FRIB

First Observation of New Isotopes at FRIB; Reaction Mechanisms for Exotic Nuclei Production

Oleg Tarasov

FRIB

FRIB

8th International Expert Meeting on challenging issues of next-generation high-intensity in-flight separators

January 14–16, 2025; RIKEN Nishina Center, Saitama, Japan

U.S. DEPARTMENT OF ENERGY | Office of Science

MICHIGAN STATE UNIVERSITY

NSF National Science Foundation

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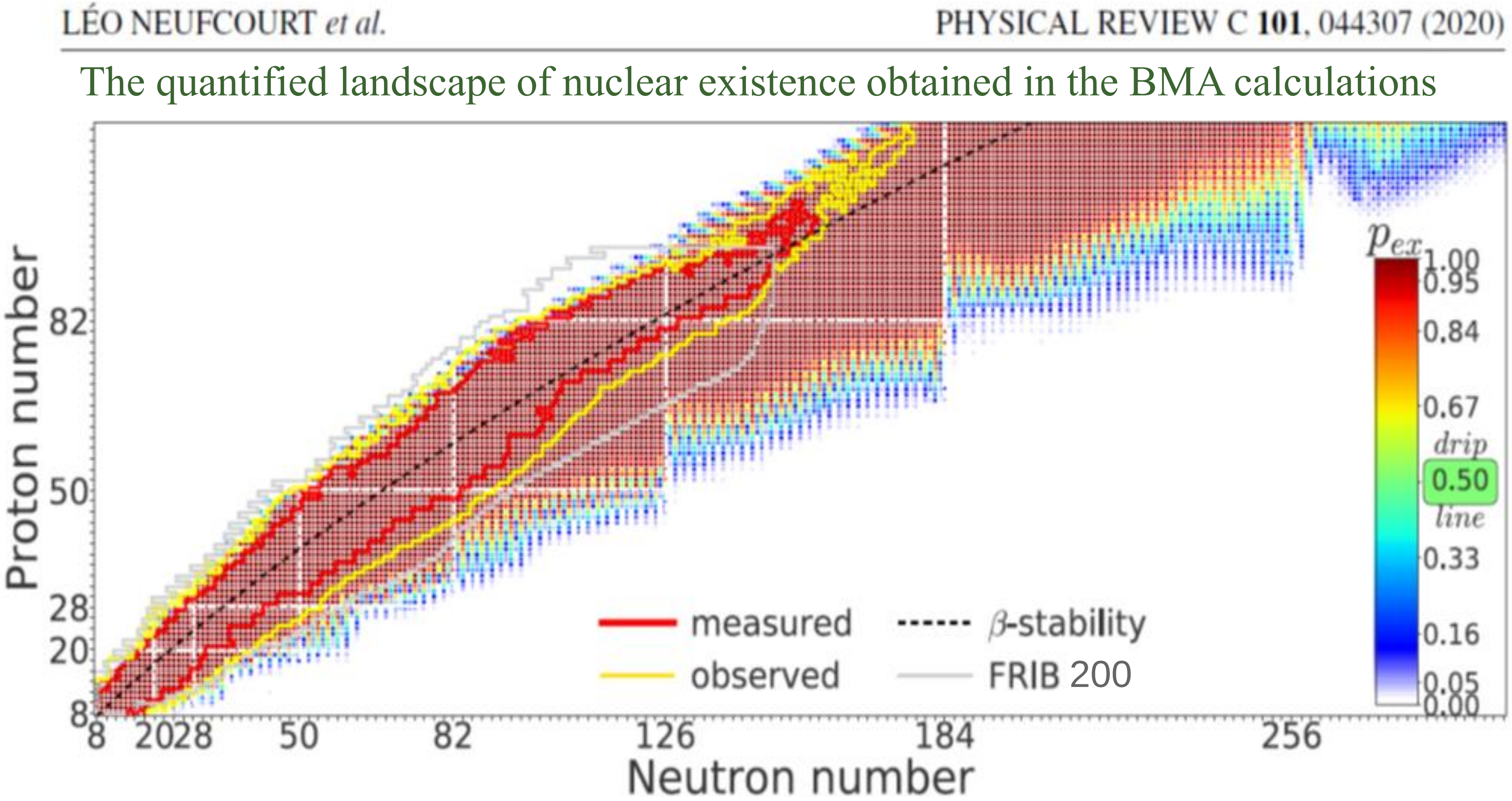
Terra Incognita



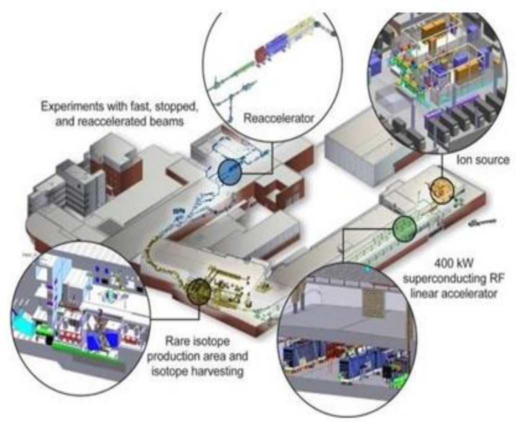
- Only around **3000** have been experimentally observed
- According to the Bayesian model averaging analysis, the number of particle-bound nuclei with Z,N ≥ 8 and Z ≤119
  - is **7708** ± 534 (>50% chance),
  - and >10% chance of **10,000** isotopes
- A vast region of the nuclear landscape remains uncharted territory (terra incognita)
- **The drip line serves as a key benchmark for nuclear models**, making it easier to observe phenomena such as 3N forces and the role of the continuum
- **Precise knowledge of the drip line is crucial for r-process calculations**, which are essential for understanding nucleosynthesis in astrophysical environments

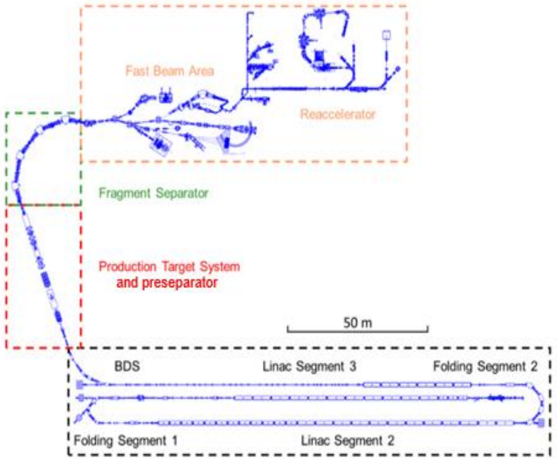
ARIS @ FRIB

See talks of Brad $_2$, Mallory

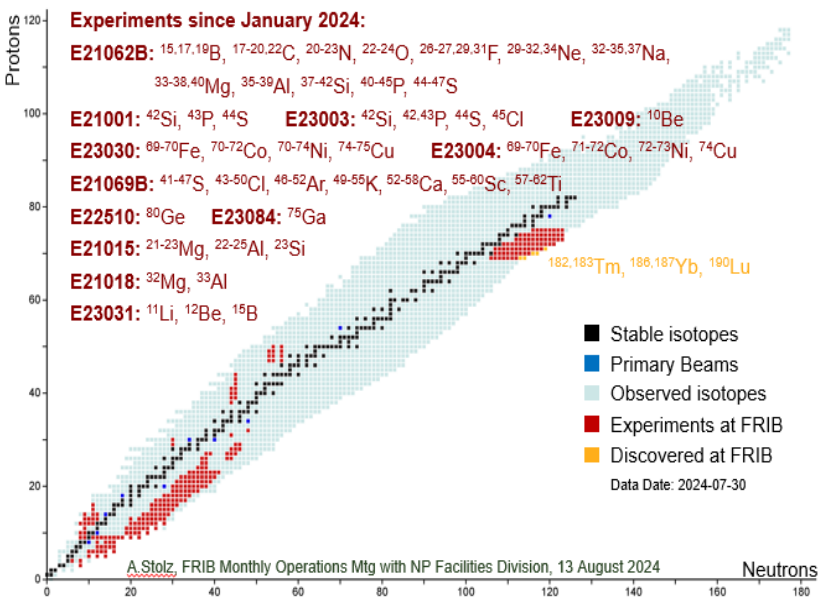
Facility for Rare Isotope Beams: FRIB

- FRIB LINAC and pre-separator operate below-ground
  - Conceptual design started: 2010
  - Constructions started: 2014
  - First rare-isotope beam: 12/2021
- Designed for 400 kW 200 MeV/u or higher (depends on beams)





More than 270 Rare Isotope Beams Have Been Delivered to FRIB Experiments



FRIB primary beams

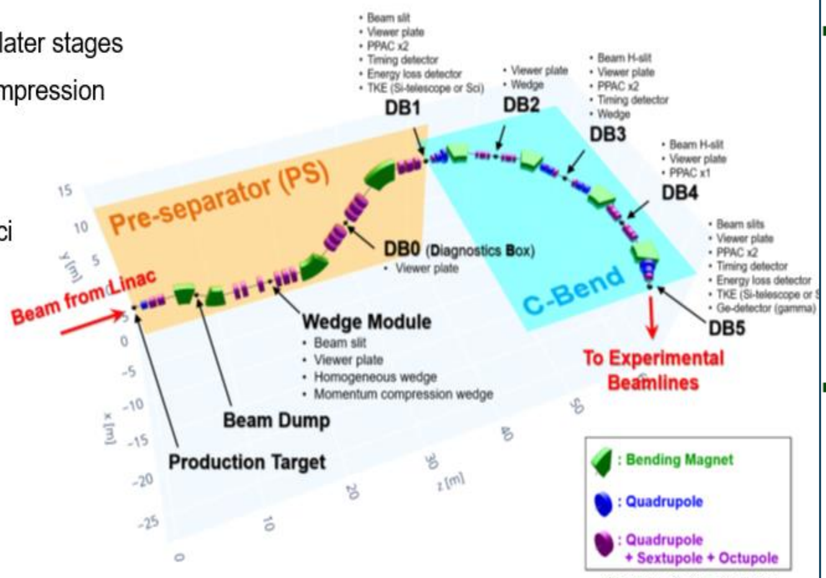
Demonstrated and available (updated 29 July 2024)

Isotope	Energy (MeV/u)	Beam current on FRIB target (pnA)
^{18}O	150	3704
^{22}Ne	170	2674
^{28}Si	175	2041
^{28}Si	155	2304
^{36}Ar	300	463
^{36}Ar	200	1389
^{40}Ar	257	973
^{40}Ar	200	1250
^{48}Ca	242	860
^{48}Ca	200	1040
^{70}Zn	240	595
^{70}Zn	200	718
^{64}Zn	254	616
^{64}Zn	200	782
^{78}Kr	254	504
^{78}Kr	200	640
^{86}Kr	230	506
^{86}Kr	200	582
^{82}Se	215	567
^{82}Se	227	537
^{124}Xe	228	354
^{124}Xe	200	404
^{198}Pt	192	55
^{208}Pb	190	94
^{209}Bi	190	93
^{238}U	177	238

https://frib.msu.edu/users/beams

ARIS Fragment Separator

- Multi-stage separation
  - Reduces impurity rates for tracking at later stages
  - First stage applies ~3x momentum compression (K3 mode) at vertical separation
    - » better matching to existing beam lines
  - Horizontal stages can operate as one (CB1) or two (CB2) achromatic foci
    - » Single stage mode (CB1) offers higher resolving power but less acceptance



Courtesy by K.Fukushima

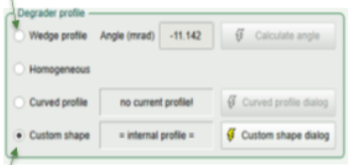
M. Hausmann et al., NIMB 317 (2013) 349-353. *Design of the Advanced Rare Isotope Separator ARIS at FRIB*

M. Portillo et al., NIMB 540 (2023) 168-173 *Commissioning of the Advanced Rare Isotope Separator ARIS at FRIB*

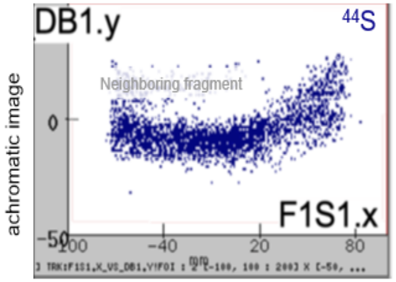
11/2023: Comparison of PreSeparator Wedges

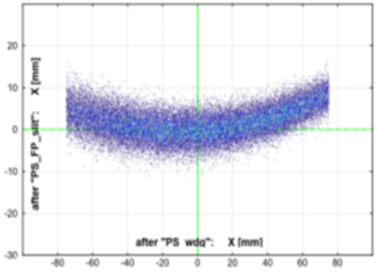
^{48}Ca + C (8 mm) → ^{44}S @ dP/P=6%

- **Linear wedge**
  - Chromatic distortions
    - » F1S1.x width wider at edges/larger dP/P



LISE $^{++}_{cute}$

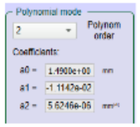


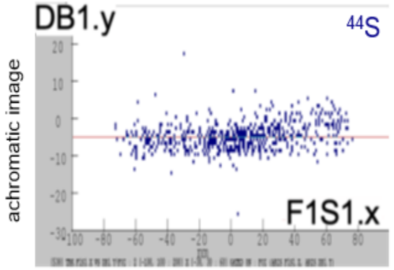


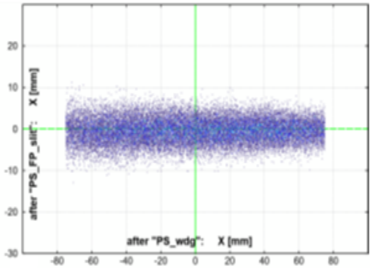
dispersive image

LISE $^{++}_{cute}$

- **Higher order wedge** "parabolic-like"
  - Smaller chromatic distortions





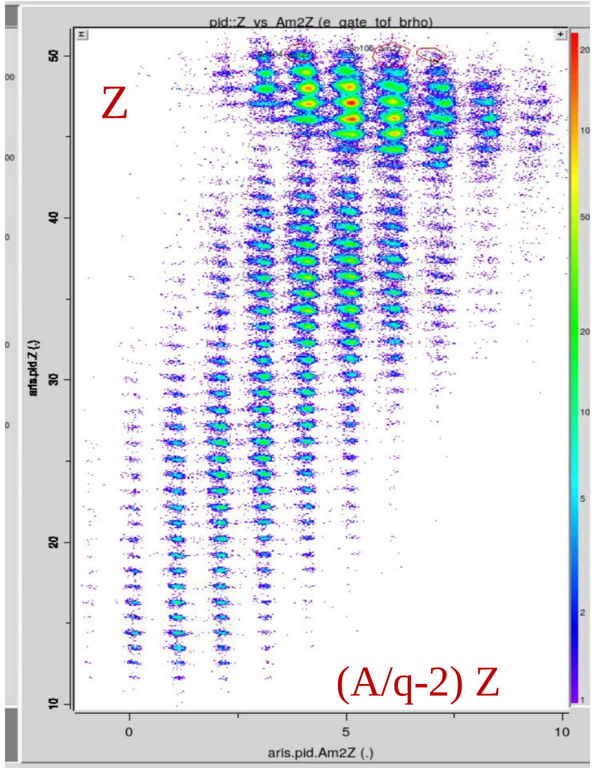


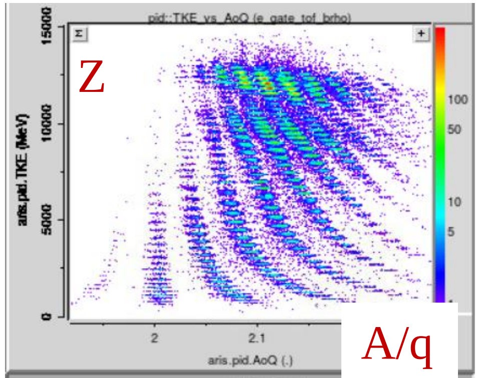
E23608, Courtesy E.Kwan

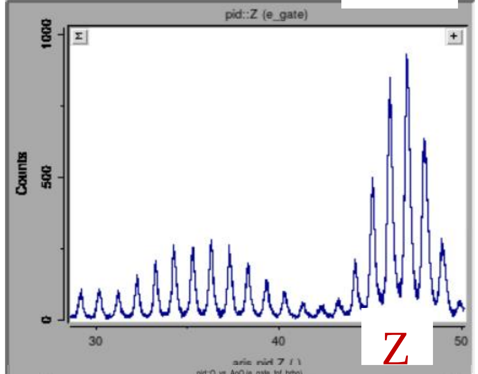
Reconstruction, Resolution

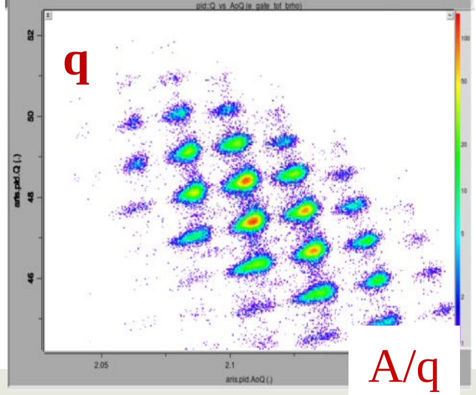
PID: results from Xe-experiments (K3-CB2 mode)

- **Delay-line PPACs provide good time resolution**
- PPAC over Sci (regarding to thickness):
  - lower charge state production
  - No “wedge” effect, if detector located in a dispersive plane
- **Good results obtained in the trajectory reconstruction process**
- High quality PID resolution observed with the combination of
  * dE-TKE (PIN-telescope),
  * ToF (db3-ppac1 & db5-ppac1),
  * Bρ (ppacs at db3,db4,db5)







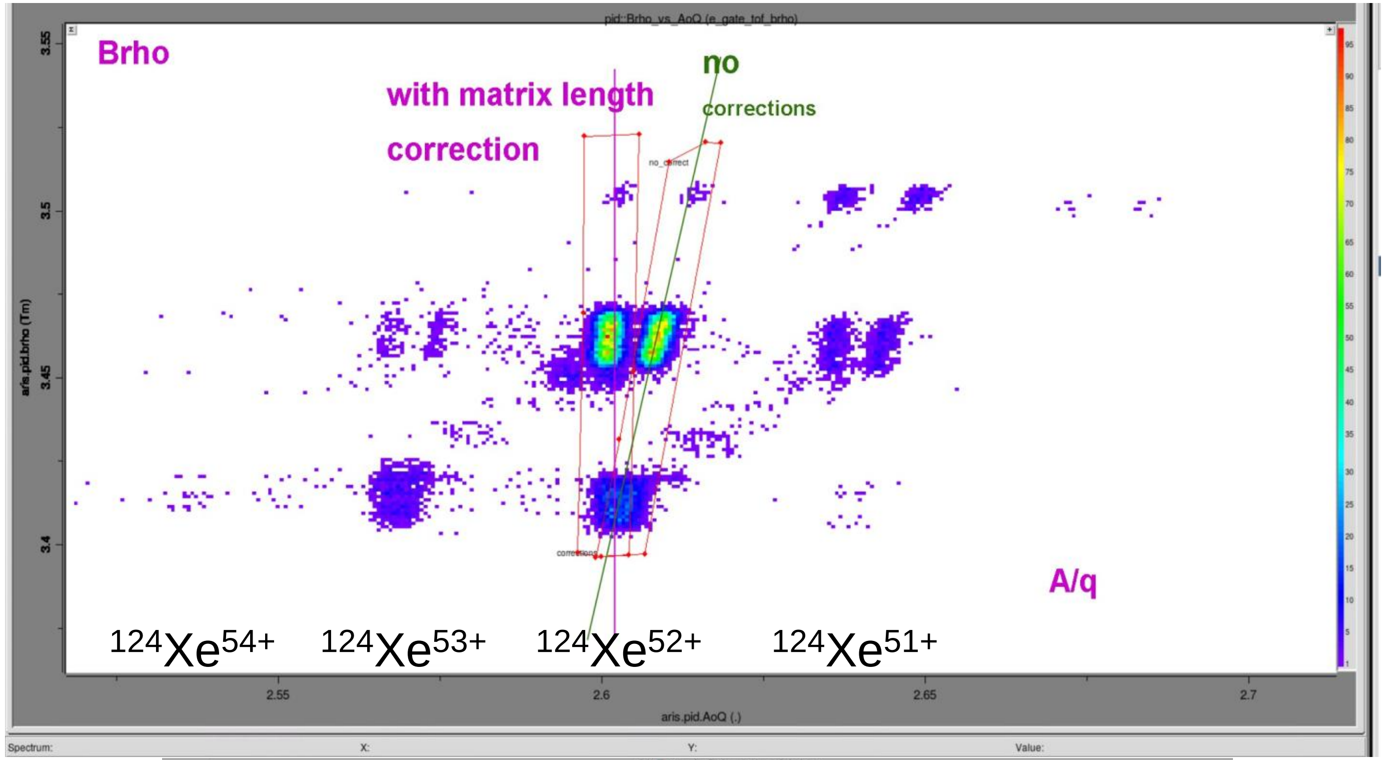


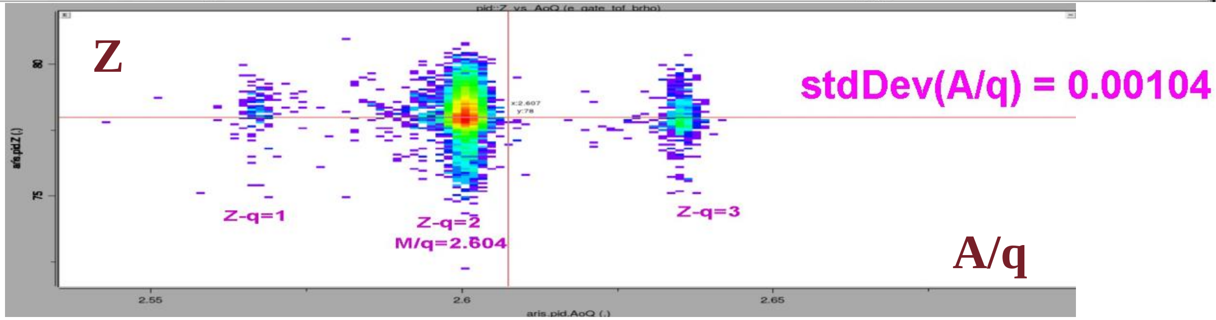
Resolution (DB3-DB4-DB5 reconstruction) [standard deviation]

σ(Z) = 0.167 (as average of first 3 PINs)		σ(q) = 0.093	
σ(A-2q) = 0.105 (mass resolution)		**σ(A/q) = 0.0024**	

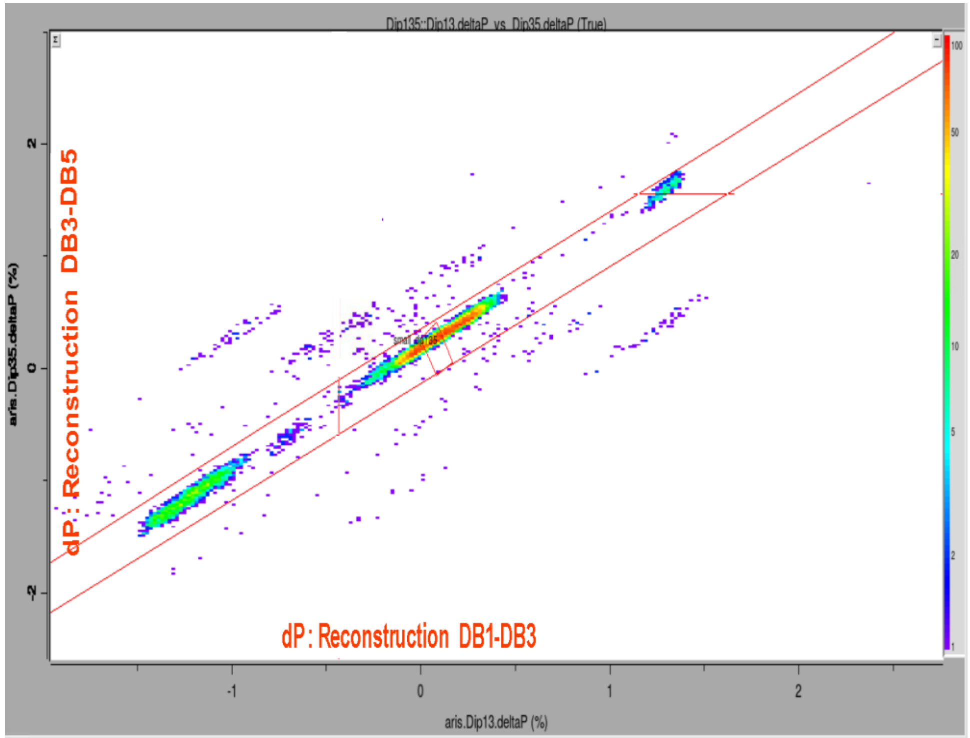
σ(A/q) = 0.001 (K3-CB1 mode)

FRIB e22501: Mass resolution in the CB1 mode (DB1-DB3-DB5 reconstruction)





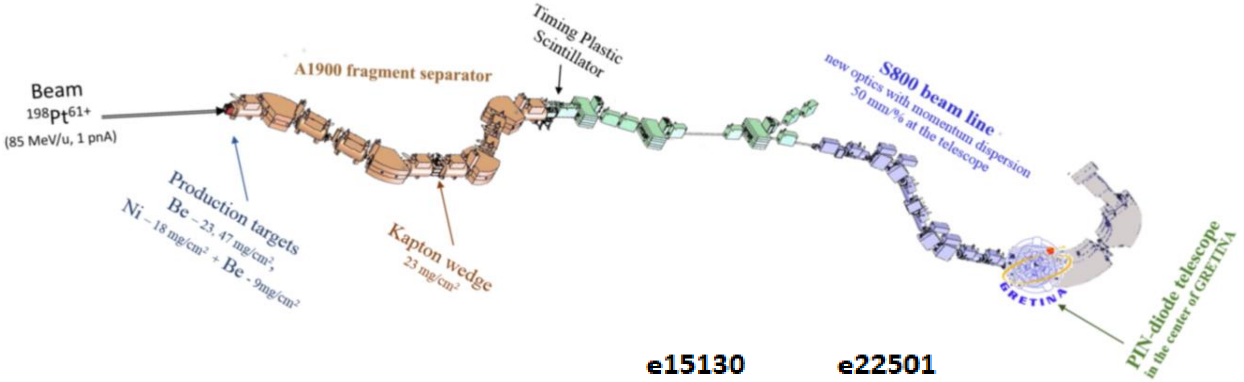
- Using 1st order maps
- Trajectory corrections are important in CB1-mode
- <ΔP/P> value (average of DB13 & DB35) to improve reconstruction
- σ(A/q) = 0.00104
- Thick target: t/Range = 0.7



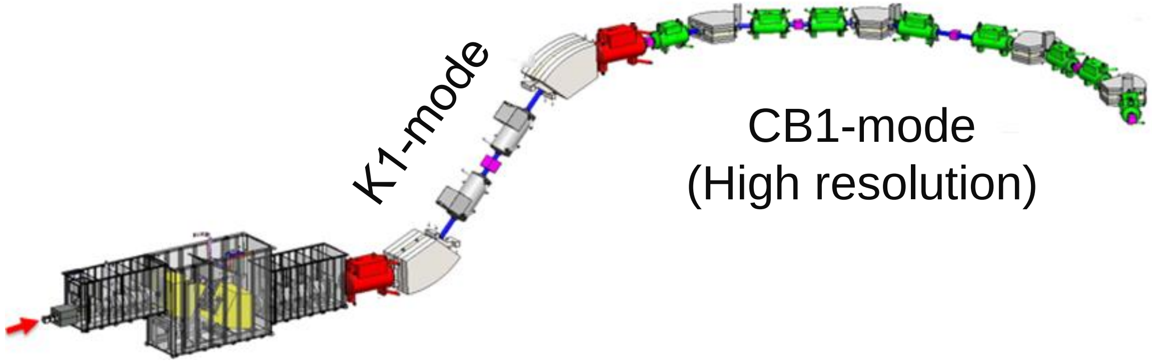
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

^{198}Pt @ NSCL & FRIB

^{198}Pt beam: e15130 @ NSCL vs. e22501 @ FRIB



		e15130	e22501
	Laboratory	NSCL	FRIB
	year	2019	2023
beam	primary beam energy, MeV/u	85	186
beam	primary beam power, kW	0.01	2
beam	Primary beam intensity, pps	3E+09	3.40E+11
target	target	Be	C
target	thickness	47 mg/cm2	3.5 mm
target	atoms/cm2	3.13E+21	3.32E+22
	momentum acceptance	0.5%	3%
	factor	1	7.21E+03
	new isotopes	3	**5 (8)**



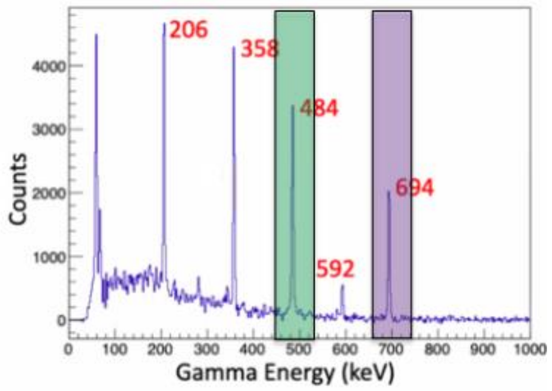
		e15130	e22501
beam charge states	method	between	shifted
	target	thin	thick
	contamination	yes	no
optics	configuration	separator+ spectrometer	2-stage fragment separator
	quality	"fresh" (special design)	well established
PID, momentum resolution	dispersion	45 mm/%	67.2 mm/%
	position detector resolution at dispersive plane,	3 mm	0.5 mm
	trajectory reconstruction	no	yes
	PID ToF	46.0 m	~~39.1~~ 19.6 m

^{198}Pt (85 MeV/u) @ NSCL : PID, new isotopes

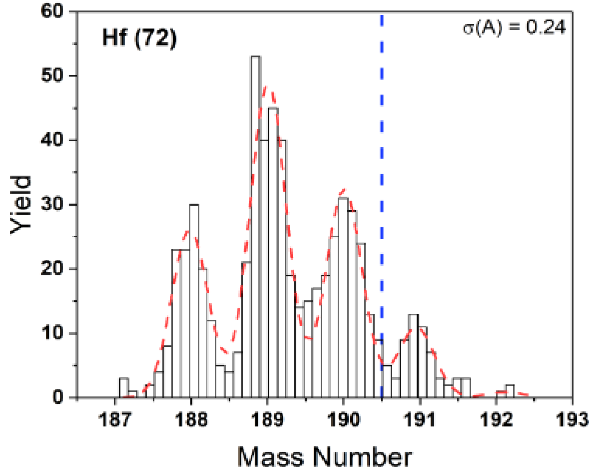
2019

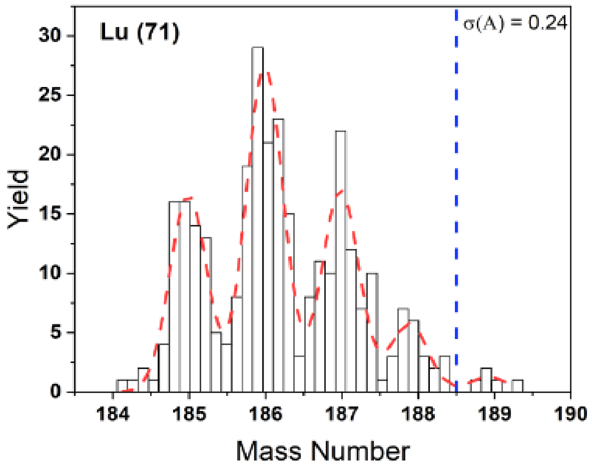
e15130 PIs :
Partha Chowdhury (UML)
Oleg Tarasov (MSU)
Andrew Rogers (UML)

K.Haak, O.B.T. et al., PRC 108, 034608 (2023)

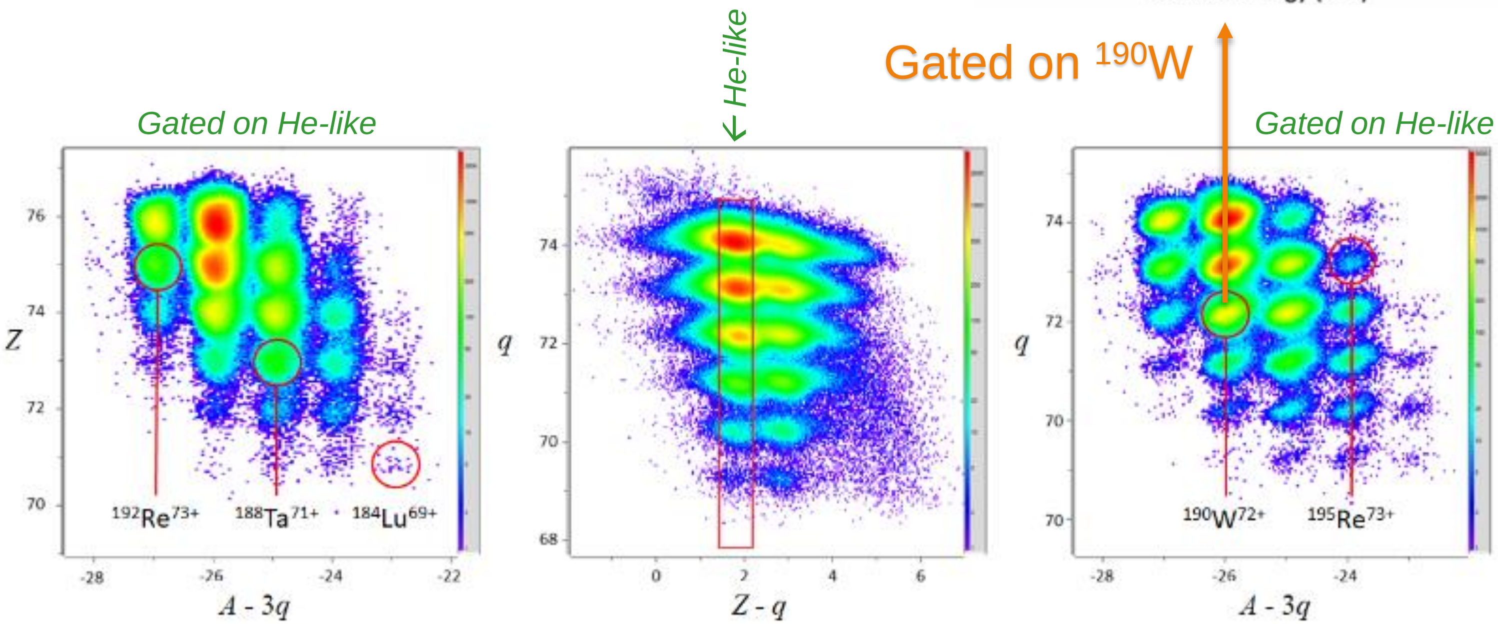


3 new isotopes



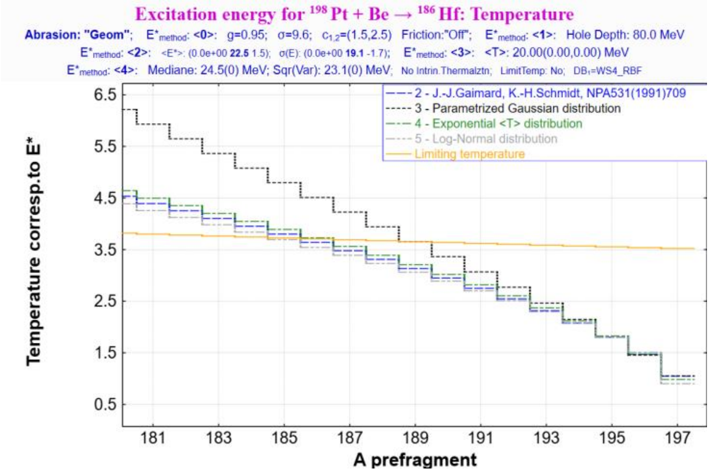


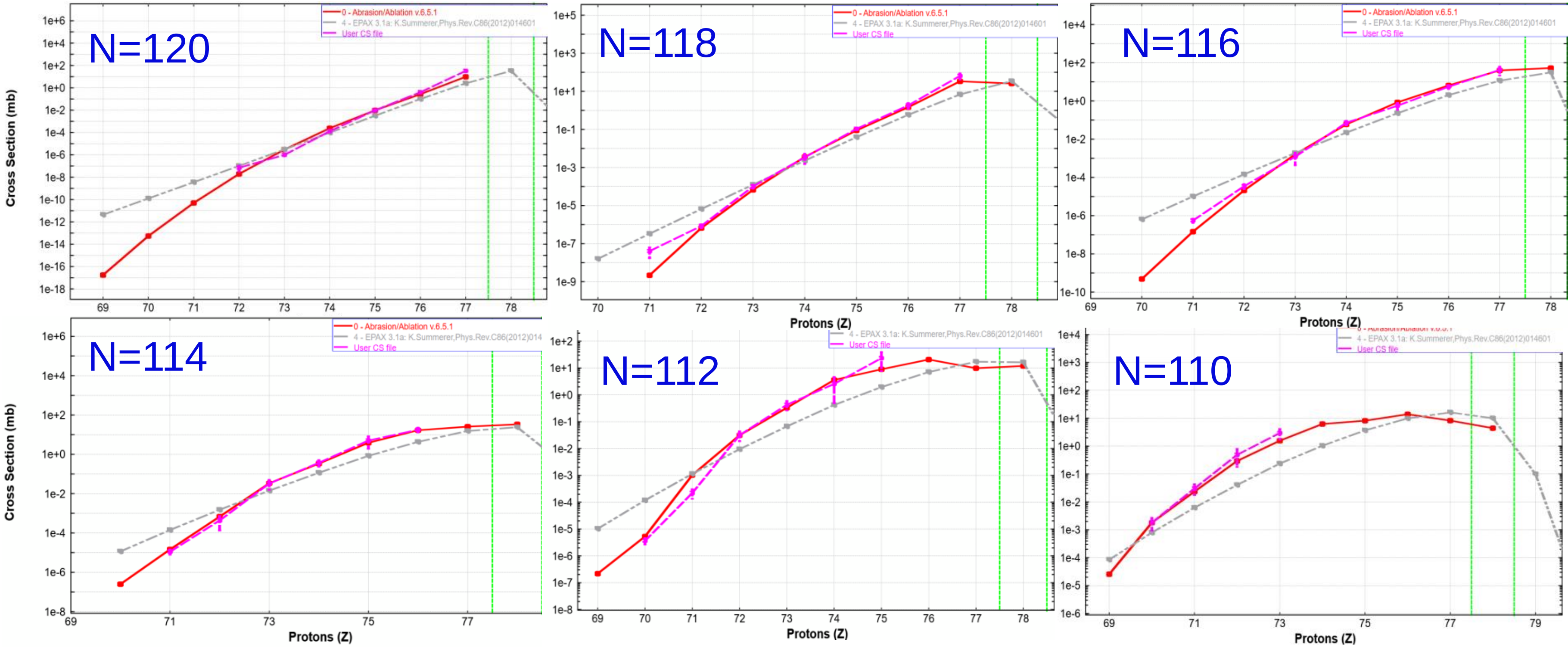
Gated on ^{190}W



^{198}Pt (85 MeV/u) + Be : LISE^{++} Abrasion-Ablation (not published)

0 - Abrasion/Ablation v.6.5.1
4 - EPAX 3.1a: K.Summerer,P
User CS file experiment





We were able to define AA settings with minimization to the experimental Cross-Section values (for WS4RBF mass table)

- Gaussian-shape model
- Higher excitation energies, then in the lead case *(agrees with BNL-FRIB EE analysis)
- Important contribution of the break-up channel

3. Parametrizied Gaussian distribution -- simplified cor

<E*>		σ(E*) =	
1.5429	*d_abr^2 +	-1.7273	*d_abr +
22.4583	*d_abr +	19.1191	*d_abr$^{1/2}$ +
0	[MeV]	0	[MeV]

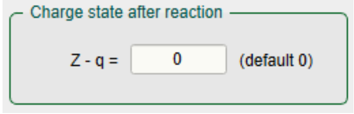
Charge state of
projectile residual after reaction

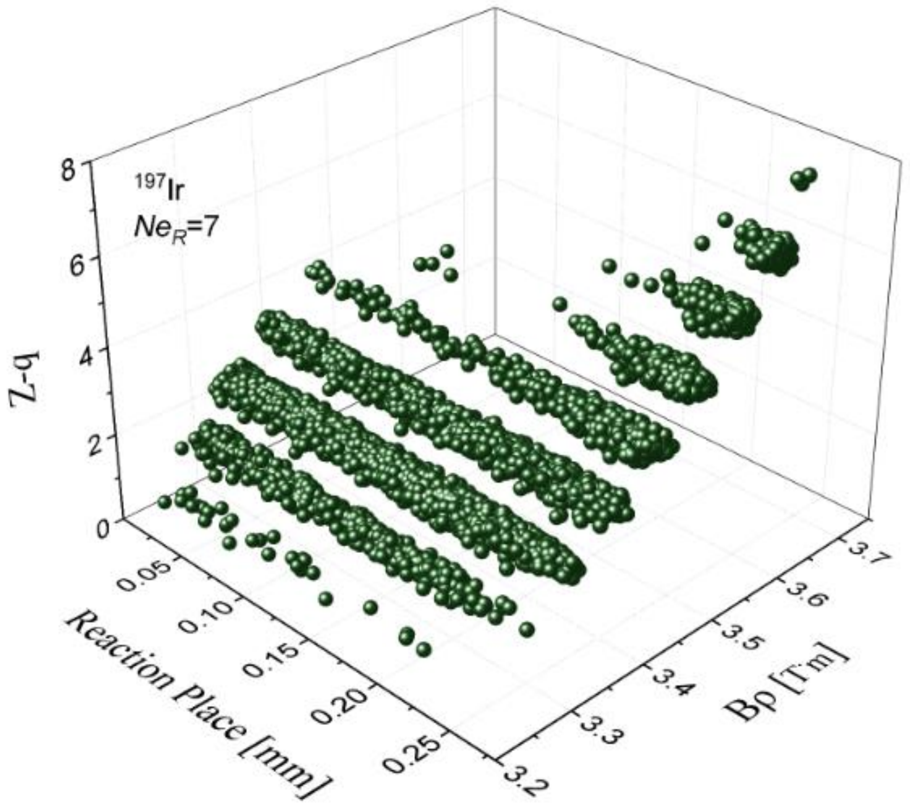
Charge state of projectile residual after reaction

<u>Formulation of the problem:</u>

- Thin target << Equilibrium thickness
- With one neutron removal from ^{198}Pt
  - Ionization energies are not changed
  - No abrupt change in speed (198 → 197)

LISE ++ cute





- What happens to 17 electrons after knocking out one neutron from ^{198}Pt?

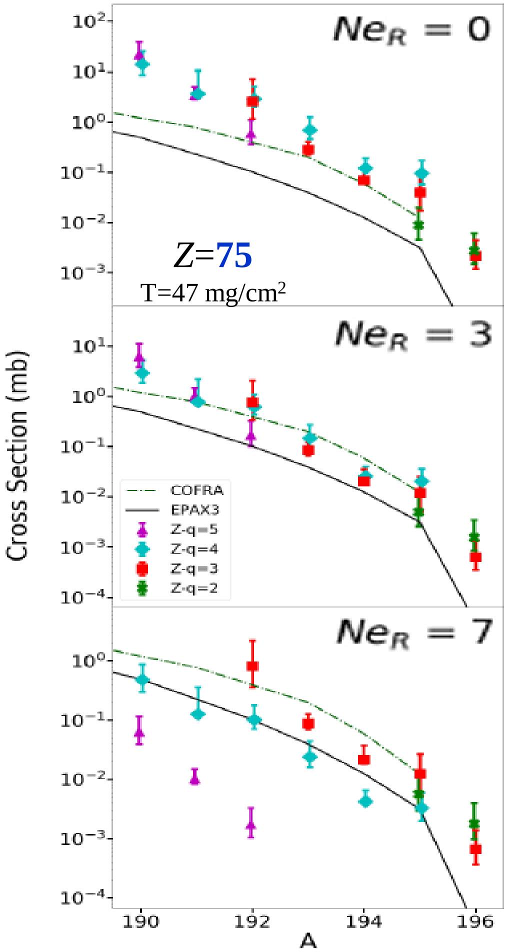
$^{198}Pt^{61+}$ (85 MeV/u) → $^{197}Pt^{?+}$

- Will the electrons fly away from orbits, or they will remain attached to the residual?

LISE^{++} 3D Monte Carlo calculations of ^{197}Ir charge state distribution versus reaction place in the target, assuming that the initial post-reaction charge state is **7**.
It demonstrates that higher lying charge state ions are coming from reactions that occurred toward the end of the target. For Ne_R=0 case: Y(Z-q=4) < 0.1%

K.Haak, O.B.T et al., PRC 108, 034608 (2023)

A novel correlation has been established between the charge state of the projectile-residue after the reaction and its atomic number



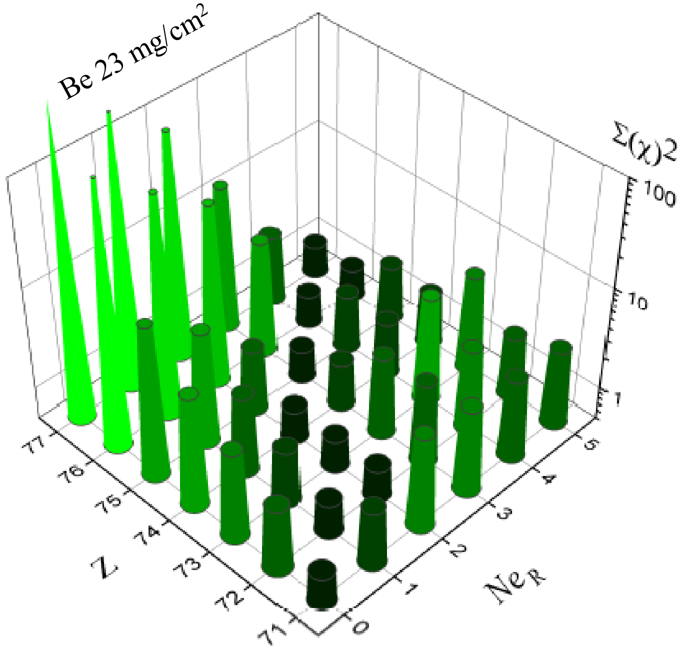
The fragment formation is independent of the charge state, which is equivalent to $\sigma_F = \sigma_{i1} = \sigma_{i2}$

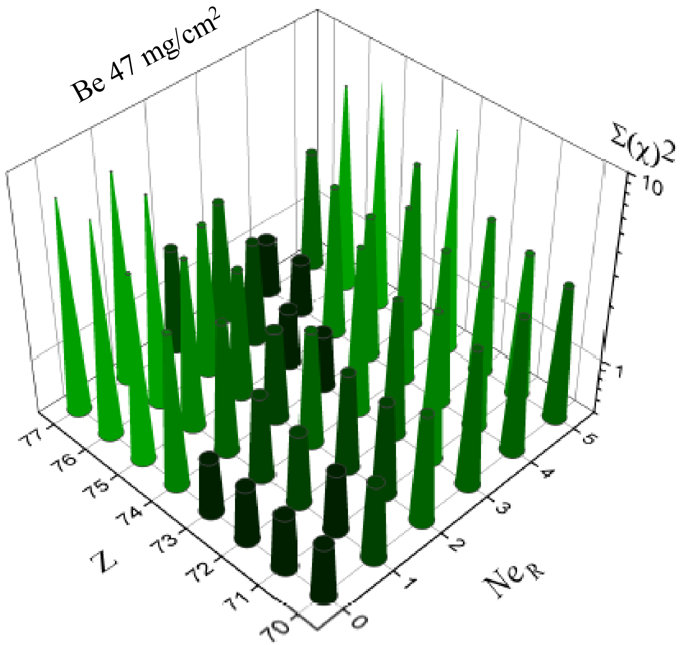
The index i represents the charge state $Z - q$.

Combined transmission based on Distribution and Monte Carlo methods to deduce production cross sections

$^{198}Pt^{61+}$ (85 MeV/u) + Be (23, 47 mg/cm^2)

K.Haak, O.B.T. et al., PRC 108, 034608 (2023)





- $\Sigma(\chi^2)$ is the sum resulting from matching the various expected trends (data scatter, amplitude, shape)
- Higher Z fragments, whose ionization energies are close to the original projectile values, retained more electrons, than fragments with lower Z, which underwent a more violent nuclear reaction with the loss of more nucleons
- This dependence is less pronounced for a thicker target, since the charge state distribution is heading to equilibrium

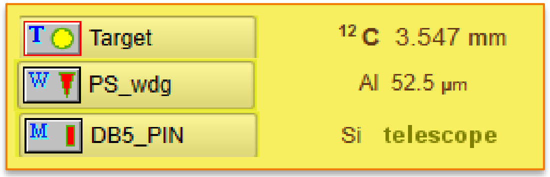
^{198}Pt @ FRIB

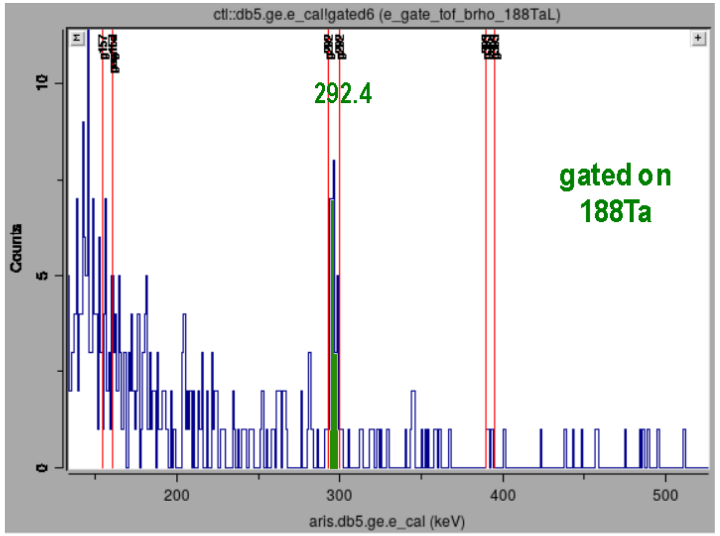
^{198}Pt (186 MeV/u) @ FRIB : PID

01/2023

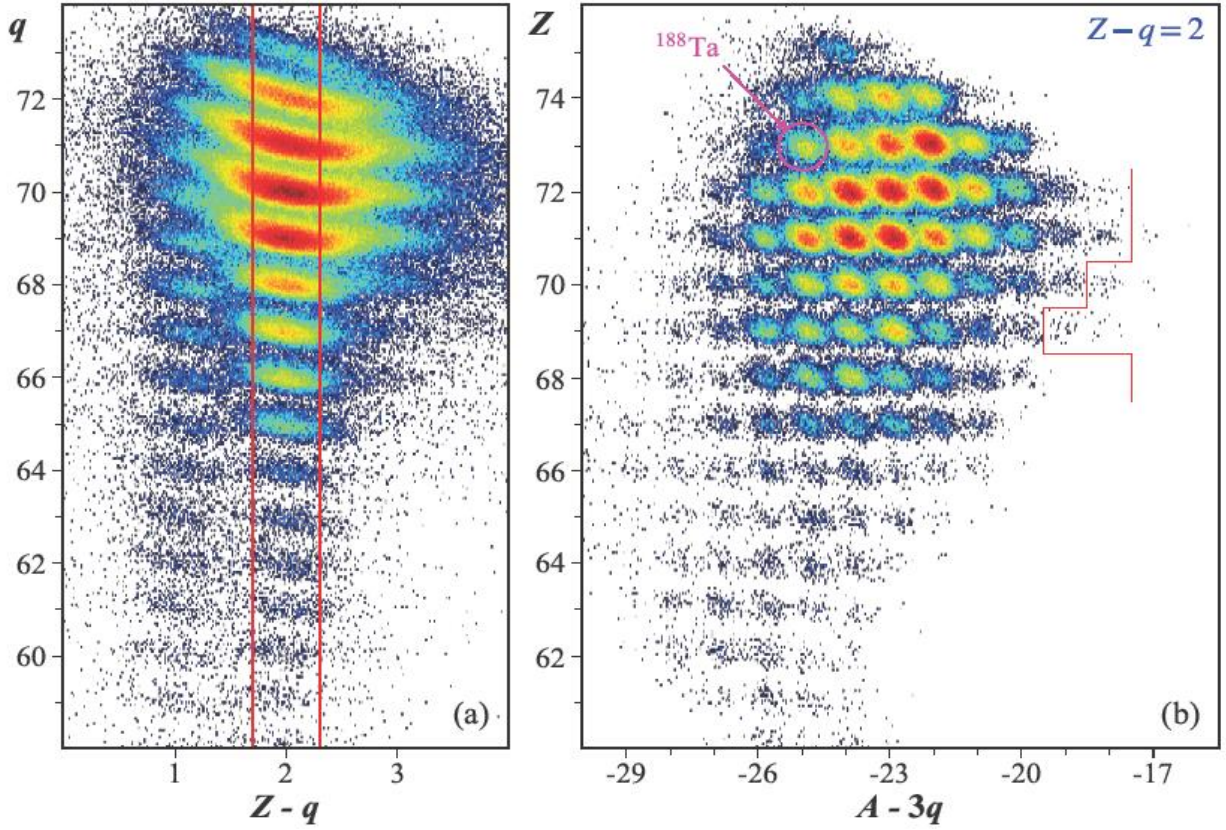
e22501 PIs:
O.Tarasov (MSU),
A.Gade (MSU)

O.B.T., A.Gade et al., PRL 132, 072501 (2024)

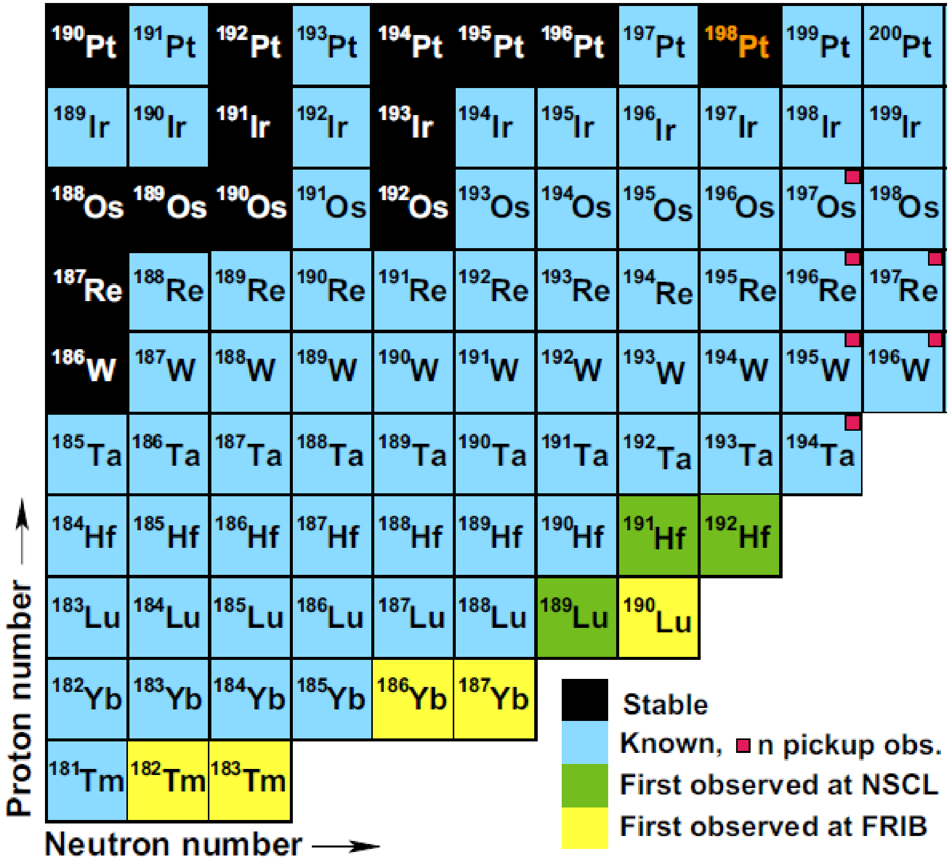




- DB1-PPACs were not used with fragments due to large background at DB1 (similar to F2 @ BigRIPS)
- DB3-PPAC0 has been damaged during the experiment
- $\sigma(A/q)$ ~ 0.003. Still works for mass resolution with TKE use



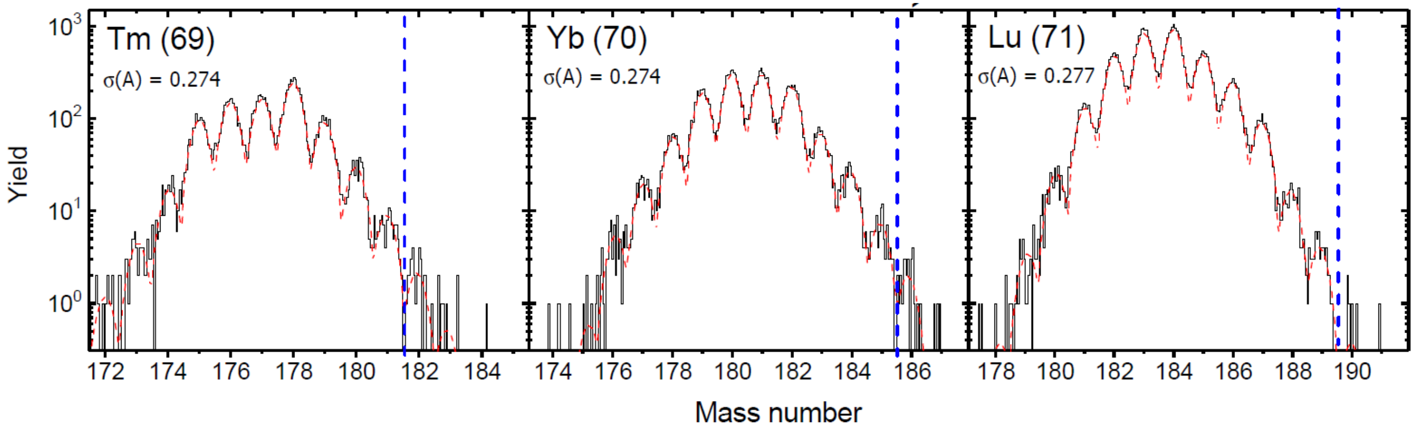
e22501: Results



O.B.T., A.Gade et al., PRL 132, 072501 (2024)

Over the course of the experiment, five new isotopes, namely ^{182}Tm (29 events), ^{183}Tm (7), ^{186}Yb (27), ^{187}Yb (3), ^{190}Lu (5), were observed for the first time. One event was found to be consistent with ^{184}Tm, and another one was found to be consistent with ^{191}Lu.

This intensity corresponds to only 1/270 of FRIB's ultimate primary-beam power.



This successful new isotope search was performed less than one year after FRIB operations began and demonstrates the discovery potential of the facility which will ultimately provide 400 kW of primary beam power.

“μs-isomer” plot (aka Grzywacz’s plot)

Stopped fragment tagging with isomeric gamma-rays

3 August 1995

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 355 (1995) 439–446

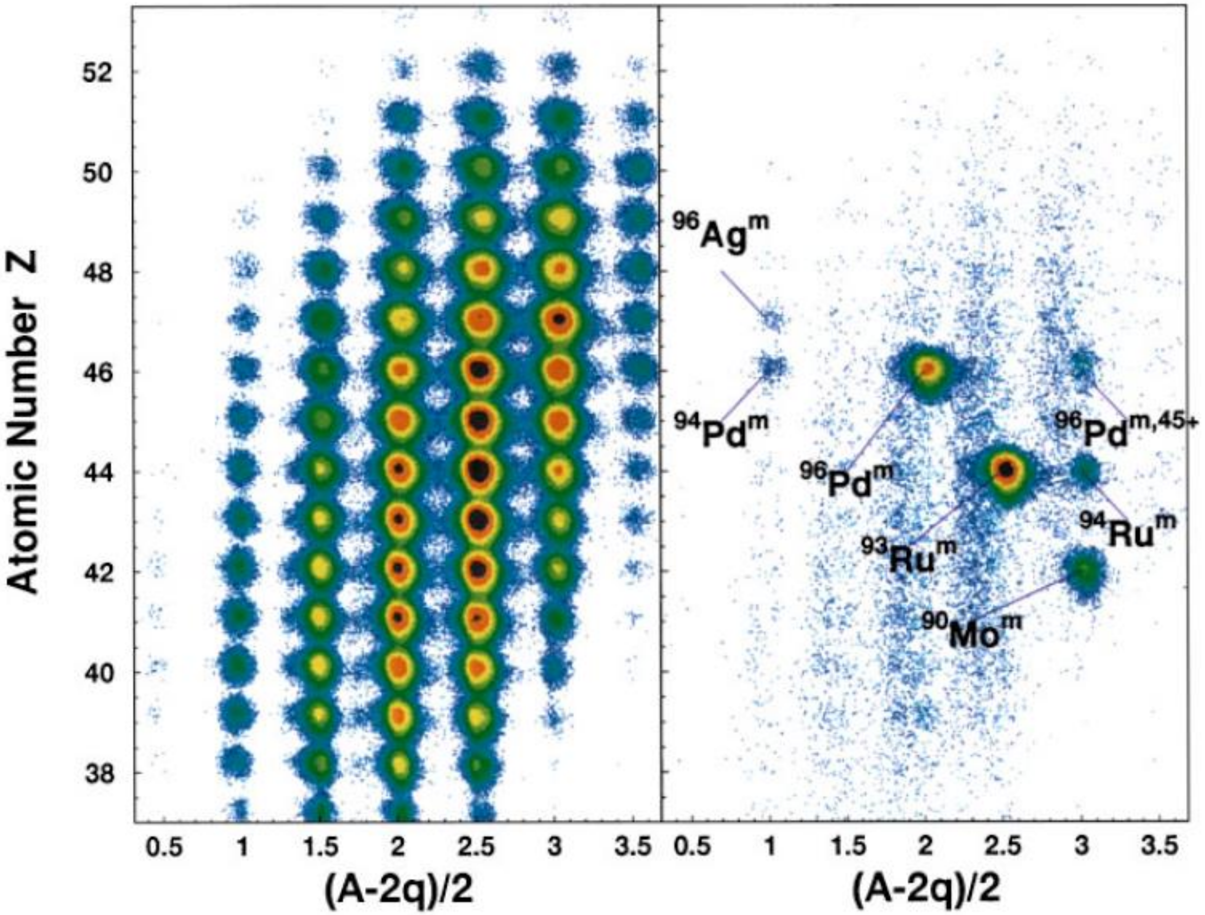
Identification of μs-isomers produced in the fragmentation of a ^{112}Sn beam

R. Grzywacz[a,b], R. Anne[b], G. Auger[b], D. Bazin[b], C. Borcea[c], V. Borrel[d], J.M. Corre[b], T. Dörfler[e], A. Fomichov[f], M. Gaelens[g], D. Guillemaud-Mueller[d], R. Hue[b], M. Huyse[g], Z. Janas[h,1], H. Keller[h], M. Lewitowicz[b], S. Lukyanov[b,f], A.C. Mueller[d], Yu. Penionzhkevich[f], M. Pfützner[a], F. Pougheon[d], K. Rykaczewski[a,b], M.G. Saint-Laurent[b], K. Schmidt[h], W.-D. Schmidt-Ott[e], O. Sorlin[d], J. Szerypo[g], O. Tarasov[b,f], J. Wauters[g], J. Żylicz[a]

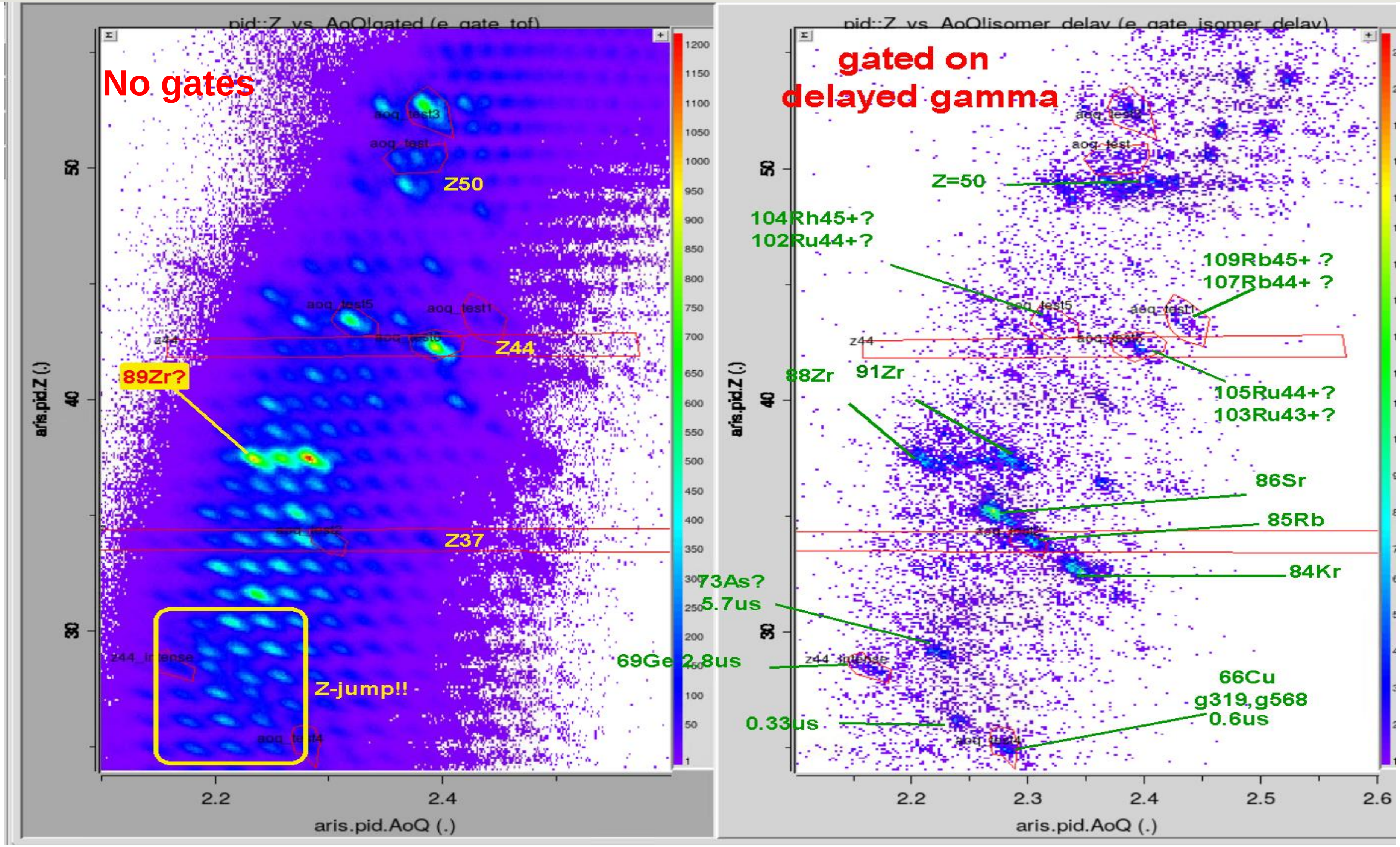
PHYSICAL REVIEW C VOLUME 55, NUMBER 3 MARCH 1997

New μs isomers in $T_z=1$ nuclei produced in the ^{112}Sn(63A MeV) + ^{nat}Ni reaction

R. Grzywacz,[1,2] R. Anne,[2] G. Auger,[2] C. Borcea,[3] J. M. Corre,[2] T. Dörfler,[4] A. Fomichov,[5] S. Grevy,[6] H. Grawe,[7] D. Guillemaud-Mueller,[6] M. Huyse,[8] Z. Janas,[7] H. Keller,[7] M. Lewitowicz,[2] S. Lukyanov,[5,2] A. C. Mueller,[6] N. Orr,[9] A. Ostrowski,[2] Yu. Penionzhkevich,[5] A. Piechaczek,[8] F. Pougheon,[6] K. Rykaczewski,[1,10] M.G. Saint-Laurent,[2] W. D. Schmidt-Ott,[4] O. Sorlin,[6] J. Szerypo,[1] O. Tarasov,[5,2] J. Wauters,[8] J. Żylicz[1]



^{198}Pt (186 MeV/u) + Be : unexpected blobs



New Facilities Provide Unprecedented Opportunities!

Less than 10^{-6} transmission for fully stripped

.. and suddenly transmission increased.

A charge was changed in PS after decay?
Z-q=1 → Z-q=0

Internal conversion electron isomer decay?

ns-isomer plot?

Holly Matthews' project

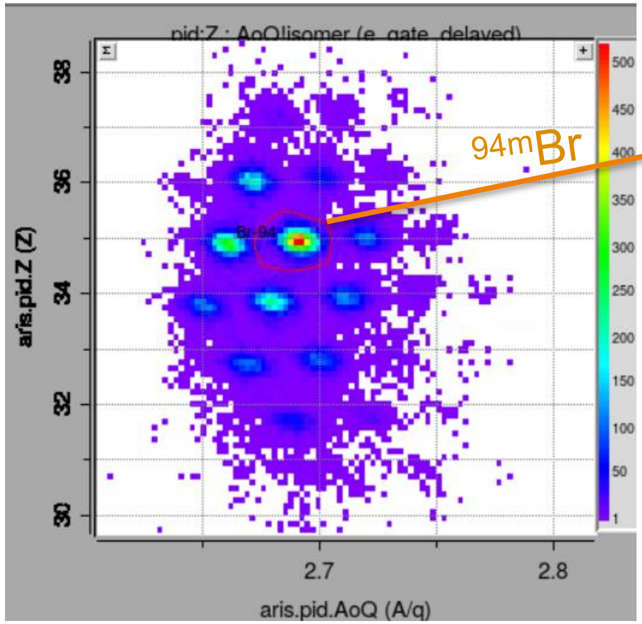
e23607: ^{238}U, 10.4 kW

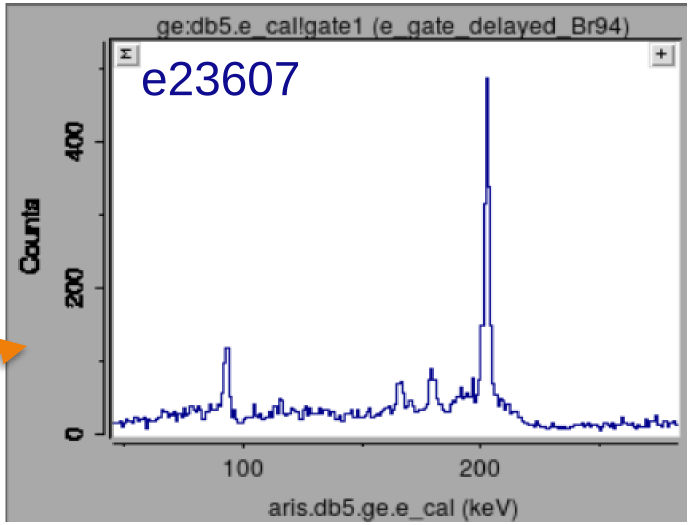
12/23/2023

E23607 "Secondary beams from ^{238}U" : Particle ID

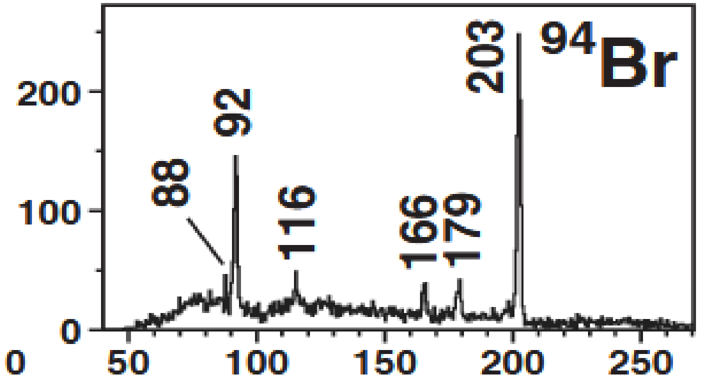
- ^{238}U 177 MeV/u, **10.4** kW
- ARIS: 1 day (22-23 December 2023),
  K3-CB2 optics
- 3 settings:
  - isomer tagging
  - new isotope regions – ^{93}As, ^{152}Cs
- Particle ID was verified by the decay of known microsecond isomers (^{88}Br, ^{94}Br, ^{98}Y)

Gated on delayed gamma





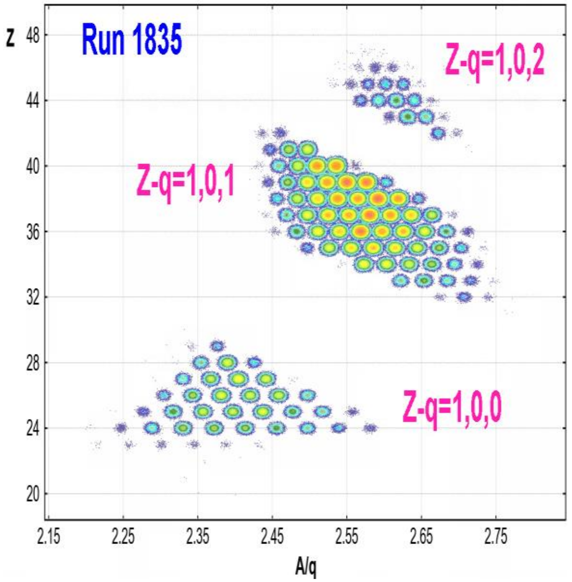
D. KAMEDA *et al.* PHYSICAL REVIEW C **86**, 054319 (2012)



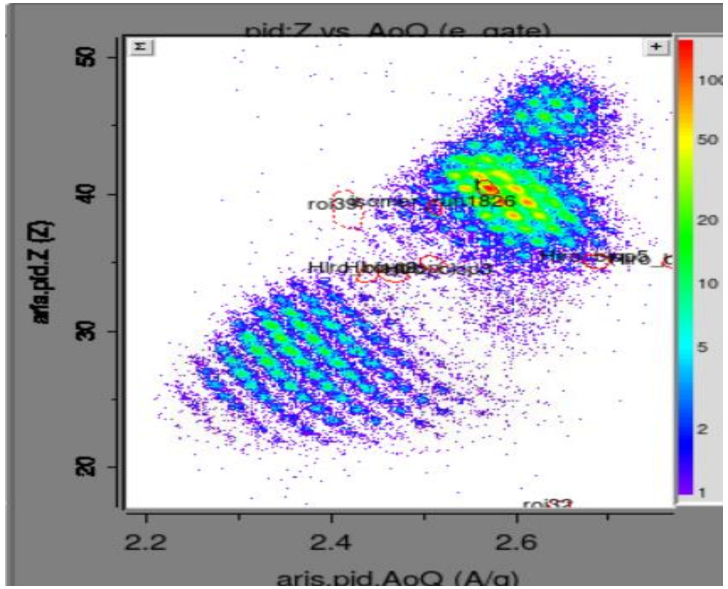
e23607: TKE, Simulations

- Total Kinetic Energy (TKE) test with a Scintillator:
  Z-q separation (additionally to separation with a Si-telescope)
- Agreement with the LISE++ simulation package

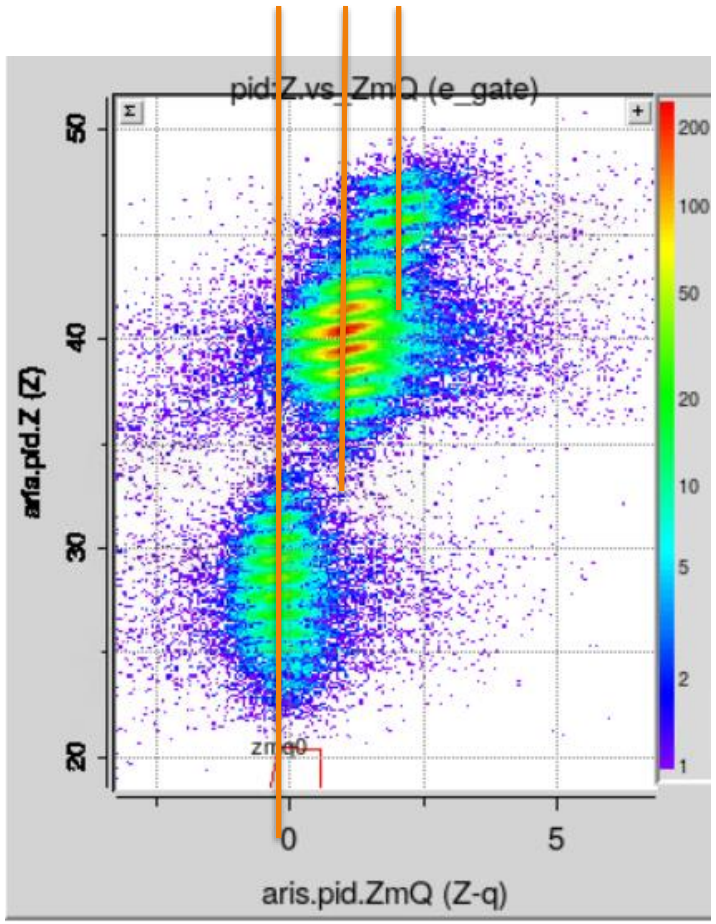
LISE++



e23607



0e⁻ 1e⁻ 2e⁻



e23607 : Results

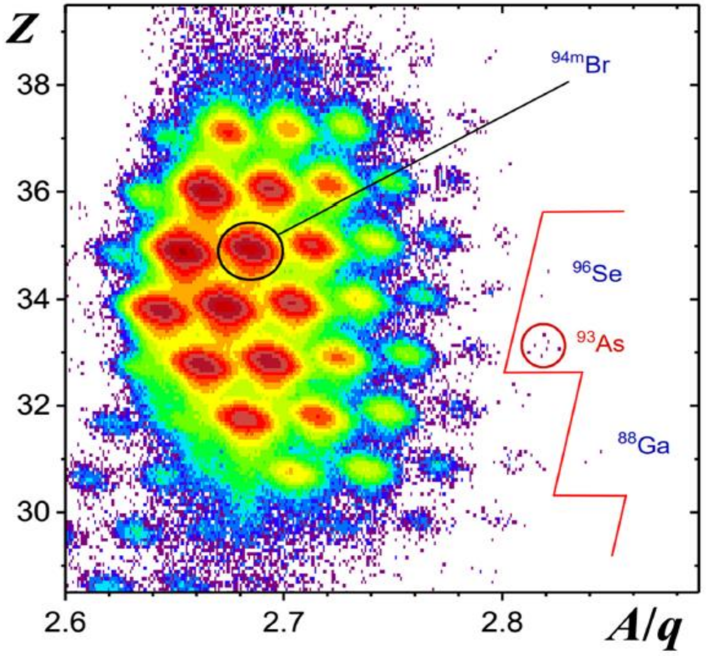
- Over 300 fission fragments identified in all settings
- In a 6-hour run with 10 kW at the Low-Z settings, three “new” isotopes were observed ^{88}Ga, ^{93}As, ^{96}Se

❖But “new” is only for a couple of months ..

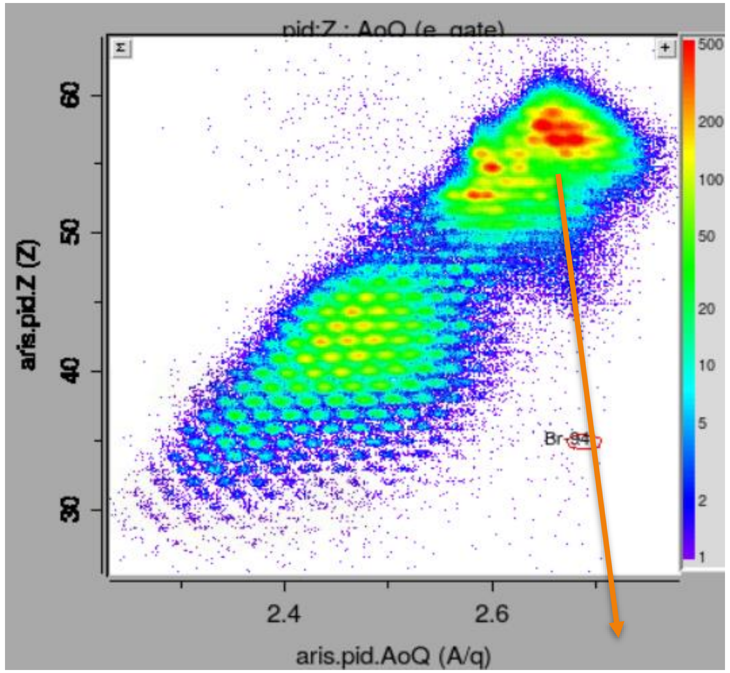
❖Y. Shimizu et al.,
PHYSICAL REVIEW C 109, 044313 (2024)
received 19 December 2023
accepted 7 March 2024
published 8 April 2024

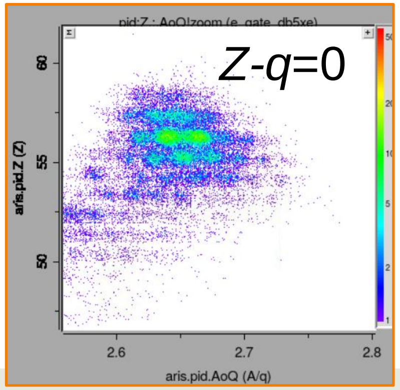
❖P. N. Ostroumov, O. B. T. et al.,
PHYSICAL REVIEW ACCELERATORS AND BEAMS 27, 060101 (2024)
Received 12 February 2024

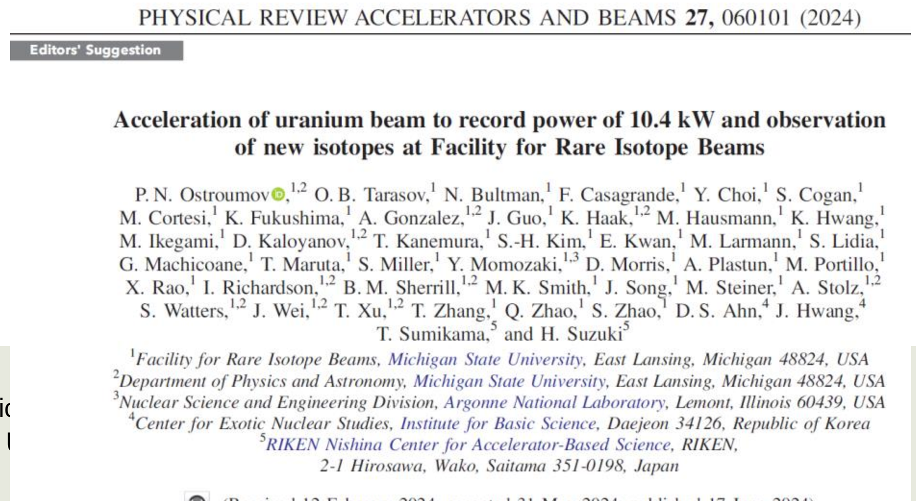
^{93}As - settings



^{152}Cs - settings






PHYSICAL REVIEW ACCELERATORS AND BEAMS 27, 060101 (2024)

Editors' Suggestion

Acceleration of uranium beam to record power of 10.4 kW and observation of new isotopes at Facility for Rare Isotope Beams

P. N. Ostroumov,[1,2] O. B. Tarasov,[1] N. Bultman,[1] F. Casagrande,[1] Y. Choi,[1] S. Cogan,[1] M. Cortesi,[1] K. Fukushima,[1] A. Gonzalez,[1,2] J. Guo,[1] K. Haak,[1,2] M. Hausmann,[1] K. Hwang,[1] M. Ikegami,[1] D. Kaloyanov,[1,2] T. Kanemura,[1] S.-H. Kim,[1] E. Kwan,[1] M. Larmann,[1] S. Lidia,[1] G. Machicoane,[1] T. Maruta,[1] S. Miller,[1] Y. Momozaki,[1,3] D. Morris,[1] A. Plastun,[1] M. Portillo,[1] X. Rao,[1] I. Richardson,[1,2] B. M. Sherrill,[1,2] M. K. Smith,[1] J. Song,[1] M. Steiner,[1] A. Stolz,[1,2] S. Watters,[1,2] J. Wei,[1,2] T. Xu,[1,2] T. Zhang,[1] Q. Zhao,[1] S. Zhao,[1] D. S. Ahn,[4] J. Hwang,[4] T. Sumikama,[5] and H. Suzuki[5]

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e24605: ^{82}Se, 20 kW
07/2024

Exp. 24605 : new isotope search run with a ^{82}Se beam (20kW)

- ^{82}Se 228 MeV/u, **20** kW
- ARIS: July 2024, K3-CB2 optics
- 4 settings:
  - Isomer tagging
  - New isotope regions – ^{65}Ti, ^{68}V, ^{71}Cr
- Particle ID was verified by
  - » decay of ^{43}S microsecond isomer
  - » Calcium anomaly vs. A/q=3 line
  - » Even Z vs. A/q=2.5

TABLE I: ARIS settings and run conditions during the experiment.

Fragment of interest	Magnetic rigidity, $B\rho(Tm)$ D_1D_2	$D_3D_4D_5$	D_6	$\Delta p/p$ (%)	PS wedge shift (mm)	DB2 wedge thick (mm)	Time (h)	Beam Particles	Part
^{43}S	5.5	5.438	5.438	0.8	0	-	0.16	8.0×10^{13}	Isomer tagging
^{68}V	5.6	5.4067	5.3249	4.4	0	0.444	9.6	2.2×10^{17}	Production of new isotopes
^{65}Ti			5.3286		7.9		12.0	2.9×10^{17}	
^{71}Cr			5.3213		-1.6		5.4	1.3×10^{17}	

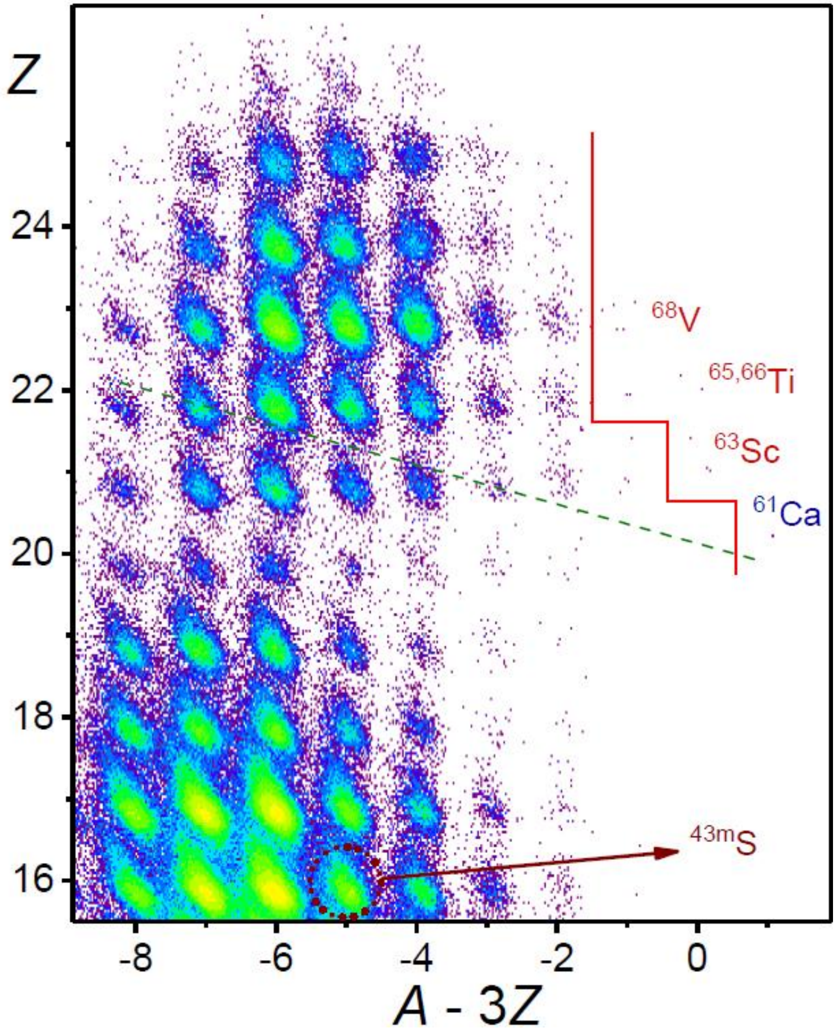
Wedge shift:
Fast moving to another FOI region

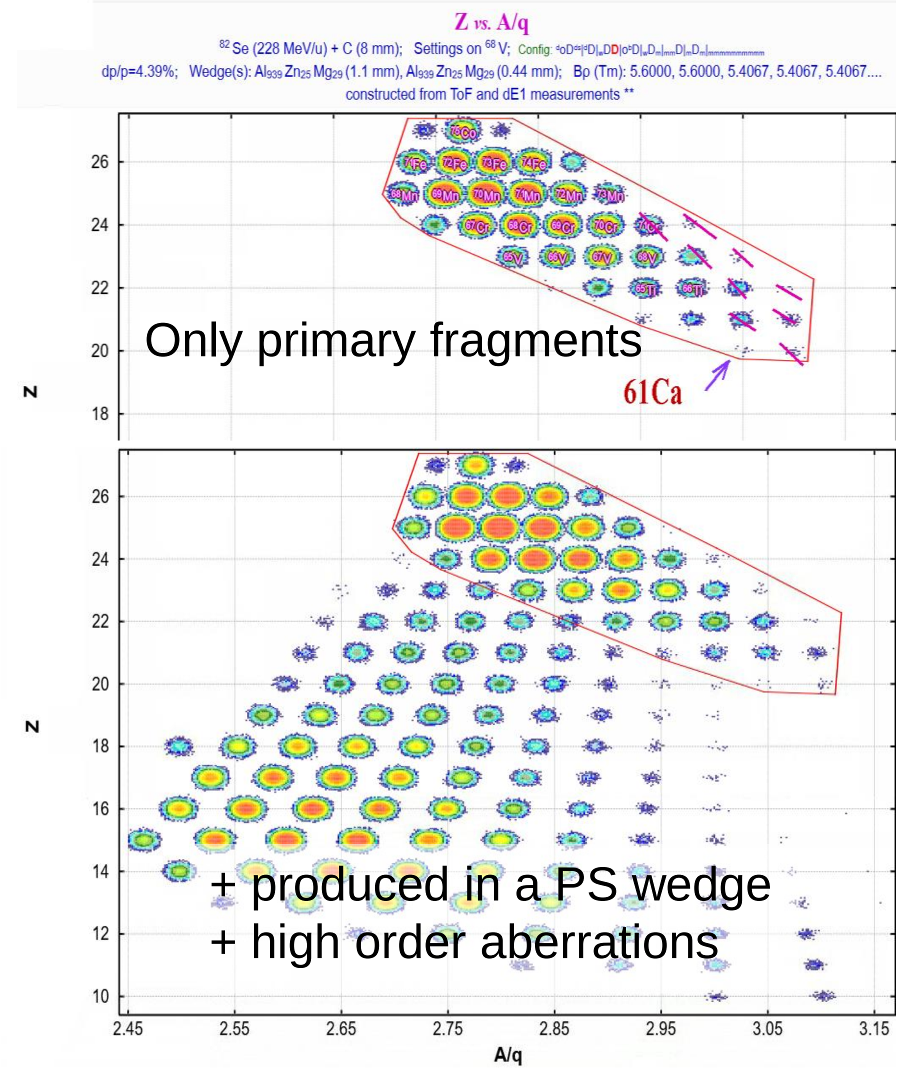
Filtering with:

- pin1.e vs. pin2.e
- Z-q=0 (TKE)
- v(tof1) = v(tof2) = v(tof3)
- ppac.sumX vs. ppac.sumY (all 5 ppacs)
- Momentum dP_34 vs. dP_45
- db3, db4, db5 frame X vs. Y
- db3 angles ~ db5 angles

Will be submitted next week to PRC

PID spectrum : Experiment vs. LISE

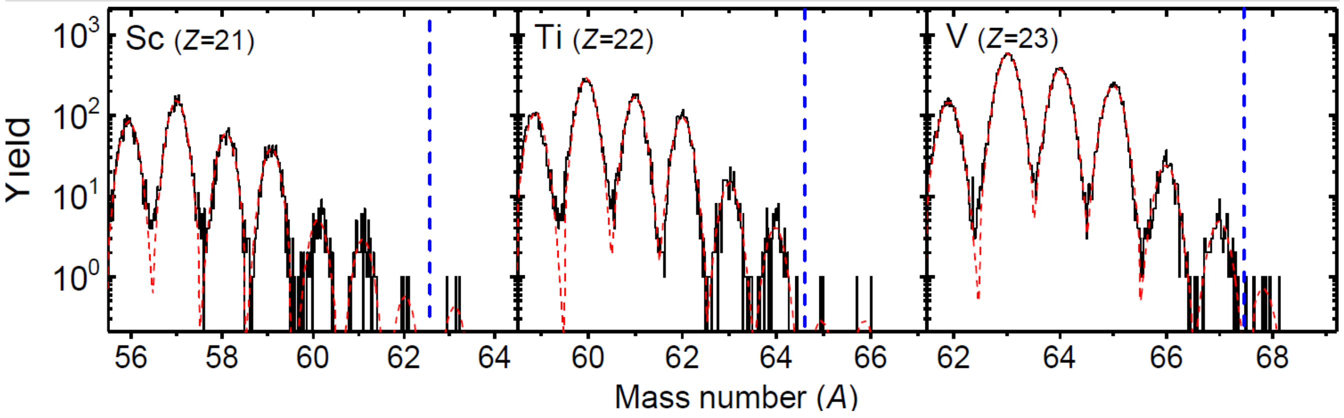


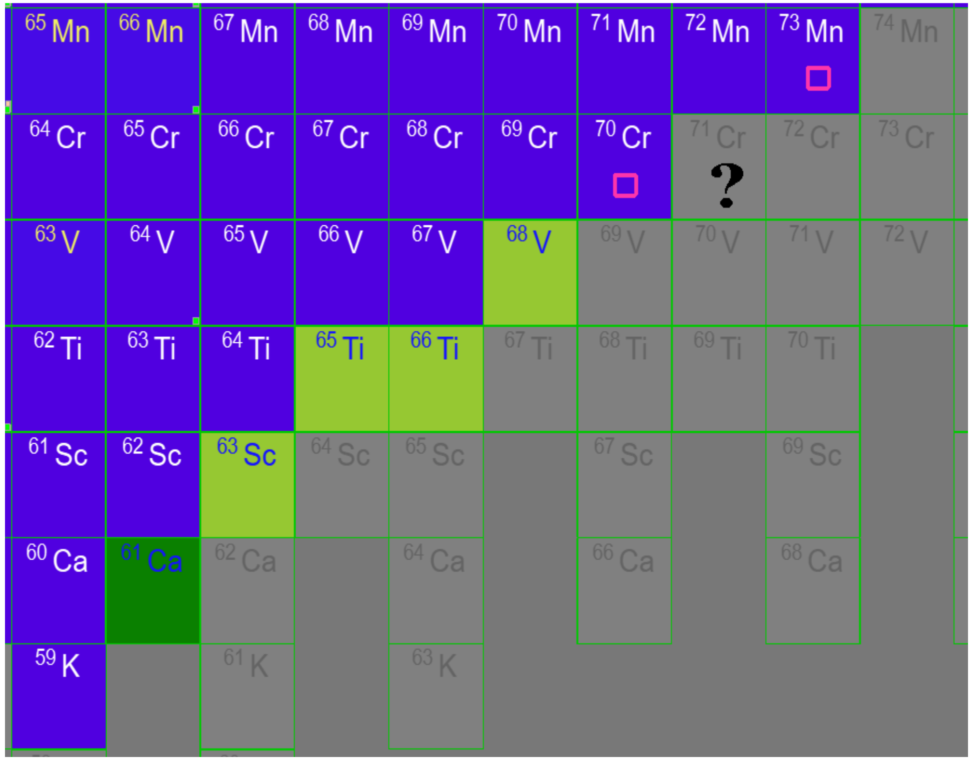


New isotope search

New isotope search results

- 27 h (6 h with stack, 19 h with Sci)
- Results: 4+1 new isotopes
  ^{63}Sc (3), ^{65}Ti (2), ^{66}Ti (2), ^{68}V (4), and ^{61}Ca (1)
- No events for ^{71}Cr (0)





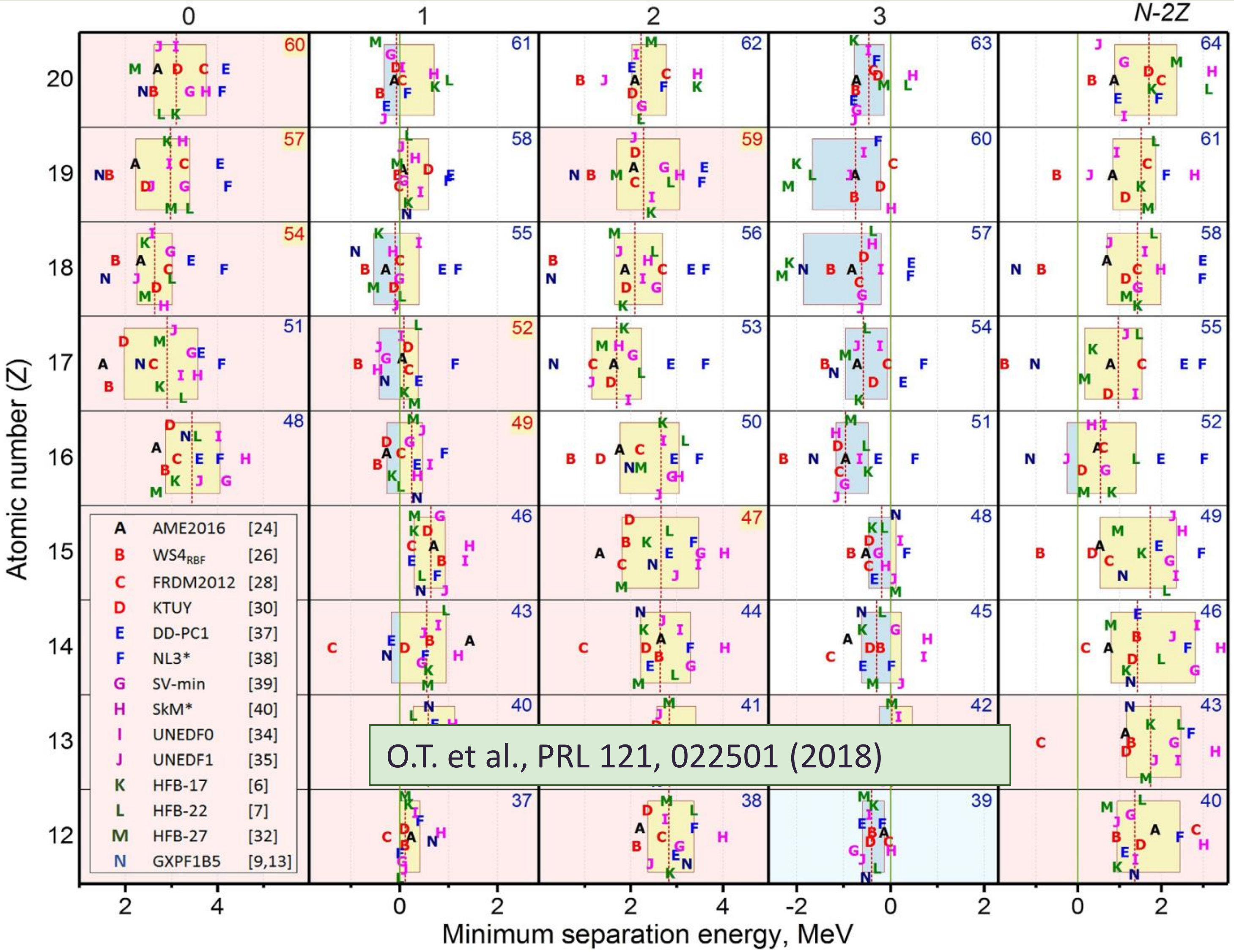
Unknown, Observed ≥ 2 events

Known, observed

Unknown, Observed 1 event

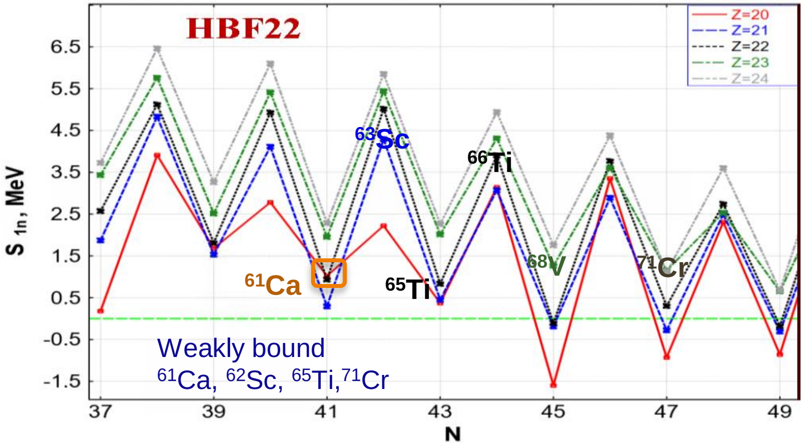
Unknown, Expected, but non-observed

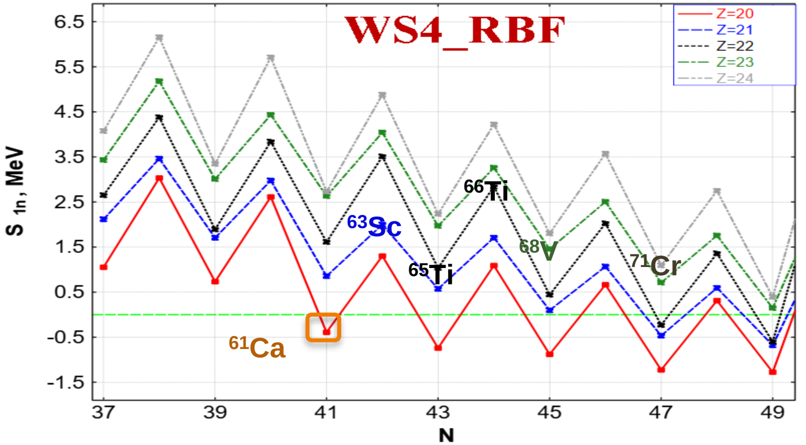
Neutron Drip Line in the Ca Region



A recent analysis of the global mass models with Bayesian machine learning investigated the neutron drip line in the Ca region and estimated the **existence probability of ^{61}Ca to be 46%**

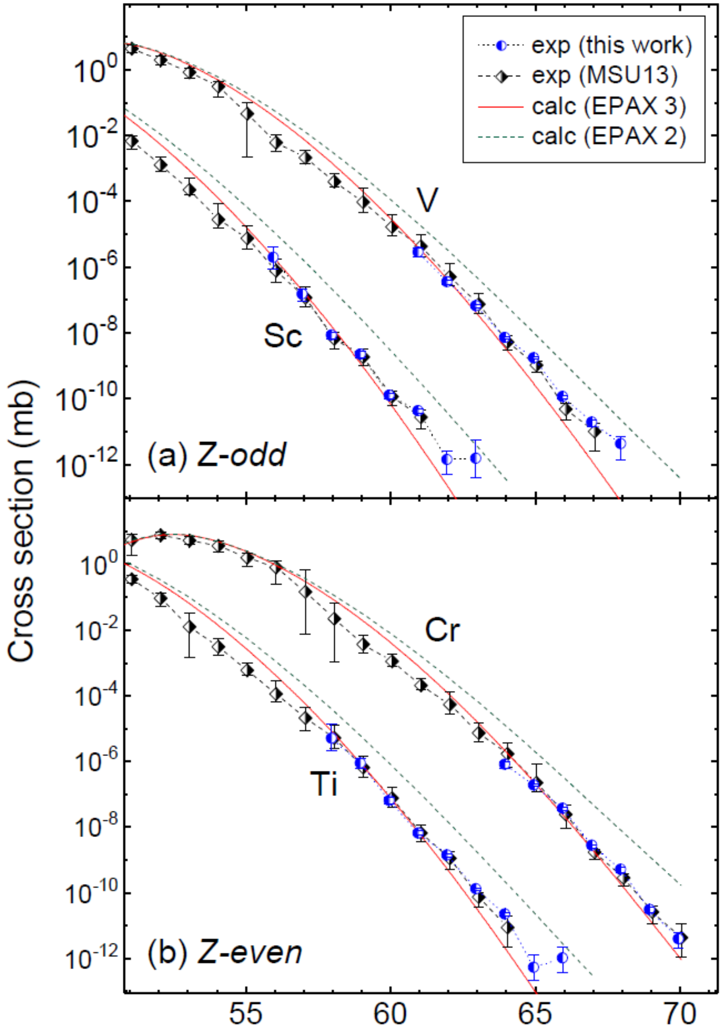
L. Neufcourt et al. PRL **122**, 062502 (2019).



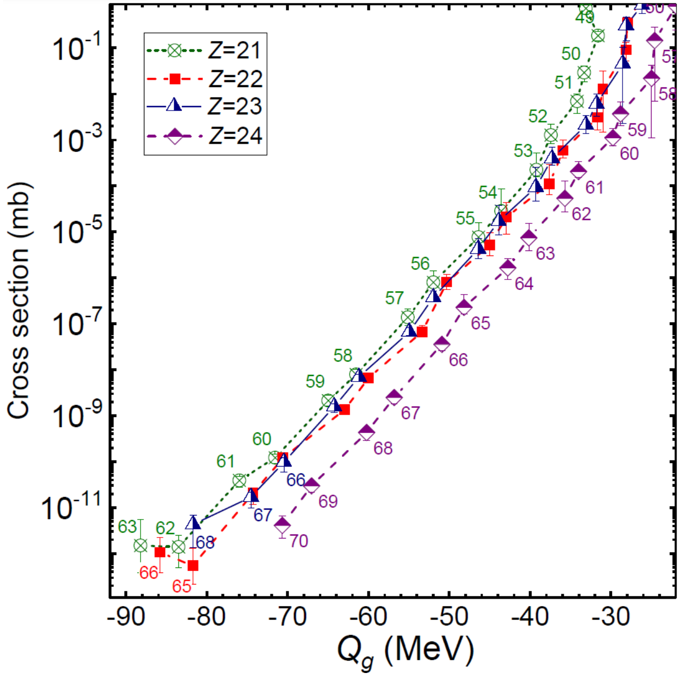


Production cross-sections

- Strong agreement with the previous ^{82}Se experimental dataset
- Significant enhancement above EPAX3 for more exotic nuclei
- The observation of two kinks ($^{62}Sc_{31}$ and $^{65}Ti_{43}$) provides insights into loosely bound odd-neutron isotopes

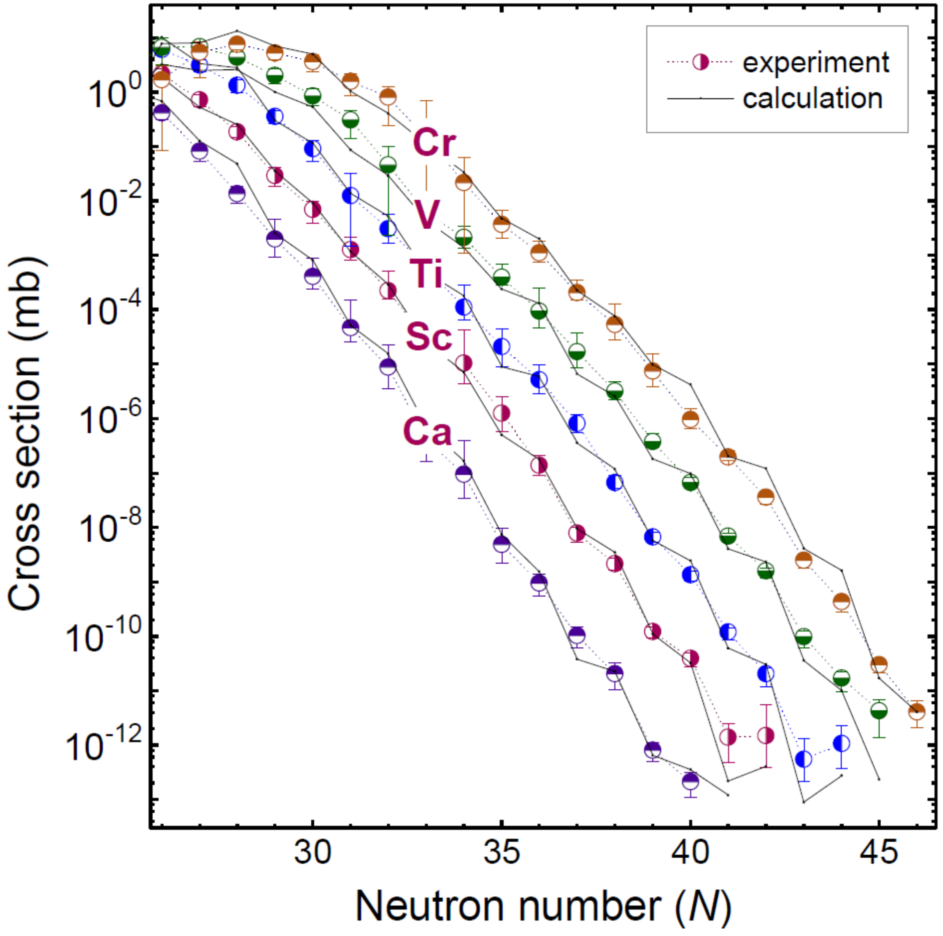


[MSU13] O.B.T. *et al.*, Phys. Rev. C **87**, 054612 (2013). ^{82}Se (140 MeV/u) + Be



- Q_g-systematics is equivalent to plotting - $ME_{fragment}$
- The systematic predicts particle-unbound isotopes
- The distance between two points corresponds to $ME_n - S1_n$. Why we plot $8 - S_n$? Why 8?
- Kinks cannot be described by Q_g systematics for $S_n < 8$ → CS(N+1) < CS(N+1) < CS(N+1)
- Additional considerations beyond Q_g -systematics that must be taken into account.

Abrasion-Ablation: minimization to experimental dataset



- HFB-22 gives better agreement with the experimental dataset
- Kink shapes well described
- Underpredictions of most exotic nuclei:
  - Localize region for minimization
  - Multistep reactions
  - Mass model

Minimization of Abrasion-Ablation calculations for ^{82}Se projectile fragmentation products in the range $20 \leq Z \leq 24$. This table presents the minimization results for 11 different mass models along with their corresponding excitation energy function parameters.

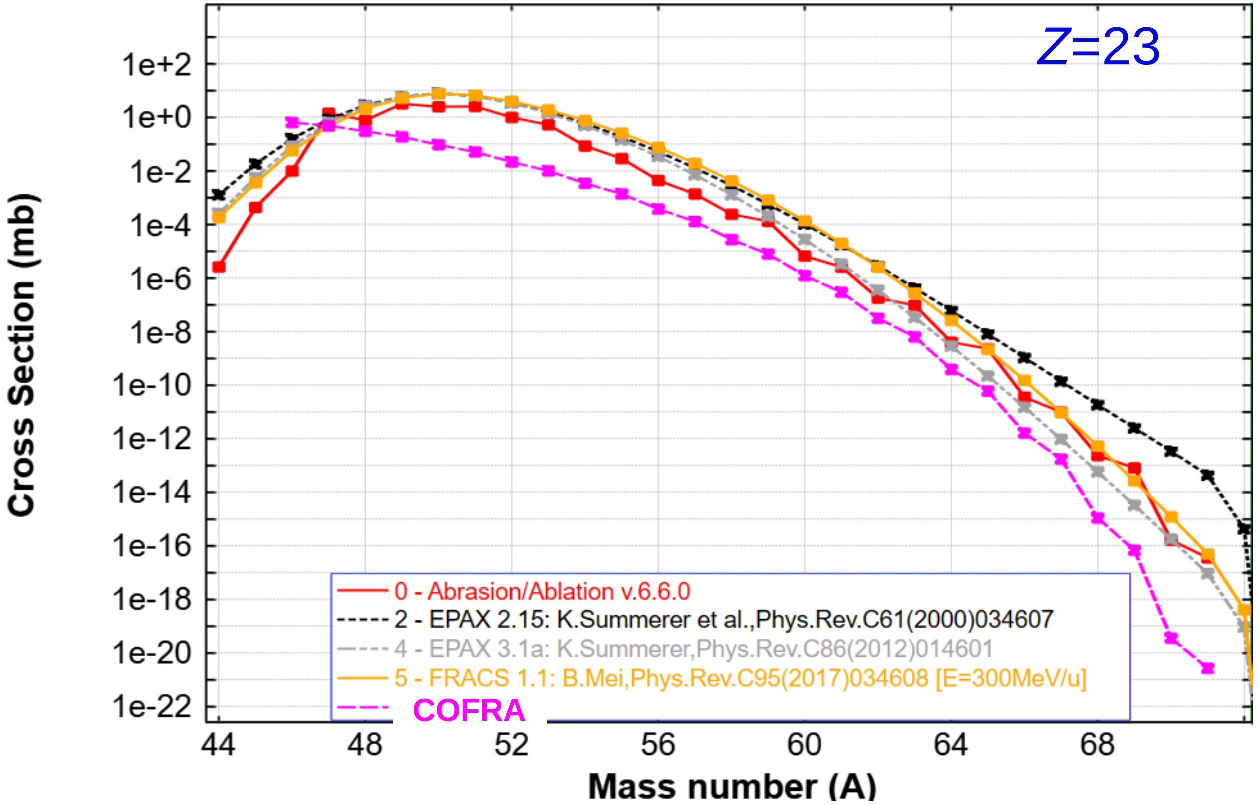
Mass model	χ^2	k_0	k_1	k_2	$S_n(^{61}Ca)$
HFB-22	1.8	17.0	-0.02	0.40	1.02
TTYY	2.5	17.0	0.31	0.35	-0.01
HFB-27	3.1	16.9	-0.15	0.10	-0.49
SV-min	3.2	16.5	-0.82	0.25	-0.18
AME2020	3.2	17.1	0.13	0.41	0.06
LISE-LDM3	3.4	16.9	1.50	0.03	-0.17
FRDM12	3.7	16.8	-0.17	0.45	0.05
$WS4_{RBF}$	3.7	16.1	1.60	0.03	-0.39
NL3*	3.7	17.4	2.00	0.48	0.17
UNEDF1	4.6	16.5	-0.51	0.23	-0.32
KTUY	4.9	17.7	-0.30	0.56	-0.07

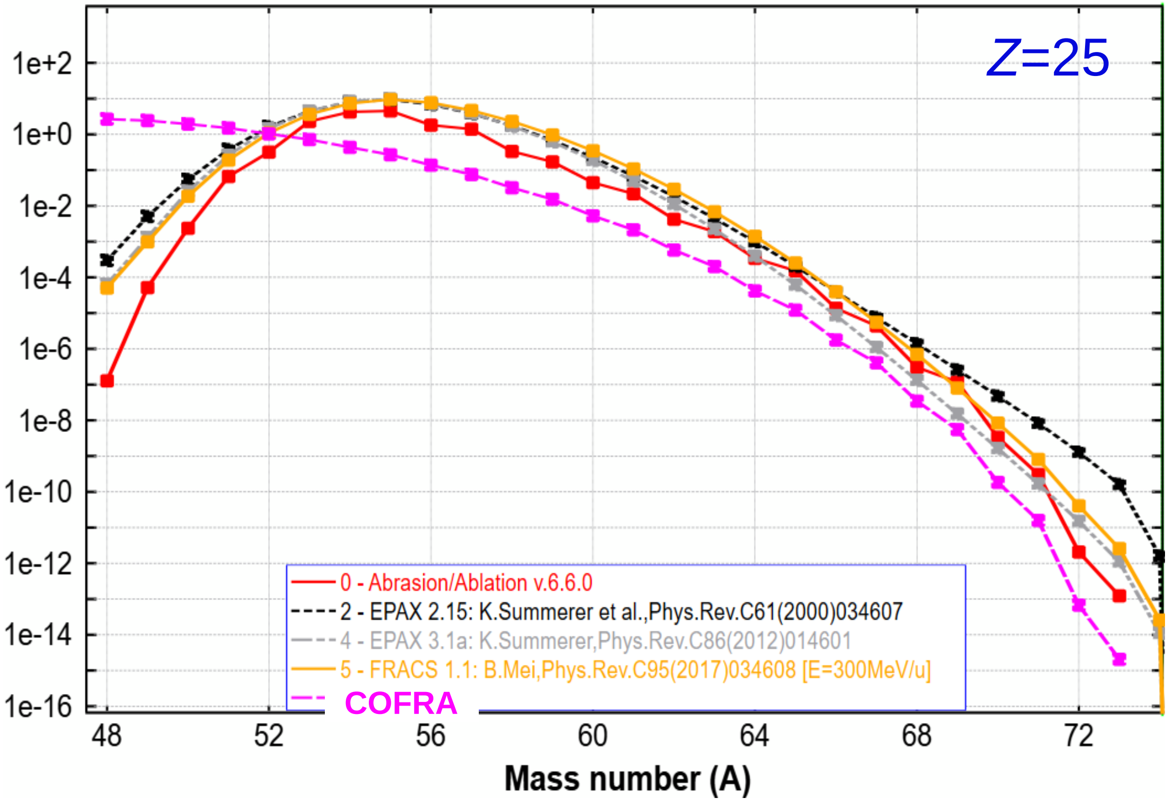
COFRA

simplified analytical AA approach, only n-channel

J. Benlliure, K.-H. Schmidt, et al., Nucl.Phys. A660, 87 (1999), https://www.usc.gal/genp/cofra/.

- Calculations were limited to isotopes with $Z \geq 23$
- It significantly underpredicts cross sections for neutron-rich isotopes with $Z < 30$
- The isotope distribution trends align reasonably well with the experimental data



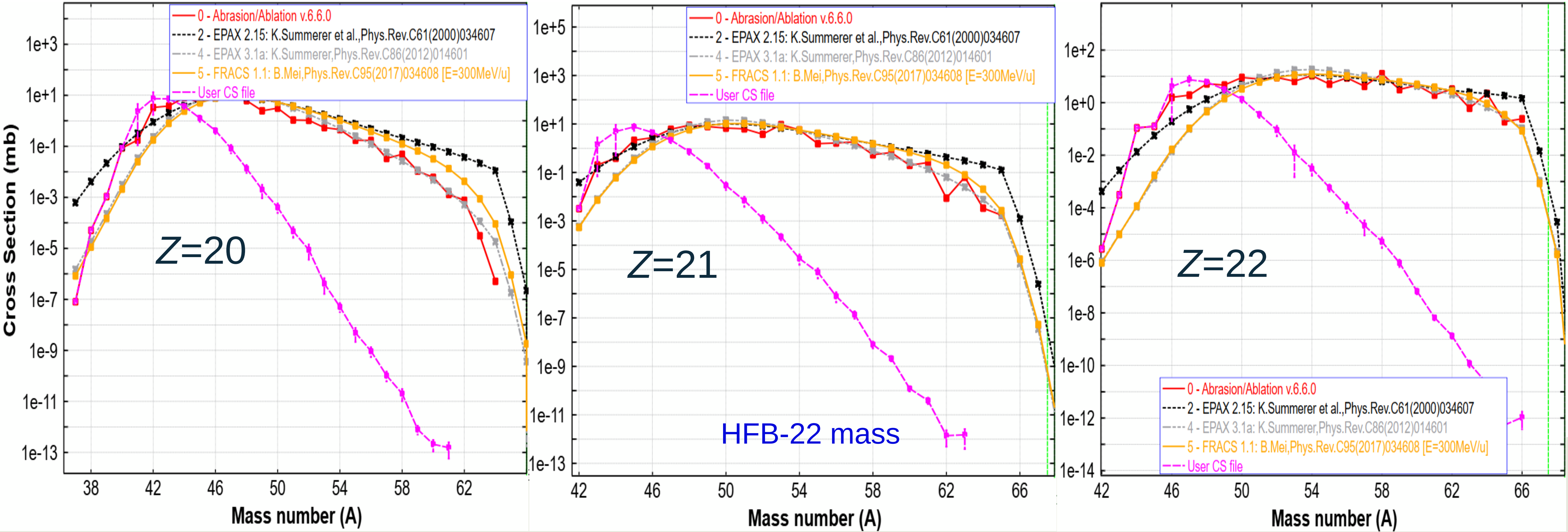


Multistep reaction: Subsequent step for rapid estimations

- AA parameters for ^{82}Se+C with HFB22
- User CS file (pink color): ^{82}Se+C experimental dataset

^{68}Cr + C

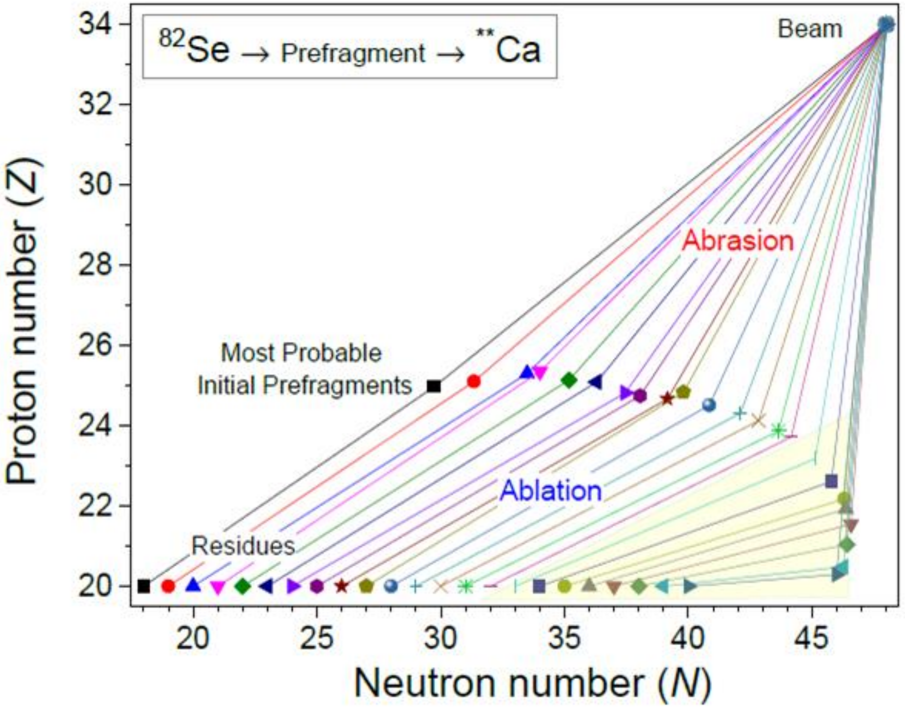
- What is a useful tool for rapid estimations of multi-step reaction contributions in this region?
- The EPAX3 parametrization showed better agreement with the AA model results
- Reasonable approach in this isotope region: 1st step :AA model, 2nd and others: EPAX3



ΔBE-systematics

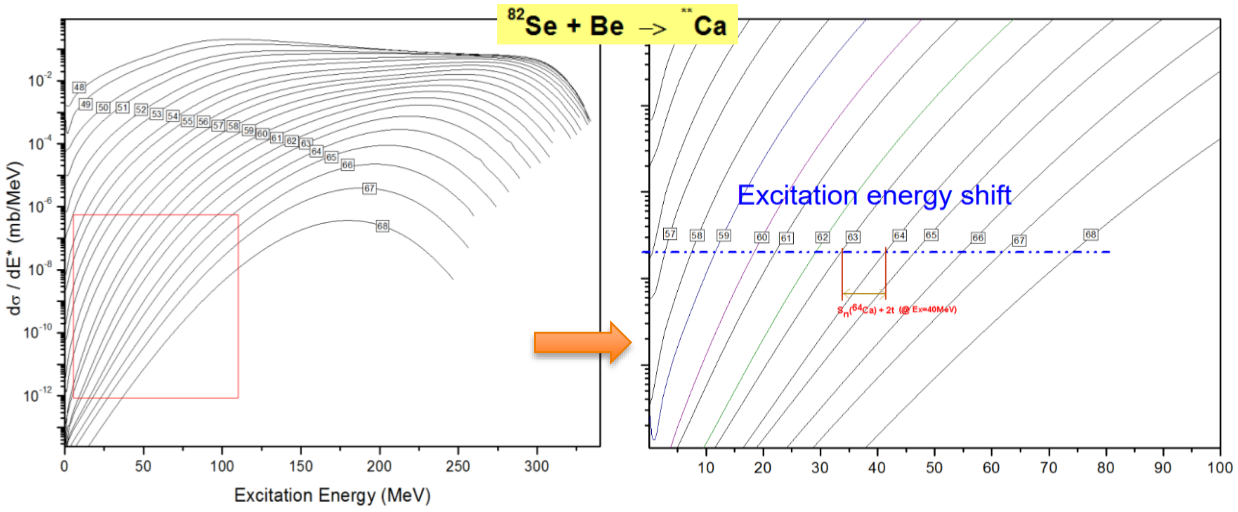
Derivation of the ΔBE-systematics

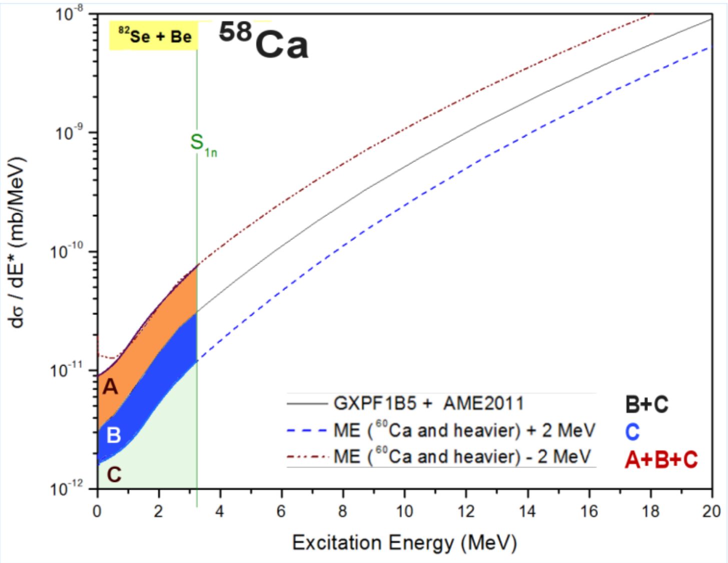
$$\lg(\sigma) = k_1 \ln(\Delta BE + 1) + k_2 \ln(S_n) + b$$



Most probable initial prefragments calculated using the LISE++ AA model for final calcium fragments resulting from the abrasion of an ^{82}Se projectile.

The most neutron-rich isotopes of calcium are produced from prefragments tightly clustered around $^{68}Ti_{46}$





$$\Delta BE(N, N_B) = BE(N_B) - BE(N),$$

which is equivalent to:

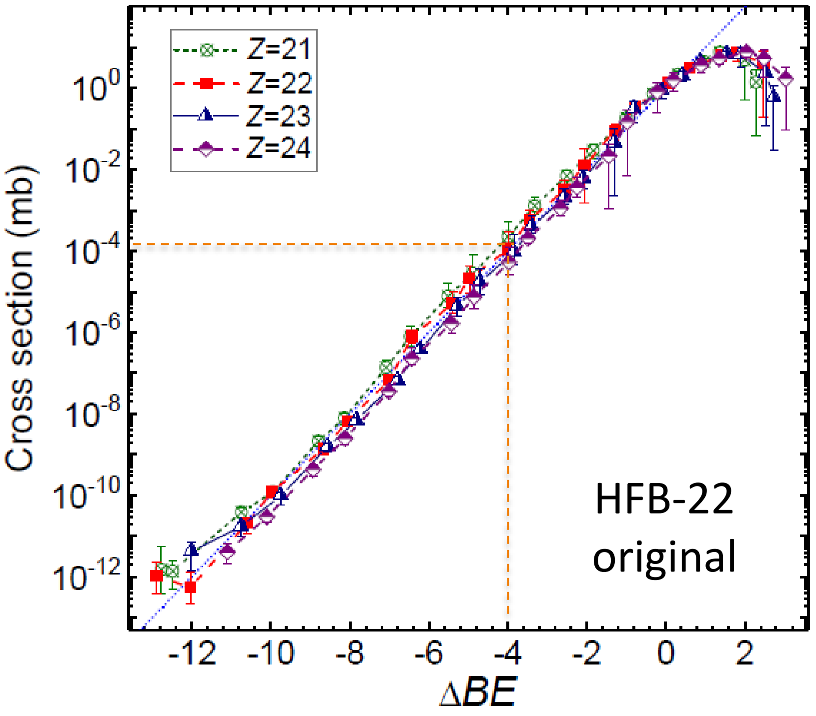
$$\Delta BE(N, N_B) = \sum_{i=N+1}^{N_B} S_{Z,i}$$

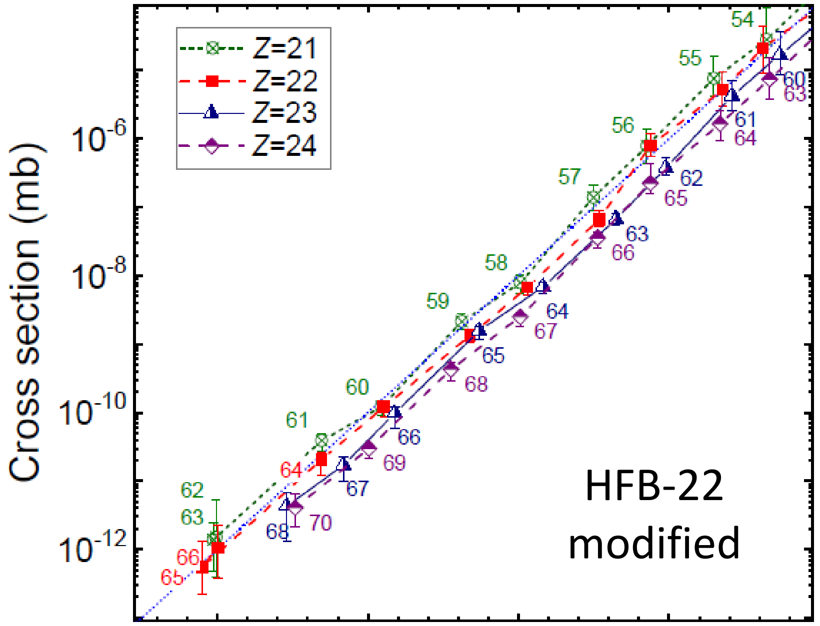
$$\sigma = a_0 \, (\Delta BE)^{a_1} \, (S_n)^{a_2}$$

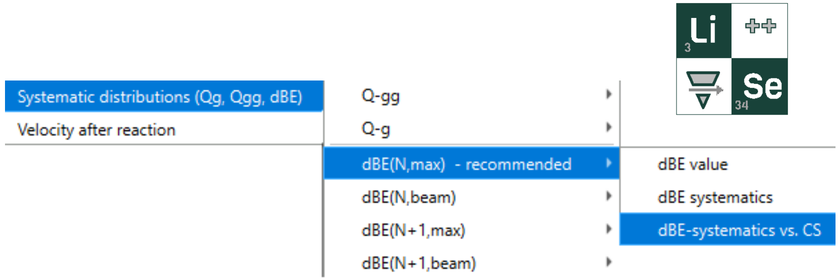
height width

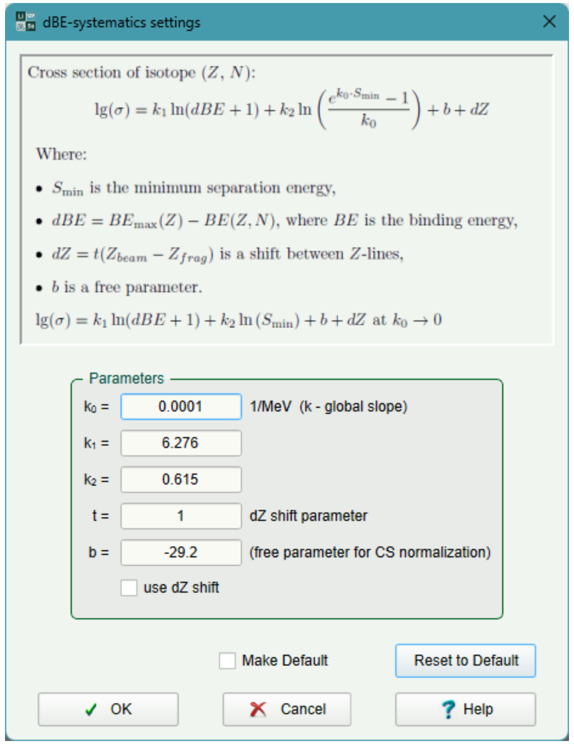
If S_n → 0, area → 0

^{82}Se + C : ΔBE-systematics









Parameters of the ΔBE-systematics for several mass models, deduced from fits to the ^{82}Se cross-section dataset.

Mass model	χ^2	k_1	k_2	b
HFB-22	0.213	6.276	0.615	-29.2
KTUY	0.214	5.673	0.827	-26.3
AME2020	0.280	5.262	0.869	-25.0
HFB-22* *modified*	0.094	6.439	0.524	-29.5

Original HFB-22 mass-excess values, modified during the ΔBE minimization, along with the corresponding one-neutron separation energies (in MeV).

Isotope	Original		Modified	
	ME	S_n	ME	S_n
^{61}Sc$_{40}$	-3.56	4.11	-2.98	3.54
^{62}Sc$_{41}$	4.22	0.29	4.82	0.27
^{63}Sc$_{42}$	8.00	4.29	10.00	2.88
^{65}Ti$_{43}$	1.62	0.83	2.14	0.31
^{66}Ti$_{44}$	5.79	3.90	8.92	1.29
^{67}V$_{44}$	-5.05	4.31	-2.98	2.24
^{68}V$_{45}$	1.76	1.26	3.64	1.45
^{70}Cr$_{46}$	-8.63	4.38	-8.10	3.86

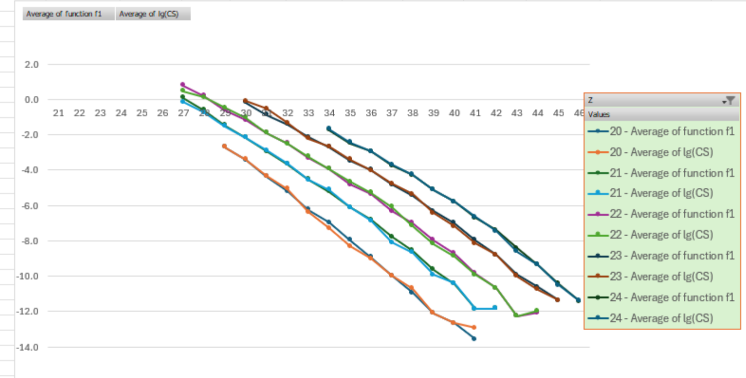
Minimization procedure of ΔBE and ME-values in Excel

All minimization procedures (ΔBE-systematics, Masses) were done in Excel.
Excel files can be shared by request for the further research in this direction

“Results” sheet

				index	Z	N	ME	S1n-link	MEorig-link	Sn-orig-link
								7	10	11
k0=	0.0001	in LN								
k1=	**6.439**	temperatur		20037	20	37	-8.50	1.40	-7.28	0.18
k2=	**0.524**	dBE f1		20038	20	38	-4.26	3.83	-3.12	3.91
				20039	20	39	2.66	1.15	3.27	1.68
				20040	20	40	9.93	0.80	8.56	2.78
				20041	20	41	15.25	2.75	15.61	1.02
np=	72			20042	20	42	22.00	1.32	21.46	2.22
np_gate=	12			21040	21	40	-3.07	3.62	-3.56	4.11
				21041	21	41	4.71	0.29	4.22	0.29
chi2=	**0.094**			21042	21	42	10.12	2.66	8.00	4.29
chi2gate=	0.096			21043	21	43	16.50	1.70	15.62	0.45
				22043	22	43	2.14	0.31	1.62	0.83
Zfilter=	21	gate		22044	22	44	8.92	1.29	5.79	3.90
				22045	22	45	12.00	4.99	13.97	-0.11
				23044	23	44	-2.98	2.25	-5.05	4.31
				23045	23	45	3.64	1.45	1.76	1.26
				23046	23	46	5.00	6.71	6.23	3.60
				24046	24	46	-8.10	3.86	-8.63	4.38

Z	b0	k0	k1	k2	chi2
16		0.000	6.439	0.524	0.302
17		0.000	6.439	0.524	0.245
18		0.000	6.439	0.524	0.324
19		0.000	6.439	0.524	0.472
20	-29.168	0.000	6.491	0.524	0.523
21	**-29.311**	0.000	6.439	0.524	0.328
22	**-29.569**	0.000	6.439	0.524	0.429
23	**-29.787**	0.000	6.439	0.524	0.868
24	**-29.957**	0.000	6.439	0.524	0.578
25					



	21		22		23
e of lg	Average of fu	Average of lg	Average of fu	Average of lg	Average of fu
	0.1	-0.2	0.8	0.5	
	-0.6	-0.8	0.2	0.1	
-2.7	-1.5	-1.5	-0.6	-0.5	
-3.4	-2.2	-2.2	-1.2	-1.0	-0.2
-4.3	-3.0	-2.9	-1.9	-1.9	-0.9
-5.1	-3.7	-3.7	-2.5	-2.5	-1.4
-6.4	-4.5	-4.5	-3.3	-3.2	-2.2
-7.3	-5.2	-5.1	-3.9	-4.0	-2.7
-8.3	-6.1	-6.1	-4.8	-4.7	-3.5
-9.0	-6.8	-6.9	-5.4	-5.3	-4.0
-10.0	-7.8	-8.1	-6.3	-6.1	-4.8
-10.7	-8.6	-8.7	-7.0	-7.2	-5.5
-12.1	-9.6	-9.9	-8.0	-8.2	-6.3
-12.7	-10.4	-10.4	-8.7	-8.9	-7.0
-12.9	-11.9	-11.9	-9.9	-9.9	-8.0

“ME” sheet

index	Z	N	ME, current	dME	BE	S1n	dBEf0	ME-orig	S1n-orig
21033	21	33	-34.17		453.59	3.661	41.31	-34.17	3.66
21034	21	34	-31.82		459.31	5.721	35.59	-31.82	5.72
21035	21	35	-26.36		461.92	2.611	32.98	-26.36	2.61
21036	21	36	-23.5		467.14	5.211	27.76	-23.50	5.21
21037	21	37	-17.3		469.01	1.871	25.89	-17.30	1.87
21038	21	38	-14.06		473.84	4.831	21.061	-14.06	4.83
21039	21	39	-7.52		475.37	1.531	19.530	-7.52	1.53
21040	21	40	-3.07		478.99	3.621	15.908	-3.56	4.11
21041	21	41	4.71		479.28	0.291	15.617	4.22	0.29
21042	21	42	10.12		481.94	2.658	12.959	8.00	4.29
21043	21	43	16.50		483.64	1.695	11.264	15.62	0.45
21044	21	44	20.62		487.59	3.951	7.313	20.62	3.07
21045	21	45	28.88		487.40	-0.189	7.502	28.88	-0.19
21046	21	46	34.06		490.29	2.891	4.611	34.06	2.89
21047	21	47	42.41		490.01	-0.279	4.889	42.41	-0.28
21048	21	48	47.99		492.50	2.491	2.398	47.99	2.49

Multistep reactions

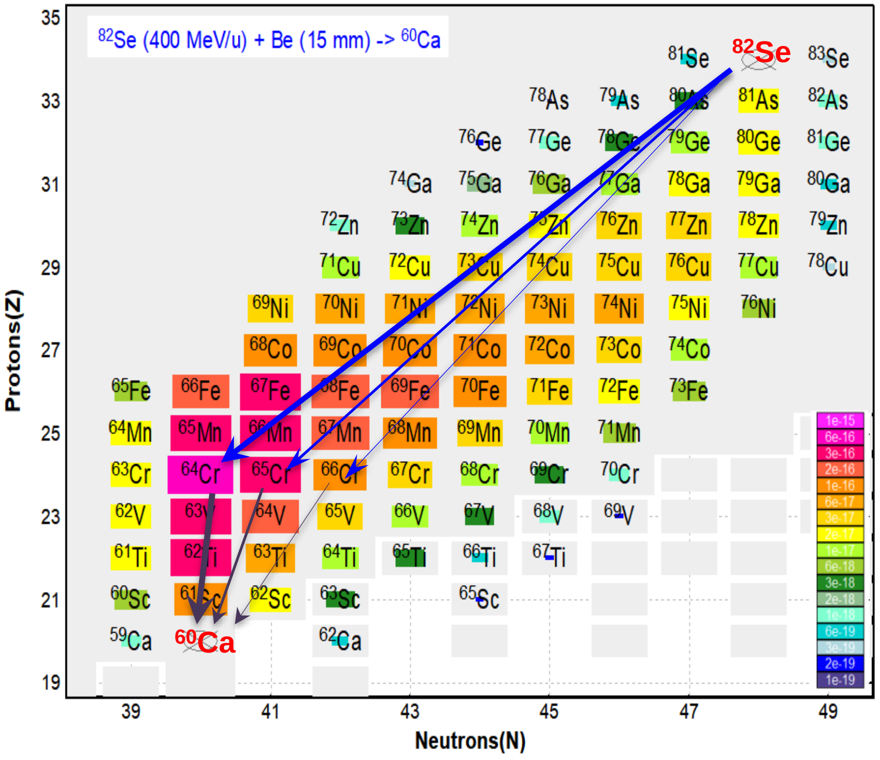
Multi-Step Reactions

- Multi-step reactions in thick targets is process then the projectile undergoes a series of successive reactions until the fragment of interest is produced

- Multistep reactions is expected to be a fundamental factor in the discovery of new isotopes

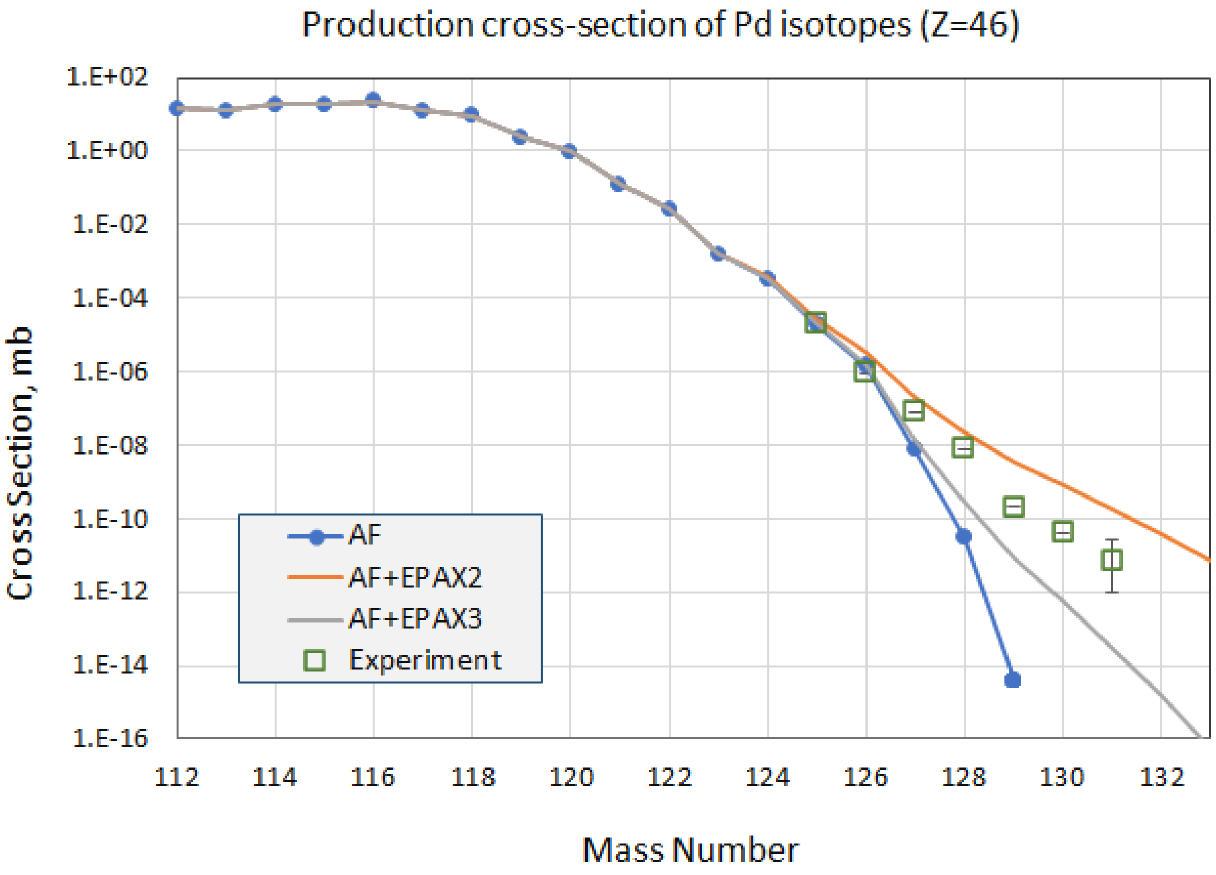
- For the second and subsequent reactions, a projectile fragmentation mechanism is assumed, and EPAX parameterizations are currently used to speed up the calculations

Parent nuclei: multistep production probability



LISE^{++} → ^{64}Cr is more probable second-step projectile to produce ^{60}Ca with an ^{82}Se beam (400 MeV/u) on Be (15 mm).
Total Multi-step reaction factor is equal to 10.1

Reduced cross sections of Palladium isotopes for Be 2.9 mm-t



- Dominated contribution of multi-step reactions starts at A=127
- Large deviations between EPAX versions
- FRIB400 C-target (d/t=0.4) twice as many atoms as this example

Experiment: Y. Shimizu et al., J. Phys. Soc. Japan 87 (2018) 014203.

*The RIKEN RIBF accelerator complex was used to bombard a **2.92-mm**-thick beryllium target with a 345 MeV/nucleon ^{238}U beam.*

AF: 3EER Abrasion-Fission model, LISE v.16.8.8, masses: WS4_RBF

Excitation energy region	LOW	MIDDLE	HIGH
Choose FISSILE nucleus	238U	232Th	220At
Excitation energy (MeV)	33.7	124.8	394
Cross section (mb)	525.5	541.7	557

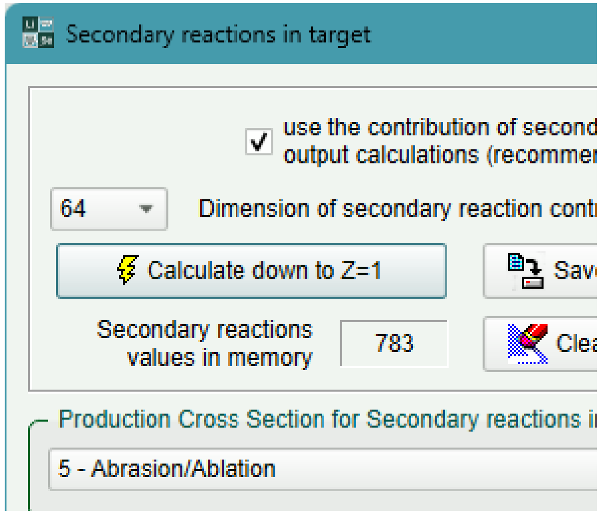
AF+EPAX2,3: With secondary reactions based on the empirical parameterizations v.2 or 3

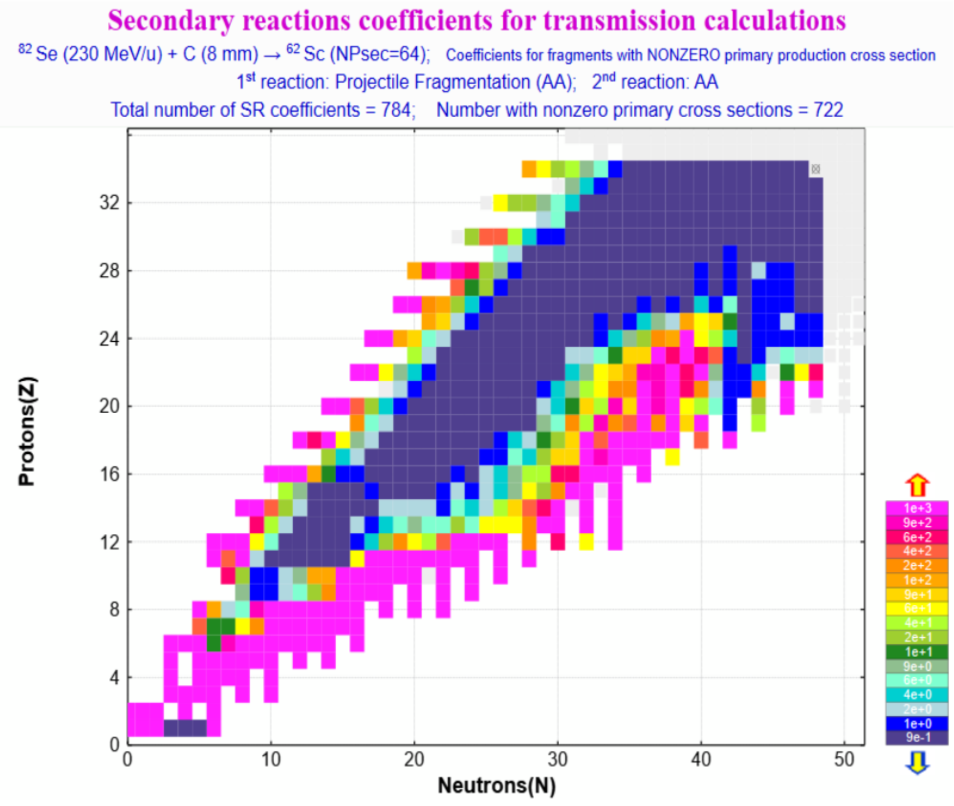
Significant uncertainties in the contribution of multistep reactions!

2024: multistep reaction modeling development in LISE++

Abrasion-Ablation and Multistep Reactions

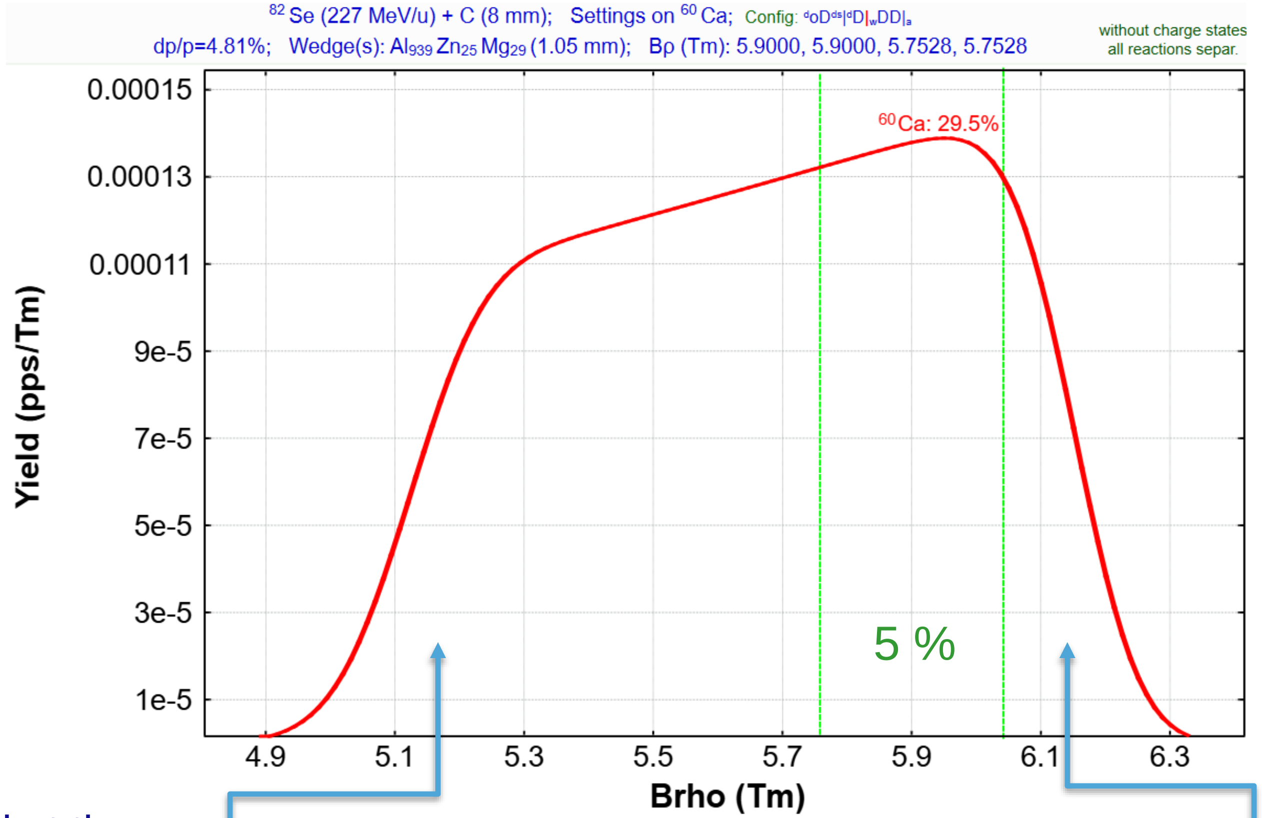
- Incorporating Abrasion-Ablation into the multistep reaction list
- Optimizing the speed of multistep reaction calculations:
  - Production cross-sections are calculated once and stored in memory using Qmap.
  - However, the process remains time-consuming. Is parallelization an option?
  - This is currently under development.





https://lise.nscl.msu.edu/17/17_03_AA_secReact.pdf

Thick target: Momentum distribution



Fragments created at the end of the target

Mostly energy loss by the primary beam

Fragments created at the beginning of the target

Mostly energy loss by the final fragment

What about the momentum distribution in the case of secondary reactions?
Note that the second reaction place most likely occurs at the end of the target.

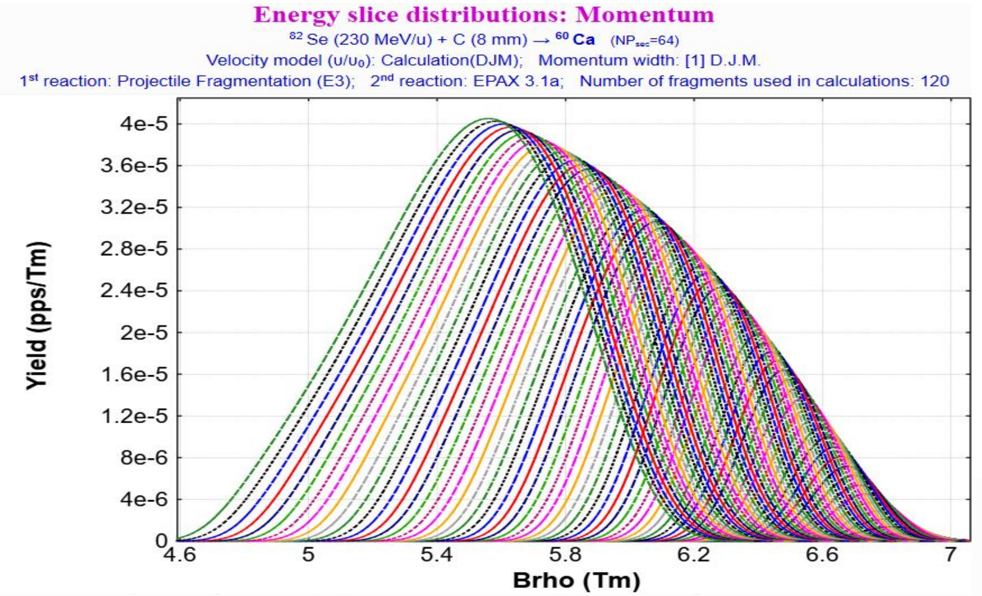
Kinematics of multistep reaction products

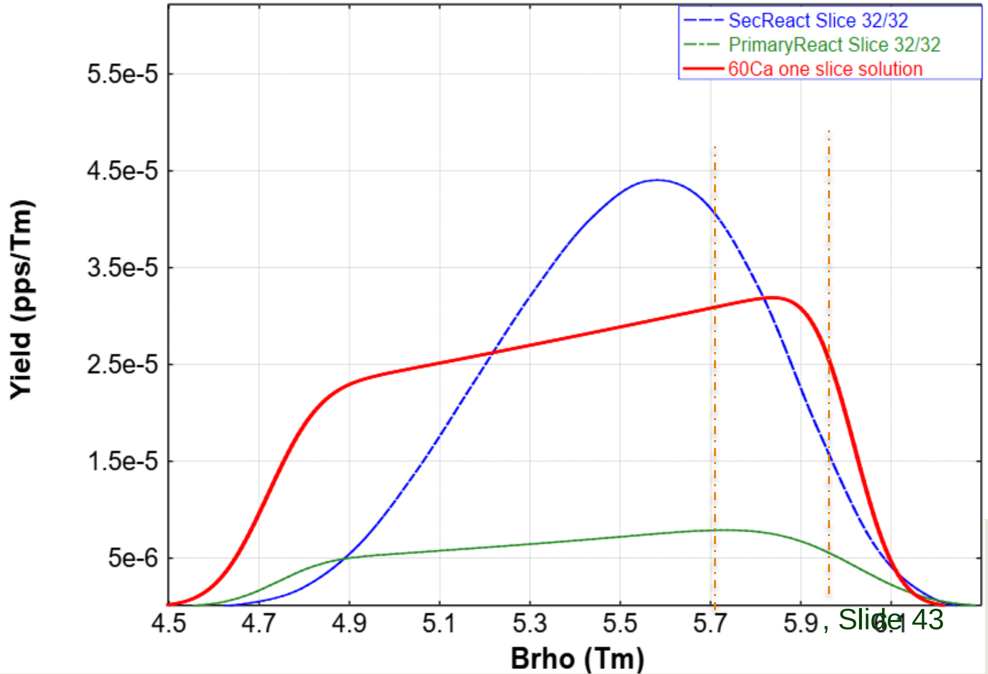
- It is hard (impossible) to directly determine multi-step reaction kinematics using the Monte Carlo method. Even for a two-step case. Current MC calculation speed is around 1 kps for passing only a target.
- Summing up all parent contributions as momentum distribution after passing the target slide

$$P(k)_{step} = \hat{F}\ P(k)_{step-1} + \sum_{i!=k}\left[\hat{F}\ P(i)_{step-1}\right] \cdot dN \cdot \sigma_{i \to k}$$

where $\hat{F}$ is an operator that modifies a momentum distribution as it passes through a target layer, where dN is the number of atoms in that layer

- Under construction for
  - fission case
  - should be optimized for high-Z
- An **important conclusion** is that the momentum distribution, significantly influenced by multistep reactions, tends to be narrow.
  - This narrowing enhances transmission,
    allowing for better particle passage through the separator.
  - Consequently, a thicker target can be employed without compromising the transmission efficiency regarding to the one-step case





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Multistep reaction contribution study

- Understanding the multistep reaction mechanism helps in selecting the optimal beam and target combination for maximizing rare isotope production, which directly influences facility upgrades and experimental planning
- Reaction outputs for experimental modeling include:
  - Production cross-sections
  - Fragment kinematics
- The current limitation in multistep production cross-section modeling is the use of EPAX parameterization for subsequent reactions, which is intended to speed up calculations but may introduce uncertainties
- Areas of study to address this issue (both experimental and theoretical) should include:
  - **Development of a faster model (analytical)** for multistep reactions using the abrasion-ablation model for subsequent steps.
  - Improving input parameters for the abrasion-ablation model, such as **excitation energy models** (abrasion step) and mass models (ablation step), through experimental and theoretical studies.
  - Measurement of experimental secondary cross-sections.

Input for Theory: Experimental cross-sections with rare isotope beams

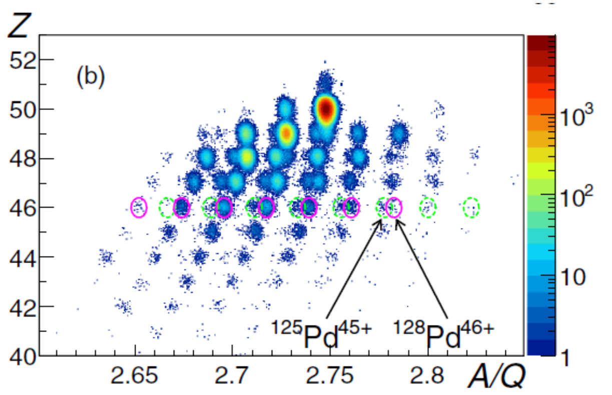
- BigRIPS @ RIKEN

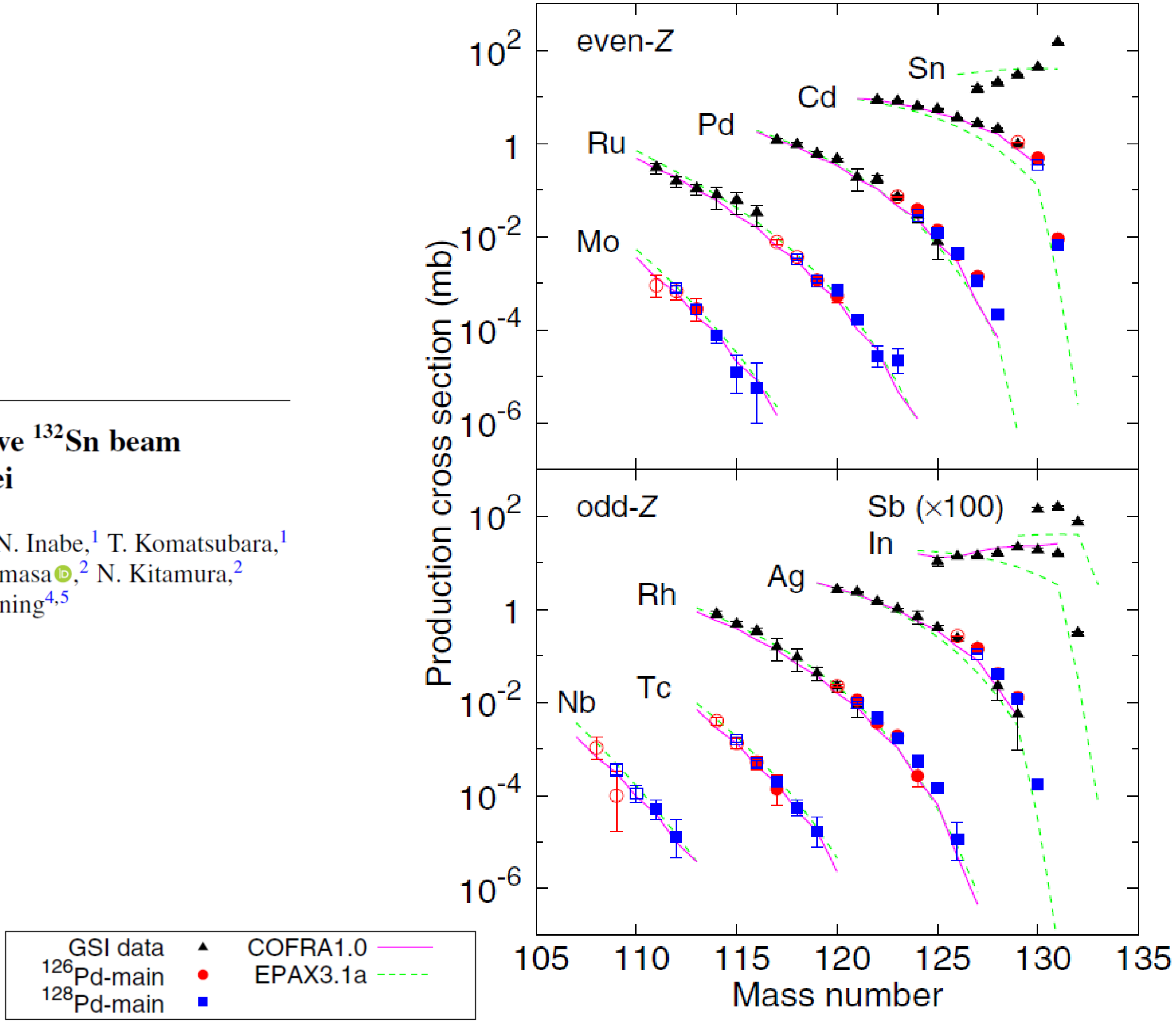
^{238}U (345 MeV/u) → abrasion-fission → ^{132}Sn (~211MeV/u)
→ projectile fragmentation → ^{126}Pd
abrasion-evaporation

PHYSICAL REVIEW C **102**, 064615 (2020)

Experimental studies of the two-step scheme with an intense radioactive ^{132}Sn beam for next-generation production of very neutron-rich nuclei

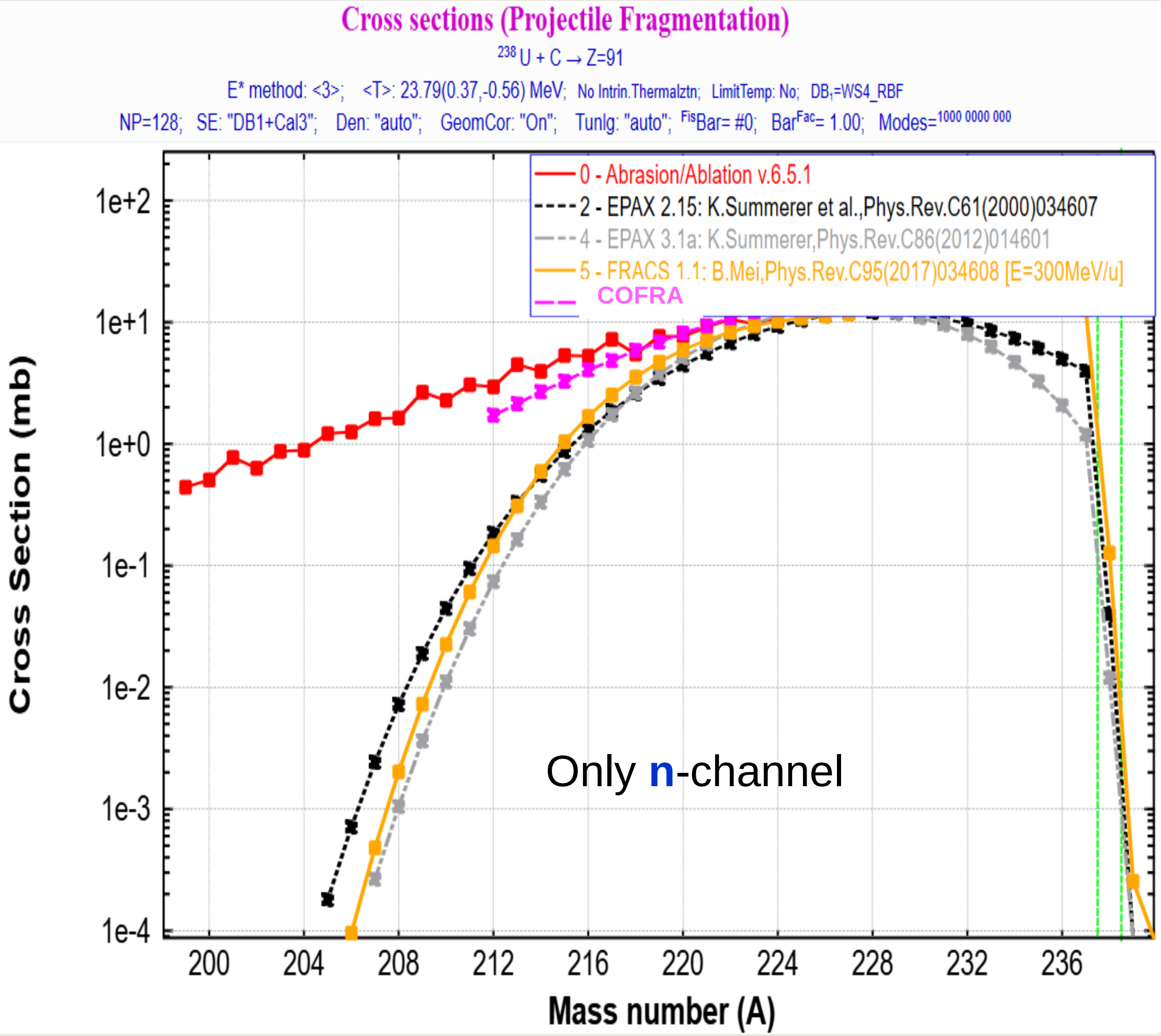
H. Suzuki,[1,*] K. Yoshida,[1] N. Fukuda,[1] H. Takeda,[1] Y. Shimizu,[1] D. S. Ahn,[1] T. Sumikama,[1] N. Inabe,[1] T. Komatsubara,[1] H. Sato,[1] Z. Korkulu,[1] K. Kusaka,[1] Y. Yanagisawa,[1] M. Ohtake,[1] H. Ueno,[1] T. Kubo,[1] S. Michimasa,[2] N. Kitamura,[2] K. Kawata,[2] N. Imai,[2] O. B. Tarasov,[3] D. Bazin,[3] J. Nolen,[4] and W. F. Henning[4,5]

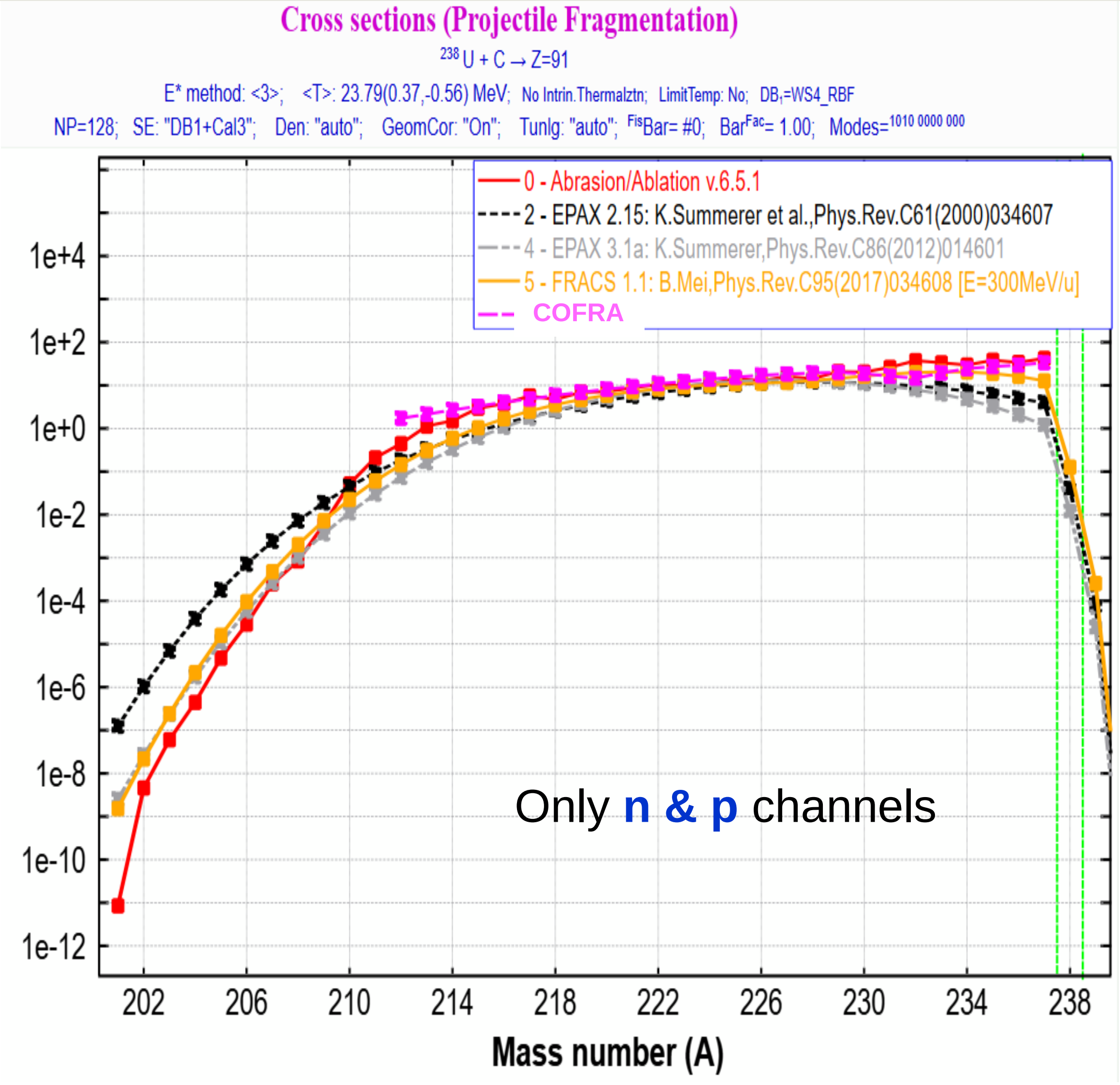




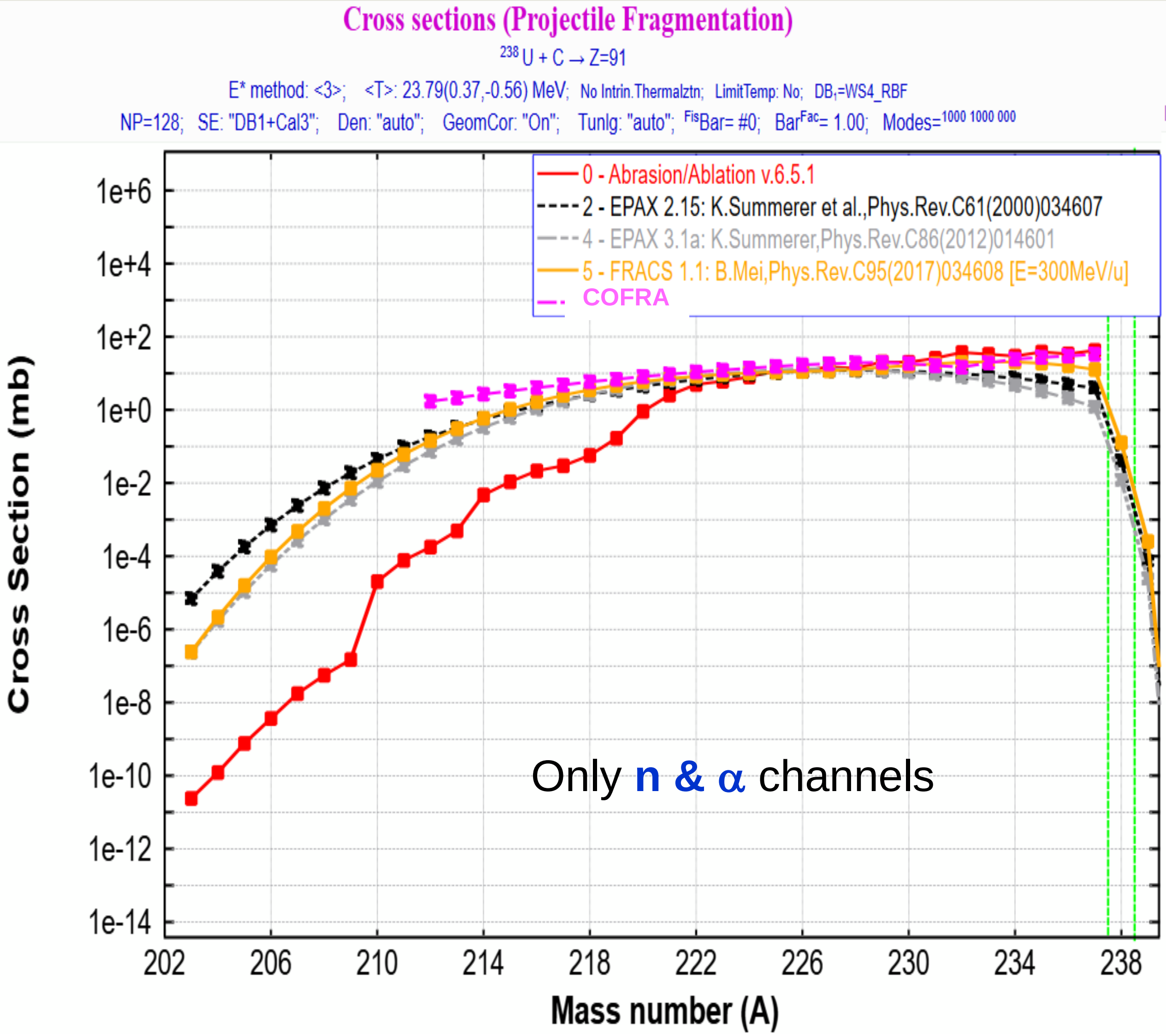
High Z isotopes production:
take into account all channels!

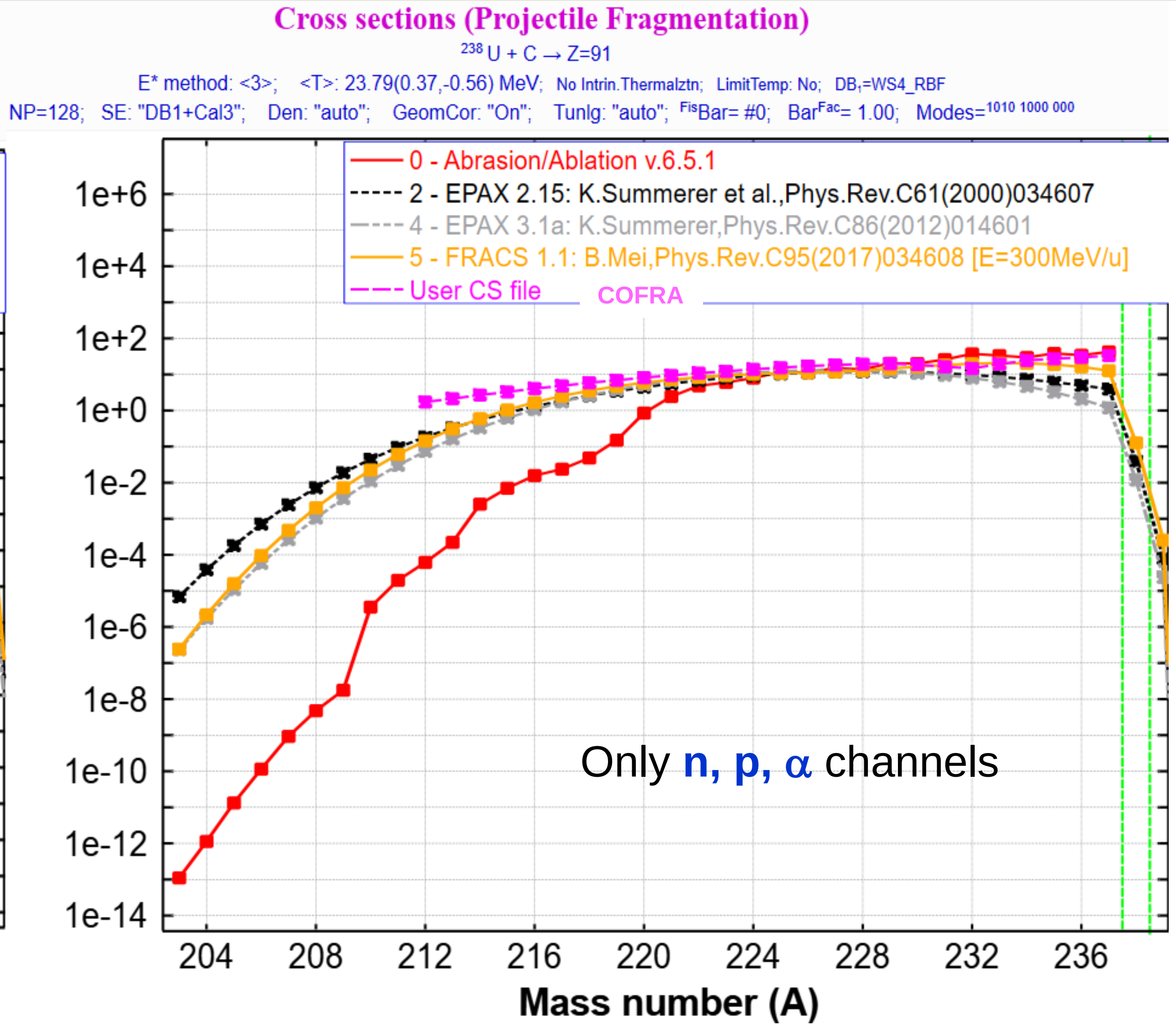
How to reproduce COFRA or EPAX? ($^{238}U \rightarrow Z=91$)



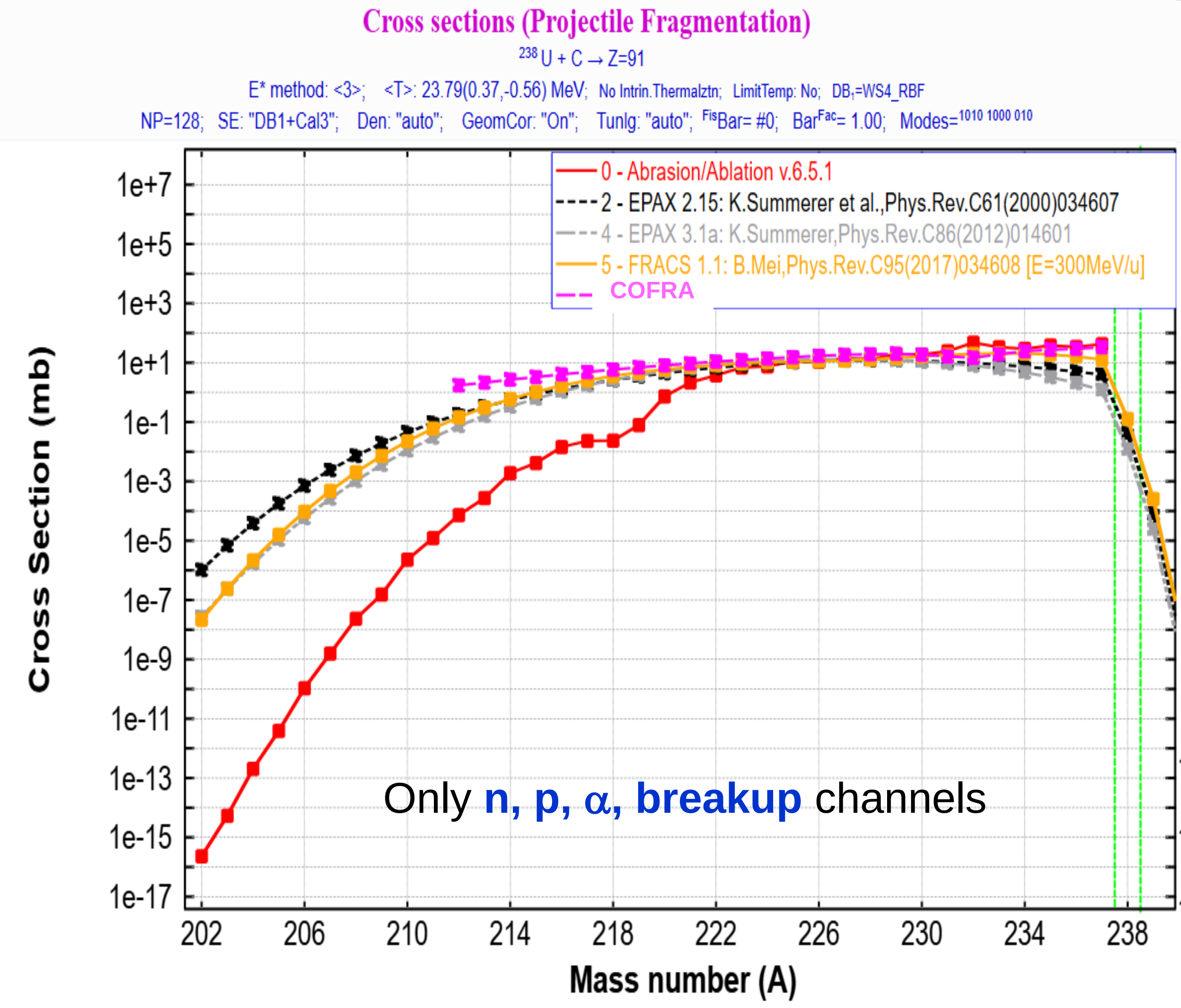


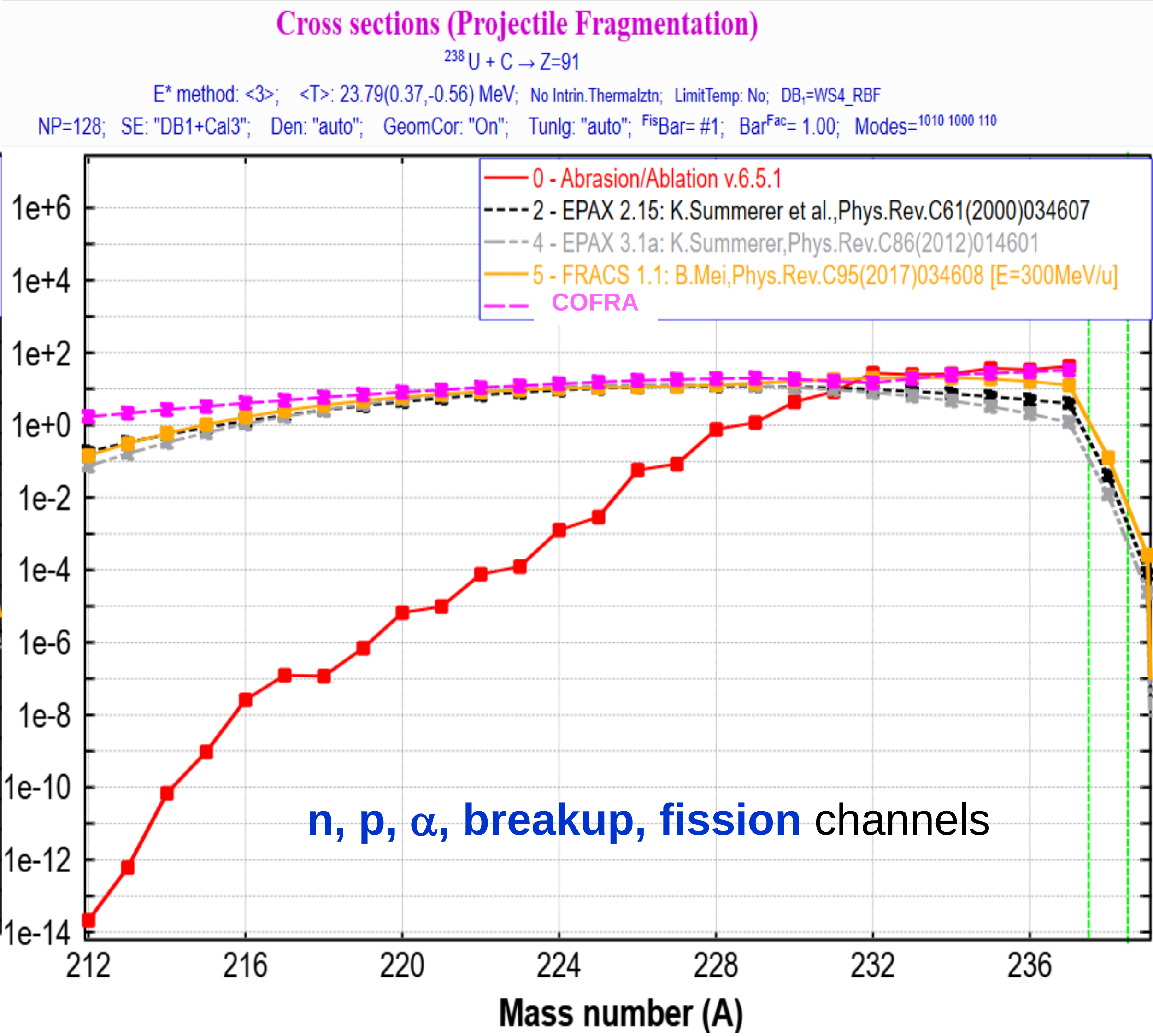
What is about α, fission, breakup? ($^{238}U \rightarrow Z=91$)





What is about α, fission, breakup? (^{238}U → Z=91)





Comparison with U experimental data

AA-settings from U-data fit

PHYSICAL REVIEW C **75**, 014602 (2007)

Isotopic production cross sections and recoil velocities of spallation-fission fragments in the reaction ^{238}U(1*A* GeV) + *d*

J. Pereira,[1,*] J. Benlliure,[1] E. Casarejos,[1] P. Armbruster,[2] M. Bernas,[3] A. Boudard,[4] S. Czajkowski,[5] T. Enqvist,[2] R. Legrain,[4] S. Leray,[4] B. Mustapha,[3] M. Pravikoff,[5] F. Rejmund,[3] K.-H. Schmidt,[2] C. Stéphan,[3] J. Taïeb,[3] L. Tassan-Got,[3] C. Volant,[4] and W. Wlazlo[4]

[1]*Universidad de Santiago de Compostela, Santiago de Compostela E-15782, Spain*
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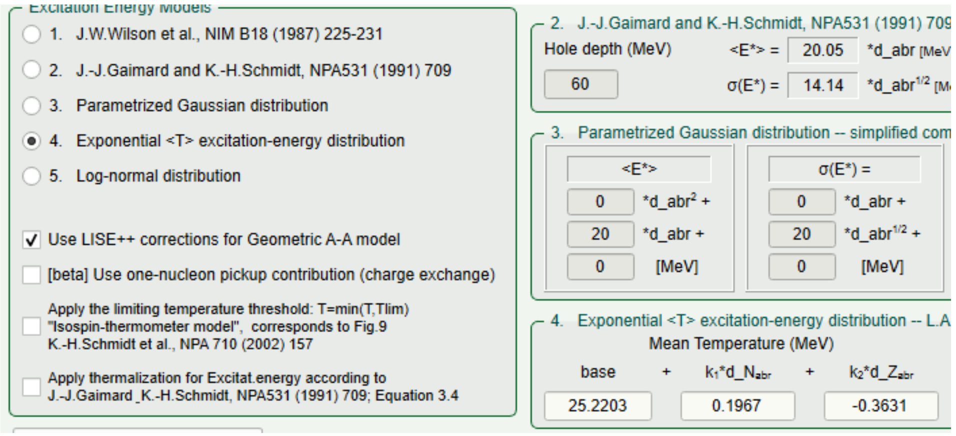
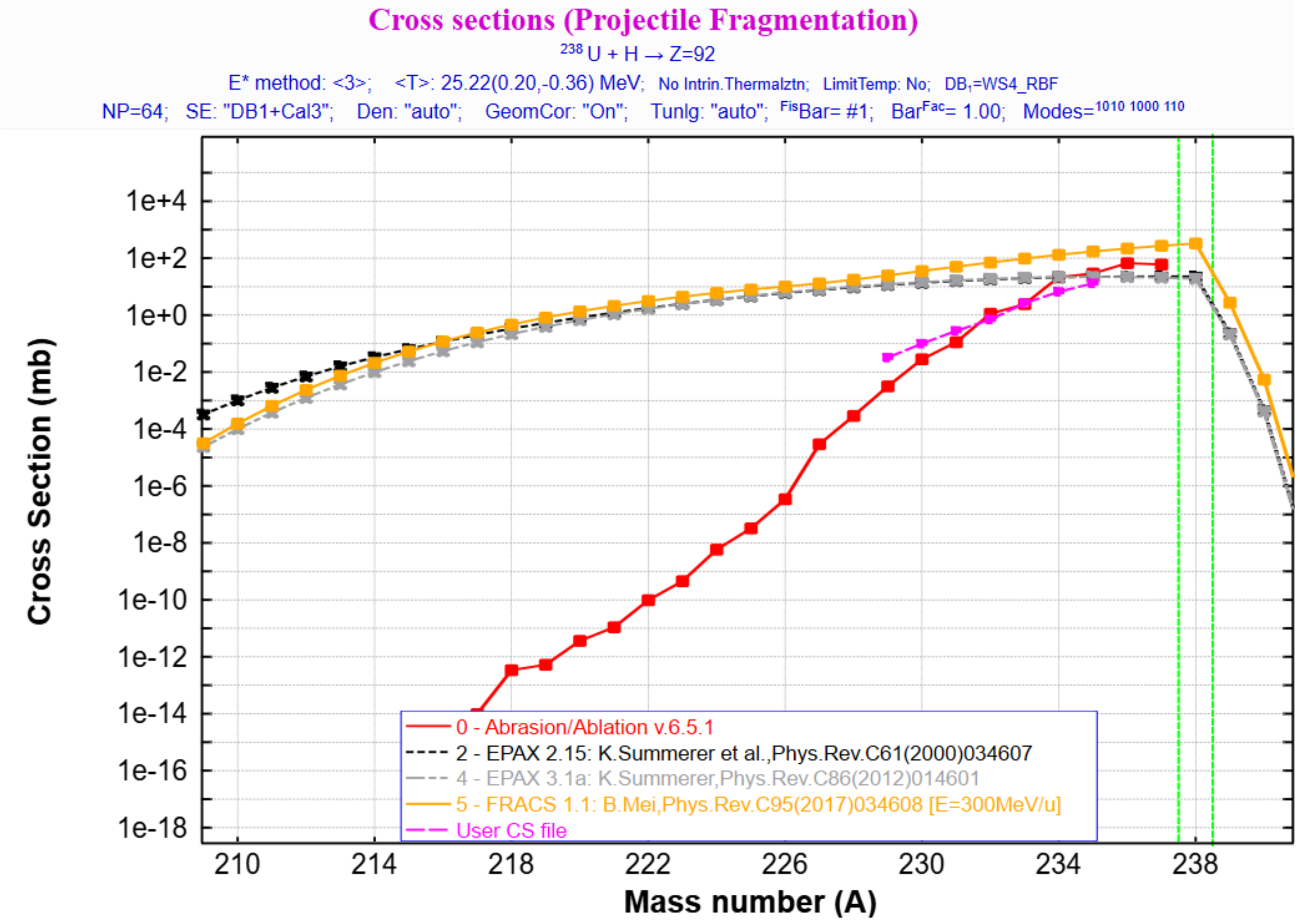
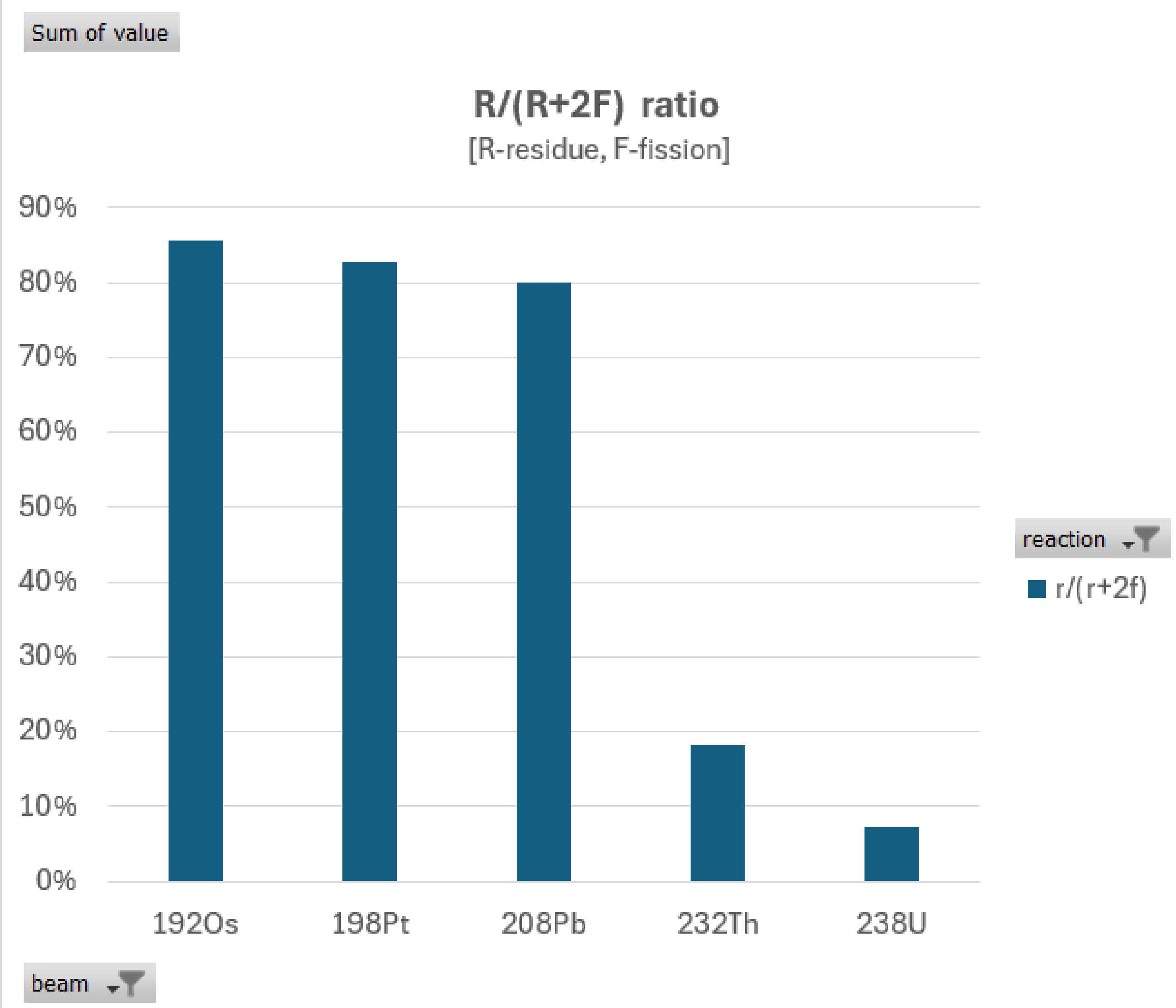
[3]*Institute de Physique Nucléaire, Orsay cedex F-91406, France*
[4]*DAPNIA/SPhN, CEA/Saclay, Gif sur Yvette cedex F-91191, France*
[5]*CENBG, Gradignan cedex F-33175, France*

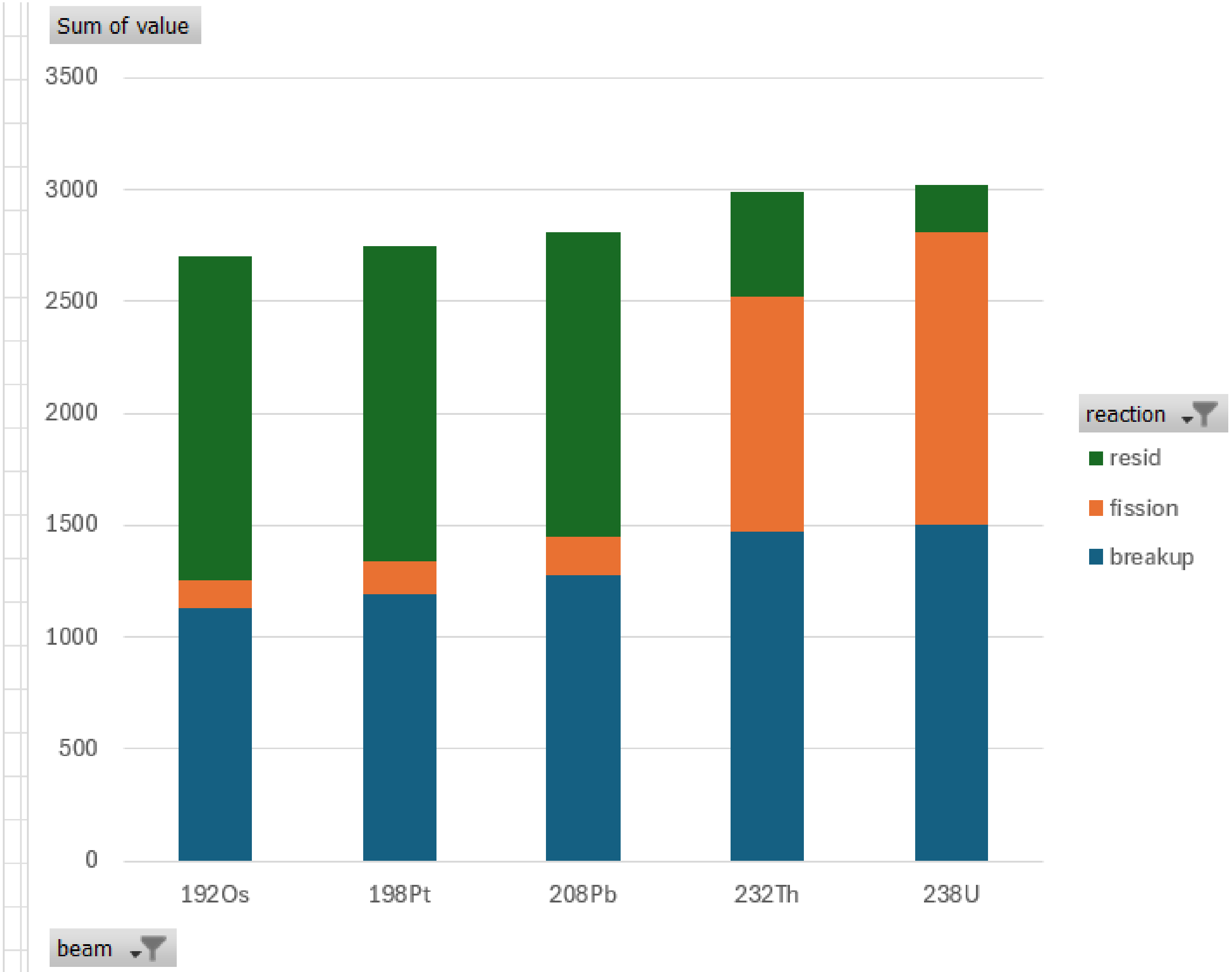




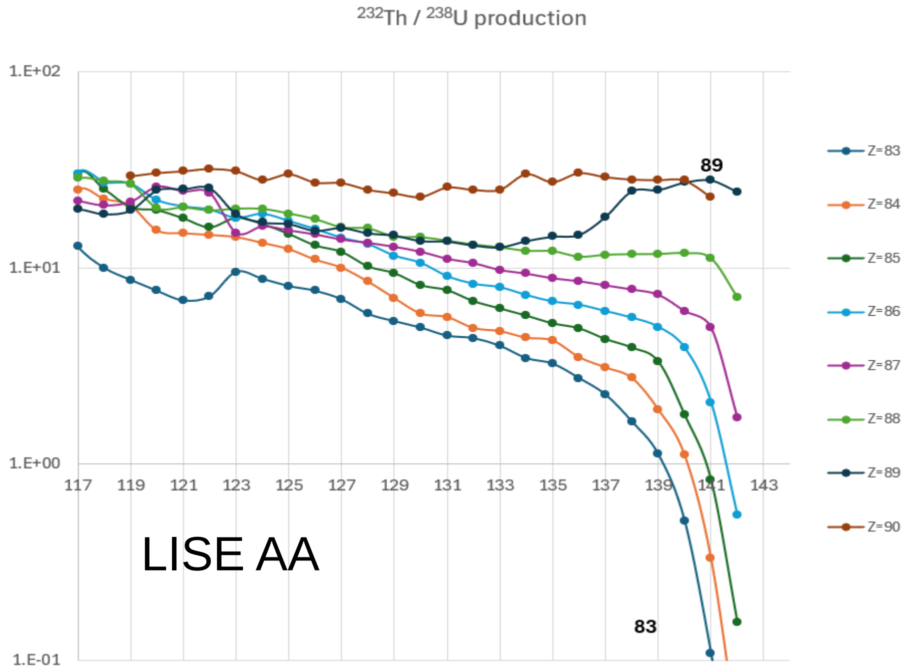
High-Z production from Projectile Fragmentation: comparison of different beams

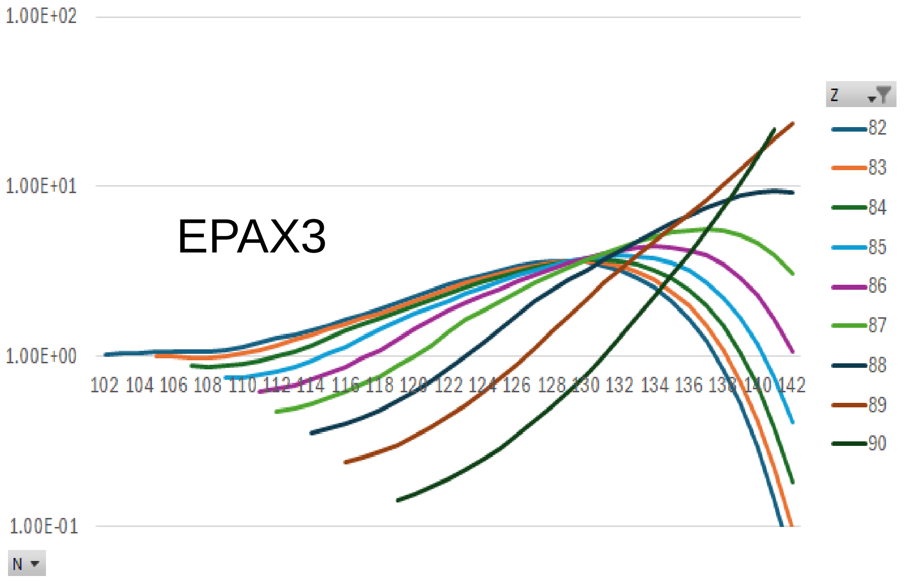
“stable” high-Z settings



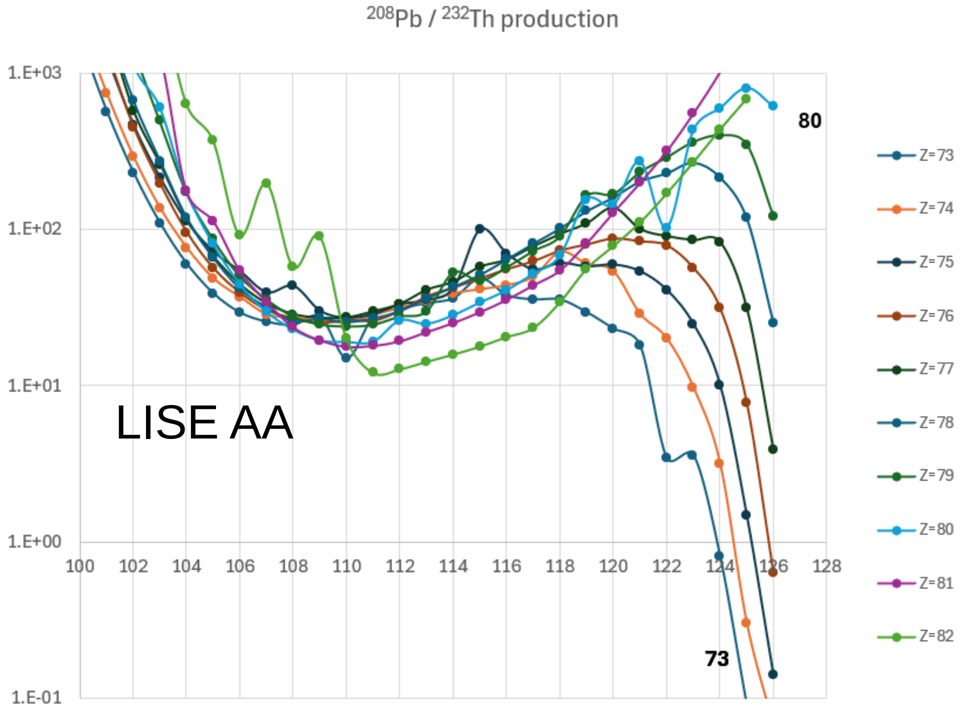


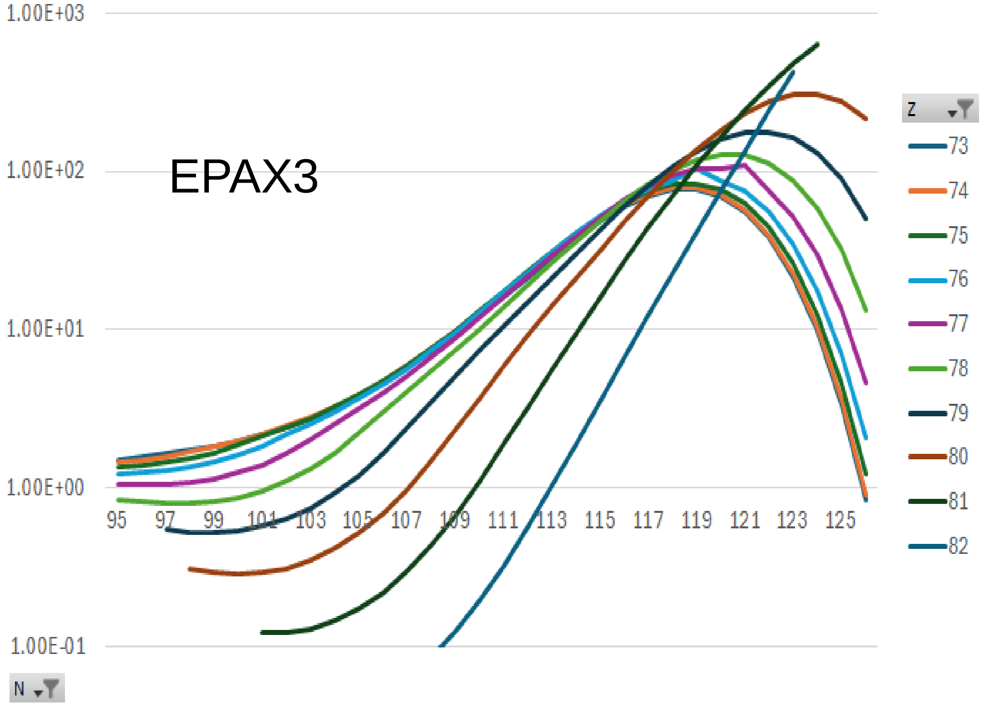
Projectile fragmentation CS ratio: ^{232}Th / ^{238}U





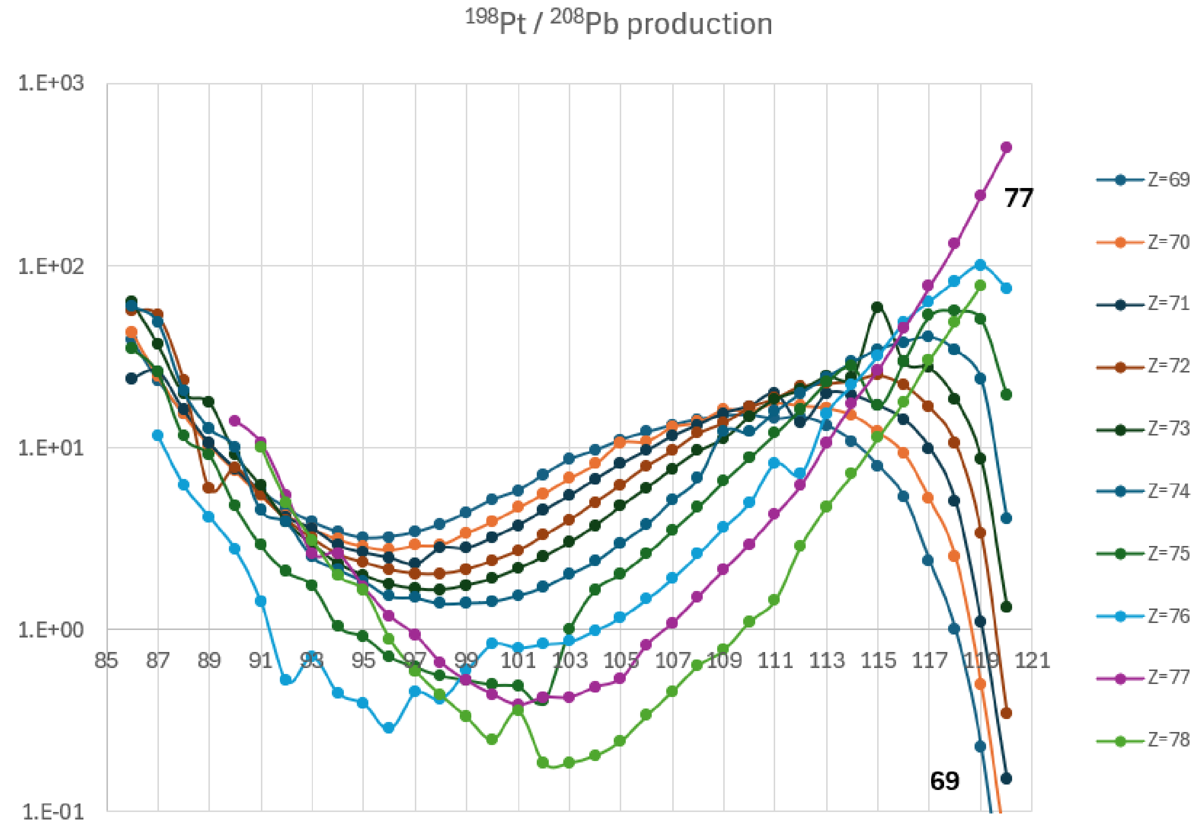
Projectile fragmentation CS ratio: ^{208}Pb / ^{232}Th



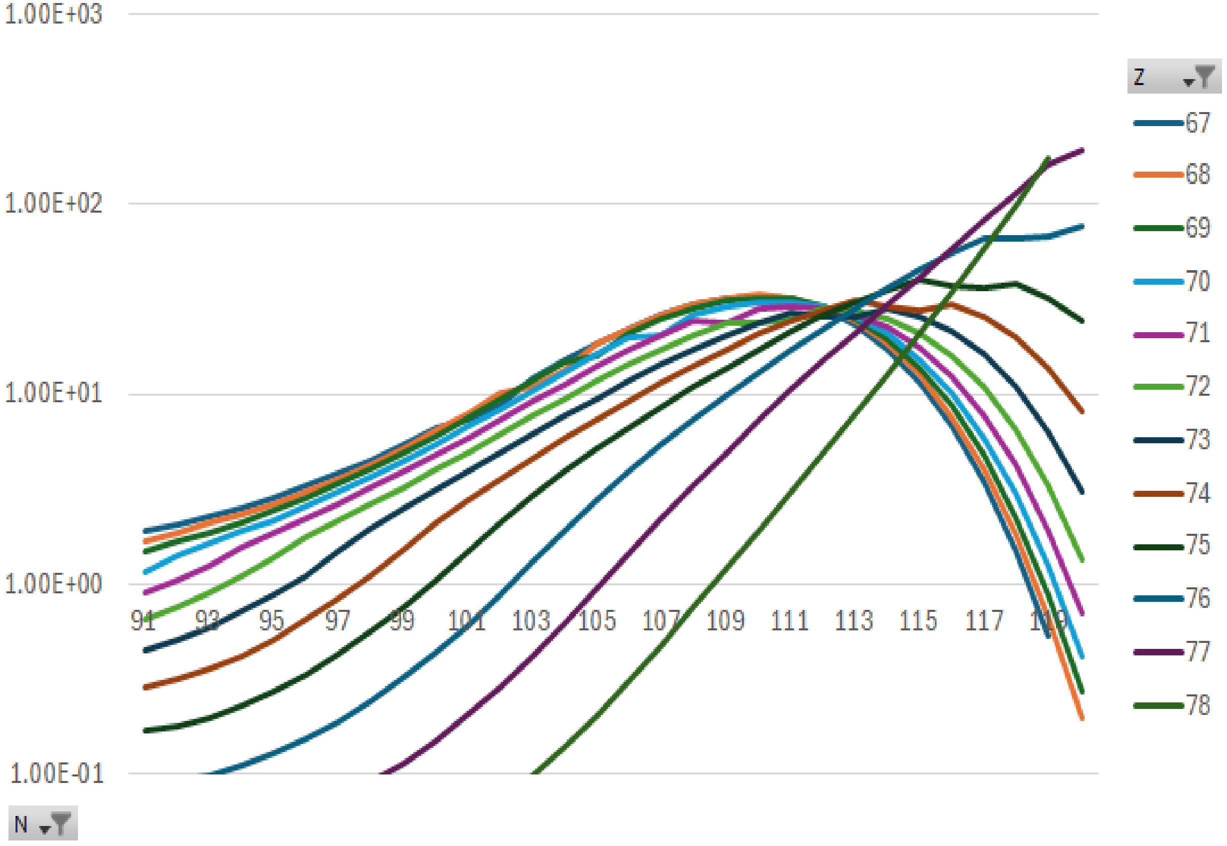


Projectile fragmentation CS ratio: ^{198}Pt / ^{208}Pb

LISE AA



EPAX3



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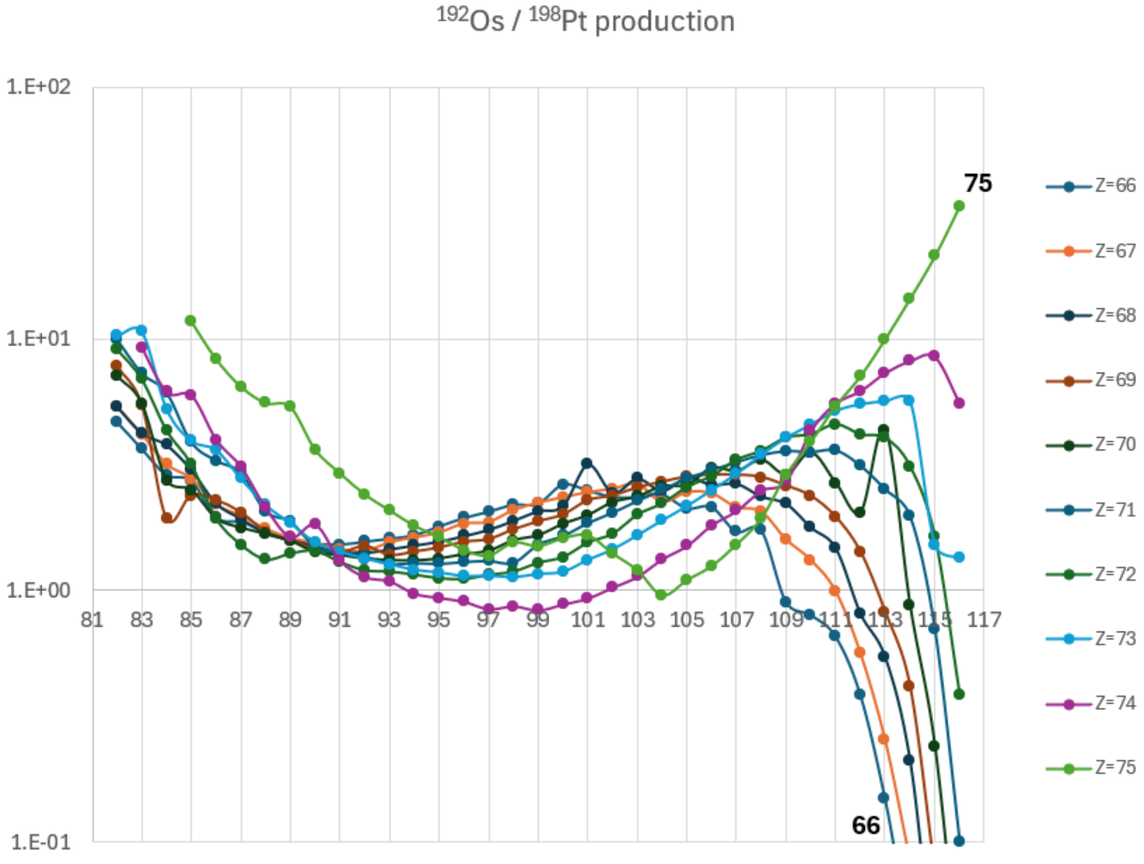
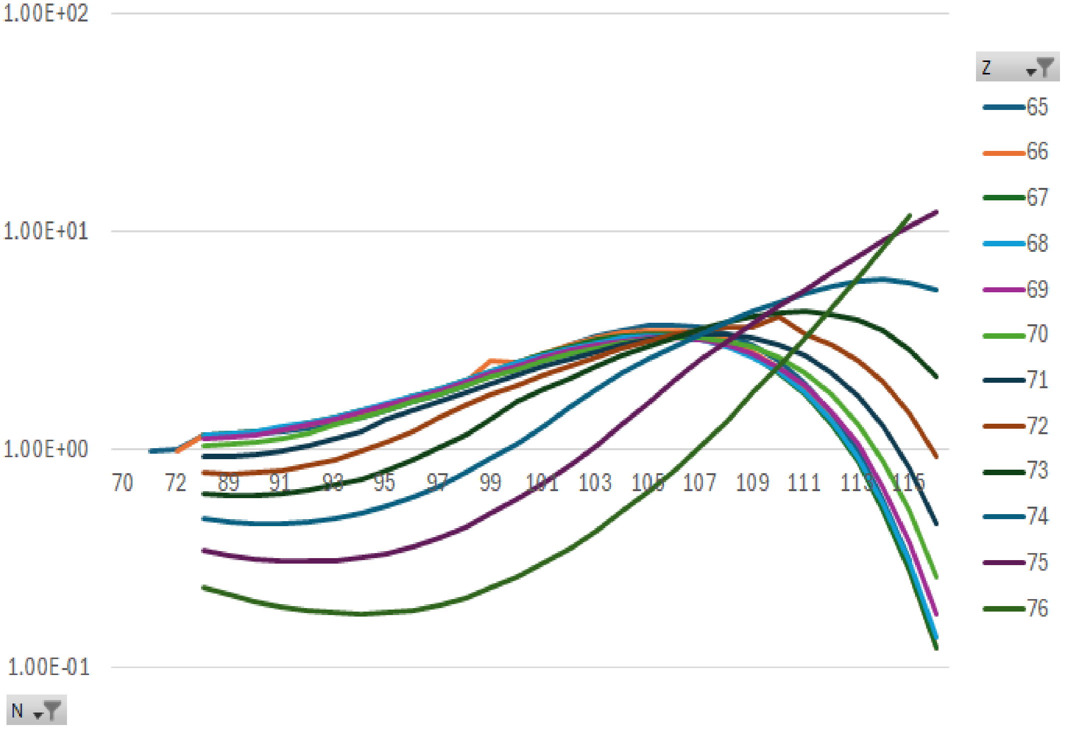
Projectile fragmentation CS ratio: ^{192}Os / ^{198}Pt

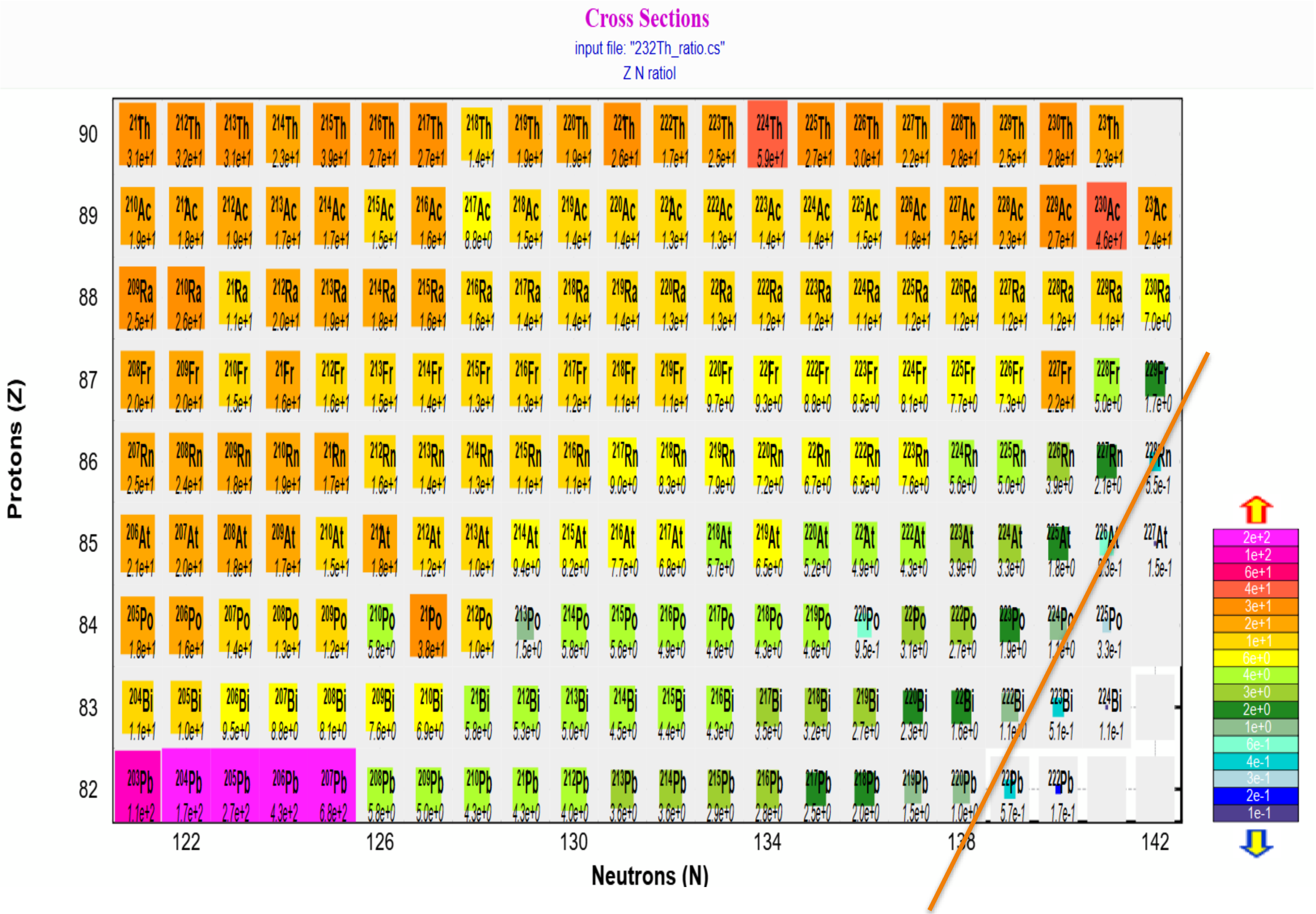
LISE AA



EPAX3

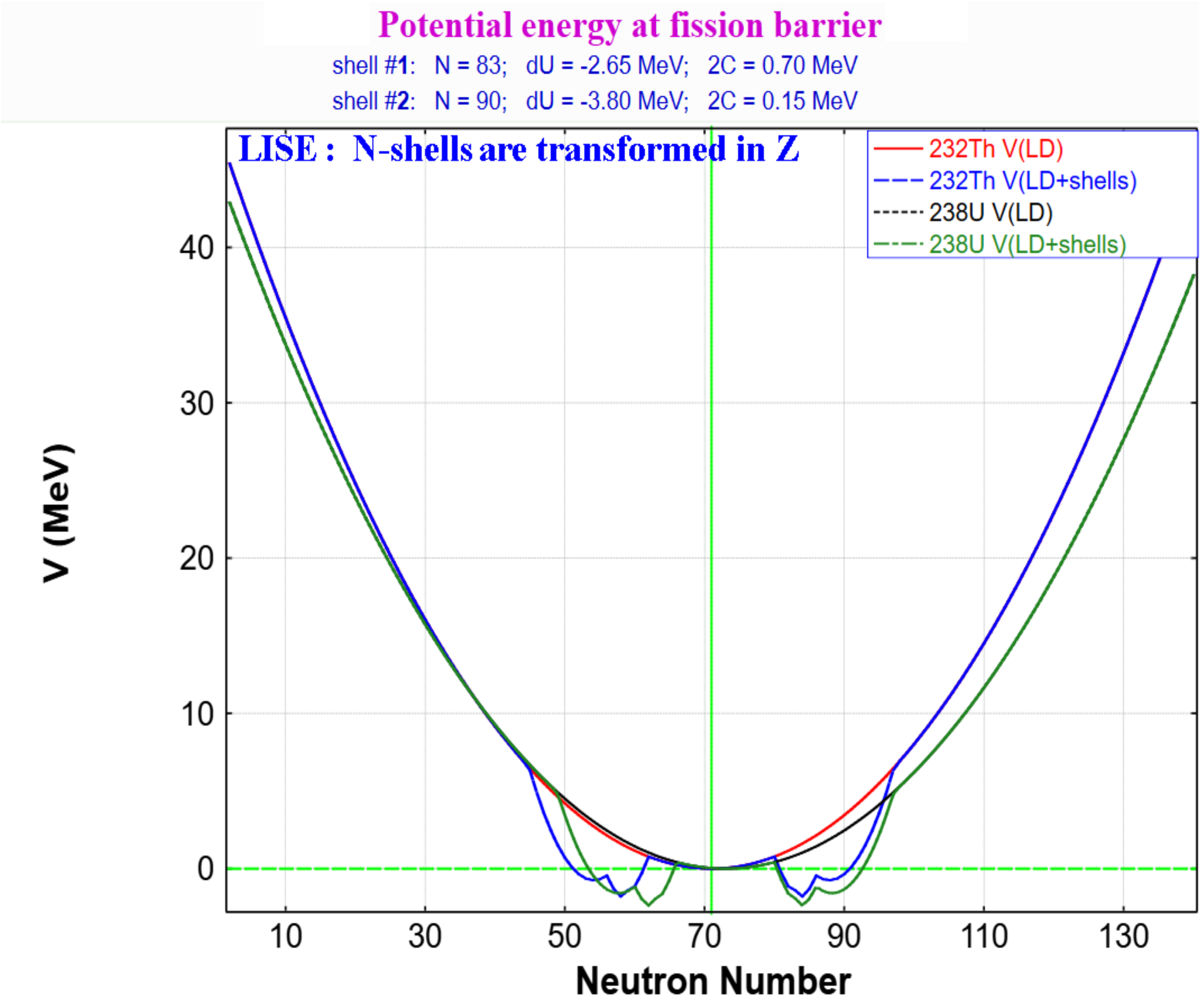


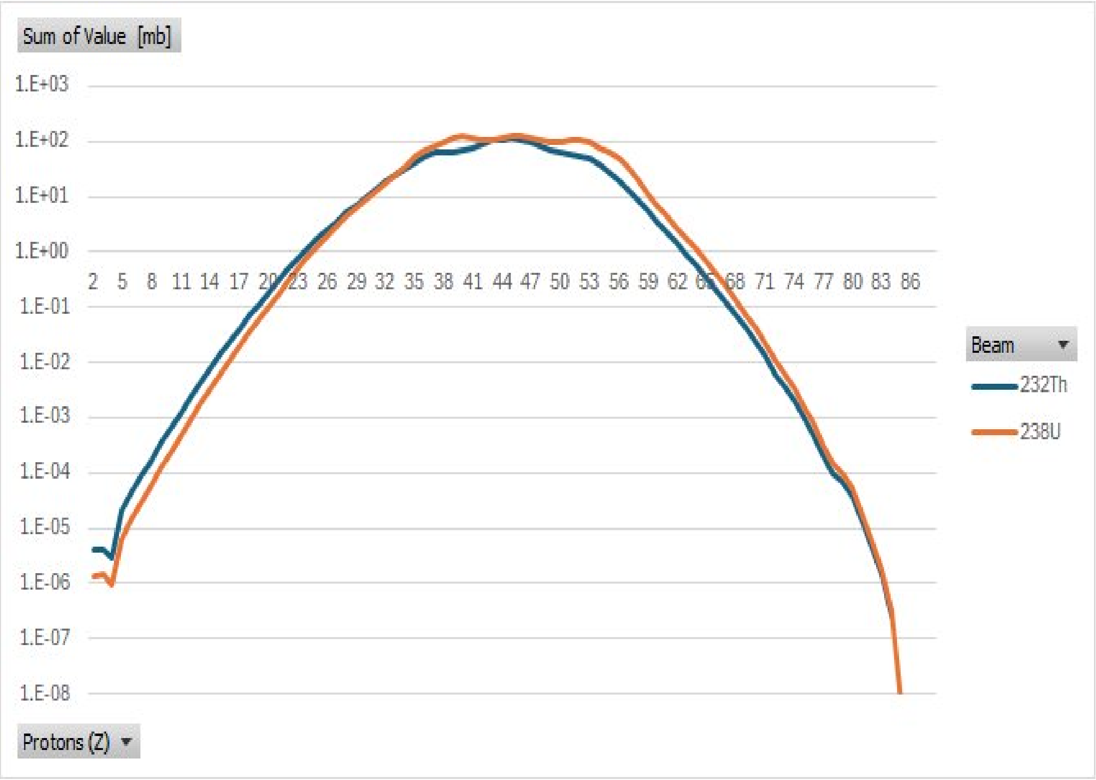
Projectile fragmentation CS ratio: ^{232}Th / ^{238}U



Low Z production from Fission: comparison of different beams

Fission: Potential energy and Sum of Cross-section by Z

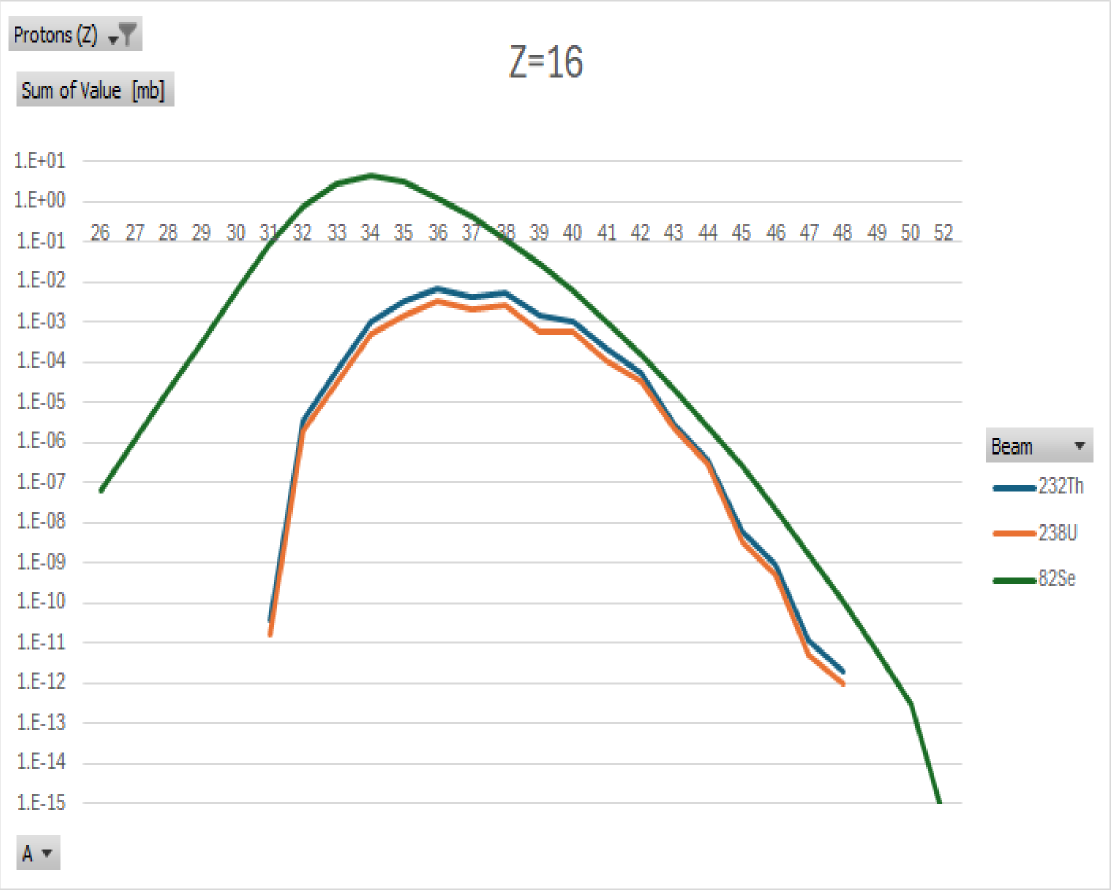


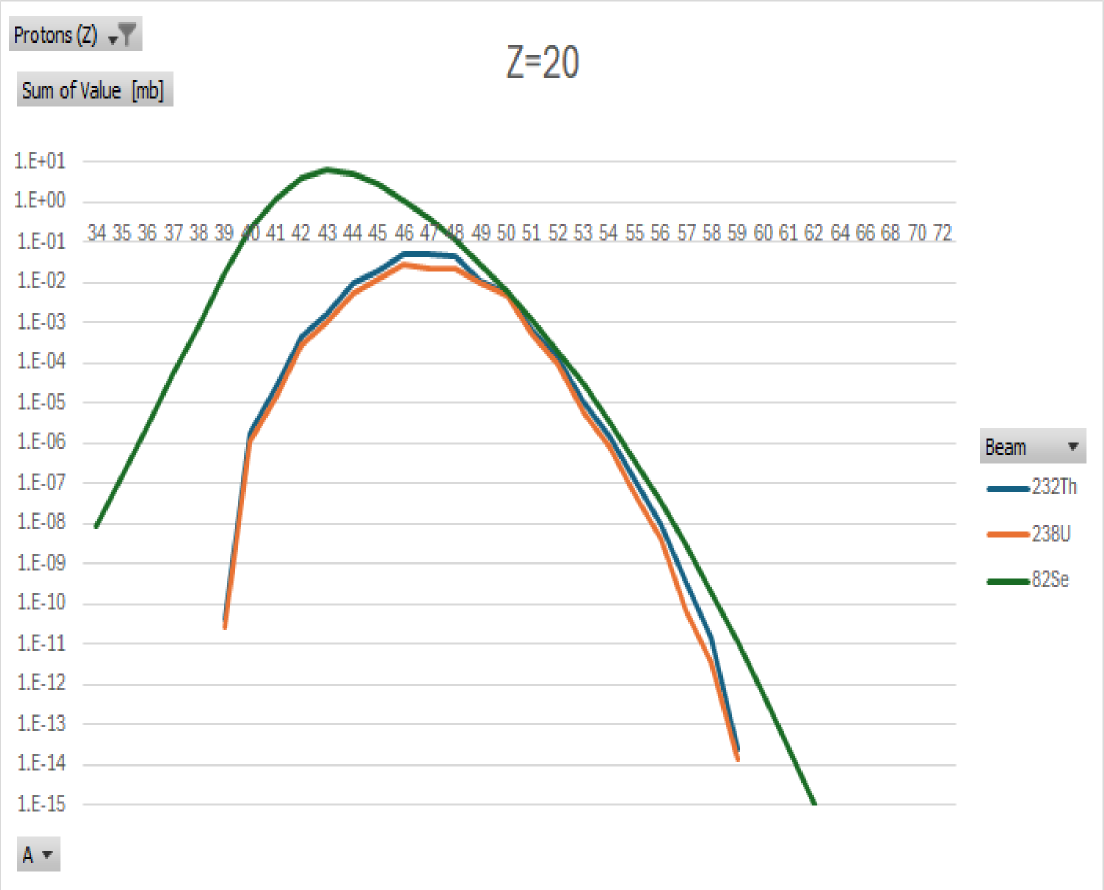


Production of isotopes of Z=16,20 with different beams

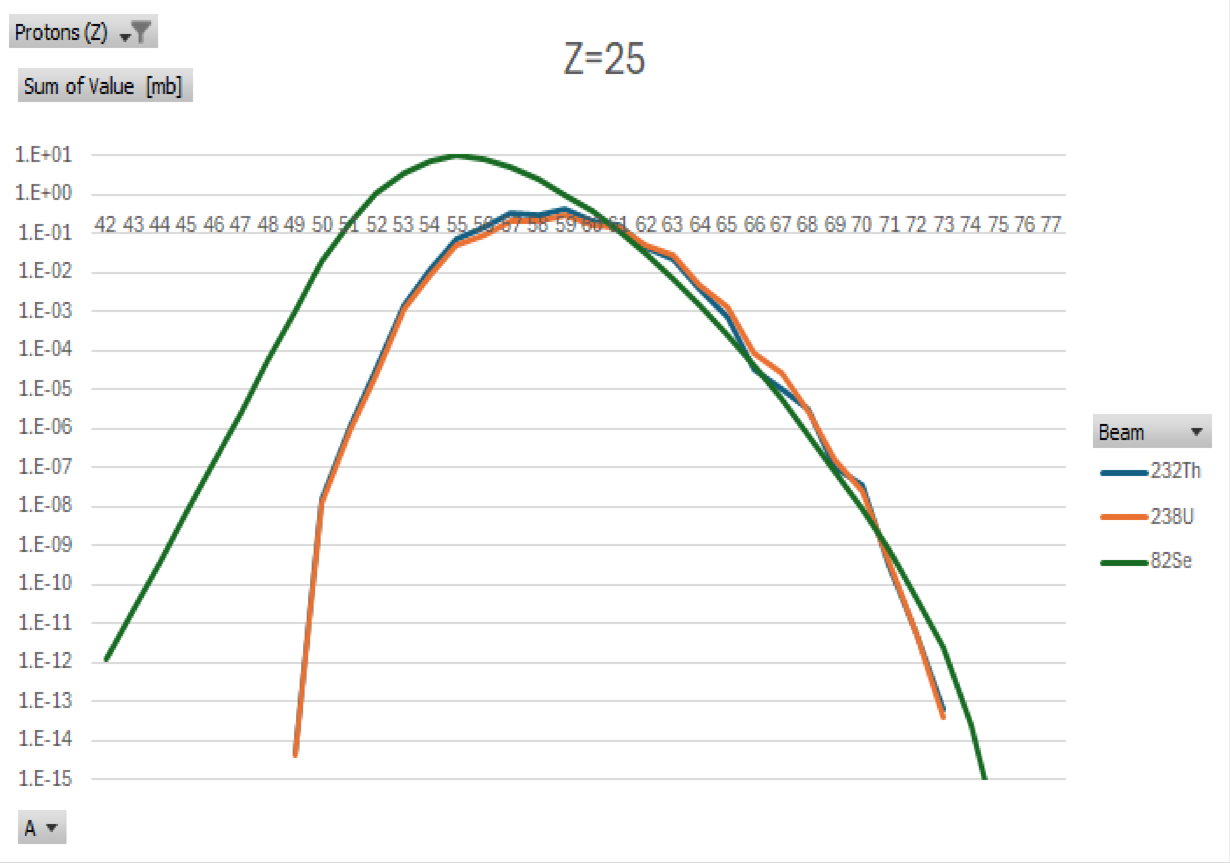
for ^{82}Se -- FRACS has been used
for fission -- stable High-Z settings

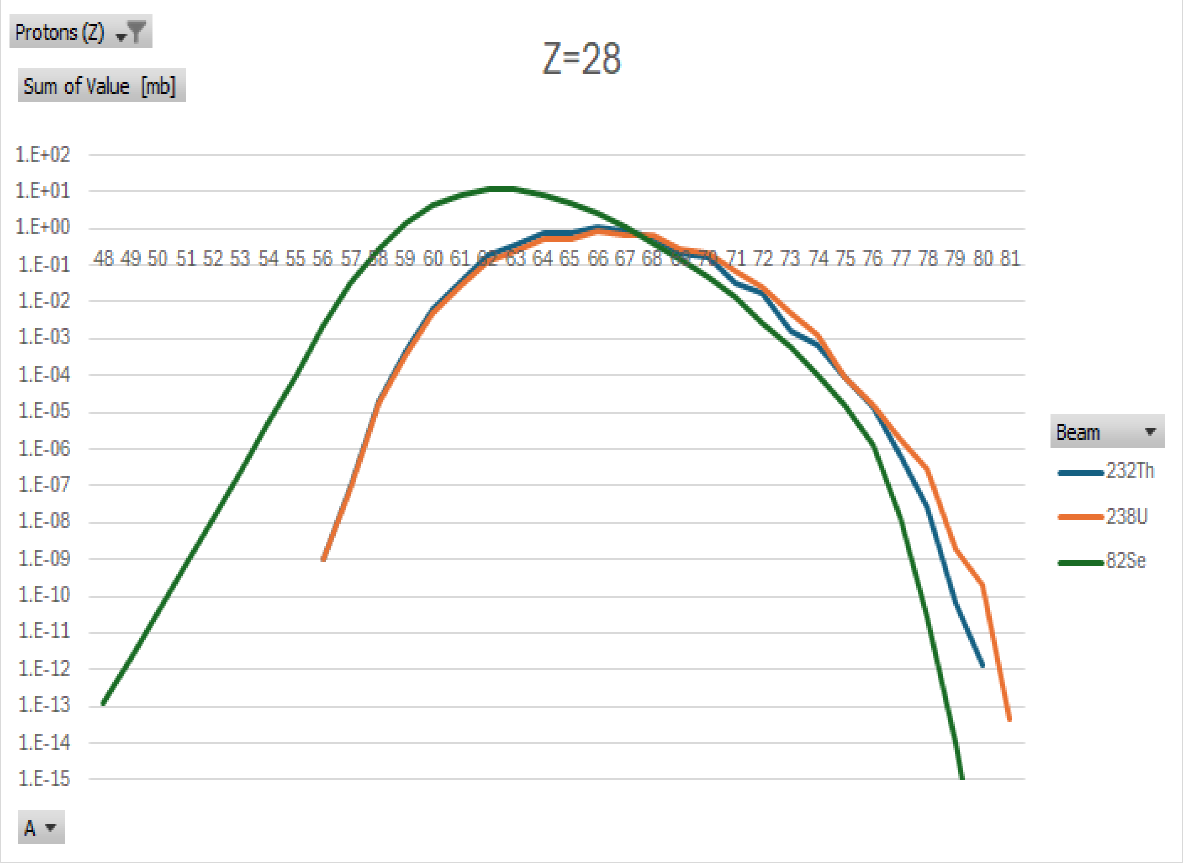
just remind you : all new neutron-rich isotopes over the past 15 years below Z=25 were obtained through projectile fragmentation





Production of isotopes of Z=25,28 with different beams





Summary

Summary

- **FRIB**: Designed to reach 400 kW 200 MeV/u or higher (depending on beam). As of July 2024, operating at 20 kW.

- **ARIS Performance:** ARIS performs well for selection, momentum compression, and particle identification.
- **Non-ambiguous PID:** Projectile-residue identification (dE-Bρ-ToF-TKE) for ^{198}Pt has been successfully.

- **New Isotope Observations:**
  - **3** isotopes were observed at NSCL and **5** isotopes at FRIB for the first time in the **^{198}Pt** experiments.
  - A novel correlation has been established between the charge state of the projectile-residue after the reaction and its atomic number.
  - **3** new isotopes* were observed in the first FRIB **^{238}U** experiment at **10 kW** (* operating at that time).
  - **4** (+1) new isotopes were preliminary observed with an **^{82}Se** beam during the first one-day **20 kW** run.

- Exploration of Their Production
  - The AA model showed good agreement with experimental data across several mass.
    The best agreement was achieved after minimization of the AA parameters using the HFB-22 mass model
  - A new **ΔBE-systematics**, derived from the AA model for neutron-rich regions, successfully addresses the limitations of Q_g -systematics. This systematic approach demonstrated its flexibility and power through the minimization of mass-model values using measured cross sections. It shows potential for revealing trends in nuclear structure within exotic regions that remain unexplored by traditional studies limited by low production rates.

- **Upgrading FRIB to 400 MeV/u**: This upgrade is expected to increase the production probability of neutron-rich isotopes in multi-step reactions by an order of magnitude.

Teams & Acknowledgements

e24605: ^{82}Se @ FRIB – 07/2024

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(Dated: January 6, 2025)

e22501: ^{198}Pt @ FRIB – 02/2023

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Portillo, Mauricio	Sherrill, Bradley
Smith, Mallory	Steiner, Mathias
Tarasov, Oleg	

Accelerator Physics Department

Ostroumov, Peter
Fukushima, Kei
……..

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