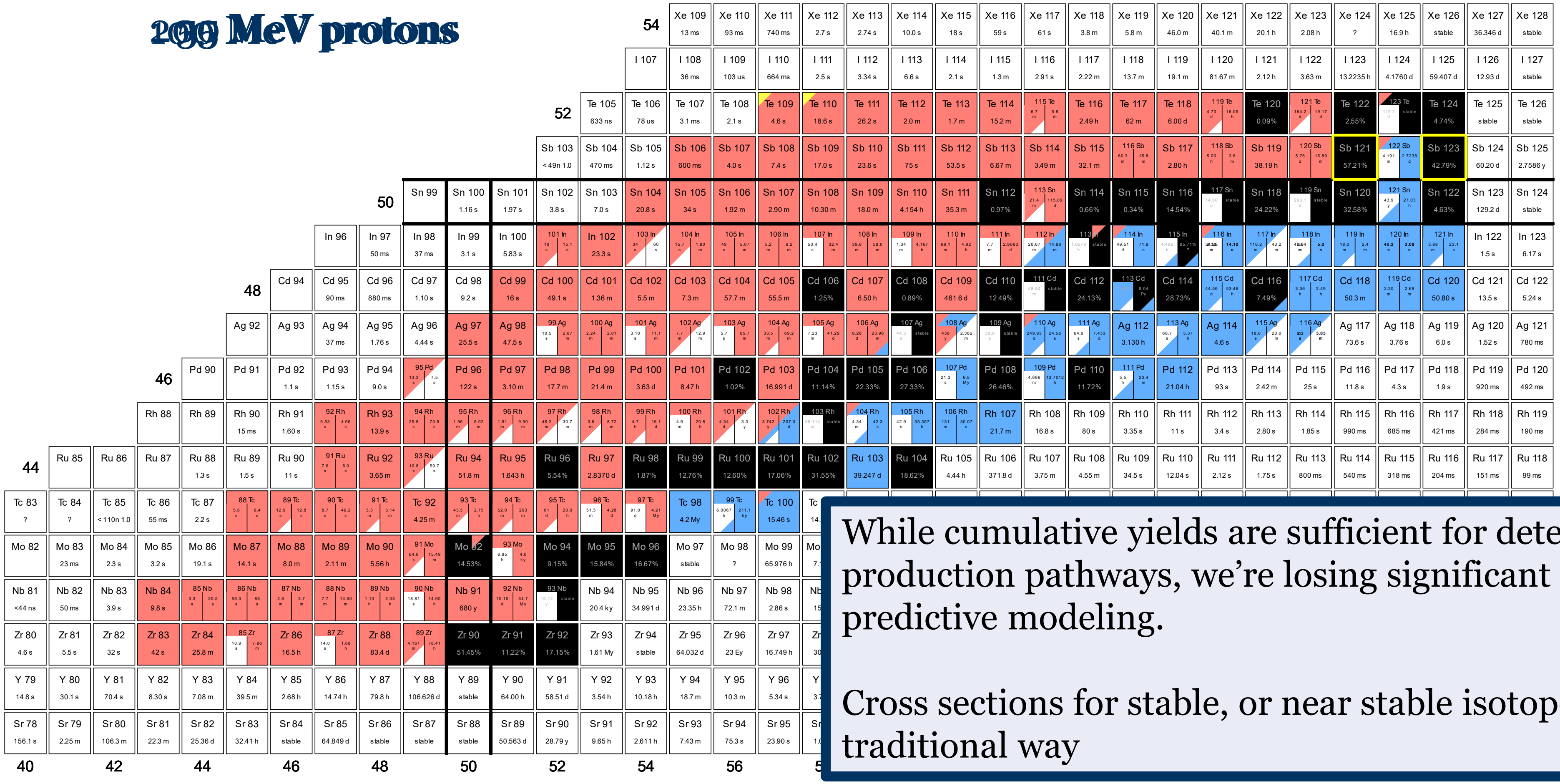
AS Voyle
Conferen

Current nuclear data needs for applications
Phys. Rev. Res. 4, 021001 (2022)

*M. B. Fox *et al.*, *PRC, 103(3):034601, 2021 & PRC 104, 064615 (2021)*

Stacked-target experiments for measuring cross sections

As we increase in incident proton energy, from 35 MeV all the way to 200 MeV, we open channels for 200+ potential products.



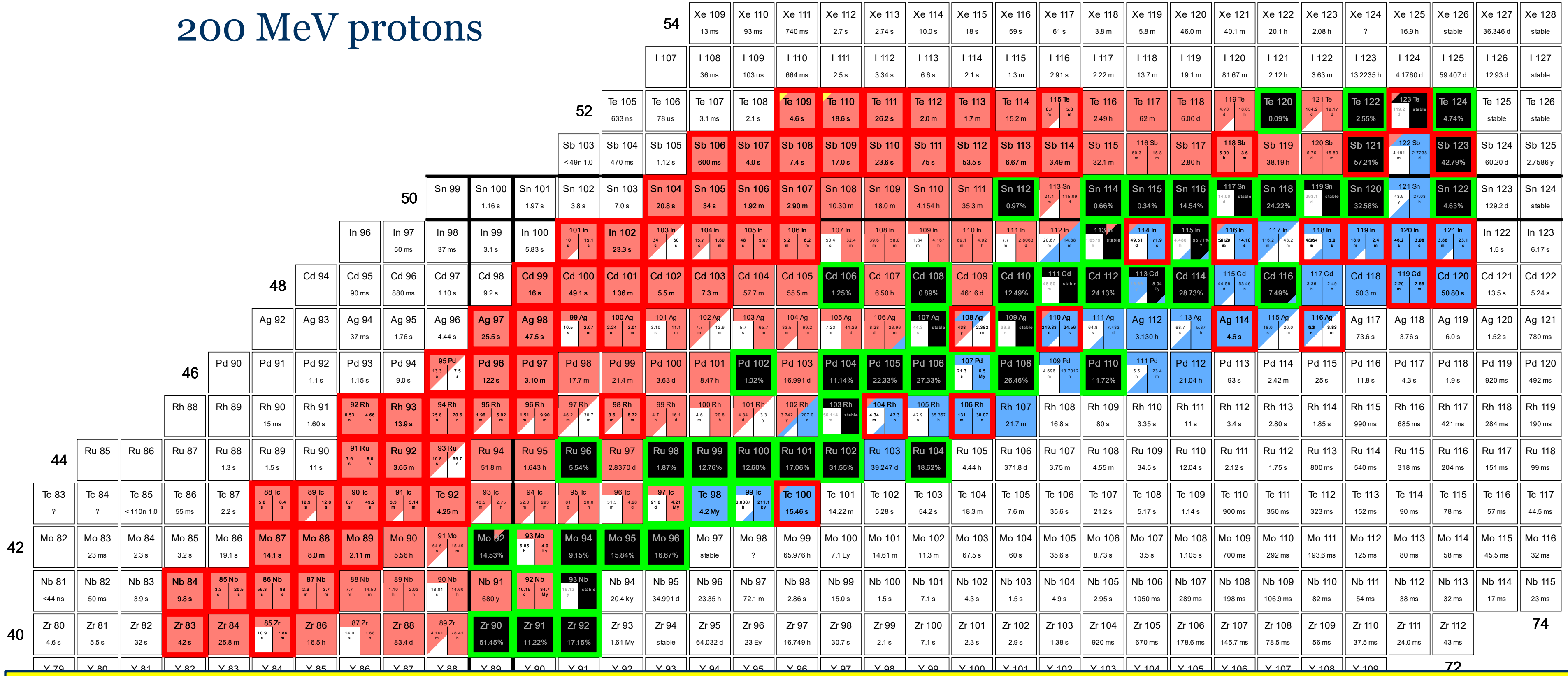
While cumulative yields are sufficient for determining medical isotope production pathways, we're losing significant granularity in terms of predictive modeling.

Cross sections for stable, or near stable isotopes cannot be measured in this traditional way

Stacked-target experiments for measuring cross sections

As we increase in incident proton energy, from 35 MeV all the way to 200 MeV, we open channels for 200+ potential products.

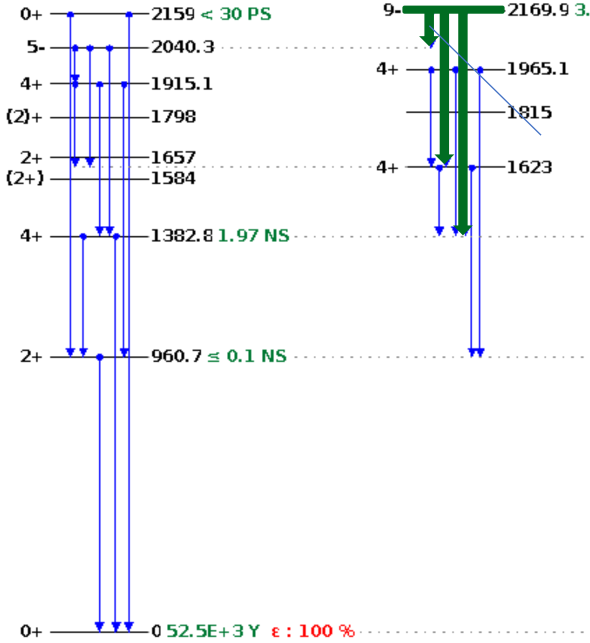
200 MeV protons

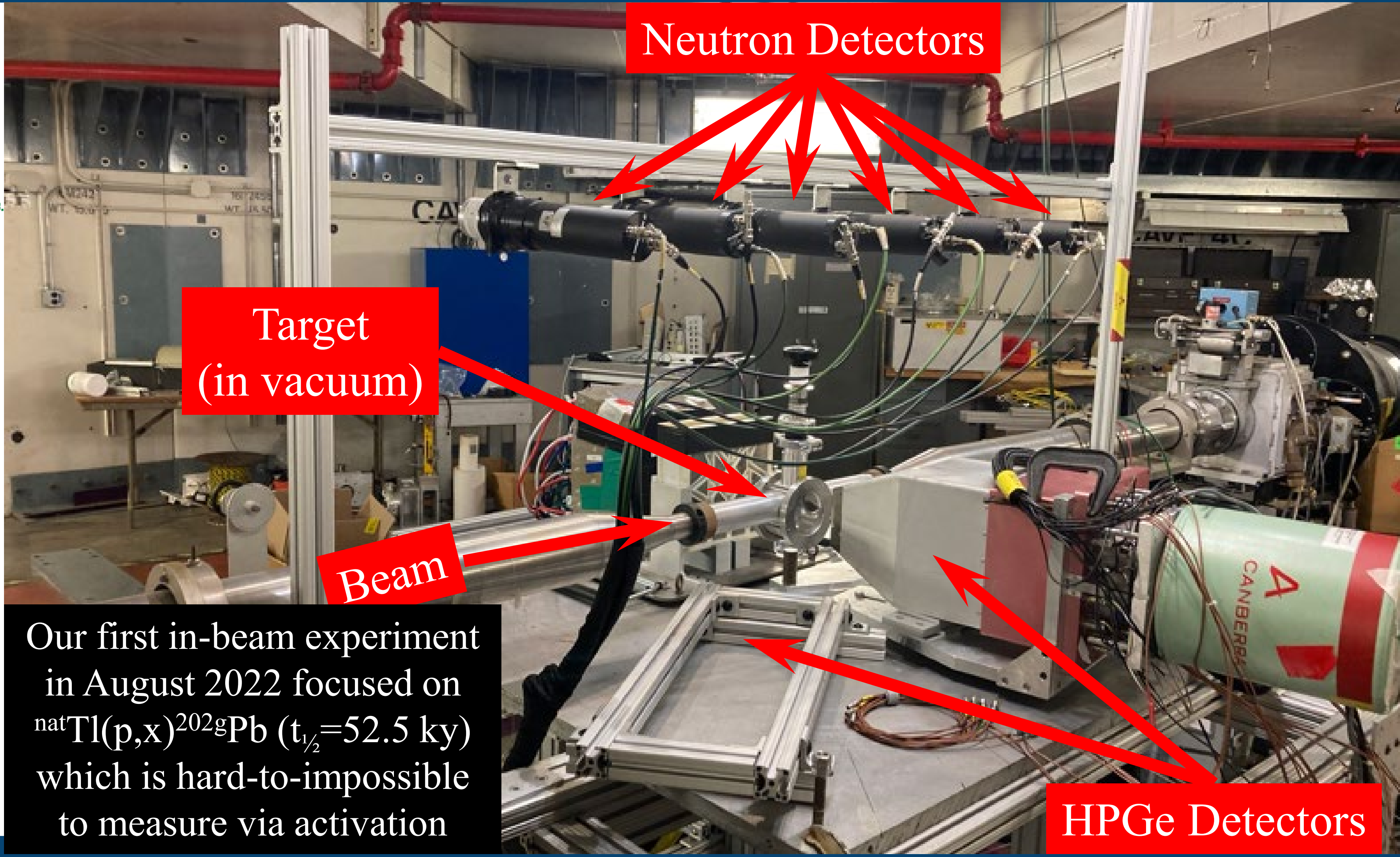


															54	Xe 109 13 ms	Xe 110 93 ms	Xe 111 740 ms	Xe 112 2.7 s	Xe 113 2.74 s	Xe 114 10.0 s	Xe 115 18 s	Xe 116 59 s	Xe 117 61 s	Xe 118 3.8 m	Xe 119 5.8 m	Xe 120 46.0 m	Xe 121 40.1 m	Xe 122 20.1 h	Xe 123 2.08 h	Xe 124 ?	Xe 125 16.9 h	Xe 126 stable	Xe 127 36.346 d	Xe 128 stable
															I 107	I 108 36 ms	I 109 103 us	I 110 664 ms	I 111 2.5 s	I 112 3.34 s	I 113 6.6 s	I 114 2.1 s	I 115 1.3 m	I 116 2.91 s	I 117 2.22 m	I 118 13.7 m	I 119 19.1 m	I 120 81.67 m	I 121 2.12 h	I 122 3.63 m	I 123 13.2235 h	I 124 4.1760 d	I 125 59.407 d	I 126 12.93 d	I 127 stable
														52	Te 105 633 ns	Te 106 78 us	Te 107 3.1 ms	Te 108 2.1 s	Te 109 4.6 s	Te 110 18.6 s	Te 111 26.2 s	Te 112 2.0 m	Te 113 1.7 m	Te 114 15.2 m	115 Te 6.7 m 5.8 m	Te 116 2.49 h	Te 117 62 m	Te 118 6.00 d	119 Te 4.70 d 16.05 h	Te 120 0.09%	121 Te 164.2 d 19.17 d	Te 122 2.55%	123 Te 119.2 d stable	Te 124 4.74%	Te 125 stable	Te 126 stable
														Sb 103 < 49n 1.0	Sb 104 470 ms	Sb 105 1.12 s	Sb 106 600 ms	Sb 107 4.0 s	Sb 108 7.4 s	Sb 109 17.0 s	Sb 110 23.6 s	Sb 111 75 s	Sb 112 53.5 s	Sb 113 6.67 m	Sb 114 3.49 m	Sb 115 32.1 m	116 Sb 60.3 m 15.8 m	Sb 117 2.80 h	118 Sb 5.00 h 3.6 m	Sb 119 38.19 h	120 Sb 5.76 d 15.89 m	Sb 121 57.21%	122 Sb 4.191 m 2.7238 d	Sb 123 42.79%	Sb 124 60.20 d	Sb 125 2.7586 y
										50	Sn 99	Sn 100 1.16 s	Sn 101 1.97 s	Sn 102 3.8 s	Sn 103 7.0 s	Sn 104 20.8 s	Sn 105 34 s	Sn 106 1.92 m	Sn 107 2.90 m	Sn 108 10.30 m	Sn 109 18.0 m	Sn 110 4.154 h	Sn 111 35.3 m	Sn 112 0.97%	113 Sn 21.4 m 115.09 d	Sn 114 0.66%	Sn 115 0.34%	Sn 116 14.54%	117 Sn 14.00 d stable	Sn 118 24.22%	119 Sn 293.1 d stable	Sn 120 32.58%	121 Sn 43.9 y 27.03 h	Sn 122 4.63%	Sn 123 129.2 d	Sn 124 stable
									In 96	In 97 50 ms	In 98 37 ms	In 99 3.1 s	In 100 5.83 s	101 In 10 s 15.1 s	In 102 23.3 s	103 In 34 s 60 s	104 In 15.7 s 1.80 m	105 In 48 s 5.07 m	106 In 5.2 m 6.2 m	107 In 50.4 s 32.4 m	108 In 39.6 m 58.0 m	109 In 1.34 m 4.167 h	110 In 69.1 m 4.92 h	111 In 7.7 m 2.8063 d	112 In 20.67 m 14.88 m	113 In 1.6579 h stable	114 In 49.51 d 71.9 s	115 In 4.486 h 95.71% ?	116 In [illegible] 14.10 s	117 In 116.2 m 43.2 m	118 In [illegible] 5.0 s	119 In 18.0 m 2.4 m	120 In [illegible] 3.08 s	121 In 3.88 m 23.1 s	In 122 1.5 s	In 123 6.17 s
						48	Cd 94	Cd 95 90 ms	Cd 96 880 ms	Cd 97 1.10 s	Cd 98 9.2 s	Cd 99 16 s	Cd 100 49.1 s	Cd 101 1.36 m	Cd 102 5.5 m	Cd 103 7.3 m	Cd 104 57.7 m	Cd 105 55.5 m	Cd 106 1.25%	Cd 107 6.50 h	Cd 108 0.89%	Cd 109 461.6 d	Cd 110 12.49%	111 Cd 48.50 m stable	Cd 112 24.13%	113 Cd 13.89 y 8.04 Py	Cd 114 28.73%	115 Cd 44.56 d 53.46 h	Cd 116 7.49%	117 Cd 3.36 h 2.49 h	Cd 118 50.3 m	119 Cd 2.20 m 2.69 m	Cd 120 50.80 s	Cd 121 13.5 s	Cd 122 5.24 s
						Ag 92	Ag 93	Ag 94 37 ms	Ag 95 1.76 s	Ag 96 4.44 s	Ag 97 25.5 s	Ag 98 47.5 s	99 Ag 10.5 s 2.07 m	100 Ag 2.24 m 2.01 m	101 Ag 3.10 s 11.1 m	102 Ag 7.7 m 12.9 m	103 Ag 5.7 s 65.7 m	104 Ag 33.5 m 69.2 m	105 Ag 7.23 m 41.29 d	106 Ag 8.28 d 23.96 m	107 Ag 44.3 s stable	108 Ag 438 y 2.382 m	109 Ag 39.6 s stable	110 Ag 249.83 d 24.56 s	111 Ag 64.8 s 7.433 d	Ag 112 3.130 h	113 Ag 68.7 s 5.37 h	Ag 114 4.6 s	115 Ag 18.0 s 20.0 m	116 Ag [illegible] 3.83 m	Ag 117 73.6 s	Ag 118 3.76 s	Ag 119 6.0 s	Ag 120 1.52 s	Ag 121 780 ms
					46	Pd 90	Pd 91	Pd 92 1.1 s	Pd 93 1.15 s	Pd 94 9.0 s	95 Pd 13.3 s 7.5 s	Pd 96 122 s	Pd 97 3.10 m	Pd 98 17.7 m	Pd 99 21.4 m	Pd 100 3.63 d	Pd 101 8.47 h	Pd 102 1.02%	Pd 103 16.991 d	Pd 104 11.14%	Pd 105 22.33%	Pd 106 27.33%	107 Pd 21.3 s 6.5 My	Pd 108 26.46%	109 Pd 4.696 m 13.7012 h	Pd 110 11.72%	111 Pd 5.5 h 23.4 m	Pd 112 21.04 h	Pd 113 93 s	Pd 114 2.42 m	Pd 115 25 s	Pd 116 11.8 s	Pd 117 4.3 s	Pd 118 1.9 s	Pd 119 920 ms	Pd 120 492 ms
					Rh 88	Rh 89	Rh 90 15 ms	Rh 91 1.60 s	92 Rh 0.53 s 4.66 s	Rh 93 13.9 s	94 Rh 25.8 s 70.6 s	95 Rh 1.96 m 5.02 m	96 Rh 1.51 m 9.90 m	97 Rh 46.2 m 30.7 m	98 Rh 3.6 m 8.72 m	99 Rh 4.7 h 16.1 d	100 Rh 4.6 m 20.8 h	101 Rh 4.34 d 3.3 y	102 Rh 3.742 y 207.0 d	103 Rh 56.114 m stable	104 Rh 4.34 m 42.3 s	105 Rh 42.9 s 35.357 h	106 Rh 131 m 30.07 s	Rh 107 21.7 m	Rh 108 16.8 s	Rh 109 80 s	Rh 110 3.35 s	Rh 111 11 s	Rh 112 3.4 s	Rh 113 2.80 s	Rh 114 1.85 s	Rh 115 990 ms	Rh 116 685 ms	Rh 117 421 ms	Rh 118 284 ms	Rh 119 190 ms
	44	Ru 85	Ru 86	Ru 87	Ru 88 1.3 s	Ru 89 1.5 s	Ru 90 11 s	91 Ru 7.6 s 8.0 s	Ru 92 3.65 m	93 Ru 10.8 s 59.7 s	Ru 94 51.8 m	Ru 95 1.643 h	Ru 96 5.54%	Ru 97 2.8370 d	Ru 98 1.87%	Ru 99 12.76%	Ru 100 12.60%	Ru 101 17.06%	Ru 102 31.55%	Ru 103 39.247 d	Ru 104 18.62%	Ru 105 4.44 h	Ru 106 371.8 d	Ru 107 3.75 m	Ru 108 4.55 m	Ru 109 34.5 s	Ru 110 12.04 s	Ru 111 2.12 s	Ru 112 1.75 s	Ru 113 800 ms	Ru 114 540 ms	Ru 115 318 ms	Ru 116 204 ms	Ru 117 151 ms	Ru 118 99 ms
	Tc 83 ?	Tc 84 ?	Tc 85 < 110n 1.0	Tc 86 55 ms	Tc 87 2.2 s	88 Tc 5.8 s 6.4 s	89 Tc 12.9 s 12.8 s	90 Tc 8.7 s 49.2 s	91 Tc 3.3 m 3.14 m	Tc 92 4.25 m	93 Tc 43.5 m 2.75 h	94 Tc 52.0 m 293 m	95 Tc 61 d 20.0 h	96 Tc 51.5 m 4.28 d	97 Tc 91.0 d 4.21 My	Tc 98 4.2 My	99 Tc 6.0067 h 211.1 ky	Tc 100 15.46 s	Tc 101 14.22 m	Tc 102 5.28 s	Tc 103 54.2 s	Tc 104 18.3 m	Tc 105 7.6 m	Tc 106 35.6 s	Tc 107 21.2 s	Tc 108 5.17 s	Tc 109 1.14 s	Tc 110 900 ms	Tc 111 350 ms	Tc 112 323 ms	Tc 113 152 ms	Tc 114 90 ms	Tc 115 78 ms	Tc 116 57 ms	Tc 117 44.5 ms
42	Mo 82	Mo 83 23 ms	Mo 84 2.3 s	Mo 85 3.2 s	Mo 86 19.1 s	Mo 87 14.1 s	Mo 88 8.0 m	Mo 89 2.11 m	Mo 90 5.56 h	91 Mo 64.6 s 15.49 m	Mo 92 14.53%	93 Mo 6.85 h 4.0 ky	Mo 94 9.15%	Mo 95 15.84%	Mo 96 16.67%	Mo 97 stable	Mo 98 ?	Mo 99 65.976 h	Mo 100 7.1 Ey	Mo 101 14.61 m	Mo 102 11.3 m	Mo 103 67.5 s	Mo 104 60 s	Mo 105 35.6 s	Mo 106 8.73 s	Mo 107 3.5 s	Mo 108 1.105 s	Mo 109 700 ms	Mo 110 292 ms	Mo 111 193.6 ms	Mo 112 125 ms	Mo 113 80 ms	Mo 114 58 ms	Mo 115 45.5 ms	Mo 116 32 ms
	Nb 81 <44 ns	Nb 82 50 ms	Nb 83 3.9 s	Nb 84 9.8 s	85 Nb 3.3 s 20.5 s	86 Nb 56.3 s 88 s	87 Nb 2.6 m 3.7 m	88 Nb 7.7 m 14.50 m	89 Nb 1.10 h 2.03 h	90 Nb 18.81 s 14.60 h	Nb 91 680 y	92 Nb 10.15 d 34.7 My	93 Nb 16.12 y stable	Nb 94 20.4 ky	Nb 95 34.991 d	Nb 96 23.35 h	Nb 97 72.1 m	Nb 98 2.86 s	Nb 99 15.0 s	Nb 100 1.5 s	Nb 101 7.1 s	Nb 102 4.3 s	Nb 103 1.5 s	Nb 104 4.9 s	Nb 105 2.95 s	Nb 106 1050 ms	Nb 107 289 ms	Nb 108 198 ms	Nb 109 106.9 ms	Nb 110 82 ms	Nb 111 54 ms	Nb 112 38 ms	Nb 113 32 ms	Nb 114 17 ms	Nb 115 23 ms
40	Zr 80 4.6 s	Zr 81 5.5 s	Zr 82 32 s	Zr 83 42 s	Zr 84 25.8 m	85 Zr 10.9 s 7.86 m	Zr 86 16.5 h	87 Zr 14.0 s 1.68 h	Zr 88 83.4 d	89 Zr 4.161 m 78.41 h	Zr 90 51.45%	Zr 91 11.22%	Zr 92 17.15%	Zr 93 1.61 My	Zr 94 stable	Zr 95 64.032 d	Zr 96 23 Ey	Zr 97 16.749 h	Zr 98 30.7 s	Zr 99 2.1 s	Zr 100 7.1 s	Zr 101 2.3 s	Zr 102 2.9 s	Zr 103 1.38 s	Zr 104 920 ms	Zr 105 670 ms	Zr 106 178.6 ms	Zr 107 145.7 ms	Zr 108 78.5 ms	Zr 109 56 ms	Zr 110 37.5 ms	Zr 111 24.0 ms	Zr 112 43 ms		74
	Y 79	Y 80	Y 81	Y 82	Y 83	Y 84	Y 85	Y 86	Y 87	Y 88	Y 89	Y 90	Y 91	Y 92	Y 93	Y 94	Y 95	Y 96	Y 97	Y 98	Y 99	Y 100	Y 101	Y 102	Y 103	Y 104	Y 105	Y 106	Y 107	Y 108	Y 109		72		

It’s not possible to get independent cross section measurements for many of the products produced using using the stacked target approach, so a different approach is needed!

Recent measurement of Tl(p,xg) ^{202}Pb via prompt gamma ray spectroscopy





Neutron Detectors

Target
(in vacuum)

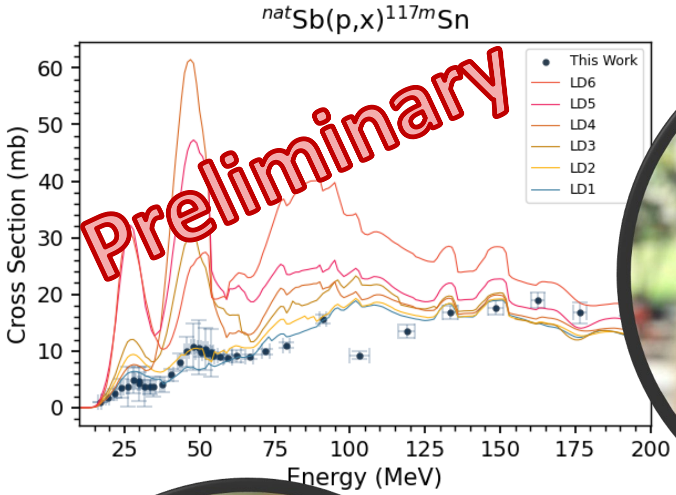
Beam

HPGe Detectors

Our first in-beam experiment in August 2022 focused on ^{nat}Tl(p,x)^{202g}Pb ($t_{1/2}$=52.5 ky) which is hard-to-impossible to measure via activation

Limitations to Residual Product-Based Fitting

- This approach can’t be used to fit to any products which are stable, lack observable decay gammas, or are too short-lived (< 10ish minutes)
  - We need something beyond the stacked-foil technique!



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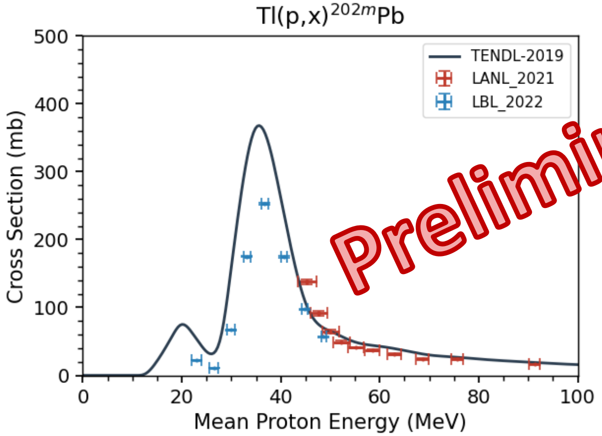
Isotope Production

Isotope	Target	Beam	Measurement focus	Energy range	Site	Year
^{72}Se, ^{68}Ge	^{75}As	p	Primary: ^{72}Se, ^{68}Ge Impurities: ^{70,71,73,75}Se, ^{66,67,69,71}Ge	Up to 200 MeV	All	1
^{202}Pb	^{205}Tl	p,d	Primary: ^{202m,202g}Pb Impurities: $^{198\text{-}205}$Pb	Up to 200 MeV	All	2
^{202}Pb	^{203}Tl	p,d	Primary: ^{202m,202g}Pb Impurities: $^{198\text{-}203}$Pb	Up to 200 MeV	All	3
^{119}Te, ^{117m}Sn	^{nat}Sb	p,d	Primary: ^{119m,119g}Te, ^{117m}Sn Impurities: $^{116\text{-}118,121m/g,123m}$Te, $^{113,119m,121m/g}$Sn	Up to 200 MeV	All	4
^{134}Ce	^{nat}La	p,d	Primary: ^{134}Ce Impurities: ^{132,133,133,137,139}Ce	Extend to 200 MeV	LANL, BNL	4

Stay tuned!

Michael Skulski

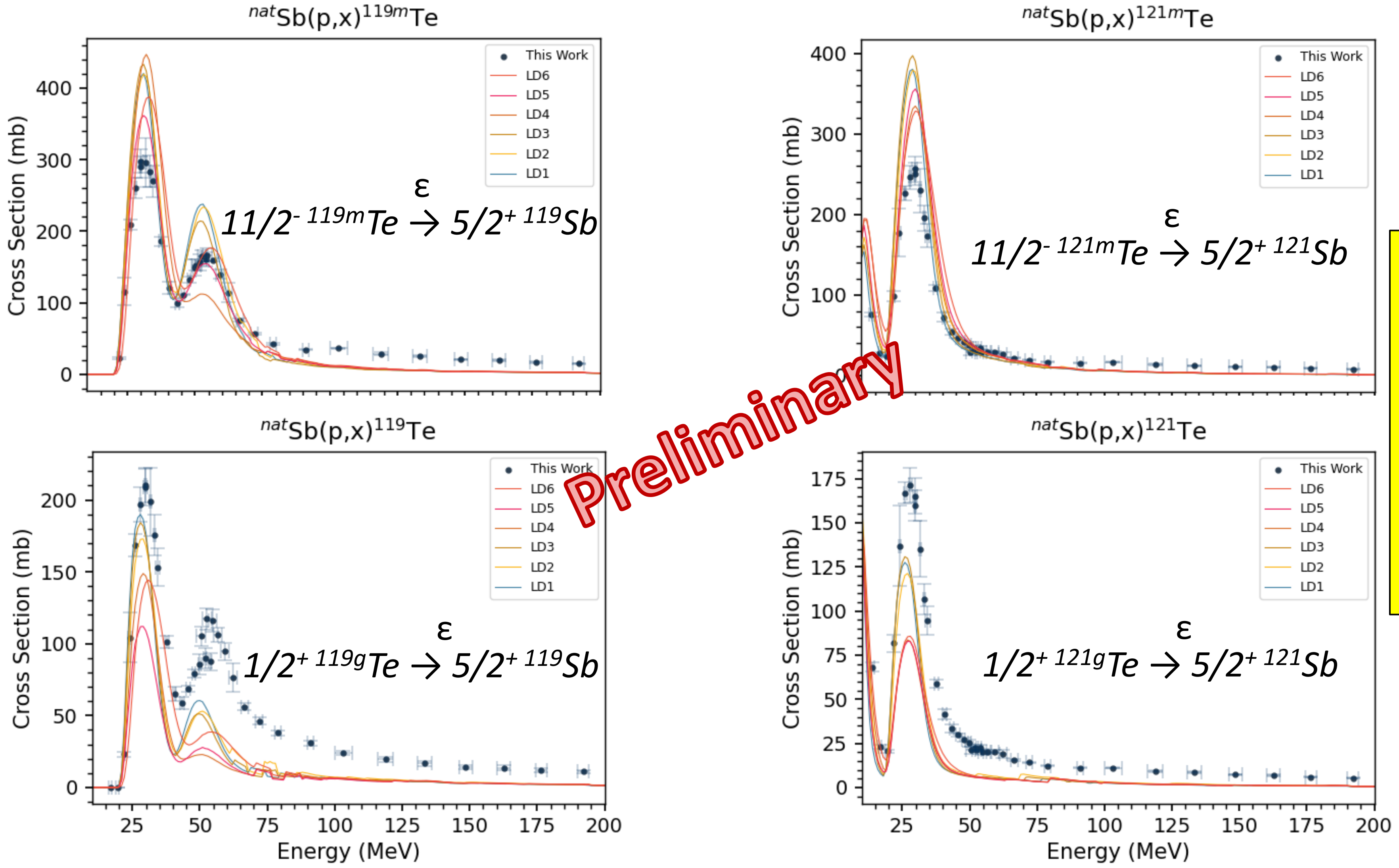


Flux Monitoring

Nuclear reaction	Energy range	Site	Year
^{nat}Ti(p,x)^{48}V	Extend to 200 MeV	All	2
^{nat}Nb(p,4n)^{90}Mo	Up to 200 MeV	BNL	Out years

*M. B. Fox *et al.*, *PRC, 103(3):034601, 2021 & PRC 104, 064615 (2021)*

Isomer Population Modeling for Sb(p,xn)



Both phenomenological & microscopic LD models overpredict Te isomer population and underpredict g.s., even with adjustments

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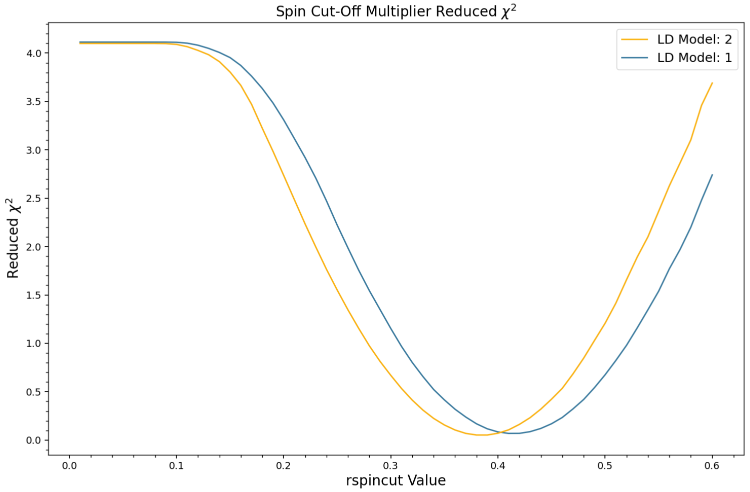
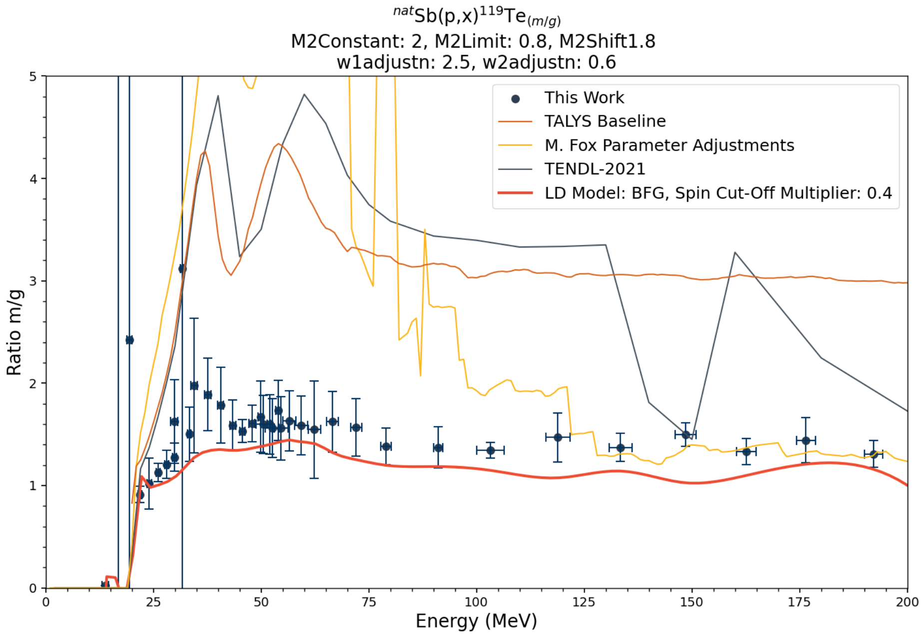
Adjustments to the Spin Cut-Off Parameter (BFM / ldmodel 2)

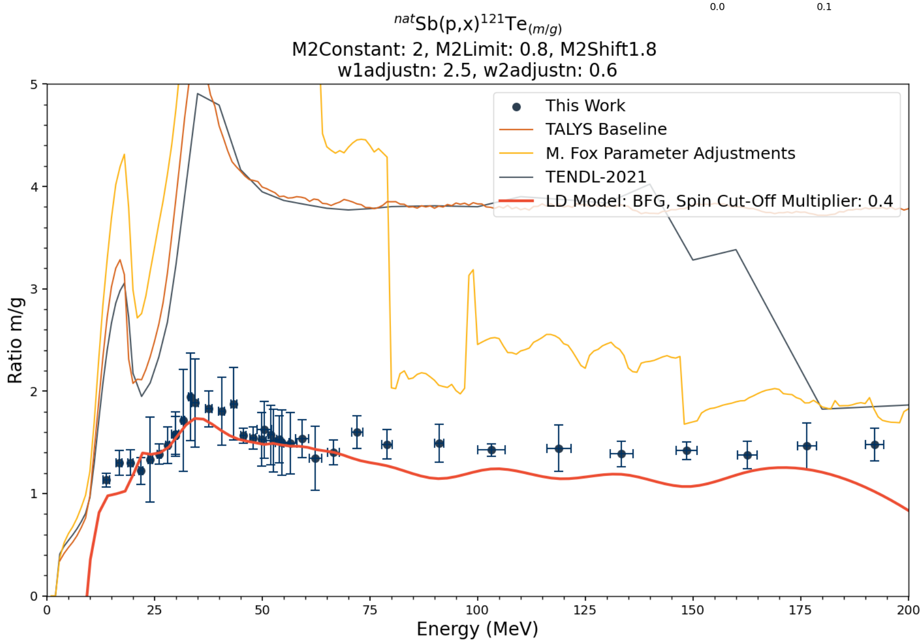
- TALYS provides the variables **Rspincut**, which functions as a global adjustment applied to the spin cut-off parameter:

$$\sigma_F^2(E_x) = 0.01389\frac{A^{\frac{5}{3}}}{\tilde{a}}\sqrt{aU}$$

Local minimum near 0.4







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Beyond Rspincut: Other Parameters to Consider

OMP adjustments to the imaginary volume term:

- **W1adjust, w2adjust** adjustments to imaginary volume term

PE reaction adjustments:

- **M2Constant, M2Limit, M2Shift** previously explored
- **Rpipi, rpinu, rnupi, rnunu** adjustments based on residual nucleon-nucleon interactions

$$W_V(E) = w_1^n \frac{(E-E_f^n)^2}{(E-E_f^n)^2+(w_2^n)^2}$$

$$\begin{aligned} M^2_{\pi\pi} &= R_{\pi\pi}M^2, \\ M^2_{\nu\nu} &= R_{\nu\nu}M^2, \\ M^2_{\pi\nu} &= R_{\pi\nu}M^2, \\ M^2_{\nu\pi} &= R_{\nu\pi}M^2. \end{aligned}$$

Variable	Default	Adjusted
$R_{\pi\nu}$	1	1.5
$R_{\pi\pi}$	1	1
$R_{\nu\pi}$	1	1.5
$R_{\nu\nu}$	1.5	1.5
W1adjust n	1	2.5
W2adjust n	1	0.6
M2Constant	1	2
M2Limit	1	0.8
M2Shift	1	1.8

Preliminary

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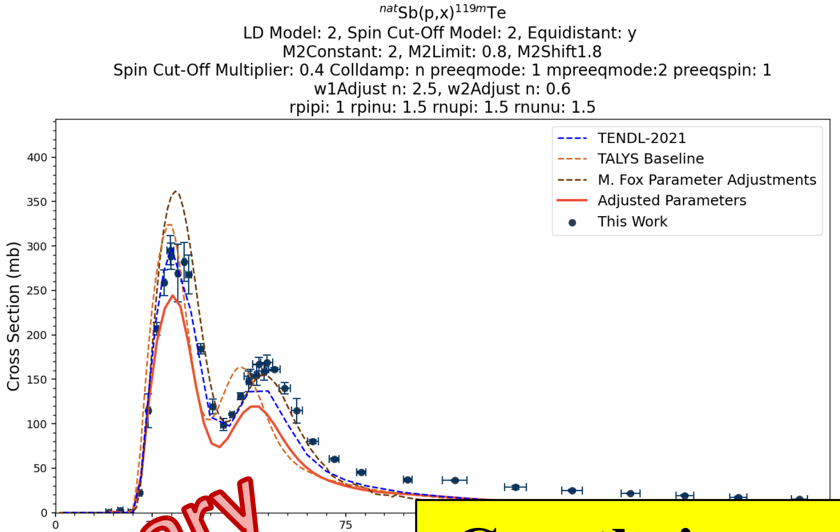
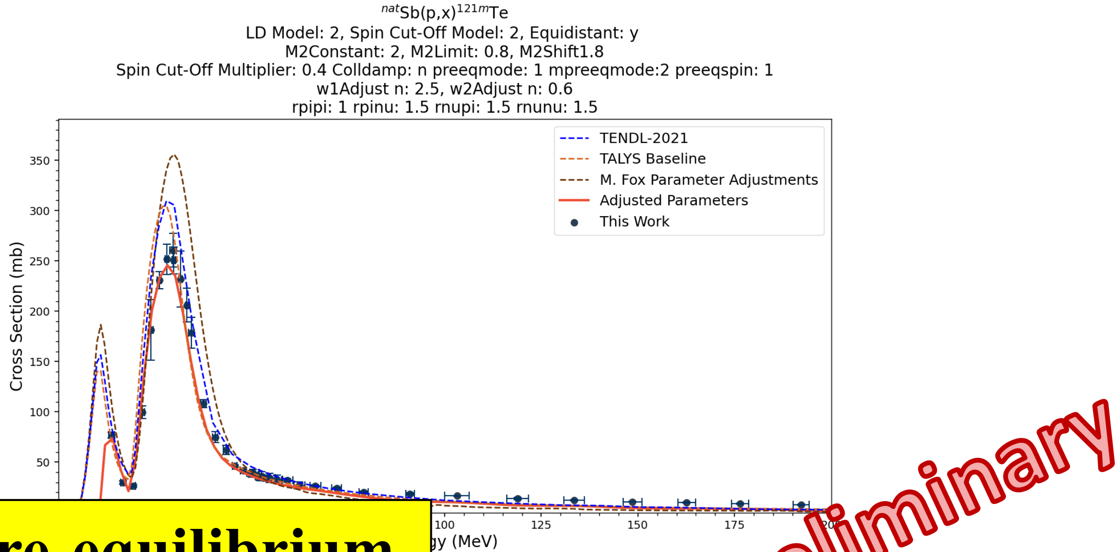
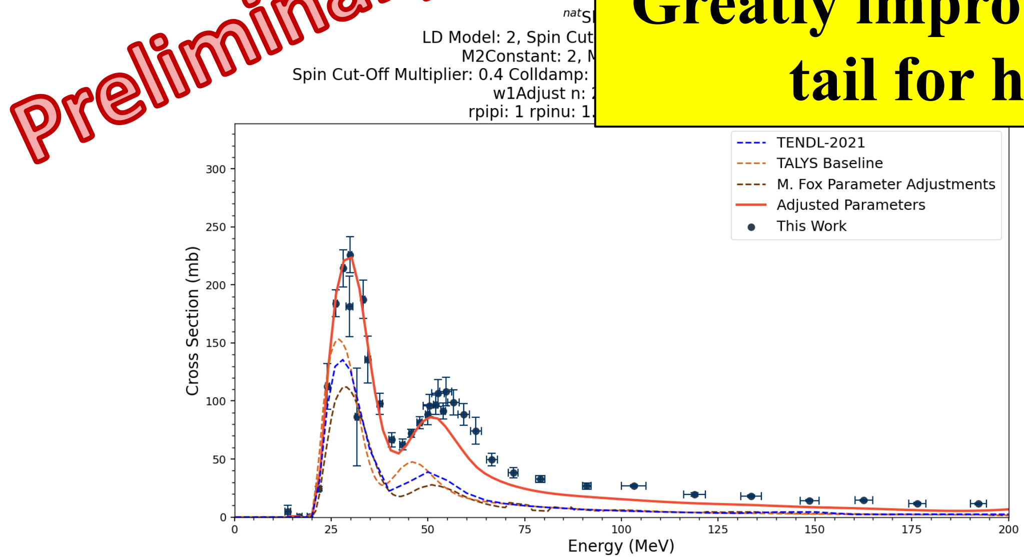
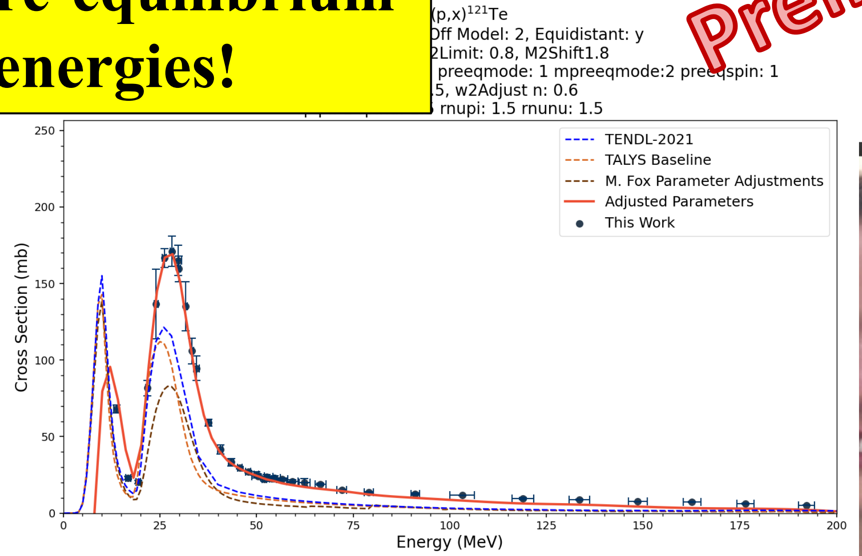
Beyond Rspincut: Other Parameters to Consider





Greatly improved fitting of pre-equilibrium tail for higher incident energies!





Catherine Apgar

Thank you for your attention!

Andrew S. Voyles[1], **Catherine E. Apgar[1]**, Jon C. Batchelder[1], Lee A. Bernstein[1,2], Eva R. Birnbaum[3], Cathy S. Cutler[4], **Morgan B. Fox**[1], Arjan Koning[5], Amanda M. Lewis[1], Dmitri Medvedev[4], Jon T. Morrell[3], F. Meiring Nortier[3], Ellen O'Brien[3], Michael A. Skulski[4], and Etienne Vermeulen[3]

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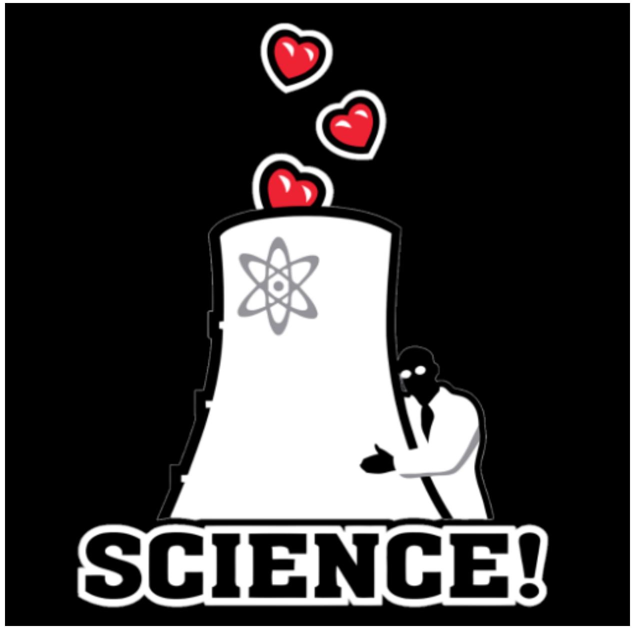
[4] *Brookhaven National Laboratory*
[5] *International Atomic Energy Agency*



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