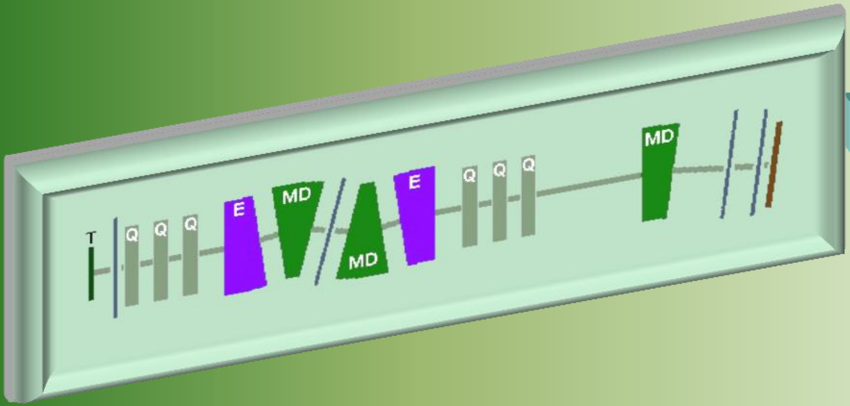
Oleg B. Tarasov
NCSL / MSU

Production of neutron-rich isotopes

IS&RDinSHN . workshop @ ECT*.Italy
09/01-04/2015



LISE++

LISE++

1. **Introduction :**
   - Experiment vs. Calculation
   - LISE^{++}
2. **Fusion-Fission experiment:**
   - inverse kinematics
3. **In-flight fission :**
   - covering 25<Z<75 region
4. **Projectile fragmentation:**
   - tool to observe shell effects close to the neutron drip-line
5. **Secondary reactions in target**
6. **Summary**

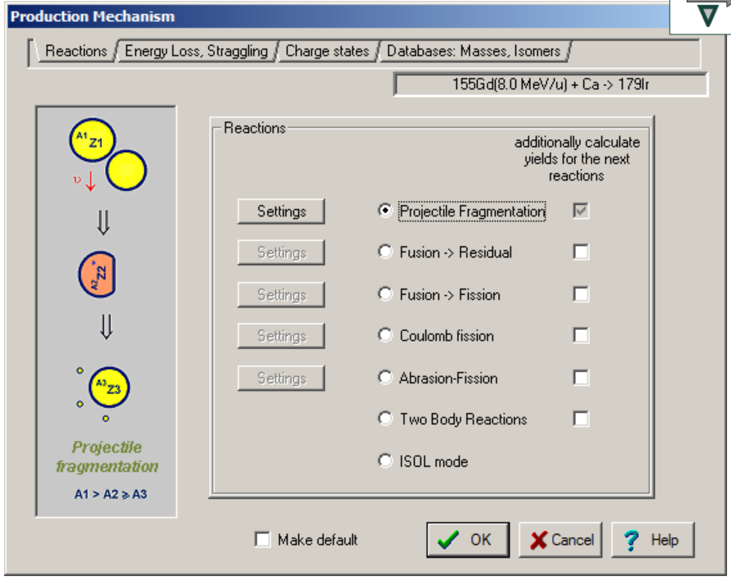
1. Introduction

Reaction mechanisms : Experiment vs. Calculation

50%
Real experimentalist

- **Fusion-Fission**
  ^{238}U(24 MeV/u)+Be,C
  GANIL
- **In-flight fission, projectile fragmentation**
  ^{238}U(345 MeV/u)+Be,Pb
  RIKEN
- **Projectile fragmentation**
  ^{76}Ge, ^{82}Se (140 MeV/u)+Be,W
  MSU
- **“Double” projectile fragmentation**
  ^{48}Ca, ^{70}Zn (345 MeV/u)+Be
  RIKEN

50%
Unreal* theorist



155Gd(8.0 MeV/u) + Ca -> 179Ir

● Projectile Fragmentation ☑
○ Fusion -> Residual ☐
○ Fusion -> Fission ☐
○ Coulomb fission ☐
○ Abrasion-Fission ☐
○ Two Body Reactions ☐
○ ISOL mode

☐ Make default

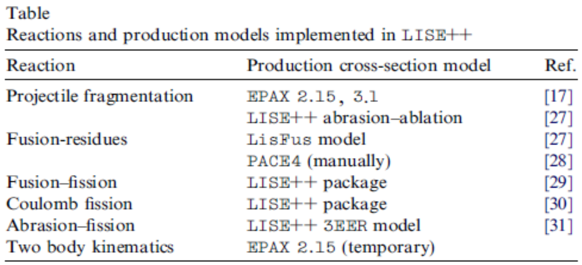


Table
Reactions and production models implemented in LISE++

Reaction	Production cross-section model	Ref.
Projectile fragmentation	EPAX 2.15, 3.1	[17]
	LISE++ abrasion–ablation	[27]
Fusion-residues	LisFus model	[27]
	PACE4 (manually)	[28]
Fusion–fission	LISE++ package	[29]
Coulomb fission	LISE++ package	[30]
Abrasion–fission	LISE++ 3EER model	[31]
Two body kinematics	EPAX 2.15 (temporary)	

References:
[17] K. Summerer, B. Blank, Phys. Rev. C 61 (2000) 034607; K. Summerer, Phys. Rev. C 86 (2012) 014601
[27] O. Tarasov, D. Bazin, Nucl. Instr. and Meth. B 204 (2003) 74.
[28] A. Gavron, Phys. Rev. C 21 (1980) 230.
[29] O.B. Tarasov, A.C.C. Villari, , Nucl. Instr. and Meth. B 266 (2008) 4670-4673.
[30] O.B. Tarasov, Eur. Phys. J. A 25 (2005) 751; Tech. Rep. MSUCL1299, NSCL, Michigan S.U. 2005.
[31] O.B. Tarasov, Tech. Rep. MSUCL1300, NSCL, Michigan State University, 2005.

* practical?

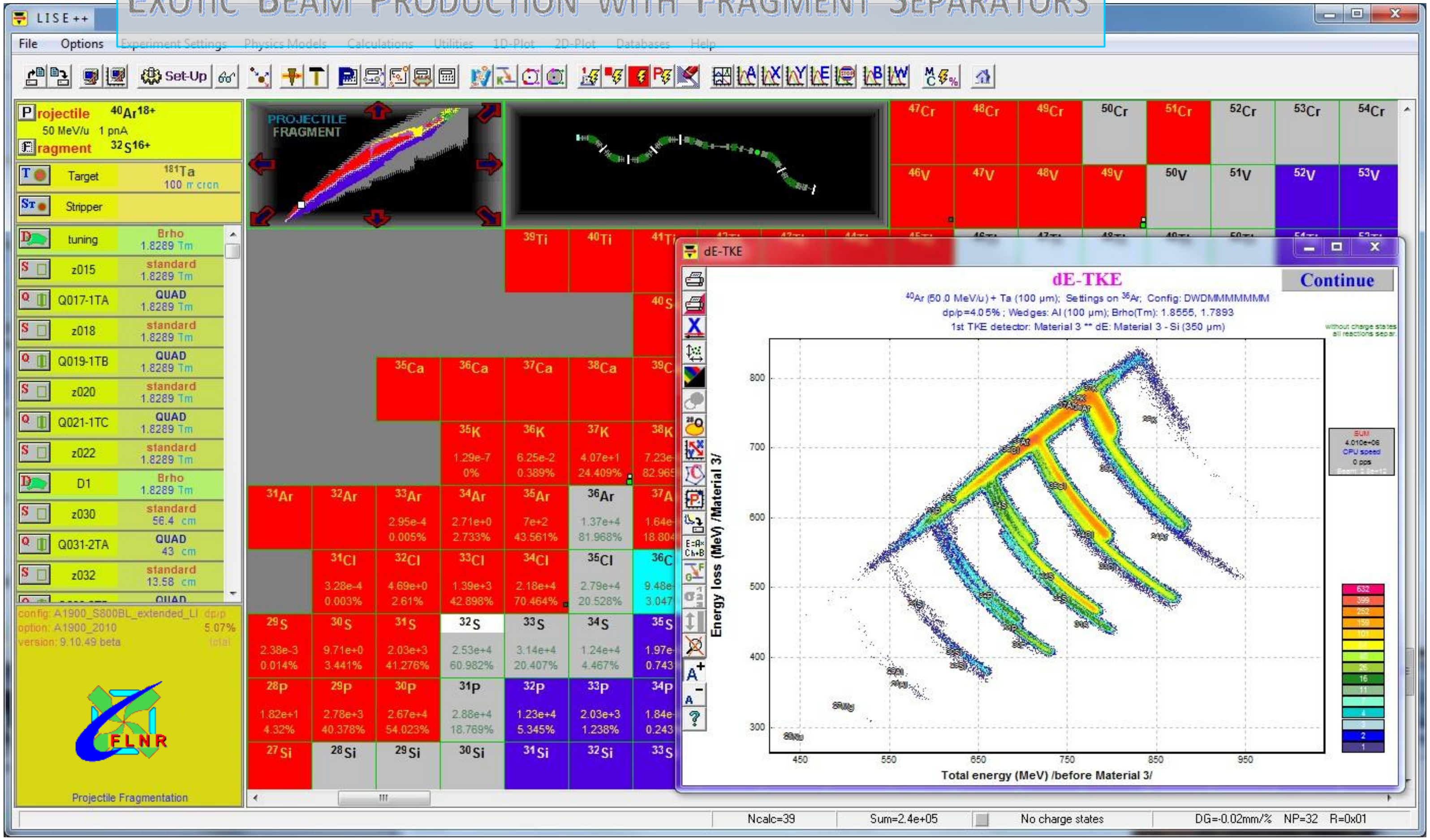
Way to talk: Experimental Result → Model → Deficiency

Introduction ⇨ LISE^{++} ⇨ Production & Separation

The program LISE^{++} is designed to predict intensities and purities for the planning of experiments with in-flight separators, as well as for tuning experiments where the results can be quickly compared to on-line data.

O. B. Tarasov and D. Bazin, Nucl. Instr. Meth. B 266 (2008) 4657

EXOTIC BEAM PRODUCTION WITH FRAGMENT SEPARATORS



Projectile $^{40}Ar^{18+}$
50 MeV/u 1 pnA
Fragment $^{32}S^{16+}$
Target ^{181}Ta 100 mcron
Stripper
tuning Brho 1.8289 Tm
z015 standard 1.8289 Tm
Q017-1TA QUAD 1.8289 Tm
z018 standard 1.8289 Tm
Q019-1TB QUAD 1.8289 Tm
z020 standard 1.8289 Tm
Q021-1TC QUAD 1.8289 Tm
z022 standard 1.8289 Tm
D1 Brho 1.8289 Tm
z030 standard 56.4 cm
Q031-2TA QUAD 43 cm
z032 standard 13.58 cm

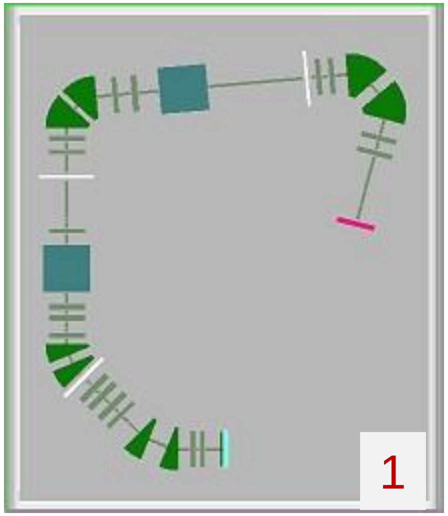
config: A1900_S800BL_extended_LI dp/p 5.07%
option: A1900_2010
version: 9.10.49 beta

dE-TKE
^{40}Ar (50.0 MeV/u) + Ta (100 μm); Settings on ^{36}Ar; Config: DWDMMMMMMM
dp/p=4.05%; Wedges: Al (100 μm); Brho(Tm): 1.8555, 1.7893
1st TKE detector: Material 3 ** dE: Material 3 - Si (350 μm)

Ncalc=39 Sum=2.4e+05 No charge states DG=-0.02mm/% NP=32 R=0x01

The LISE^{++} package which includes also the PACE4, Global, Charge, Spectroscopic calculator codes can be downloaded freely from the following site: **http://lise.nscl.msu.edu**.

Example of set-ups in LISE^{++}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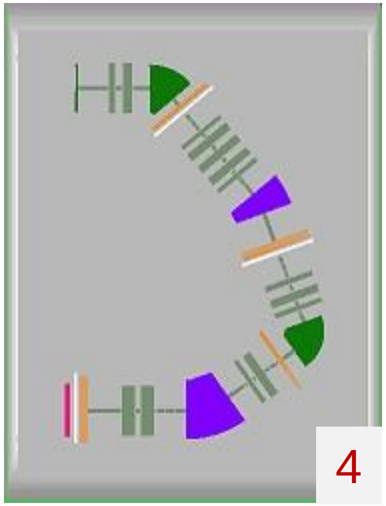
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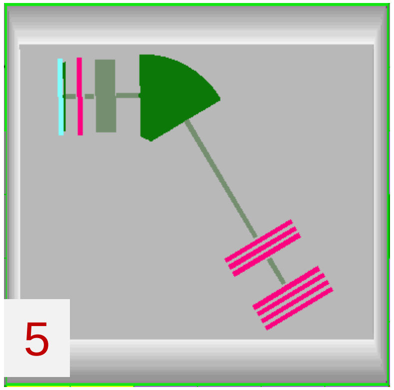
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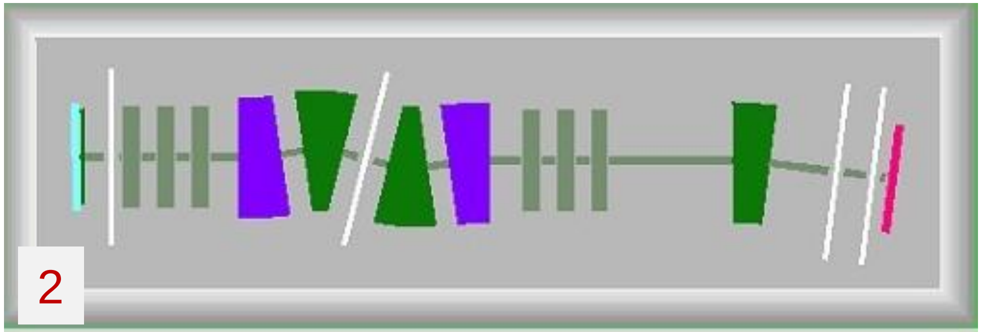
8

Darek,
what is about
FMA? ☺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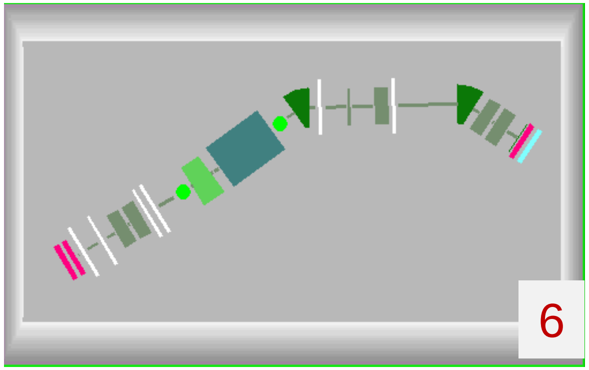
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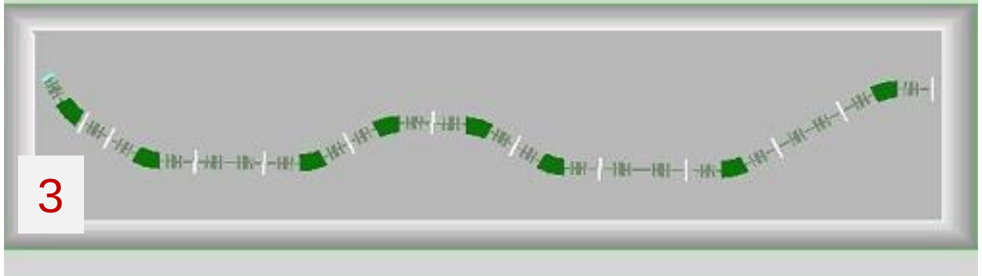
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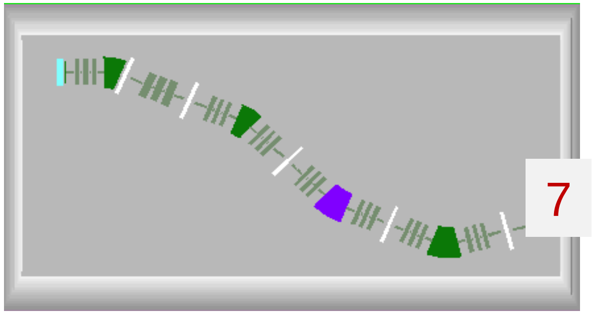
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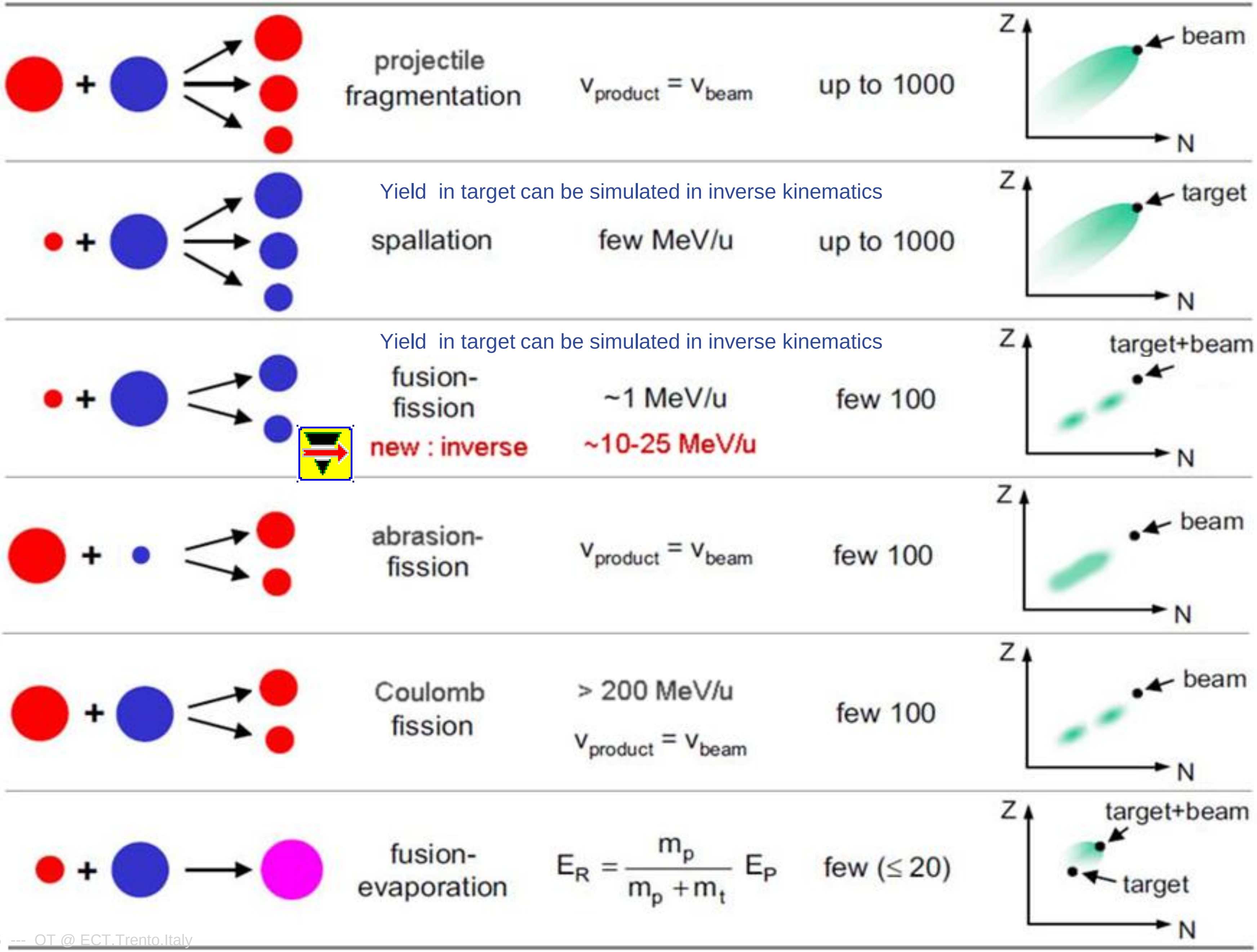
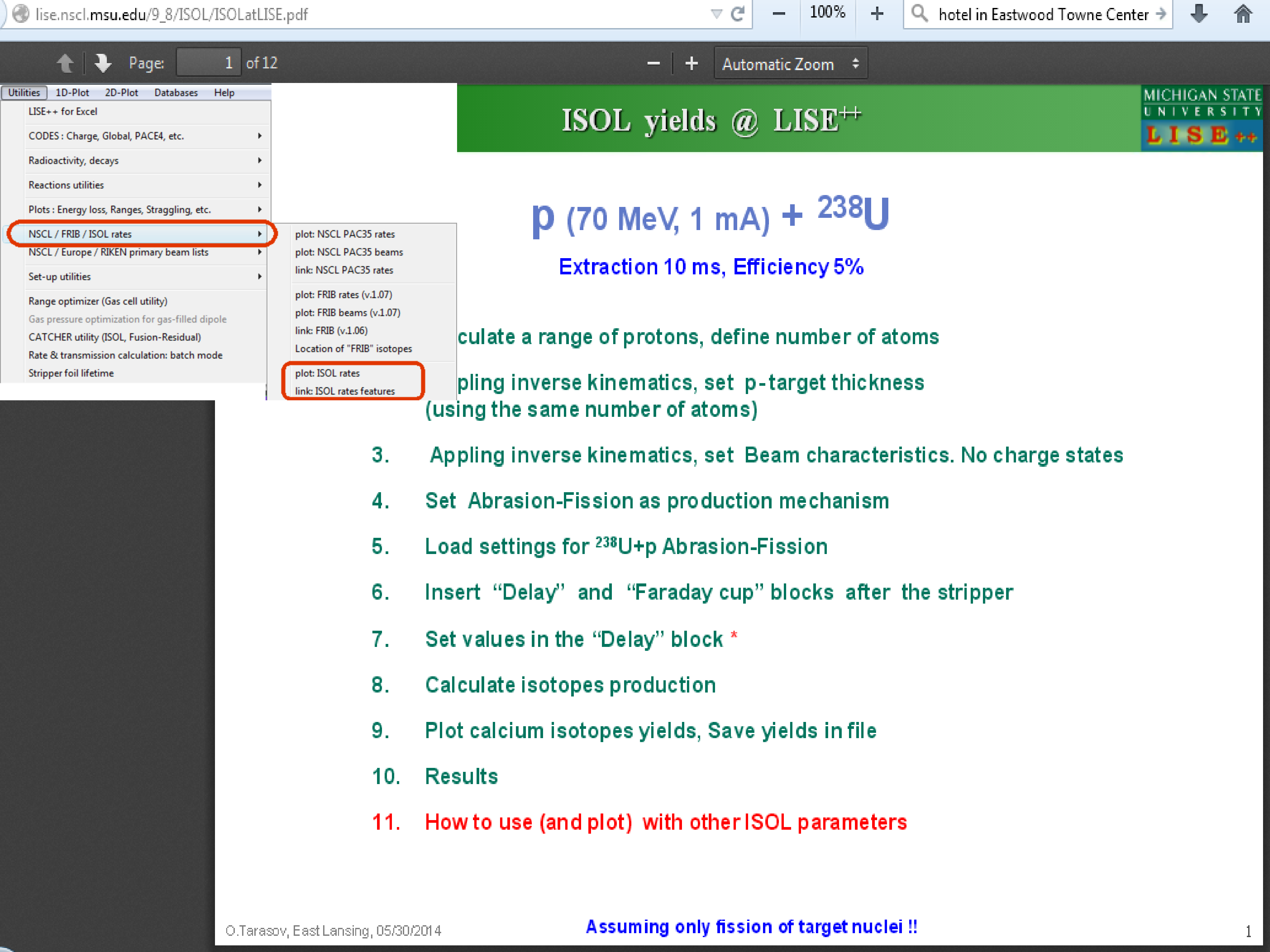
Sketch of main production mechanisms for RIB



projectile fragmentation	$v_{product} = v_{beam}$	up to 1000
Yield in target can be simulated in inverse kinematics spallation	few MeV/u	up to 1000
Yield in target can be simulated in inverse kinematics fusion-fission new : inverse	~1 MeV/u ~10-25 MeV/u	few 100
abrasion-fission	$v_{product} = v_{beam}$	few 100
Coulomb fission	> 200 MeV/u $v_{product} = v_{beam}$	few 100
fusion-evaporation	$E_R = \frac{m_p}{m_p + m_t} E_P$	few (≤ 20)



ISOL yields @ LISE^{++}

p (70 MeV, 1 mA) + ^{238}U

Extraction 10 ms, Efficiency 5%

culate a range of protons, define number of atoms

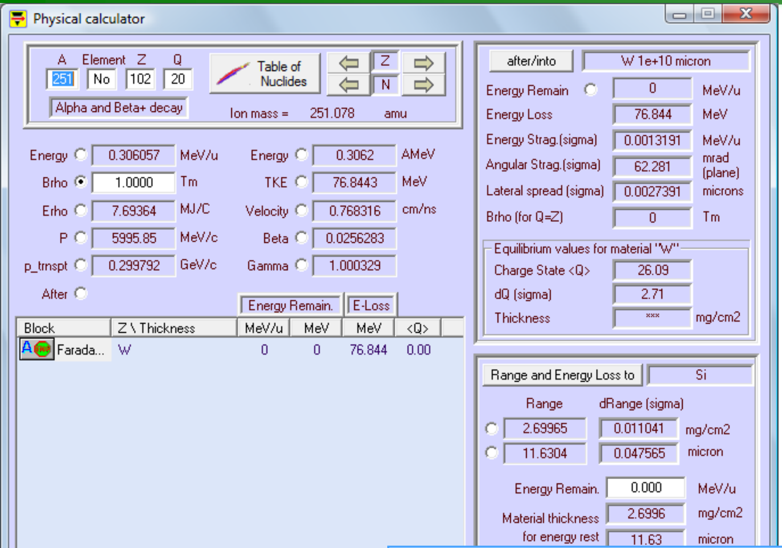
pling inverse kinematics, set p-target thickness (using the same number of atoms)

3. Appling inverse kinematics, set Beam characteristics. No charge states
4. Set Abrasion-Fission as production mechanism
5. Load settings for ^{238}U+p Abrasion-Fission
6. Insert “Delay” and “Faraday cup” blocks after the stripper
7. Set values in the “Delay” block *
8. Calculate isotopes production
9. Plot calcium isotopes yields, Save yields in file
10. Results
11. How to use (and plot) with other ISOL parameters

O.Tarasov, East Lansing, 05/30/2014

Assuming only fission of target nuclei !!

LISE++ for theorists


Physical calculator

A	Element	Z	Q
251	No	102	20

Alpha and Beta+ decay

Ion mass = 251.078 amu

Energy ○ 0.306057 MeV/u
Brho ● 1.0000 Tm
Erho ○ 7.69364 MJ/C
P ○ 5995.85 MeV/c
p_trnspt ○ 0.299792 GeV/c
After ○

Energy ○ 0.3062 AMeV
TKE ○ 76.8443 MeV
Velocity ○ 0.768316 cm/ns
Beta ○ 0.0256283
Gamma ○ 1.000329

Block	Z \ Thickness	MeV/u	MeV	MeV	<Q>
Farada...	W	0	0	76.844	0.00

after/into: W 1e+10 micron

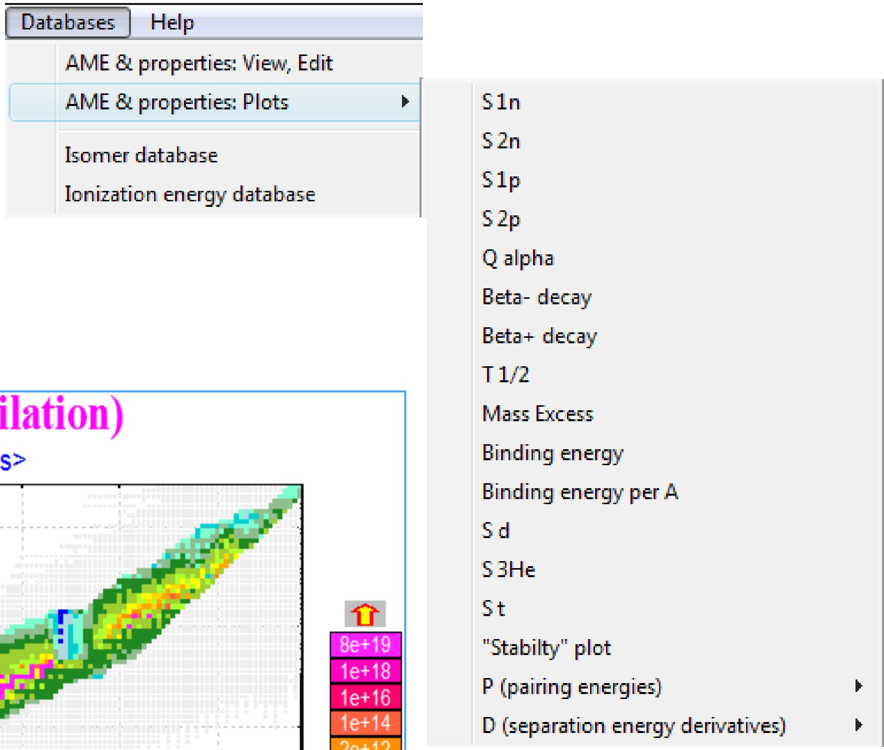
Energy Remain ○ 0 MeV/u
Energy Loss 76.844 MeV
Energy Strag.(sigma) 0.0013191 MeV/u
Angular Strag.(sigma) 62.281 mrad (plane)
Lateral spread (sigma) 0.0027391 microns
Brho (for Q=Z) 0 Tm

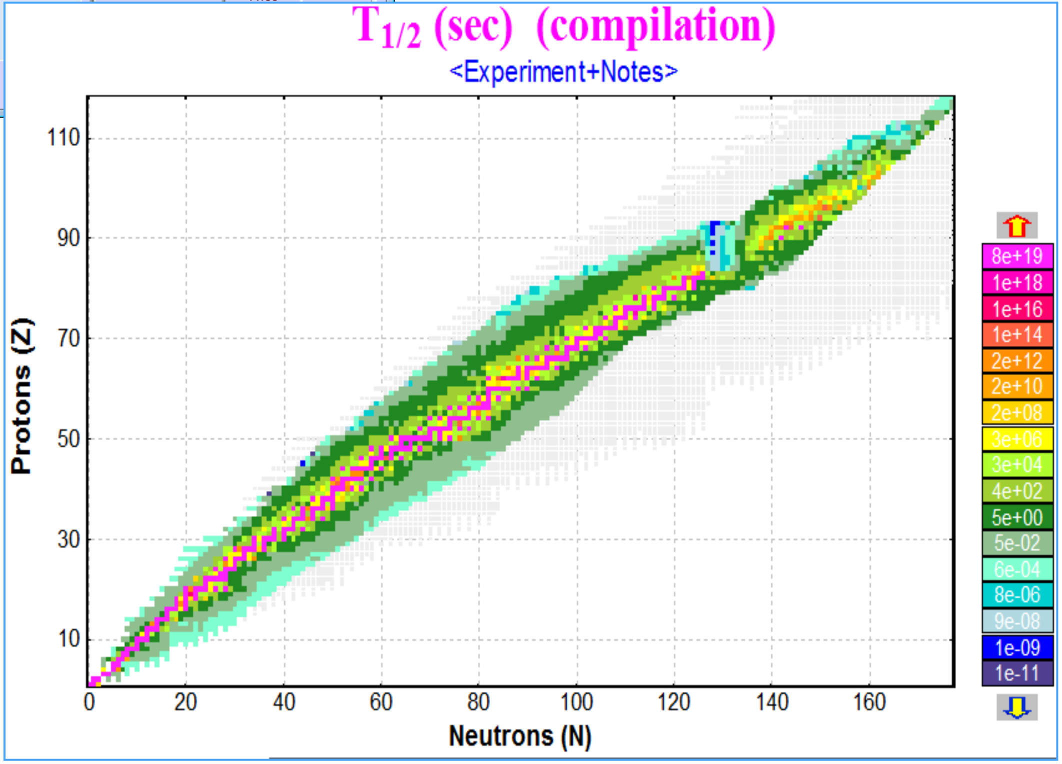
Equilibrium values for material "W"
Charge State <Q> 26.09
dQ (sigma) 2.71
Thickness *** mg/cm2

Range and Energy Loss to: Si

	Range	dRange (sigma)	
○	2.69965	0.011041	mg/cm2
○	11.6304	0.047565	micron

Energy Remain. 0.000 MeV/u
Material thickness for energy rest 2.6996 mg/cm2
11.63 micron



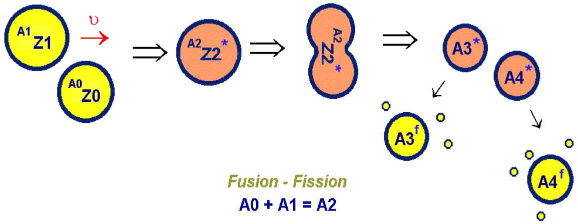


2. Fusion-Fission

Fusion-Fission is a new reaction mechanism for rare beam production

The LISE^{++} fusion-fission model [1] has been developed to estimate secondary beams intensities based on:

- ☐ The Bass algorithm to estimate complete fusion cross section [2],
- ☐ The fast analytical evaporation model LisFus [3] to calculate a fission channel value and de-excitation of fission fragments.
- ☐ The semi-empirical model of J.Benlliure [4] which describes fission properties of a large number of fissile nuclei are a wide range of excitation energies.



[1] O.T. and A.C.C.Villari, NIM B 266 (2008) 4670.
[2] R.Bass, Phys.Rev.Lett. 39 (1977) 265.
[3] O.T. and D.Bazin, NIM B 204 (2003) 174.
[4] J.Benlliure et al., Nucl.Phys. A628 (1998) 458.

Main features of the model:

- *Production cross-section of fragments*
- *Kinematics of reaction products*
- *Spectrometer tuning to the fragment of interest optimized on maximal yield (or on good purification)*

Towards the neutron drip-line via Fusion-Fission

Advantages of in-flight fusion-fission to explore
neutron-rich 55 < Z < 75 region are comparing to AF & CF:

- *the heavier fissile nucleus competing with abrasion-fission (Z < 92),*
- *the higher excitation energy of a fissile nucleus competing with Coulomb fission of the ^{238}U primary beam.*

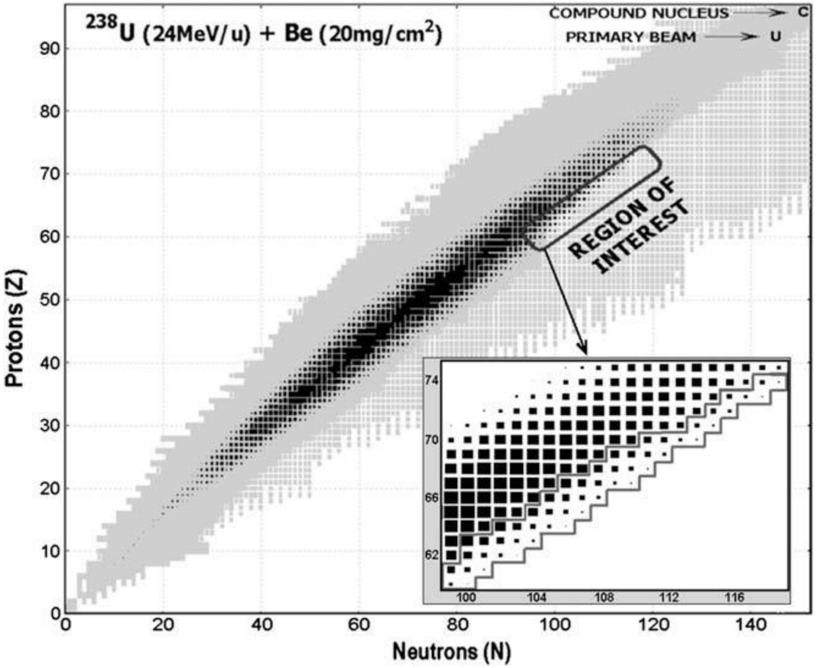


Fig. Two-dimensional yield plot for fragments produced in the ^{238}U (20 MeV/u,1pnA) + D (12 mg/cm^2) reaction and separated by SISSI + Alpha

<u>Using low energy fusion-fission beams:</u>

- *Several tens of new* isotopes are expected to be produced in the region 55 < Z < 75 using a ^{238}U beam with light targets according to the LISE^{++} Fusion-Fission model,*
- *Properties of these new nuclei allow to test nuclear models, in particular to understand the r-process abundance patterns,*
- *Reaction mechanism study.*

Open Questions:

- *What is optimal conditions, for example the energy of primary beam, the target material, thickness and so on?*
- *How reliable are simulations? Intensities, purification?*
- *What are contributions from other reaction mechanisms?*
- *Separation, Identification, Resolution?*

A experiment to show separation and identification of fusion-fission products has been performed using the LISE3 fragment-separator at GANIL.

* *in 2008*

Fusion-Fission experiment in inverse kinematics @ LISE separator

GANIL e547

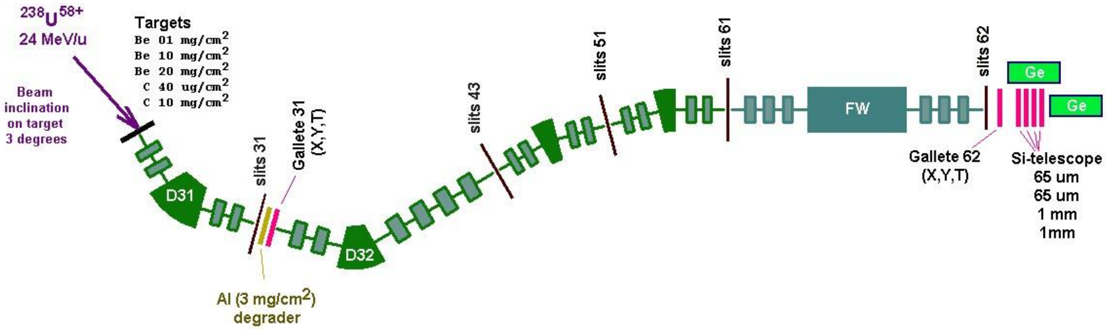
Spokesperson: O.Tarasov

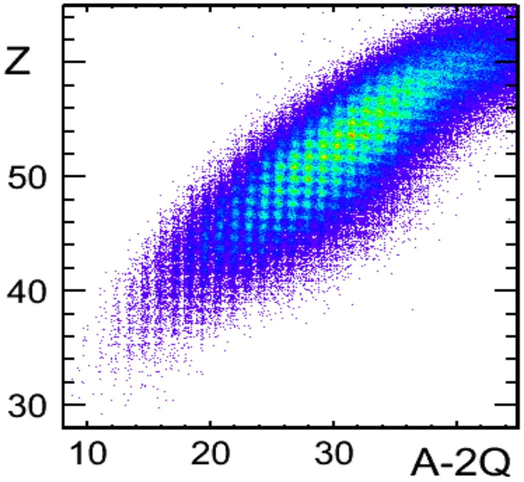
Preliminary arxiv.org:1302.1981
By O. Delaune, F. Farget, et al.

O.Delaune,[2] F.Farget,[2] O.B.T.[1], A.M.Amthor,[2] B.Bastin,[2] D.Bazin,[1] B.Blank,[3] L.Caceres,[2] A.Chbihi,[2] B.Fernandez-Domnguez,[4] S.Grevy,[3] O.Kamalou,[2] S. Lukyanov,[5] W.Mittig,[1,6] D.J.Morrissey,[1,7] J.Pereira,[1] L.Perrot,[8] M.-G.Saint-Laurent,[2] H. Savajols,[2] B.M.Sherrill,[1,6] C. Stodel,[2] J. C. Thomas,[2] A. C. Villari[9]

[1] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[2] *Grand Accélérateur National d'Ions Lourds, CEA/DSM-CNRS/IN2P3, F-14076 Caen, France*
[3] *CENBG, UMR 5797 CNRS/IN2P3, Université Bordeaux 1, F-33175 Gradignan, France*
[4] *Universidade de Santiago de Compostela, E-15782 Santiago de Compostela, Spain*
[5] *FLNR, JINR, 141980 Dubna, Moscow region, Russian Federation*
[6] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[7] *Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA*
[8] *IPN Orsay, CNRS/IN2P3, F-91406 Orsay, France*
[9] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*

- A ^{238}U beam at 24 MeV/u with a typical intensity of 10^9 pps was used to irradiate a series of Be & C targets
- The beam was incident at an angle of 3° in order not to overwhelm the detectors with the beam charge states
- Preliminary detectors calibration with the primary beam, then particle identification has to be proved by gamma from know isomers

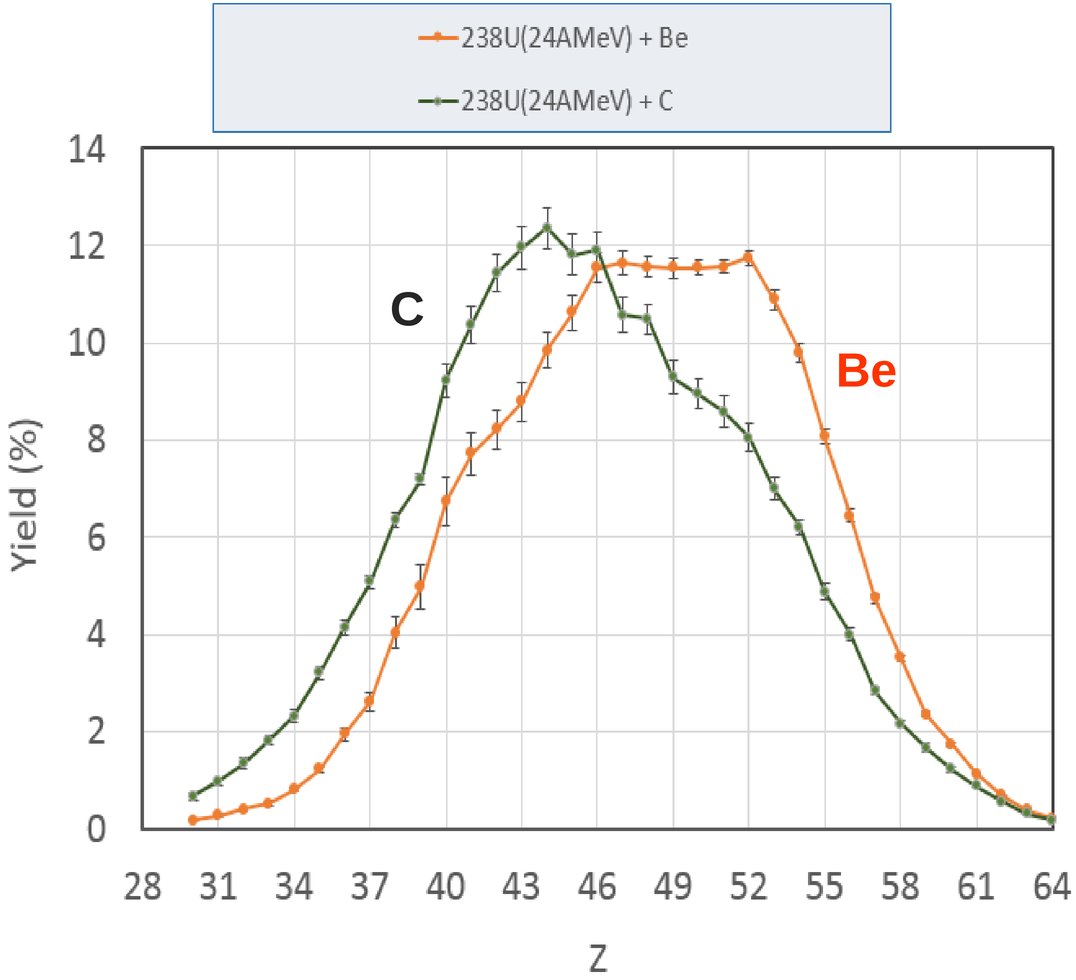




- **The experiment demonstrated excellent resolution, in *Z, A*, and *q*.**
- **The results demonstrate that a fragment separator can be used to produce radioactive beams using fusion-fission reactions in inverse kinematics,**
- **In-flight fusion-fission can become a useful production method to identify new neutron-rich isotopes, investigate their properties and study production mechanisms.**

Elemental distributions of fission fragments

Preliminary!!!



^{238}U Energy	**24 AMeV**	**24 AMeV**
Target	**Be**	**C**
<Z>	**48.01**	**45.75**
d<Z>	0.22	0.21
sig(Z)	**6.03**	**6.40**
d(sig(Z))	0.17	0.16

Two light targets (A=9 & 12) at the same beam energy,
but why so different distributions?

We need a fast analysis of partial cross sections!!

Update of Fusion mechanism in LISE^{++}

v.9.10.54
from 04/25/2015

See details @
LISE^{++} Update of Fusion reaction mechanism
http://lise.nscl.msu.edu/9_10/9_10_Fusion.pdf

$$\sigma_{\mathrm{ER}}^{xn}(E) = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)P_{\mathrm{cont}}(E,l)P_{\mathrm{CN}}(E^*,l)\,P_{xn}(E^*,l)$$

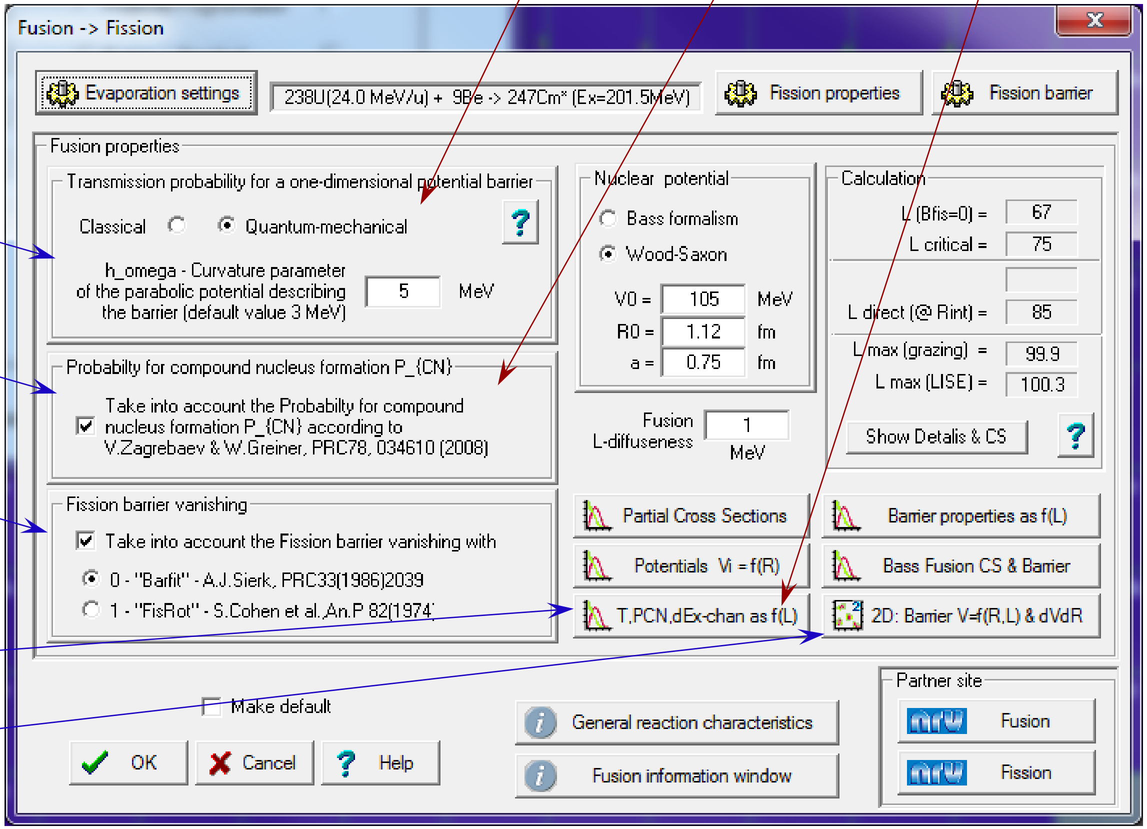
Fusion or Quasi-Elastic?

Compound or Quasi-Fission?

Capture or Fast Fission?

Fusion-Evaporation or Fusion-Fission?

Capture or Deep-Inelastic?



Fusion -> Fission

Evaporation settings | 238U(24.0 MeV/u) + 9Be -> 247Cm* (Ex=201.5MeV) | Fission properties | Fission barrier

Fusion properties

Transmission probability for a one-dimensional potential barrier
Classical ○ ● Quantum-mechanical
h_omega - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV) 5 MeV

Probabilty for compound nucleus formation P_{CN}
☑ Take into account the Probabilty for compound nucleus formation P_{CN} according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)

Fission barrier vanishing
☑ Take into account the Fission barrier vanishing with
● 0 - "Barfit" - A.J.Sierk, PRC33(1986)2039
○ 1 - "FisRot" - S.Cohen et al. An.P 82(1974)

Nuclear potential
○ Bass formalism
● Wood-Saxon
V0 = 105 MeV
R0 = 1.12 fm
a = 0.75 fm

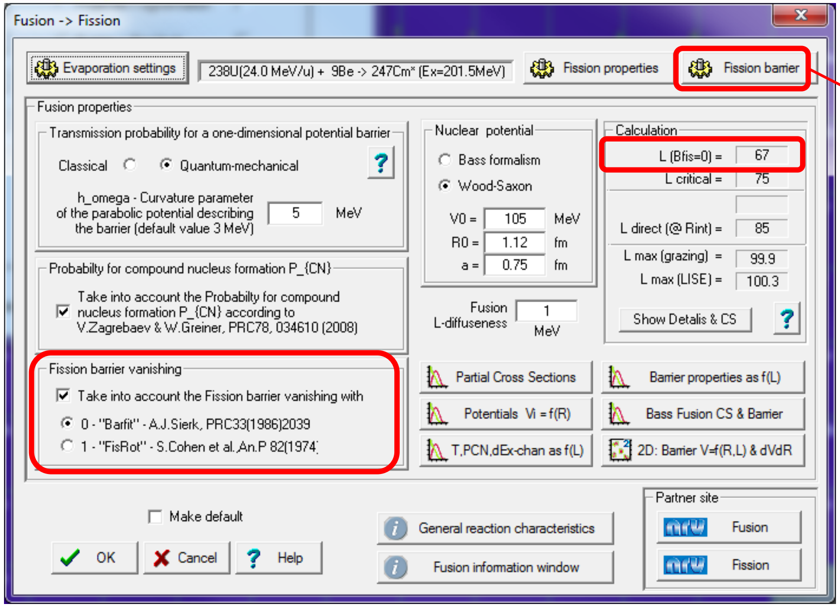
Fusion L-diffuseness 1 MeV

Calculation
L (Bfis=0) = 67
L critical = 75
L direct (@ Rint) = 85
L max (grazing) = 99.9
L max (LISE) = 100.3

Projectile Fragmentation and Abrasion-Fission are dominated reaction mechanisms in LISE^{++} for rare beam production, where we are developing our own models

Do not hesitate to use Low-Energy reaction computing centers as NRV for more sophisticated solutions with Channel Coupling, Langevin equations and so on

Fission Barrier Vanishing as f(L)



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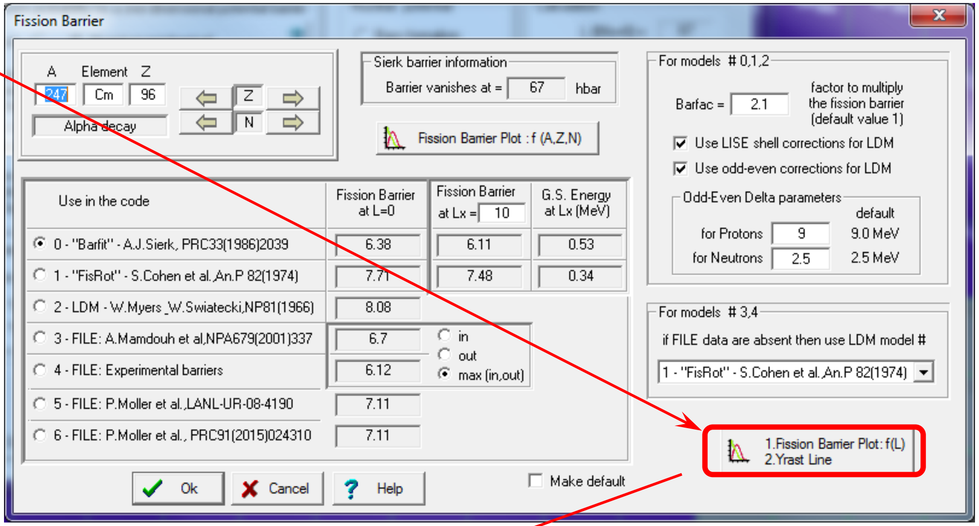


Fission Barrier

A 247 Element Cm Z 96

Sierk barrier information

Barrier vanishes at = 67 hbar

For models # 0,1,2

Barfac = 2.1 factor to multiply the fission barrier (default value 1)

☑ Use LISE shell corrections for LDM

☑ Use odd-even corrections for LDM

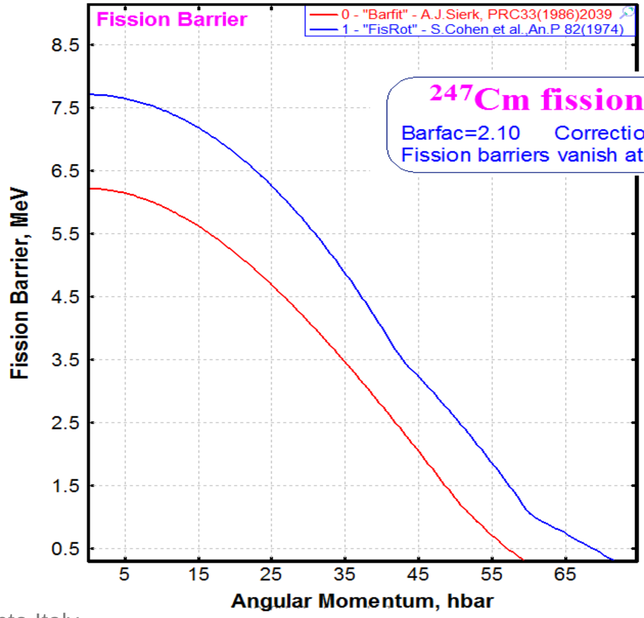
Odd-Even Delta parameters

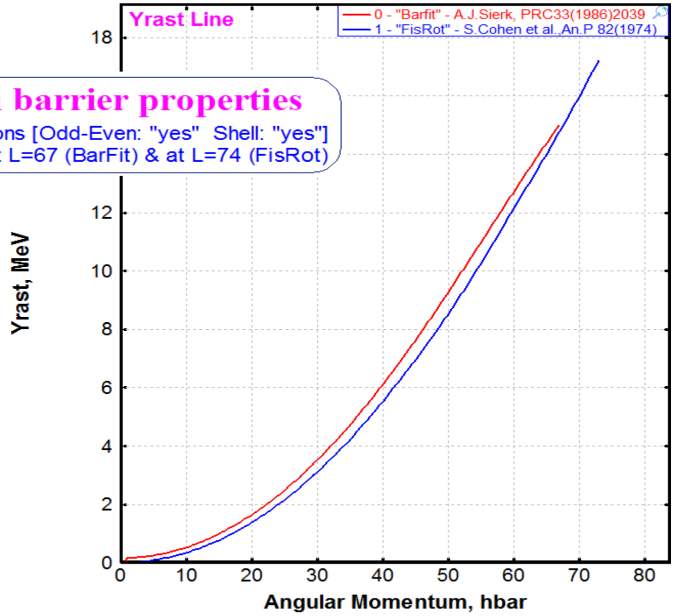
		default
for Protons	9	9.0 MeV
for Neutrons	2.5	2.5 MeV

For models # 3,4

if FILE data are absent then use LDM model # 1 - "FisRot" - S.Cohen et al. An.P 82(1974)

Use in the code	Fission Barrier at L=0	Fission Barrier at Lx = 10	G.S. Energy at Lx (MeV)
● 0 - "Barfit" - A.J.Sierk, PRC33(1986)2039	6.38	6.11	0.53
○ 1 - "FisRot" - S.Cohen et al. An.P 82(1974)	7.71	7.48	0.34
○ 2 - LDM - W.Myers _W.Swiatecki,NP81(1966)	8.08		
○ 3 - FILE: A.Mamdouh et al,NPA679(2001)337	6.7	○ in	
○ 4 - FILE: Experimental barriers	6.12	○ out ● max (in,out)	
○ 5 - FILE: P.Moller et al.,LANL-UR-08-4190	7.11		
○ 6 - FILE: P.Moller et al., PRC91(2015)024310	7.11		



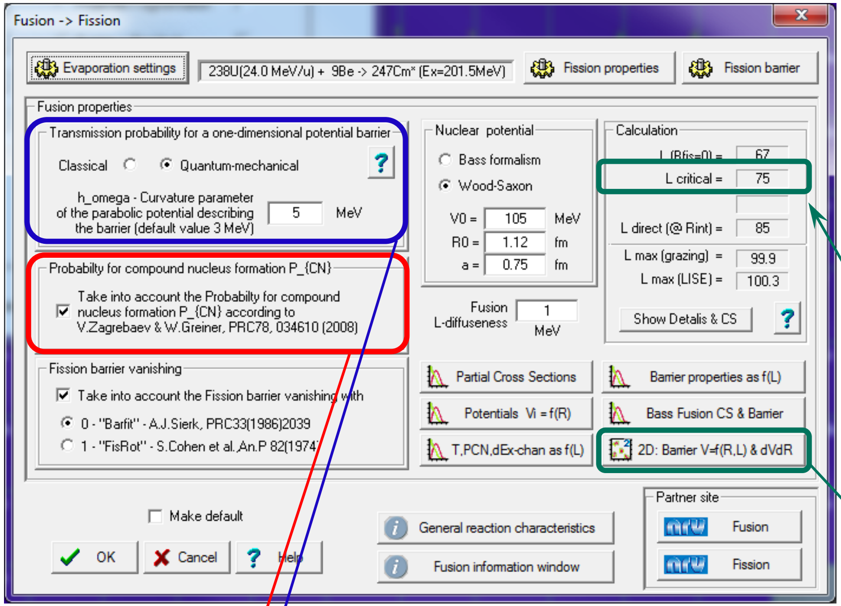


^{247}Cm fission barrier properties

Barfac=2.10 Corrections [Odd-Even: "yes" Shell: "yes"]

Fission barriers vanish at L=67 (BarFit) & at L=74 (FisRot)

Transmission for a barrier & CN formation probabilities as f(L)



Fusion -> Fission

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Transmission probability for a one-dimensional potential barrier

Classical ○ ● Quantum-mechanical

h_omega - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV): 5 MeV

Probabilty for compound nucleus formation P_{CN}

☑ Take into account the Probabilty for compound nucleus formation P_{CN} according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)

Fission barrier vanishing

☑ Take into account the Fission barrier vanishing with

● 0 - "Barfit" - A.J.Sierk, PRC33(1986)2039

○ 1 - "FisRot" - S.Cohen et al. An.P 82(1974)

Nuclear potential

○ Bass formalism

● Wood-Saxon

V0 = 105 MeV

R0 = 1.12 fm

a = 0.75 fm

Fusion L-diffuseness: 1 MeV

Calculation

L (Bfis=0) = 67

L critical = 75

L direct (@ Rint) = 85

L max (grazing) = 99.9

L max (LISE) = 100.3

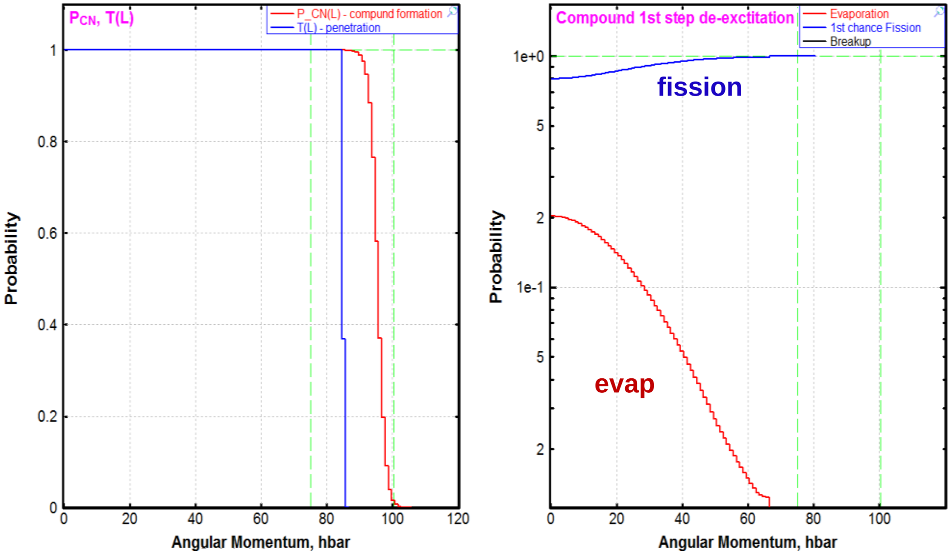
☐ Make default

Probabilities as f (L)

^{238}U(24.0MeV/u) + ^{9}Be -> ^{247}Cm* (E_{CM}=208.3 MeV); h_omega=5.0

L_{crit}=75; L_{max}^{Graz}=99.9; L_{max}^{LISE}=100.3; Nuclear potential: WoodSaxon

Vertical lines correspond to $L_{critical}$ & $L_{maximum}$

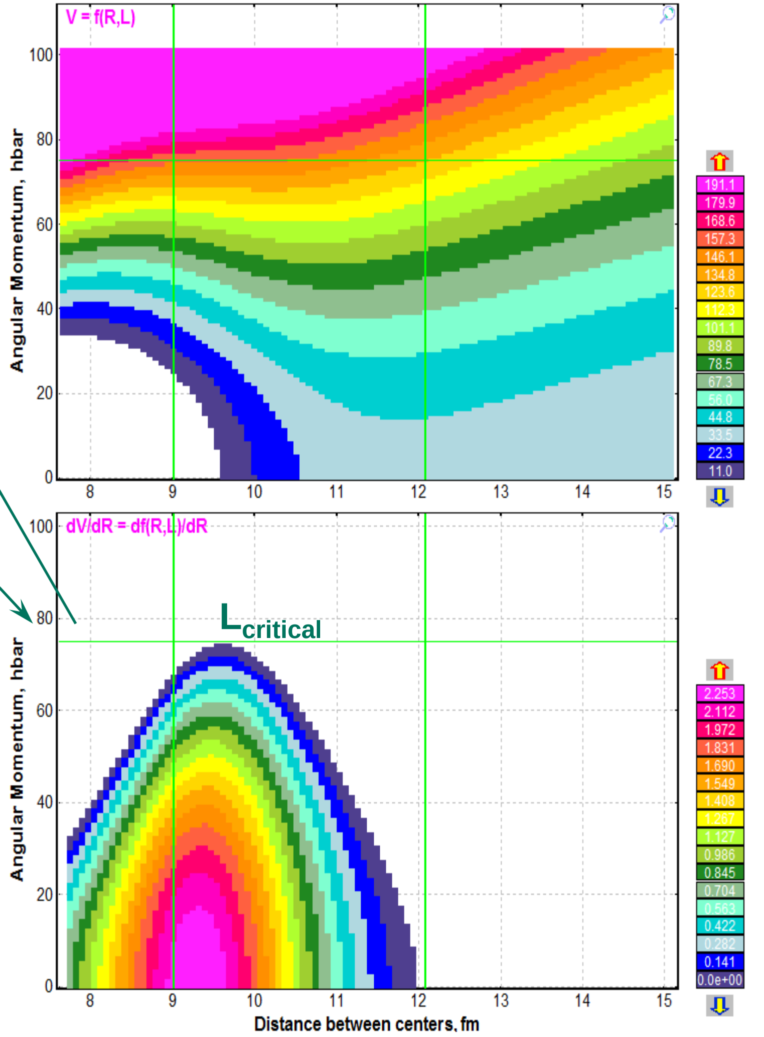


2D Potential plots as f(R,L) & df(R,L)/dR

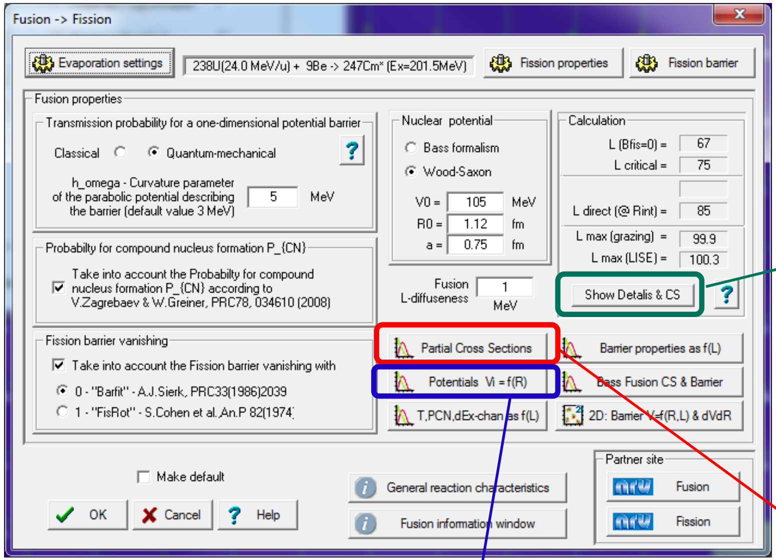
^{238}U(24.0 MeV/u) + ^{9}Be -> ^{247}Cm* (E_{CM}=208.3 MeV)

L_{crit}=75; L_{max}^{Graz}=99.9; L_{max}^{LISE}=100.3; Nuclear potential: WoodSaxon; WS params: 105.0,1.12,0.75

Vertical lines correspond to (C_p + C_t) and $R_{interaction}$, Horizontal line to $L_{critical}$



Potential energy and Partial cross sections


Fusion -> Fission

238U(24.0 MeV/u) + 9Be -> 247Cm* (Ex=201.5MeV)

Fusion properties

Transmission probability for a one-dimensional potential barrier

Classical ○ ● Quantum-mechanical

h_omega - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV): 5 MeV

Probabilty for compound nucleus formation P_{CN}

☑ Take into account the Probabilty for compound nucleus formation P_{CN} according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)

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○ 1 - "FisRot" - S.Cohen et al. An.P 82(1974)

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V0 = 105 MeV

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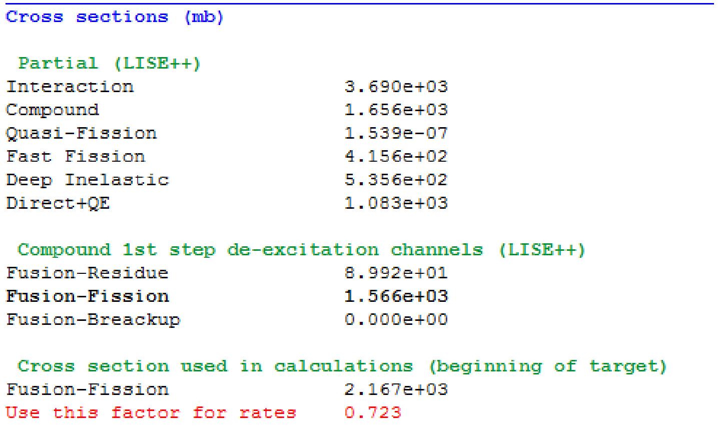
L critical = 75

L direct (@ Rint) = 85

L max (grazing) = 99.9

L max (LISE) = 100.3

☐ Make default

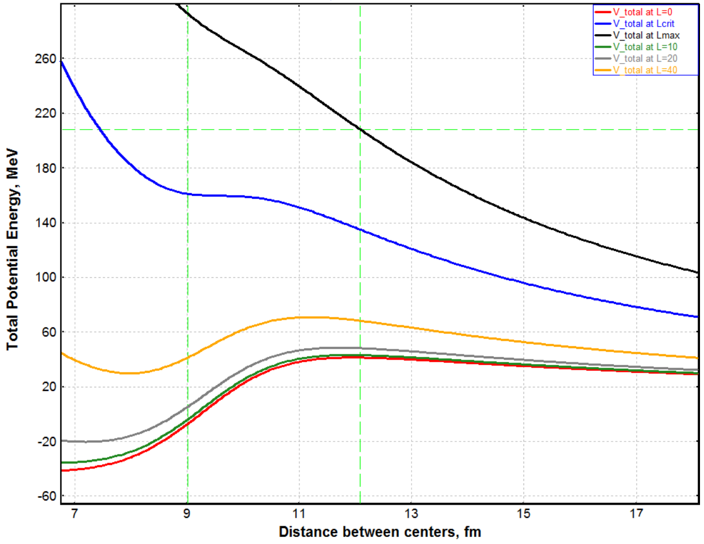

```
Cross sections (mb)

 Partial (LISE++)
Interaction                3.690e+03
Compound                   1.656e+03
Quasi-Fission              1.539e-07
Fast Fission               4.156e+02
Deep Inelastic             5.356e+02
Direct+QE                  1.083e+03

 Compound 1st step de-excitation channels (LISE++)
Fusion-Residue             8.992e+01
Fusion-Fission             1.566e+03
Fusion-Breackup            0.000e+00

 Cross section used in calculations (beginning of target)
Fusion-Fission             2.167e+03
Use this factor for rates  0.723
```

Potential energy plot: Total

^{238}U(24.0 MeV/u) + ^{9}Be -> ^{247}Cm* (E_{CM}=208.3 MeV)

L_{crit}=75; L_{max}^{Graz}=99.9; L_{max}^{LISE}=100.3; Nuclear potential: WoodSaxon; WS params: 105.0,1.12,0.75

Vertical lines correspond to ($C_p + C_t$) and $R_{interaction}$, Right horizontal line to E_{CM}

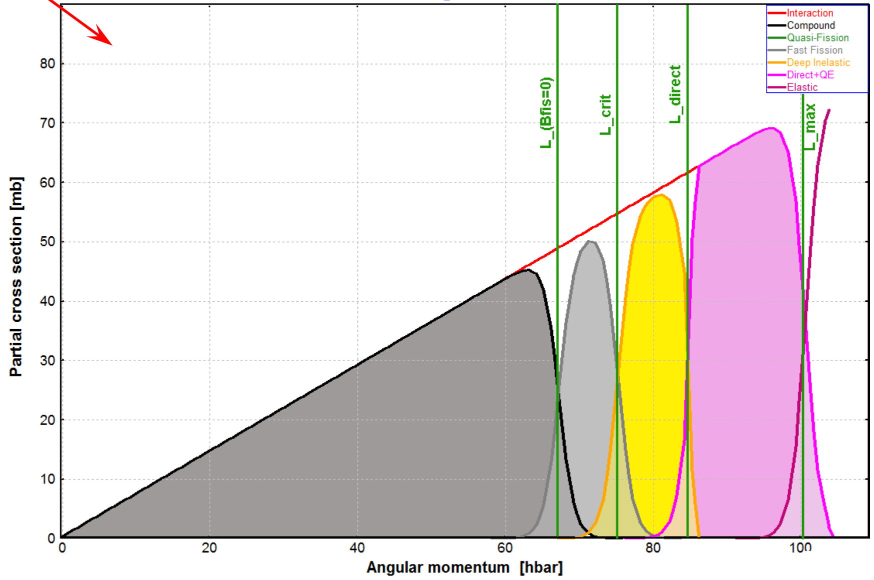


Partial cross sections

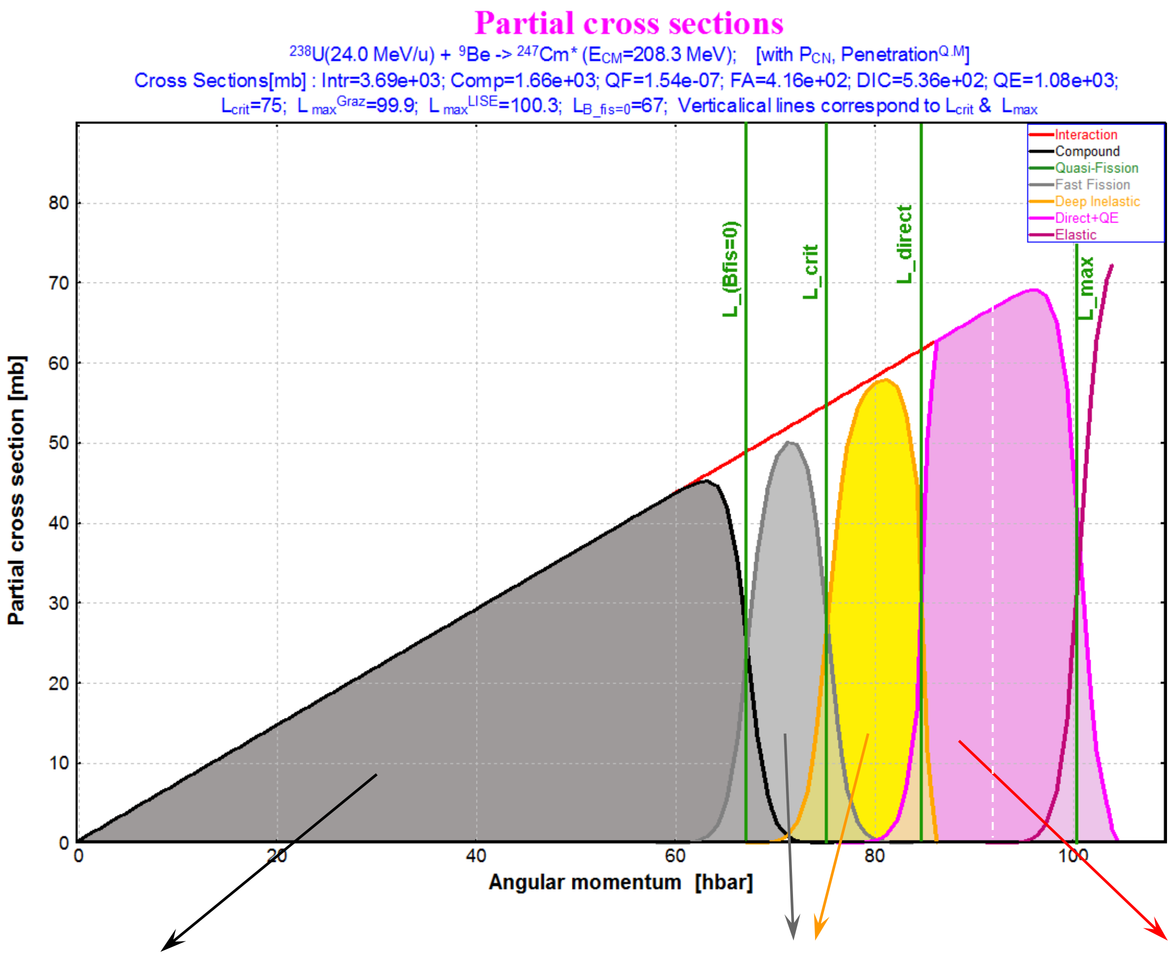
^{238}U(24.0 MeV/u) + ^{9}Be -> ^{247}Cm* (E_{CM}=208.3 MeV); [with P_{CN}, Penetration$^{Q.M}$]

Cross Sections[mb] : Intr=3.69e+03; Comp=1.66e+03; QF=1.54e-07; FA=4.16e+02; DIC=5.36e+02; QE=1.08e+03;

L_{crit}=75; L_{max}^{Graz}=99.9; L_{max}^{LISE}=100.3; $L_{B\_fis=0}$=67; Verticalical lines correspond to L_{crit} & L_{max}



Output channels in the e547 experiment : ^{238}U (24 MeV/u)

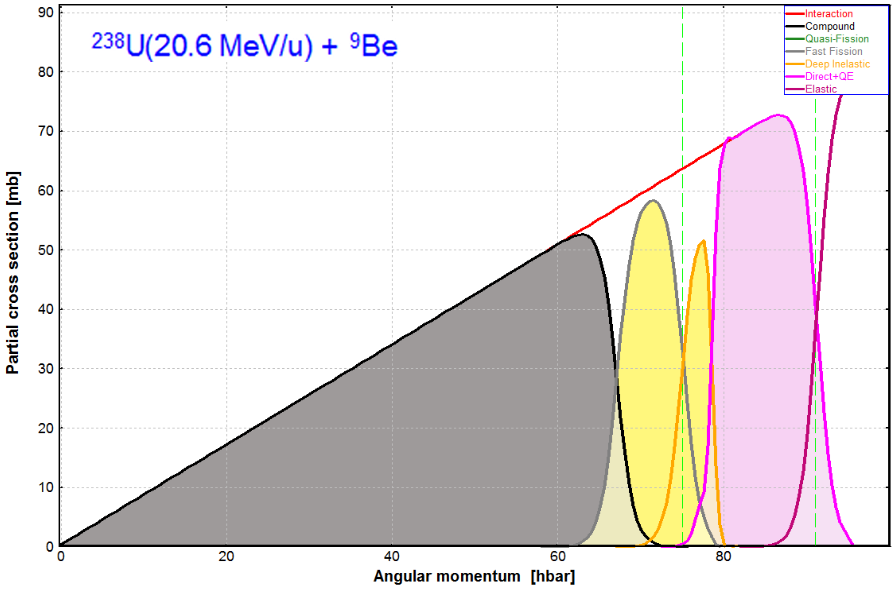


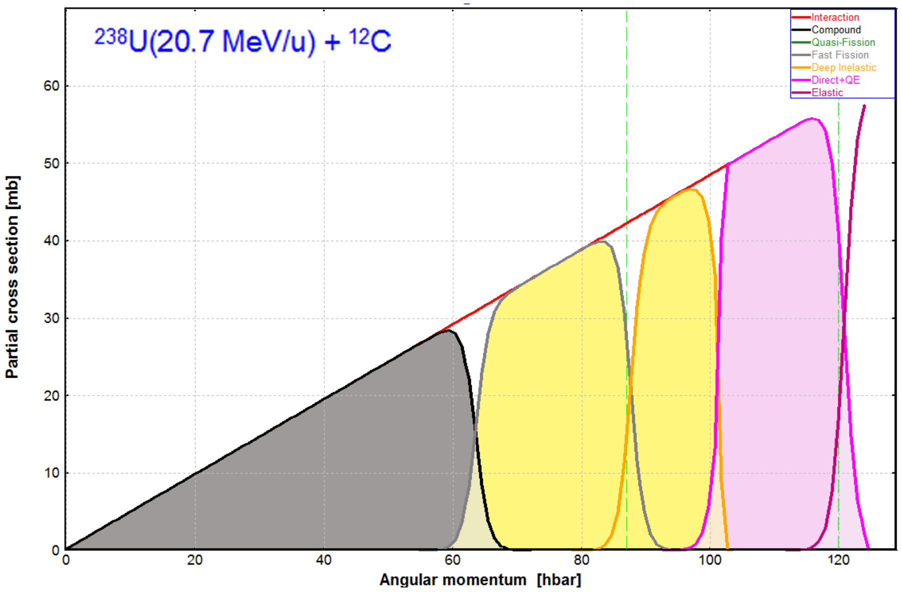
Compound fission ~100%
Fissile Z = 96
High Excitation Energy

Sequential fission after DIC
Fissile Z < 92
High Excitation Energy

Partially go to fission
Fissile Z~92
Low Excitation Energy

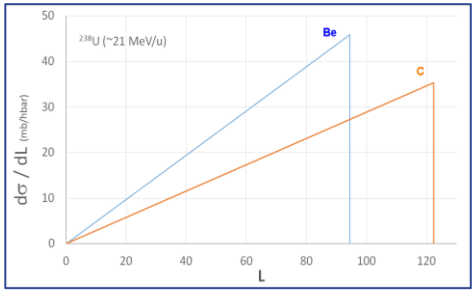
e547 experiment : Be vs. C targets





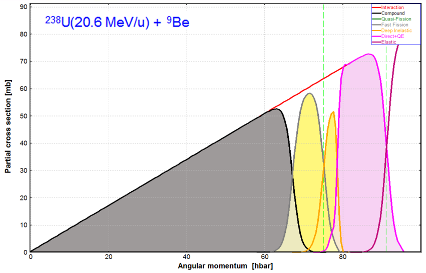
average for 17-24 MeV/u range			
		Targets	
Fission Barrier Vanishing	Reactions	**Be**	**C**
Sierk	DIC+FA	19%	42%
	Fusion-Fission	56%	29%
	QE	25%	29%
Cohen	DIC+FA	8%	29%
	Fusion-Fission	66%	41%
	QE	25%	29%

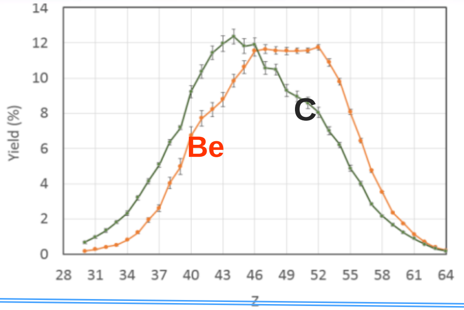
Momentum (hbar)	Be	C
L (Bfis=0)	67	63
L critical	75	87
L direct @ Rint	79	101
	12	38
L max (grazing)	90.5	118.9
L max (LISE)	91.0	119.5

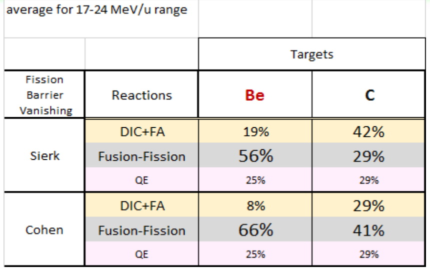


Carbon target.. 50% split… Why?
This is due to difference of moments of inertia between C+U and Be+U just above where fission barrier go to zero

e547 experiment: results interpretation



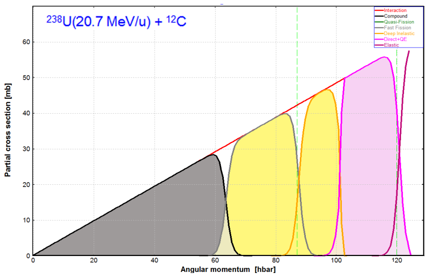




average for 17-24 MeV/u range

Fission Barrier Vanishing	Reactions	Targets: Be	Targets: C
Sierk	DIC+FA	19%	42%
	Fusion-Fission	56%	29%
	QE	25%	29%
Cohen	DIC+FA	8%	29%
	Fusion-Fission	66%	41%
	QE	25%	29%

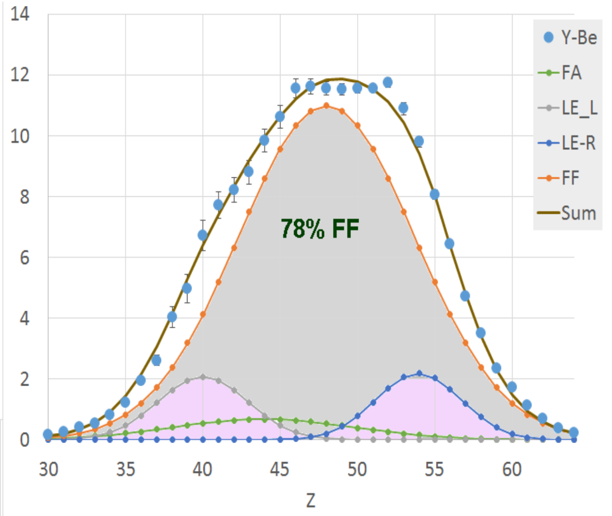
QE-channel partially goes to Low-excitation fission

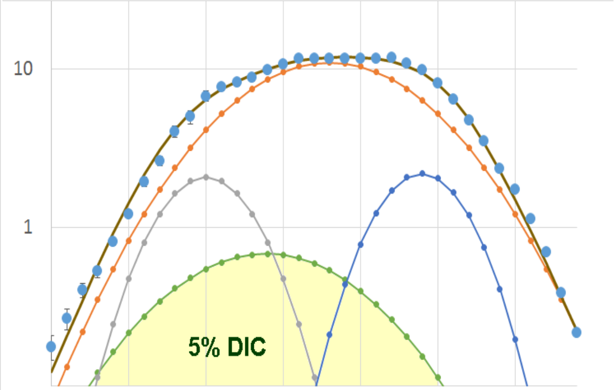


Preliminary!!!

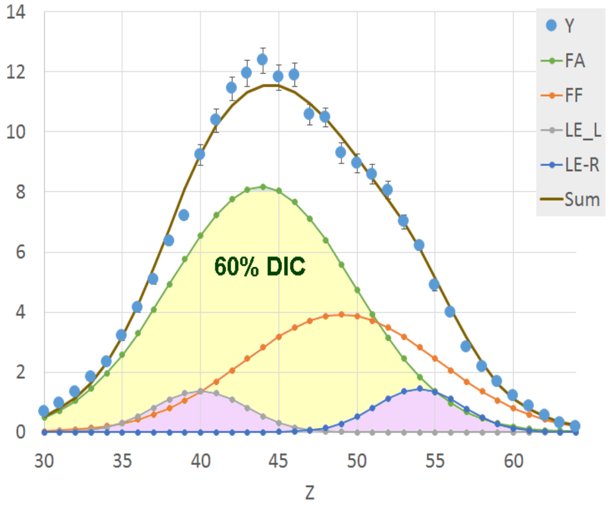
Be-target

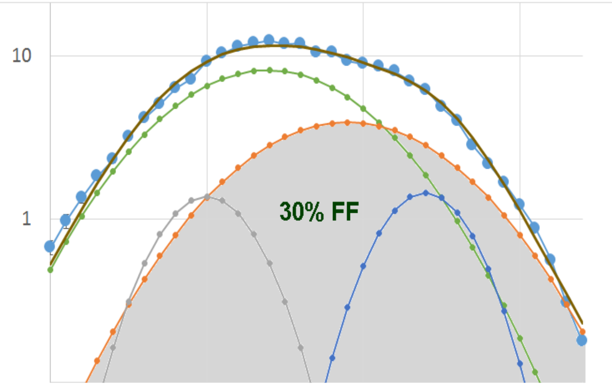
C-target



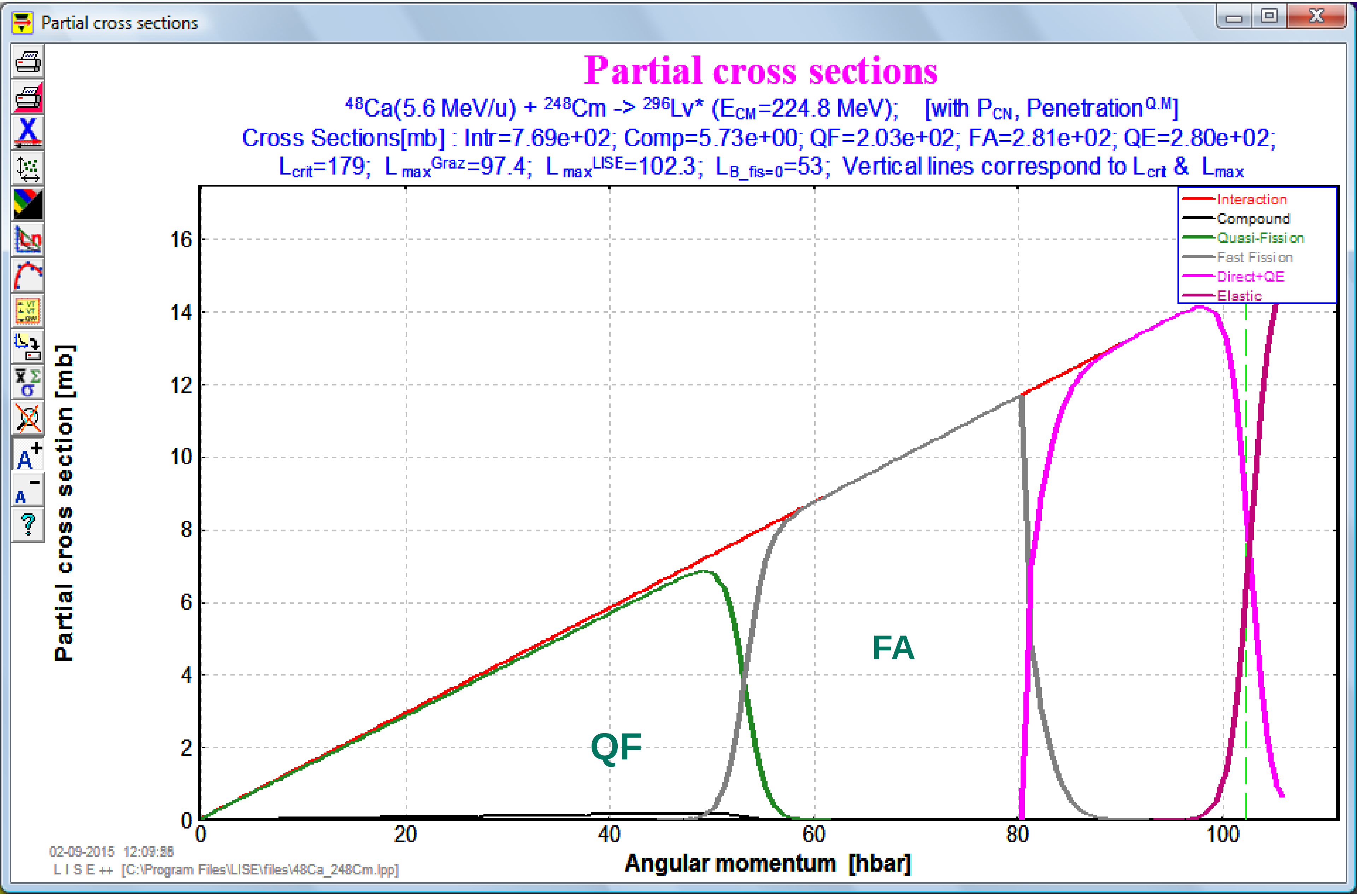


- Three main channels with earlier discussed parameters were used in fitting
- Reaction positions and widths were used the same in both case during fitting process except FF positions (48 and 49)
- From fitting results it follows, that Fusion-fission dominates in the case of Be-target, and sequential fission in the case of C-target
- New LISE^{++} partial cross section analysis fairly describes experimental results
- Significant distinction in elemental distributions of fragments produced with two different light target is explained by larger DIC component with C-target due to fission barrier vanishing
- **Fusion-Fission mechanism is responsible in both cases for High-Z isotope production (Z>60)**





Sophie's talk



Partial cross sections

^{48}Ca(5.6 MeV/u) + ^{248}Cm -> ^{296}Lv* (E_{CM}=224.8 MeV); [with P_{CN}, Penetration$^{Q.M}$]

Cross Sections[mb] : Intr=7.69e+02; Comp=5.73e+00; QF=2.03e+02; FA=2.81e+02; QE=2.80e+02;

L_{crit}=179; L_{max}^{Graz}=97.4; L_{max}^{LISE}=102.3; $L_{B\_fis=0}$=53; Vertical lines correspond to L_{crit} & L_{max}

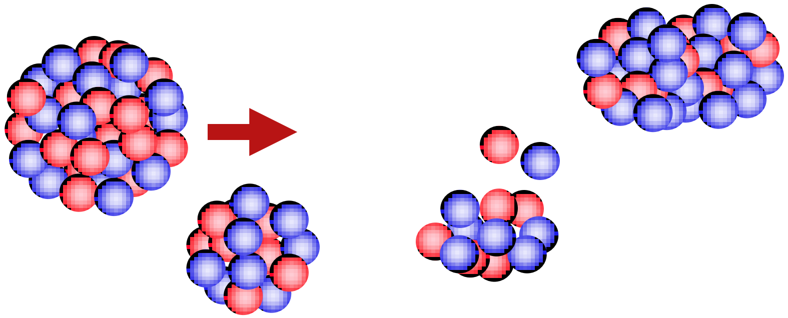
02-09-2015 12:09:38

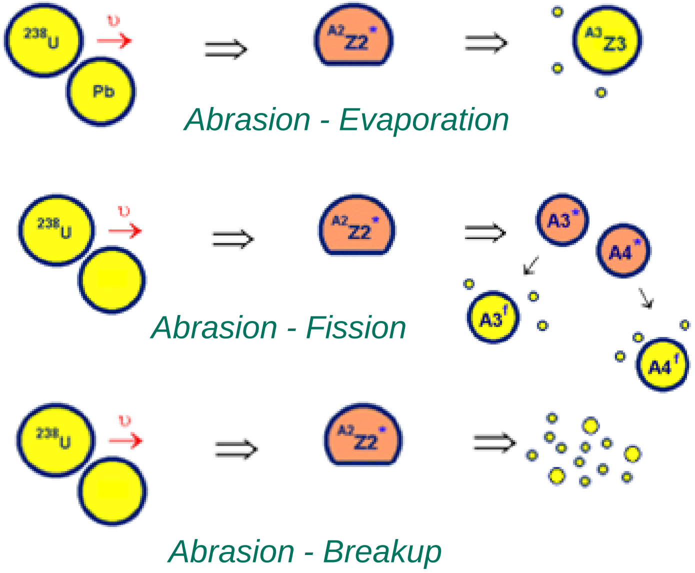
LISE++ [C:\Program Files\LISE\files\48Ca_248Cm.lpp]

3. Abrasion-Fission

3.1 Abrasion reactions: models

Abrasion reactions : LISE^{++} de-excitation channels



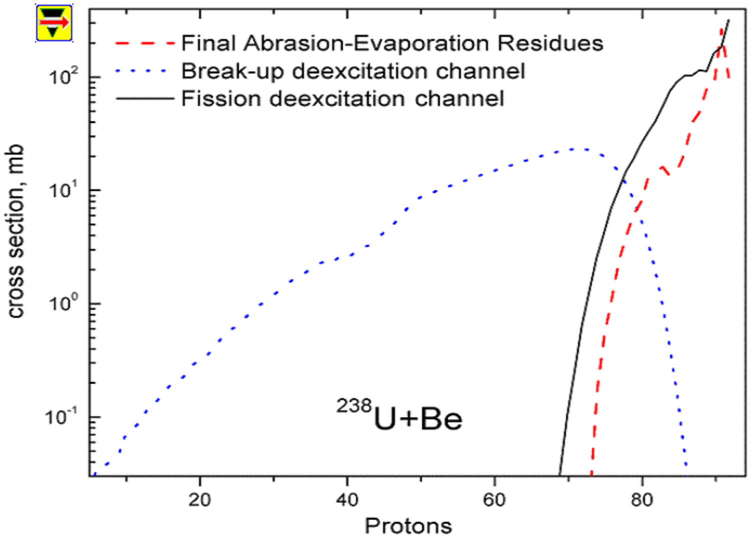


Abrasion - Evaporation

Abrasion - Fission

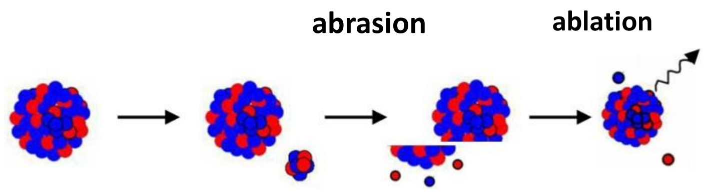
Abrasion - Breakup

De-excitation channel	Collisions	Reaction
Abrasion – Evaporation Abrasion – Ablation	peripheral	Projectile fragmentation
Abrasion – Fission	peripheral	In-flight fission ~~*Projectile fission*~~
Abrasion – Breakup	central	Multi-fragmentation



Nuclear charge yields for different de-excitation channels after ^{238}U(1AGeV) abrasion on a Be-target.

Details on Abrasion-Ablation



Projectile ^{82}Se

Target ^{9}Be

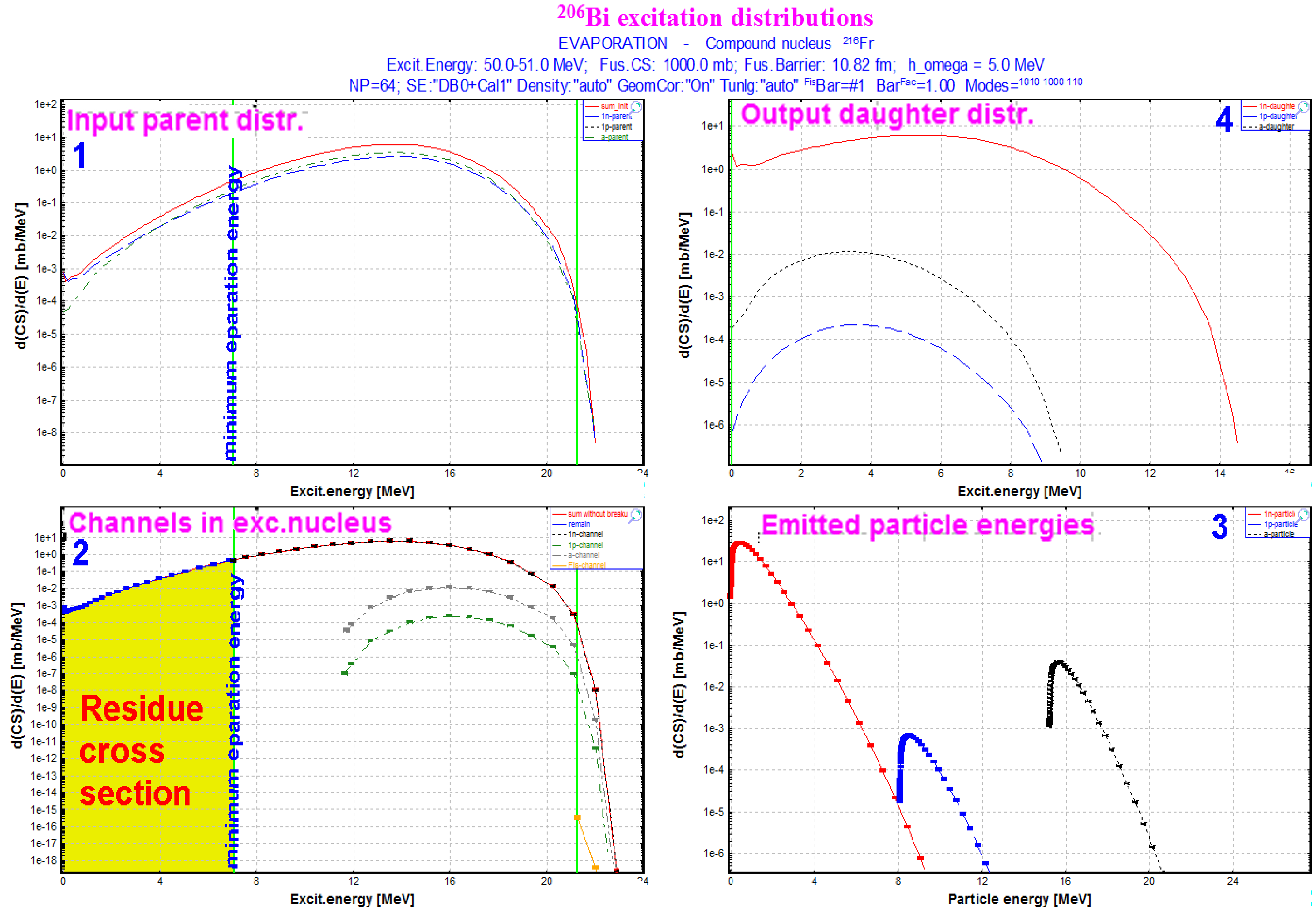
Initial prefragment ^{68}Ti*

Final fragment ^{54}Ca

- The LISE^{++} AA model is initially based on the version of J.-J.Gaimard and K.H.Schmidt, NPA531 (1991) 709
- The LISE^{++} AA model is analytical, that allows to calculate low cross sections of very exotic nuclei
- The Abrasion-Ablation approach meets three principal difficulties
  - *a. Determination of Excitation energy parameters (models) for each reaction*
  - *b. Plenty of other parameters*
  - *c. Suggesting negligible contribution of dissipation processes during abrasion (it can be true at high energies with light targets)*

- Four excitation energy models are implanted in the code
- The Ablation step (Evaporation cascade) uses a mass table to obtain separation energies

Example : ^{216}Fr, E*=50 MeV, σ=1 barn ⇒ ^{206}Bi



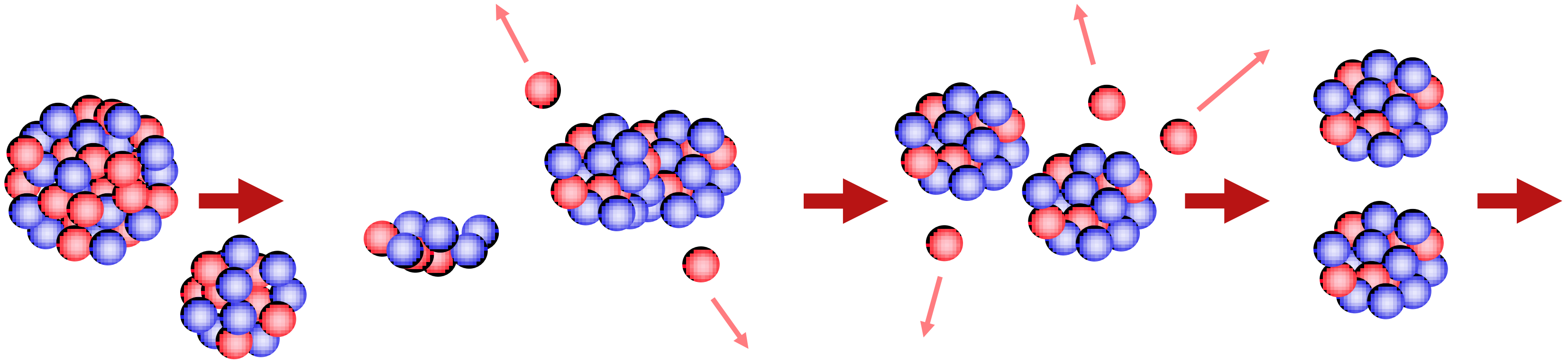
^{206}Bi excitation distributions

EVAPORATION - Compound nucleus ^{216}Fr

Excit.Energy: 50.0-51.0 MeV; Fus.CS: 1000.0 mb; Fus.Barrier: 10.82 fm; h_omega = 5.0 MeV

NP=64; SE:"DB0+Cal1" Density:"auto" GeomCor:"On" Tunlg:"auto" ^{Fis}Bar=#1 Bar^{Fac}=1.00 Modes=$^{1010\ 1000\ 110}$

Abrasion-Fission



- ☐ ABRABLA : Abrasion-Ablation Monte Carlo

  J.-J. Gaimard, K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709.

- ☐ PROFI : semi-empirical fission Monte-Carlo code

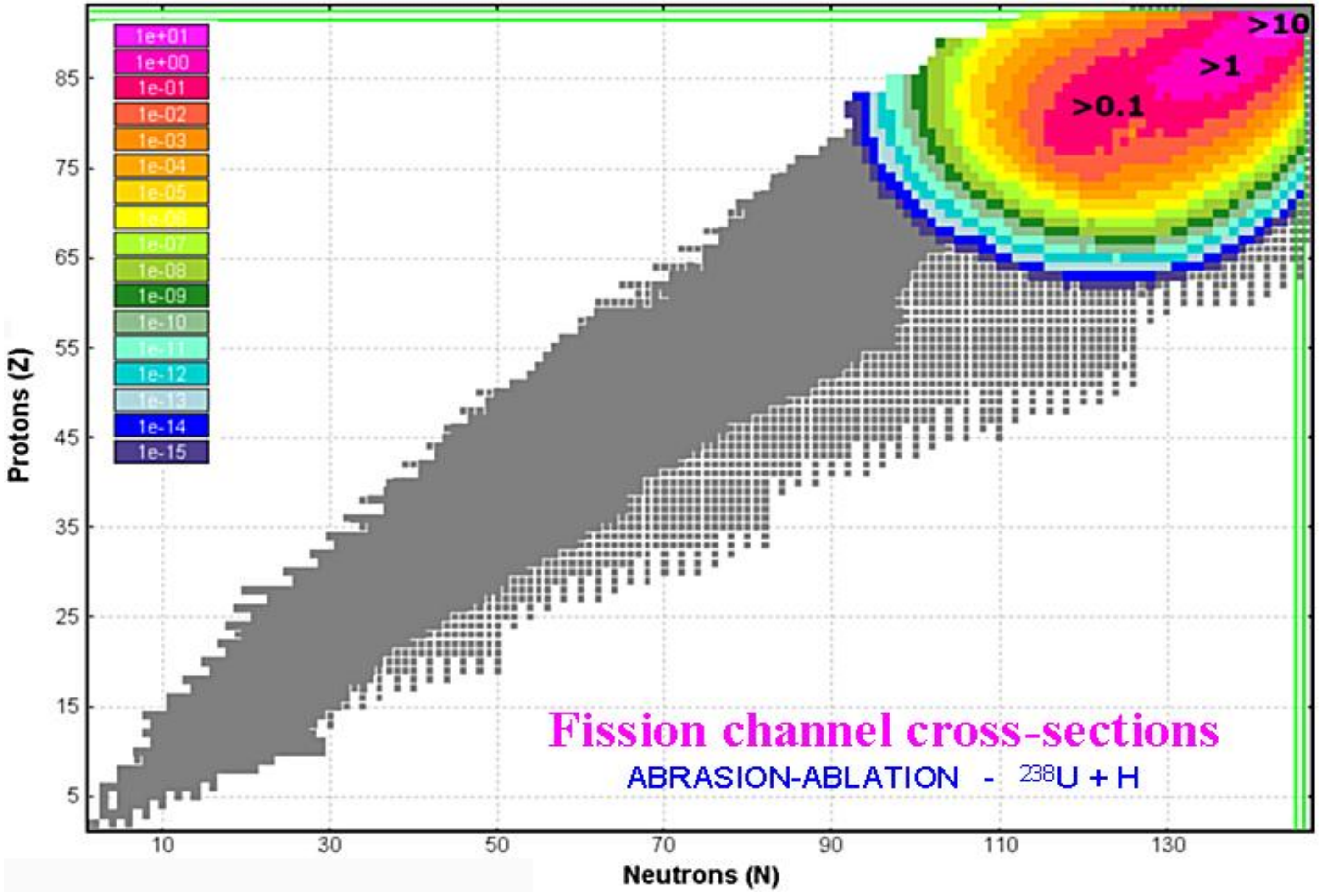
  J. Benlliure, A. Grewe, M. de Jong, K.-H. Schmidt, S. Zhdanov, Nucl. Phys. A 628 (1998) 458

- ☐ LISE^{++} 3EER Abrasion-Fission model (analytical)

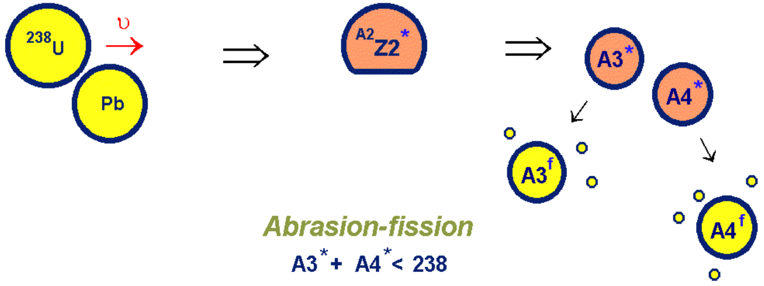
  O.T., Tech. Rep. MSUCL1300, NSCL, Michigan State University, 2005

  [*http://lise.nscl.msu.edu/7_5/lise++_7_5.pdf*](http://lise.nscl.msu.edu/7_5/lise++_7_5.pdf)

Abrasion-Fission : ocean of fissile nuclei

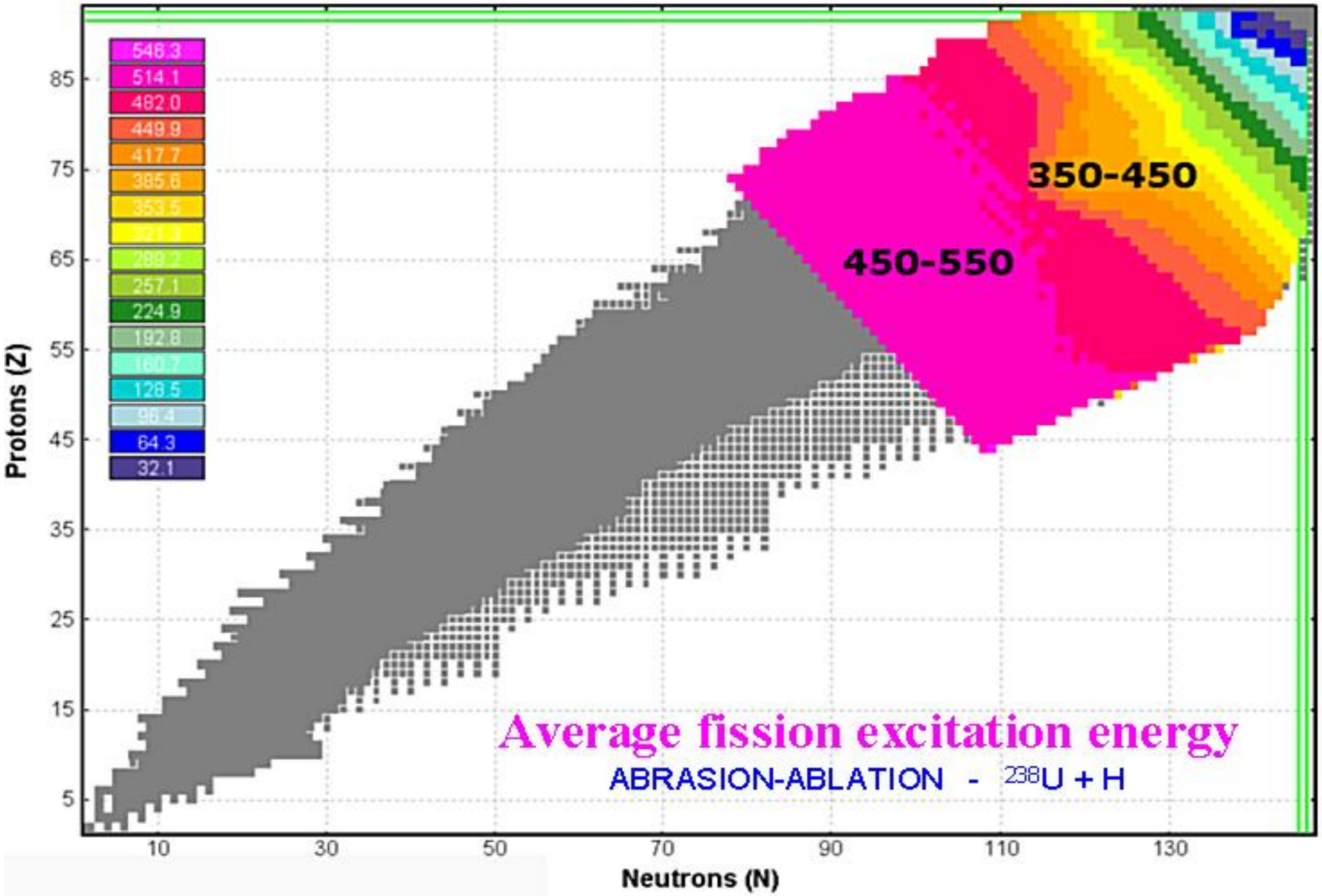


Abrasion-Fission : ocean of hot fissile nuclei

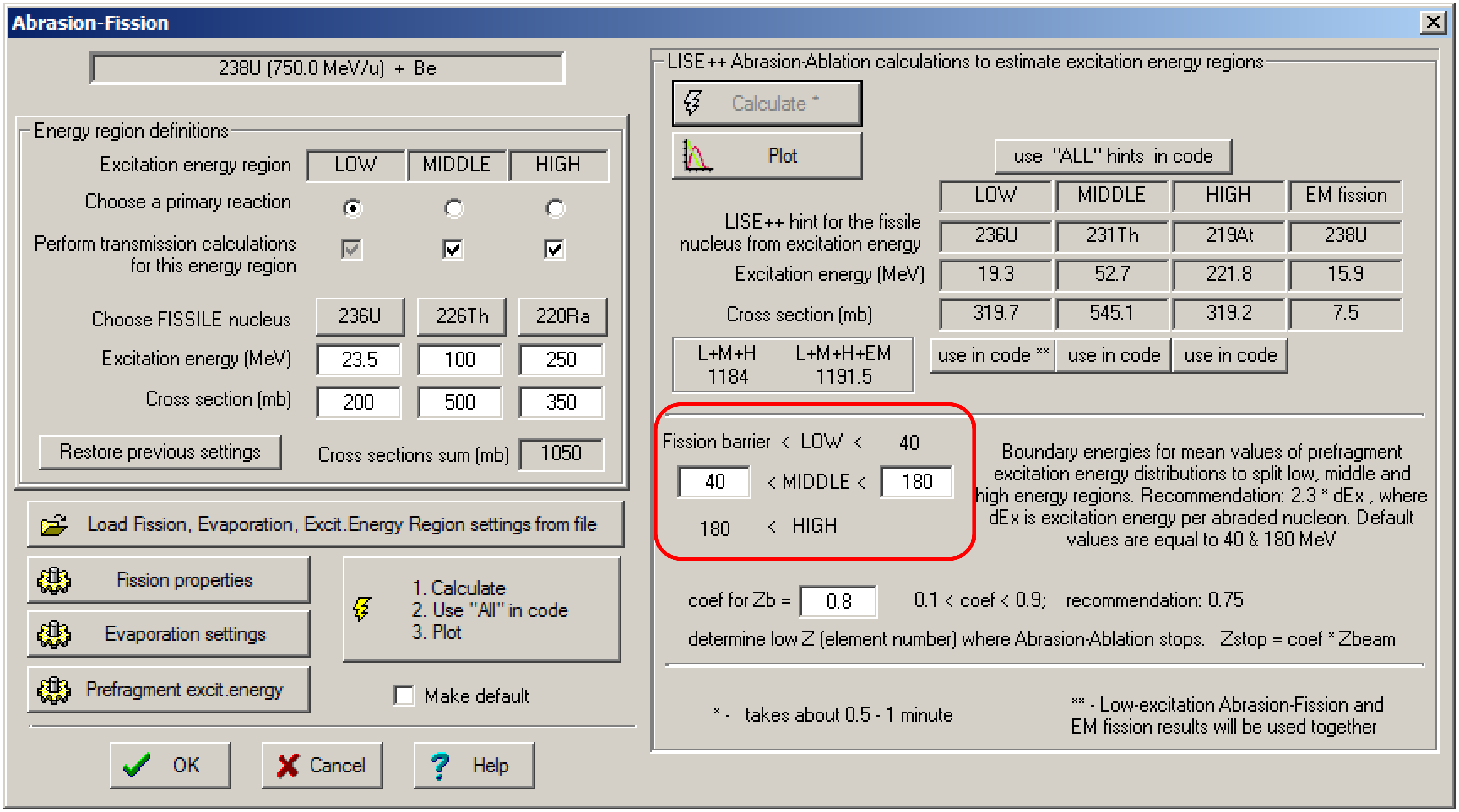


Abrasion-fission

$A3^* + A4^* < 238$



Three-excitation-energy-region model



Abrasion-Fission

238U (750.0 MeV/u) + Be

Energy region definitions

Excitation energy region	LOW	MIDDLE	HIGH
Choose a primary reaction	●	○	○
Perform transmission calculations for this energy region	☑	☑	☑
Choose FISSILE nucleus	236U	226Th	220Ra
Excitation energy (MeV)	23.5	100	250
Cross section (mb)	200	500	350

Restore previous settings

Cross sections sum (mb) 1050

Load Fission, Evaporation, Excit.Energy Region settings from file

Fission properties

Evaporation settings

Prefragment excit.energy

1. Calculate
2. Use "All" in code
3. Plot

☐ Make default

OK Cancel Help

LISE++ Abrasion-Ablation calculations to estimate excitation energy regions

Calculate *

Plot

use "ALL" hints in code

	LOW	MIDDLE	HIGH	EM fission
LISE++ hint for the fissile nucleus from excitation energy	236U	231Th	219At	238U
Excitation energy (MeV)	19.3	52.7	221.8	15.9
Cross section (mb)	319.7	545.1	319.2	7.5
	use in code **	use in code	use in code	

L+M+H 1184 L+M+H+EM 1191.5

Fission barrier < LOW < 40

40 < MIDDLE < 180

180 < HIGH

Boundary energies for mean values of prefragment excitation energy distributions to split low, middle and high energy regions. Recommendation: 2.3 * dEx , where dEx is excitation energy per abraded nucleon. Default values are equal to 40 & 180 MeV

coef for Zb = 0.8 0.1 < coef < 0.9; recommendation: 0.75

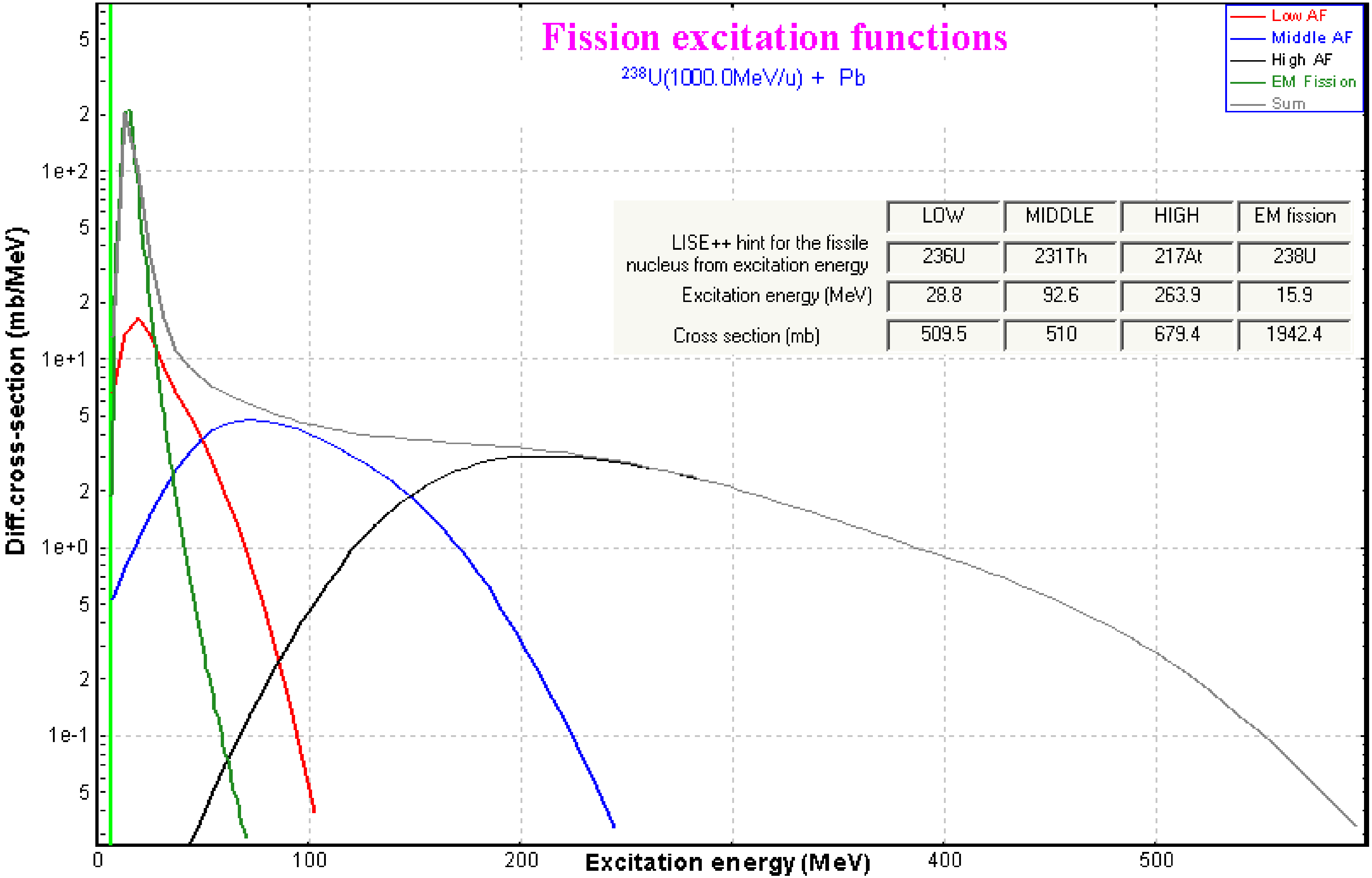
determine low Z (element number) where Abrasion-Ablation stops. Zstop = coef * Zbeam

* - takes about 0.5 - 1 minute

** - Low-excitation Abrasion-Fission and EM fission results will be used together

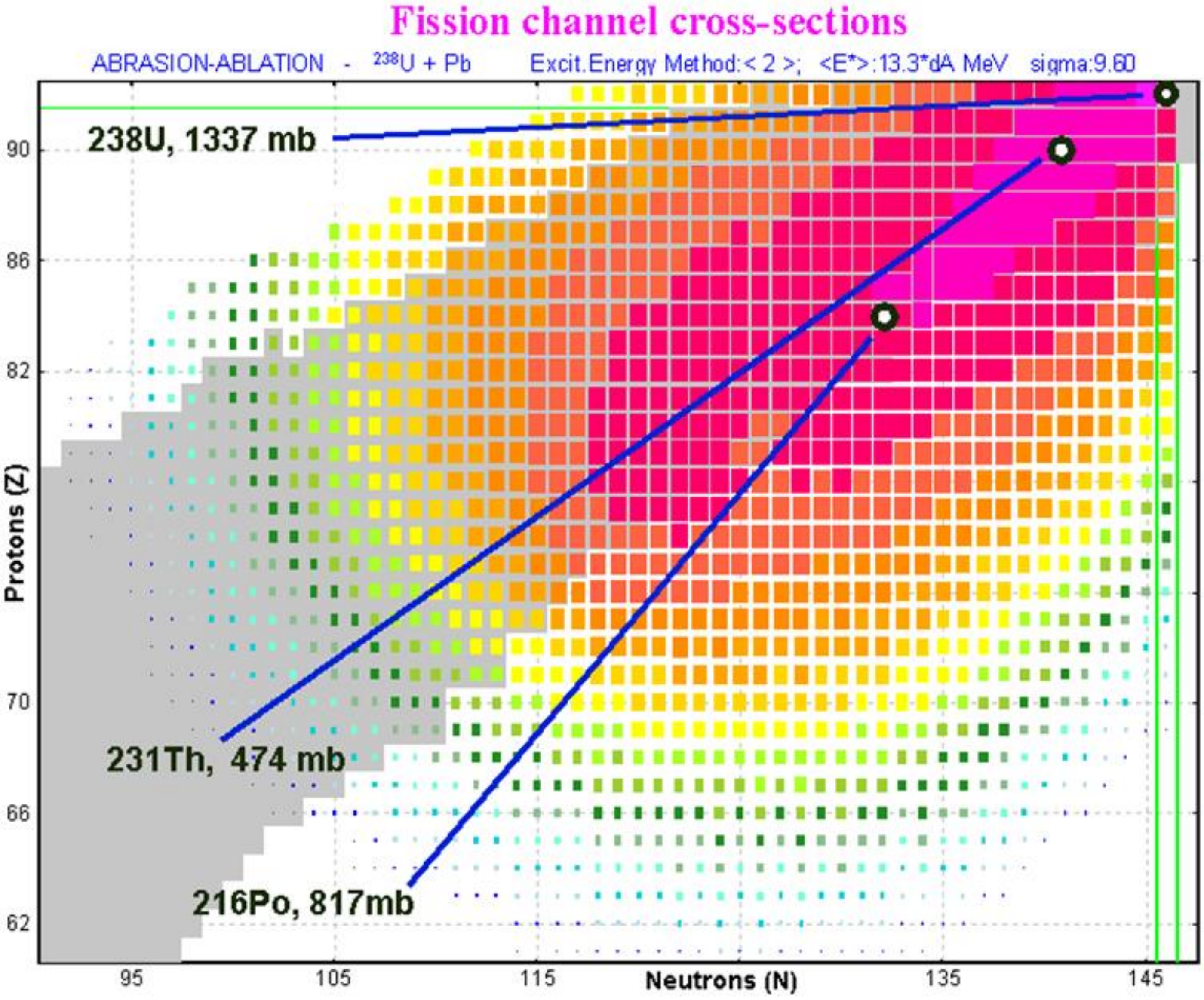
Splitting 1000 fissile nuclei on 3 regions based on their excitation energy,
Getting mean A,Z,E* values based on their cross sections

Fission excitation functions



	LOW	MIDDLE	HIGH	EM fission
LISE++ hint for the fissile nucleus from excitation energy	236U	231Th	217At	238U
Excitation energy (MeV)	28.8	92.6	263.9	15.9
Cross section (mb)	509.5	510	679.4	1942.4

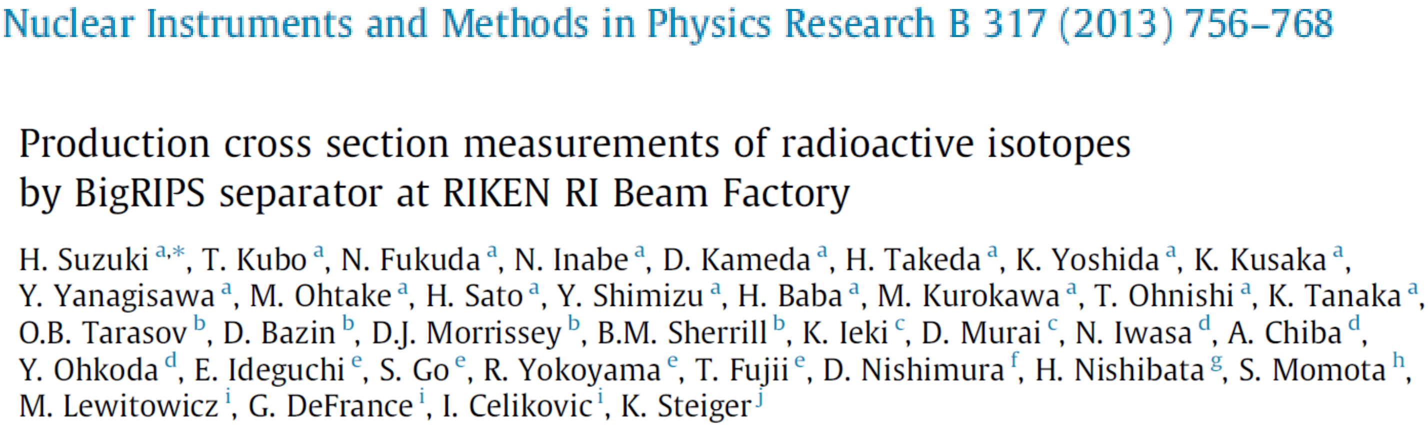
Abrasion-Fission : 3 EER model



Describes well intense final fragments

3.2 Abrasion fission: experiment

Reaction mechanisms : Experiment vs. Calculation



Nuclear Instruments and Methods in Physics Research B 317 (2013) 756–768

Production cross section measurements of radioactive isotopes by BigRIPS separator at RIKEN RI Beam Factory

H. Suzuki [a,*], T. Kubo [a], N. Fukuda [a], N. Inabe [a], D. Kameda [a], H. Takeda [a], K. Yoshida [a], K. Kusaka [a], Y. Yanagisawa [a], M. Ohtake [a], H. Sato [a], Y. Shimizu [a], H. Baba [a], M. Kurokawa [a], T. Ohnishi [a], K. Tanaka [a], O.B. Tarasov [b], D. Bazin [b], D.J. Morrissey [b], B.M. Sherrill [b], K. Ieki [c], D. Murai [c], N. Iwasa [d], A. Chiba [d], Y. Ohkoda [d], E. Ideguchi [e], S. Go [e], R. Yokoyama [e], T. Fujii [e], D. Nishimura [f], H. Nishibata [g], S. Momota [h], M. Lewitowicz [i], G. DeFrance [i], I. Celikovic [i], K. Steiger [j]

In-flight fission of ^{238}U with Be and Pb targets

Abrasion fission

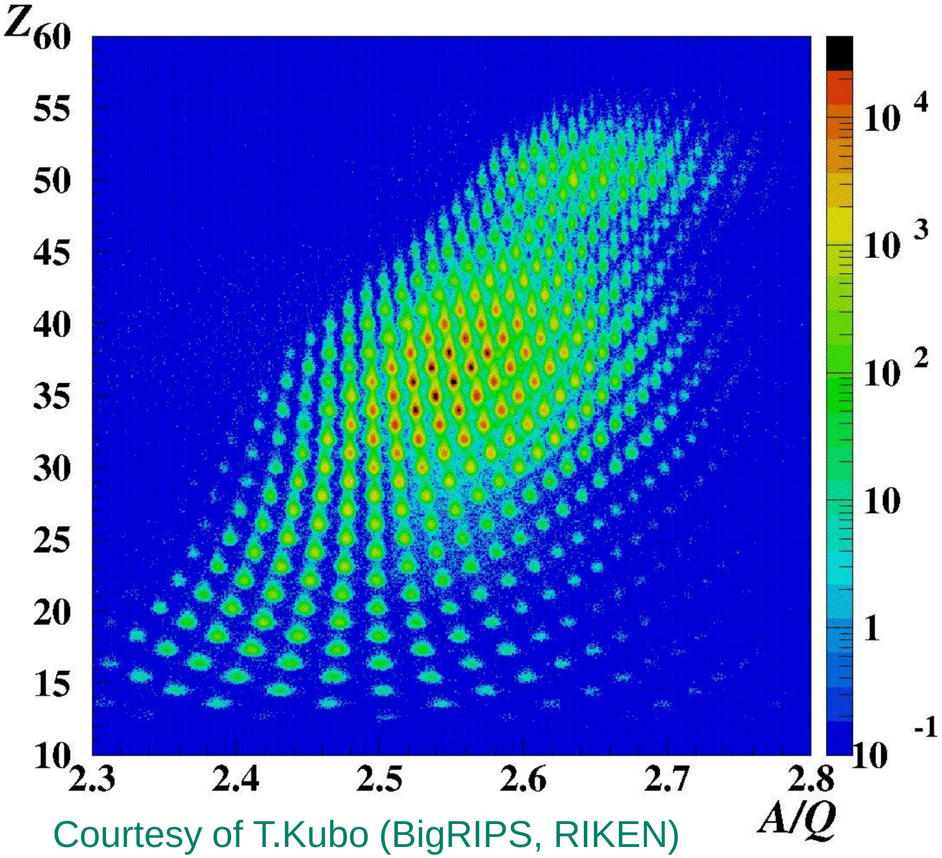
Coulomb fission

^{238}U + Be (7mm) at 345 MeV/u

^{238}U + Pb (1.5 mm) at 345 MeV/u

Be target

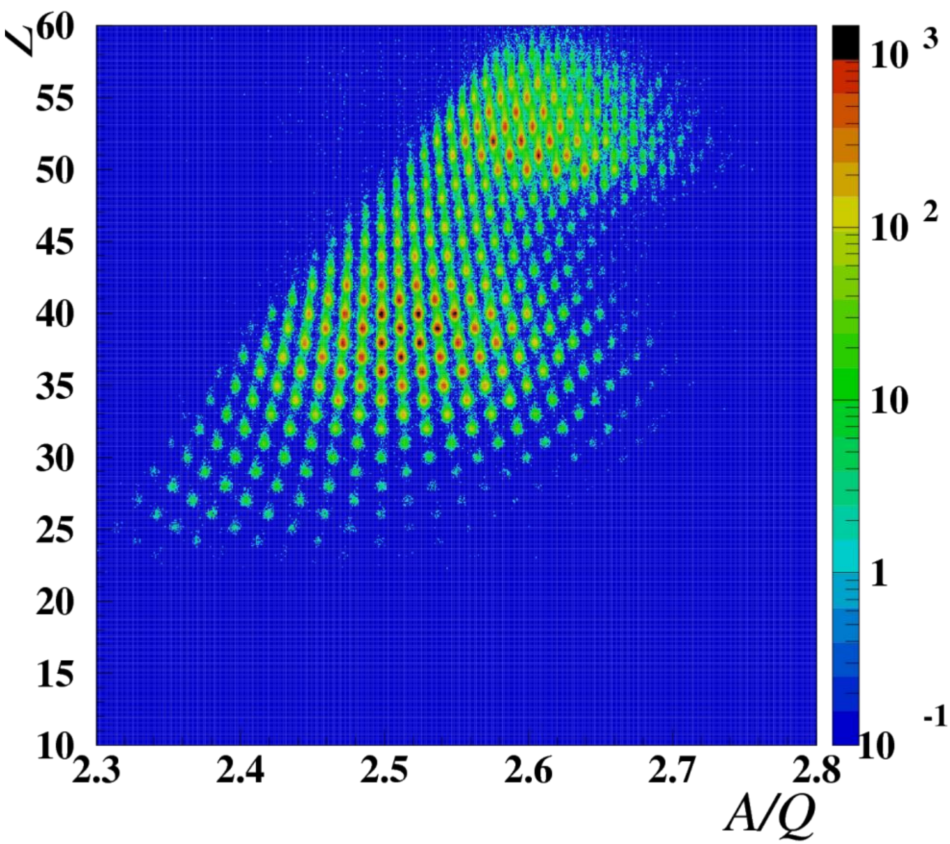
Bρ = 7.249 Tm



Courtesy of T.Kubo (BigRIPS, RIKEN)

Pb target

Bρ = 6.992 Tm



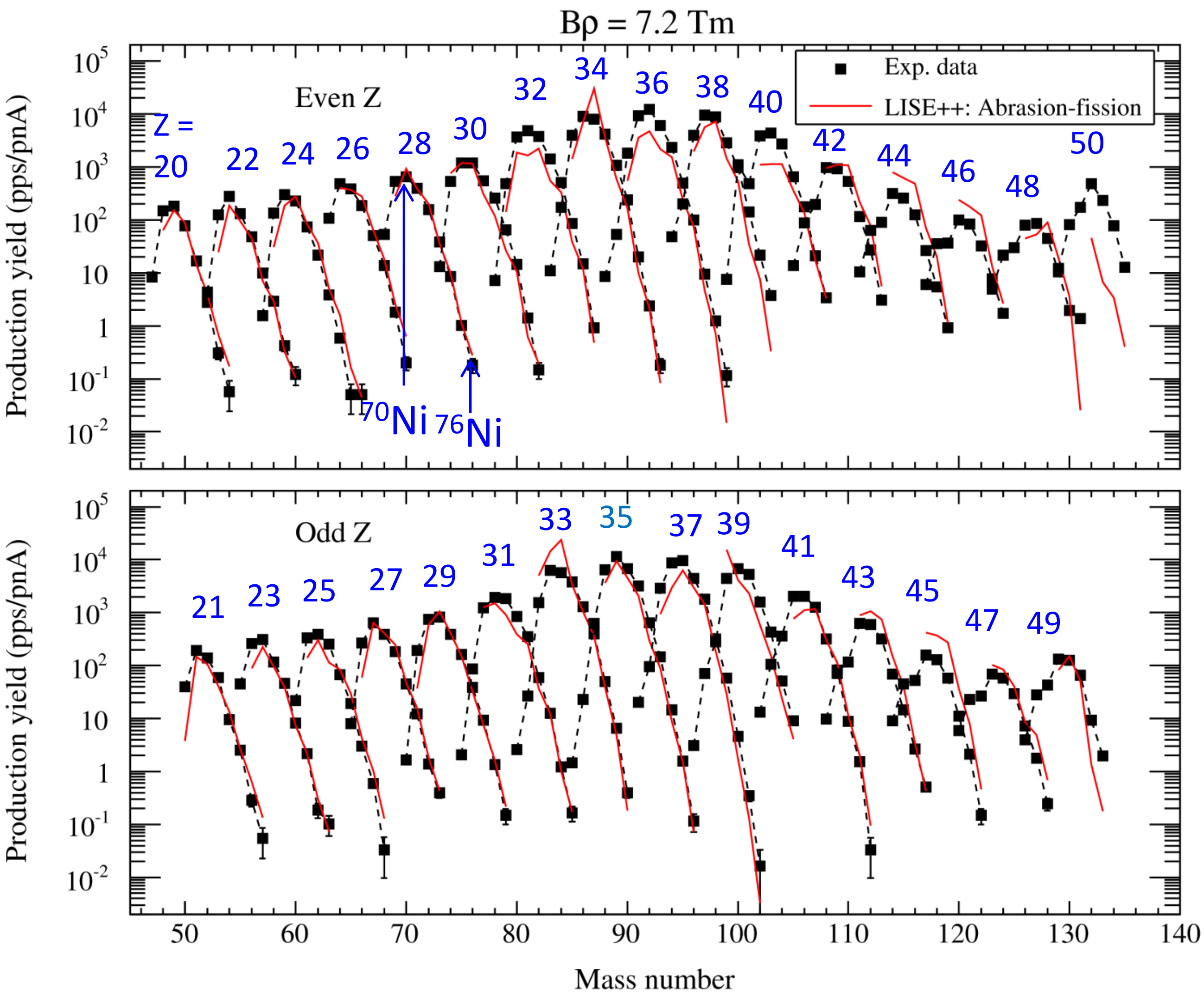
Production rates by ^{238}U + Be(7mm) at $B\rho = 7.249$ Tm

LISE^{++} : Cross Sections & Kinematics & Separation

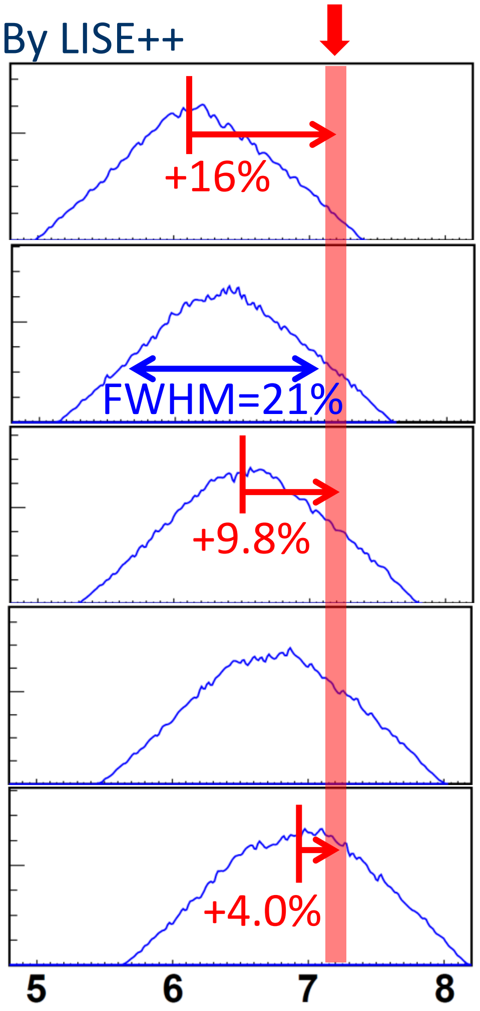
1 setting, no energy degraders used

$B\rho = 7.2$ Tm ± 1%

Fairly good reproduction



By LISE++

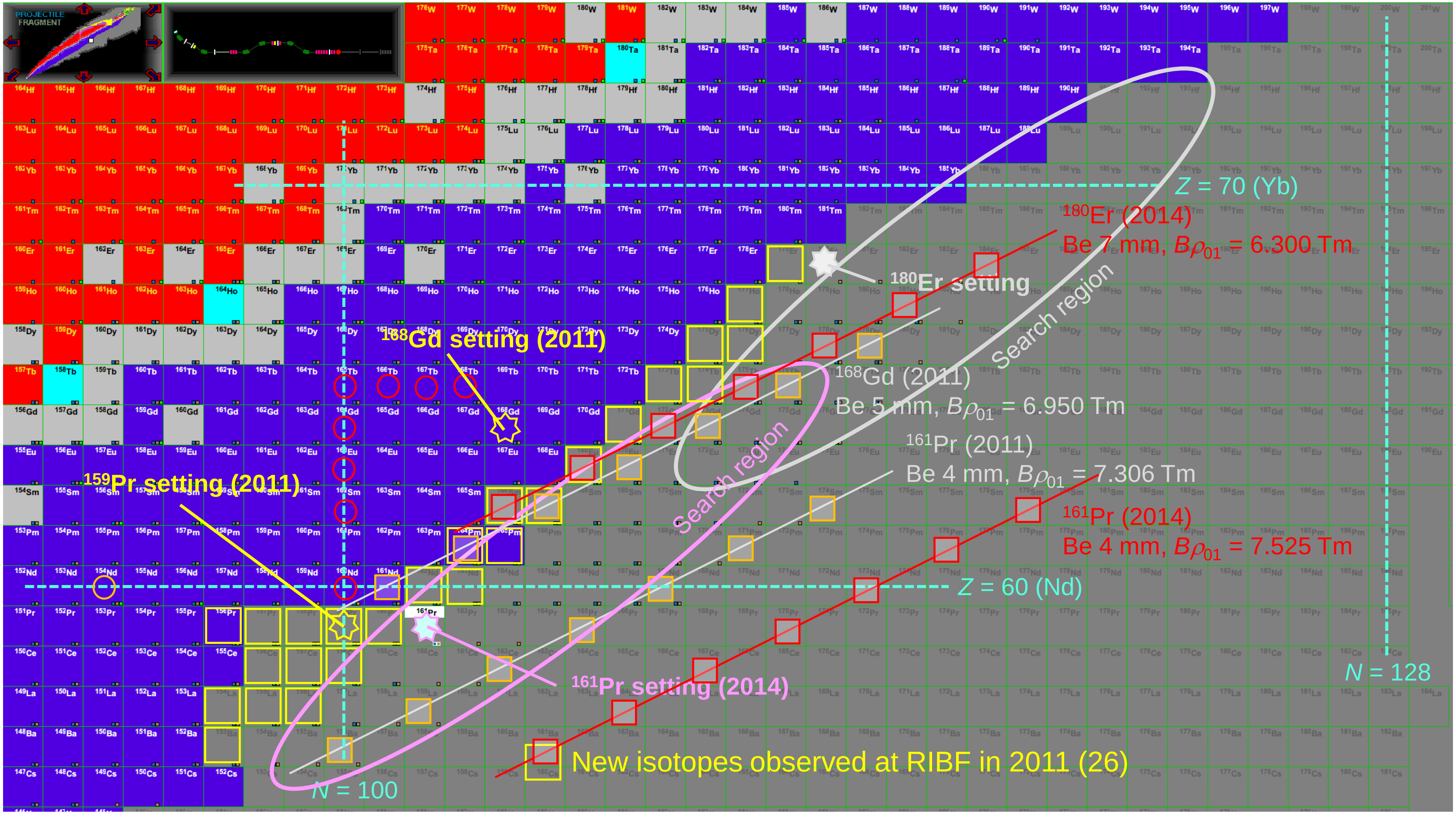


Courtesy of T.Kubo (BigRIPS, RIKEN)

Search region of the new isotope search experiment

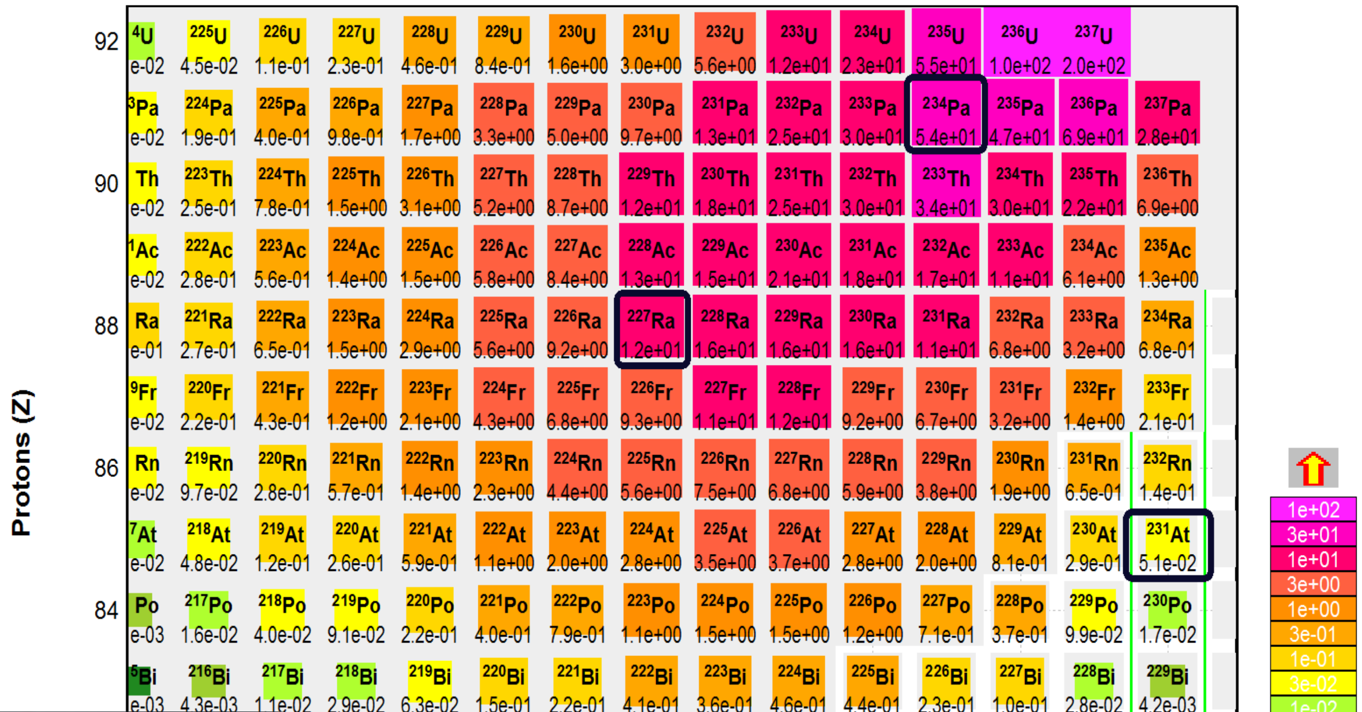
2 settings: ^{161}Pr setting and ^{180}Er setting

- ○ Selected isomers for isomer tagging among new isomers in 2011
- ○ Known isomers used for isomer tagging in 2011, 2013



Based on GSI & RIKEN experimental data

New Reaction Mechanism Settings for the 2014 experiment



Fission channel cross-sections

ABRASION-ABLATION - ^{238}U + Be

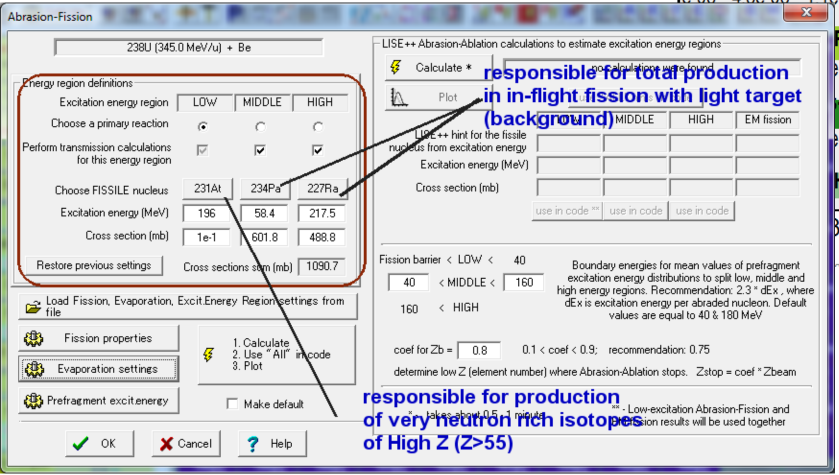
Excit.Energy Method:< 2 >; <E*>:27.0*dA MeV Sigma:13.00; No Intrinsic Thermalization

NP=32; SE:"DB0+Cal2" Density:"auto" GeomCor:"Off" TunIg:"auto" ^{Fis}Bar=#0 Bar^{Fac}=1.10 Modes=1010 1000 110

92	4U e-02	^{225}U 4.5e-02	^{226}U 1.1e-01	^{227}U 2.3e-01	^{228}U 4.6e-01	^{229}U 8.4e-01	^{230}U 1.6e+00	^{231}U 3.0e+00	^{232}U 5.6e+00	^{233}U 1.2e+01	^{234}U 2.3e+01	^{235}U 5.5e+01	^{236}U 1.0e+02	^{237}U 2.0e+02	
	3Pa e-02	^{224}Pa 1.9e-01	^{225}Pa 4.0e-01	^{226}Pa 9.8e-01	^{227}Pa 1.7e+00	^{228}Pa 3.3e+00	^{229}Pa 5.0e+00	^{230}Pa 9.7e+00	^{231}Pa 1.3e+01	^{232}Pa 2.5e+01	^{233}Pa 3.0e+01	^{234}Pa 5.4e+01	^{235}Pa 4.7e+01	^{236}Pa 6.9e+01	^{237}Pa 2.8e+01
90	Th e-02	^{223}Th 2.5e-01	^{224}Th 7.8e-01	^{225}Th 1.5e+00	^{226}Th 3.1e+00	^{227}Th 5.2e+00	^{228}Th 8.7e+00	^{229}Th 1.2e+01	^{230}Th 1.8e+01	^{231}Th 2.5e+01	^{232}Th 3.0e+01	^{233}Th 3.4e+01	^{234}Th 3.0e+01	^{235}Th 2.2e+01	^{236}Th 6.9e+00
	1Ac e-02	^{222}Ac 2.8e-01	^{223}Ac 5.6e-01	^{224}Ac 1.4e+00	^{225}Ac 1.5e+00	^{226}Ac 5.8e+00	^{227}Ac 8.4e+00	^{228}Ac 1.3e+01	^{229}Ac 1.5e+01	^{230}Ac 2.1e+01	^{231}Ac 1.8e+01	^{232}Ac 1.7e+01	^{233}Ac 1.1e+01	^{234}Ac 6.1e+00	^{235}Ac 1.3e+00
88	Ra e-01	^{221}Ra 2.7e-01	^{222}Ra 6.5e-01	^{223}Ra 1.5e+00	^{224}Ra 2.9e+00	^{225}Ra 5.6e+00	^{226}Ra 9.2e+00	^{227}Ra 1.2e+01	^{228}Ra 1.6e+01	^{229}Ra 1.6e+01	^{230}Ra 1.6e+01	^{231}Ra 1.1e+01	^{232}Ra 6.8e+00	^{233}Ra 3.2e+00	^{234}Ra 6.8e-01
	9Fr e-02	^{220}Fr 2.2e-01	^{221}Fr 4.3e-01	^{222}Fr 1.2e+00	^{223}Fr 2.1e+00	^{224}Fr 4.3e+00	^{225}Fr 6.8e+00	^{226}Fr 9.3e+00	^{227}Fr 1.1e+01	^{228}Fr 1.2e+01	^{229}Fr 9.2e+00	^{230}Fr 6.7e+00	^{231}Fr 3.2e+00	^{232}Fr 1.4e+00	^{233}Fr 2.1e-01
86	Rn e-02	^{219}Rn 9.7e-02	^{220}Rn 2.8e-01	^{221}Rn 5.7e-01	^{222}Rn 1.4e+00	^{223}Rn 2.3e+00	^{224}Rn 4.4e+00	^{225}Rn 5.6e+00	^{226}Rn 7.5e+00	^{227}Rn 6.8e+00	^{228}Rn 5.9e+00	^{229}Rn 3.8e+00	^{230}Rn 1.9e+00	^{231}Rn 6.5e-01	^{232}Rn 1.4e-01
	7At e-02	^{218}At 4.8e-02	^{219}At 1.2e-01	^{220}At 2.6e-01	^{221}At 5.9e-01	^{222}At 1.1e+00	^{223}At 2.0e+00	^{224}At 2.8e+00	^{225}At 3.5e+00	^{226}At 3.7e+00	^{227}At 2.8e+00	^{228}At 2.0e+00	^{229}At 8.1e-01	^{230}At 2.9e-01	^{231}At 5.1e-02
84	Po e-03	^{217}Po 1.6e-02	^{218}Po 4.0e-02	^{219}Po 9.1e-02	^{220}Po 2.2e-01	^{221}Po 4.0e-01	^{222}Po 7.9e-01	^{223}Po 1.1e+00	^{224}Po 1.5e+00	^{225}Po 1.5e+00	^{226}Po 1.2e+00	^{227}Po 7.1e-01	^{228}Po 3.7e-01	^{229}Po 9.9e-02	^{230}Po 1.7e-02
	5Bi e-03	^{216}Bi 4.3e-03	^{217}Bi 1.1e-02	^{218}Bi 2.9e-02	^{219}Bi 6.3e-02	^{220}Bi 1.5e-01	^{221}Bi 2.2e-01	^{222}Bi 4.1e-01	^{223}Bi 3.6e-01	^{224}Bi 4.6e-01	^{225}Bi 4.4e-01	^{226}Bi 2.3e-01	^{227}Bi 1.0e-01	^{228}Bi 2.8e-02	^{229}Bi 4.2e-03
			Pb -03	^{217}Pb 1.1e-02	^{218}Pb 2.5e-02	^{219}Pb 5.1e-02	^{220}Pb 7.2e-02	^{221}Pb 1.3e-01	^{222}Pb 1.7e-01	^{223}Pb 1.4e-01	^{224}Pb 1.3e-01	^{225}Pb 6.7e-02	^{226}Pb 3.7e-02	^{227}Pb 7.3e-03	^{228}Pb 1.3e-03
			Tl -03	^{216}Tl 5.9e-03	^{217}Tl 8.0e-03	^{218}Tl 1.9e-02	^{219}Tl 3.0e-02	^{220}Tl 2.9e-02	^{221}Tl 3.9e-02	^{222}Tl 2.8e-02	^{223}Tl 2.5e-02	^{224}Tl 1.3e-02	^{225}Tl 7.3e-03	^{226}Tl 1.4e-03	^{227}Tl 2.5e-04
			Hg	^{215}Hg	^{216}Hg	^{217}Hg	^{218}Hg	^{219}Hg	^{220}Hg	^{221}Hg	^{222}Hg	^{223}Hg	^{224}Hg	^{225}Hg	^{226}Hg
			34		136		138		140		142		144		146

Protons (Z)

Neutrons (N)



Abrasion-Fission

238U (345.0 MeV/u) + Be

Energy region definitions

Excitation energy region	LOW	MIDDLE	HIGH
Choose a primary reaction	●	○	○
Perform transmission calculations for this energy region	☑	☑	☑
Choose FISSILE nucleus	231At	234Pa	227Ra
Excitation energy (MeV)	196	58.4	217.5
Cross section (mb)	1e-1	601.8	488.8

Restore previous settings

Cross sections sum (mb) 1090.7

Load Fission, Evaporation, Excit.Energy Region settings from file

Fission properties

Evaporation settings

Prefragment excit.energy

1. Calculate
2. Use "All" in code
3. Plot

☐ Make default

LISE++ Abrasion-Ablation calculations to estimate excitation energy regions

Calculate *

no calculations were found

Plot

	LOW	MIDDLE	HIGH	EM fission
LISE++ hint for the fissile nucleus from excitation energy				
Excitation energy (MeV)				
Cross section (mb)				
	use in code **	use in code	use in code	

Fission barrier < LOW < 40

40 < MIDDLE < 160

160 < HIGH

Boundary energies for mean values of prefragment excitation energy distributions to split low, middle and high energy regions. Recommendation: 2.3 * dEx , where dEx is excitation energy per abraded nucleon. Default values are equal to 40 & 180 MeV

coef for Zb = 0.8 0.1 < coef < 0.9; recommendation: 0.75

determine low Z (element number) where Abrasion-Ablation stops. Zstop = coef * Zbeam

* - takes about 0.5 - 1 minute

** - Low-excitation Abrasion-Fission and EM fission results will be used together

responsible for total production in in-flight fission with light target (background)

responsible for production of very neutron rich isotopes of High Z (Z>55)

^{161}Pr

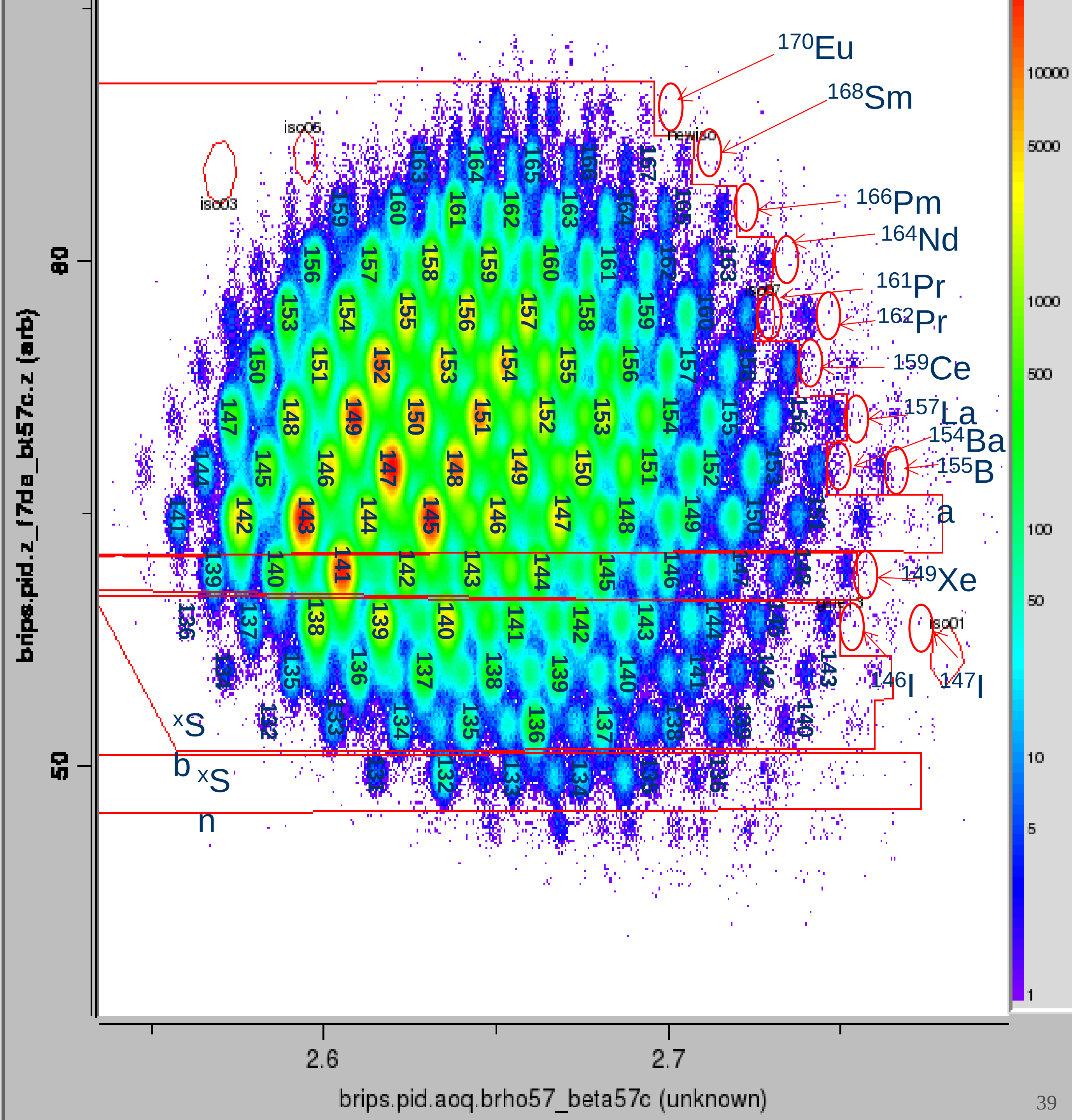
No attenuator,
I=10-15 pnA

PID plot for 161Pr Setting

Accumulation of runs:
1023-1037, 1043-1092
Total : 54.8 hours

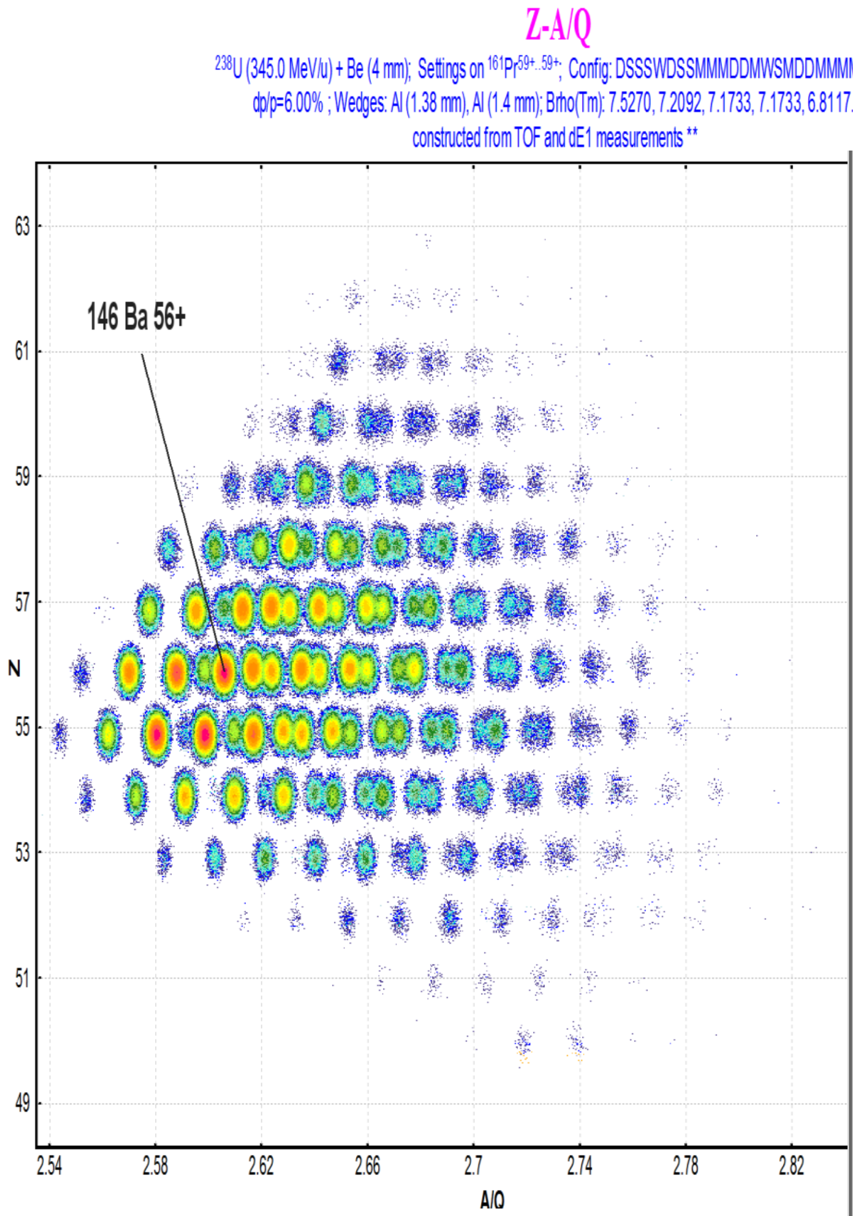
PRELIMINARY for 2014

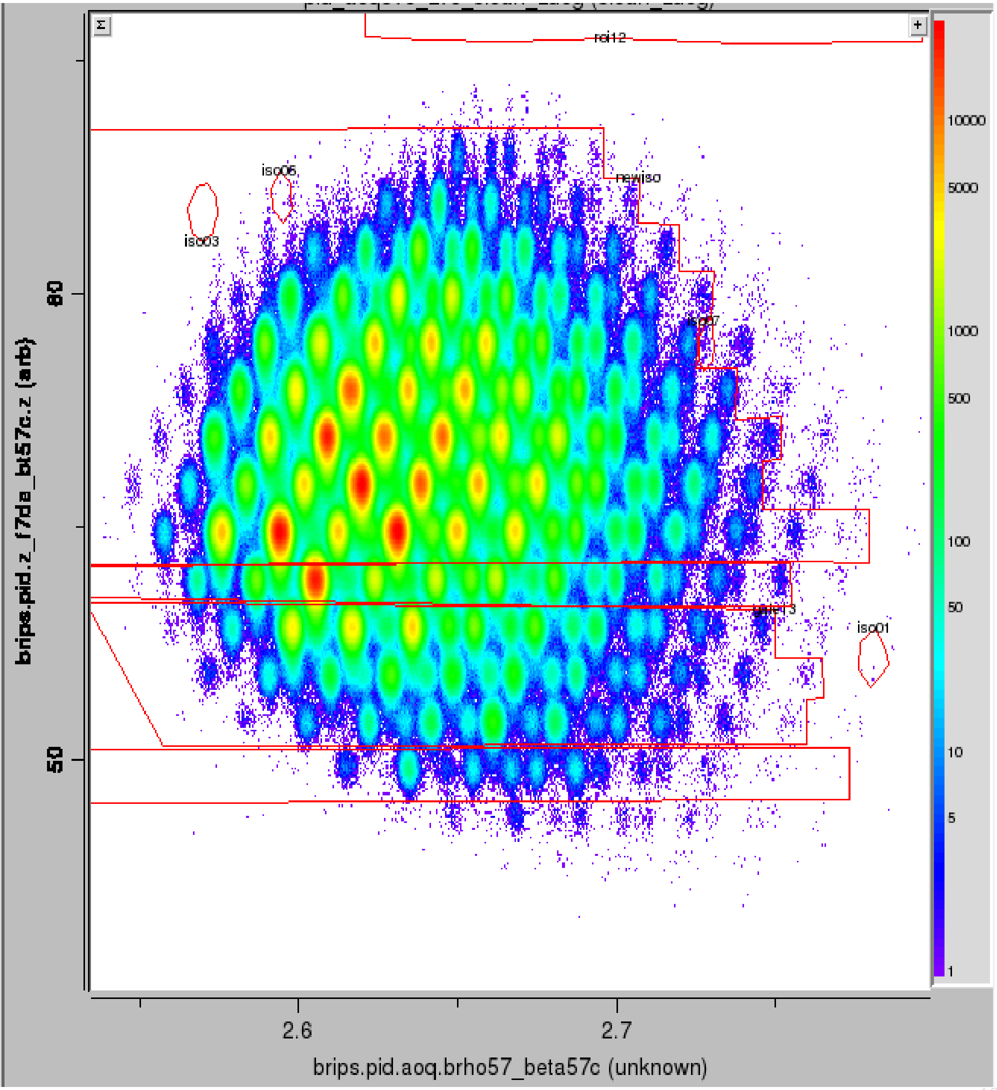
New Isotope : 13 nuclides



BigRIPS group courtesy

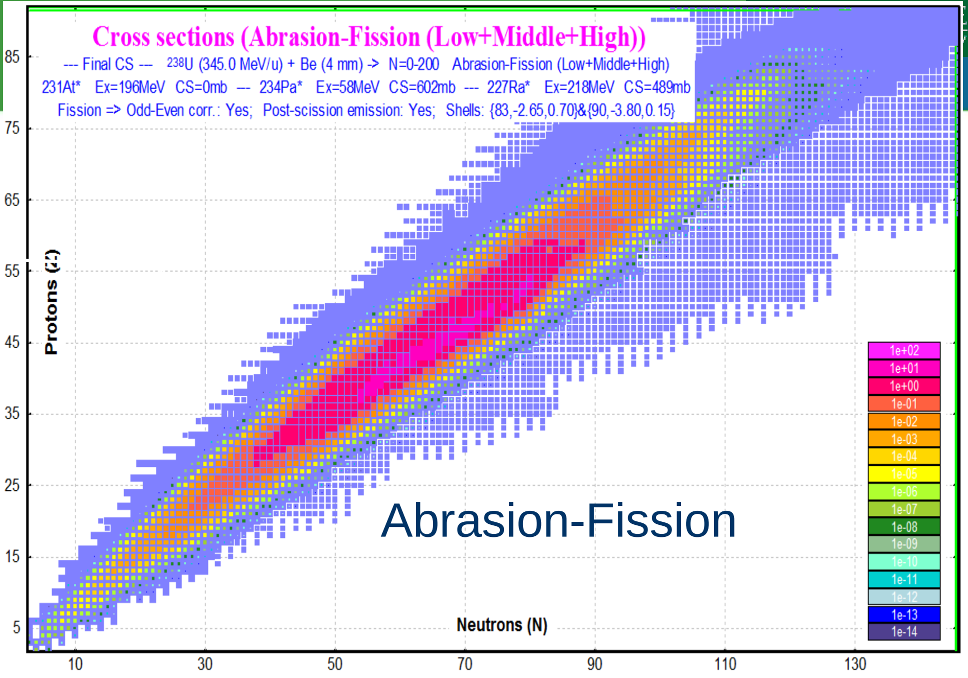
^{161}Pr : LISE^{++} vs. Experiment (using wedge)



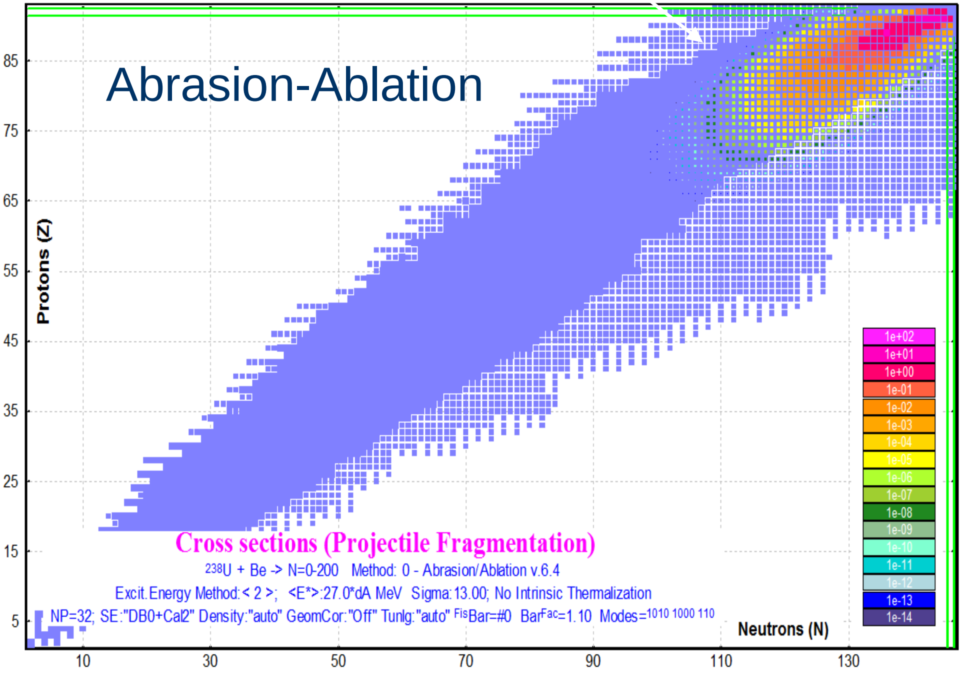


3.3 Competition between A-Fission & P-Fragmentation

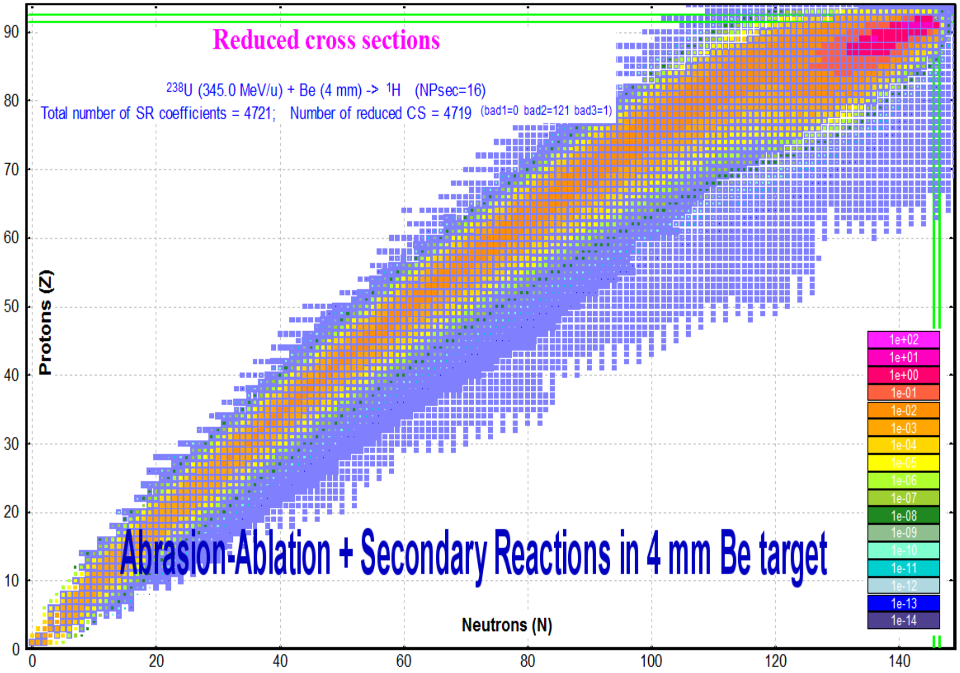
Abrasion-Fission
vs.
Projectile Fragmentation (Abrasion-Ablation)



Abrasion-Fission

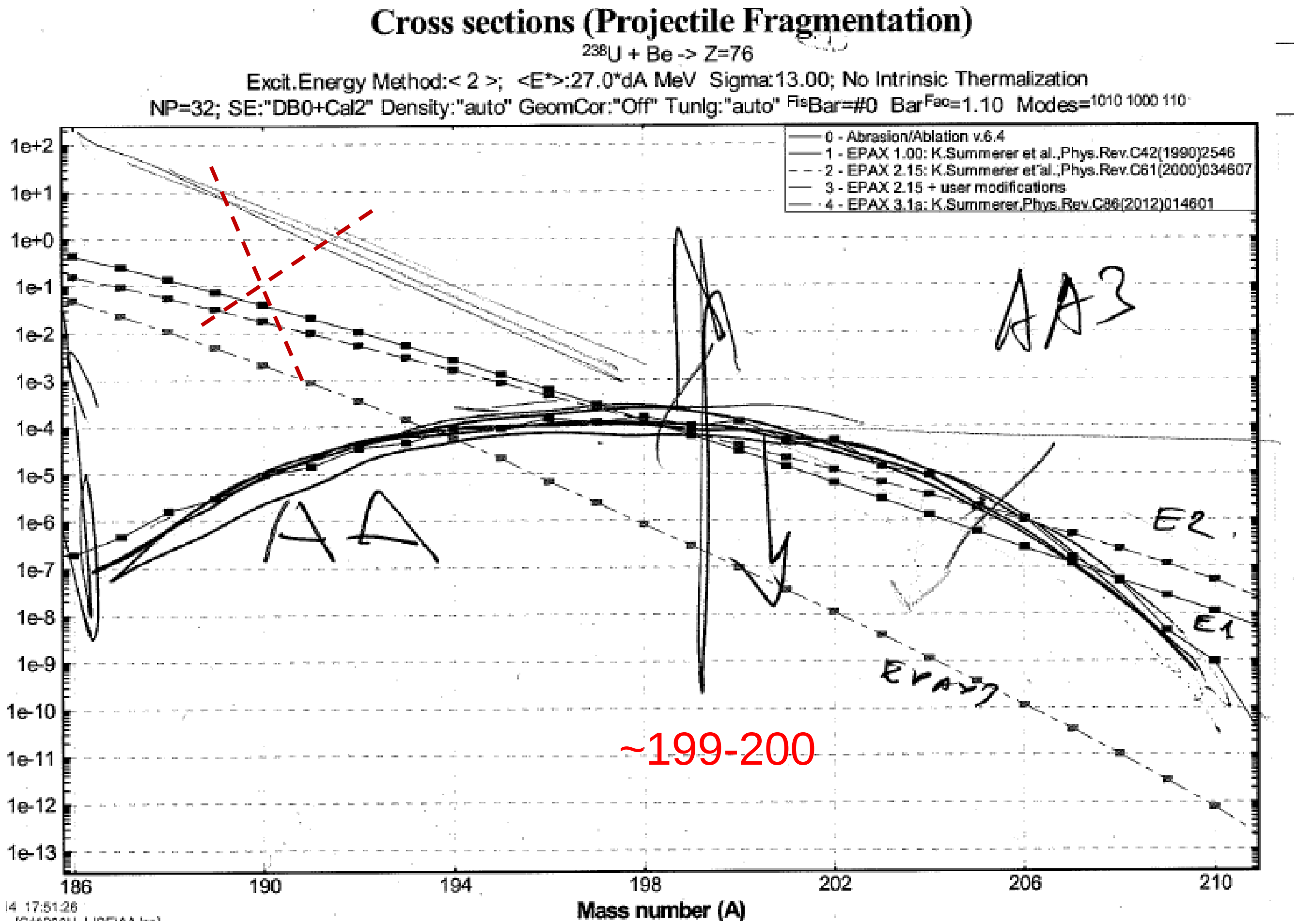


Abrasion-Ablation



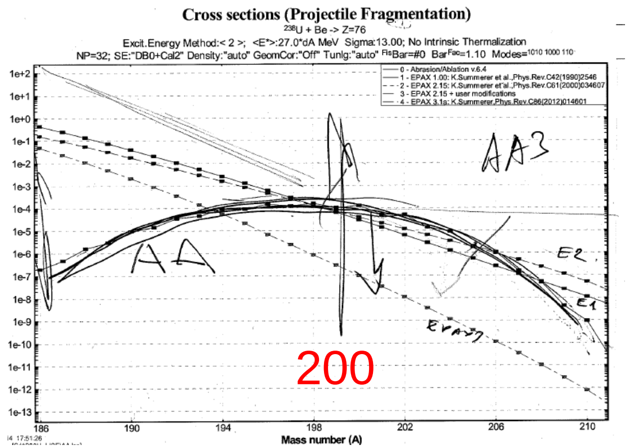
Abrasion-Ablation + Secondary Reactions in 4 mm Be target

Projectile fragmentation : Z=76 fragments

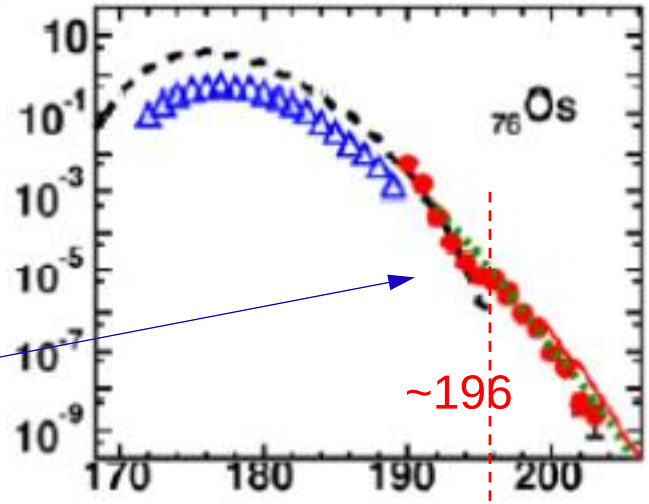


~199-200

Projectile fragmentation : Z=76 fragments

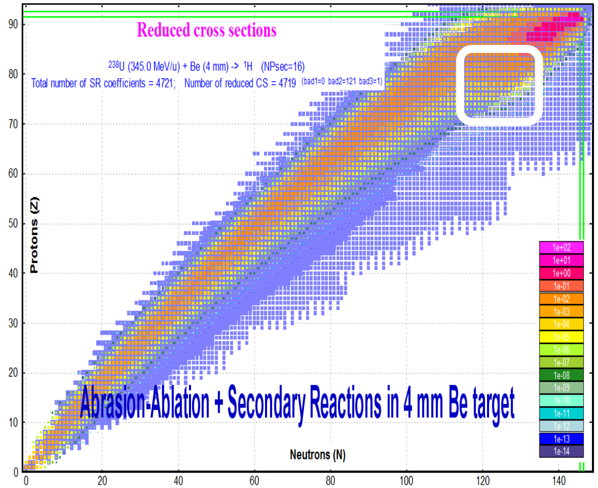


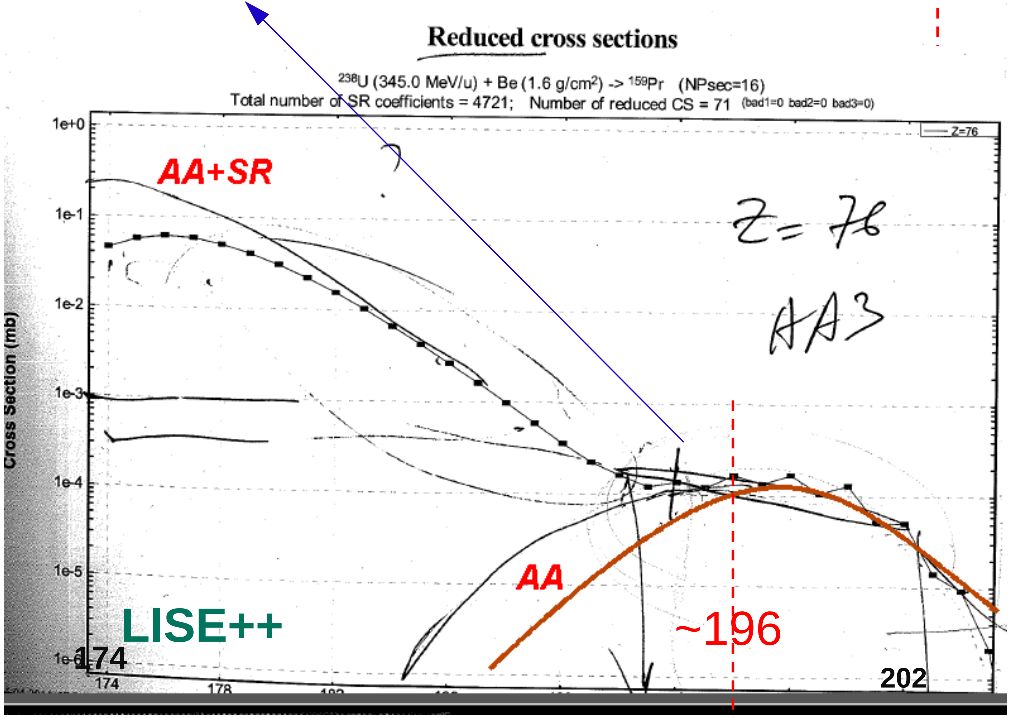
J.Kurcewicz et al., PLB 717 (2012) 371



???

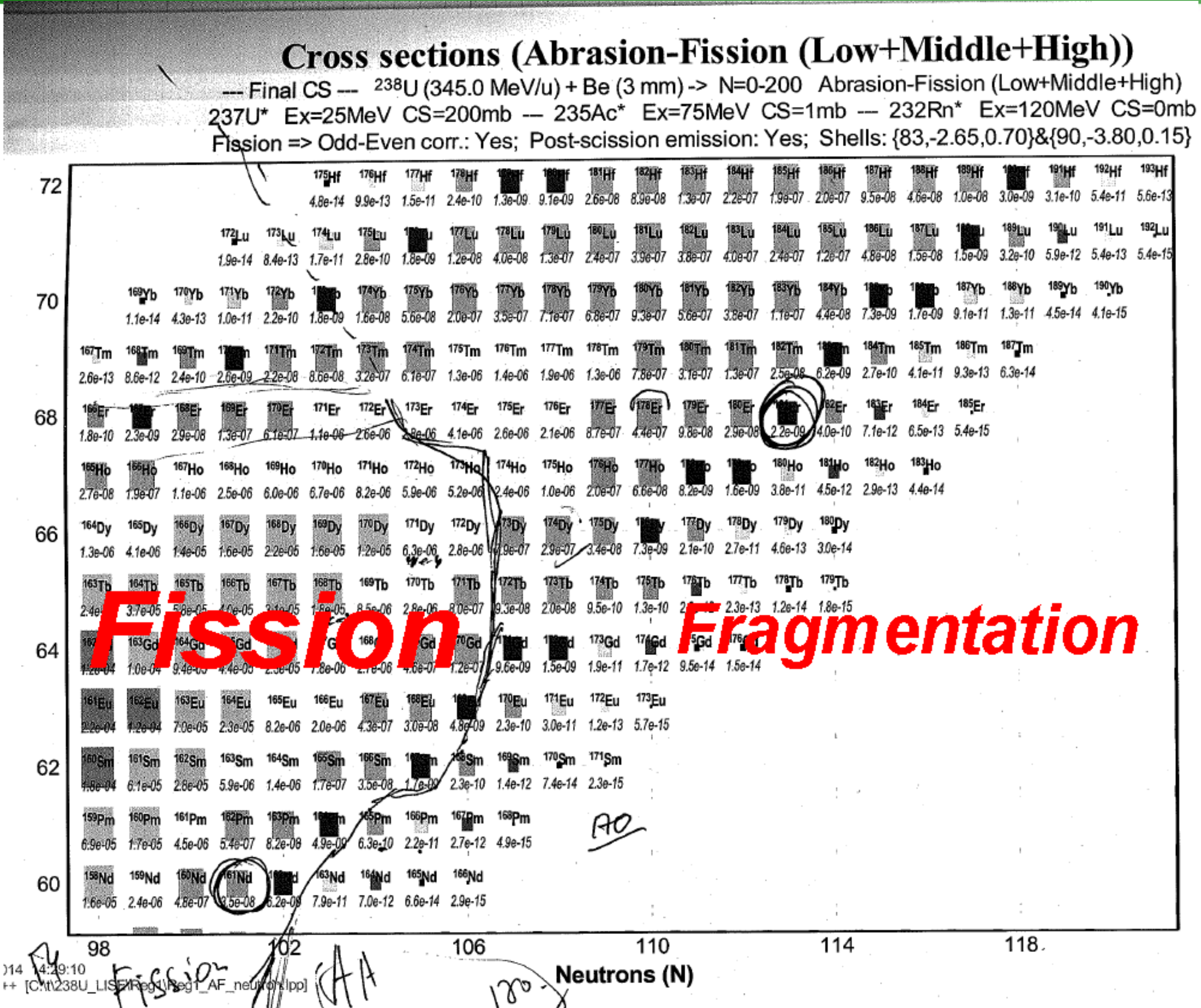
Should be the plateau in experiment!!





We need primary cross sections with thin target!! E9063 @ MSU

Comparison LISE^{++} AF & AA cross sections



Cross sections (Abrasion-Fission (Low+Middle+High))

--- Final CS --- ^{238}U (345.0 MeV/u) + Be (3 mm) -> N=0-200 Abrasion-Fission (Low+Middle+High)
237U* Ex=25MeV CS=200mb --- 235Ac* Ex=75MeV CS=1mb --- 232Rn* Ex=120MeV CS=0mb
Fission => Odd-Even corr.: Yes; Post-scission emission: Yes; Shells: {83,-2.65,0.70}&{90,-3.80,0.15}

Z	N=98	99	100	101	102	103	104	105	106	107	108	109
72						^{175}Hf 4.8e-14	^{176}Hf 9.9e-13	^{177}Hf 1.5e-11	^{178}Hf 2.4e-10	Hf 1.3e-09	Hf 9.1e-09	^{181}Hf 2.6e-08
71				^{172}Lu 1.9e-14	^{173}Lu 8.4e-13	^{174}Lu 1.7e-11	^{175}Lu 2.8e-10	Lu 1.8e-09	^{177}Lu 1.2e-08	^{178}Lu 4.0e-08	^{179}Lu 1.3e-07	^{180}Lu 2.4e-07
70		^{169}Yb 1.1e-14	^{170}Yb 4.3e-13	^{171}Yb 1.0e-11	^{172}Yb 2.2e-10	Yb 1.8e-09	^{174}Yb 1.6e-08	^{175}Yb 5.6e-08	^{176}Yb 2.0e-07	^{177}Yb 3.5e-07	^{178}Yb 7.1e-07	^{179}Yb 6.8e-07
69	^{167}Tm 2.6e-13	^{168}Tm 8.6e-12	^{169}Tm 2.4e-10	Tm 2.6e-09	^{171}Tm 2.2e-08	^{172}Tm 8.6e-08	^{173}Tm 3.2e-07	^{174}Tm 6.1e-07	^{175}Tm 1.3e-06	^{176}Tm 1.4e-06	^{177}Tm 1.9e-06	^{178}Tm 1.3e-06
68	^{166}Er 1.8e-10	Er 2.3e-09	^{168}Er 2.9e-08	^{169}Er 1.3e-07	^{170}Er 6.1e-07	^{171}Er 1.1e-06	^{172}Er 2.6e-06	^{173}Er 2.8e-06	^{174}Er 4.1e-06	^{175}Er 2.6e-06	^{176}Er 2.1e-06	^{177}Er 8.7e-07
67	^{165}Ho 2.7e-08	^{166}Ho 1.9e-07	^{167}Ho 1.1e-06	^{168}Ho 2.5e-06	^{169}Ho 6.0e-06	^{170}Ho 6.7e-06	^{171}Ho 8.2e-06	^{172}Ho 5.9e-06	^{173}Ho 5.2e-06	^{174}Ho 2.4e-06	^{175}Ho 1.0e-06	^{176}Ho 2.0e-07
66	^{164}Dy 1.3e-06	^{165}Dy 4.1e-06	^{166}Dy 1.4e-05	^{167}Dy 1.6e-05	^{168}Dy 2.2e-05	^{169}Dy 1.6e-05	^{170}Dy 1.2e-05	^{171}Dy 6.3e-06	^{172}Dy 2.8e-06	Dy [illegible].9e-07	^{174}Dy 2.9e-07	^{175}Dy 3.4e-08
65	^{163}Tb 2.4e[illegible]	^{164}Tb 3.7e-05	^{165}Tb 5.8e-05	^{166}Tb 4.0e-05	^{167}Tb 3.1e-05	^{168}Tb 1.5e-05	^{169}Tb 8.5e-06	^{170}Tb 2.8e-06	^{171}Tb 8.0e-07	^{172}Tb 9.3e-08	^{173}Tb 2.0e-08	^{174}Tb 9.5e-10
64	Gd 1.2e-04	^{163}Gd 1.0e-04	^{164}Gd 9.4e-05	Gd 4.4e-05	Gd 2.5e-05	Gd 7.8e-06	Gd 2.7e-06	Gd 4.6e-07	Gd 1.2e-07	Gd 9.6e-09	Gd 1.5e-09	^{173}Gd 1.9e-11
63	^{161}Eu 2.2e-04	^{162}Eu 1.2e-04	^{163}Eu 7.0e-05	^{164}Eu 2.3e-05	^{165}Eu 8.2e-06	^{166}Eu 2.0e-06	^{167}Eu 4.3e-07	^{168}Eu 3.0e-08	Eu 4.8e-09	^{170}Eu 2.3e-10	^{171}Eu 3.0e-11	^{172}Eu 1.2e-13
62	^{160}Sm 4.8e-04	^{161}Sm 6.1e-05	^{162}Sm 2.8e-05	^{163}Sm 5.9e-06	^{164}Sm 1.4e-06	^{165}Sm 1.7e-07	^{166}Sm 3.5e-08	Sm 1.7e-09	^{168}Sm 2.3e-10	^{169}Sm 1.4e-12	^{170}Sm 7.4e-14	^{171}Sm 2.3e-15
61	^{159}Pm 6.9e-05	^{160}Pm 1.7e-05	^{161}Pm 4.5e-06	^{162}Pm 5.4e-07	^{163}Pm 8.2e-08	Pm 4.9e-09	^{165}Pm 6.3e-10	^{166}Pm 2.2e-11	^{167}Pm 2.7e-12	^{168}Pm 4.9e-15		
60	^{158}Nd 1.6e-05	^{159}Nd 2.4e-06	^{160}Nd 4.8e-07	^{161}Nd 3.5e-08	Nd 6.2e-09	^{163}Nd 7.9e-11	^{164}Nd 7.0e-12	^{165}Nd 6.6e-14	^{166}Nd 2.9e-15			

Z	N=110	111	112	113	114	115	116	117	118	119	120	121
72	^{182}Hf 8.9e-08	^{183}Hf 1.3e-07	^{184}Hf 2.2e-07	^{185}Hf 1.9e-07	^{186}Hf 2.0e-07	^{187}Hf 9.5e-08	^{188}Hf 4.6e-08	^{189}Hf 1.0e-08	Hf 3.0e-09	^{191}Hf 3.1e-10	^{192}Hf 5.4e-11	^{193}Hf 5.6e-13
71	^{181}Lu 3.9e-07	^{182}Lu 3.8e-07	^{183}Lu 4.0e-07	^{184}Lu 2.4e-07	^{185}Lu 1.2e-07	^{186}Lu 4.8e-08	^{187}Lu 1.5e-08	Lu 1.5e-09	^{189}Lu 3.2e-10	^{190}Lu 5.9e-12	^{191}Lu 5.4e-13	^{192}Lu 5.4e-15
70	^{180}Yb 9.3e-07	^{181}Yb 5.6e-07	^{182}Yb 3.8e-07	^{183}Yb 1.1e-07	^{184}Yb 4.4e-08	Yb 7.3e-09	Yb 1.7e-09	^{187}Yb 9.1e-11	^{188}Yb 1.3e-11	^{189}Yb 4.5e-14	^{190}Yb 4.1e-15	
69	^{179}Tm 7.8e-07	^{180}Tm 3.1e-07	^{181}Tm 1.3e-07	^{182}Tm 2.5e-08	Tm 6.2e-09	^{184}Tm 2.7e-10	^{185}Tm 4.1e-11	^{186}Tm 9.3e-13	^{187}Tm 6.3e-14			
68	^{178}Er 4.4e-07	^{179}Er 9.8e-08	^{180}Er 2.9e-08	Er 2.2e-09	Er 4.0e-10	^{183}Er 7.1e-12	^{184}Er 6.5e-13	^{185}Er 5.4e-15				
67	^{177}Ho 6.6e-08	Ho 8.2e-09	Ho 1.6e-09	^{180}Ho 3.8e-11	^{181}Ho 4.5e-12	^{182}Ho 2.9e-13	^{183}Ho 4.4e-14					
66	Dy 7.3e-09	^{177}Dy 2.1e-10	^{178}Dy 2.7e-11	^{179}Dy 4.6e-13	^{180}Dy 3.0e-14							
65	^{175}Tb 1.3e-10	Tb 2[illegible]	^{177}Tb 2.3e-13	^{178}Tb 1.2e-14	^{179}Tb 1.8e-15							
64	^{174}Gd 1.7e-12	Gd 9.5e-14	Gd 1.5e-14									
63	^{173}Eu 5.7e-15											

Ao

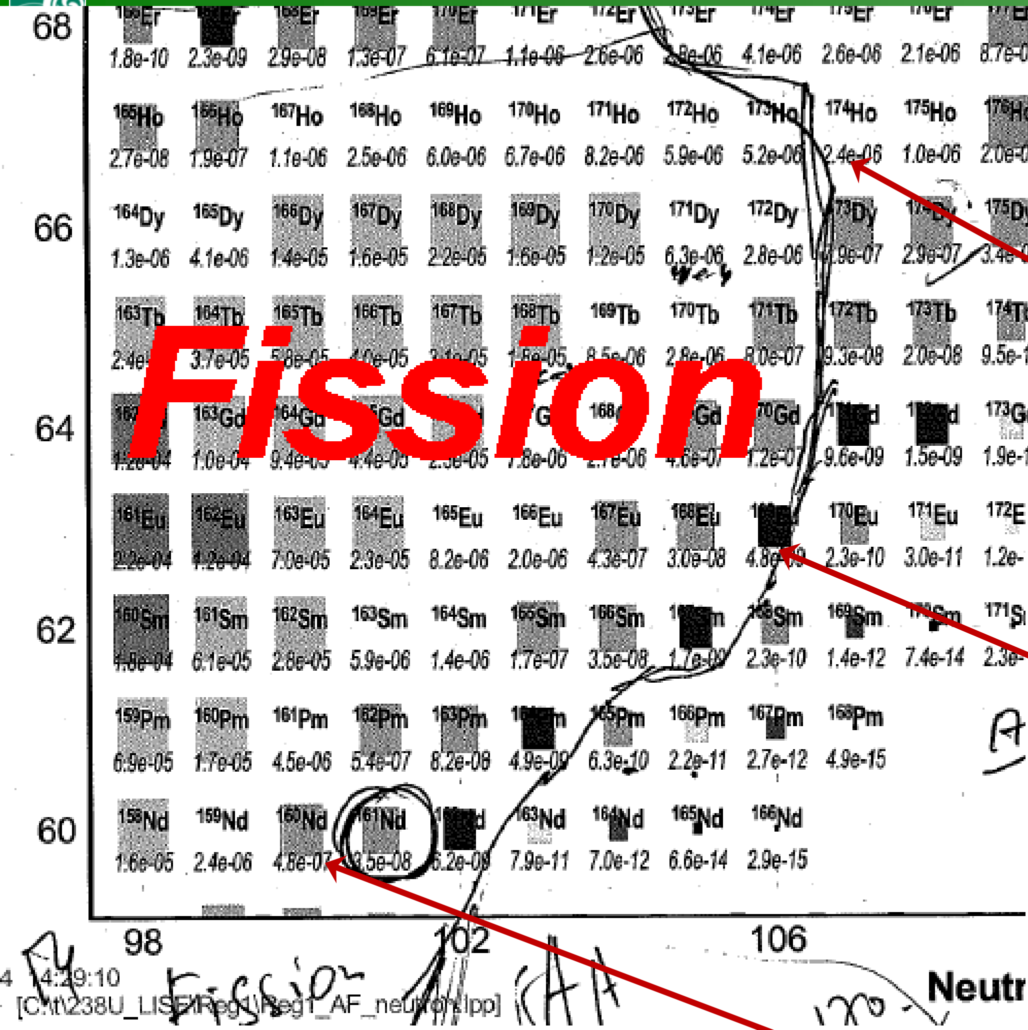
Fission

AA

120

For what reaction products do you tune your separator??

Very different kinematics of PF and AF



Fission Fr

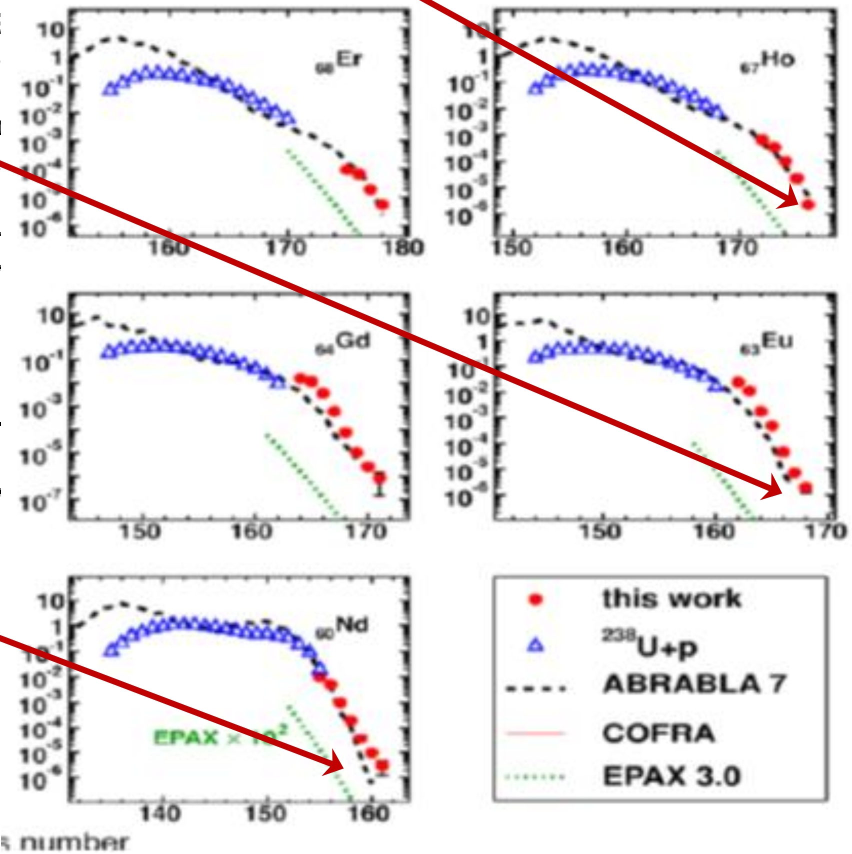
68	Er 1.8e-10	Er 2.3e-09	Er 2.9e-08	Er 1.3e-07	Er 6.1e-07	Er 1.1e-06	Er 2.6e-06	Er 2.8e-06	Er 4.1e-06	Er 2.6e-06	Er 2.1e-06	Er 8.7e-07	Er 4.4e-07	Er 9.8e-08	2.9
	^{165}Ho 2.7e-08	^{166}Ho 1.9e-07	^{167}Ho 1.1e-06	^{168}Ho 2.5e-06	^{169}Ho 6.0e-06	^{170}Ho 6.7e-06	^{171}Ho 8.2e-06	^{172}Ho 5.9e-06	^{173}Ho 5.2e-06	^{174}Ho 2.4e-06	^{175}Ho 1.0e-06	^{176}Ho 2.0e-07	^{177}Ho 6.6e-08	[illegible] 8.2e-09	1.6
66	^{164}Dy 1.3e-06	^{165}Dy 4.1e-06	^{166}Dy 1.4e-05	^{167}Dy 1.6e-05	^{168}Dy 2.2e-05	^{169}Dy 1.6e-05	^{170}Dy 1.2e-05	^{171}Dy 6.3e-06	^{172}Dy 2.8e-06	^{173}Dy 1.9e-07	^{174}Dy 2.9e-07	^{175}Dy 3.4e-08	[illegible] 7.3e-09	^{177}Dy 2.1e-10	2.7
	^{163}Tb 2.4e-	^{164}Tb 3.7e-05	^{165}Tb 5.8e-05	^{166}Tb 4.0e-05	^{167}Tb 3.1e-05	^{168}Tb 1.6e-05	^{169}Tb 8.5e-06	^{170}Tb 2.8e-06	^{171}Tb 8.0e-07	^{172}Tb 9.3e-08	^{173}Tb 2.0e-08	^{174}Tb 9.5e-10	^{175}Tb 1.3e-10	^{176}Tb [illegible]	2.3
64	[illegible] 1.2e-04	^{163}Gd 1.0e-04	^{164}Gd 9.4e-05	Gd 4.4e-05	[illegible] 2.3e-05	G 7.8e-06	^{168} 2.7e-06	Gd 4.6e-07	^{170}Gd 1.2e-07	[illegible] 9.6e-09	[illegible] 1.5e-09	^{173}Gd 1.9e-11	^{174}Gd 1.7e-12	Gd 9.5e-14	1.5
	^{161}Eu 2.2e-04	^{162}Eu 1.2e-04	^{163}Eu 7.0e-05	^{164}Eu 2.3e-05	^{165}Eu 8.2e-06	^{166}Eu 2.0e-06	^{167}Eu 4.3e-07	^{168}Eu 3.0e-08	[illegible] 4.8e-09	^{170}Eu 2.3e-10	^{171}Eu 3.0e-11	^{172}E 1.2e-			
62	^{160}Sm 1.6e-04	^{161}Sm 6.1e-05	^{162}Sm 2.8e-05	^{163}Sm 5.9e-06	^{164}Sm 1.4e-06	^{165}Sm 1.7e-07	^{166}Sm 3.5e-08	[illegible] 1.7e-09	^{168}Sm 2.3e-10	^{169}Sm 1.4e-12	^{170}Sm 7.4e-14	^{171}S 2.3e-			
	^{159}Pm 6.9e-05	^{160}Pm 1.7e-05	^{161}Pm 4.5e-06	^{162}Pm 5.4e-07	^{163}Pm 8.2e-08	[illegible] 4.9e-09	^{165}Pm 6.3e-10	^{166}Pm 2.2e-11	^{167}Pm 2.7e-12	^{168}Pm 4.9e-15					
60	^{158}Nd 1.6e-05	^{159}Nd 2.4e-06	^{160}Nd 4.8e-07	^{161}Nd 3.5e-08	[illegible] 6.2e-09	^{163}Nd 7.9e-11	^{164}Nd 7.0e-12	^{165}Nd 6.6e-14	^{166}Nd 2.9e-15						
	98				102				106						

Neutr

4 14:29:10
[C:\t\238U_LIS[illegible]Reg1\Reg1_AF_neu[illegible]lpp]

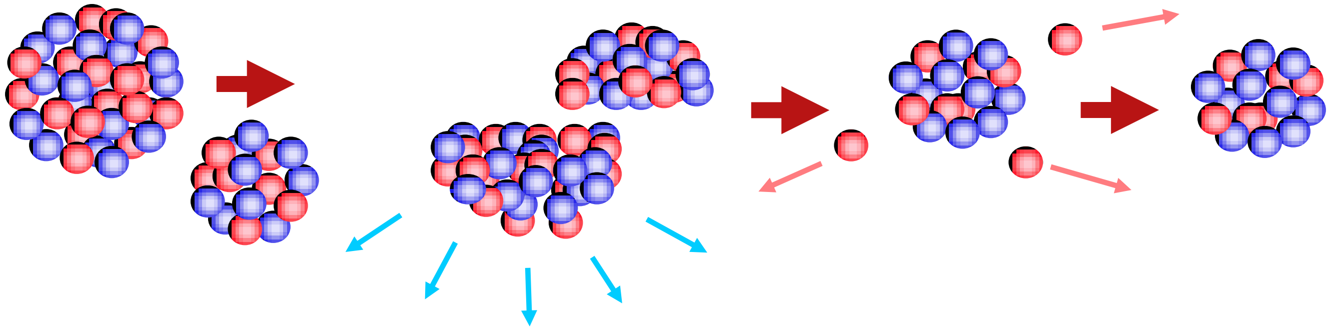
Fission

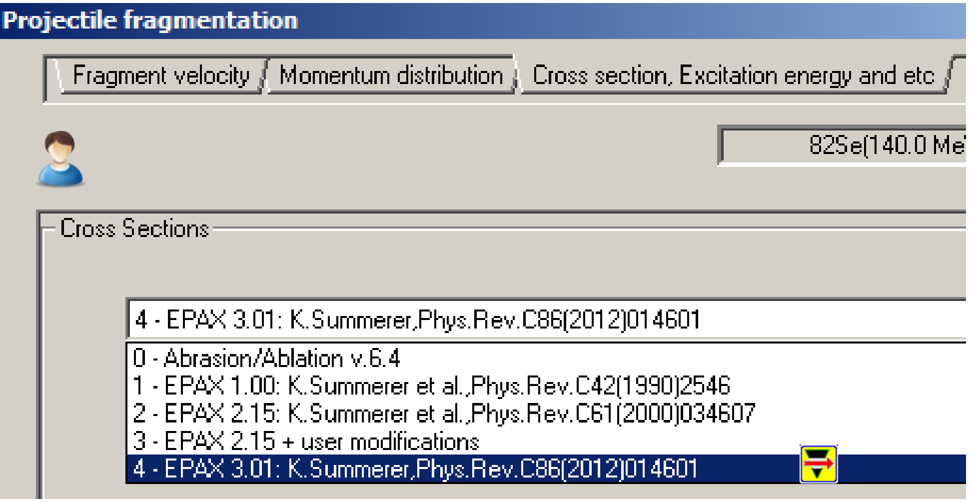
120



4. Projectile Fragmentation

Projectile fragmentation





82Se(140.0 Me

4 - EPAX 3.01: K.Summerer,Phys.Rev.C86(2012)014601

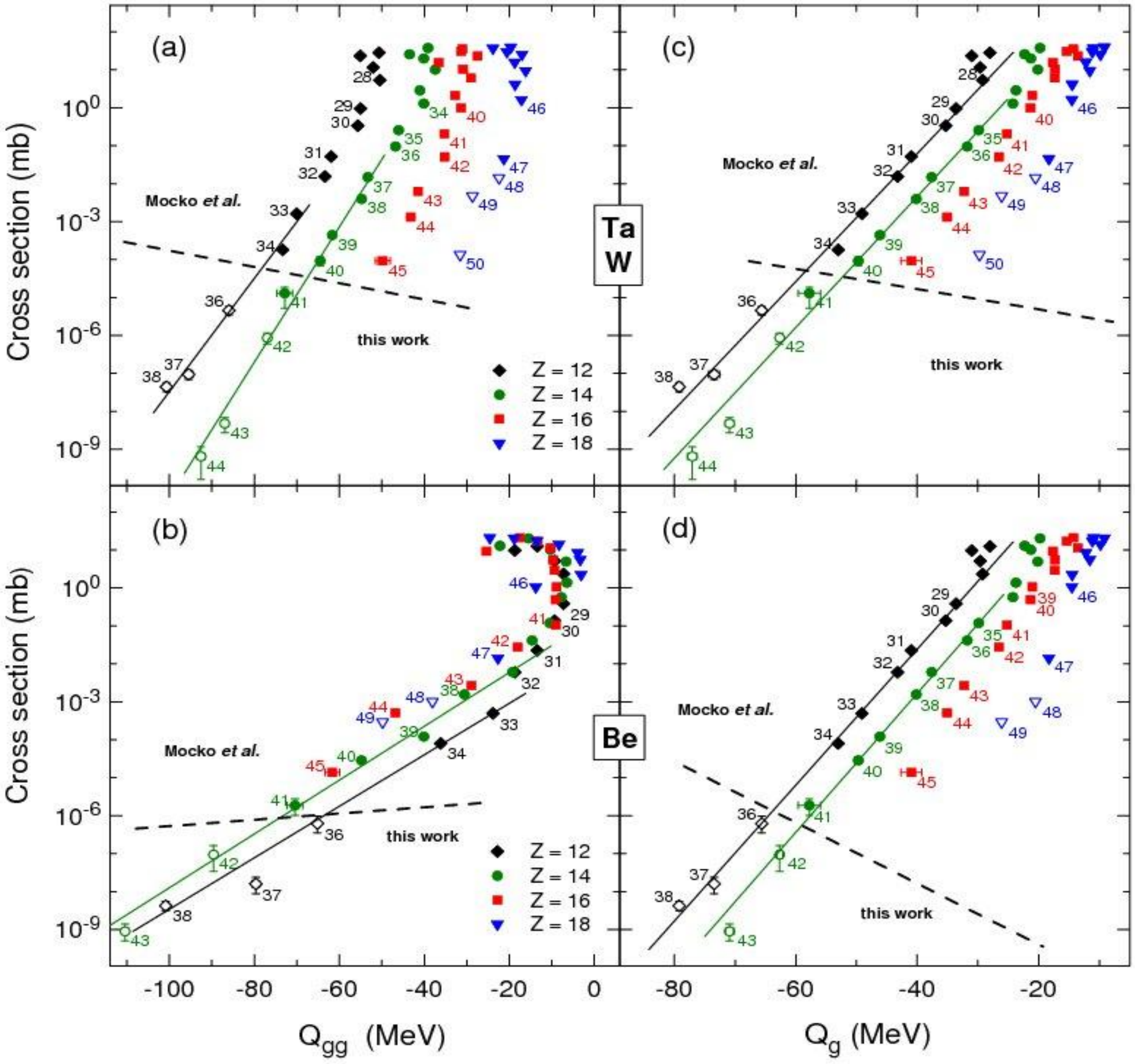
0 - Abrasion/Ablation v.6.4
1 - EPAX 1.00: K.Summerer et al.,Phys.Rev.C42(1990)2546
2 - EPAX 2.15: K.Summerer et al.,Phys.Rev.C61(2000)034607
3 - EPAX 2.15 + user modifications
4 - EPAX 3.01: K.Summerer,Phys.Rev.C86(2012)014601

- **Cross sections for projectile fragmentation**
    - EPAX parametrizations [1] based on fragmentation data
    - LISE^{++} Abrasion-Ablation model (analytical) [2]
    - Possibility to input cross sections manually via file
- ABRABLA : Abrasion-Ablation Monte Carlo [3]
- COFRA : a simplified, analytical version of ABRABLA, which only considers neutron evaporation from the pre-fragments formed in the abrasion stage [4].
- Intra-nuclear Cascade Models, e.g. ISABEL [5]

References:

[1] K. Summerer, B. Blank, Phys. Rev. C 61 (2000) 034607;
K. Summerer, Phys. Rev. C 86 (2012) 014601
[2] O. Tarasov, D. Bazin, Nucl. Instr. and Meth. B 204 (2003) 74.
[3] J.-J. Gaimard, K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709.
[4] J. Benlliure , et al. Nucl. Phys. A 660 (1999) 87.
[5] Yariv and Fraenkel,Phys. Rev. C20 (1979) 2227.

Production cross sections → Q_g- systematics



^{48}Ca(140MeV/u) + W,Be

A simple systematic framework was found to describe the production cross sections based on thermal evaporation from excited prefragments that allows extrapolation to other weak reaction products.

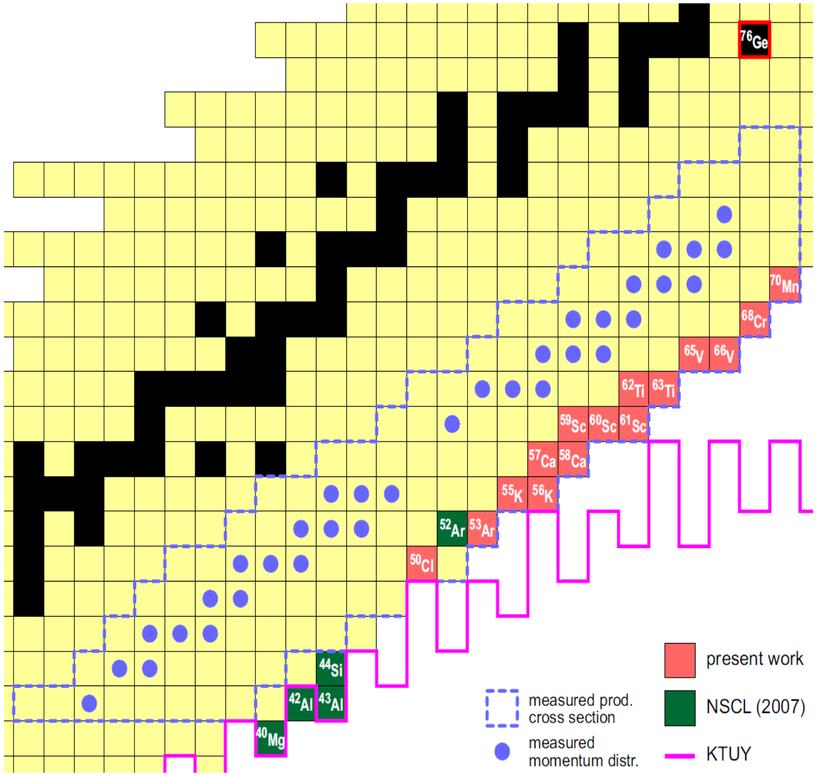
O.T. et al., Phys.Rev. C 75, 064613 (2007)

Compilation with data from M. Mocko et al., Phys. Rev. C 74, 054612 (2006)

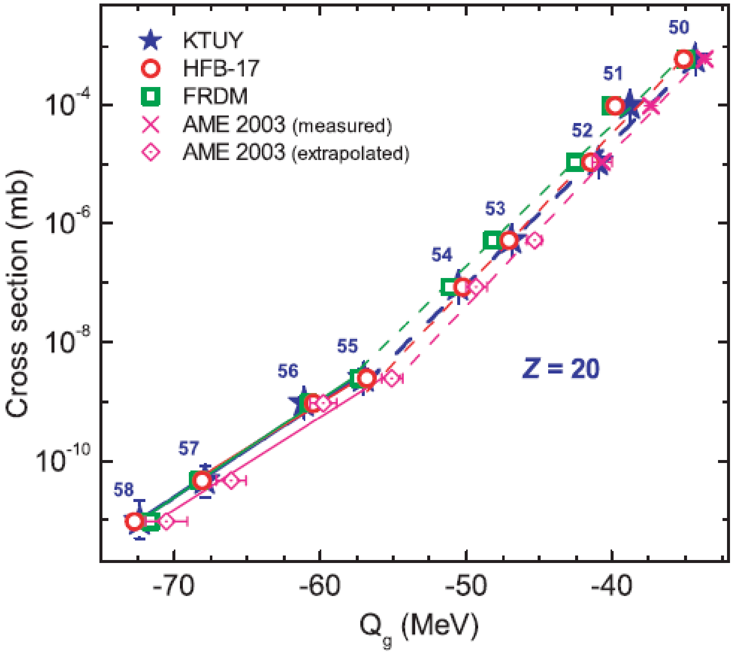
$$Q_g = ME(Z=20, A=48) - ME(Z,A)$$

^{76}Ge (130 MeV/u) → new isotopes, CS, momentum distributions
Q_g systematics → Possible new island of inversion ?

^{50}Cl, ^{53}Ar, ^{55,56}K, ^{57,58}Ca, ^{59,60,61}Sc, ^{62,63}Ti, ^{65,66}V, ^{68}Cr, ^{70}Mn



"Calcium anomaly"



Enhanced cross sections might be the result of increased binding

This region (around ^{62}Ti) was previously predicted to be a new island of inversion
B. A. Brown Prog. Part. Nucl. Phys. 47 (2001) 517

OT et sal., Phys.Rev.Lett. 102, 142501 (2009) :	New isotopes, Evidence for a Change in the Nuclear Mass Surface
OT et sal., Phys.Rev.C. 80, 034609 (2009) :	Set-up, cross sections, momentum distributions
OT et sal., NIM A 620, 578-584 (2010) :	A new approach to measure momentum distributions

^{82}Se (139 MeV/u) → new isotopes, CS, momentum distributions
Q_g systematics → Confirmation of Calcium anomaly

So, what is "Calcium anomaly" ?
Reaction property or
Nuclear structure feature?

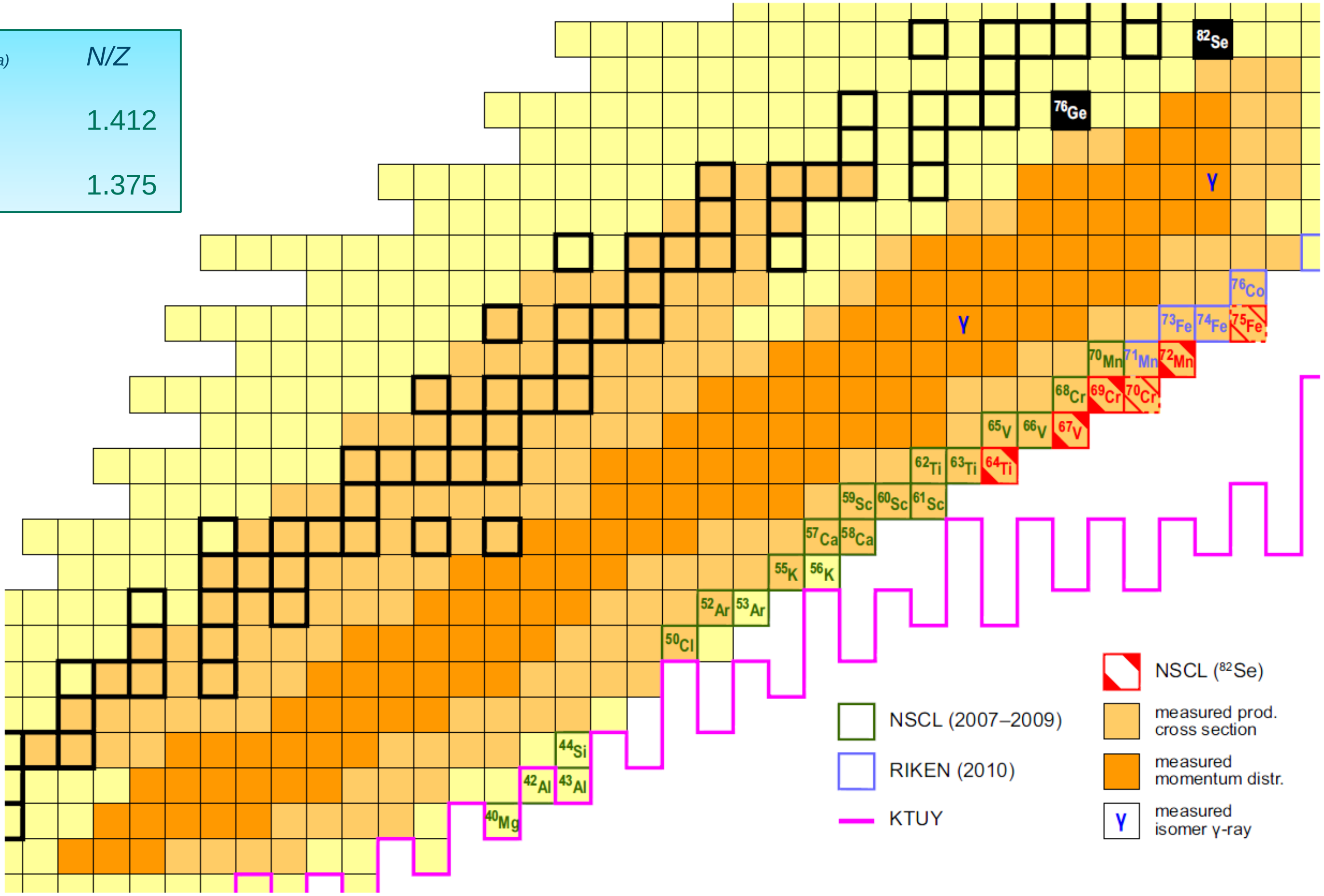
It should be checked with another beam

^{64}Ti, ^{67}V, ^{69}Cr, ^{72}Mn
^{70}Cr 1event **& ^{75}Fe** 1event

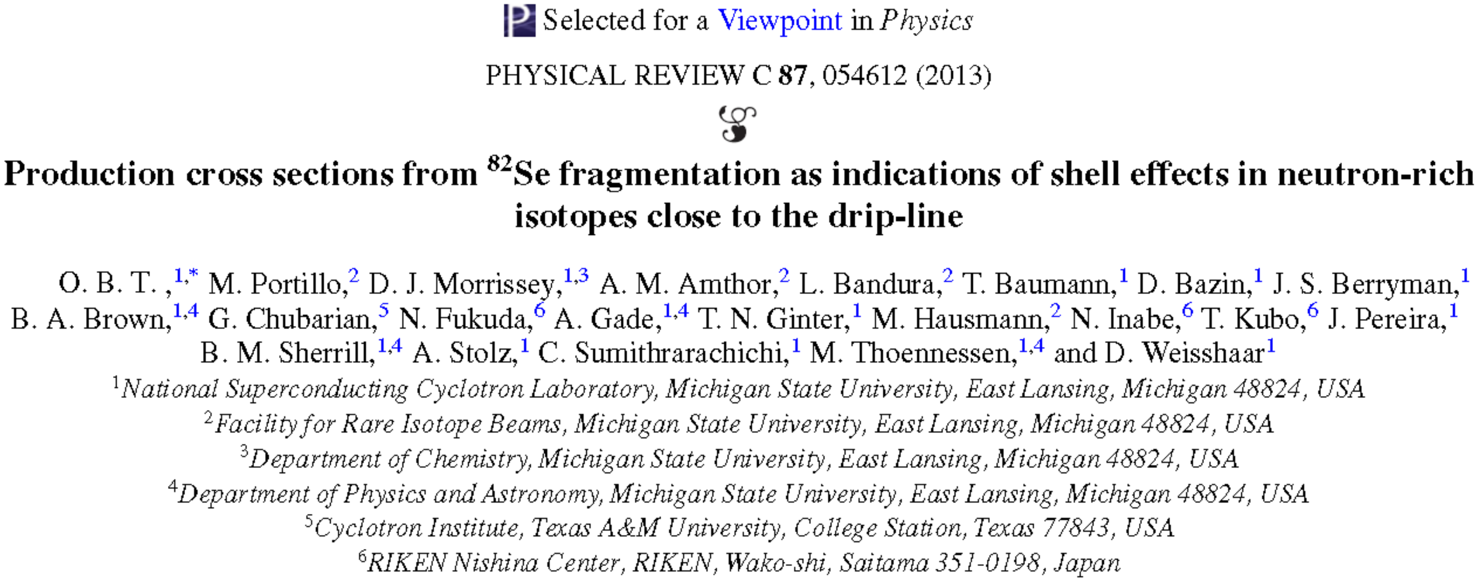
$N(\sigma_W) = 90$
$N(\sigma_{Be}) = 330$
$N(d\sigma/dp) = 126$

Beam	*E* *(MeV/u)*	*I* *(pna)*	*N/Z*
^{82}Se	139	35	1.412
^{76}Ge	130	20	1.375

$\Delta N / \Delta Z = 2$



2013 : Calcium anomaly as shell effects close to drip line



Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW C **87**, 054612 (2013)

Production cross sections from ^{82}Se fragmentation as indications of shell effects in neutron-rich isotopes close to the drip-line

O. B. T. ,[1,*] M. Portillo,[2] D. J. Morrissey,[1,3] A. M. Amthor,[2] L. Bandura,[2] T. Baumann,[1] D. Bazin,[1] J. S. Berryman,[1] B. A. Brown,[1,4] G. Chubarian,[5] N. Fukuda,[6] A. Gade,[1,4] T. N. Ginter,[1] M. Hausmann,[2] N. Inabe,[6] T. Kubo,[6] J. Pereira,[1] B. M. Sherrill,[1,4] A. Stolz,[1] C. Sumithrarachichi,[1] M. Thoennessen,[1,4] and D. Weisshaar[1]

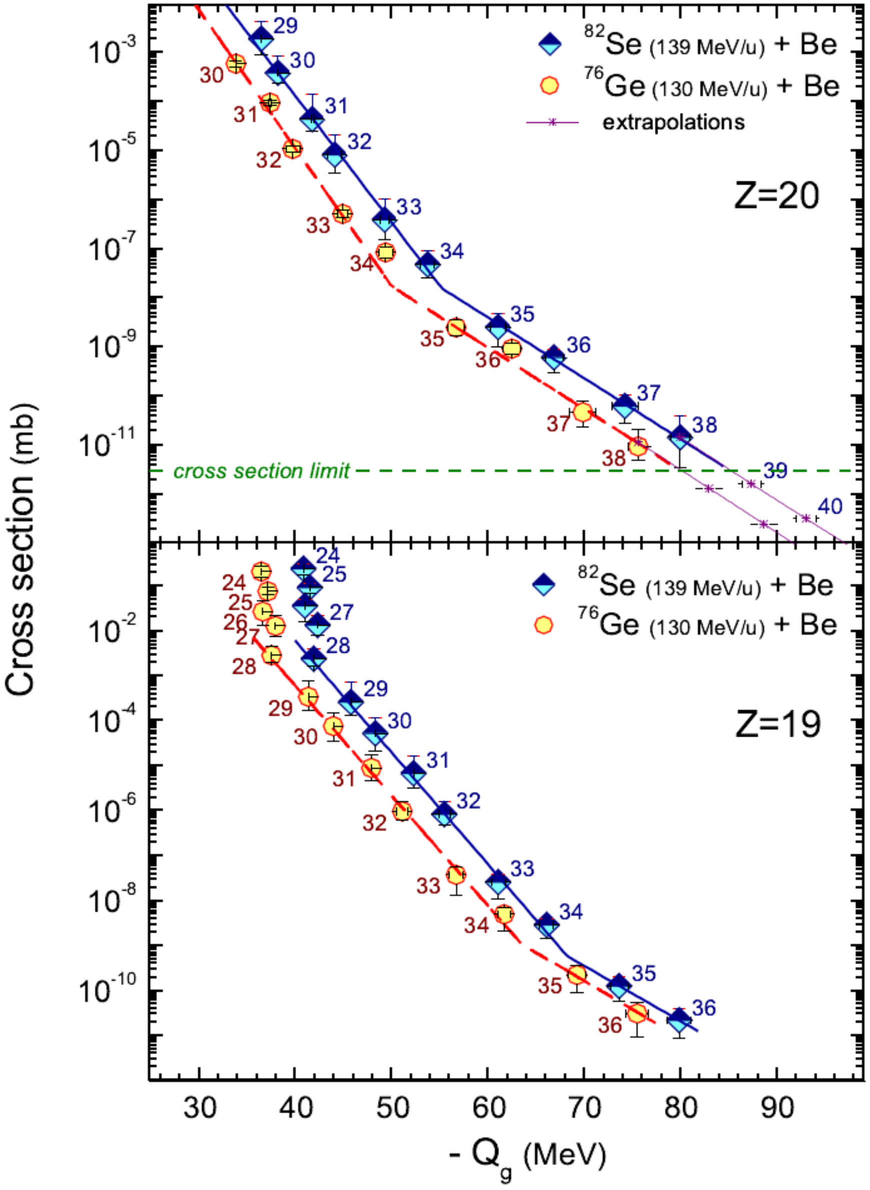
[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[6]*RIKEN Nishina Center, RIKEN, Wako-shi, Saitama 351-0198, Japan*

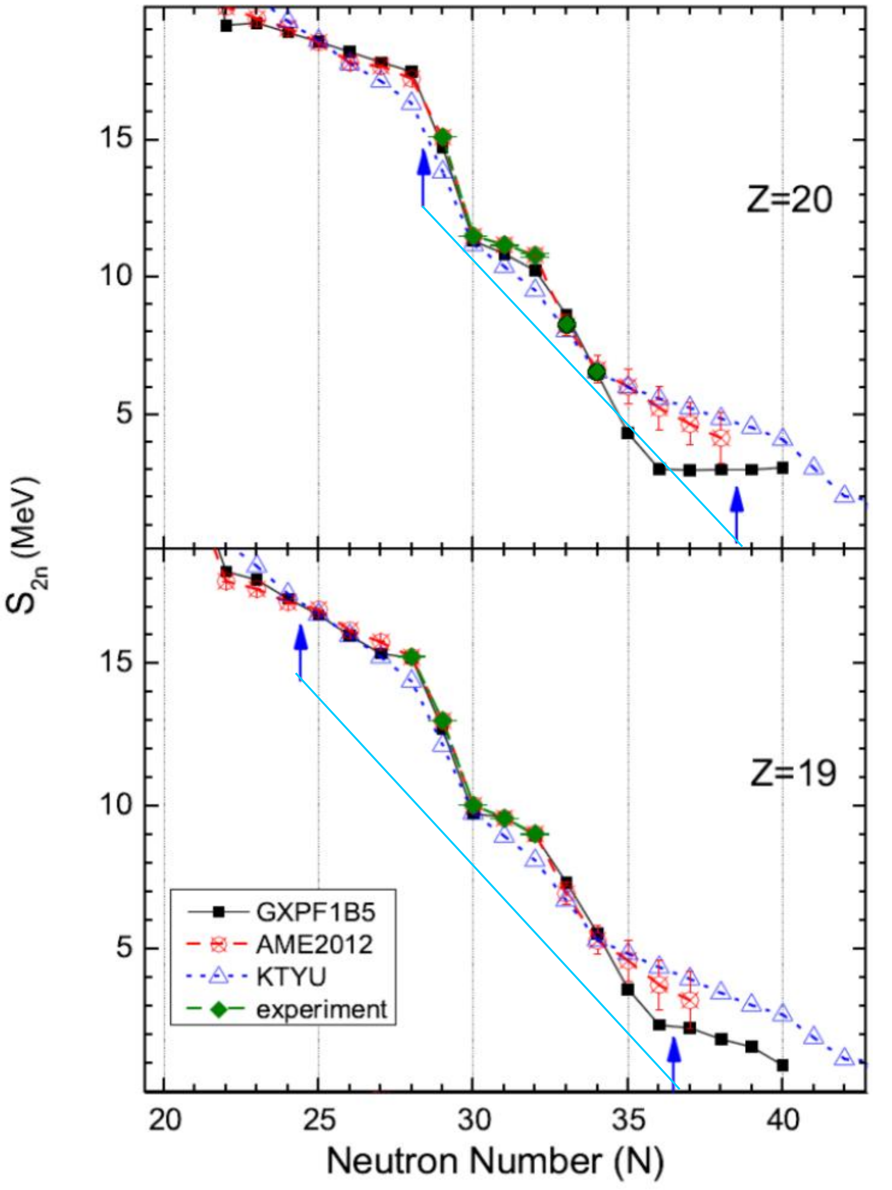
The measured cross sections were best reproduced by using masses derived from the full *pf* shell-model space with the GXPF1B5 [1] effective interaction modified to a recent ^{54}Ca $E_x(2^+_1)$ measurement [2].

The "Calcium anomaly" can be explained with a shell model that predicts a subshell closure at $N = 34$ around $Z = 20$.

[1] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Eur. Phys. J. A 25, Suppl. 1, 499 (2005)
[2] D. Steppenbeck et al., Nature 502, 207 (2013)

Q_g systematics, Two-neutron separation energy





Experimental masses:
A.T. Gallant et al., Phys. Rev. Lett. 109, 032506 (2012)
F. Wienholtz et al., Nature 498 (2013) 346

Global trends of cross sections

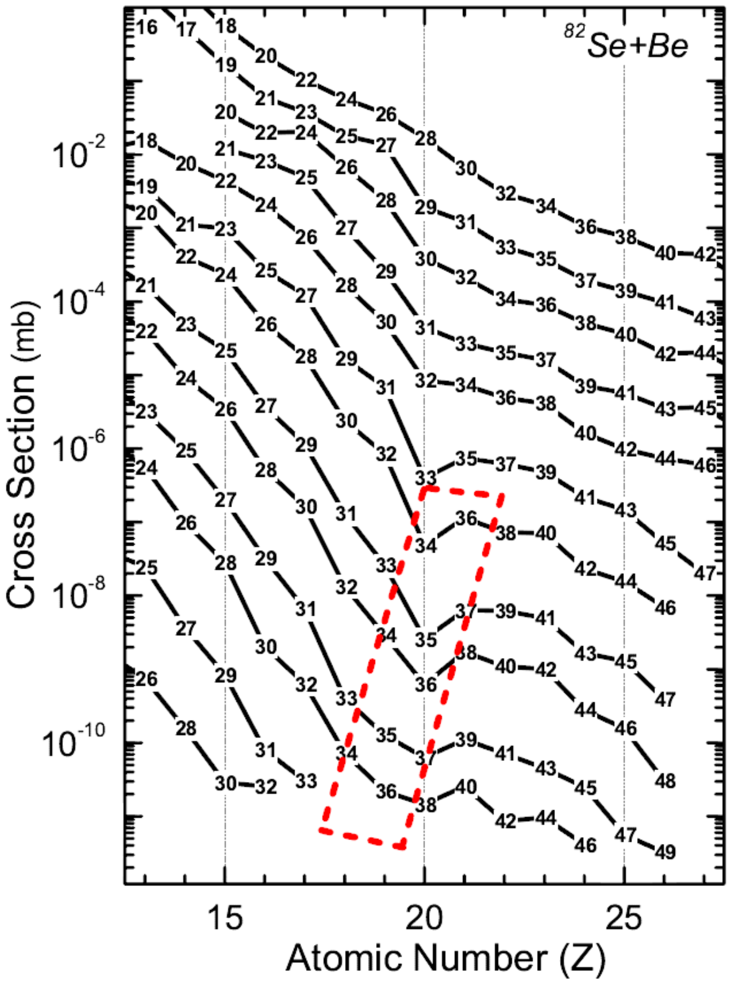


FIG. Production cross section versus atomic number (Z) for fragments from reaction of ^{82}Se with beryllium targets. **Lines are connected according to constant** $N - 2Z$, while labels represent the neutron number.

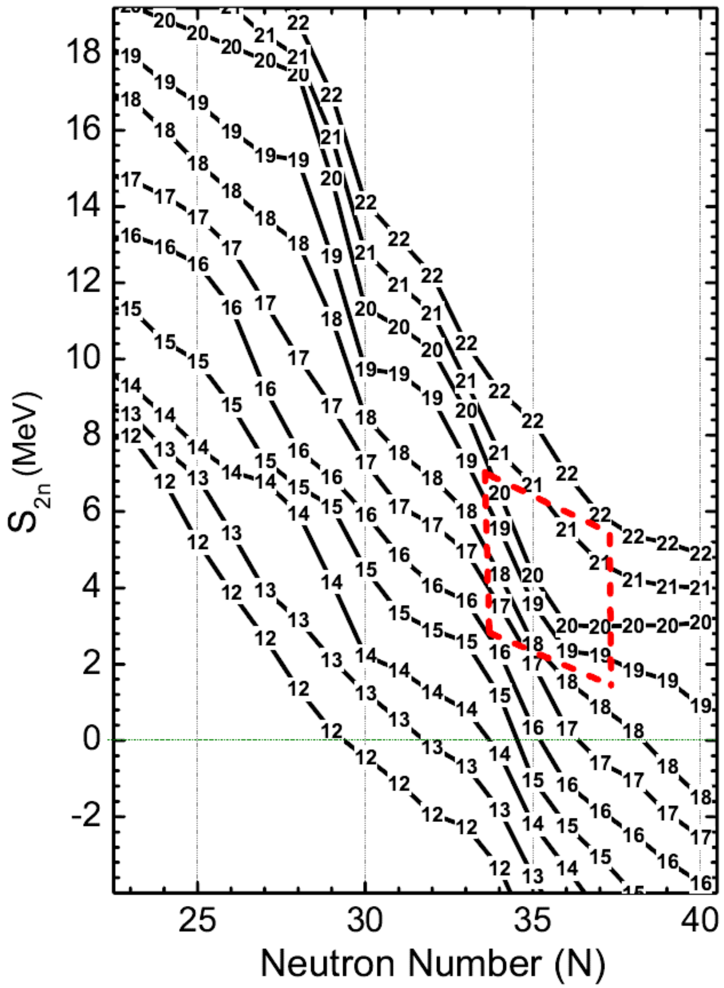
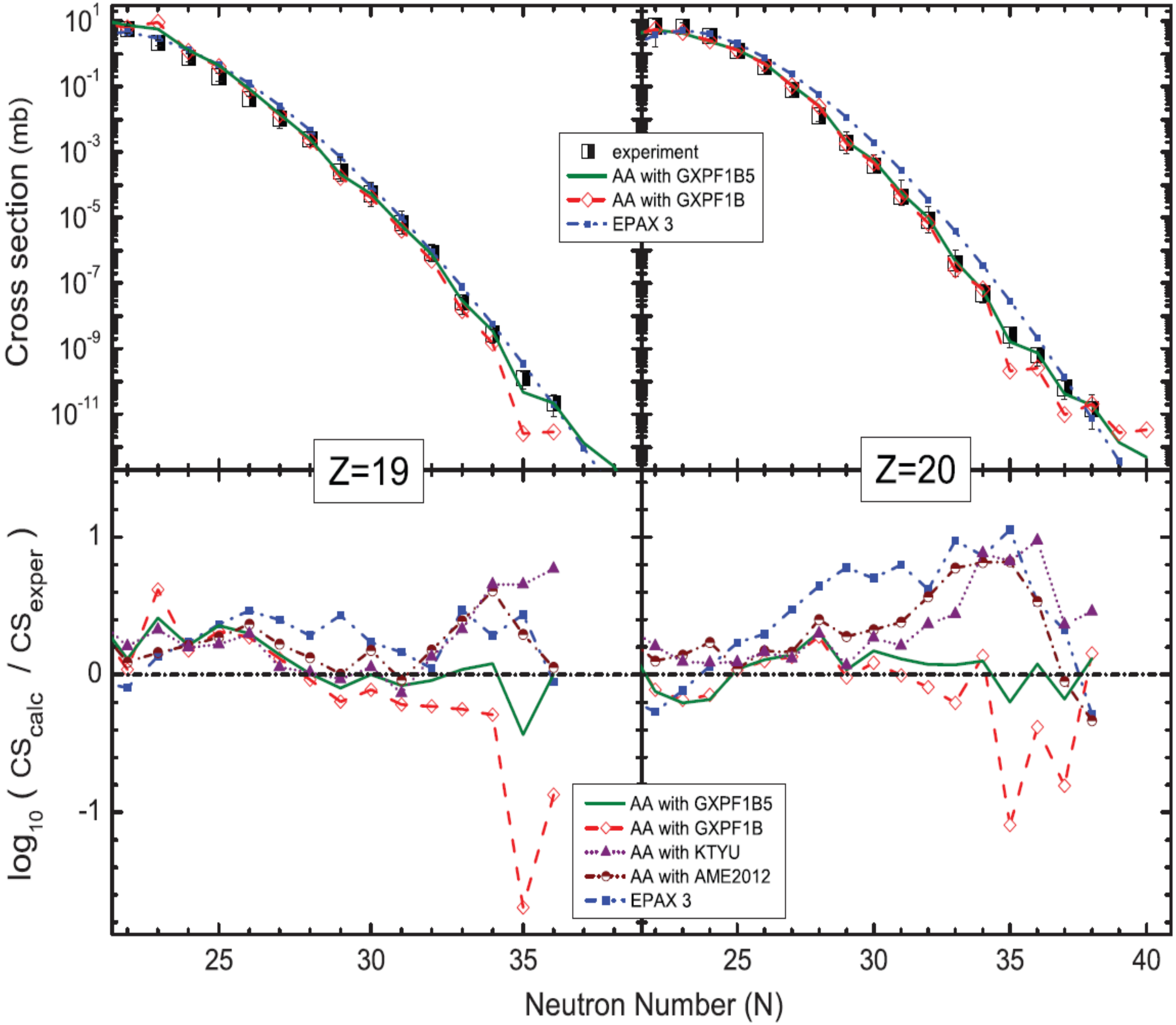


FIG. Two-neutron separation energy S_{2n} versus neutron number (N) for elements $12 \leq Z \leq 22$. Values are calculated using results from the GXPF1B5 model. Labels in the lines show atomic numbers of nuclei.

No such dump with other theoretical models

LISE^{++} Abrasion-Ablation model



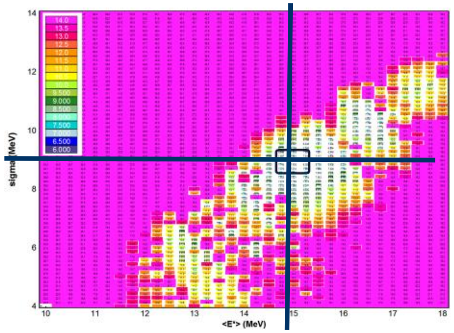
Different mass models as

- HFB9,
- HBF17,
- KTYU
- TUYY
- AME2003
- AME2012
- GXPF1B,
- GXPF1B5

were used in LISE^{++} Abrasion-Ablation excitation energy minimization procedures to compare with the experimental data

Abrasion-Ablation: Excitation energy

σ

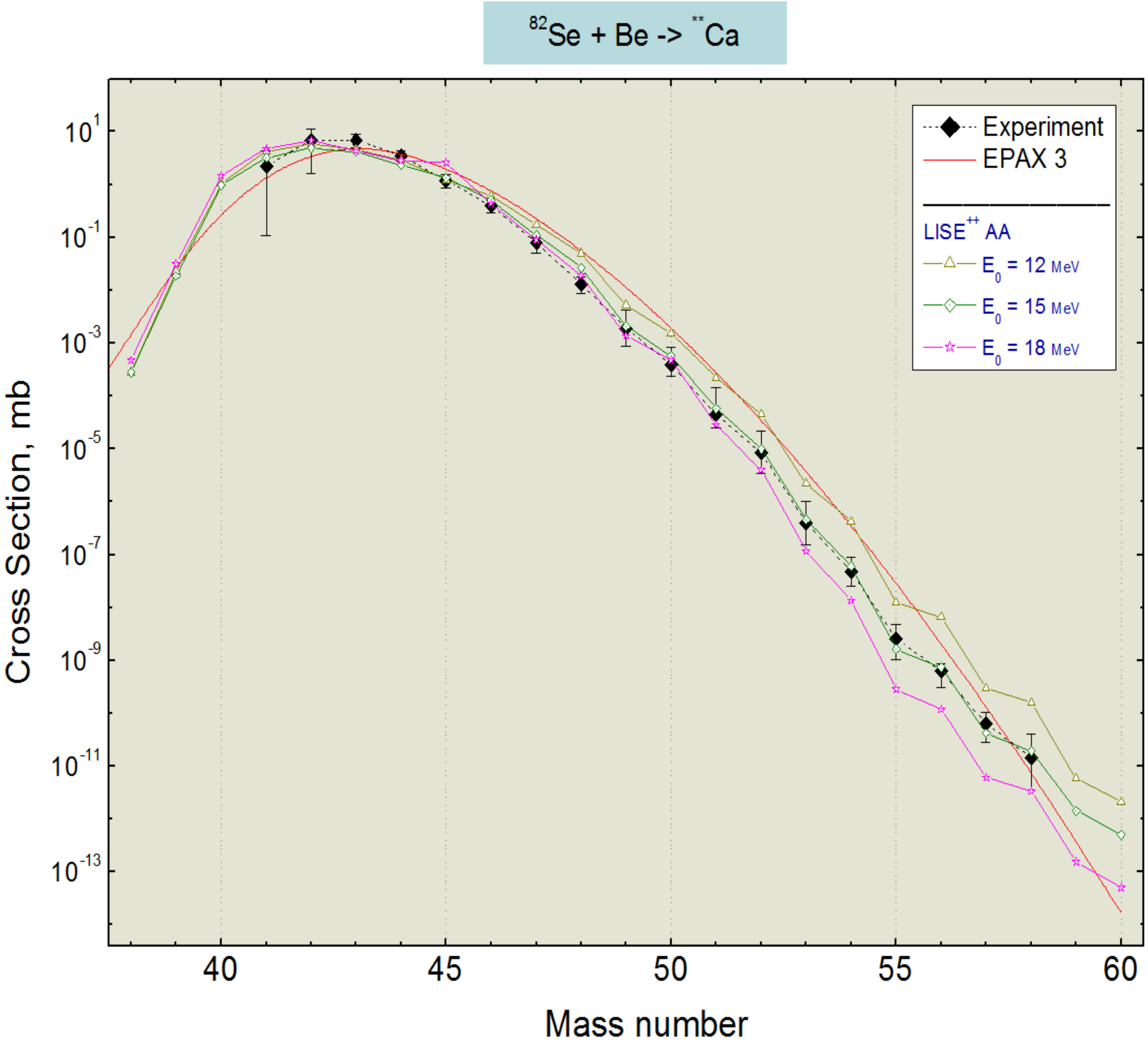


The best result to describe the experimental data of isotopes of elements 16<Z<24 has been obtained with GXPF1B5 (+ LDM0) at E*=15.0 (σ=9.15) MeV

GSI:

^{40}Ar beam:
<E>= 13.3 MeV
NPA 531 ,709 (1991)

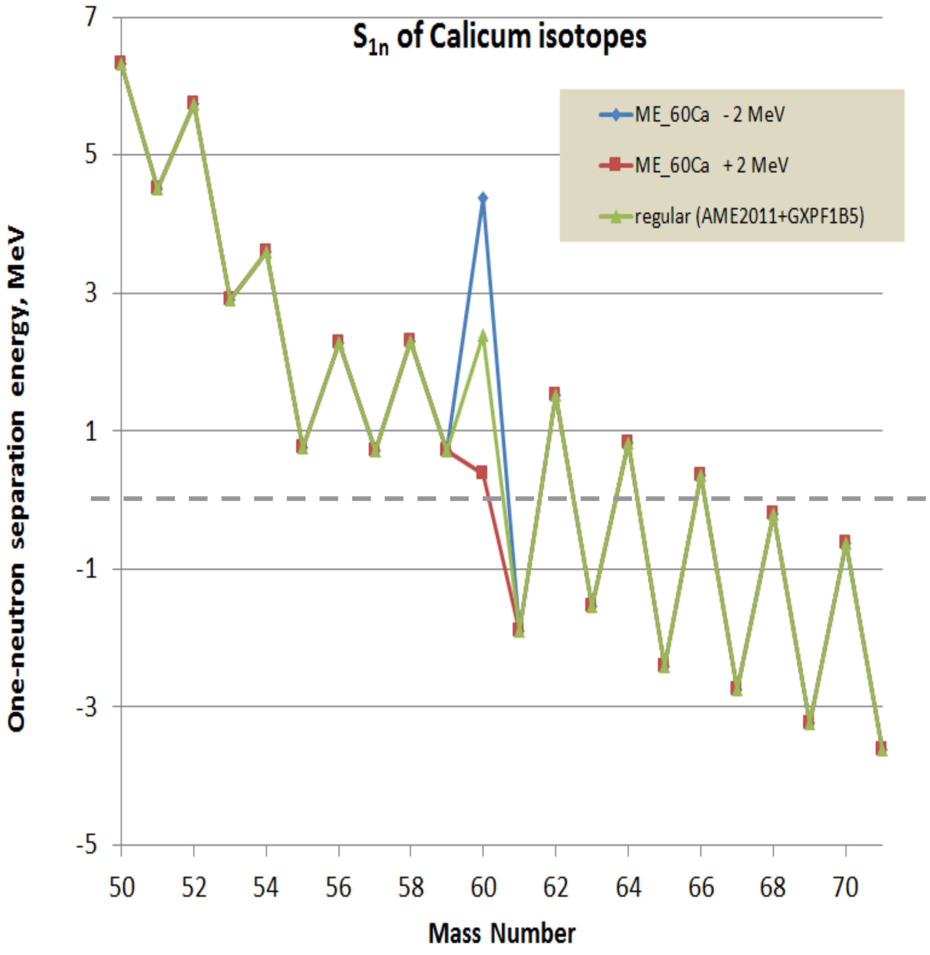
^{238}U beam:
<E>= 27 MeV (K.H.S.)

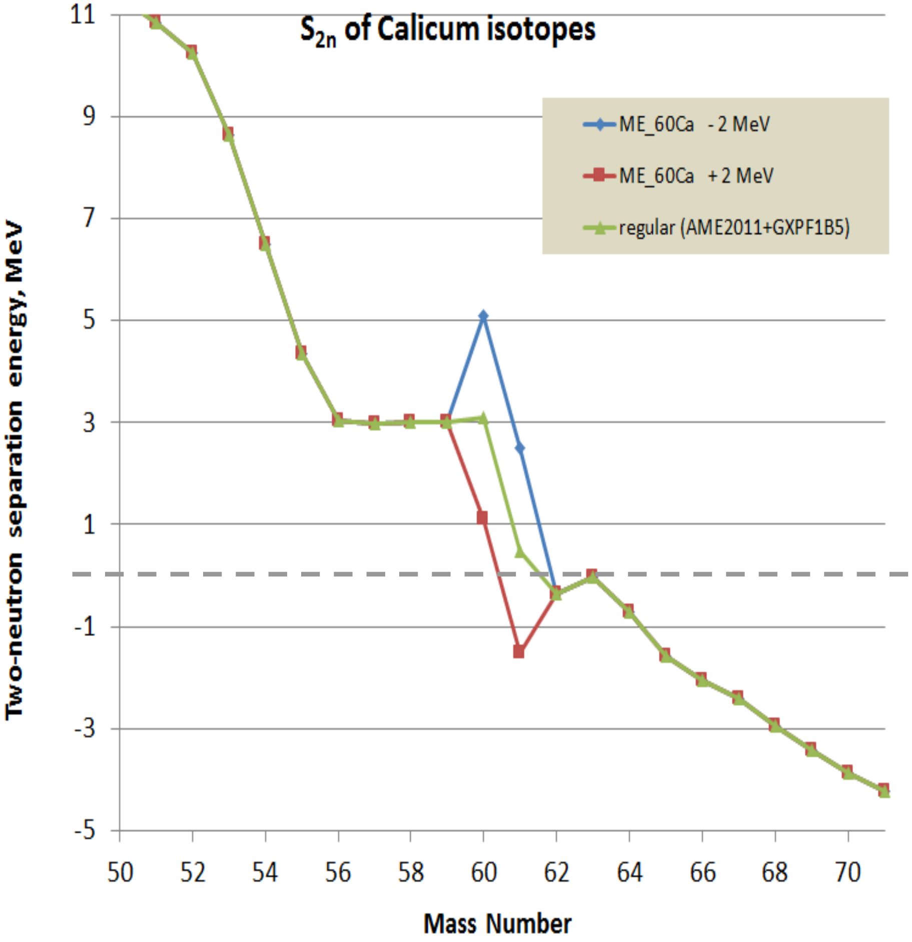


Varying masses for Abrasion-Ablation benchmarks

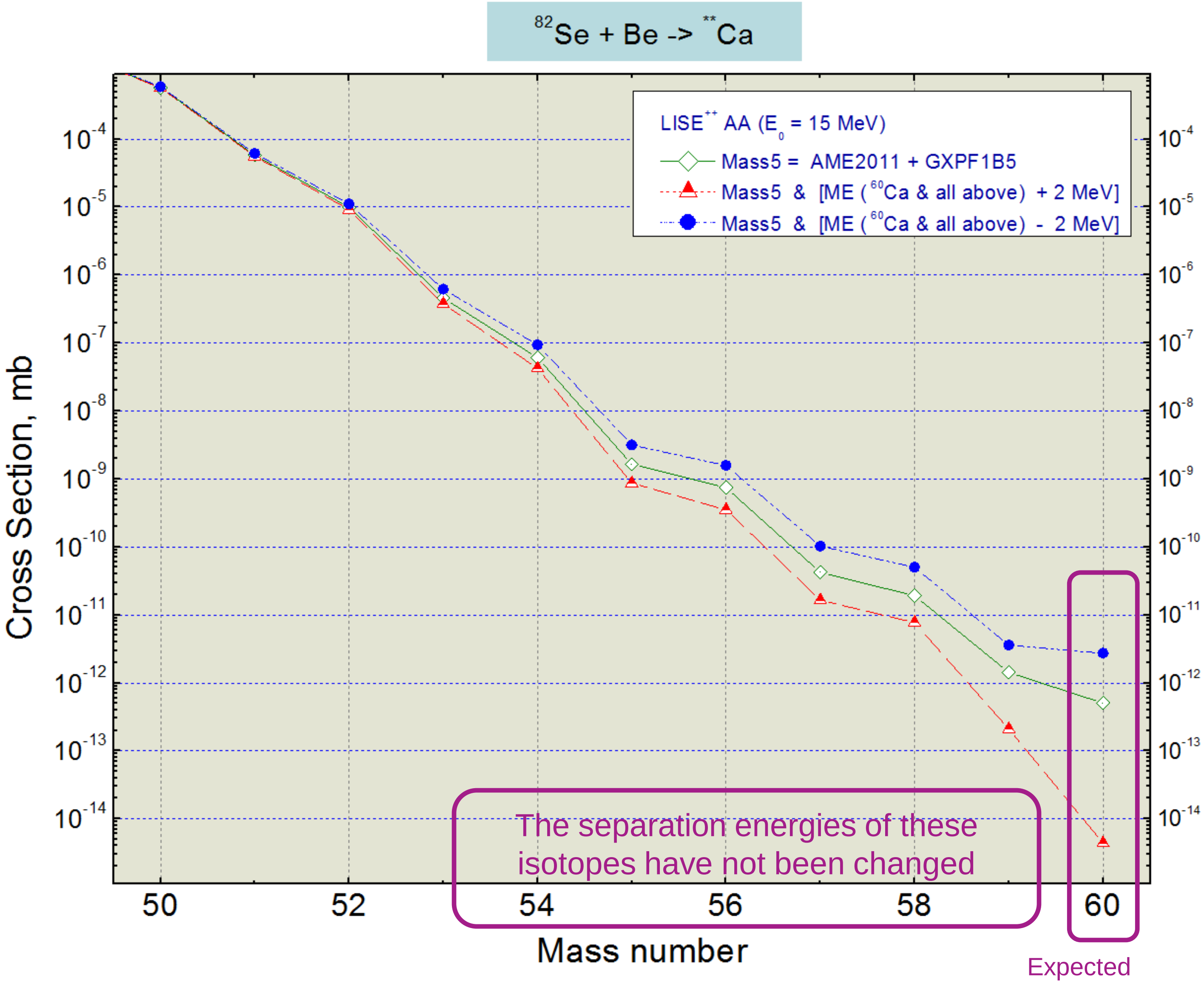
increase decrease

decreased [increased]





Influence of de-excitation chain precedent isotopes masses on “daughters” production cross sections



The separation energies of these isotopes have not been changed

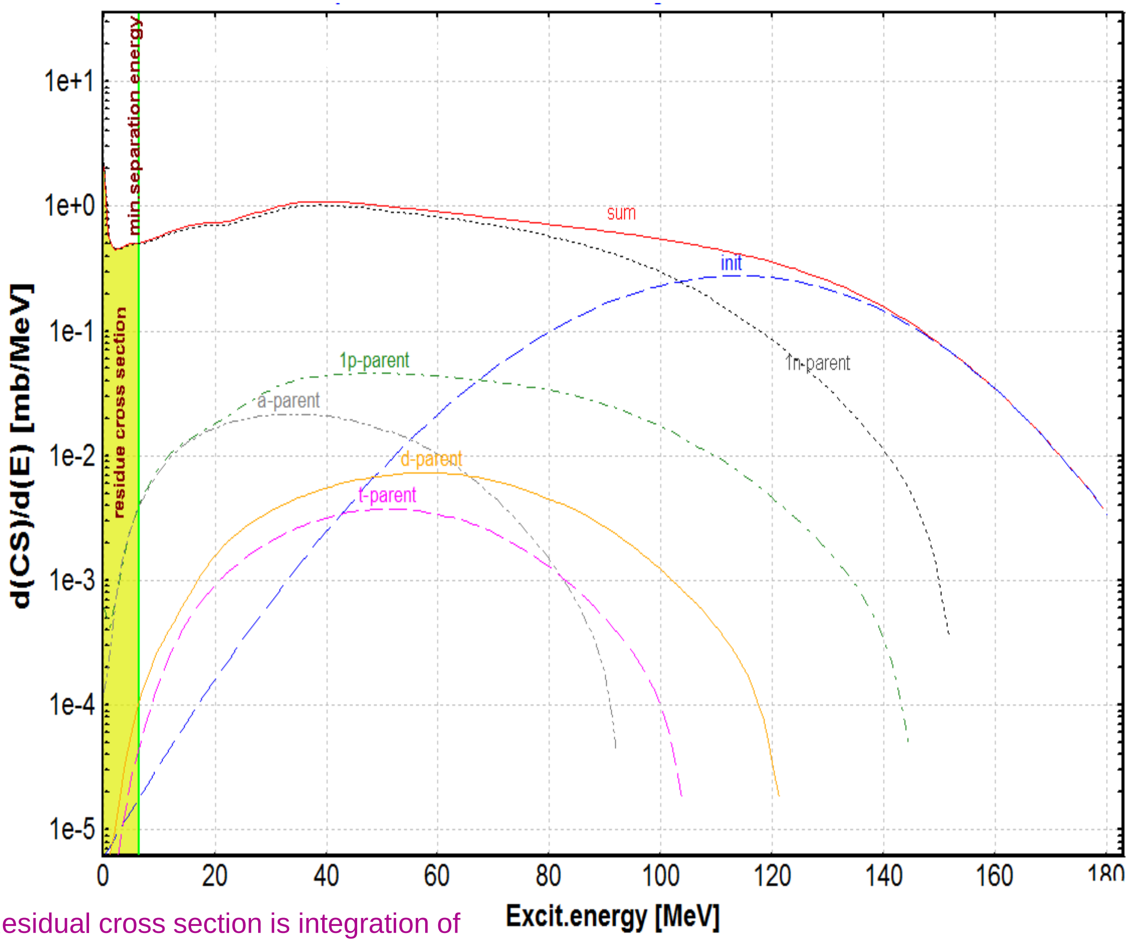
Expected Cross section changes

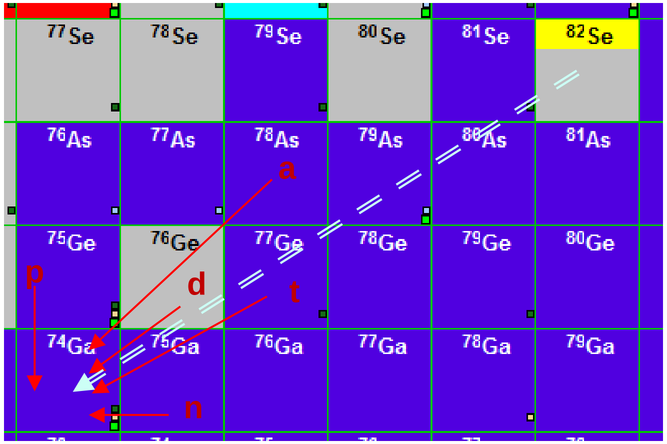
1. Separation energy changes influence drastically of cross section close to the drip-line (this ^{60}Ca example)

2. **Residue cross section depends how <u>much bound are preceding isotopes</u>**

3. Deviations in cross sections are not just indicators for local low separation energies (as ^{31}Ne, ^{37}Mg), but also might provide information about shell effects close to the neutron drip-line

LISE^{++} Abrasion-Ablation: Input channels



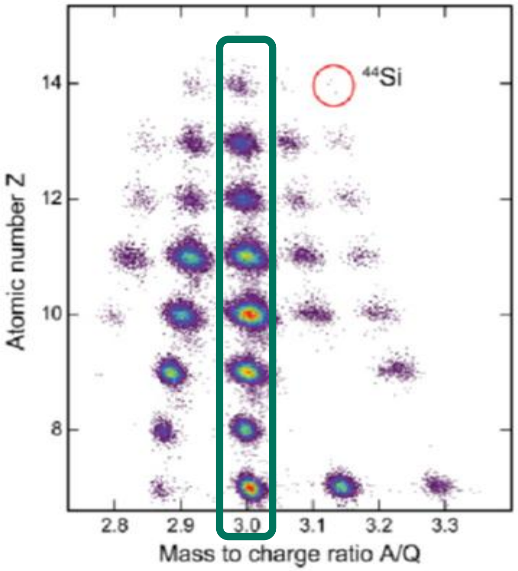


Residual cross section is integration of the excitation function from 0 to the minimum of separation energy

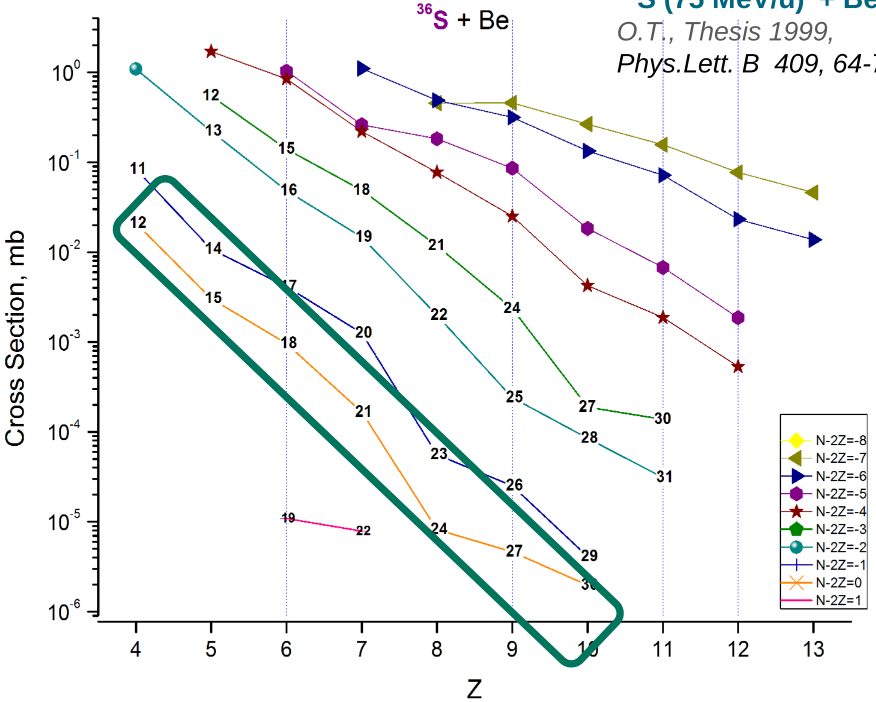
1. Largest incoming contribution to the Total excitation function is 1n-channel
2. Largest incoming contribution to the Residue cross section

Oxygen “anomaly”

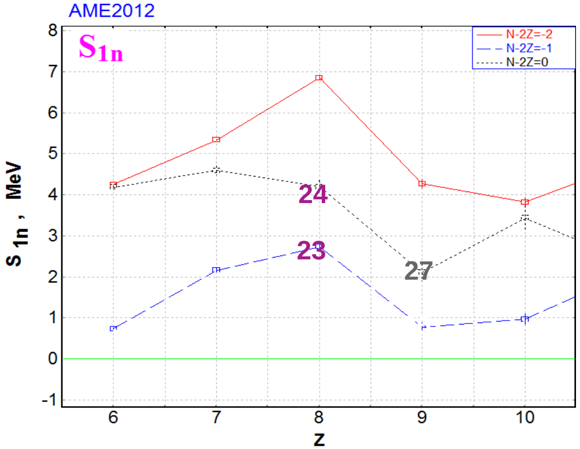
NSCL/MSU
^{48}Ca (140 MeV/u) + Ta
O.T. et al., Phys.Rev. C 75, 064613 (2007)



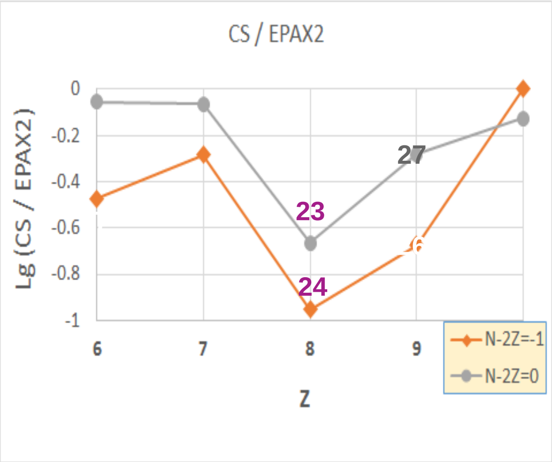
GANIL
^{36}S (75 MeV/u) + Be
O.T., Thesis 1999,
Phys.Lett. B 409, 64-70 (1997)



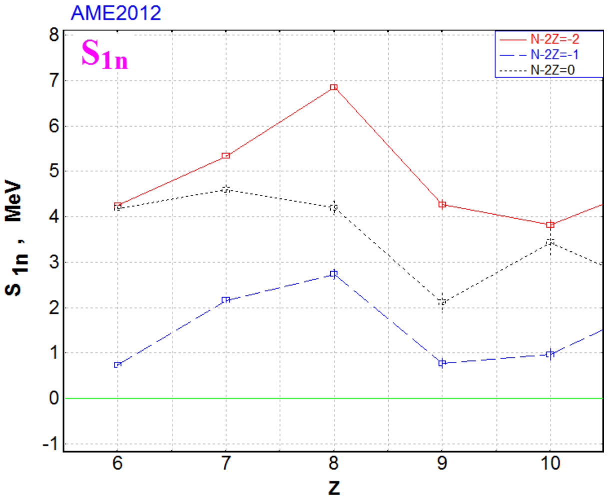
Oxygen isotopes are more particle bound



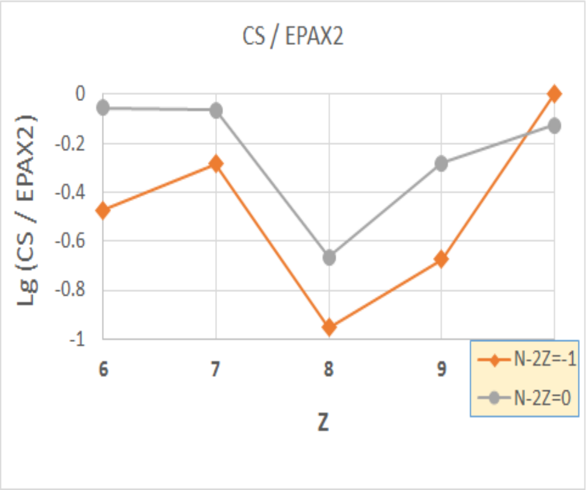
Oxygen isotopes are less produced

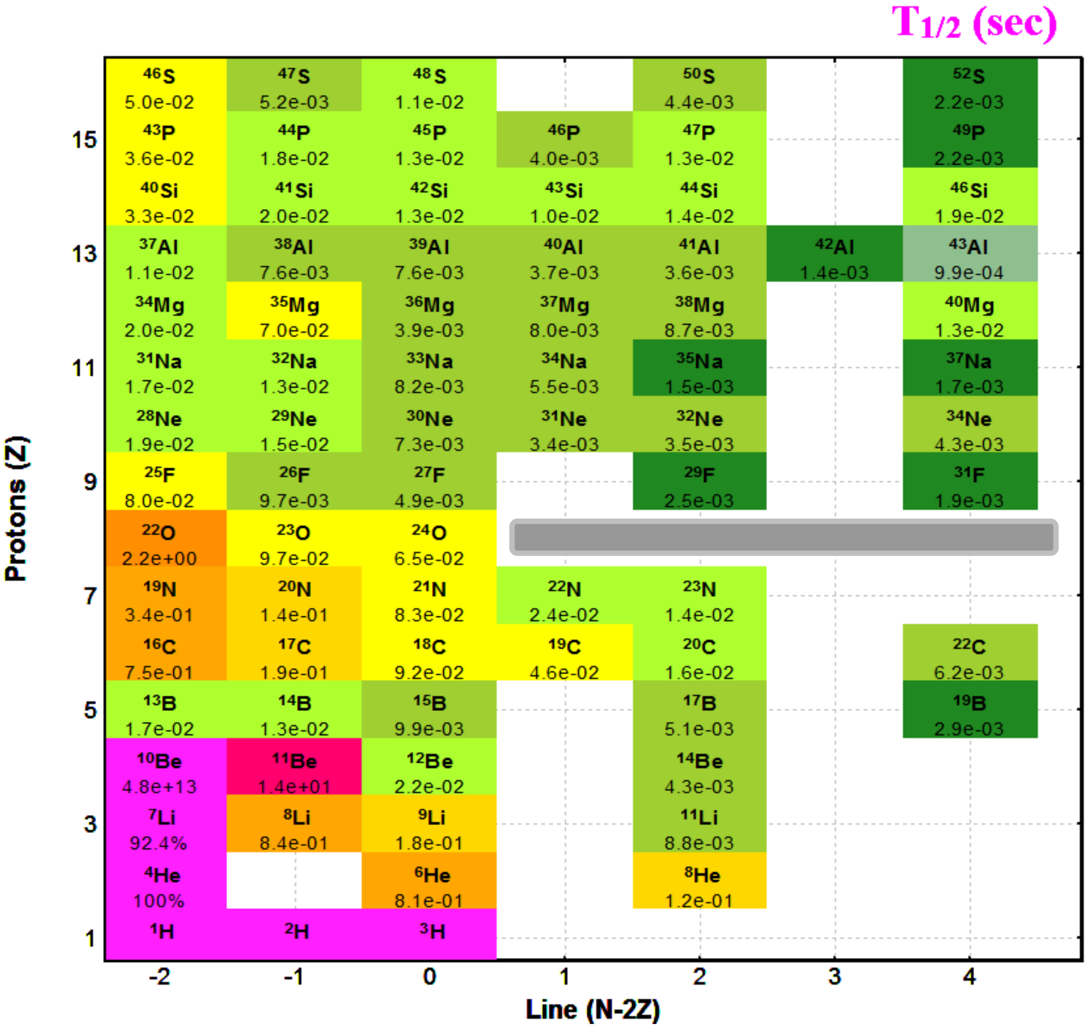


Oxygen “anomaly” : no particle-bound isotopes above ^{24}O



Oxygen isotopes are more particle bound, but less produced !?

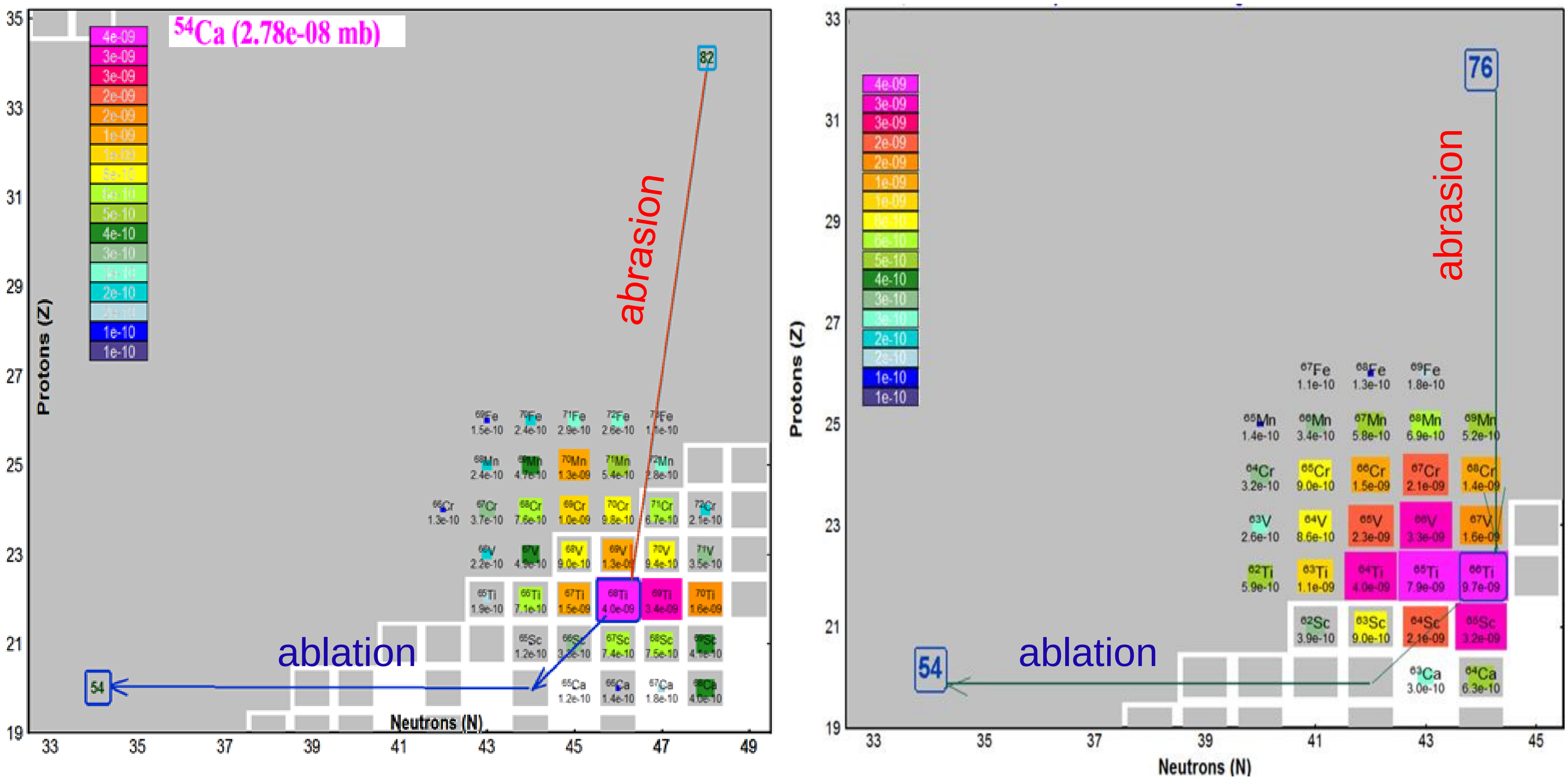




Z	-2	-1	0	1	2	3	4
	^{46}S 5.0e-02	^{47}S 5.2e-03	^{48}S 1.1e-02		^{50}S 4.4e-03		^{52}S 2.2e-03
15	^{43}P 3.6e-02	^{44}P 1.8e-02	^{45}P 1.3e-02	^{46}P 4.0e-03	^{47}P 1.3e-02		^{49}P 2.2e-03
	^{40}Si 3.3e-02	^{41}Si 2.0e-02	^{42}Si 1.3e-02	^{43}Si 1.0e-02	^{44}Si 1.4e-02		^{46}Si 1.9e-02
13	^{37}Al 1.1e-02	^{38}Al 7.6e-03	^{39}Al 7.6e-03	^{40}Al 3.7e-03	^{41}Al 3.6e-03	^{42}Al 1.4e-03	^{43}Al 9.9e-04
	^{34}Mg 2.0e-02	^{35}Mg 7.0e-02	^{36}Mg 3.9e-03	^{37}Mg 8.0e-03	^{38}Mg 8.7e-03		^{40}Mg 1.3e-02
11	^{31}Na 1.7e-02	^{32}Na 1.3e-02	^{33}Na 8.2e-03	^{34}Na 5.5e-03	^{35}Na 1.5e-03		^{37}Na 1.7e-03
	^{28}Ne 1.9e-02	^{29}Ne 1.5e-02	^{30}Ne 7.3e-03	^{31}Ne 3.4e-03	^{32}Ne 3.5e-03		^{34}Ne 4.3e-03
9	^{25}F 8.0e-02	^{26}F 9.7e-03	^{27}F 4.9e-03		^{29}F 2.5e-03		^{31}F 1.9e-03
	^{22}O 2.2e+00	^{23}O 9.7e-02	^{24}O 6.5e-02				
7	^{19}N 3.4e-01	^{20}N 1.4e-01	^{21}N 8.3e-02	^{22}N 2.4e-02	^{23}N 1.4e-02		
	^{16}C 7.5e-01	^{17}C 1.9e-01	^{18}C 9.2e-02	^{19}C 4.6e-02	^{20}C 1.6e-02		^{22}C 6.2e-03
5	^{13}B 1.7e-02	^{14}B 1.3e-02	^{15}B 9.9e-03		^{17}B 5.1e-03		^{19}B 2.9e-03
	^{10}Be 4.8e+13	^{11}Be 1.4e+01	^{12}Be 2.2e-02		^{14}Be 4.3e-03		
3	^{7}Li 92.4%	^{8}Li 8.4e-01	^{9}Li 1.8e-01		^{11}Li 8.8e-03		
	^{4}He 100%		^{6}He 8.1e-01		^{8}He 1.2e-01		
1	^{1}H	^{2}H	^{3}H				

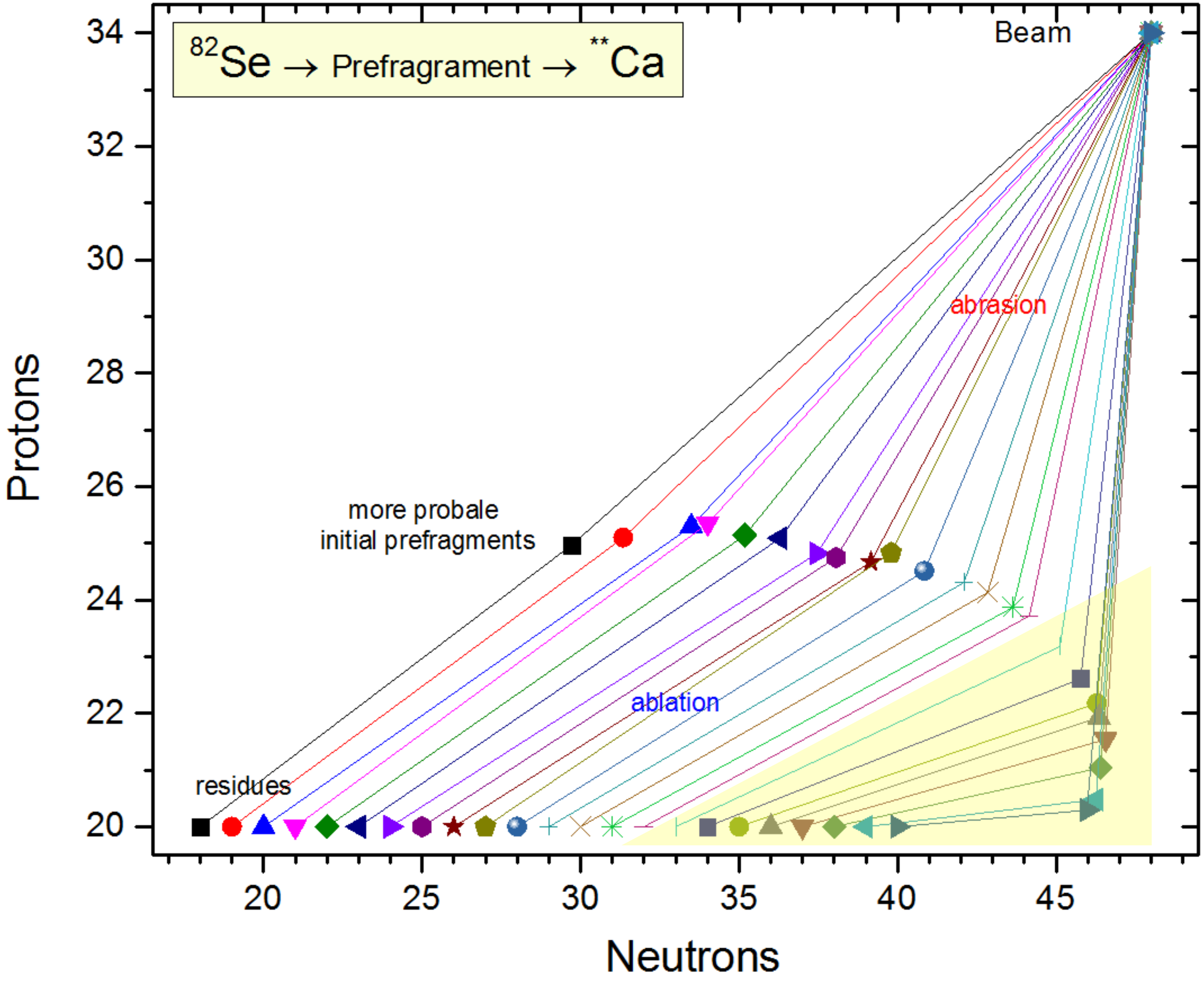
- No particle bound preceding isotopes of the same element, So “excitation energy train” cannot be slow down
- Absence of excited bound states?

LISE^{++} AA: Initial prefragments plot for final residue ^{54}Ca



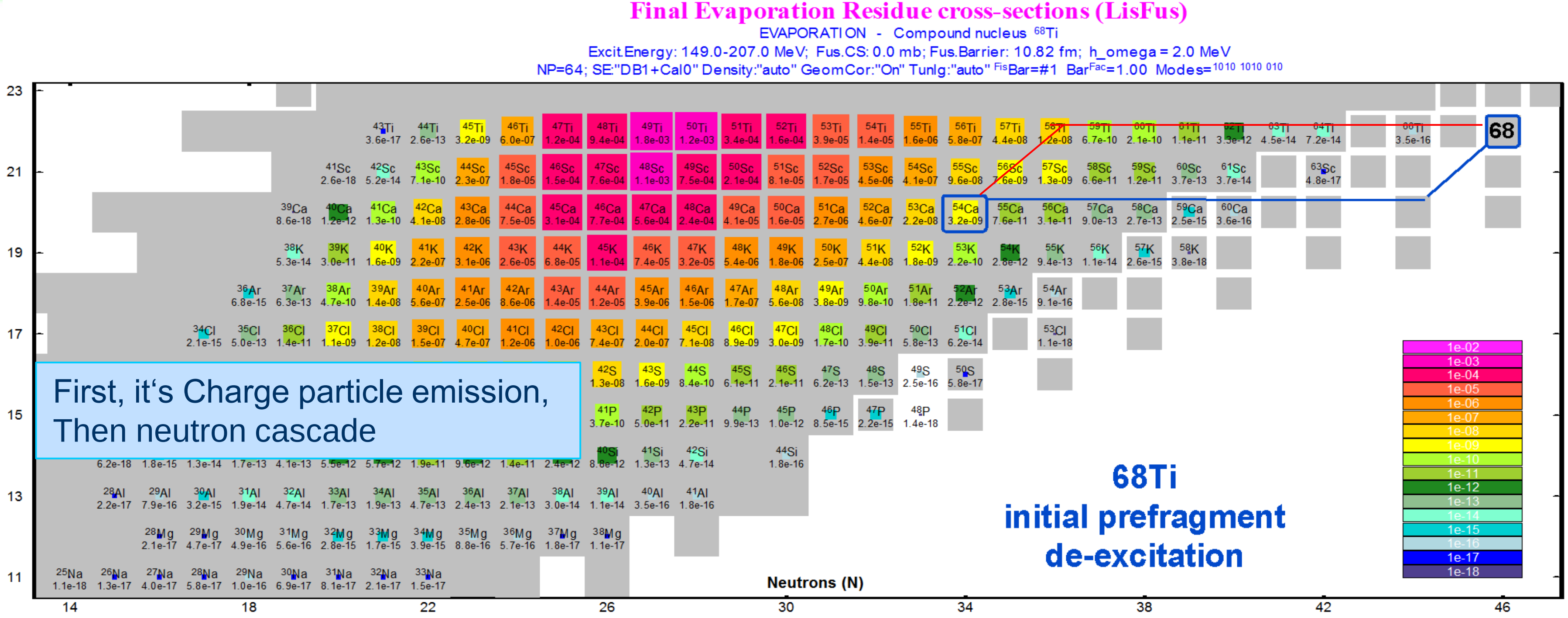
More probable prefragments are Ti-isotopes (dZ=2)

Initial prefragments to produce Calcium isotopes



Region of interest
“Calcium anomaly”

$^{68}\text{Ti}^* \rightarrow {}^{54}\text{Ca}$



Final Evaporation Residue cross-sections (LisFus)

EVAPORATION - Compound nucleus ^{68}Ti

Excit.Energy: 149.0-207.0 MeV; Fus.CS: 0.0 mb; Fus.Barrier: 10.82 fm; h_omega = 2.0 MeV

NP=64; SE:"DB1+Cal0" Density:"auto" GeomCor:"On" Tunlg:"auto" $^{\text{Fis}}$Bar=#1 Bar$^{\text{Fac}}$=1.00 Modes=$^{1010\ 1010\ 010}$

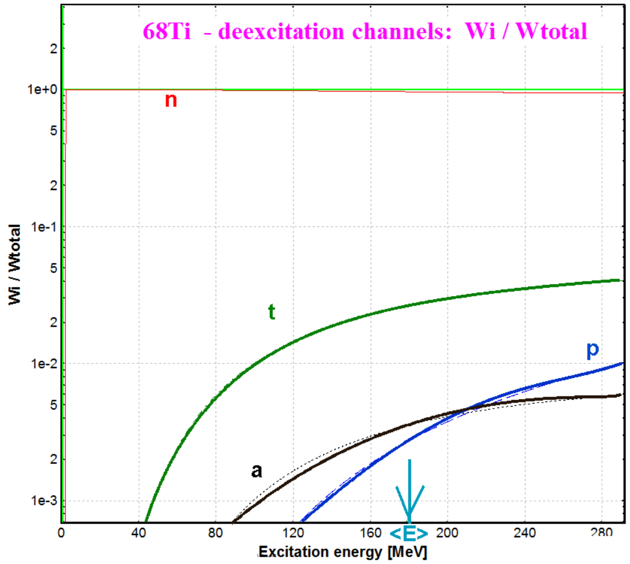
First, it's Charge particle emission,
Then neutron cascade

68Ti
initial prefragment
de-excitation

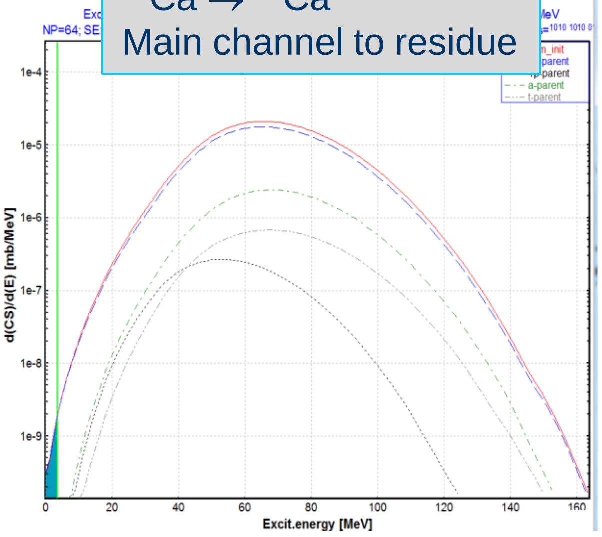
Probability for $^{68}\text{Ti}^*$(Ex=180MeV)
t = 2.6e-2
a = 3.6e-3
p =9.3e-3

Probability (dZ=2)
t^2 = 6.8e-4
a = 3.6e-3
p^2 =8.7e-5

It is necessary to create the MC version to gate for ^{54}Ca residual in order to answer where ($^{**}\text{Ti} \rightarrow {}^{**-4}\text{Ca}$) de-excitation by charge particles is more probable



68Ti - deexcitation channels: Wi / Wtotal

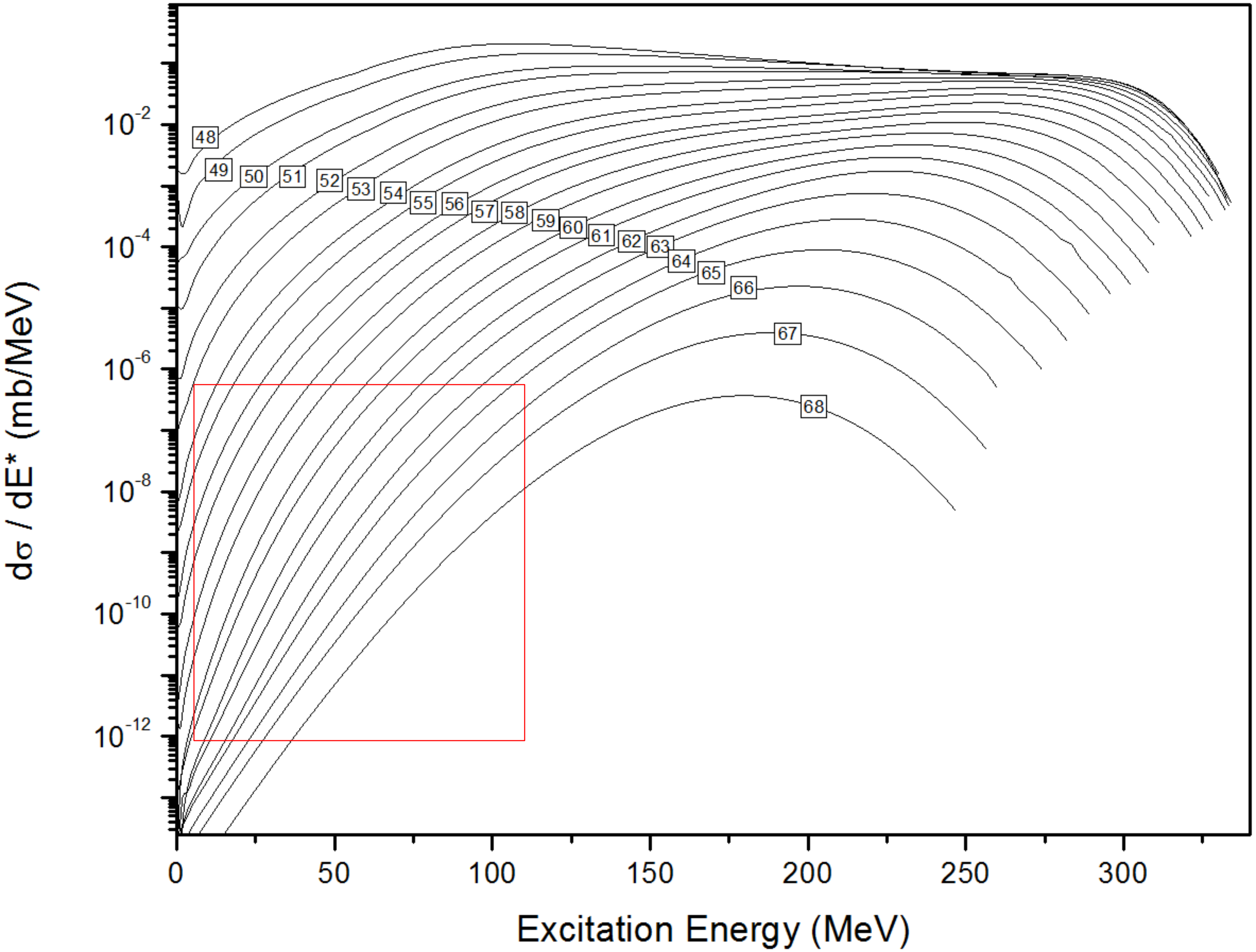


$^{55}\text{Ca} \rightarrow {}^{54}\text{Ca}$
Main channel to residue

Excitation functions A=48-68 (E^*_0 = 15 MeV)

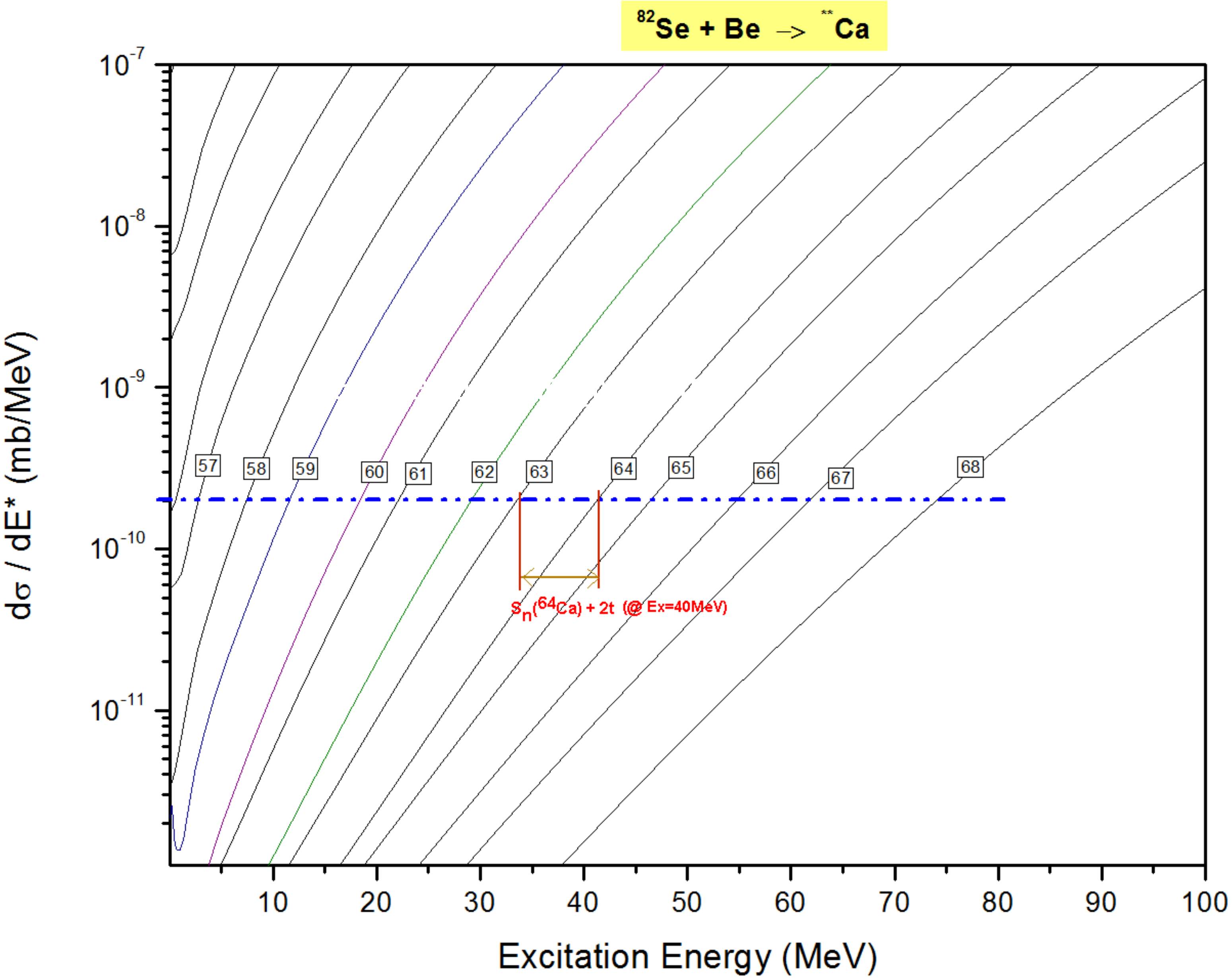
LISE++ AA

^{82}Se + Be –> **Ca



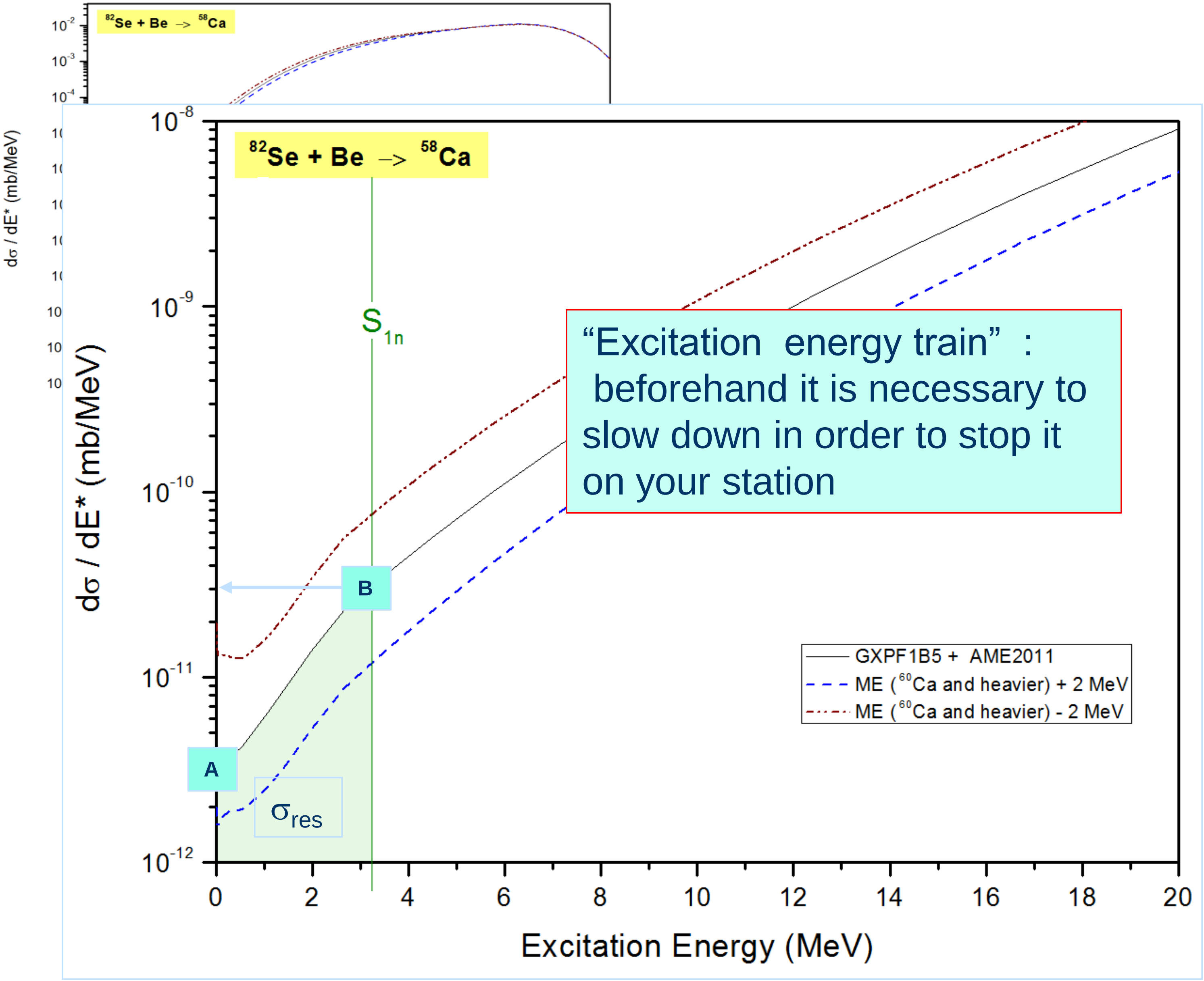
Excitation functions A=48-68 (E^*_0 = 15 MeV)

Zoom



De-excitation process & excitation energy of daughter nucleus:

Excitation energy shift



"Excitation energy train" : beforehand it is necessary to slow down in order to stop it on your station

^{58}Ca: dσ(0)/dE = A

^{58}Ca: dσ(3.2)/dE = B

1. S_{1n}(^{58}Ca)=3.2 MeV : σ(S_{1n})=B is moving to E*=0 for ^{57}Ca excitation function
   ^{57}Ca: dσ(0)/dE = B

2. Let's assume S_{1n}(^{58}Ca)=0 MeV, then in the first rough approach :

   dσ(0/dE)=A is the same value @ E*=0 for ^{57}Ca

   ^{57}Ca: dσ(0)/dE ~ A

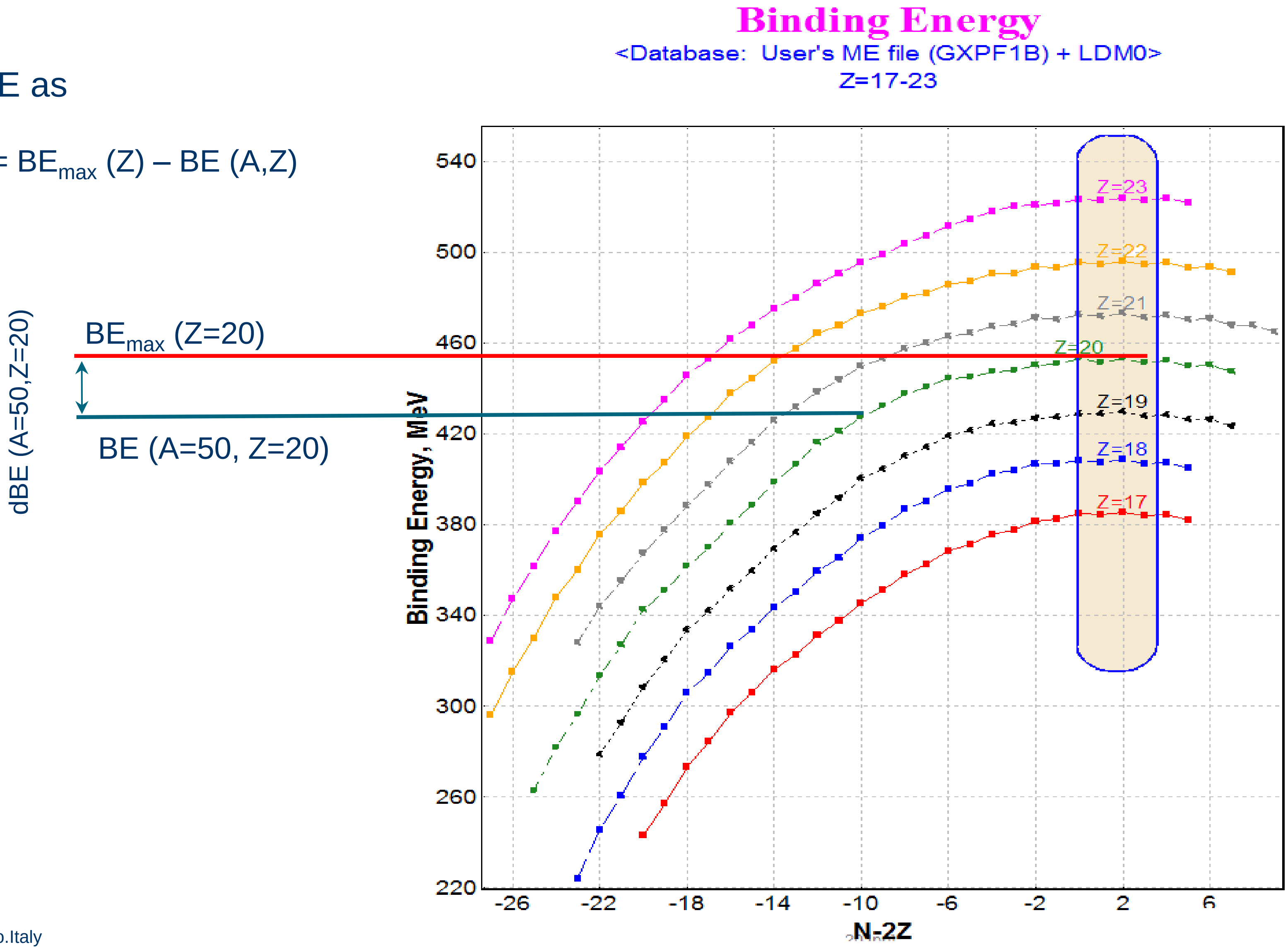
   ^{57}Ca: dσ(2.6)/dE ~ B

Excitation energy several times shifts by S_n

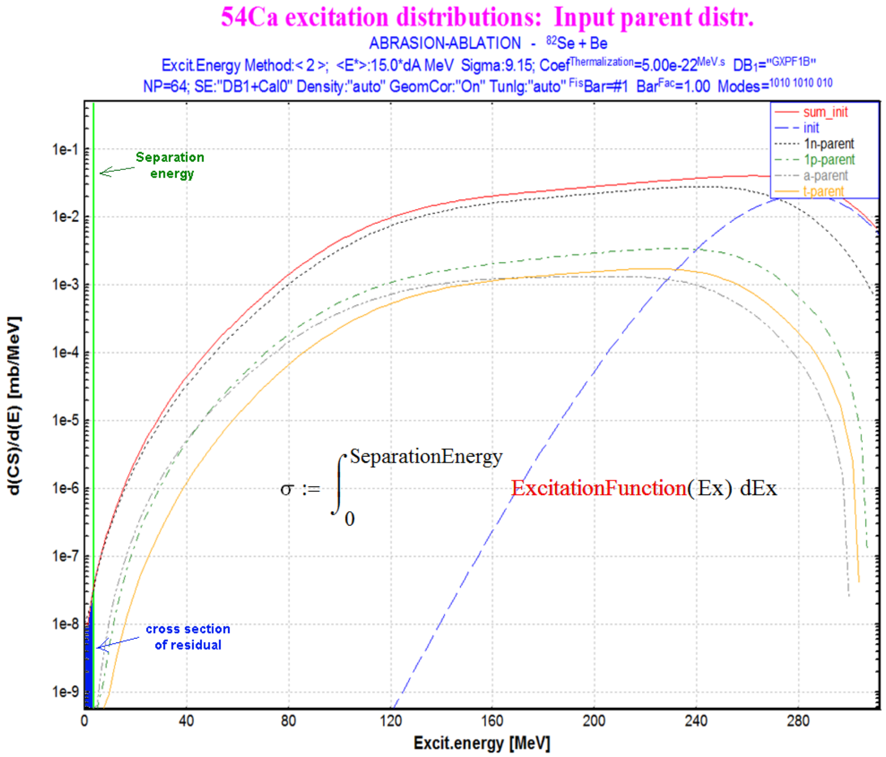
$\Sigma S_n(A,Z) = BE_{max}(Z) - BE(A,Z)$

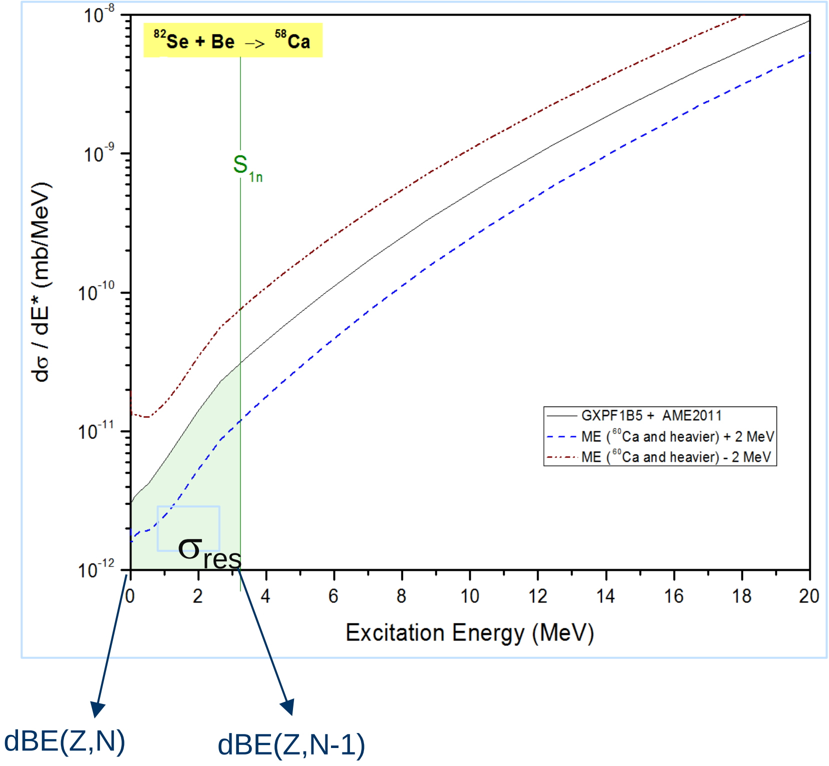
Lets call dBE as

$dBE(A,Z) = BE_{max}(Z) - BE(A,Z)$



Residue Cross Section of neutron-rich isotopes





dBE(Z,N)

dBE(Z,N-1)

$$\sigma\,(Z,N) = f\,[\,dBE(Z,N),\ S_n(Z,N)]$$

$S_n(Z,N)$	minimum separation energy
$dBE(Z,N)$	difference between the maximum biding energy for isotopes (Z) and binding energy of the nucleus (Z,N)

1. $\sigma\,(Z,N) \sim [dBE(Z,N)+a_1)]^{a2} * S_n(Z,N)$

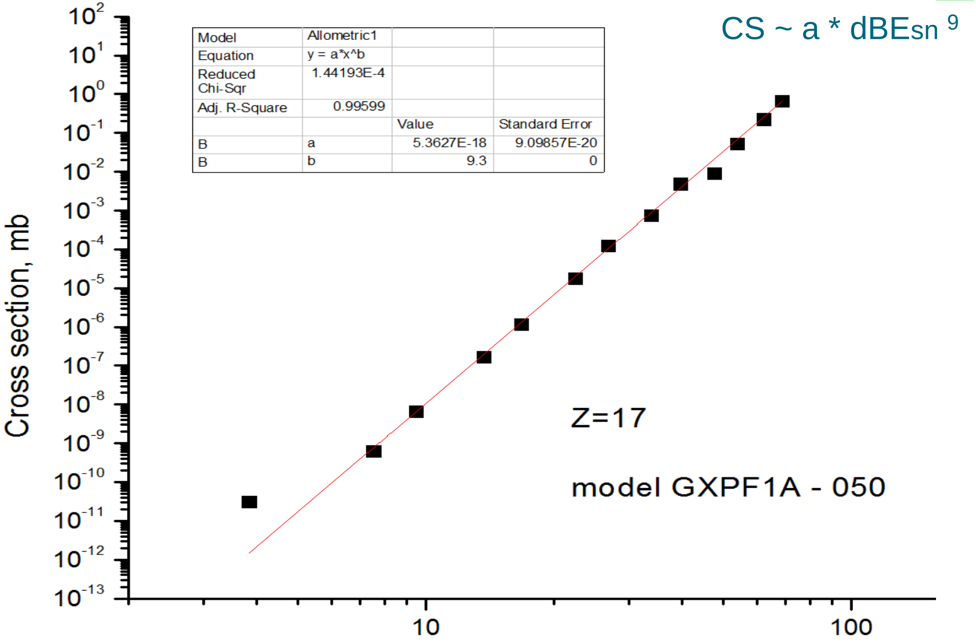
If $S_n(Z,N) \leq 0$, Then $\sigma\,(Z,N) = 0$,
whereas Q_g or BE/A systematics show unbound nuclei

Or Using $dBE(Z,N\text{-}1) = dBE(Z,N) + S_n(Z,N)$,

2. $\sigma\,(Z,N) \sim dBE(Z,N\text{-}1)$

If $S_n(Z,N) \rightarrow 0$ it becomes incorrect

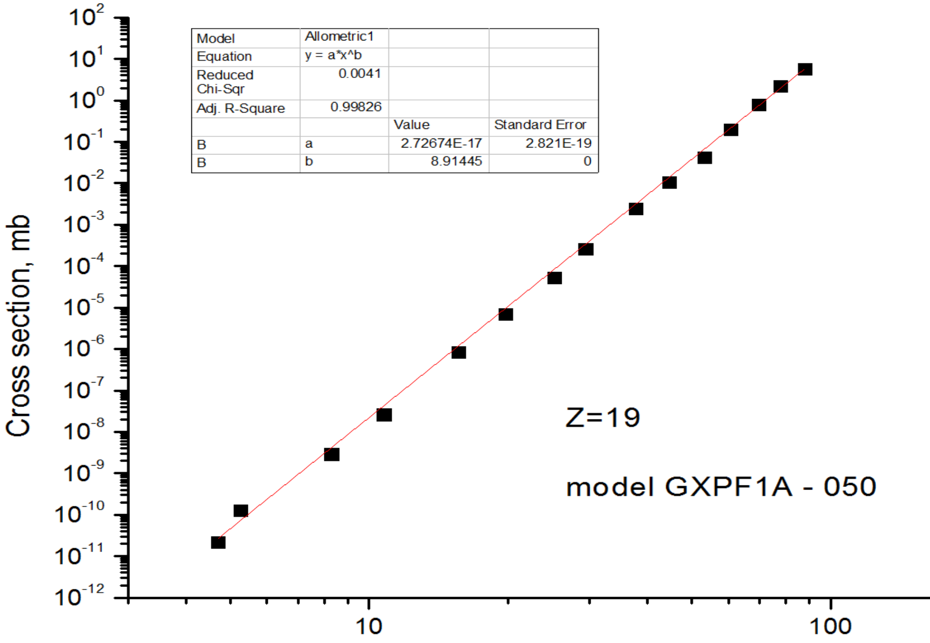
*d*_BEsn Cross Section Systematic vs. Experiment


CS ~ a * dBEsn 9

Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	1.44193E-4		
Adj. R-Square	0.99599		
		Value	Standard Error
B	a	5.3627E-18	9.09857E-20
B	b	9.3	0

Z=17

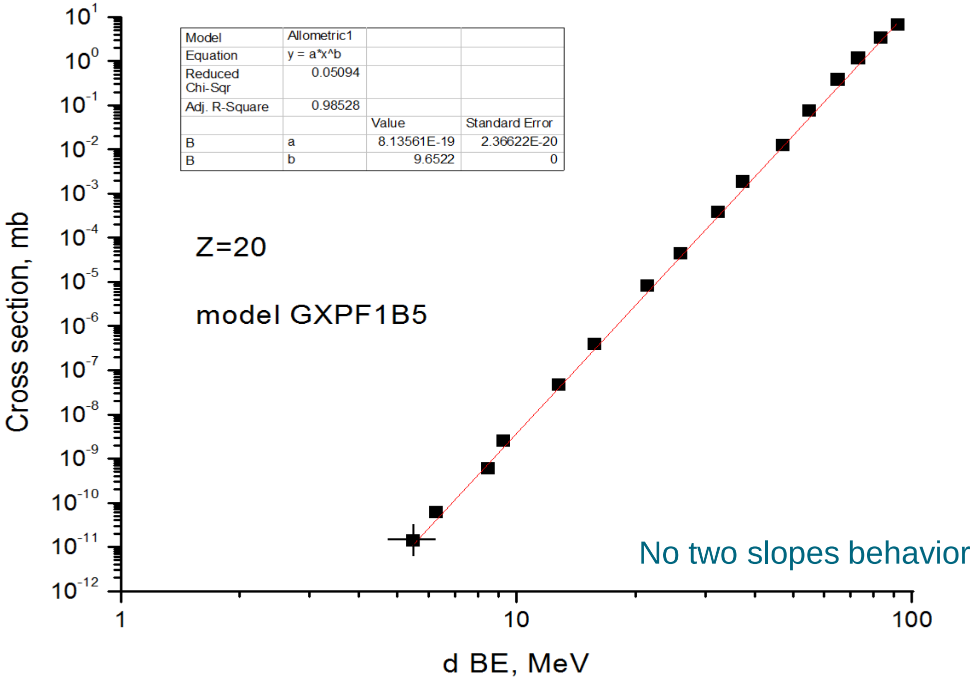
model GXPF1A - 050



Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	0.0041		
Adj. R-Square	0.99826		
		Value	Standard Error
B	a	2.72674E-17	2.821E-19
B	b	8.91445	0

Z=19

model GXPF1A - 050

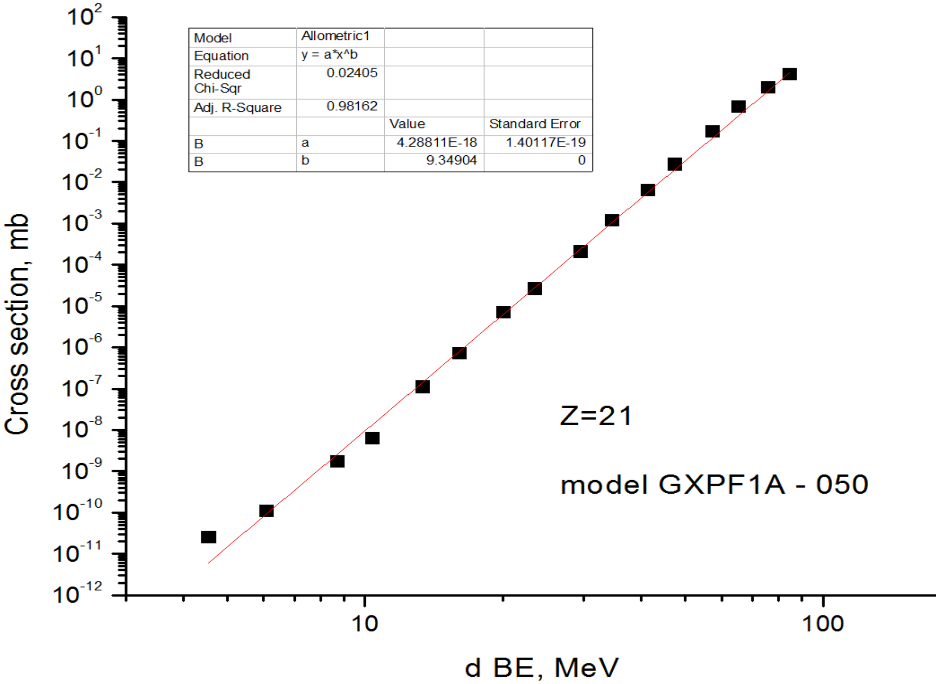


Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	0.05094		
Adj. R-Square	0.98528		
		Value	Standard Error
B	a	8.13561E-19	2.36622E-20
B	b	9.6522	0

Z=20

model GXPF1B5

No two slopes behavior

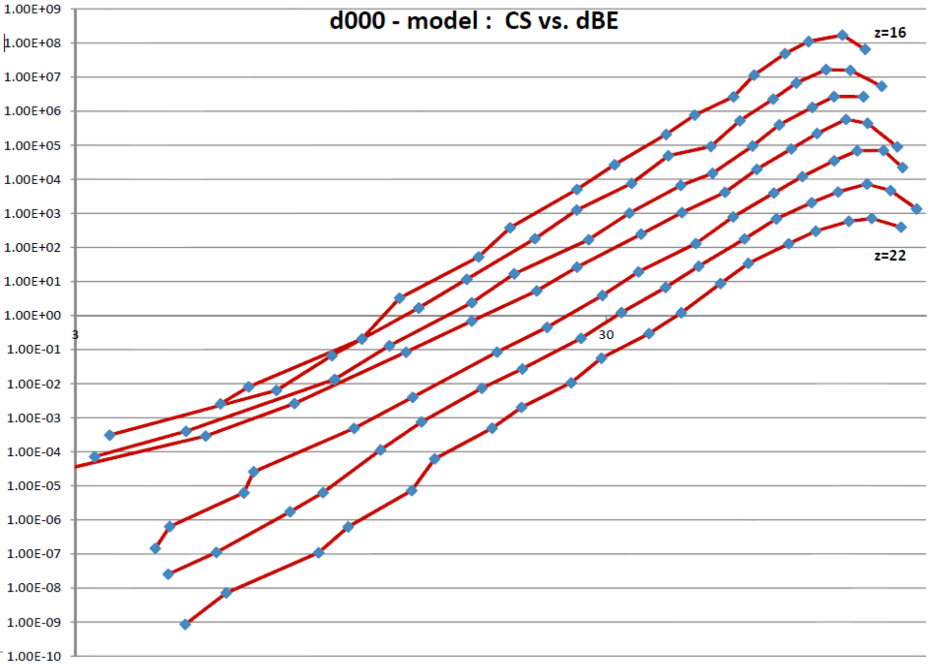


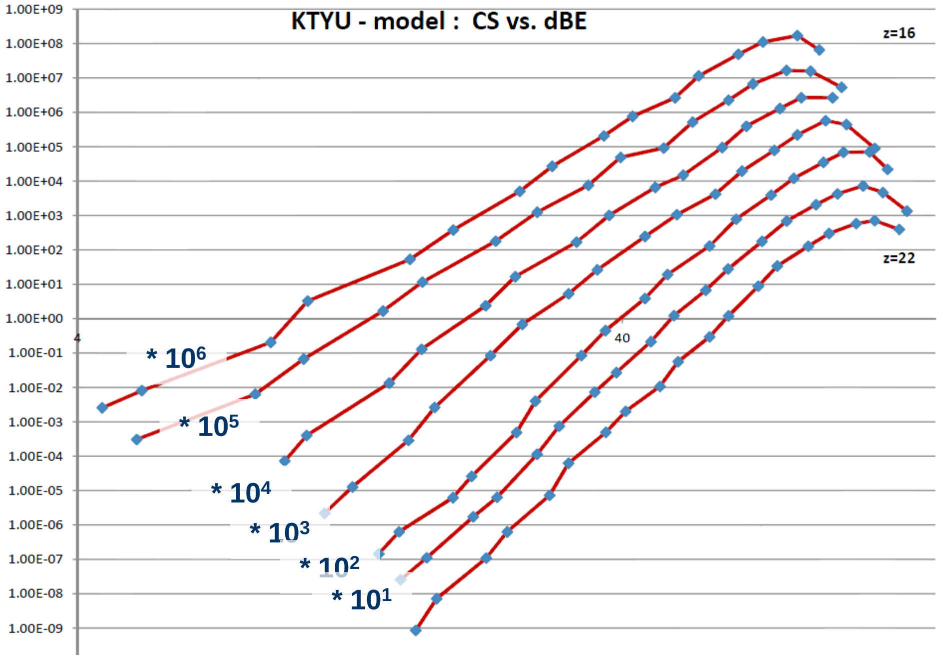
Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	0.02405		
Adj. R-Square	0.98162		
		Value	Standard Error
B	a	4.28811E-18	1.40117E-19
B	b	9.34904	0

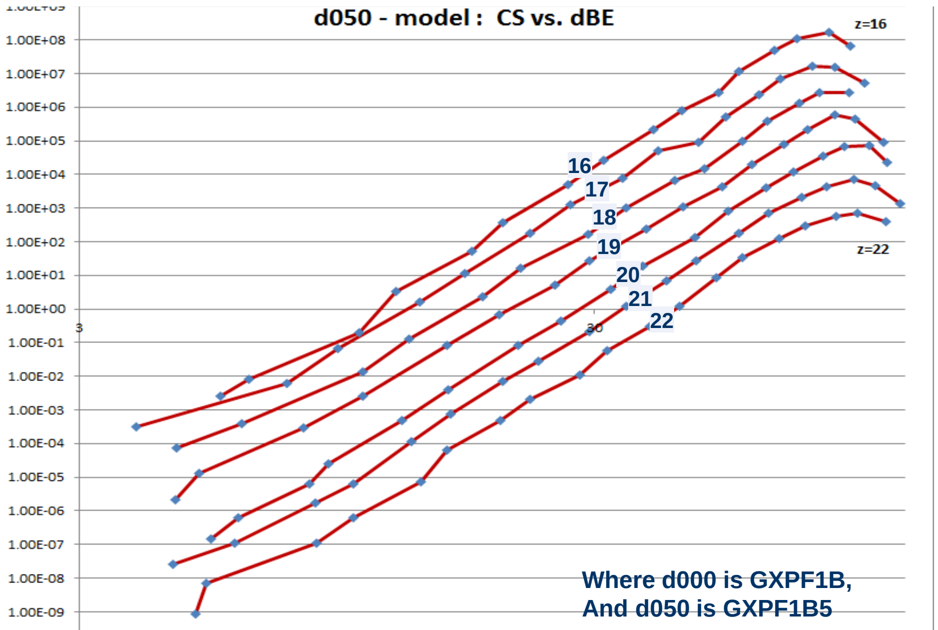
Z=21

model GXPF1A - 050

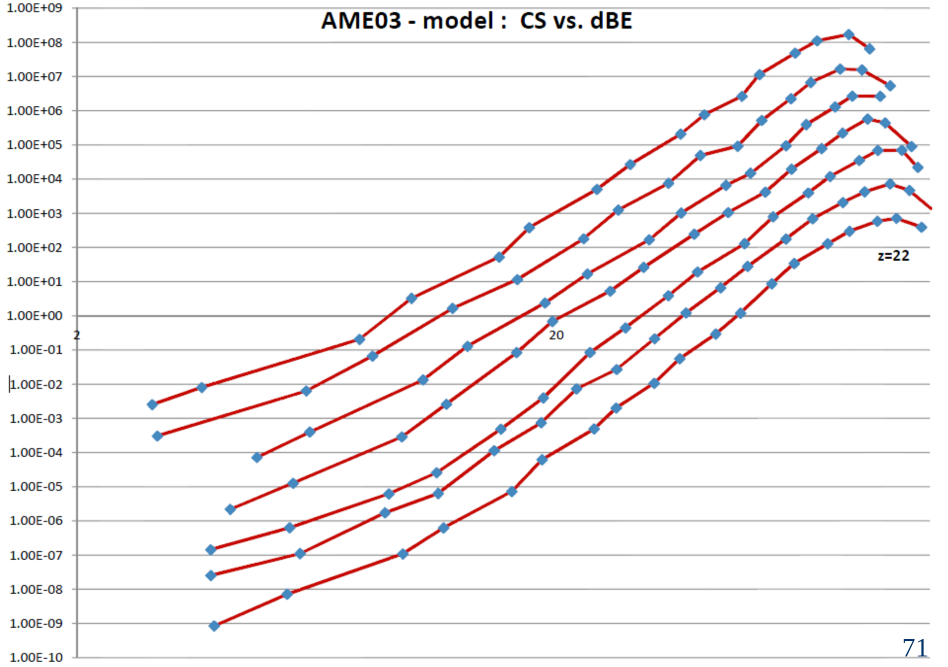
*d*_BE$_{sn}$ Cross Section Systematic with different Mass Models vs. ^{82}Se Experimental Data



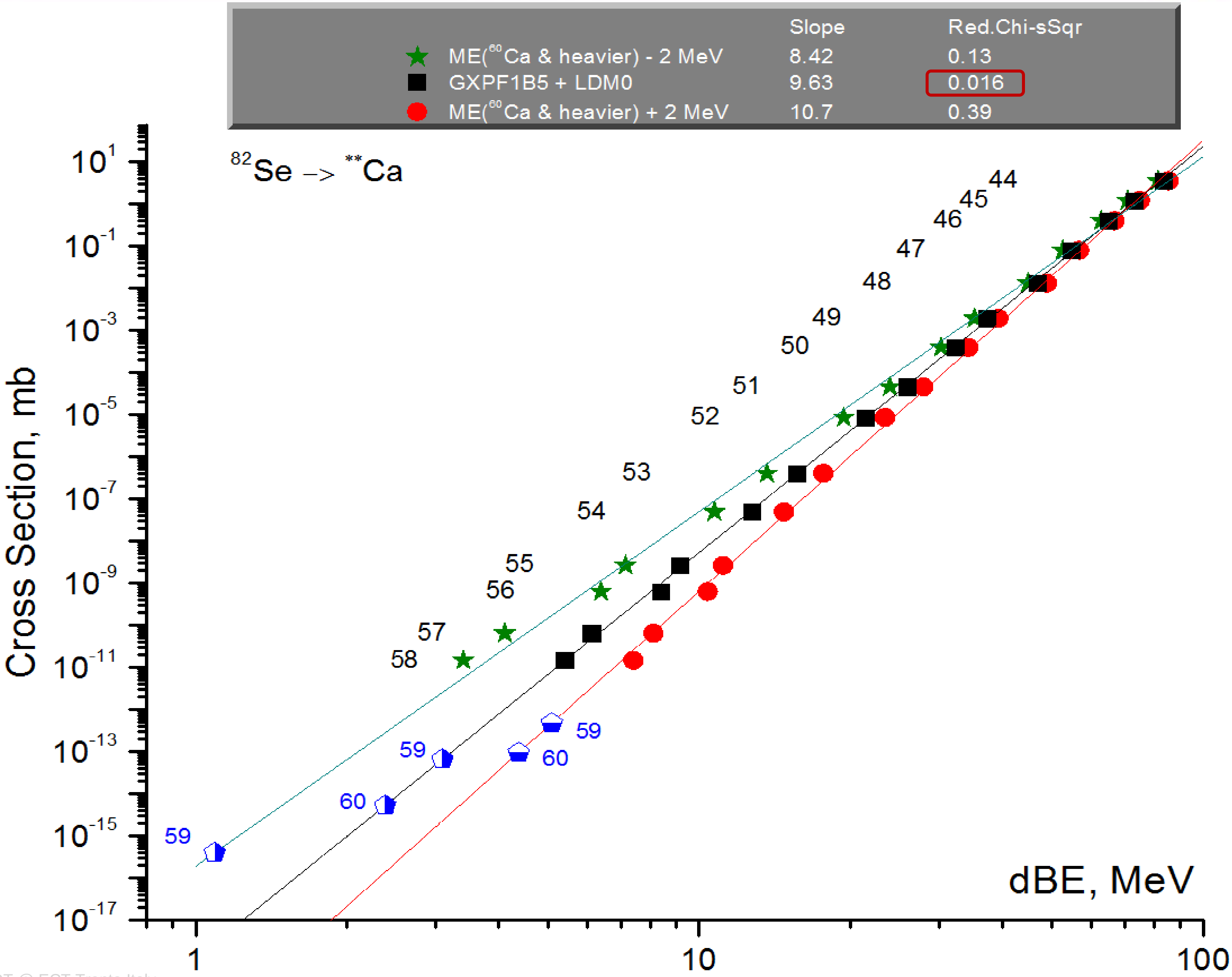




Where d000 is GXPF1B,
And d050 is GXPF1B5

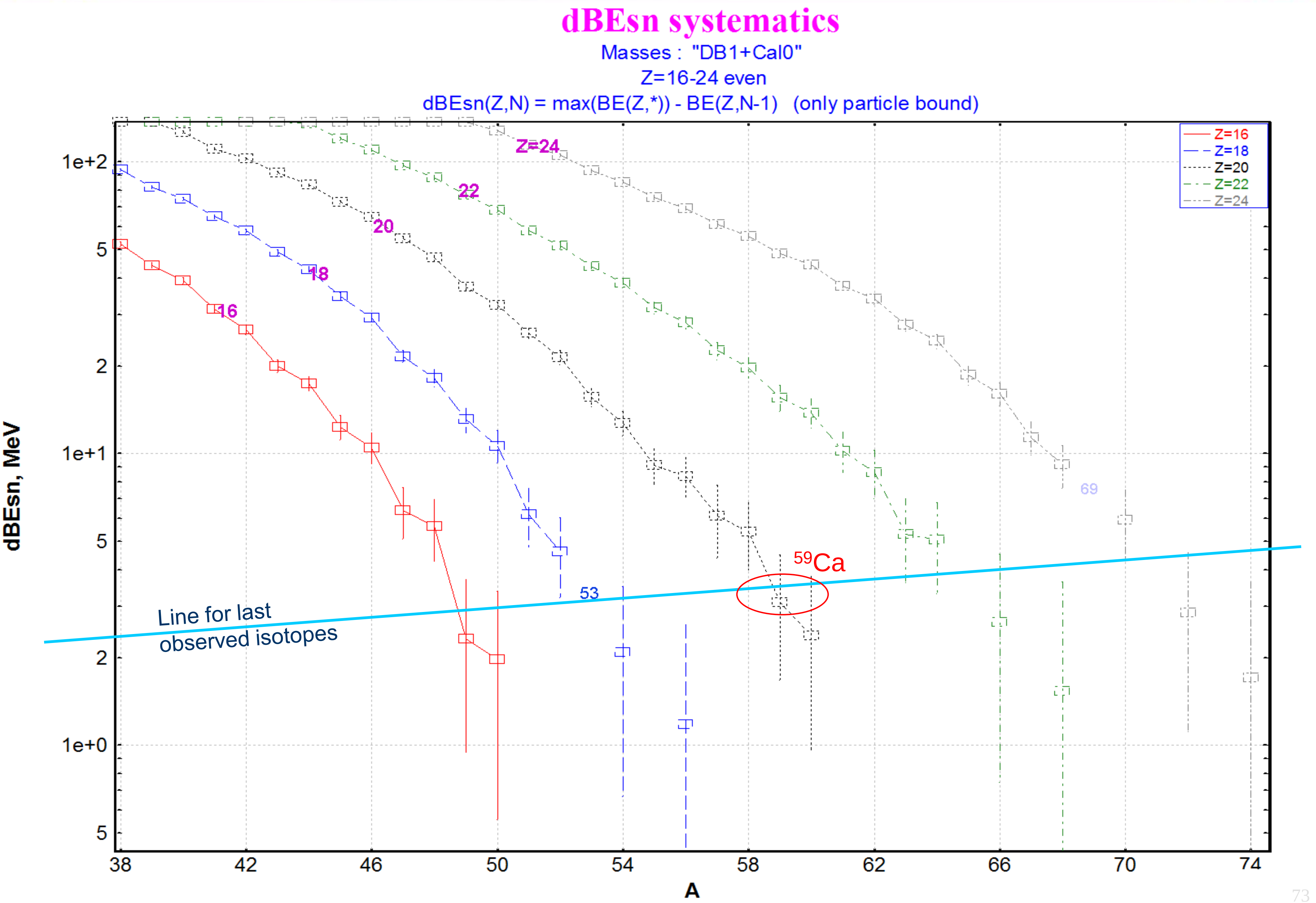


*d*BE distributions : ME value variations



	Slope	Red.Chi-sSqr
★ ME(^{60}Ca & heavier) - 2 MeV	8.42	0.13
■ GXPF1B5 + LDM0	9.63	0.016
● ME(^{60}Ca & heavier) + 2 MeV	10.7	0.39

*d*BE distributions in LISE^{++} : GXPF1B5



dBE-systematics issues

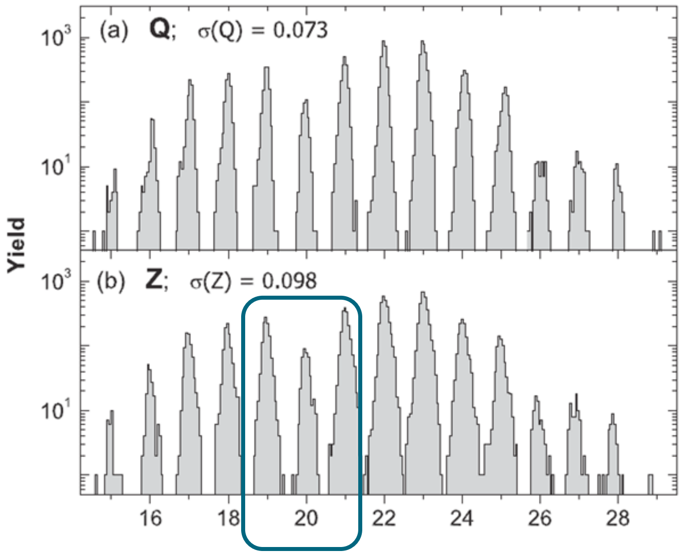
- Deduced, not assumed
- Start energy point
- Unbound nuclei are out of the systematics
- Can be used for other reaction mechanisms, where neutron rich nuclei are produced after emission large number of neutrons
- No parameters (for dBEsn), the same slope?
- No needs for any odd-even corrections and so on

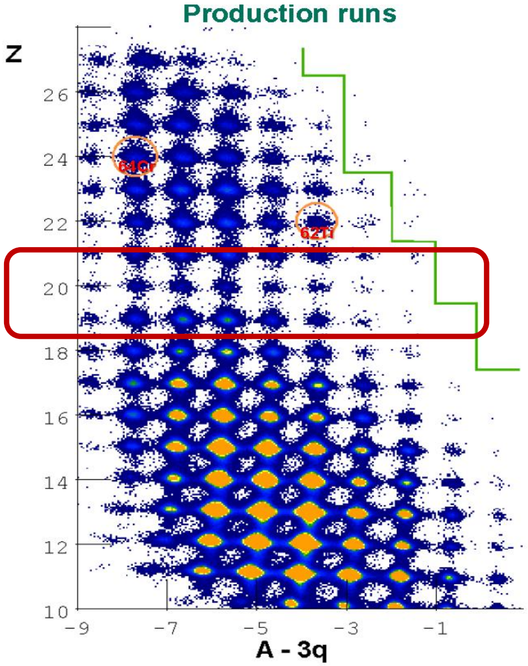
- Unknown isotopes cross section predictions (mass model dependent) using experimental CS data
- Indication for particle stability of nuclei from agreement experimental CS data with theoretical models

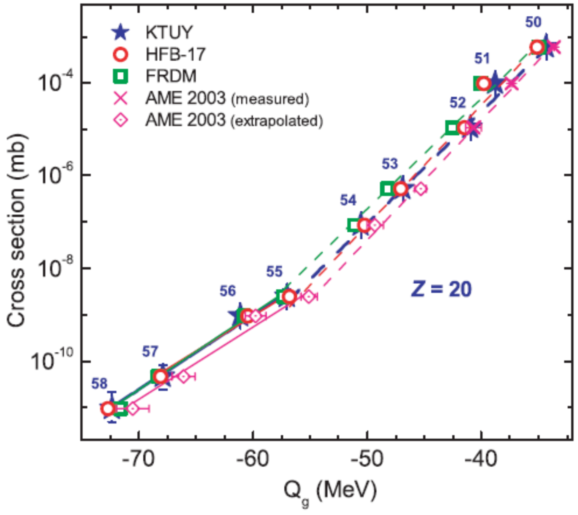
- Works only for regions where neutron de-excitation dominates (de-excitation neutron train)
- In the case of very small S_n the dBE-systematics has to be used instead dBEsn
- Secondary reactions vs. dBE systematics (next slide)

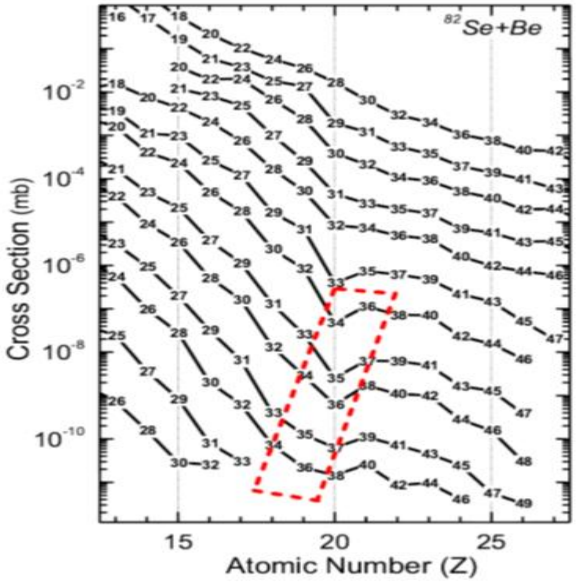
4.1 Anomaly observation

“Calcium anomaly” observation







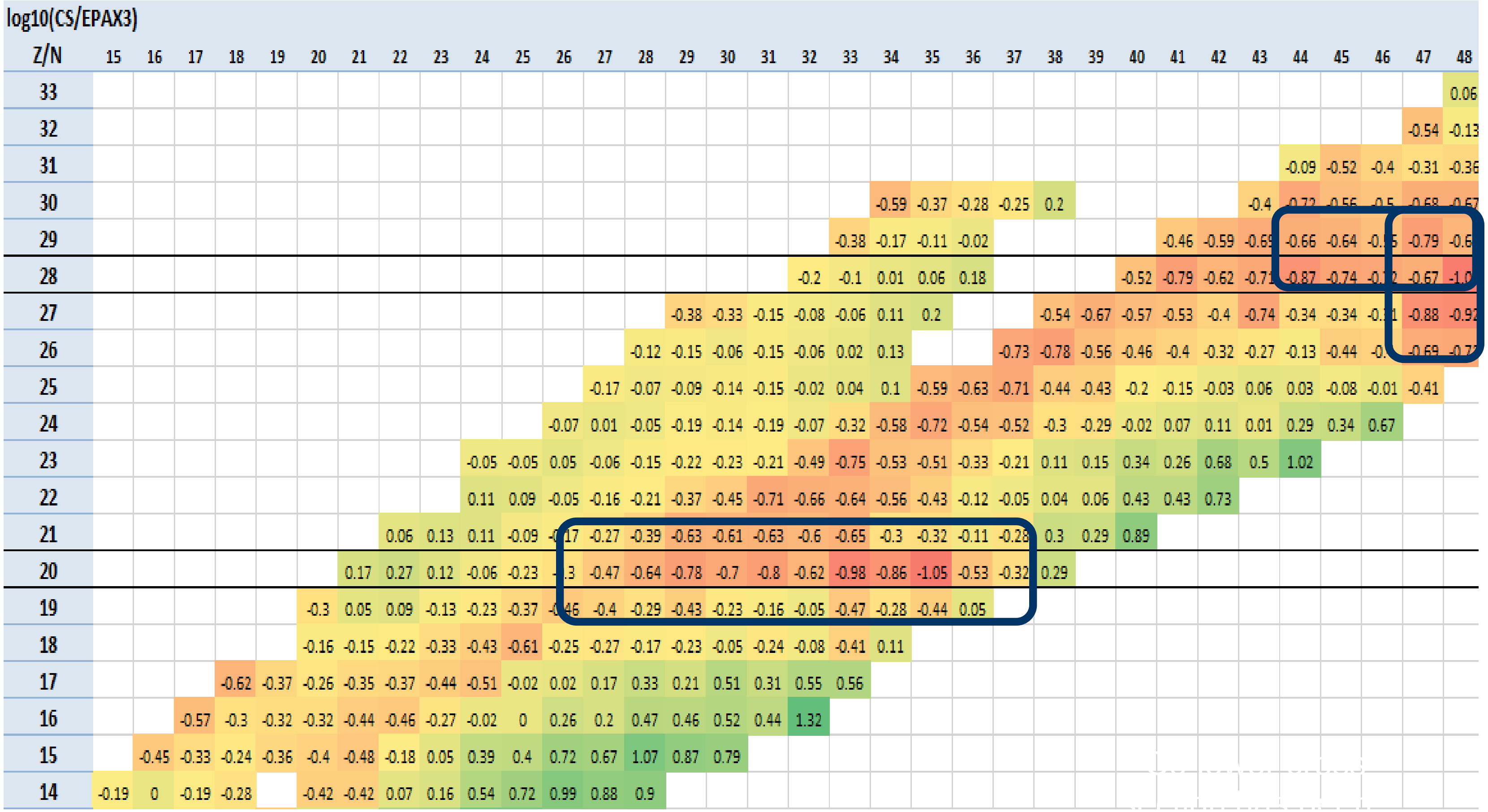


Another representation of Anomalies

^{82}Se (139 MeV/u) + Be

Phys. Rev. C **87**, 054612 (2013)

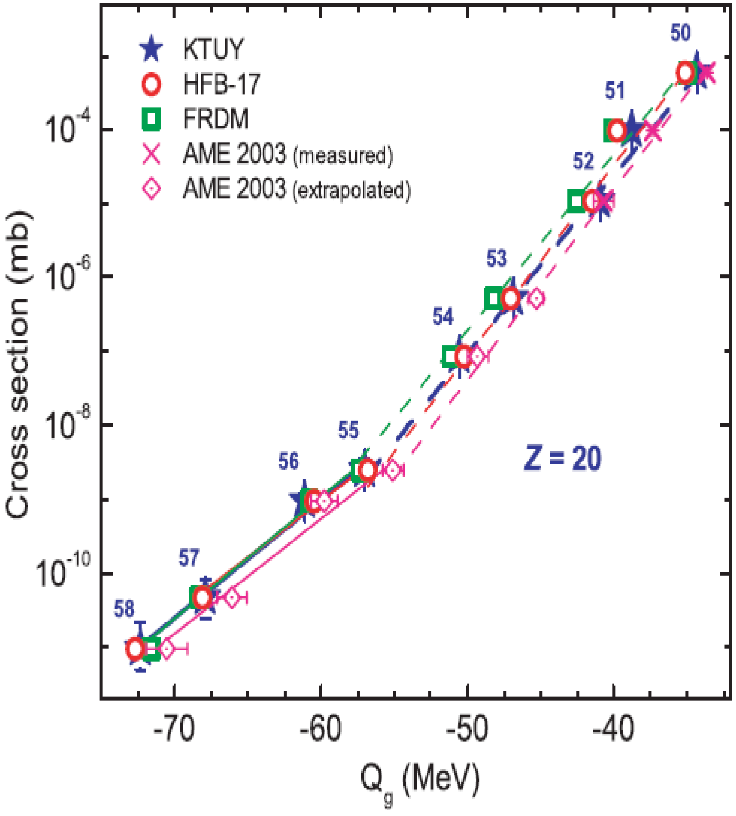
Log10 (Experimental Cross Sections / EPAX 3.15)

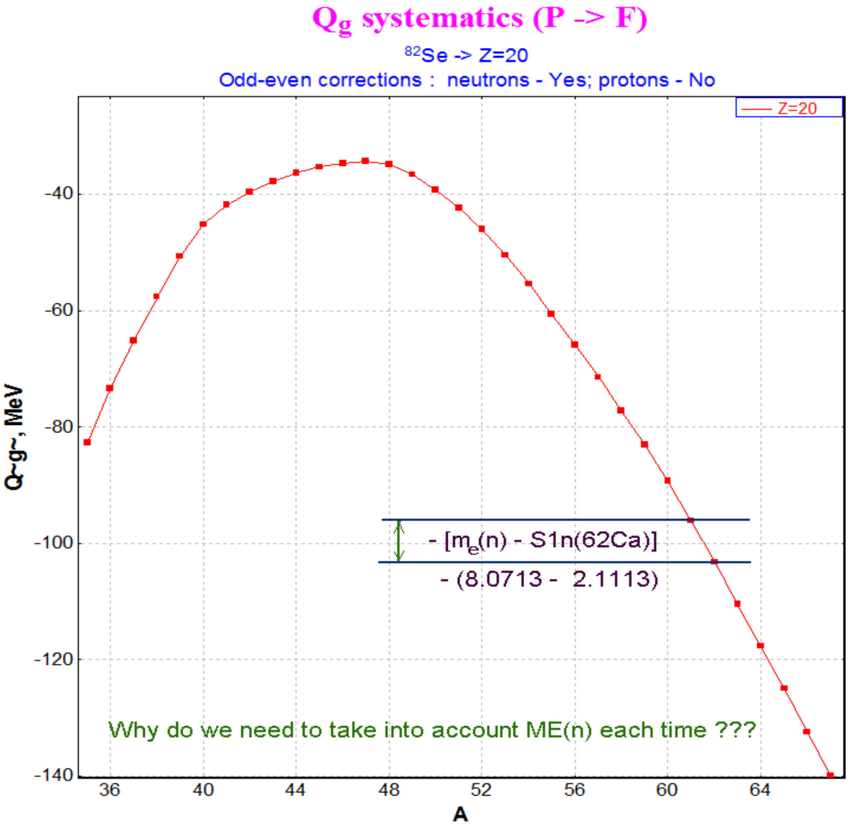


log10(CS/EPAX3)

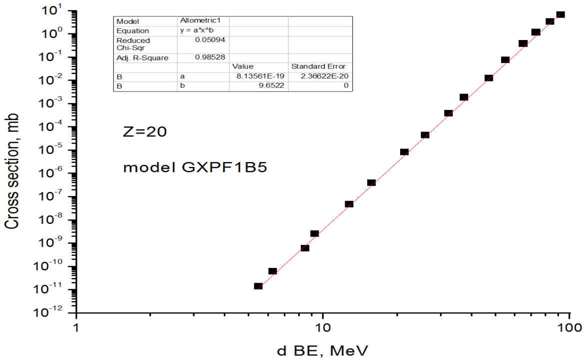
Z/N	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
33																																		0.06
32																																	-0.54	-0.13
31																														-0.09	-0.52	-0.4	-0.31	-0.36
30																				-0.59	-0.37	-0.28	-0.25	0.2					-0.4	-0.72	-0.56	-0.5	-0.68	-0.67
29																			-0.38	-0.17	-0.11	-0.02					-0.46	-0.59	-0.69	-0.66	-0.64	[illegible]	-0.79	-0.6
28																		-0.2	-0.1	0.01	0.06	0.18				-0.52	-0.79	-0.62	-0.71	-0.87	-0.74	[illegible]	-0.67	-1.0
27															-0.38	-0.33	-0.15	-0.08	-0.06	0.11	0.2			-0.54	-0.67	-0.57	-0.53	-0.4	-0.74	-0.34	-0.34	[illegible]	-0.88	-0.92
26														-0.12	-0.15	-0.06	-0.15	-0.06	0.02	0.13			-0.73	-0.78	-0.56	-0.46	-0.4	-0.32	-0.27	-0.13	-0.44	[illegible]	-0.69	-0.77
25													-0.17	-0.07	-0.09	-0.14	-0.15	-0.02	0.04	0.1	-0.59	-0.63	-0.71	-0.44	-0.43	-0.2	-0.15	-0.03	0.06	0.03	-0.08	-0.01	-0.41	
24												-0.07	0.01	-0.05	-0.19	-0.14	-0.19	-0.07	-0.32	-0.58	-0.72	-0.54	-0.52	-0.3	-0.29	-0.02	0.07	0.11	0.01	0.29	0.34	0.67		
23										-0.05	-0.05	0.05	-0.06	-0.15	-0.22	-0.23	-0.21	-0.49	-0.75	-0.53	-0.51	-0.33	-0.21	0.11	0.15	0.34	0.26	0.68	0.5	1.02				
22										0.11	0.09	-0.05	-0.16	-0.21	-0.37	-0.45	-0.71	-0.66	-0.64	-0.56	-0.43	-0.12	-0.05	0.04	0.06	0.43	0.43	0.73						
21								0.06	0.13	0.11	-0.09	-0.17	-0.27	-0.39	-0.63	-0.61	-0.63	-0.6	-0.65	-0.3	-0.32	-0.11	-0.28	0.3	0.29	0.89								
20							0.17	0.27	0.12	-0.06	-0.23	-0.3	-0.47	-0.64	-0.78	-0.7	-0.8	-0.62	-0.98	-0.86	-1.05	-0.53	-0.32	0.29										
19						-0.3	0.05	0.09	-0.13	-0.23	-0.37	-0.46	-0.4	-0.29	-0.43	-0.23	-0.16	-0.05	-0.47	-0.28	-0.44	0.05												
18						-0.16	-0.15	-0.22	-0.33	-0.43	-0.61	-0.25	-0.27	-0.17	-0.23	-0.05	-0.24	-0.08	-0.41	0.11														
17				-0.62	-0.37	-0.26	-0.35	-0.37	-0.44	-0.51	-0.02	0.02	0.17	0.33	0.21	0.51	0.31	0.55	0.56															
16			-0.57	-0.3	-0.32	-0.32	-0.44	-0.46	-0.27	-0.02	0	0.26	0.2	0.47	0.46	0.52	0.44	1.32																
15		-0.45	-0.33	-0.24	-0.36	-0.4	-0.48	-0.18	0.05	0.39	0.4	0.72	0.67	1.07	0.87	0.79																		
14	-0.19	0	-0.19	-0.28		-0.42	-0.42	0.07	0.16	0.54	0.72	0.99	0.88	0.9																				

What is Q_g systematics? Just tendency indicator





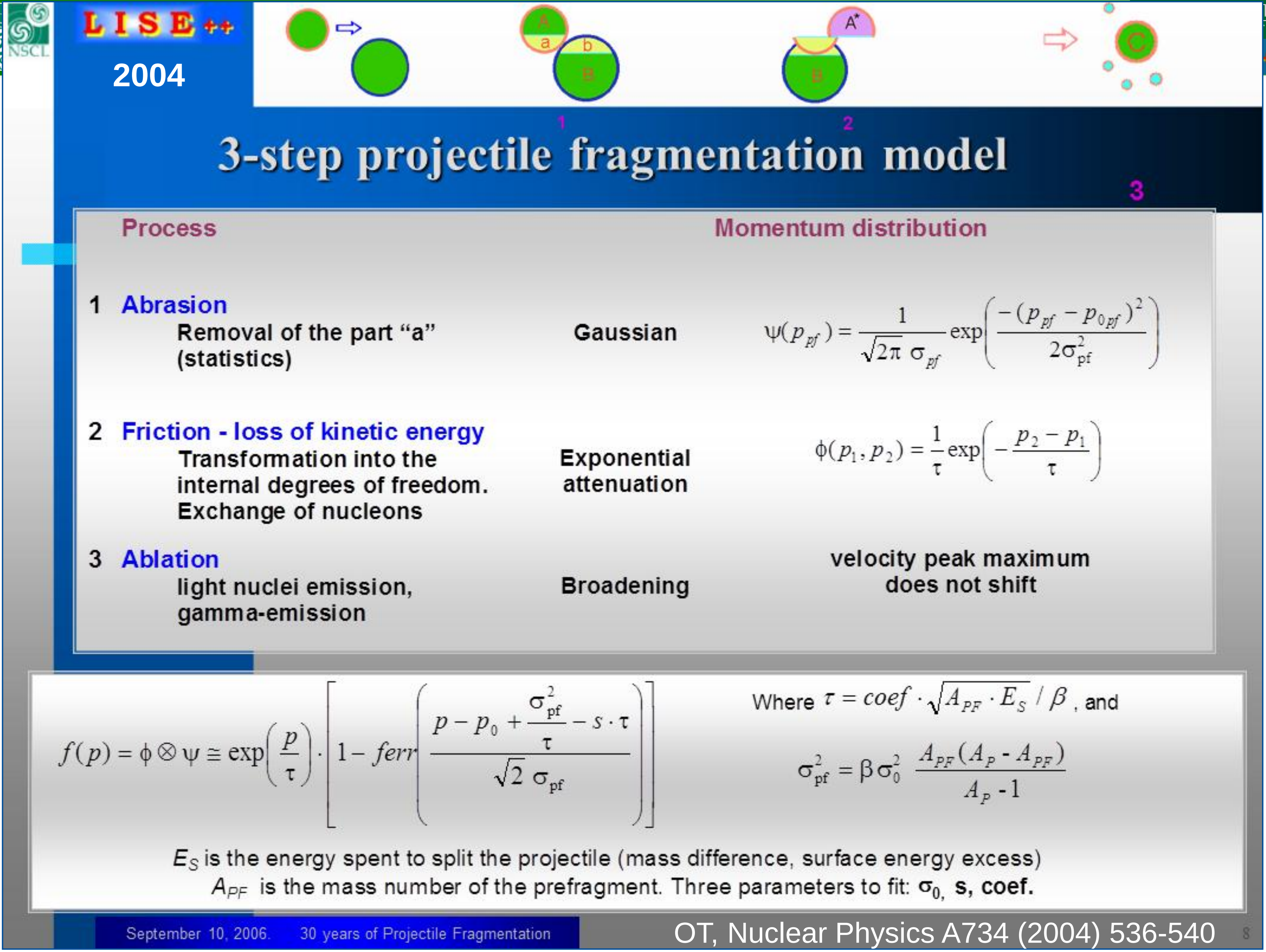
In Q_{gg} systematics “this” neutron is compensated by conjugated products



Model	Allometric1		
Equation	y = a*x^b		
Reduced Chi-Sqr	0.05094		
Adj. R-Square	0.98528		
		Value	Standard Error
B	a	8.13561E-19	2.36622E-20
B	b	9.6522	0

Your version (tendency, law) is correct if you are getting a LINE!

4.2 Projectile fragmentation: Dissipation contribution



2004

3-step projectile fragmentation model

Process		Momentum distribution
1 **Abrasion** Removal of the part "a" (statistics)	Gaussian	$\psi(p_{pf}) = \frac{1}{\sqrt{2\pi}\,\sigma_{pf}} \exp\left(\frac{-(p_{pf}-p_{0pf})^2}{2\sigma_{\mathrm{pf}}^2}\right)$
2 **Friction - loss of kinetic energy** Transformation into the internal degrees of freedom. Exchange of nucleons	Exponential attenuation	$\phi(p_1, p_2) = \frac{1}{\tau}\exp\left(-\frac{p_2 - p_1}{\tau}\right)$
3 **Ablation** light nuclei emission, gamma-emission	Broadening	velocity peak maximum does not shift

$$f(p) = \phi \otimes \psi \cong \exp\left(\frac{p}{\tau}\right) \cdot \left[1 - ferr\left(\frac{p - p_0 + \frac{\sigma_{\mathrm{pf}}^2}{\tau} - s \cdot \tau}{\sqrt{2}\,\sigma_{\mathrm{pf}}}\right)\right]$$

Where $\tau = coef \cdot \sqrt{A_{PF} \cdot E_S} / \beta$, and

$$\sigma_{\mathrm{pf}}^2 = \beta \sigma_0^2 \frac{A_{PF}(A_P - A_{PF})}{A_P - 1}$$

E_S is the energy spent to split the projectile (mass difference, surface energy excess)
A_{PF} is the mass number of the prefragment. Three parameters to fit: σ_0, **s, coef.**

September 10, 2006. 30 years of Projectile Fragmentation 8

OT, Nuclear Physics A734 (2004) 536-540

Abrasion-Friction-Ablation

What do we know from experiments?

1. Decreasing the projectile velocity → increase of production cross-section of neutron-rich isotopes
2. Increasing target mass → increase of production cross-section of neutron-rich isotopes
3. Low Exponential tail in momentum distribution is due to dissipative processes

Why do cross-sections increase?

From the AA formalism:
Increasing excitation low-energy tail.

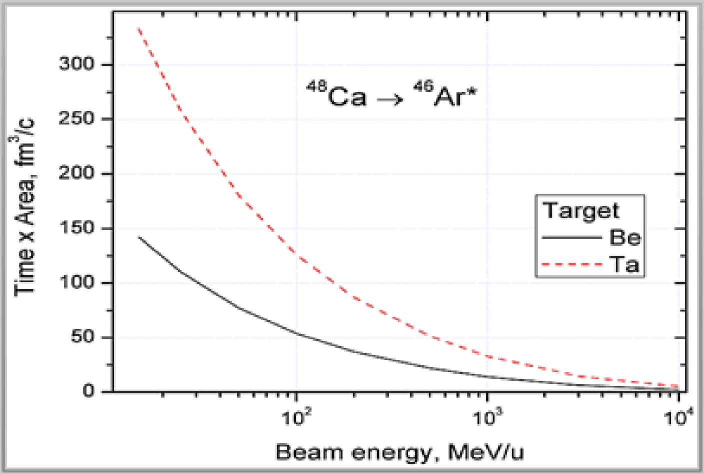
Broadening or/and shift of excitation energy distribution take place due to **friction?**

If assume dissipation processes it is possible to answer on preceding questions:

1. Dissipation Time is increasing
2. Dissipation Time and Touching Area are increasing due to target size

Time of dissipation	**~ to beam velocity & Chord_max**
Touching area is	**~ to Chord_min^2**
Target thermal capacity	**~ target mass**

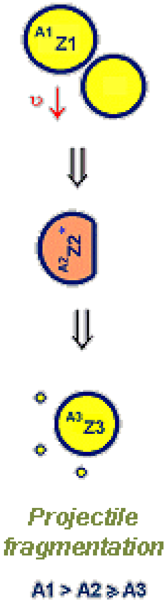
$$dQ = -K\frac{dT}{dx}\enclose{circle}{dS\,dt}$$



Projectile fragmentation & Transfer reactions

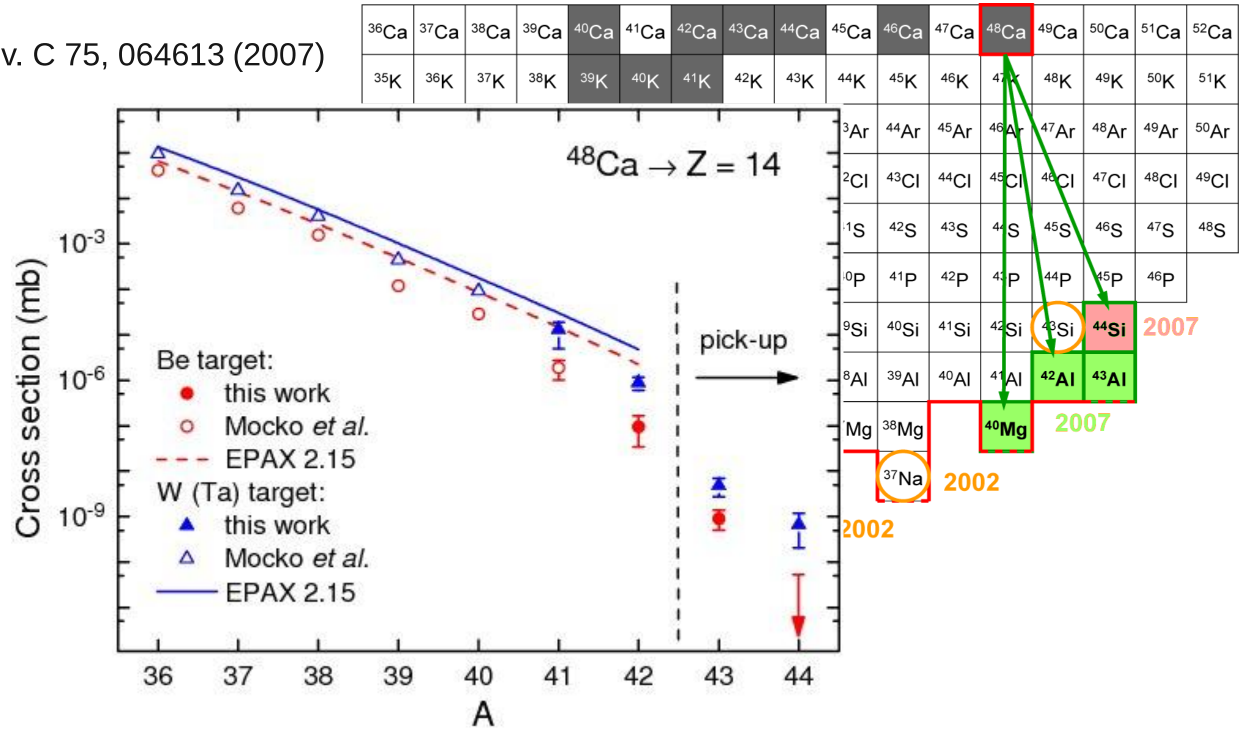
EMIS2007

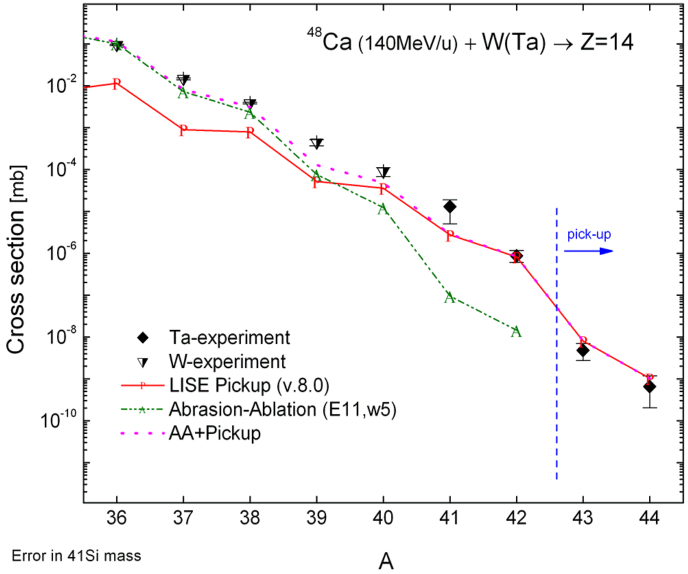
^{44}Si O.T. et al., Phys. Rev. C 75, 064613 (2007)



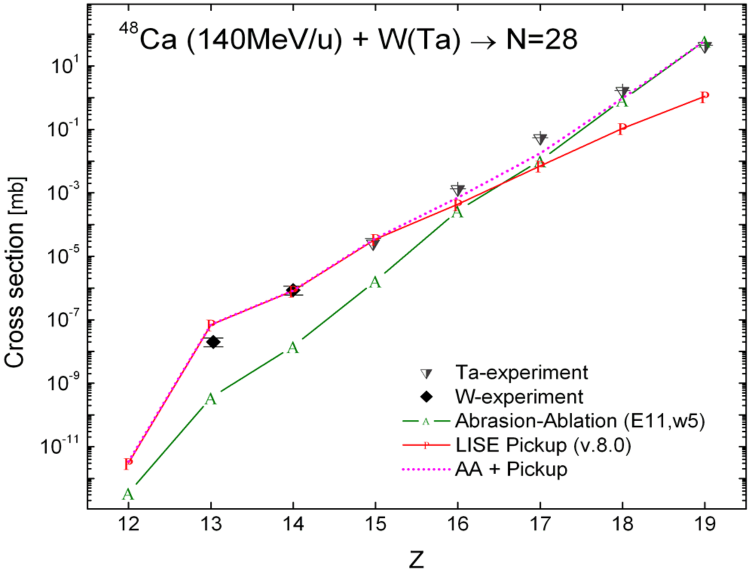
LISE^{++} Abrasion-Ablation cannot explain production cross section dependences from target properties (size, N/Z ratio) and projectile energy.

No explanation for pickup contribution





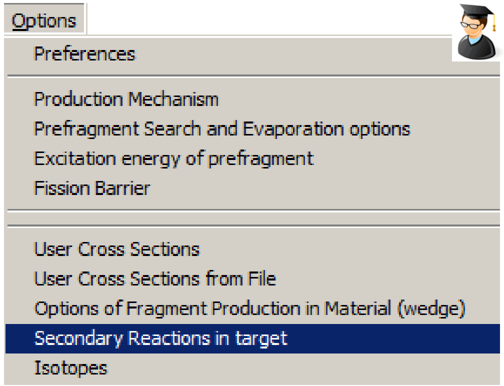
Error in 41Si mass



LISE^{++} Abrasion-Dissipation-Ablation model (ADA) /under construction/

5. Secondary reactions in target

Secondary (multi-step) reactions in target



Options

Preferences

Production Mechanism

Prefragment Search and Evaporation options

Excitation energy of prefragment

Fission Barrier

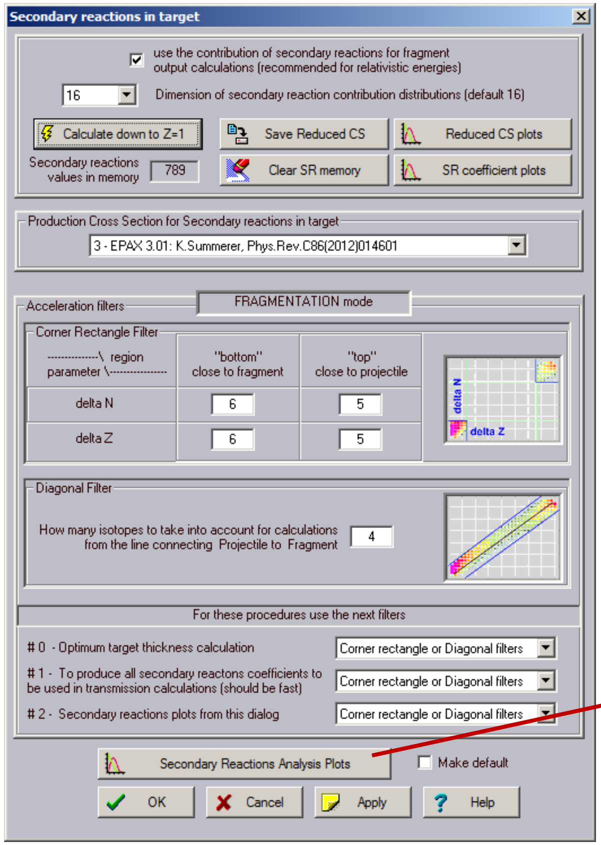
User Cross Sections

User Cross Sections from File

Options of Fragment Production in Material (wedge)

Secondary Reactions in target

Isotopes



Secondary reactions in target

☑ use the contribution of secondary reactions for fragment output calculations (recommended for relativistic energies)

16 — Dimension of secondary reaction contribution distributions (default 16)

Secondary reactions values in memory: 789

Production Cross Section for Secondary reactions in target: 3 - EPAX 3.01: K.Summerer, Phys.Rev.C86(2012)014601

Acceleration filters — FRAGMENTATION mode

Corner Rectangle Filter

region / parameter	"bottom" close to fragment	"top" close to projectile
delta N	6	5
delta Z	6	5

Diagonal Filter

How many isotopes to take into account for calculations from the line connecting Projectile to Fragment: 4

For these procedures use the next filters

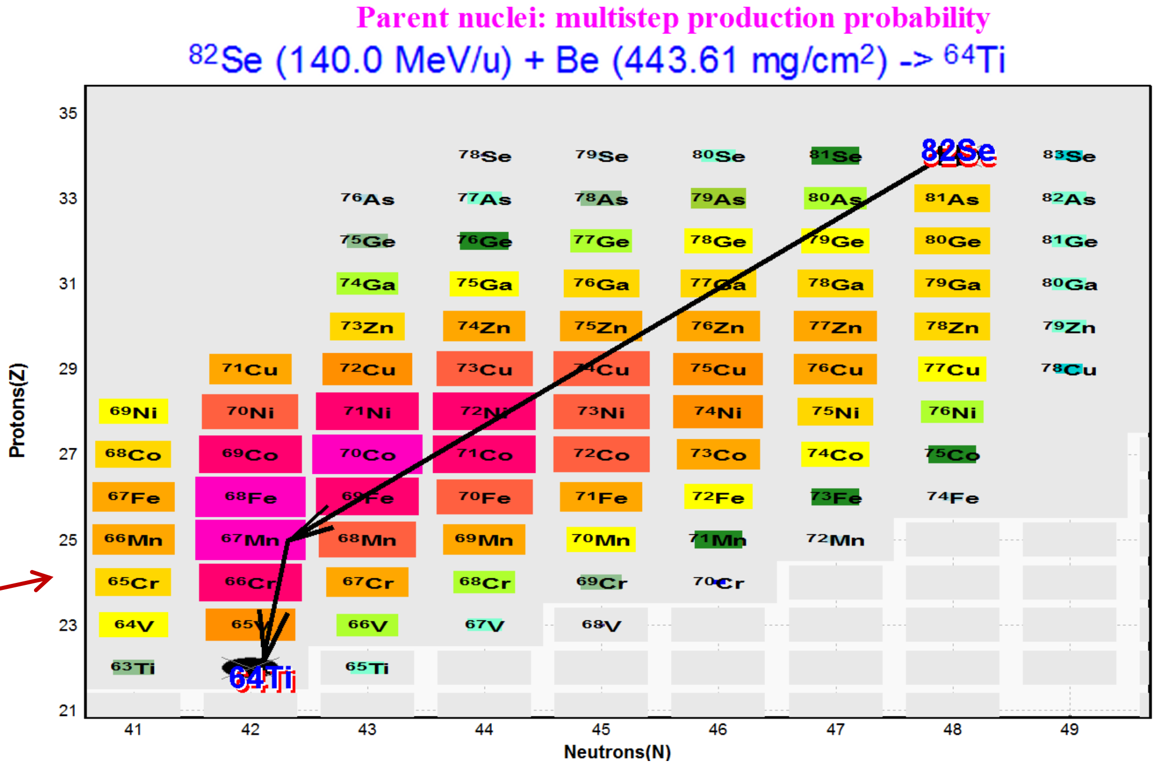
0 - Optimum target thickness calculation: Corner rectangle or Diagonal filters

1 - To produce all secondary reactons coefficients to be used in transmission calculations (should be fast): Corner rectangle or Diagonal filters

2 - Secondary reactions plots from this dialog: Corner rectangle or Diagonal filters

Applied for thick targets

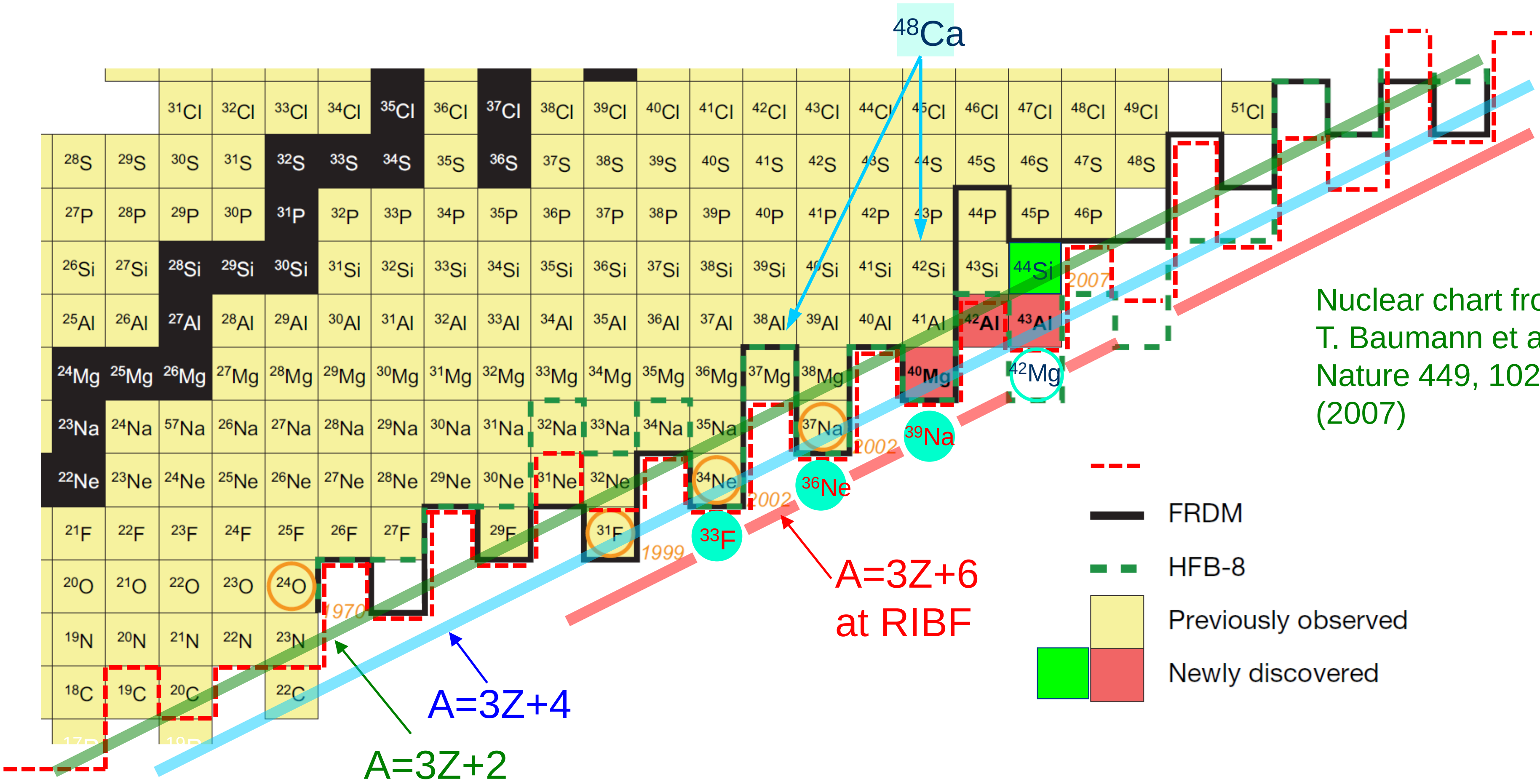
- In this process, the projectile undergoes a series of successive reactions until the fragment of interest is produced
- For the second and next reactions LISE^{++} always assumes a projectile fragmentation and *uses the EPAX parameterizations* to speed up calculations



Parent nuclei: multistep production probability

^{82}Se (140.0 MeV/u) + Be (443.61 mg/cm^2) -> ^{64}Ti

Search for the A=3Z+6 nuclei: 33F, 36Ne, 39Na → Determination of existence/non-existence, Neutron drip-line search



Nuclear chart from T. Baumann et al.: Nature 449, 1022 (2007)

Presented by T. Kubo at NSCL User Meeting in Aug.

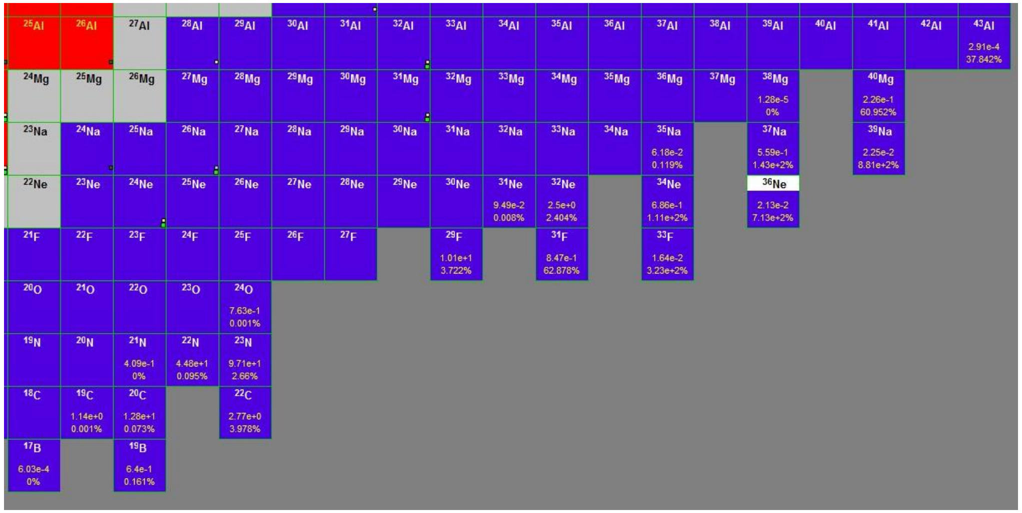
Search for the A=3Z+6 nuclei: ^{33}F, ^{36}Ne, ^{39}Na, (^{42}Mg) : determination of existence/non-existence using an intense ^{48}Ca beam at RIBF

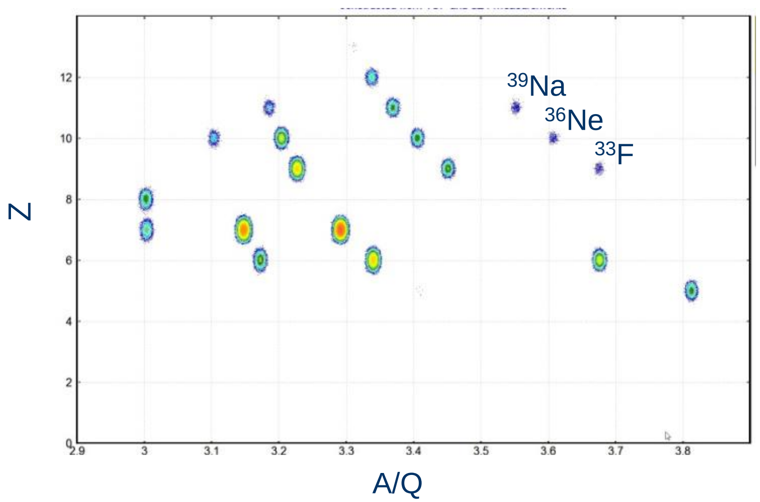
🟩 Oleg Tarasov et al.: Phys. Rev. C75 (2007) 064613 ^{44}Si

🟥 T. Baumann et al.: Nature 449 (2007)1022 ^{40}Mg and ^{42,43}Al

Results of LISE^{++} simulation by Inabe san

^{48}Ca 400pnA, 2.5 days irradiation
Be 30 mm, D1 8.766 Tm, ΔP/P=±3%, F1 degrader 2 mm, F2 ±2 mm

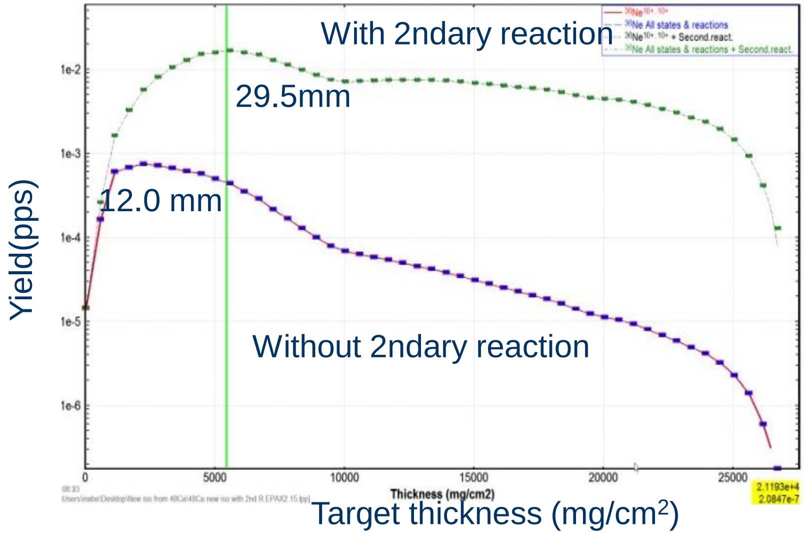




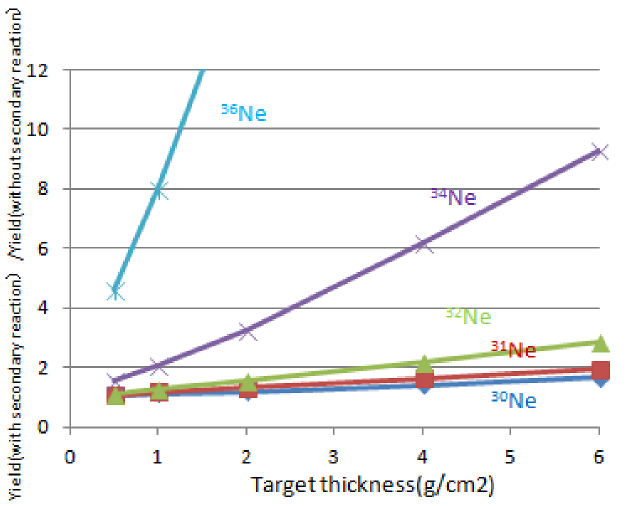
With/without 2nd
→ with/without secondary reaction effects in the target

Isotopes	Yield during 2.5 days with 400pnA（Counts/2.5days）					
	EPAX2.15			EPAX3.01		
	with 2nd	without 2nd	(with/without)	with 2nd	without 2nd	(with/without)
29F	1.7E+06	8.6E+05	2.0	8.6E+04	2.8E+04	3.1
31F	1.5E+05	2.9E+04	5.1	2.1E+03	2.8E+02	7.5
33F	2.9E+03	1.1E+02	27.0	6.7E+00	2.2E-01	30.0
31Ne	1.6E+04	8.6E+03	1.9	1.2E+03	4.3E+02	2.8
32Ne	4.3E+05	1.6E+05	2.7	1.9E+04	4.7E+03	4.1
34Ne	1.2E+05	1.4E+04	8.6	1.3E+03	1.1E+02	11.4
36Ne	3.8E+03	7.3E+01	52.4	6.4E+00	1.2E-01	51.4
35Na	1.1E+04	2.9E+03	3.6	4.0E+02	7.8E+01	5.1
37Na	9.8E+04	7.3E+03	13.6	8.5E+02	5.0E+01	16.9
39Na	4.0E+03	7.4E+01	53.5	5.7E+00	1.1E-01	52.4

Target thickness vs. Secondary reactions



Effect of Secondary reaction

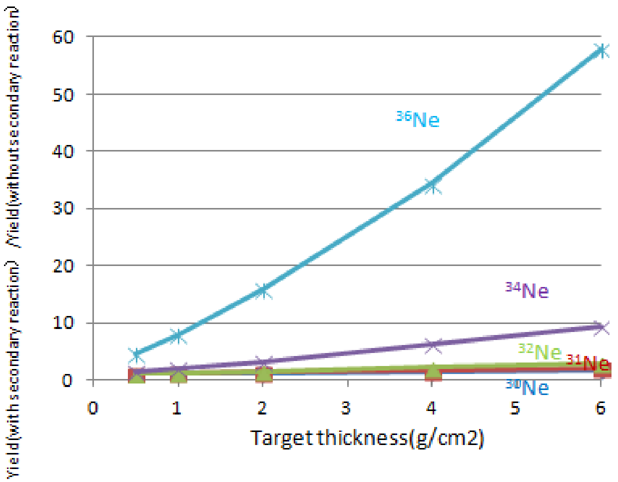


Secondary reactions

The RI which produced from target react with target again and generate different RI.
(Example)
48Ca → 37Na→36Ne

If the target thickness becomes thicker, this process can not be ignored.
The first-step reaction of 37Na to 36Ne is easy to produce with stable. The yield of 48Ca→37Na→36Ne can not be ignored because the cross section of the 37Na→36Ne(1p removal) is large.

Enlarge the above chart

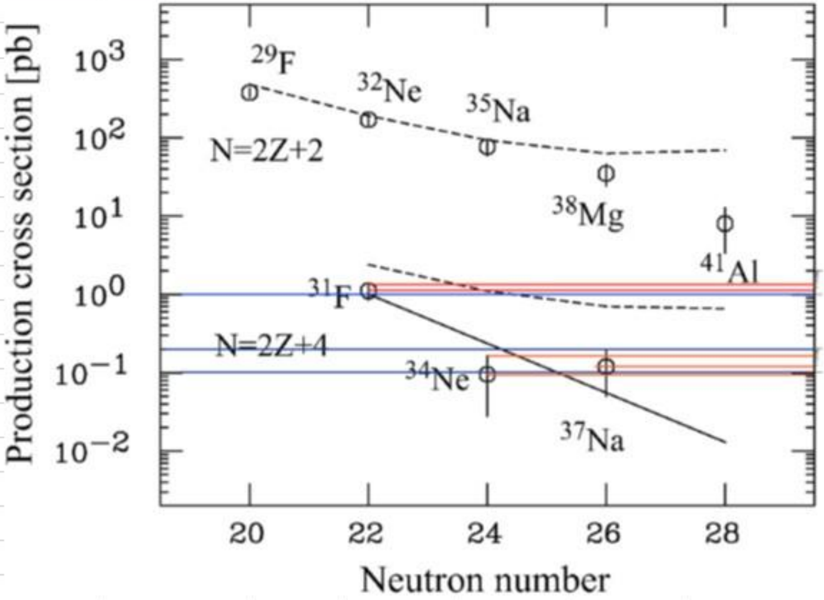


Estimation of Secondary Reactions

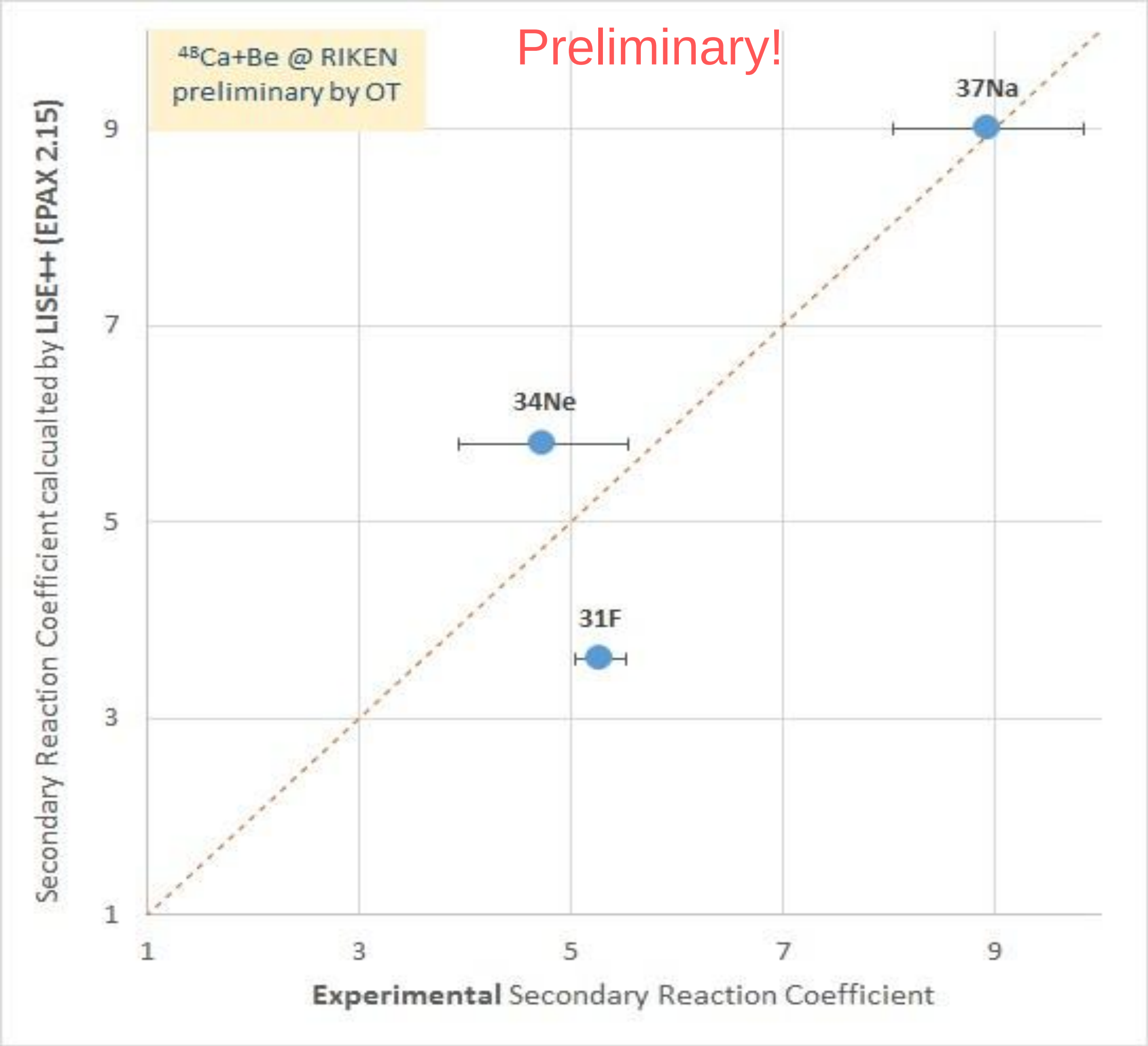
EPAX 2.15 Ratio CS(Ta)/CS(Be)= 2.1

	Cross section, pb								
	Measu-rement BigRIPS, 12/2013	error	LISE++ Calculation EPAX 2.15 (no 2ndary reactions)	RIPS ** 64 MeV/u Ta target	error (+)	RIPS ** 64 MeV/u Be target	ratio BigRIPS/ RIPS Be target	ratio error	LISE++ secondary reaction coefficient
^{31}F	sorry		1.16	1.006	0.01	0.48	sorry		
^{34}Ne			0.53	0.093	0.013	0.04			
^{37}Na			0.34	0.101	0.009	0.05			

** RIPS 64 AMeV:
M. Notani et al., Phys. Lett. B542 (2002) 49



Estimation of Secondary Reactions Contribution

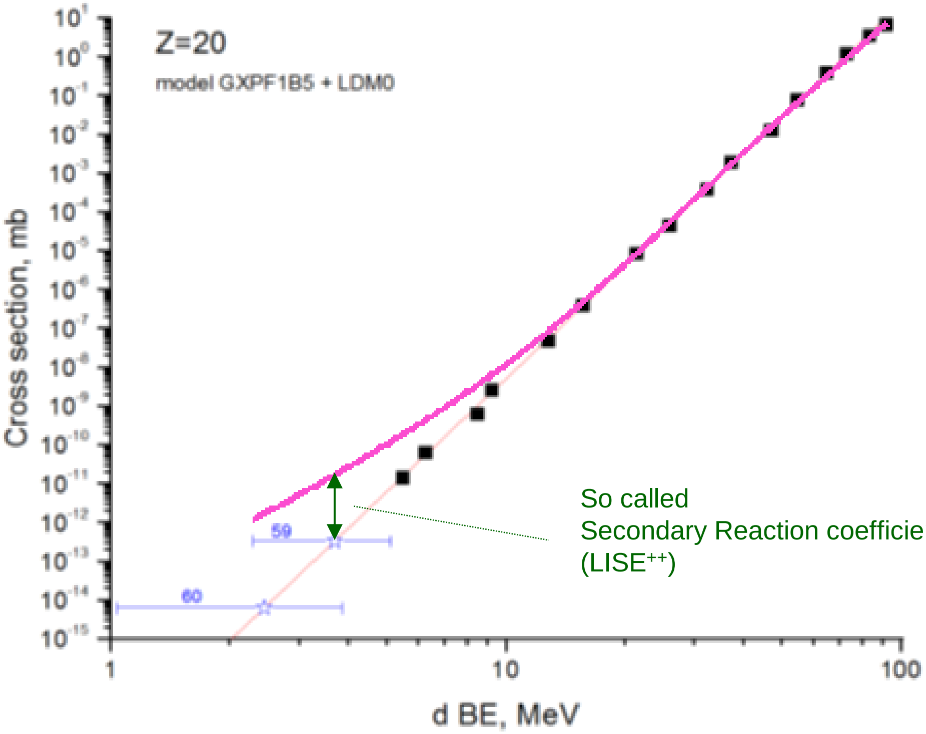


We got ^{37}Na almost one order more due to secondary reactions!

Secondary reactions vs. dBE systematics

dBE-systematics can be important tool to study secondary reactions!!

Recent proposals: several settings (different target thickness) have to be done to study secondary reactions. It's possible only in RIKEN (energy + intensity)…



So called
Secondary Reaction coefficient
(LISE^{++})

Incoming experiment :

^{60}Ca & secondary reactions

- **^{70}Zn (345 MeV/u)+Be**
  RIKEN

6. Summary

Summary for reaction mechanism models to produce rare beams

- **Fusion-Fission**
  ^{238}U(24 MeV/u)+Be,C
- **In-flight fission**
  ^{238}U(345 MeV/u)+Be,U
- **In-flight fission vs projectile fragmentation**
  ^{238}U(345 MeV/u)+Be,U
- **Projectile fragmentation**
  ^{76}Ge, ^{82}Se (140 MeV/u)+Be,W
- **Secondary reactions**
  ^{48}Ca, ^{70}Zn (345 MeV/u)+Be

- Secondary beams production in inverse kinematics
- Update for output channels in low energy domain
- Deformation use

- Fair simulation of intense secondary beams
- Poor reproduction of neutron-rich high Z by the 3-EER m
- New algorithm without averaging regions
- MC benchmarks (+angular momentum)

- What reaction mechanism should be used for Z=65-75 region? (AF, PF, FF, MTR)
- Is there a plateau in isotope cross section distribution? (or how important are secondary reactions? “Evaporation tail” is due to large target thickness?)

- Tool to observe shell effects close to the drip-line
- New dBE-systematics of neutron-rich products
- Dissipation to describe pick-up contribution
- More sophisticated and accurate models

- Observation of Secondary reactions contribution
- Fair reproduction? Should be and will be checked
- What model to use for the secondary step? EPAX2, EPAX3 or other?

Acknowledgements

Thanks to collaborators from MSU, RIKEN, GANIL, JINR, GSI, and many other labs.

Thank you for your attention!

Thank for using (even if it will be in future) the LISE^{++} code!
We are doing all possible from us based on
latest scientific approaches and your requests!

Thank you for choosing our company!

We appreciate your business

Comfort

Speed

Quality

Large Variety of destinations

It is evidently a joke for this community , but …some utilities, and it 's a good tool for students

Go White, Go Green!!!

5 Michigan State Spartans

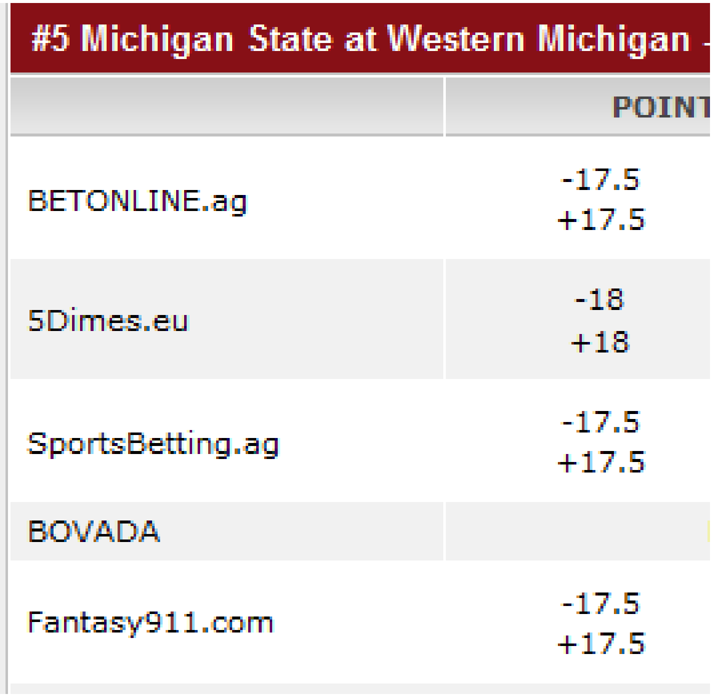
9/5
1:00 AM CEST

This Saturday early morning

@ Western Michigan Broncos

Go Spartans!!! Beat these Broncos!!! ☺

Go White, Go Green!!!



#5 Michigan State at Western Michigan

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Go Spartans!!! Beat these Broncos!!! ☺