Measurements and Reaction Modeling for Proton Bombardment on Natural Antimony

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Berkeley, CA

Introduction

University Affiliation:
University of California, Berkeley

Standing:
PhD Candidate, Nuclear Engineering

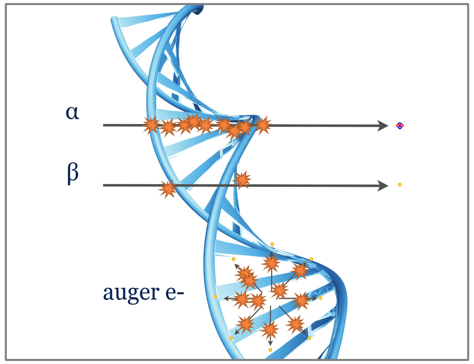
Research Focus:
Medical padioisotope production
Nuclear data
Charged particle reaction modeling

Lab Affiliation:
Los Alamos National Lab
Lawrence Berkeley National Lab
Brookhaven National Lab

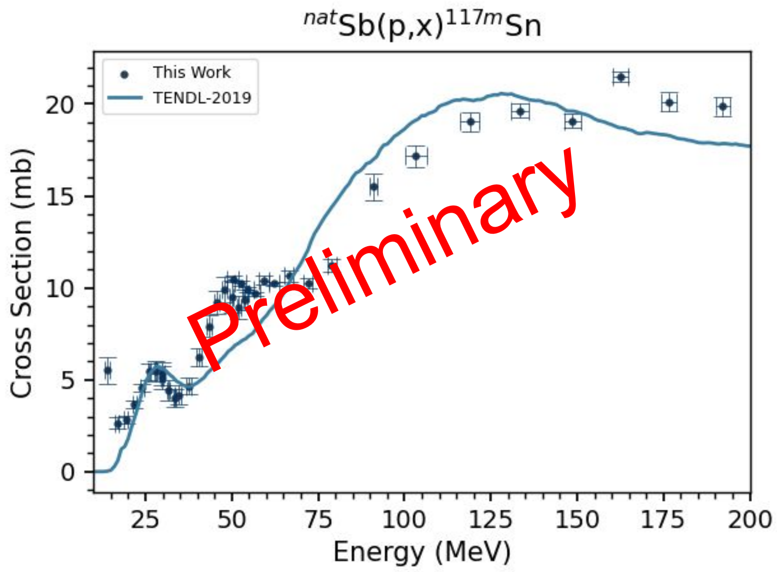


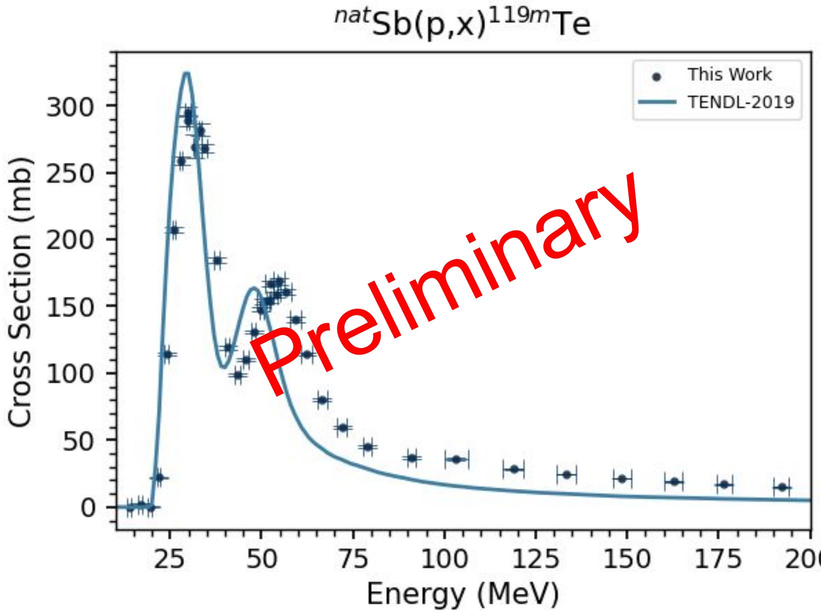
Motivation: Nuclear Medicine

- Cross section measurements of **^{117m}Sn** and **^{119m}Te** (a cow for **^{119}Sb**) to optimize production for high SA with minimal impurities
  - These products can be produced via ^{nat}Sb(p,x)



Primary Isotopes:
^{119m,119g}Te, ^{117m}Sn
Potential Impurities:
^{116,117,118,121m,121g,123m}Te,
^{113,119m,121m,121g}Sn





This is a compelling motivation, but there's more!

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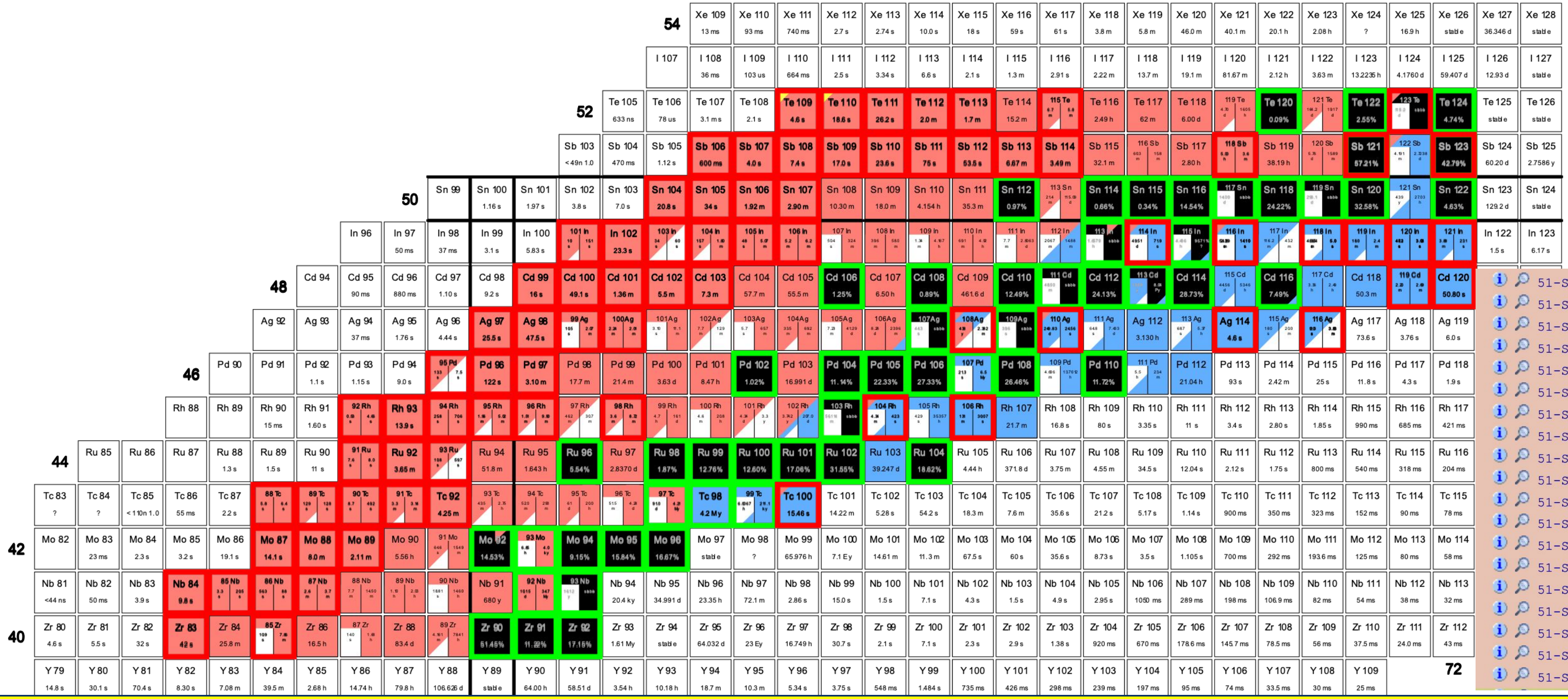
Motivation: Sb(p,x) Reaction Modeling

Incident proton energy up to 200 MeV opens channels for 200+ potential products!



Sb(p,x)

```
51-SB-0(P,X)49-IN-111,CUM,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)49-IN-114-M,,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)50-SN-113,CUM,SIG  C4: MF=3   MT=9000 Op=0
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51-SB-0(P,X)51-SB-120-M,,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)51-SB-122,,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)52-TE-117,,SIG  C4: MF=3   MT=9000 Op=0
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51-SB-0(P,X)52-TE-119-M,,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)52-TE-121,,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)52-TE-121-G,,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)52-TE-121-G,M-,SIG  C4: MF=3   MT=?   Op=0
51-SB-0(P,X)52-TE-121-M,,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)52-TE-123-M,,SIG  C4: MF=3   MT=9000 Op=0
51-SB-0(P,X)9-F-18,,SIG  C4: MF=3   MT=9000 Op=0
```

We can use this data to improve our reaction modeling capabilities!

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Experimental Setup: Overview

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*.

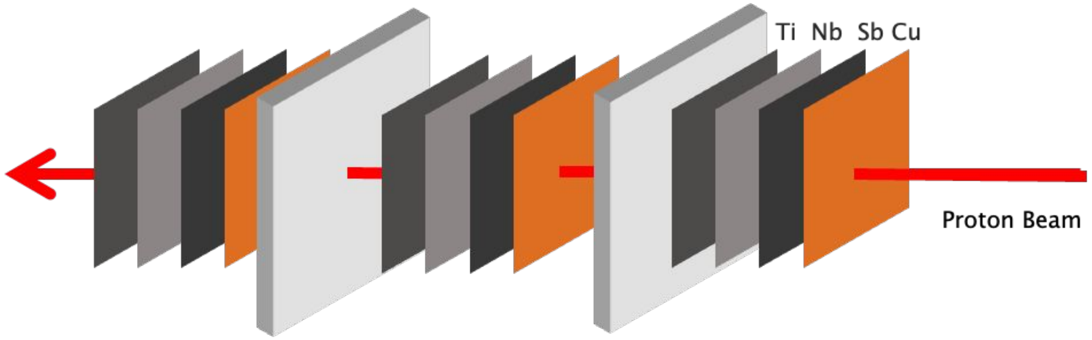
LBNL 88-Inch Cyclotron
$E_{p,max}$ = 60 MeV

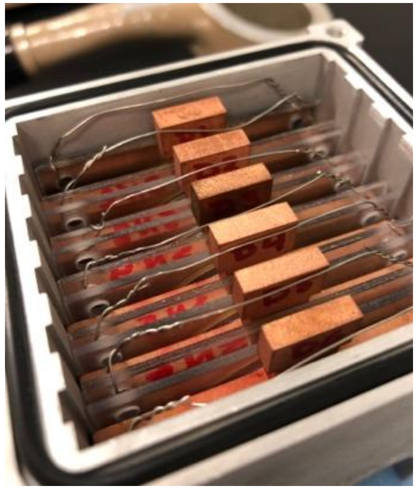
LANL IPF
$E_{p,max}$ = 100 MeV

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

Experimental Setup: Stacked Target Measurements

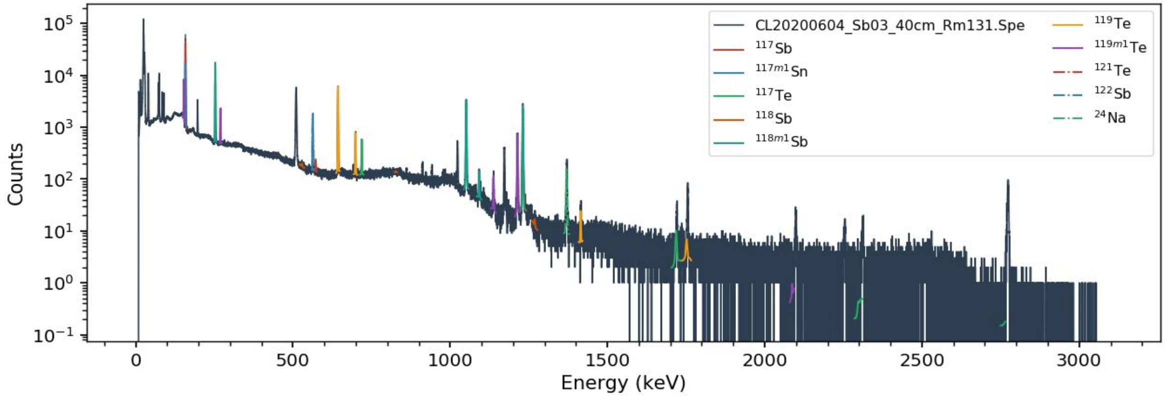
Target stack irradiated with 150 nA proton beam





Beam boxes at LBNL, BNL

Foils removed and counted on HPGe detectors



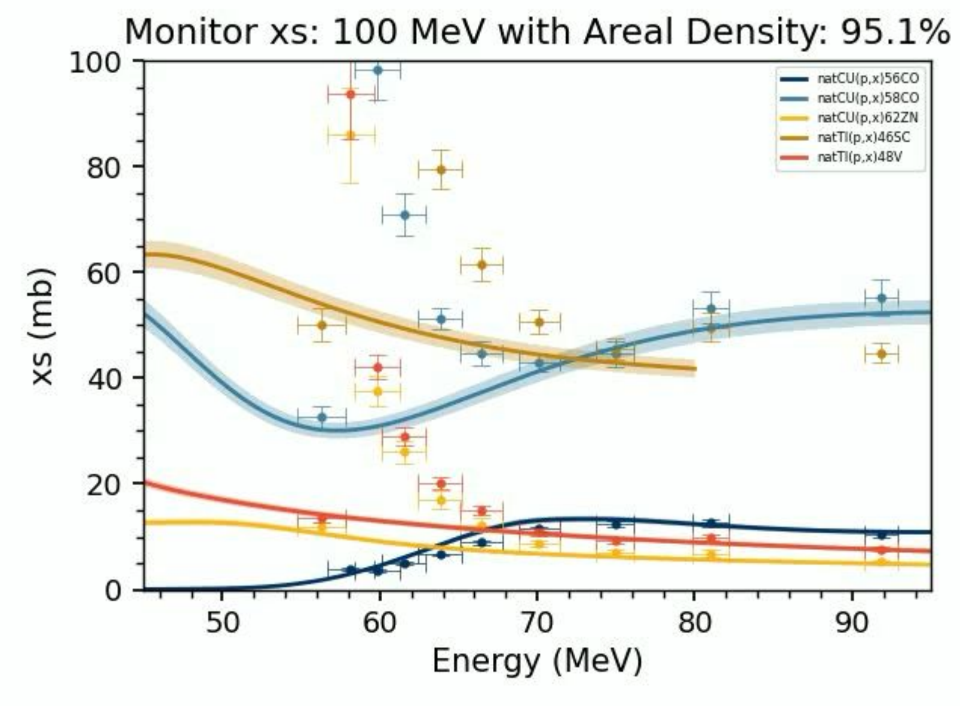
Sample gamma spectrum of irradiated Sb, with products identified

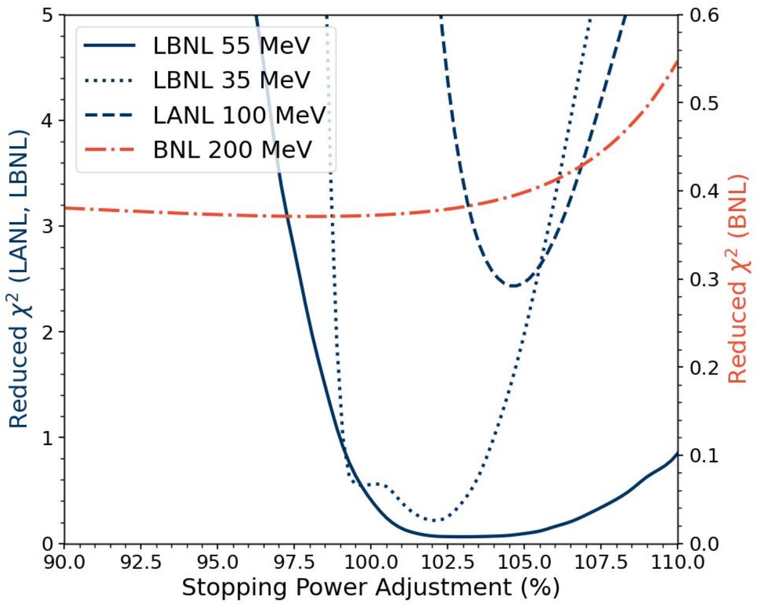
Experimental Analysis: Determining Current

Nominally varying the areal density of the stack materials provides a better representation of current and energy in each bin reduces systematic uncertainty due to range straggling and limitations in stopping power characterization.

This variance minimization technique has been utilized *in Graves et al., Voyles et al., Fox et al., and Morrell et al.*

$$I = \frac{A_0}{\rho \Delta x (1 - e^{-\lambda t}) \int \sigma(E) \frac{d\phi}{dE} dE}$$





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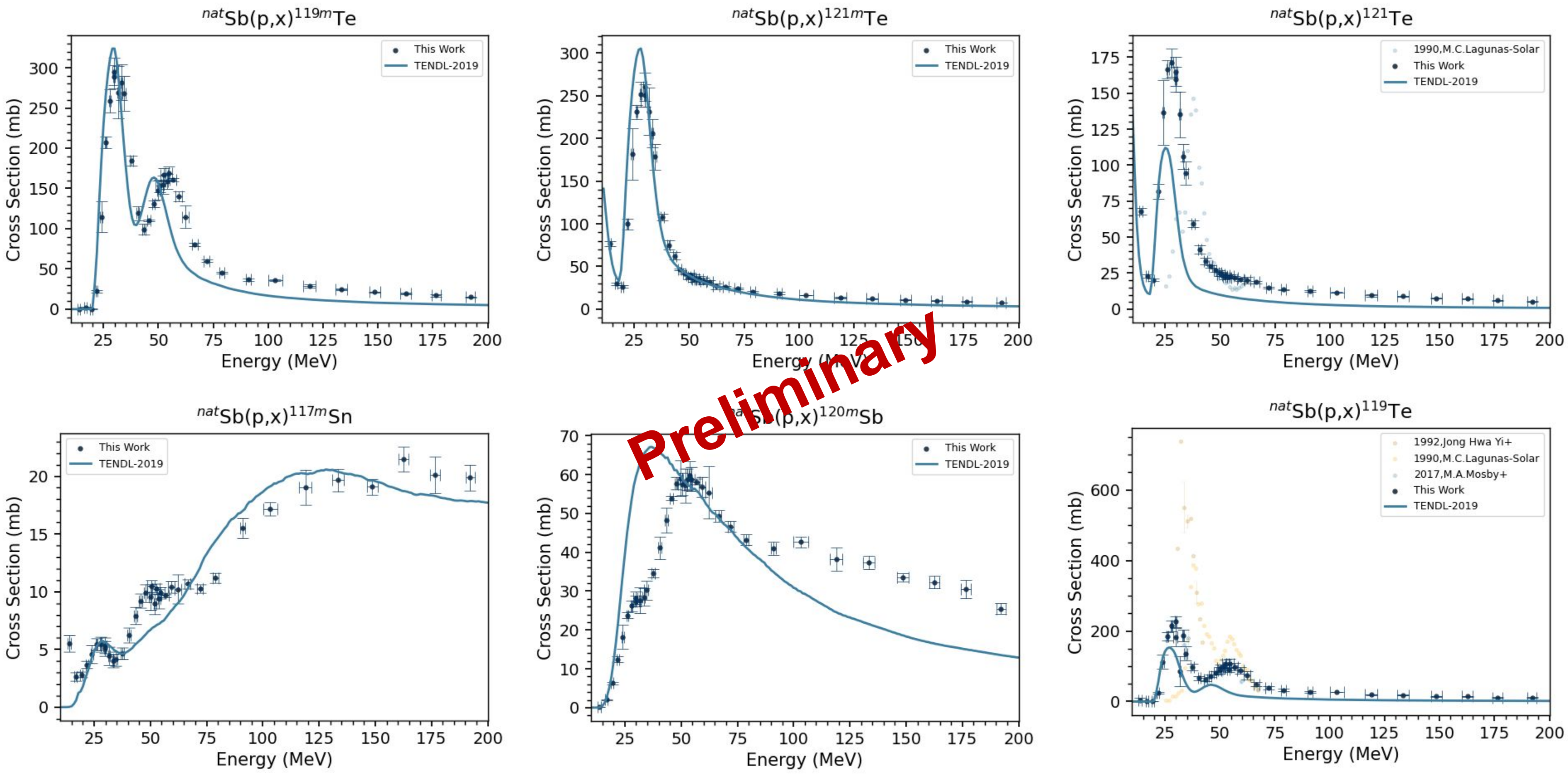
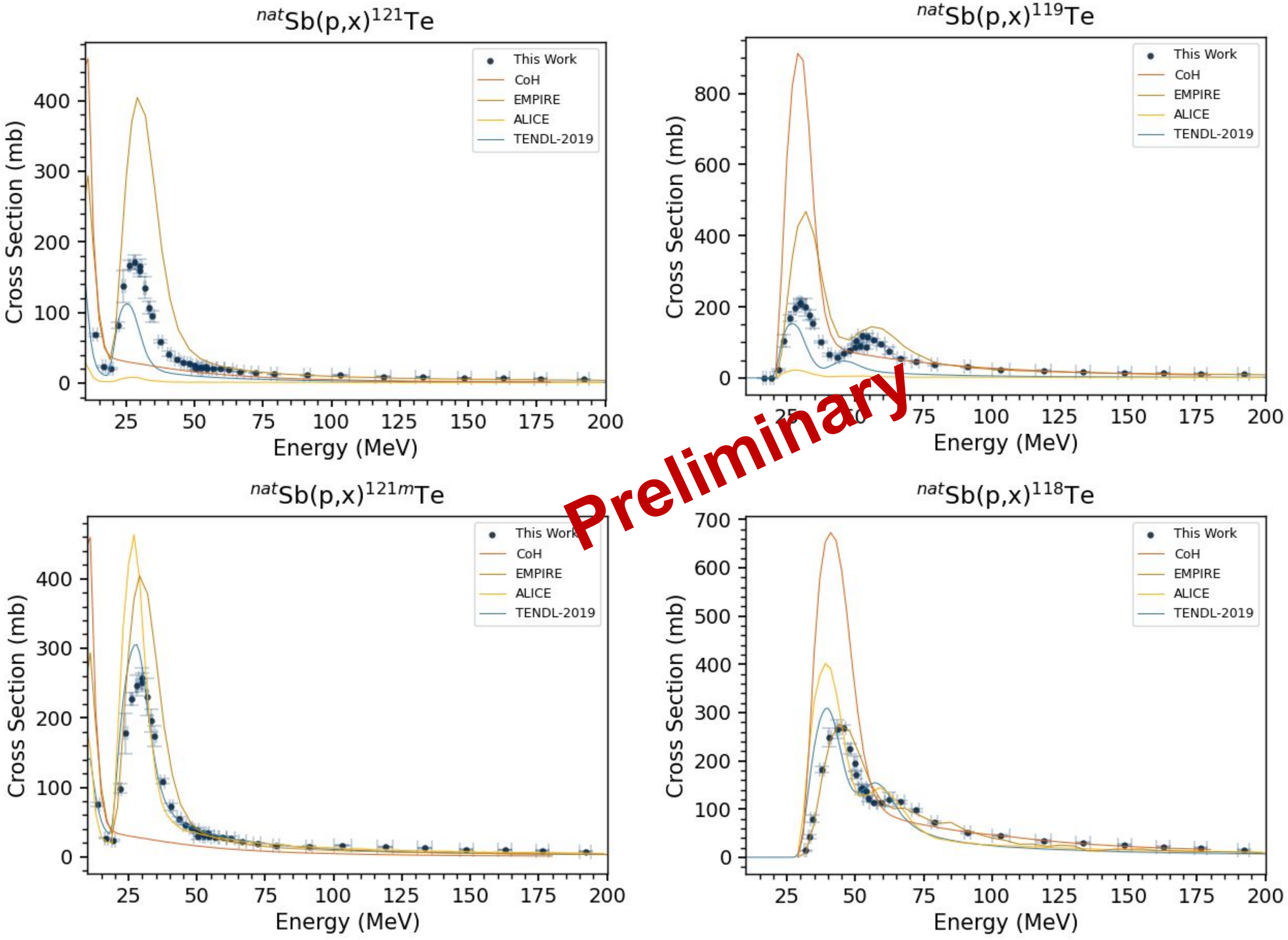
Experimental Analysis: Cross Section Measurements



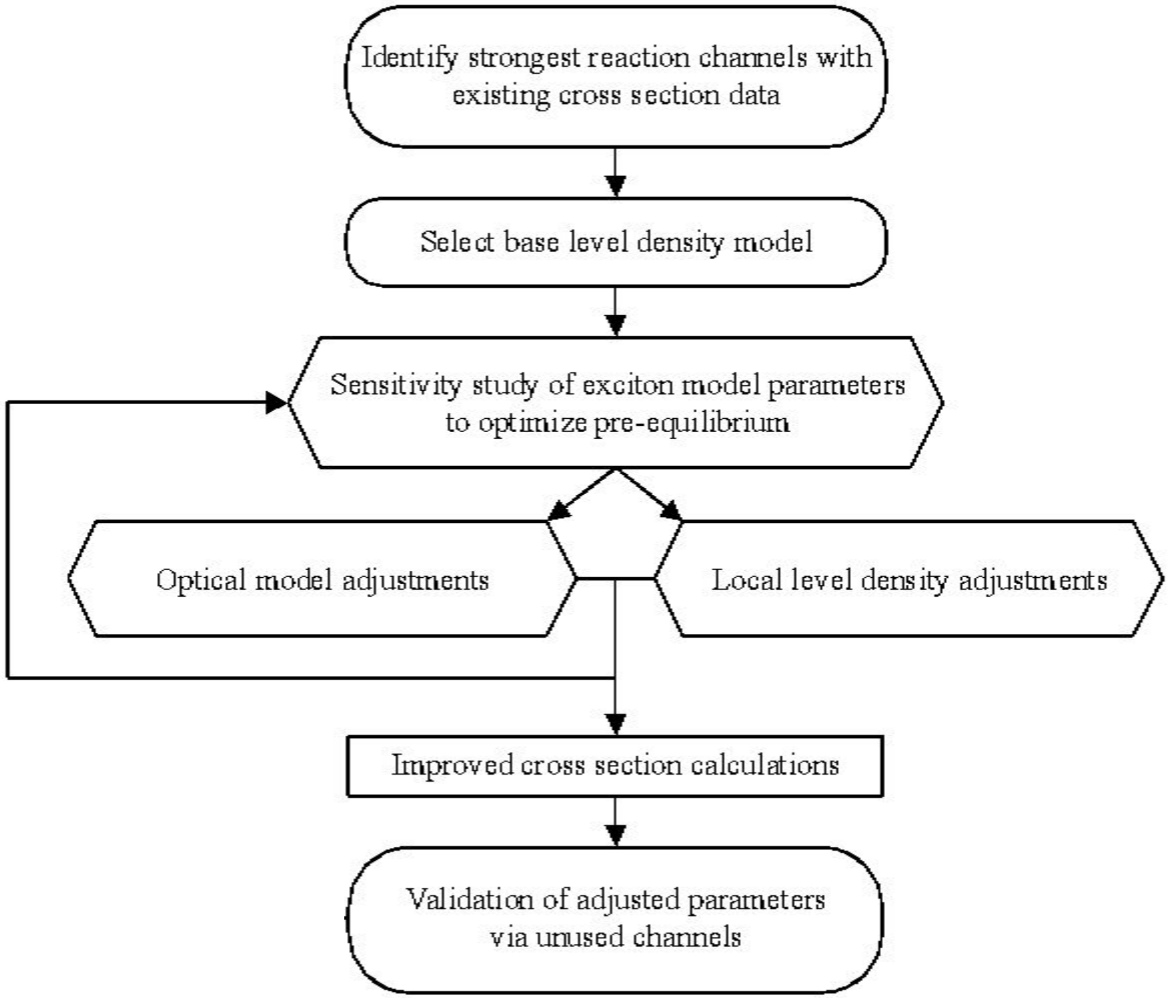
Reaction Modeling: Introduction



Compared experimental results to standard inputs for:

- ALICE 3.5.3
- CoH 3.2.3
- EMPIRE 3.2.3
- TENDL 2019

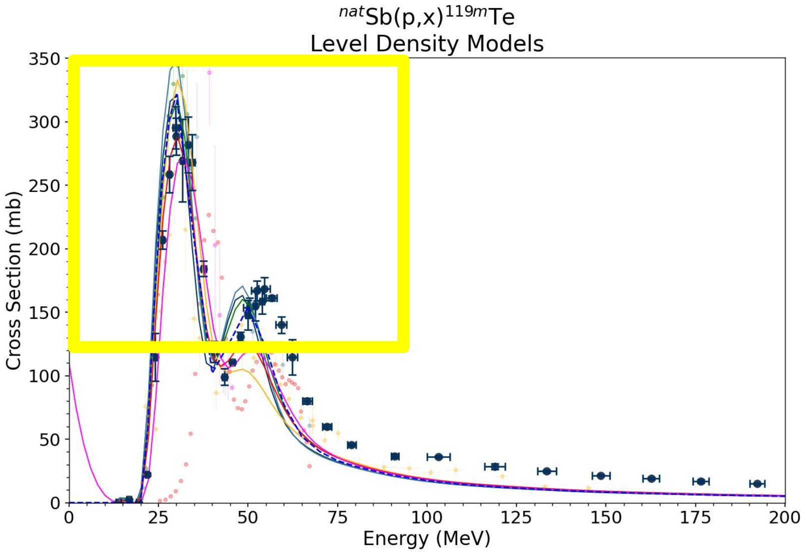
Reaction Modeling: Evaluation for (p,x) reactions

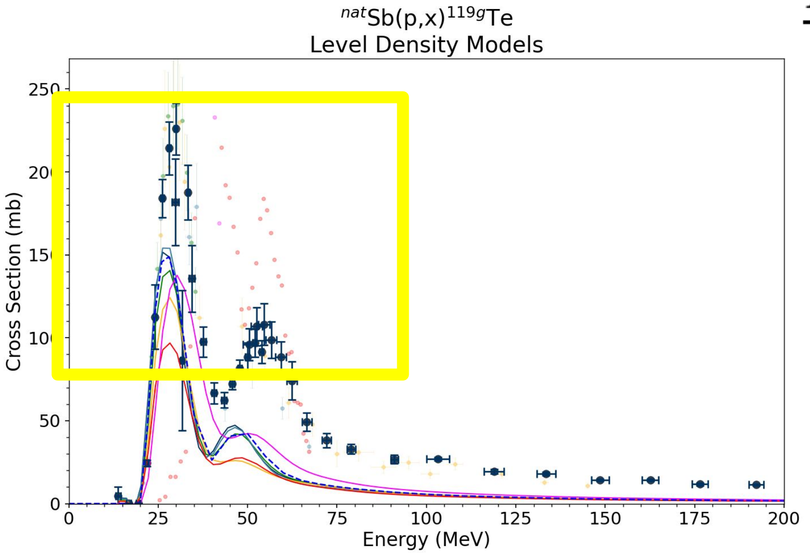


Courtesy Fox et al. 2021

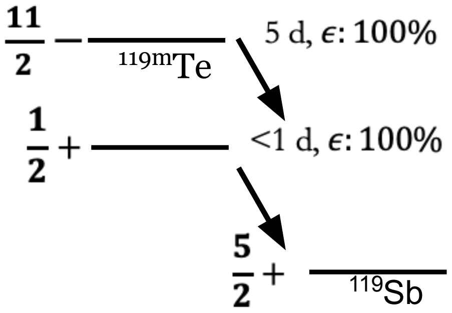
- Iterative approach
  - Select level density model
  - Adjust level density models
  - Adjust pre-equilibrium parameters
  - Adjust optical model potential parameters
  - Sensitivity review on previous adjustments

Reaction Modeling: High Spin Isomers

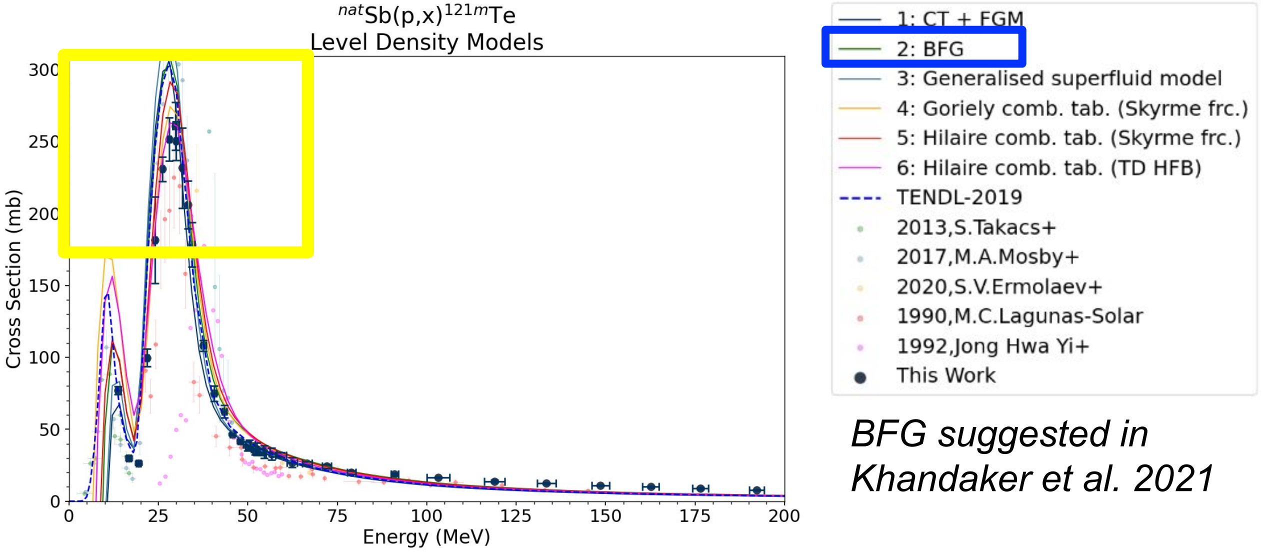




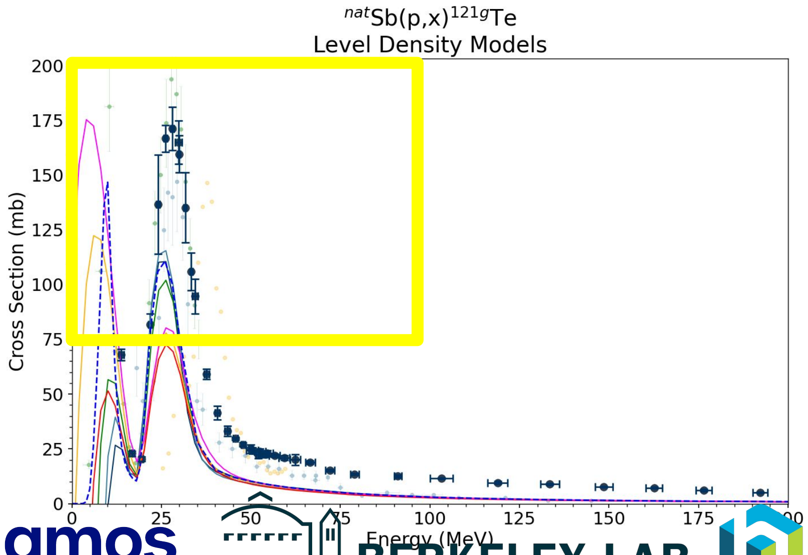
Preliminary



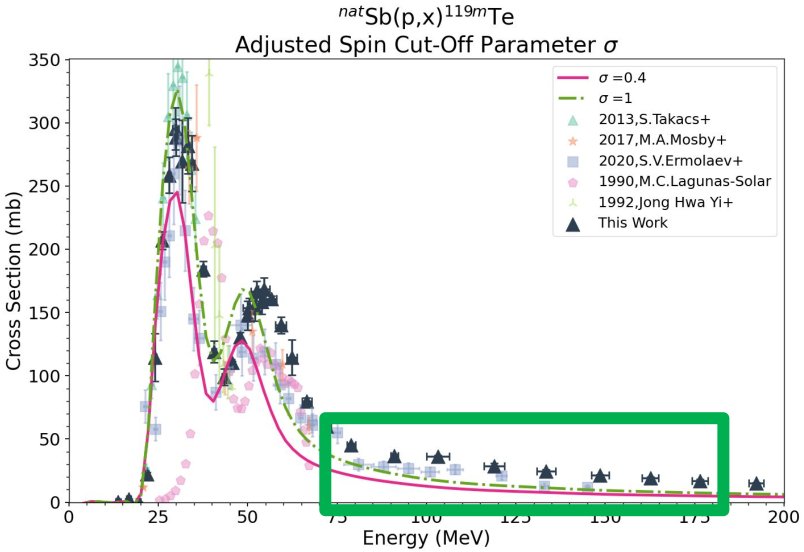
Underprediction for ground states



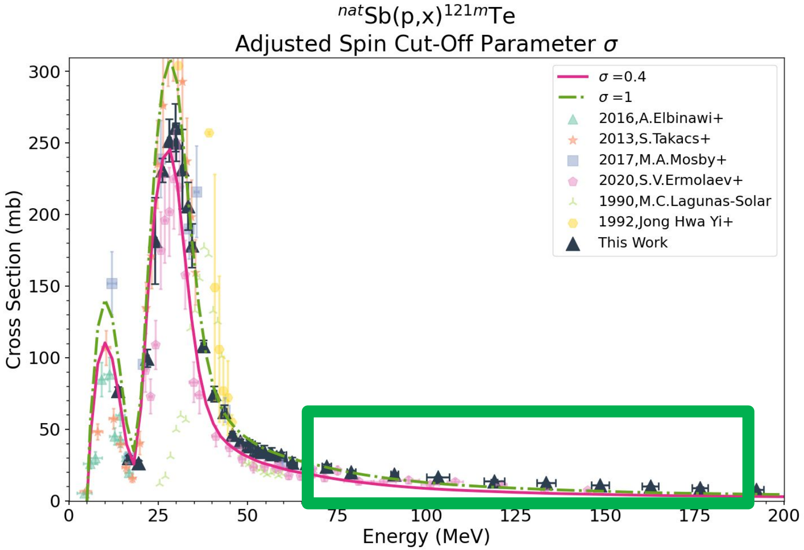
BFG suggested in Khandaker et al. 2021

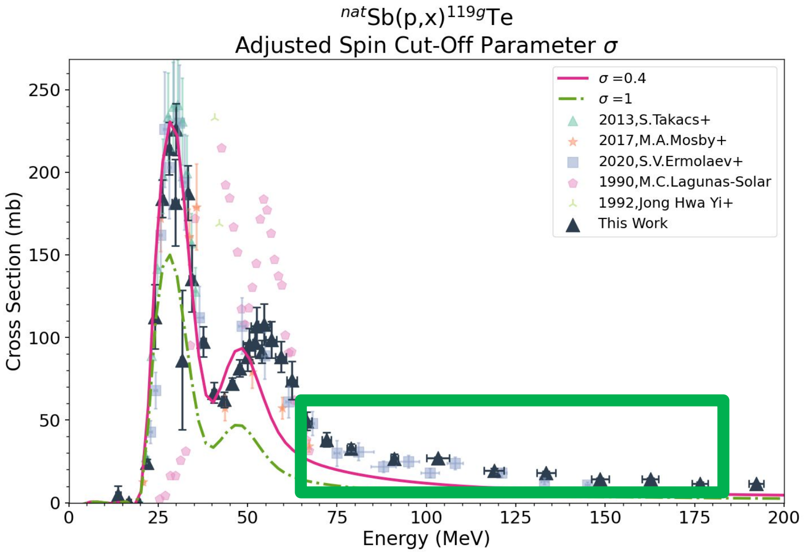


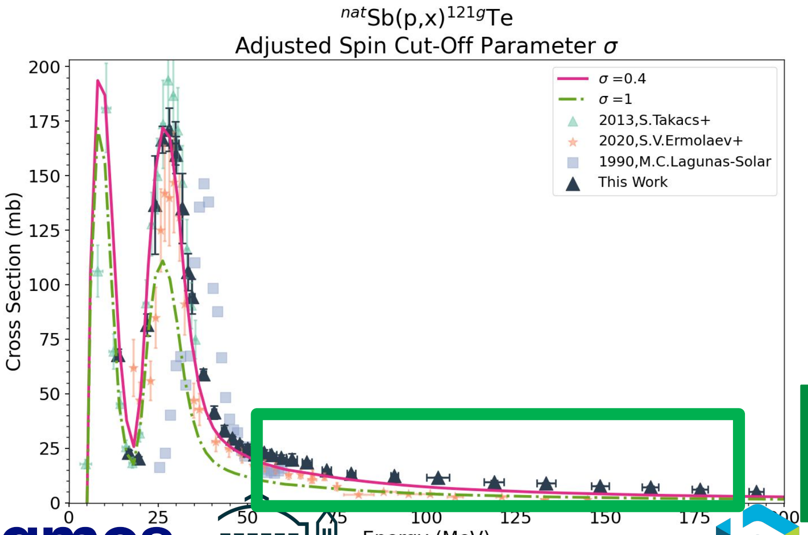
Reaction Modeling: Adjusting the Spin Cut-off Parameter



Preliminary







Consistent under-prediction in

Reaction Modeling: Pre-Equilibrium Parameters

Preequilibrium reaction adjustments -2 component exciton model:

- **M2Constant, M2Limit, M2Shift** previously explored by *Fox et al*. to adjust the effective squared matrix M^2

$$M^2 = \frac{C_1 A_p}{A^3}\left[7.48 C_2 + \frac{4.62 \times 10^5}{\left(\frac{E^{tot}}{n.A_p} + 10.7 C_3\right)^3}\right]$$

- **Rpipi, rpinu, rnupi, rnunu** adjustments based on nucleon-nucleon interactions

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

Variable	Default	Range	Adjusted
M2Constant	1	0-100	2
M2Limit	1	0-100	0.8
M2Shift	1	0-100	1.8
	1	0-100	1.5
	1	0-100	1
	1	0-100	1.5
	1.5	0-100	1.5

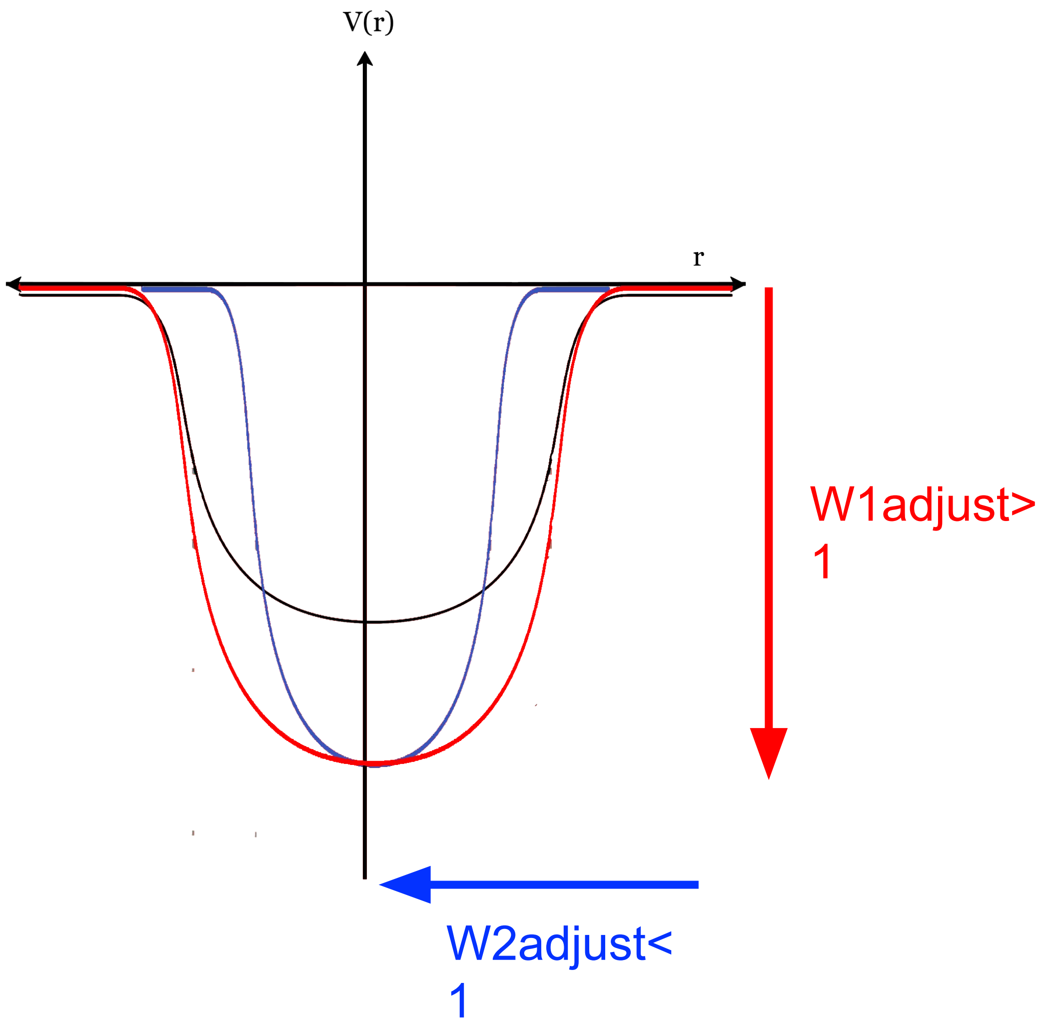
Reaction Modeling: Optical Model Parameters

OMP adjustments to the imaginary volume term:

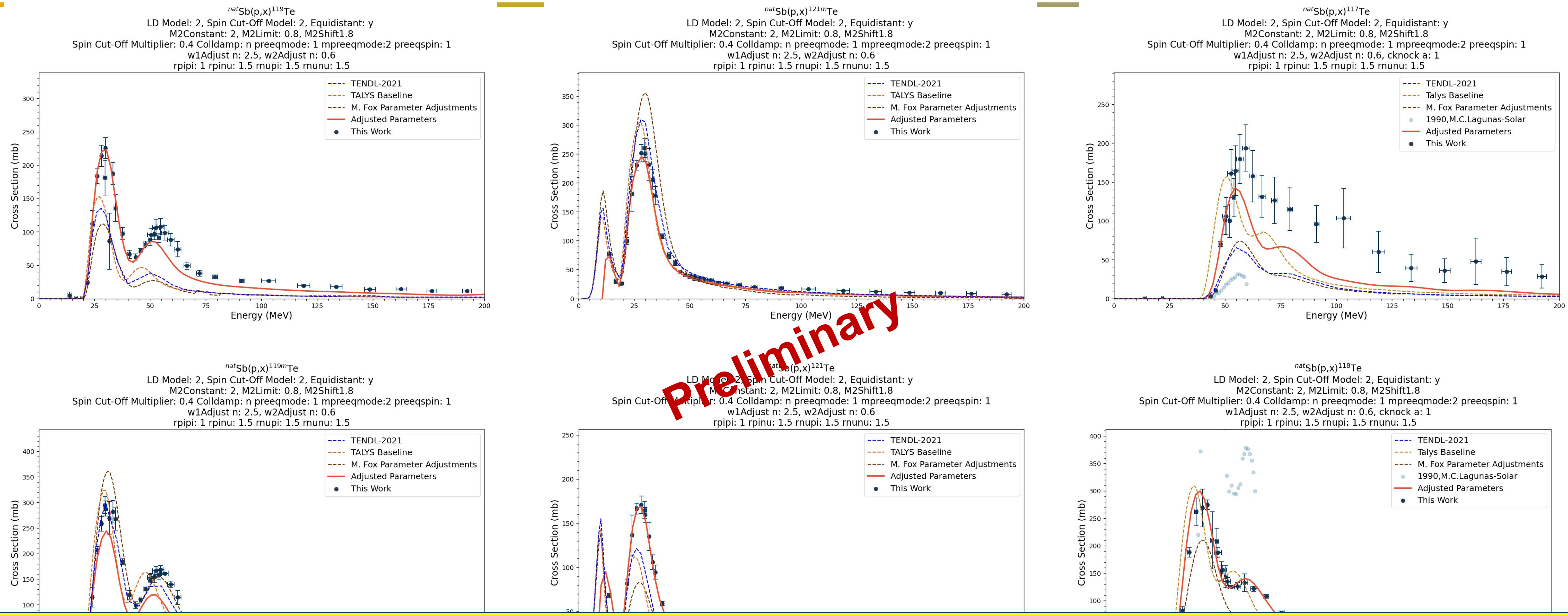
- **W1adjust, w2adjust** adjustments to imaginary volume term

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

Variable	Default	TALYS Range	Adjusted
W1adjust n	1	0.1-10	2.5
W2adjust n	1	0.1-10	0.6



Reaction Modeling: Results

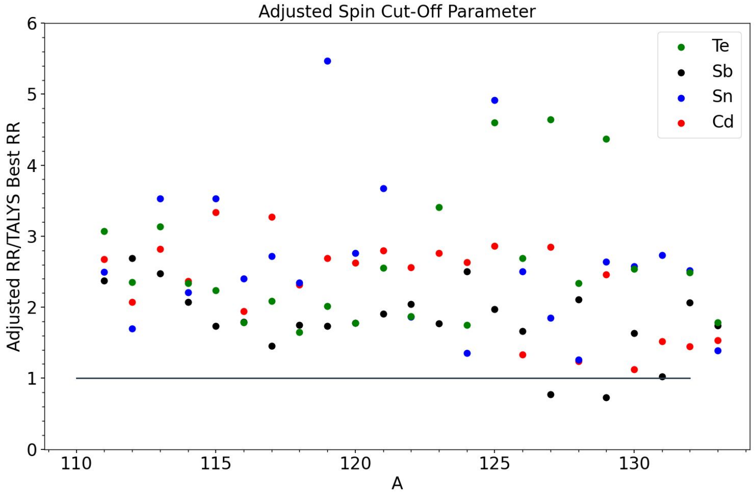


What are the effects of implementing these parameter adjustments?

Reaction Modeling: Results

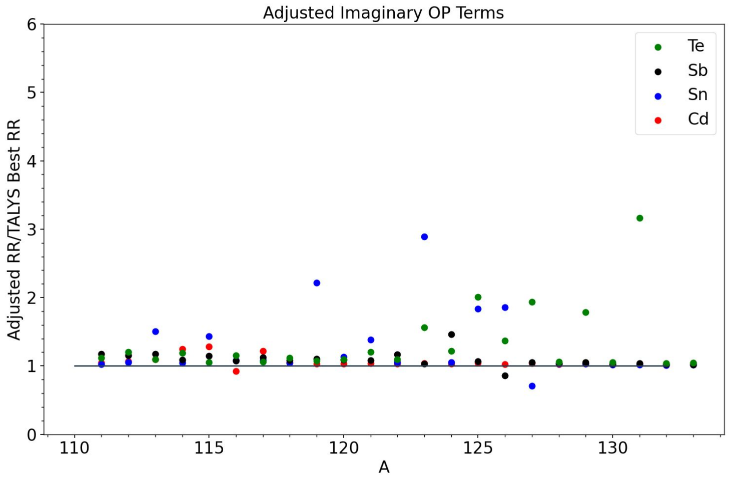
Astrophysical Reaction Rates (n, γ) *at 30 keV*

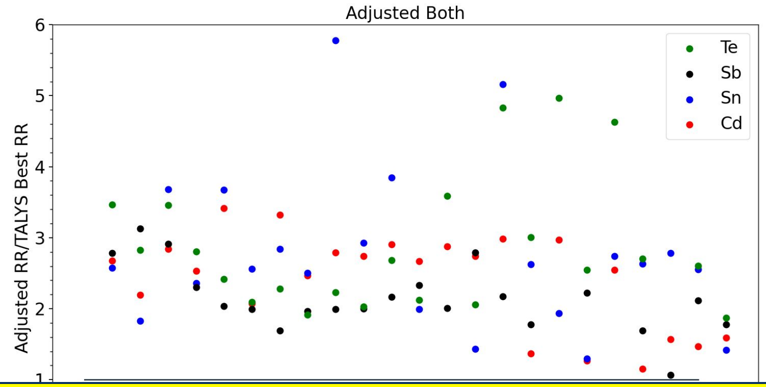
Rspincut=0.4



Preliminary

W1adjust n=2.5, W2adjust n=0.6





Improving reaction models can impact many different nuclear applications!

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The NSSC Experience

NSSC Sponsored Events:

<u>Poster at:</u>

- DOE NNSA University Program Review, *remote* (2021)

Other conferences, workshops, etc. attended w/ funding from NSSC:

<u>Presented at:</u>

- 8th Workshop on Level Density and Gamma Strength, *Oslo NO* (2022)
- 15th International Conference on Nuclear Data for Science and Technology, *remote* (2022)
- Low Energy Community Meeting, *East Lansing, MI* (2023)
- Taking the Temperature (T3) Workshop, *Athens, OH* (2023)
- 10th International Auger Symposium, *Montpellier FR* (2023)
- Radioisotope Production at SNS, *Oak Ridge, TN* (2023)

<u>Poster at:</u>

- Lawrence Livermore National Lab/Rutgers/UCB workshop, *Livermore CA* (2023)

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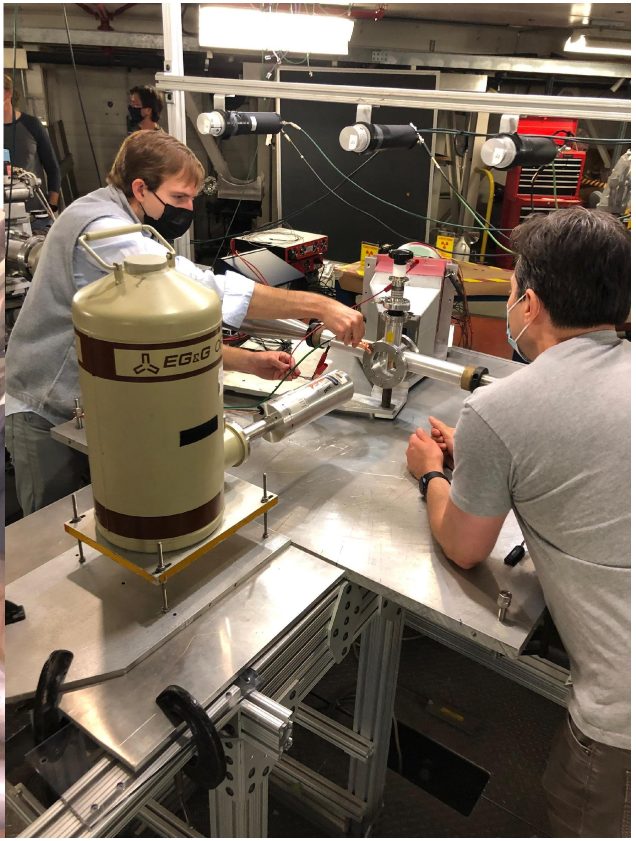
The NSSC Experience

Other research opportunities:

- Performed experiments at Los Alamos National Lab in 2020 and 2021
    - Toured Isotope Production Facility, Countroom, and Weapons Neutron Research facility
- Performed experiments at Brookhaven National Lab in 2021 and 2022
    - Toured Brookhaven LINAC Isotope Producer
- Performed experiments at Lawrence Berkeley National Lab in 2020 and 2022
    - Participated in other experimental work.
- Toured Facility for Rare Isotope Beams at MSU
- Wonderful opportunity to collaborate and network with folks from other universities and national laboratories



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Thank You!

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Andrew Voyles

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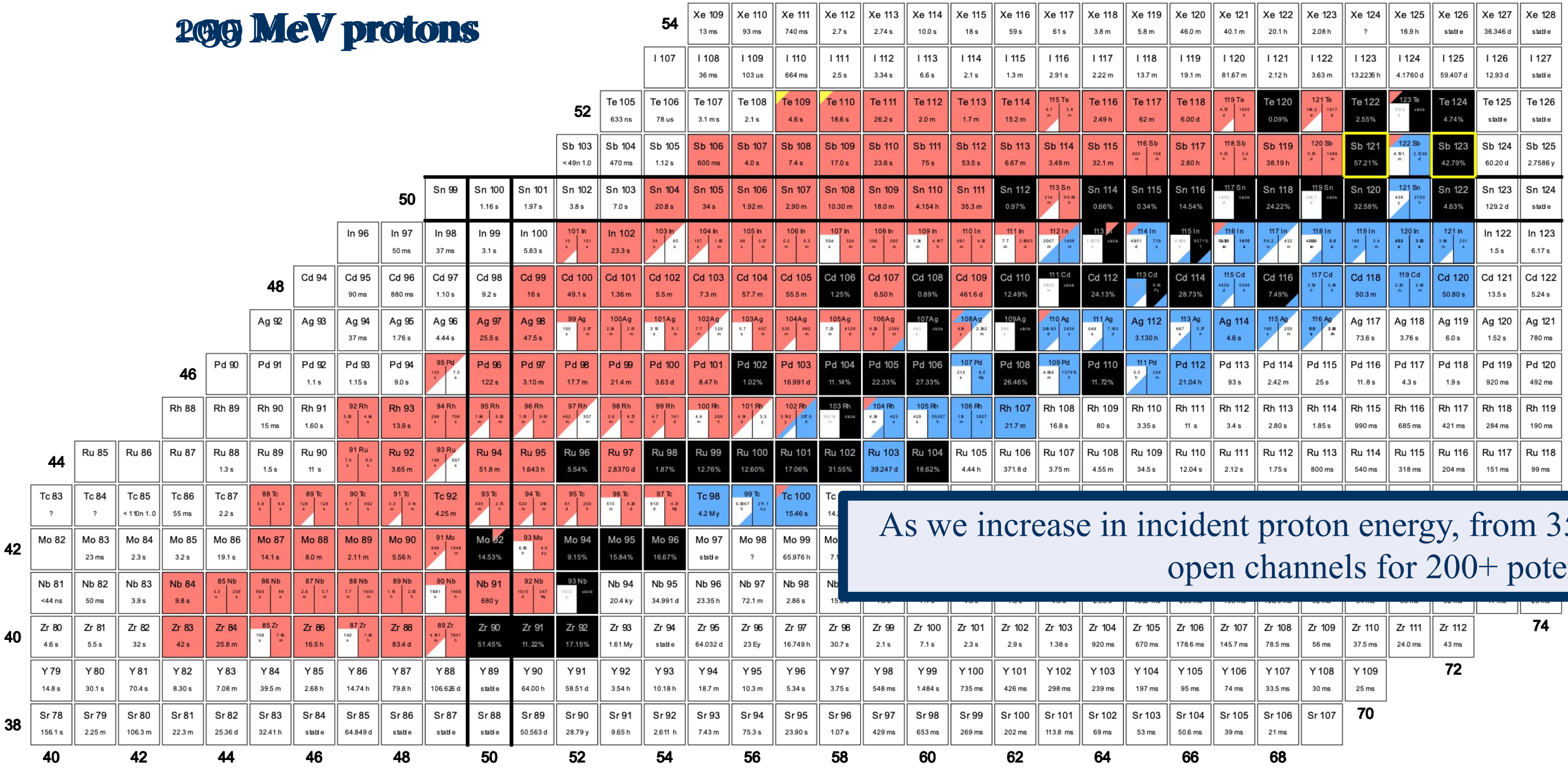
Motivation

200 MeV protons



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