

Oleg B. Tarasov  
NCSL / MSU, USA

# Production of Fast Rare Ion Beams

Euroschool on Exotic Beams 2013, Dubna  
Euroschool on Exotic Beams 2013, Dubna

26-31 / 08 / 2013

LISE++

1. Introduction to production of  
Fast Rare Ion Beams

2. **Production Area**

3. Separation

4. Identification

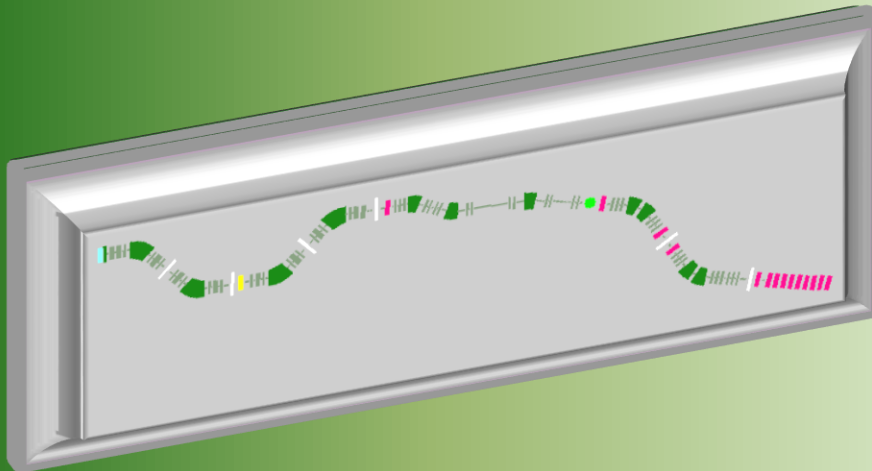
5. Production of new isotopes

6. LISE++: Utilities

7. Radioactive beam  
physicist task



LISE++



## 1. Choice of place for the experiment

- ✓ Intensities
- ✓ Primary beam lists

## 2. Planning of Fast RIB Experiment

- ✓ Ion yields after target

## 3. Settings

- ✓ Beam
- ✓ Target
- ✓ Fragment of interest
- ✓ Charge state model
- ✓ Energy loss model
- ✓ Secondary reactions in target
- ✓ Reaction mechanism

## 4. Reaction mechanisms

- ✓ Evaporation cascade
  - Fission barrier
- ✓ Projectile fragmentation
- ✓ Fission fragment production model
- ✓ Coulomb fission
- ✓ Abrasion-Fission
- ✓ Fusion-Fission
- ✓ Fusion-Residual
- ✓ Two body reactions
- ✓ others

## 5. Efficiency transmission at target

**Some definitions will be used in the lectures**

- for whom this information
- who is responsible



**User**



**Advanced**



**Beam physicist**

- **What is priority?**
  - ❖ **Energy & Intensity combination**
  - ❖ **Energy**
  - ❖ **Intensity**
  - ❖ **Purity**
  
- **Technical devices** (Detector arrays, specific targets)
- **Beam Inclination on target** (LISE@GANIL, A1900@NSCL)
- **Specific separation devices** (Wien-filter, RF-kicker )
- **Reliability of accelerator complex**
  
- **Out of discussion**
  - ❖ Your proposal: how difficult to pass through a PAC
  - ❖ How expensive travelling and lodging
  - ❖ Visa troubles, local food, and so on
  
- **Accelerator type is not criteria**

## Information:

- **Primary beam list**
- **Technical devices availability**
- **Call for proposal**

$$Y = I t N_t \sigma \epsilon_t \epsilon_s \epsilon_i$$

Laboratory	Separator	Energy, Mev/u	target thickness	atoms/cm <sup>2</sup>	Intensity, pnA	Experiment time	published measured cross section [barn]		dose, beam particles	reduced* CS, barn
GSI	FRS	500-1000	Be:1-10g	8.00E+22	3.00E-03	1 week	1E-10	M.Bernas et al., PL B 415 (1997) 111	1E+13	1E-12
GANIL	LISE	75	Ta:1g	3.60E+21	10-100	1 week	2E-13	O.Tarasov et al., PL B409 (1997)64	2E+17	1E-15
RIKEN	RIPS	90	Ta:0.7g	2.30E+21	10-100	1 week	2E-14	H.Sakurai et al., PL B448 (1999) 180	2E+17	3E-15
GANIL	LISE	60	Ta:0.3g	8.80E+20	10-100	1 week	6E-14	S.Lukyanov et al., J Phys G 28 (2002) L41	4E+17	3E-15
RIKEN	BigRIPS	340	Be:1g	6.20E+22	0.1-10	1 week	1E-13	T.Ohnishi et al., JPSJ 79 (2010) 073201	9E+14	2E-14
Dubna	GFS	6-10	Bk: 3e-4 g	7.30E+17	1000	half year	1E-13	Yu.Oganessian et al., PRL 104 (2010) 142502	1E+20	1E-14
NSCL	A1900	140	W:1.9g	6.30E+21	8.00E+01	11 days	9.4E-15	T.Baumann et al., Nature 449 (2007) 1022	5E+17	3.3E-16
NSCL	A1900	130	Be:0.7g	4.70E+22	2.50E+01	1 week	8E-15	O.Tarasov et al., PRL 102 (2009) 142501	9E+16	2.3E-16
NSCL	A1900	140	Be:0.8g	5.35E+22	3.50E+01	1 week	3E-15	O.T. et al., PRC 87 (2013) 054612	1E+17	1.4E-16
FUTURE										
GSI	SuperFRS	1.50E+03	Be:15g	1.00E+24	1.60E+02	1 week			6E+17	1.7E-18
FRIB	A2400	200	Be:1g	6.20E+22	1.00E+04	1 week			4E+19	4.3E-19

\* reduced,  $Y=1$ , assuming  $\epsilon_t \epsilon_s \epsilon_i$  equal to 100%, 100% time just for one production run

\*\* RIKEN : <sup>48</sup>Ca 345 MeV/u 150 pnA

<http://www.nsl.ms.edu/exp/propexp/beamlist>

Home > NSCL Primary Beam List



## Developed Primary Beams

Particle	Energy (MeV/nucleon)	Intensity (pnA)
<sup>16</sup> O	150	175
<sup>18</sup> O	120	150
<sup>20</sup> Ne	170	80
<sup>22</sup> Ne	120	80
<sup>22</sup> Ne	150	100
<sup>24</sup> Mg	170	60
<sup>36</sup> Ar	150	75
<sup>40</sup> Ar	140	75
<sup>40</sup> Ca	140	50
<sup>48</sup> Ca	90	15
<sup>48</sup> Ca	140	80
<sup>58</sup> Ni	160	20
<sup>64</sup> Ni	140	7
<sup>76</sup> Ge	130	25
<sup>82</sup> Se	140	35
<sup>78</sup> Kr	150	25
<sup>86</sup> Kr	100	15
<sup>86</sup> Kr	140	25
<sup>90</sup> Zr	120	1.5
<sup>112</sup> Sn	120	4
<sup>118</sup> Sn	120	1.5
<sup>124</sup> Sn	120	1.5
<sup>124</sup> Xe	140	10
<sup>136</sup> Xe	120	2
<sup>208</sup> Pb	85	1.5
<sup>209</sup> Bi	80	1
<sup>238</sup> U	45	0.1
<sup>238</sup> U	80	0.2



<http://www.nishina.riken.jp/RIBF/accelerator/tecinfo.html>

Beam particle	E/A(MeV)	Beam current (pnA)		Injector
		Maximum (instantaneous) achieved so far	Expected $\uparrow$ (for exp. planning in your proposal)	
d	250	1000	200	AVF
d(pol.)	250	120	30	AVF
<sup>4</sup> He	320	1000	1000	AVF
<sup>14</sup> N	250	400	400	RILAC
<sup>18</sup> O	345	1000	500	RILAC
<sup>48</sup> Ca	345	415	150	RILAC
<sup>70</sup> Zn	345	100	75	RILAC
<sup>76</sup> Ge	345	not tested	N/A	RILAC
<sup>78</sup> Kr	345	under development	50	RILAC
<sup>86</sup> Kr	345	30	50	RILAC
<sup>136</sup> Xe	345	not tested	20	RILAC2
<sup>124</sup> Xe	345	27	20	RILAC2
<sup>238</sup> U	345	15.1	10	RILAC2

$\uparrow$  Some intensities are limited by shielding requirements

## Stable beams

Grand Accélérateur National d'Ions Lourds

**GANIL**

Laboratoire commun CEA/DSM - CNRS IN2P3

<http://pro.ganil-spiral2.eu/users-guide/accelerators/available-stable-ion-beams-at-ganil/view/>

**SPIRAL beams** <http://pro.ganil-spiral2.eu/users-guide/accelerators/spiral-beams/>

- ❑ **Select correct configuration file**
- ❑ **Choose reaction for desired product**
- ❑ **Choose of primary beam and production target based on the reaction choice**
- ❑ **Settings**
  - **Set desired fragment**
  - **Multi-step fragmentation in very thick targets?**
  - **Set options (energy loss, charge state and so on) corresponding to these energies, reaction and so on**
  - **Define momentum acceptance**
  - **Set wedge slits**
- ❑ **Define detector system in beam-line**
- ❑ **Optimize target thickness**
  - **Compromise between target yield and energy loss**
  - **Use optimum target calculator**
- ❑ **Choose wedge thickness**
  - **Compromise between intensity and purity**
  - **Also depends on the type of experiment**
  - **Can use target-wedge optimizer, but slow...**
- ❑ **Forecast of yields and purity**
- ❑ **Define detector system in the focal plane**
- ❑ **Test of experiment feasibility**

- ❑ Select correct configuration file

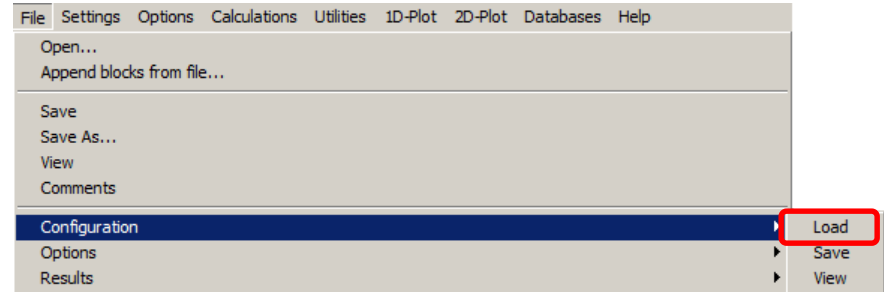
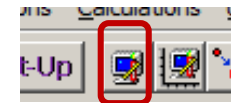


Table 1. File extensions used by LISE++.

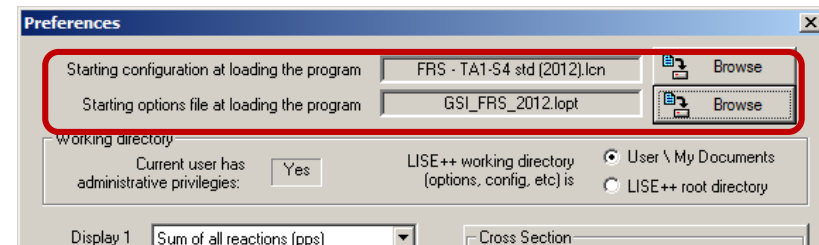
Type of file	LISE++	Default directory
Regular	lpp	/files
Configuration (set-up)	lcn	/config
Option	lopt	/options
Degrader	degra	/degrader
Calibration	cal	/calibrations
Matrix	mat	/files
Cross section	cs	/CrossSections
....	...	...

**LPP = LCN +  
LOPT +  
Experiment settings +  
Calculation results +  
User Cross sections**

After installation of the LISE++ package

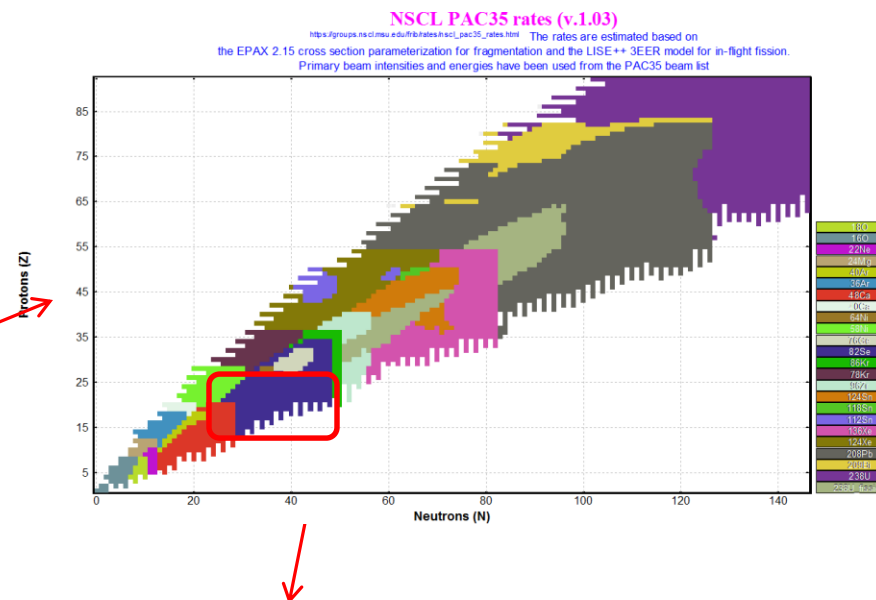
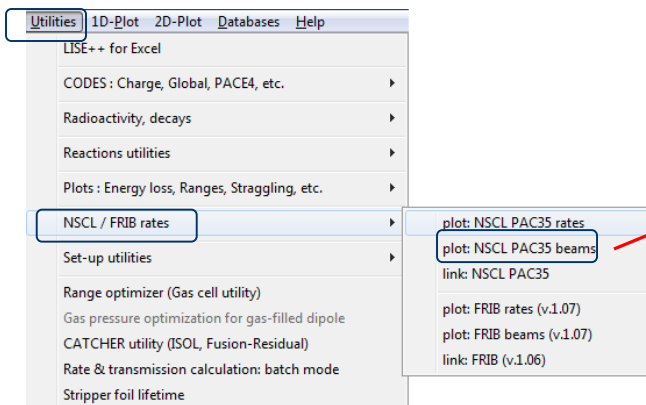


**Default configuration:** A1900\_2013.lcn  
**Default option file:** A1900\_2013.lopt  
 which are set for projectile fragmentation (~80-200 MeV/u)



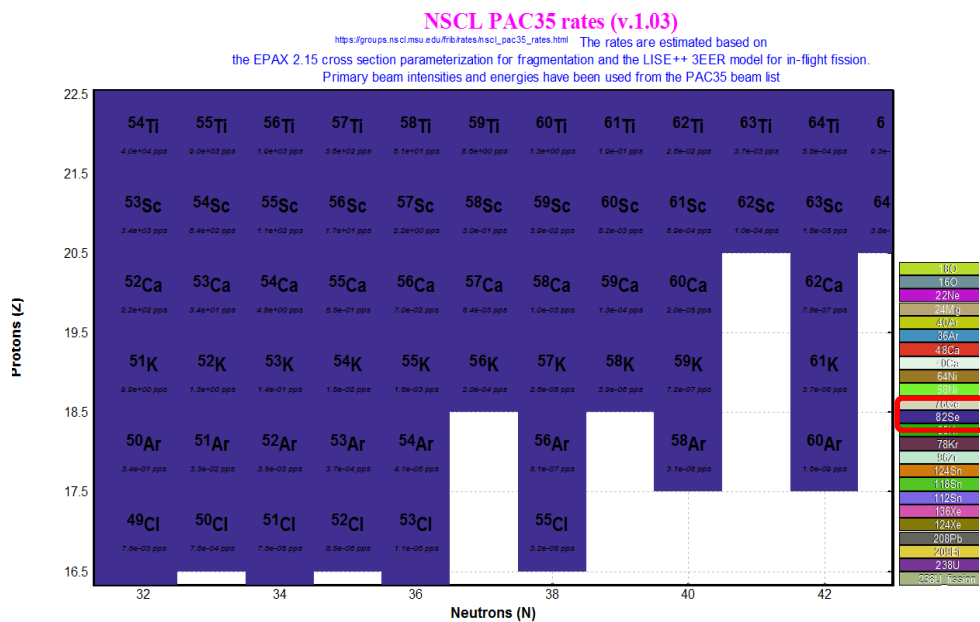
## Question:

What reaction and beam for production of neutron rich calcium isotopes?



## Answer:

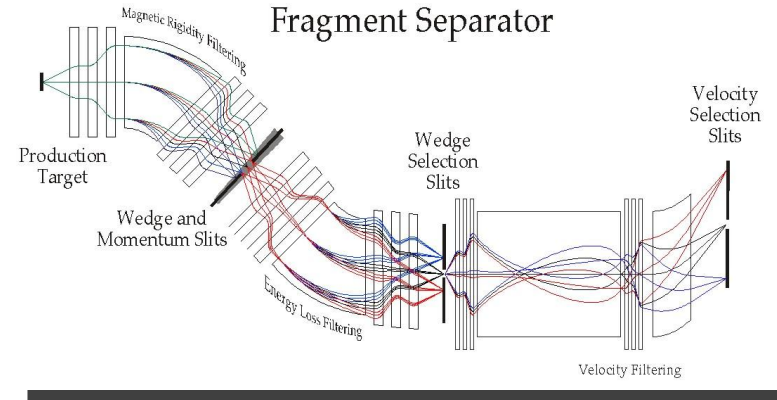
Projectile fragmentation of  $^{82}\text{Se}$





$$Y = I \cdot t \cdot N_t \cdot \sigma \cdot \epsilon_t \cdot \epsilon_s \cdot \epsilon_i$$

1. Production Area



3. Identification

2. Separation

<p><b>Y</b> number of registered events</p> <p><b><math>\sigma</math></b> production cross section</p> <p><b><math>N_t</math></b> number of target atoms  <math>N_t = d_t M_t / N_A</math>          where  <math>d_t</math> target thickness  <math>N_A</math> Avogadro number  <math>M_t</math> atomic mass number</p> <p><b>I</b> beam intensity  <b>t</b> duration of measurement</p> <p><b><math>\epsilon_t</math></b> efficiency transmission at target  <b><math>\epsilon_s</math></b> efficiency transmission through separator  <b><math>\epsilon_i</math></b> identification efficiency</p>	<p><b>Reaction</b></p> <p><b>Target</b></p> <p><b>Beam</b></p> <p><b>Settings, Options</b></p>	<p><b><math>\epsilon_t</math></b> efficiency transmission at target</p> <ul style="list-style-type: none"> <li>lost of primary beam and fragments of interest due to reaction in target and stripper</li> <li>Charge state factor after target (stripper)</li> <li>Gain due to secondary reactions</li> </ul> <p><b><math>\epsilon_s</math></b> efficiency transmission through separator</p> <ul style="list-style-type: none"> <li>lost of fragments of interest due to reaction in materials located in the separator</li> <li>charge state factor after materials</li> <li>Angular acceptance</li> <li>Momentum selection</li> <li>Wedge selection</li> <li>Other selections</li> </ul> <p><b><math>\epsilon_i</math></b> identification efficiency</p> <ul style="list-style-type: none"> <li>lost of fragments of interest due to reaction in detectors</li> <li>Live time (as well pile-ups)</li> </ul>
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for all icons in the toolbar and in the production panel there are corresponding commands in the menu

Home - NSCL Primary Beam List

Developed Primary Beams

Particle	Energy (MeV/nucleon)	Intensity (pA)
<sup>16</sup> O	150	175
<sup>18</sup> O	120	150
<sup>20</sup> Ne	170	80
<sup>22</sup> Ne	120	80
<sup>22</sup> Ne	150	100
<sup>24</sup> Mg	170	60
<sup>36</sup> Ar	150	75
<sup>40</sup> Ar	140	75
<sup>40</sup> Ca	140	50
<sup>48</sup> Ca	90	15
<sup>48</sup> Ca	140	80
<sup>58</sup> Ni	160	20
<sup>64</sup> Ni	140	7
<sup>76</sup> Ge	130	25
<b><sup>82</sup>Se</b>	<b>140</b>	<b>35</b>
<sup>86</sup> Kr	100	15
<sup>86</sup> Kr	140	25
<sup>90</sup> Zr	120	1.5
<sup>112</sup> Sn	120	4
<sup>118</sup> Sn	120	1.5
<sup>124</sup> Sn	120	1.5
<sup>124</sup> Xe	140	10
<sup>136</sup> Xe	120	2
<sup>208</sup> Pb	85	1.5
<sup>209</sup> Bi	80	1
<sup>238</sup> U	45	0.1
<sup>238</sup> U	80	0.2



**Beam**

A Element q+  
82 Se 32  
34  
Z  
Stable  
Table of Nuclides  
Z N  
Ok Cancel

**Beam energy**  
Energy  140 MeV/u  
TKE  11468.34 MeV  
Brho  4.5217 Tm  
P  43.379 GeV/c  
U  3.58e+5 KV

**Beam intensity**  
 1120 enA  
 35 pA  
 2.1875e+11 pps  
 0.4018 KW

**Emittance**  
Beam CARD (sigma, semi-axis, half-width...)  
1D - shape (Distribution method)  
2D mode  
2D - shape (Monte Carlo method)  
Correlated with  
mm  cm   
beam respect to spectrometer  
dX 0 mm  
dT 0 mrad  
dY 0 mm  
dP 0 mrad  
dT 0 degrees  
dP 0 degrees

Energy Loss in the target box [KW] 0.0902

RF frequency 20 MHz  
Bunch length 1 ns

## projectile fragmentation

- Heavy target : larger cross sections
- Light targets have more nuclei per electron, hence larger nuclear interaction probability at fixed electronic slowing down than heavy target
- Overall case for projectile fragmentation:  $(\sigma N_t)_{\text{light}} > (\sigma N_t)_{\text{heavy}}$
- Chemical and physical properties of material as melting point, thermal conductivity etc,  
*so lifetime of Be target  $\gg$  lifetime of equivalent Ta target*
- Charge state distribution after target:  
light targets provide higher average  $q$  of ions  
*\* using strippers after heavy targets*
- Dissipation process larger with heavy targets  
*so  $^{40}\text{Mg}$  and  $^{44}\text{Si}$  been have observed in  $^{48}\text{Ca}+\text{W}$*

This favors light targets (NSCL uses Be)

**Projectile**  $^{82}\text{Se}^{32+}$   
 140 MeV/u 35 pA  
**Fragment**  $^{56}\text{Ca}^{20+}$   
**Target** **Be**  
 443.607 mg/cm<sup>2</sup>



Calculate density

**Gas density**

These calculations are correct just for molecular formula !!!

Parameter	Value	Dimension
Temperature (K)	293.15	K
Pressure (Torr)	760	Torr
Density	0.0419	mg/cm <sup>3</sup> kg/m <sup>3</sup> g/L

Units converter    Fix    Cancel

**Target**

Be    Density: 1.85 g/cm<sup>3</sup>

State:  Solid    Dimension:  mg/cm<sup>2</sup> & micron

Angle: 0 degrees

Z	Element	Mass
<input checked="" type="checkbox"/>	4 Be	PT 9.012
<input type="checkbox"/>	14	
<input type="checkbox"/>	14	
<input type="checkbox"/>	14	
<input type="checkbox"/>	14	

Thickness at 0 degrees:  443.6074 mg/cm<sup>2</sup>

Effective Thickness:  443.6074 mg/cm<sup>2</sup>

Thickness defect:     Absorbed Dose:

d / Range (beam): 0.345    Energy Loss in the target box [KW]: 0.0902    Atoms / cm<sup>2</sup>: 2.96e+22

Compound dictionary    OK    Cancel



**Calculation of Absorbed Dose**

Shape:  2D Gaussian

Reduced 2D-Gaussian Sigma = 1 mm

Beam percent in interaction area = 68 % (should be between 0.1 and 99.9 %)

Interaction area = 7.12 mm<sup>2</sup>

Exposure time = 24 hours

Absorbed Dose = 5.550e+11 Gray

Quit



**Compounds**

	Common Name	Atomic Stoich.	Density	Cancel
Nuclear physics materials	Aluminum Oxide alpha	Al <sub>2</sub> O <sub>3</sub>	3.98	Input
Plastic-Polimers	Bakelite	H <sub>9</sub> C <sub>9</sub> O <sub>1</sub>	1.45	Input
Liquids	1-2 - Ethanediol	H <sub>6</sub> C <sub>2</sub> O <sub>2</sub>	1.1088	Input
Gases	1-2 Difluoroethane	H <sub>4</sub> C <sub>2</sub> F <sub>2</sub>	0.0012	Input

**Thickness defect**

Thickness defect:  0.1 %

%     micron

OK    Cancel

<b>Projectile</b>	$^{82}\text{Se}^{32+}$
140 MeV/u	35 ppA
<b>Fragment</b>	$^{56}\text{Ca}^{20+}$
<b>Target</b>	Be
	44.607 mg/cm <sup>2</sup>



**Setting Fragment**

A	Element	Z	Table of Nuclides
56	Ca	20	
Beta-decay			<input type="button" value="Z"/> <input type="button" value="N"/>

Charge states

20+ D1

If Charge state option is ON

**Charge states of the selected nucleus**

Block	Given Name	Z-Q	Q
Target	Target		
Stripper	Stripper		
Dipole	D1	0	20
Dipole	D2	0	20
Drift	I2_slits		
Wedge	I2_wedge		
Dipole	D3	0	20
Dipole	D4	0	20
Material	FP_PPAC0		
Material	FP_PPAC1		

Selected ion:  $^{56}\text{Ca}^{20+ 20+ 20+ 20+}$

Selected block

Charge (Q) = 20    Block name = D1

It is used to tune the fragment separator on setting ions

Use "Charge state" for

- Low energy
- Heavy fragments

For example in the reaction  $^{82}\text{Se}(140\text{MeV/u}) + \text{Be}$  no charge states expected.

It is recommended to turn off charge states to provide fast calculation.

**Alternative:**  
LISE++ can find the optimum charge state combination

Calculations   Utilities   1D-Plot   2D-Plot   Databases   Help

- Optics
- Goodies
- Calibrations
- Transmission and rate
- Optimum Target
- Optimum Target-Wedge and Wedge-Wedge configurations
- Brho scanning
- Optimum charge state combination**
- Monte Carlo calculation of transmission
- Calculators

**Should pay attention for charge state distribution  
after target and each time passing material.**

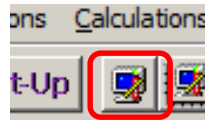
**Then more materials  
(at low energies or with heavy elements experiment),  
then less setting ion transmission**

***Depends on:***

- ❑ **Primary beam atomic number**
- ❑ **Primary beam energy**
- ❑ **Target atomic number**
- ❑ **Initial ionic charge before passing material (for non-equilibrium process)**

***Complicates particle identification of radioactive beam***

- **Isotopes of different masses and charges become mixed up during B $\rho$  selection**



**Preferences**

Starting configuration at loading the program: A1900\_2009.lcn Browse

Starting options file at loading the program: A1900\_2009.lopt Browse

Working directory:  User \ My Documents,  LISE++ root directory

Display 1: Sum of all reactions (pps)

Display 2: Total transmission (%)

Apply the "Edge" effect in distribution cuts:  Yes (default),  No (recommended for extended configurations)

Calculation threshold = 1.0e-10

Dimension of distribution (NP):  
 calculation WITHOUT charge states: 64 (recommended)  
 calculation WITH charge states: 32  
 wedge calculation: 32 (recommended) 16

Charge States:  Yes,  No

Sound,  3D-Balls Animation

Navigation map,  Spectrometer scheme

Show transmission calculation time

Hold angles of an inclination of a target and a stripper together

Primary beam scattering in a target

Charge State Optimization Debugging Mode

Distribution Debugging Mode (file 'distrib.txt')

Check LIZ-file consistency (Configurations)

Check LIZ-file consistency (Options)

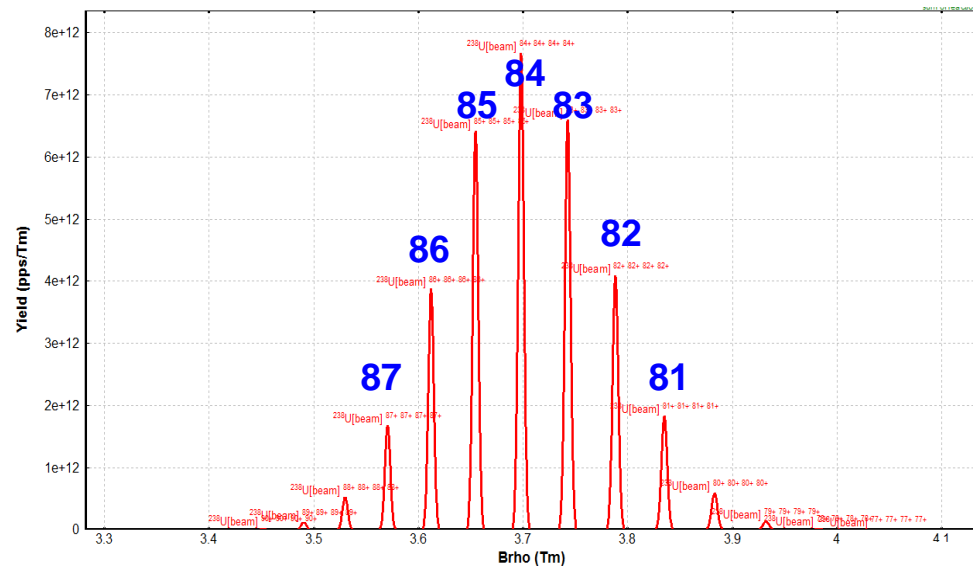
Make default

OK,  Cancel,  Help

	48Ca	49Ca	50Ca	51Ca	52Ca
	47K	48K	49K	50K	51K
Sum=0	<input checked="" type="checkbox"/>				
Z-Q=0,0,0,0					

New Alternative way

**B<sub>p</sub> distribution of <sup>238</sup>U(80MeV/u) after Au(10 mg/cm<sup>2</sup>)**



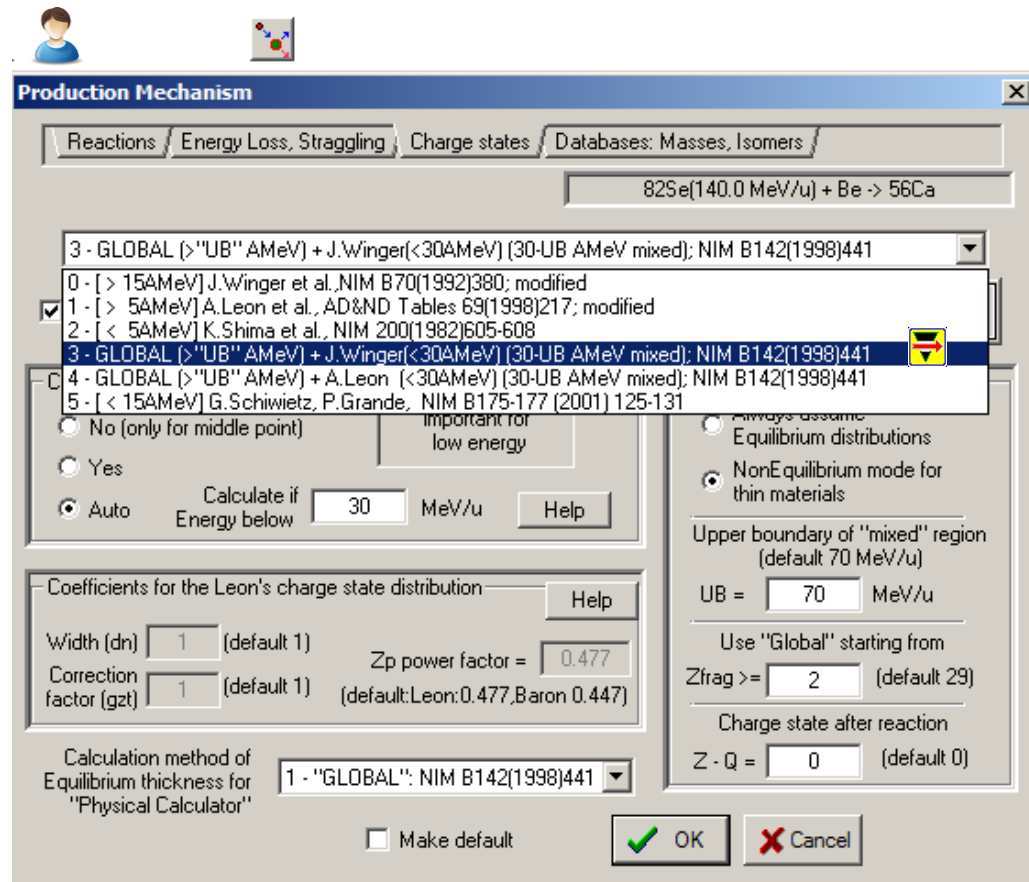
	Model	Ref.	Region (AMeV)
1	J. Winger	[10]	>15
2	A. Leon	[11]	>5
3	K. Shima	[12]	<5
4	Global	[13]	>30
5	G. Schiwietz	[14]	<15

[10] J. Winger et al., Nucl. Instr. and Meth. B 70 (1992) 380.  
 [11] A. Leon et al., Atom. Data Nucl. Data Tabl. 69 (1998) 217.  
 [12] K. Shima et al., Nucl. Instr. and Meth. 200 (1982) 605.  
 [13] C. Scheidenberger et al., Nucl. Instr. and Meth. B 142 (1998) 441.  
 [14] G. Schiwietz et al., Nucl. Instr. and Meth. B 175 (2001) 125.

• The model used in Global allows to calculate non-equilibrium charge states distributions

• The programs Global and Charge [13] have been incorporated into the LISE++ package

• These programs developed in GSI are intended to calculate atomic charge-changing cross-sections, charge state evolution





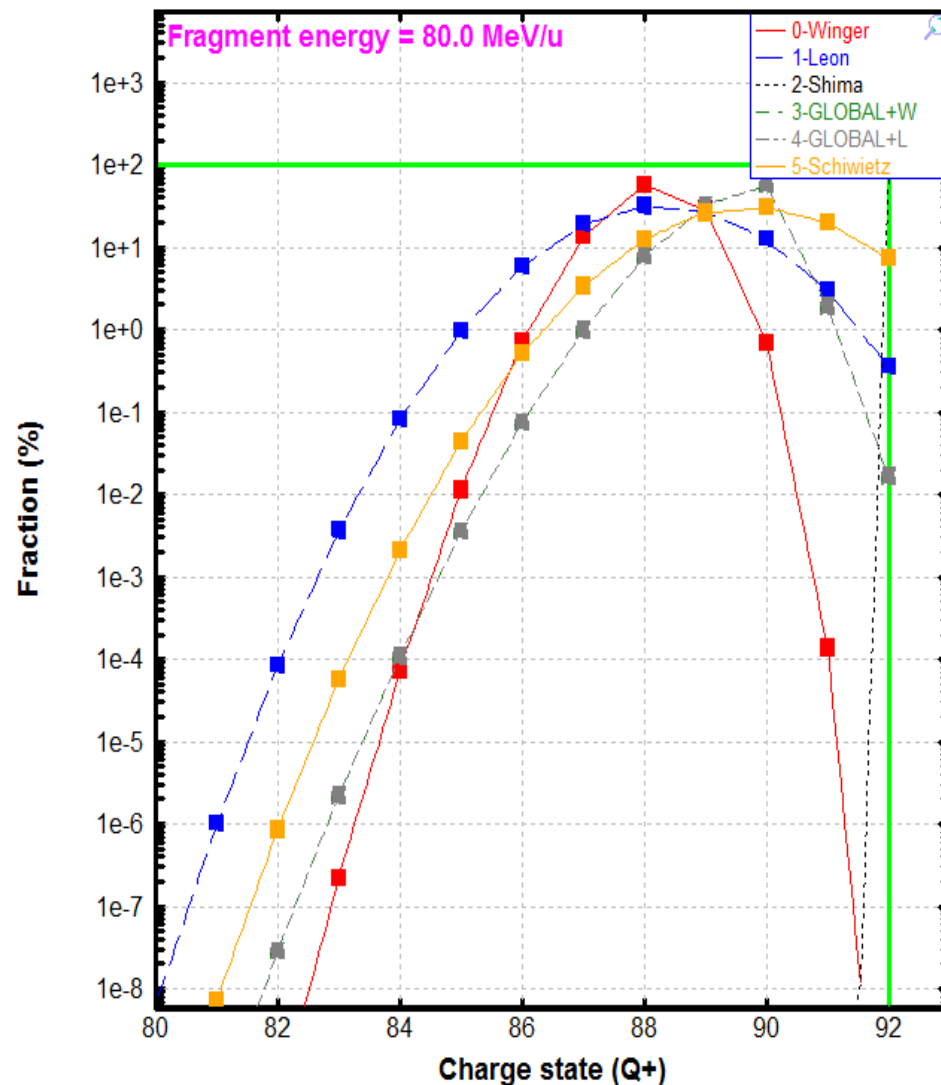
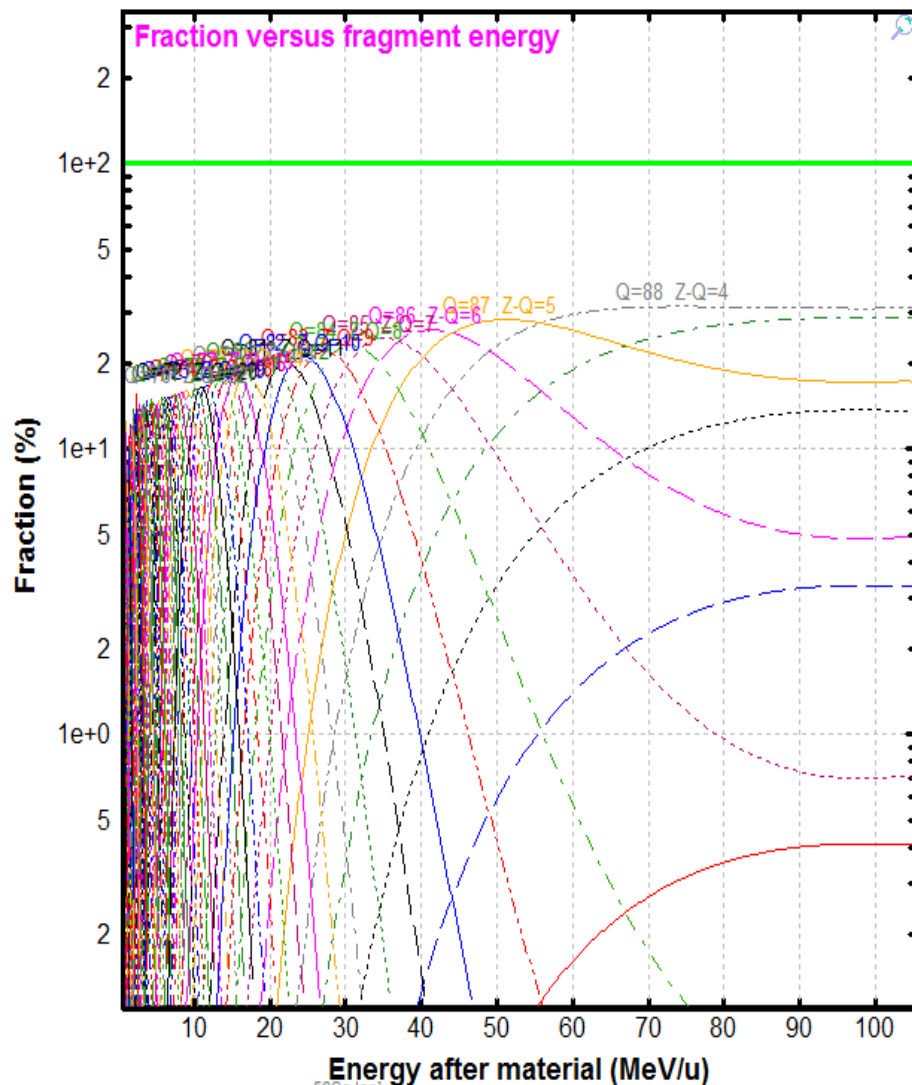
Menu  
 "1D-plot" ⇒  
 "Charge distributions"

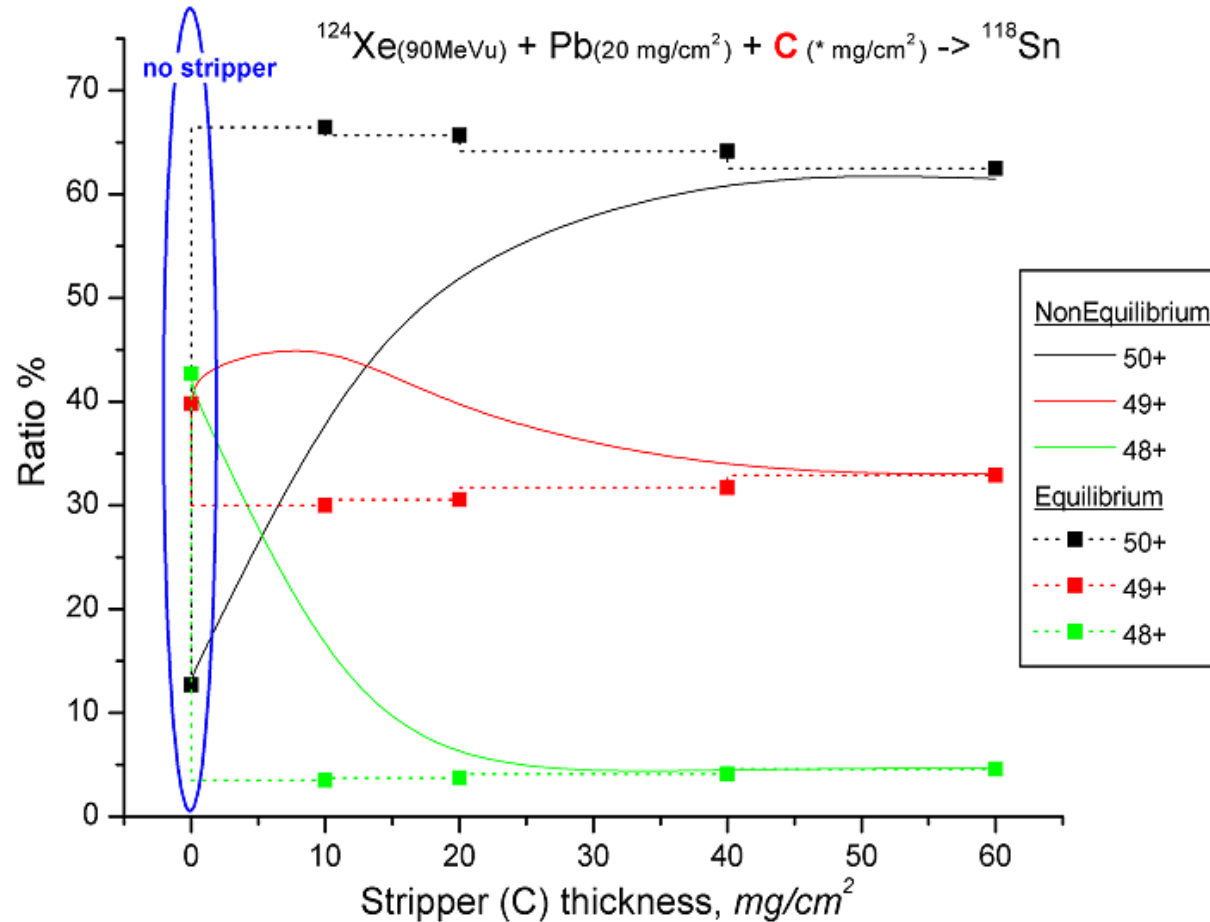
## $^{238}\text{U}$ equilibrium charge distribution after Target (Be)

$^{238}\text{U}$  (80.0 MeV/u) + Be (443.61 mg/cm<sup>2</sup>)

Calculations for  $^{238}\text{U}$ ; Material Be

Charge Distribution Method is 1; Coefficient Width=1.00



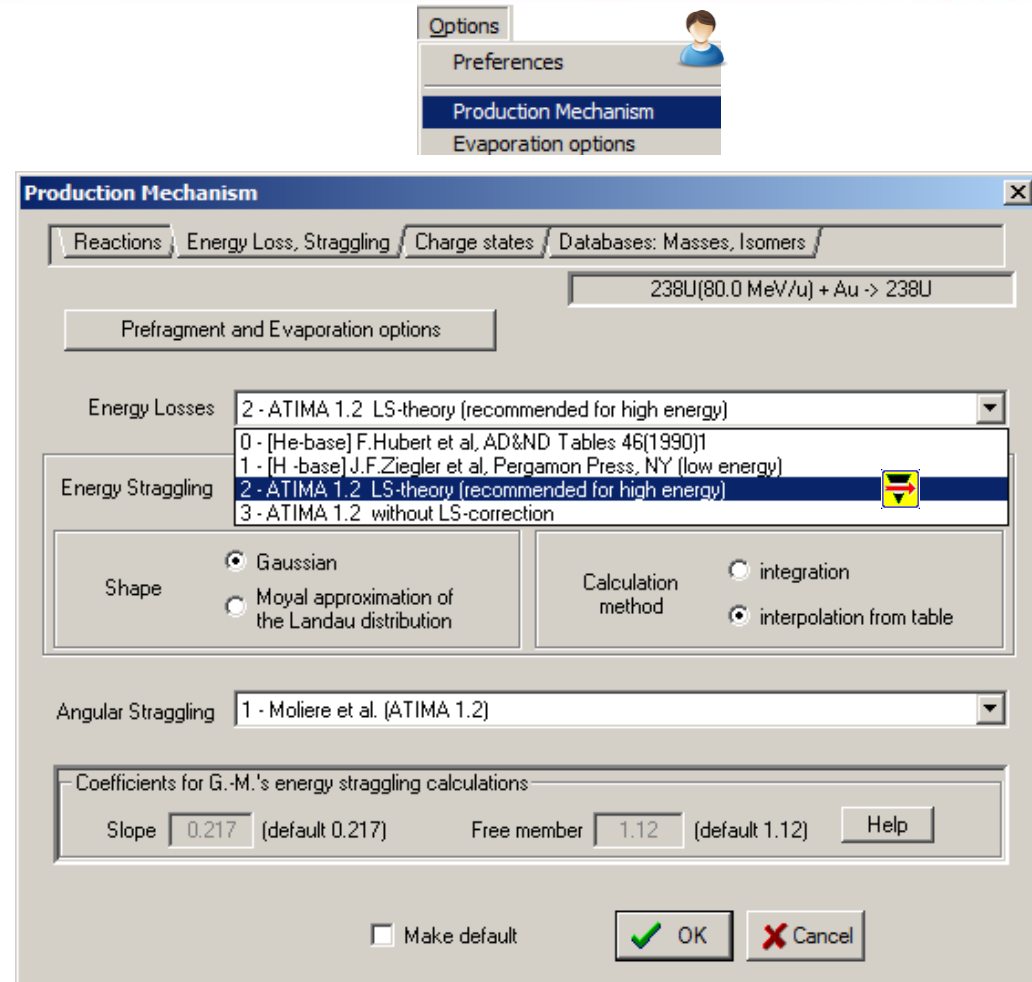


Charge state evolution\* of the fragment  $^{118}\text{Sn}$  after a C-stripper as a function of its thickness for equilibrium and non-equilibrium cases in the reaction  $^{124}\text{Xe} (90\text{ MeV/u})+\text{Pb}(20\text{mg/cm}^2)+\text{C}(x\text{ mg/cm}^2)$ .

\* C.Scheidenberger et al, NIM **B142** (1998) 441-462;  
[web-docs.gsi.de/~weick/charge\\_states/](http://web-docs.gsi.de/~weick/charge_states/)

The following energy loss calculation methods are available in LISE++ :

1. He-parameterization [1]; the starting point at 2.5 AMeV is given by range tables [2]
2. H-parameterization: TRIM code [3]
3. ATIMA 1.2: LS-theory [4]
4. ATIMA 1.2: without LS-corrections



Options

- Preferences
- Production Mechanism**
- Evaporation options

Production Mechanism

Reactions | Energy Loss, Straggling | Charge states | Databases: Masses, Isomers

238U(80.0 MeV/u) + Au -> 238U

Prefragment and Evaporation options

Energy Losses: 2 - ATIMA 1.2 LS-theory (recommended for high energy)

Energy Straggling: 2 - ATIMA 1.2 LS-theory (recommended for high energy)

Shape:  Gaussian  Moyal approximation of the Landau distribution

Calculation method:  integration  interpolation from table

Angular Straggling: 1 - Moliere et al. (ATIMA 1.2)

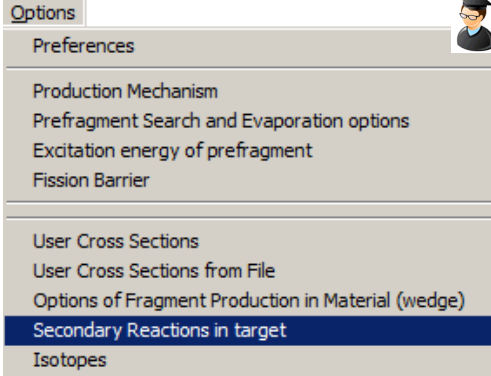
Coefficients for G.-M.'s energy straggling calculations:

Slope: 0.217 (default 0.217) Free member: 1.12 (default 1.12) Help

Make default

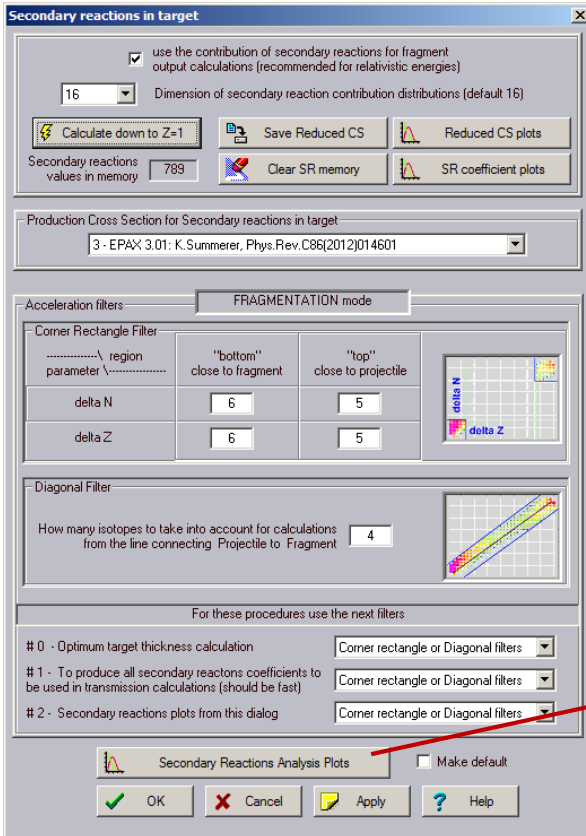
## References:

- [1] F. Hubert et al., Atom. Data Nucl. Data Tabl. 46 (1990) 1.
- [2] L.C. Northcliffe et al., Nucl. Dat. Tabl. A 7 (1970) 233.
- [3] J.F. Ziegler et al., The Stopping and Range of Ions in Solids, Pergamon Press, New York, 1985.
- [4] J. Lindhard, A.H. Soerensen, Phys. Rev. A 53 (1996) 2443; ATIMA site: <http://web-docs.gsi.de/~weick/atima/>

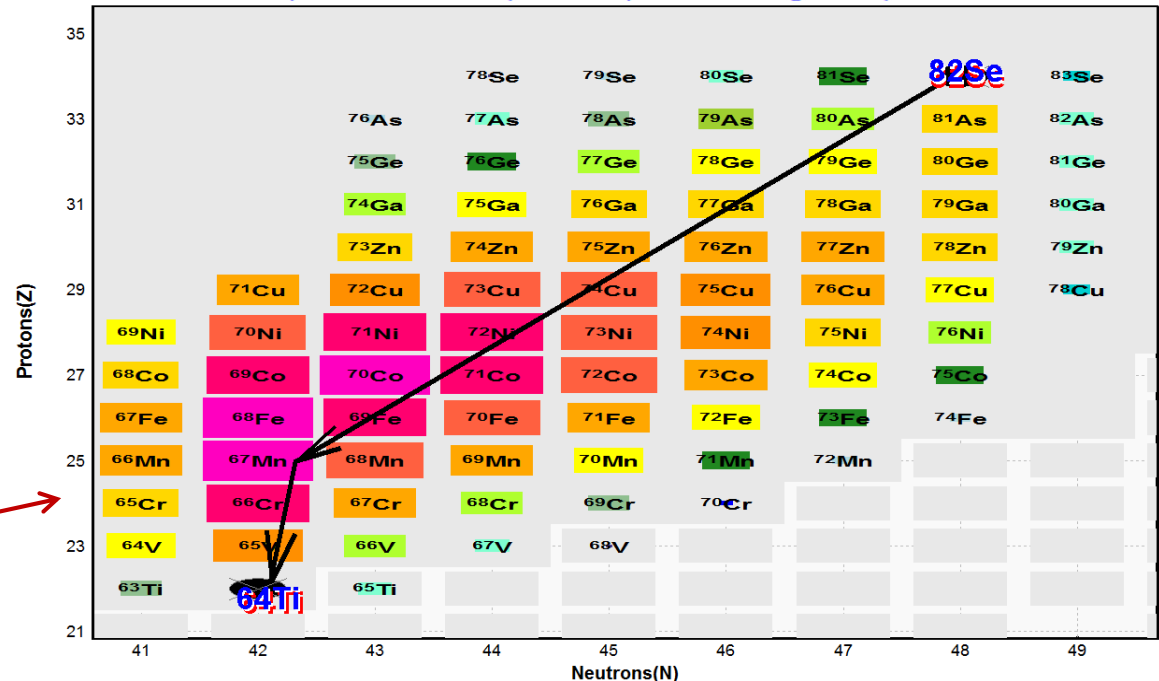


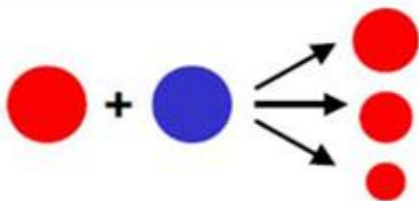
## Applied for thick targets

- ❑ 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  
 $^{82}\text{Se} (140.0 \text{ MeV/u}) + \text{Be} (443.61 \text{ mg/cm}^2) \rightarrow ^{64}\text{Ti}$

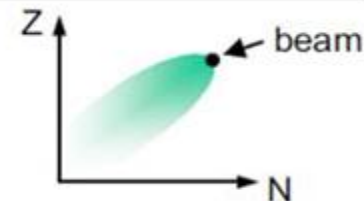




projectile fragmentation

$$v_{\text{product}} = v_{\text{beam}}$$

up to 1000



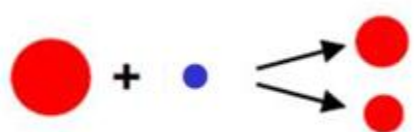
Yield in target can be simulated in inverse kinematics

Yield in target can be simulated in inverse kinematics



new : inverse

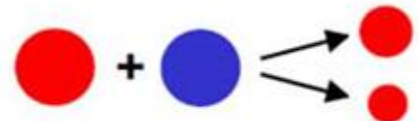
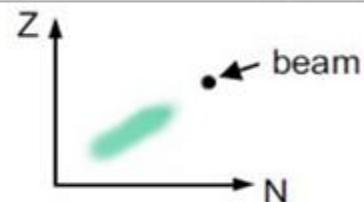
$$\sim 10-25 \text{ MeV/u}$$



abrasion-fission

$$v_{\text{product}} = v_{\text{beam}}$$

few 100

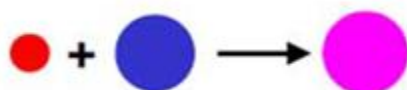
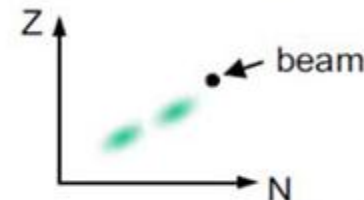


Coulomb fission

$$> 200 \text{ MeV/u}$$

$$v_{\text{product}} = v_{\text{beam}}$$

few 100



fusion-evaporation

$$E_R = \frac{m_p}{m_p + m_t} E_P$$

few ( $\leq 20$ )

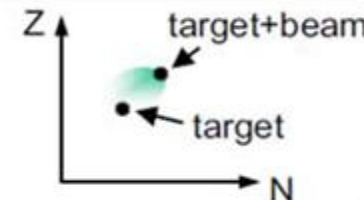


Table  
Reactions and production models implemented in LISE++

Reaction	Production cross-section model	Ref.
Projectile fragmentation	EPAX 2.15, 3.1 LISE++ abrasion-ablation	[17] [27]
Fusion-residues	LisFus model PACE4 (manually)	[27] [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 State University, 2005.
- [31] O.B. Tarasov, Tech. Rep. MSUCL1300, NSCL, Michigan State University, 2005.

❑ The evaporation cascade is used in Abrasion-Ablation (Projectile Fragmentation), All fission reactions, Fusion-Residue

❑ It is treated in a macroscopic way on the basis of a master equation which leads to a diffusion equations

X. Campi, J. HuË fner, Phys. Rev. C 24 (1981) 2199; J.-J. Gaimard, K.-H. Schmidt, Nucl. Phys. A 531 (1991) 709

❑ The LISE++ evaporation model works with **probability distributions** as a function of excitation energy, taking into account possible parent and daughter channels (n, 2n, p, 2p, d, t, 3He,a), as well as fission and breakup de-excitation channels

❑ The influence of dissipation on the fission process is taken into account B. Jurado et al., Phys. Lett. B 553 (2003) 186

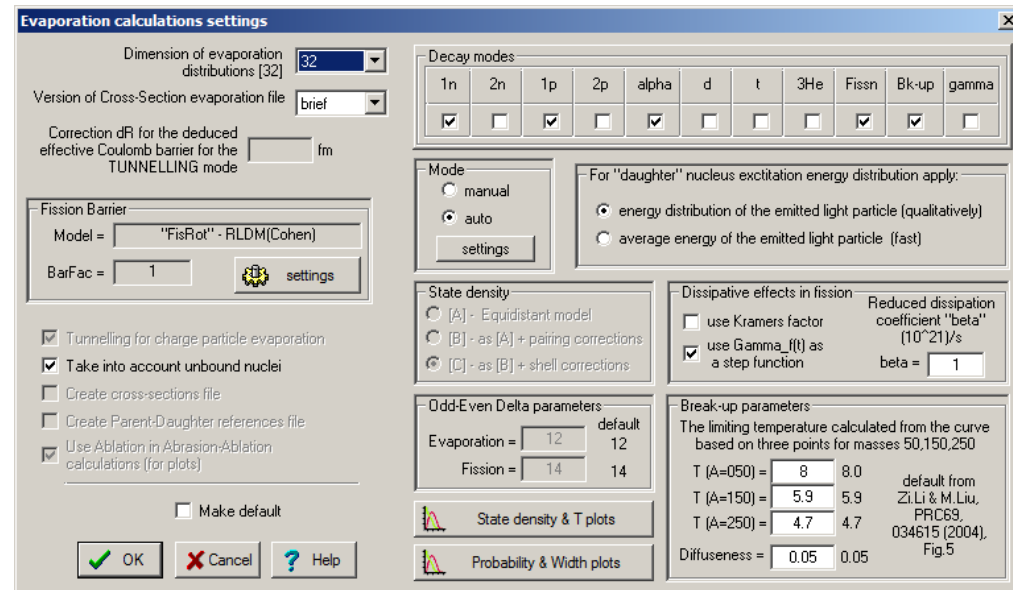
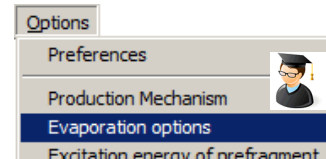
❑ The **analytical solution** of the evaporation cascade is performed using the transport integral

D. Bazin, B. Sherrill, Phys. Rev. E 50 (1994) 4017

❑ The main advantage is speed. Only such a type of fast calculations is suitable for calculating the production of nuclei with very low cross-sections

❑ Disadvantages are ...

❑ Monte Carlo version will be done soon



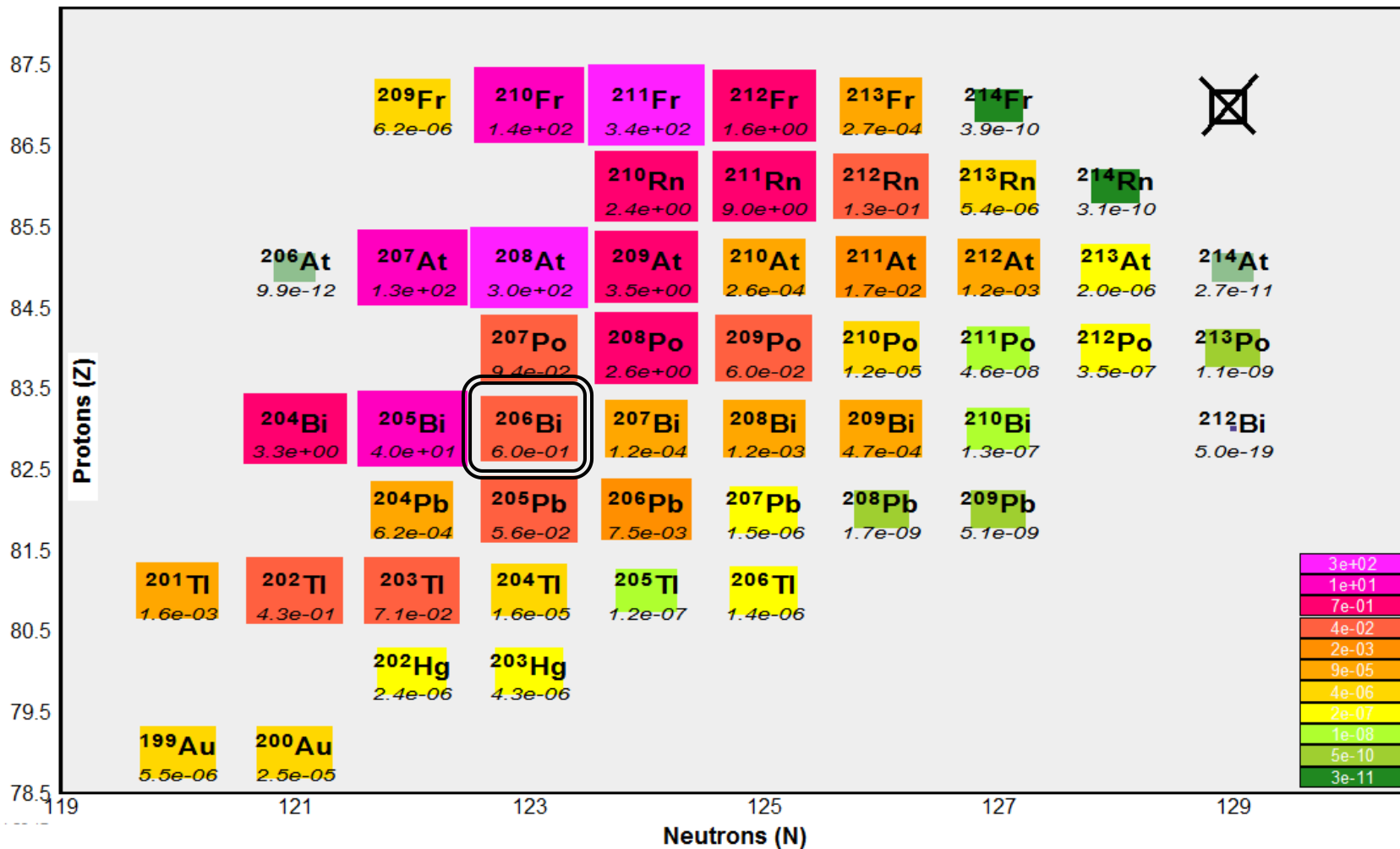
Couple seconds and... Fission = 18.6 mb, Residues 981 mb

## Final Evaporation Residue cross-sections (LisFus)

EVAPORATION - Compound nucleus  $^{216}\text{Fr}$

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:"DBO+Cal1" Density:"auto" GeomCor:"On" Tunlg:"auto" FisBar=#1 Bar<sup>FaC</sup>=1.00 Modes=1010 1000 110



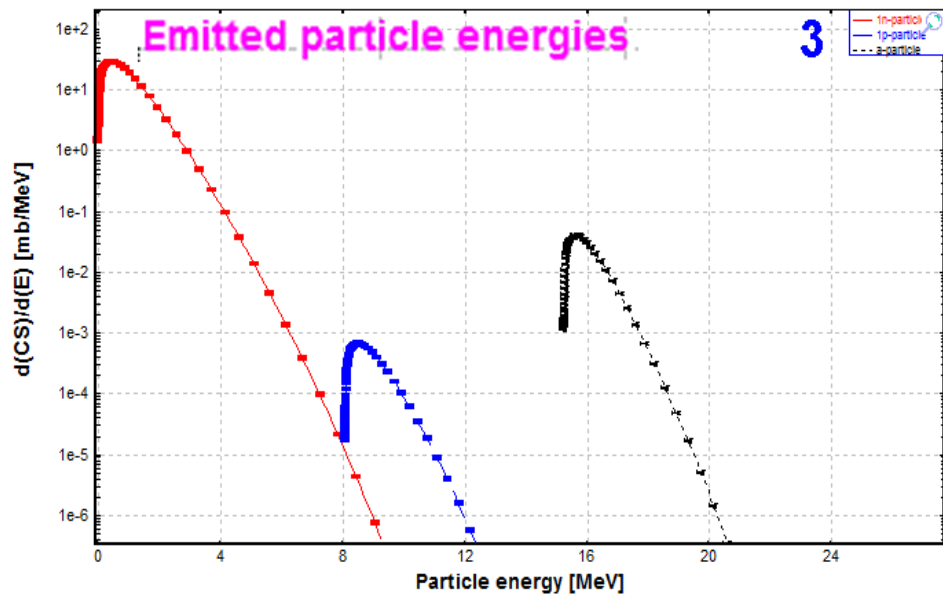
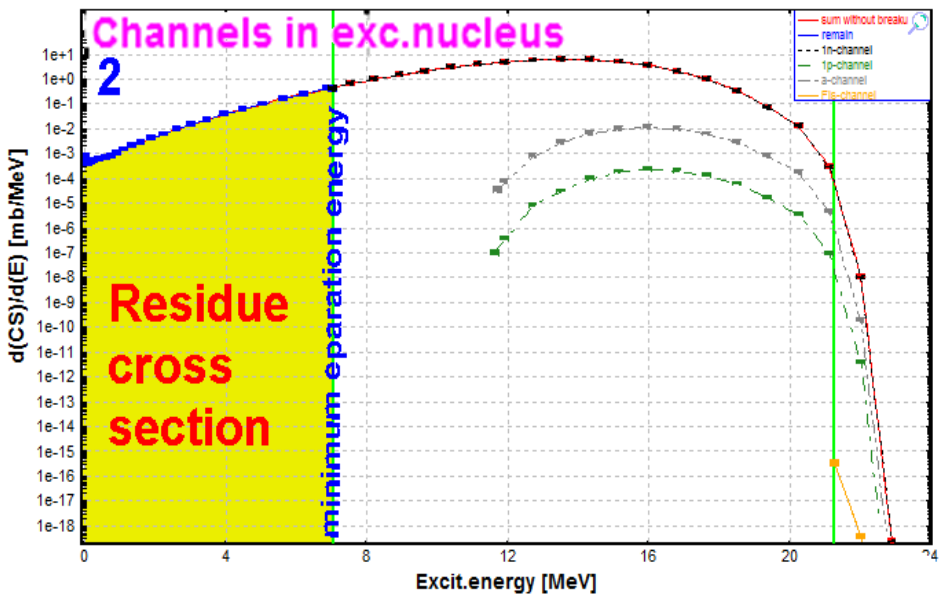
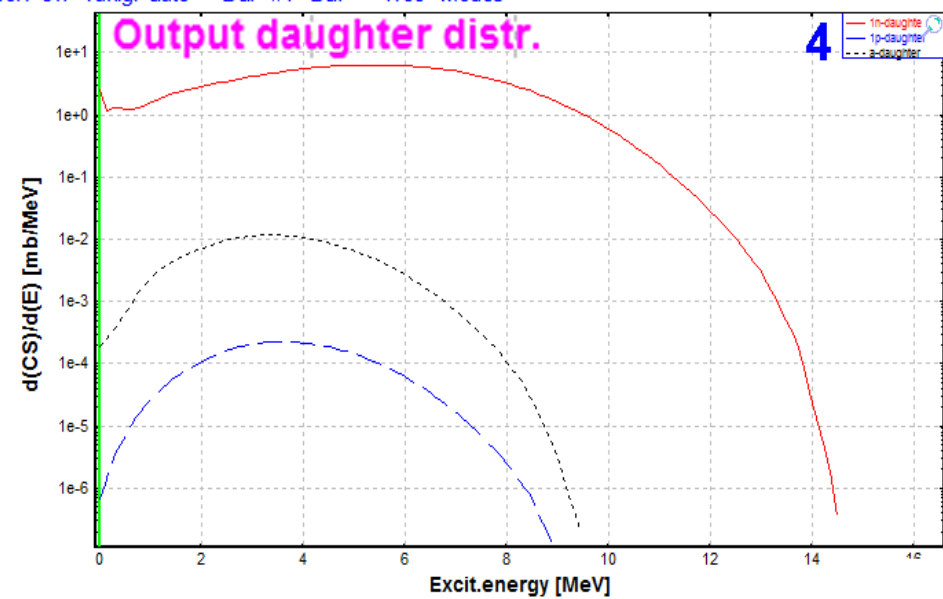
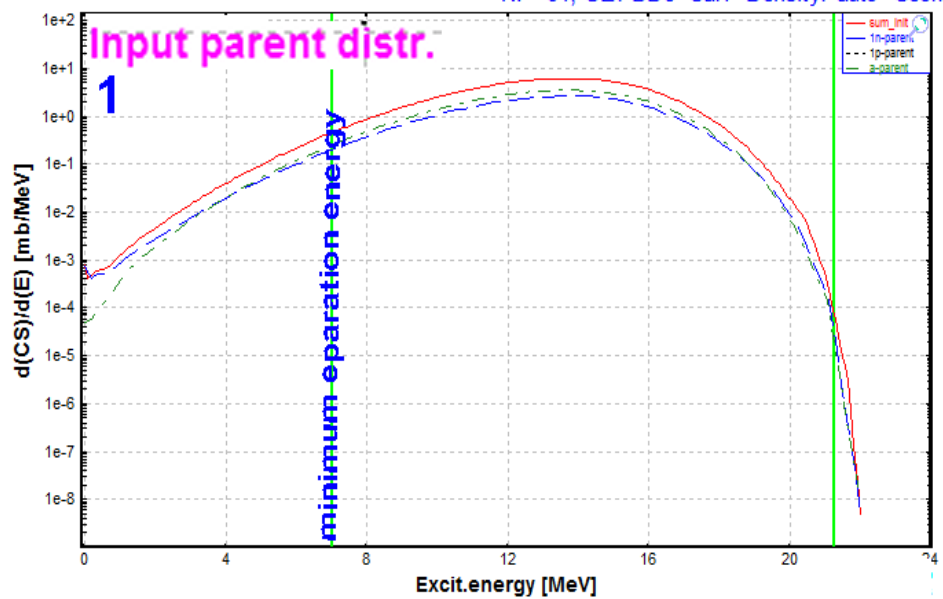
Evaporation calculator will be discussed on Friday



## $^{206}\text{Bi}$ excitation distributions

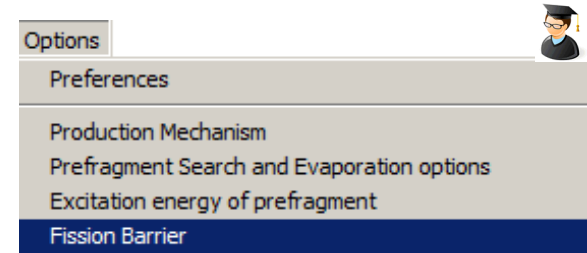
EVAPORATION - Compound nucleus  $^{216}\text{Fr}$

Excit. Energy: 50.0-51.0 MeV; Fus. CS: 1000.0 mb; Fus. Barrier: 10.82 fm;  $h_{\omega} = 5.0 \text{ MeV}$   
 NP=64; SE:"DB0+Cal1" Density:"auto" GeomCor:"On" Tunlg:"auto"  $^{216}\text{Fr}$ Bar=#1 Bar<sup>Fac</sup>=1.00 Modes=<sup>10</sup>10 <sup>1000</sup>110



Fission barriers are necessary to calculate fission de-excitation channels and estimate

- total cross-sections of fission reactions
- evaporation residue cross-sections
- decay widths in the post-scission nucleon emission process



**Fission Barrier**

A: 206, Element: bi, Z: 83

Barrier vanishes at = 79 hbar

Barfac = 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:

for Protons: 9 (default 9.0 MeV)

for Neutrons: 2.5 (default 2.5 MeV)

Use in the code	Fission Barrier at L=0	Fission Barrier at Lx = 10	G.S. Energy at Lx (MeV)
<input type="radio"/> 0 - "Barfil" - A.J.Sierk, PRC33(1986)2039	20.35	20.05	0.77
<input checked="" type="radio"/> 1 - "FisRot" - S.Cohen et al.,An.P 82(1974)	21.26	20.98	0.47
<input type="radio"/> 2 - LDM - W.Myers_W.Swiatecki,NP81(1966)	22.05		
<input type="radio"/> 3 - FILE: A.Mamdouh et al,NPA679(2001)337	24.9	<input type="radio"/> in	
<input type="radio"/> 4 - FILE: Experimental barriers	22.4	<input type="radio"/> out	
<input type="radio"/> 5 - FILE: P.Moller et al.,LANL-UR-08-4190	21.42	<input checked="" type="radio"/> max (in,out)	

For models # 3,4: if FILE data are absent then use LDM model # 1 - "FisRot" - S.Cohen et al.,An.P 82(1974)

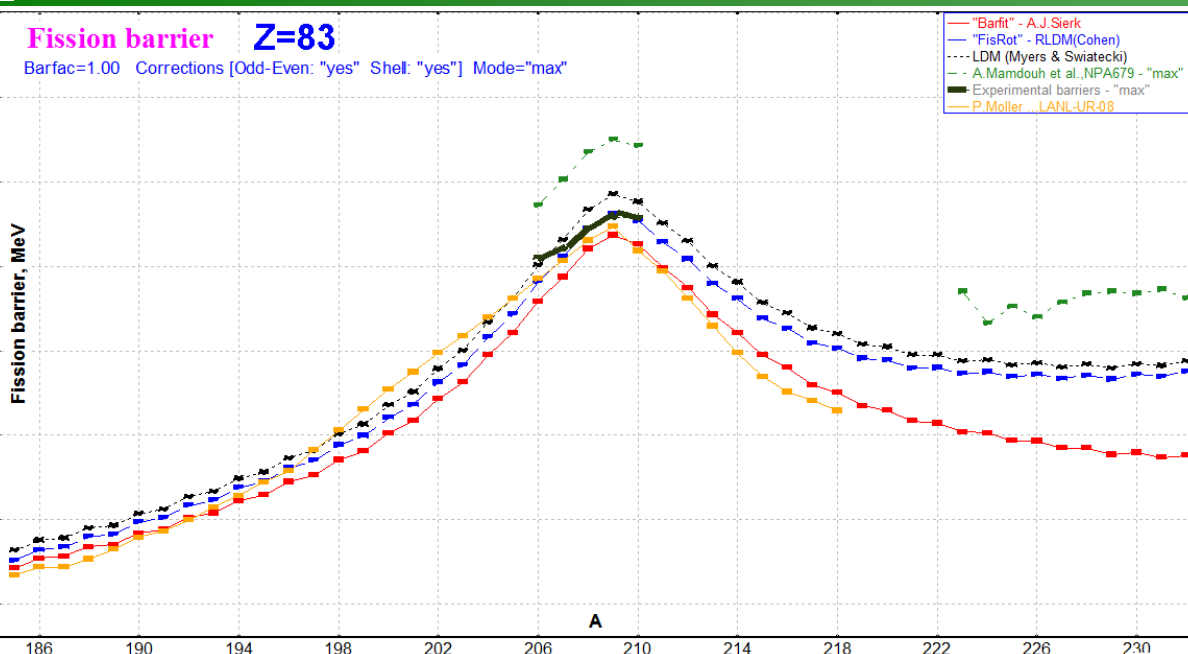
Ok Cancel Help Make default

$$B_f^{\text{final}} = B_f^{\text{init}} \cdot b + \varepsilon_{\text{shell}} + \varepsilon_{\text{odd-even}}$$

default value of  $b = 1$

## Fission barrier Z=83

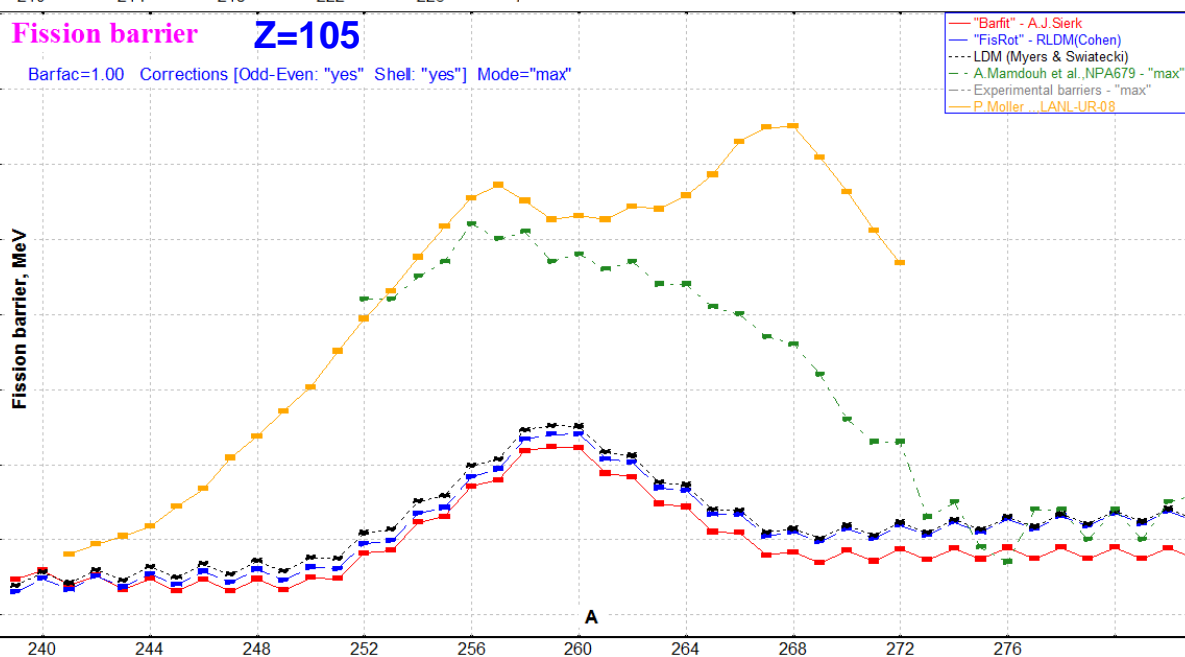
Barfac=1.00 Corrections [Odd-Even: "yes" Shell: "yes"] Mode="max"



Below Uranium  
general agreement

## Fission barrier Z=105

Barfac=1.00 Corrections [Odd-Even: "yes" Shell: "yes"] Mode="max"



In SHE region first three models significantly underpredict

**Fission Barrier**

A Element Z

290 FI 114

Unknown

Sierk barrier information

Barrier vanishes at = 0 hbar

For models # 0,1,2

Barfac = 10 factor to multiply the fission barrier (default value 1)

Use in the code

Use in the code	Fission Barrier at L=0	Fission Barrier at Lx = 10	G.S. Energy at Lx (MeV)
<input type="radio"/> 0 - "Barfit" - A.J.Sierk, PRC33(1986)2039	-	0	0
<input checked="" type="radio"/> 1 - "FisRot" - S.Cohen et al.,An.P 82(1974)	4.23	4.08	0.25
<input type="radio"/> 2 - LDM - W.Myers_w.Swiatecki,NP81(1966)	1.62		
<input type="radio"/> 3 - FILE: A.Mamdouh et al,NPA679(2001)337	6.6		
<input type="radio"/> 4 - FILE: Experimental barriers	-		
<input type="radio"/> 5 - FILE: P.Moller et al.,LANL-UR-08-4190	9.89		

Use LISE shell corrections for LDM  
 Use odd-even corrections for LDM

Odd-Even Delta parameters

for Protons	9	9.0 MeV
for Neutrons	2.5	2.5 MeV

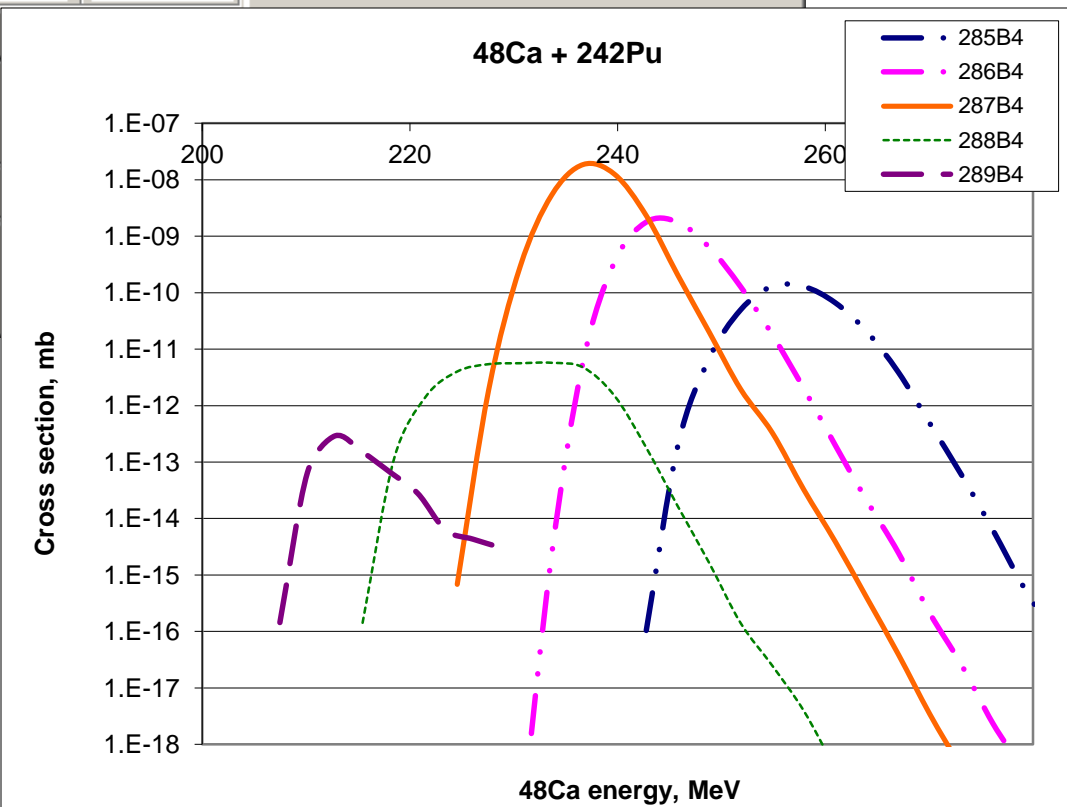
in  
 out  
 max

Fission Barrier Plot

Ok
Cancel
Help

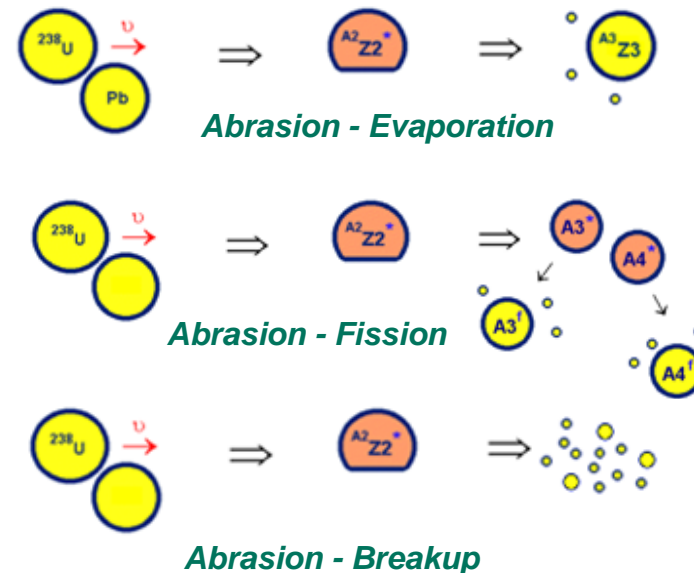
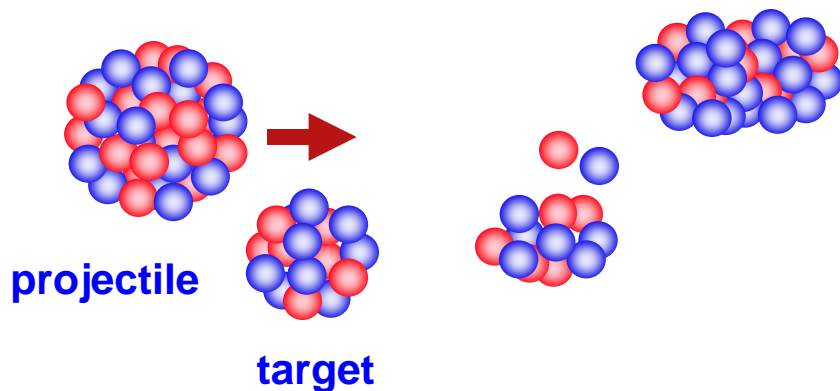
Energies and channels ratio, In order to estimate kinematics and transmission

For estimation it is possible to take experimental data (if they exist) or calculations from Prof.V.I.Zagrebaev in order to normalize Fusion-Residue cross sections playing with the Barfac value

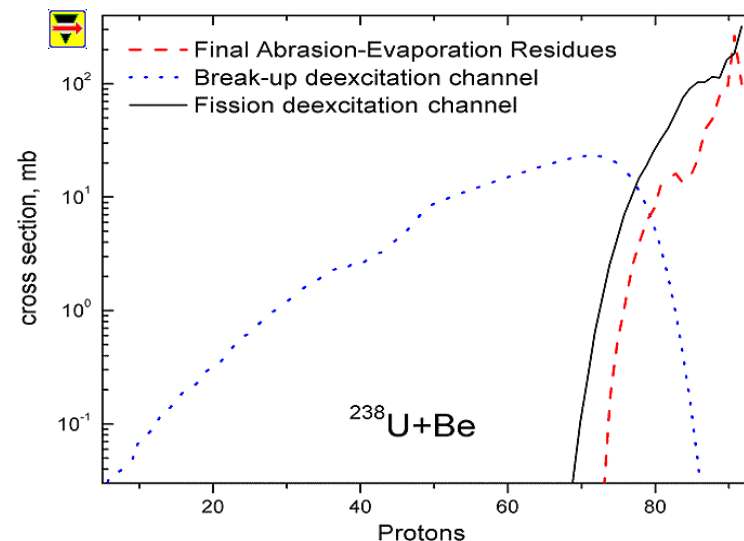


[http://lise.nsl.mscl.msu.edu/8\\_5/2009\\_catcher.pdf](http://lise.nsl.mscl.msu.edu/8_5/2009_catcher.pdf)

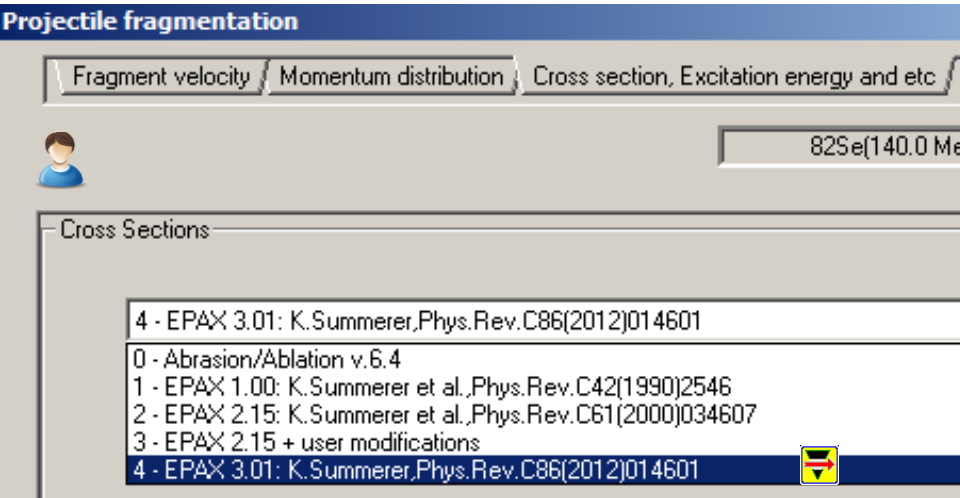
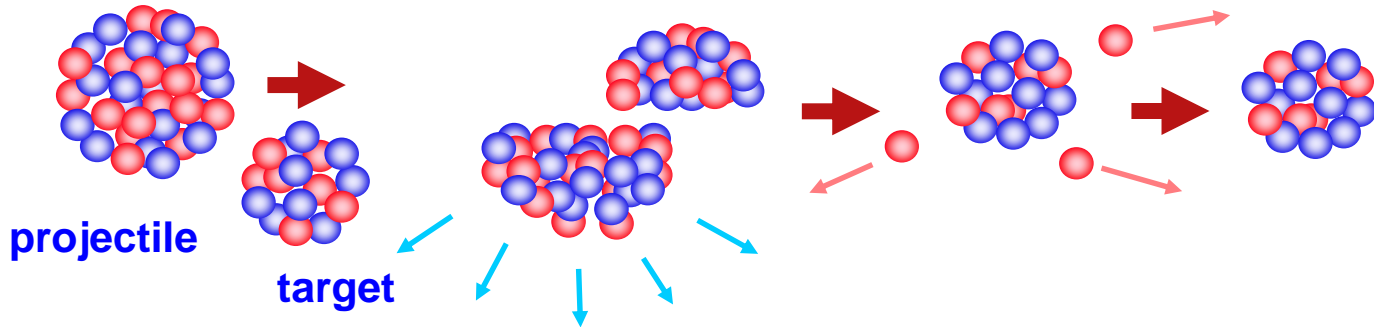
# Abrasion reactions : LISE<sup>++</sup> de-excitation channels



De-excitation channel	Collisions	Reaction
<u>Abrasion – Evaporation</u> Abrasion – Ablation	peripheral	<b>Projectile fragmentation</b>
<u>Abrasion – Fission</u>	peripheral	<b>In-flight fission</b> <i>Projectile fission</i>
<u>Abrasion – Breakup</u>	<b>central</b>	<b>Multi-fragmentation</b>



Nuclear charge yields for different de-excitation channels after <sup>238</sup>U(1AGeV) abrasion on a Be-target.



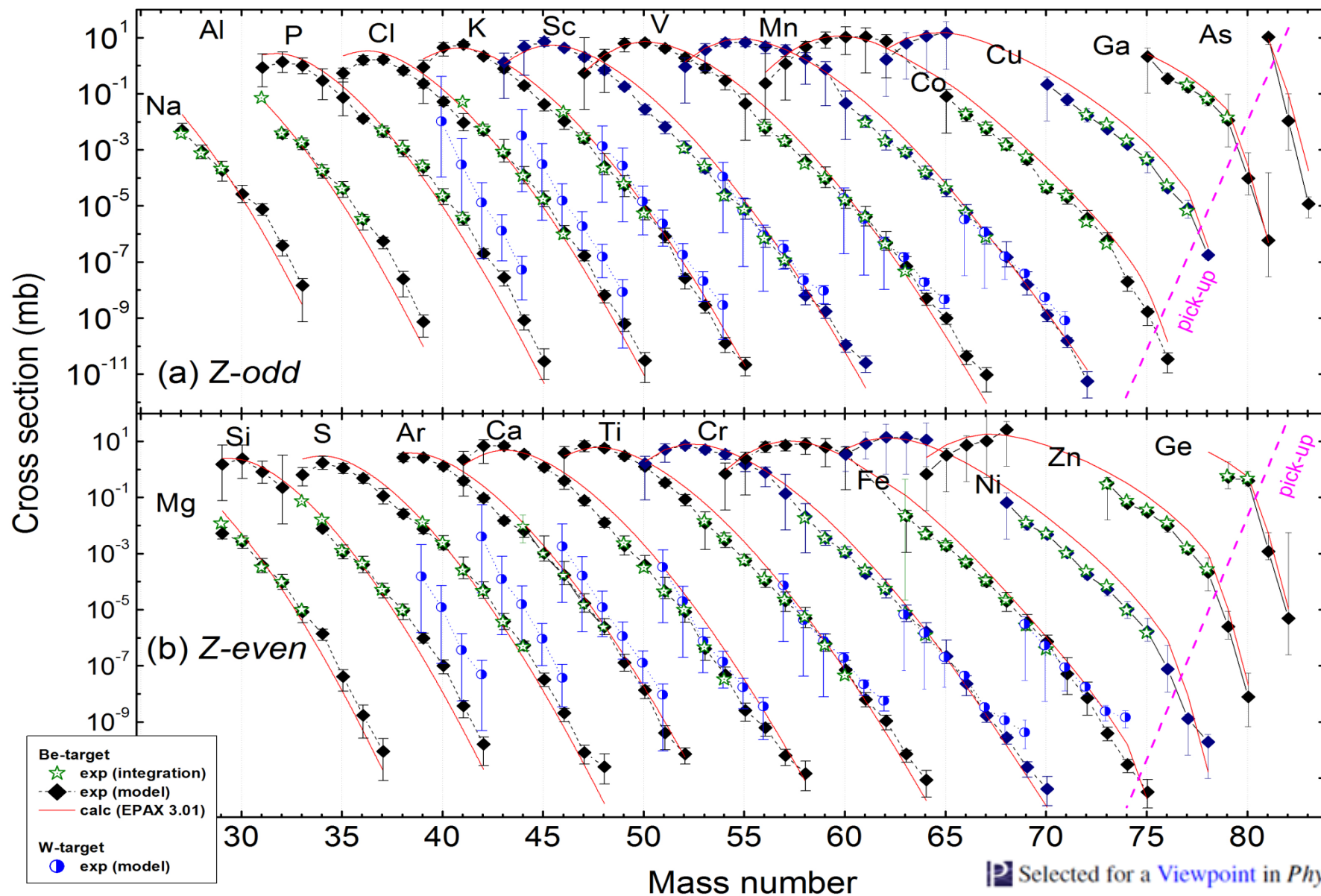
- ❑ **Cross sections for projectile fragmentation**
- EPAX parametrizations [1] based on fragmentation data
- LISE++ Abrasion-Ablation model (analytical) [2]
- Possibility to input cross sections manually via file
- ❑ **ABRABLA : Abrasion-Ablation Monte Carlo [3]**
- ❑ **COFRA : a simplified, analytical 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. C 20 (1979) 2227.

Model	Plus		Minus
EPAX 1-step calculation	fast	wide distributed no parameters to modify EPAX modifications are very rare	no primary beam energy dependence
	reference line		does not take nuclide masses: predicts yield for unbound isotopes, no shell and even-even effects
LISE <sup>++</sup> Abrasion-Ablation (analytical)  2 steps	Takes nuclide masses for evaporation cascade		no beam energy dependence (yet)
	Using experimental results, it can be applied to deduce excitation energy parameters in order to predict an yield of more exotic nucleus		difficult choice of excitation energy initial parameters
	User-friendly results analysis and visualization		large set of parameters to play
HIPSE D.Lacroix et al., PRC69, 054604 (2004)  3 steps	More physics involved	Building partition Reaggregation phase evaporation stage	developed for multifragmentation and multi-nucleon transfers: significant overprediction for stripping of several nucleons
	Excitation energy of prefragment and fragment kinetic energy can be extracted		slow, difficulties to predict exotic yield (Monte Carlo)  Fixed parameters just for 25,50,80 MeV/u

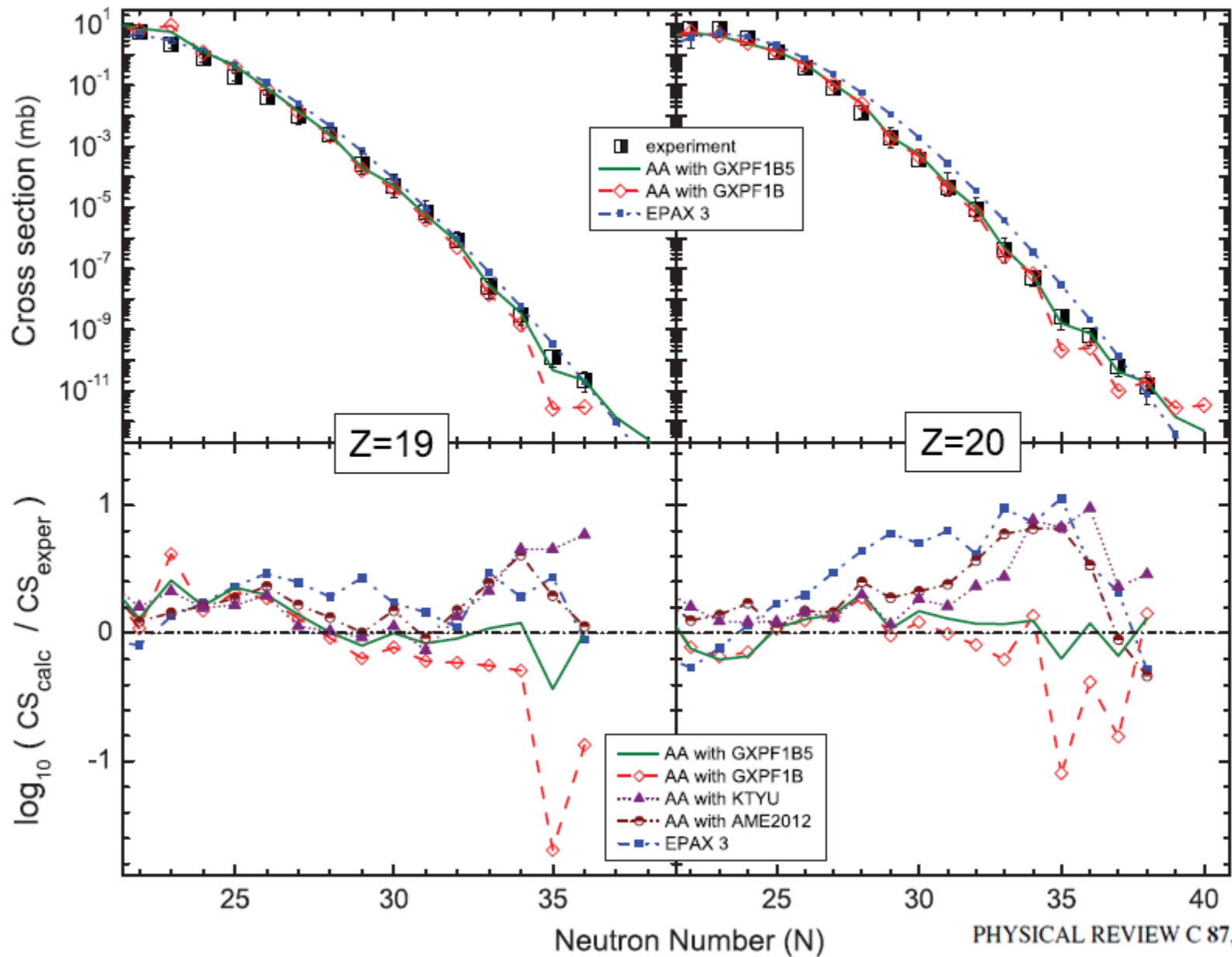
AMD, Isabel and so on..



Selected for a *Viewpoint in Physics*  
 PHYSICAL REVIEW C 87, 054612 (2013)



# $^{82}\text{Se}$ (139 MeV/u) + Be, W : exp. cross sections vs. AA



PHYSICAL REVIEW C 87, 054612 (2013)

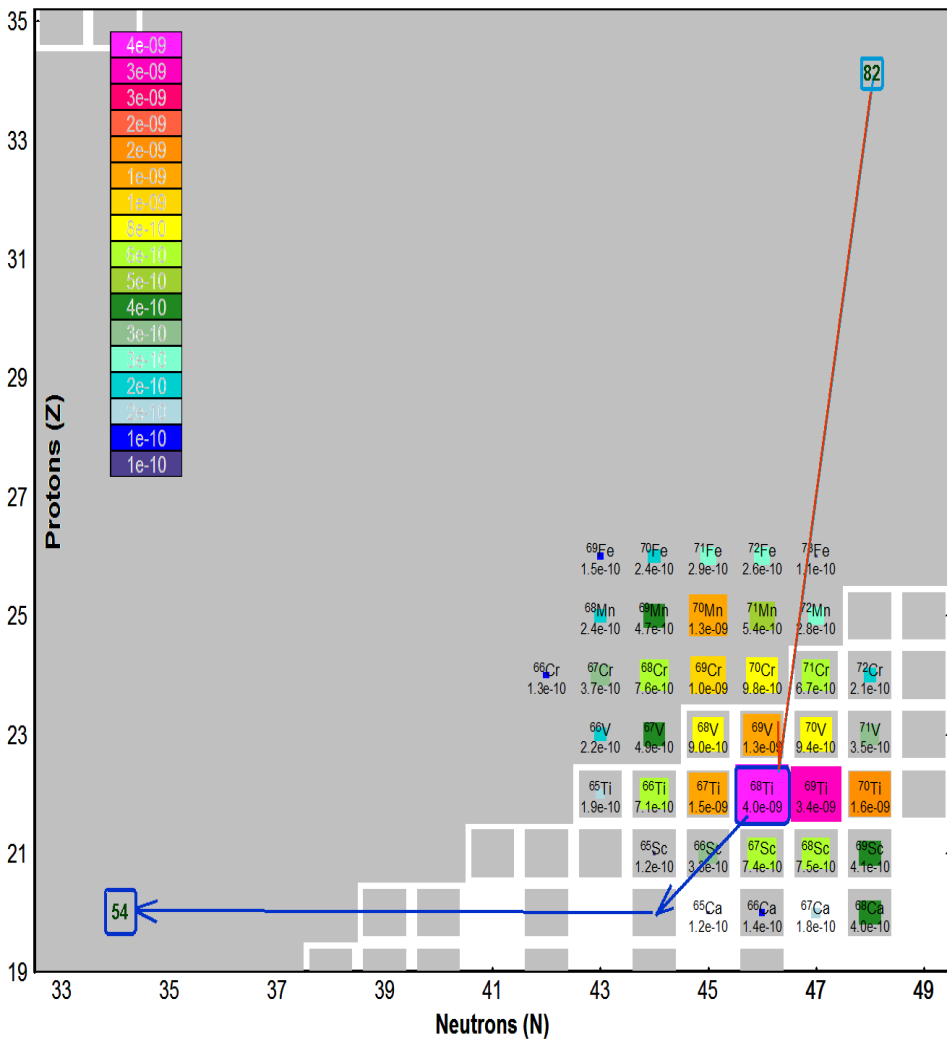


## Initial Prefragments Plot for <sup>54</sup>Ca (2.78e-08 mb)

ABRASION-ABLATION - <sup>82</sup>Se + Be: more probable <sup>68</sup>Ti(4.02e-09 mb); <-dZ>=2.88 <-dN>=11.78

Excit.Energy Method:< 2 >; <E\*>:15.0\*dA MeV sigma:9.20; Thermal.Intr.Coef. = 5.00e-22 MeV\*s

NP=64; SE:"DB1+CaI0" Density:"auto" Geom.Corr:"On" Tunlg:"auto" FisBar=#1 BarFac=1.00 Modes=1010 1010 010

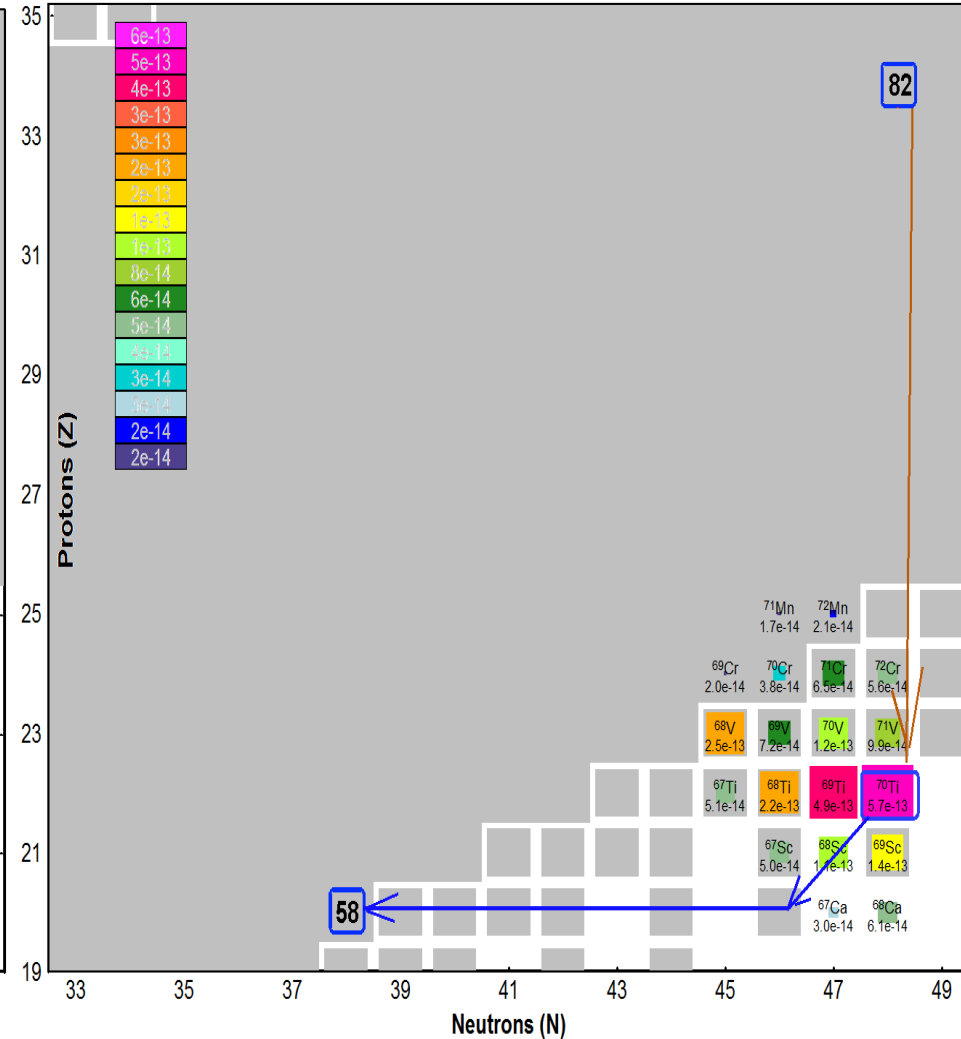


## Initial Prefragments Plot for <sup>58</sup>Ca (2.57e-12 mb)

EVAPORATION - Compound nucleus <sup>68</sup>Ti: more probable <sup>70</sup>Ti(5.73e-13 mb); <-dZ>=2.27 <-dN>=8.89

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+CaI0" Density:"auto" GeomCor:"On" Tunlg:"auto" FisBar=#1 BarFac=1.00 Modes=1010 1010 010



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

## $^{48}\text{Ca}(140\text{MeV/u}) + \text{W,Be}$

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.

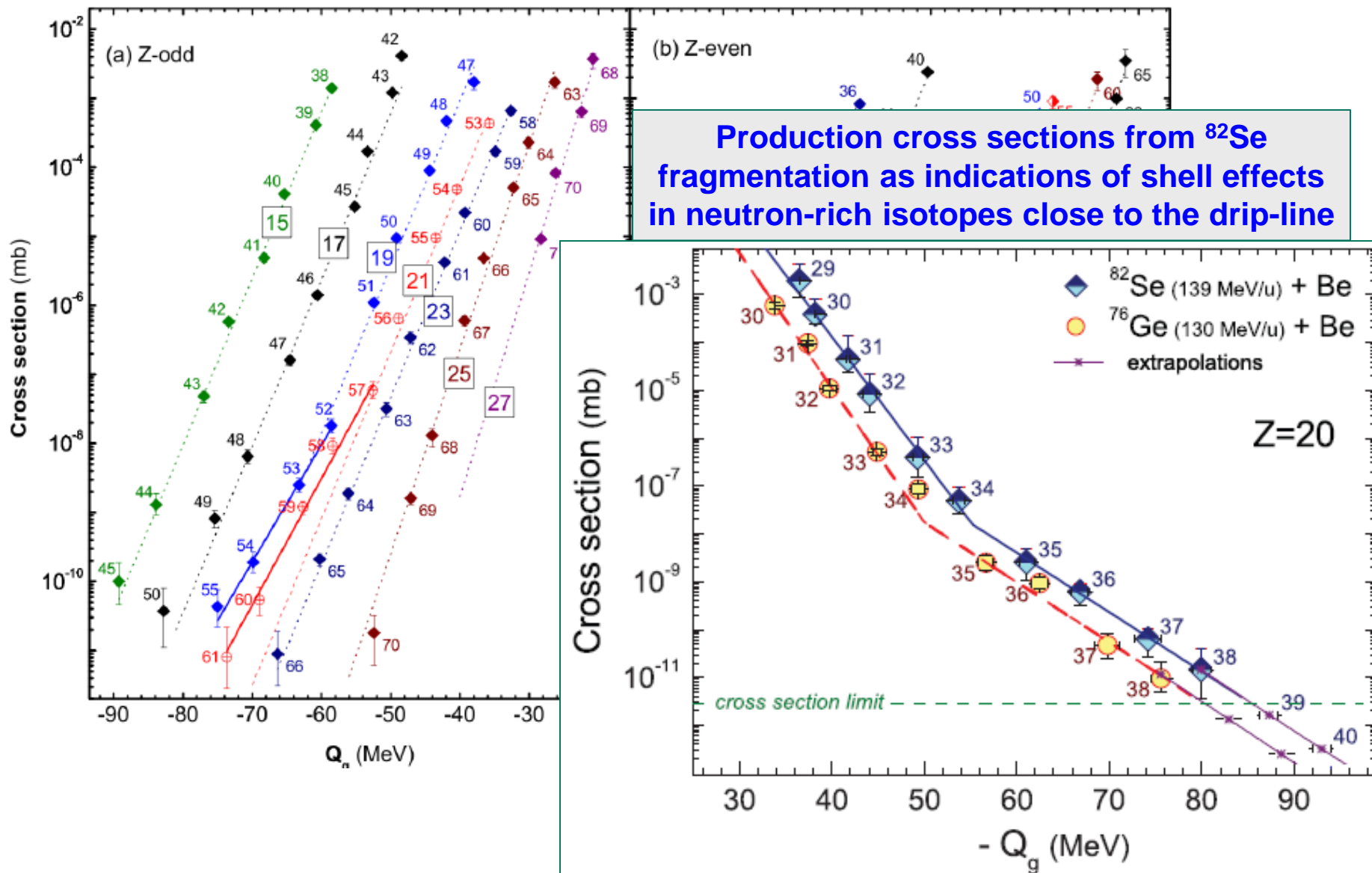
O.T. et al., Phys.Rev. C 75, 064613 (2007)

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

Figure. The variation of the cross sections for the production of neutron rich nuclei as a function of the two-body  $Q$  values [ $Q_{gg}$ , left panels (a), (b)] and as a function of the one-body  $Q$  value [ $Q_g$ , right panels (c), (d)]. Upper panels (a), (c) show data for W (Ta), lower panels (b), (d) for Be targets.

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

O.T. et al., Phys. Rev. Lett. 102, 142501 (2009)



O.T. et al., Phys. Rev. C 87, 054612 (2013)

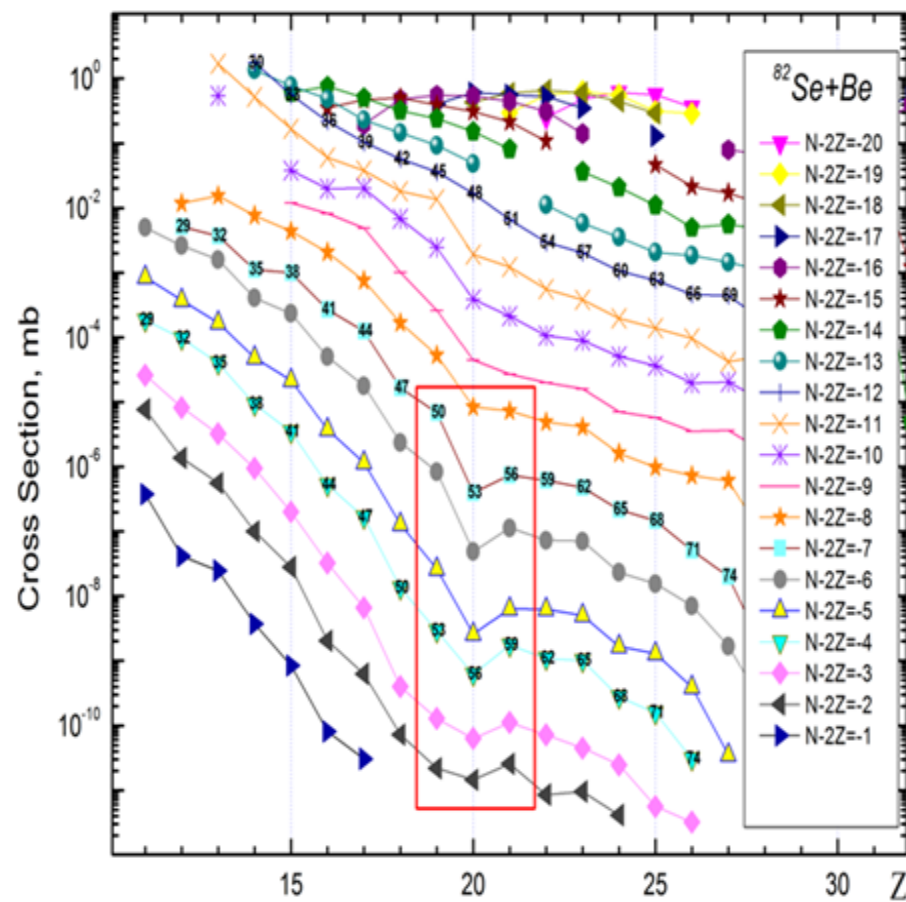


Figure 1. Production cross sections for fragments from the reaction of  $^{82}\text{Se}$  with beryllium targets vs. the atomic number of the fragment. The cross sections are connected by lines of constant  $N-2Z$ .

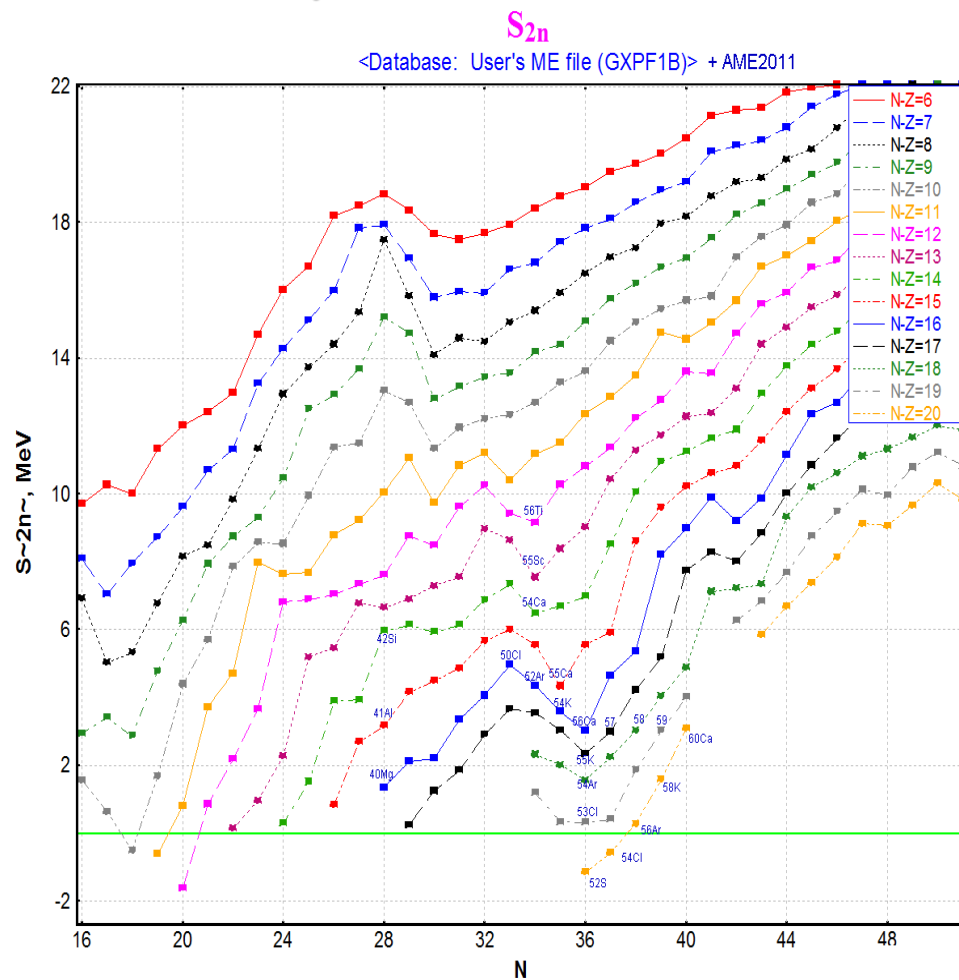


Figure 2. Two-neutron separation energy ( $S_{2n}$ ) versus neutron number ( $N$ ), and connected by lines of constant  $N-Z$ . Values are calculated using results from the GXPF1B5\* model.

\* Y. Utsuno, T. Otsuka, B. A. Brown, M. Honma, T. Mizusaki, and N. Shimizu, Phys. Rev. C 86, 051301(R) (2012).

**Projectile fragmentation**

Fragment velocity | **Momentum distribution** | Cross section, Excitation energy and etc

82Se(140.0 MeV/u) + Be -> 56Ca

Parallel momentum distribution been used in the program (MeV/c) = 392.5 with Gamma-factor = 451.5\*

Parallel momentum distribution:

- [1] A.S.Goldhaber  
Phys.Lett.B 53(1974)306  
 $\sigma_{||}^2 = \sigma_0^2 \frac{A_F(A_P - A_F)}{A_P - 1}$   $\sigma_0 = 90$   $\sigma_{||} = 381.3$
- [2] D.J.Morrissey  
Phys.Rev.C 39(1989)460  
 $\sigma_{||}^2 = \sigma_M^2 (A_P - A_F)$   $\sigma_M = 87$   $\sigma_{||} = 443.0$
- [3] W.A.Friedman  
Phys.Rev.C 27(1983)569  
 $\sigma_{||}^2 = \frac{\mu}{2x_0} \left[ \frac{1+0.5y}{\sqrt{1+y}} + \frac{1}{\mu x_0} \right]$  settings  $\sigma_{||} = 287.9$

Asymmetry coefficient for Gaussian-like distributions [1-3] alpha (%) = 0  $\alpha = \frac{\sigma_{low}}{\sigma_{||}} - 1 = 1 - \frac{\sigma_{high}}{\sigma_{||}}$  ? Help

- [4] Universal parameterization (Convolution)  
O.Tarasov, NPA 734(2004)536 settings  $\sigma_0^{conv} = 91.5$   $\sigma_{||} = 392.5$

Corrections of the momentum distribution width

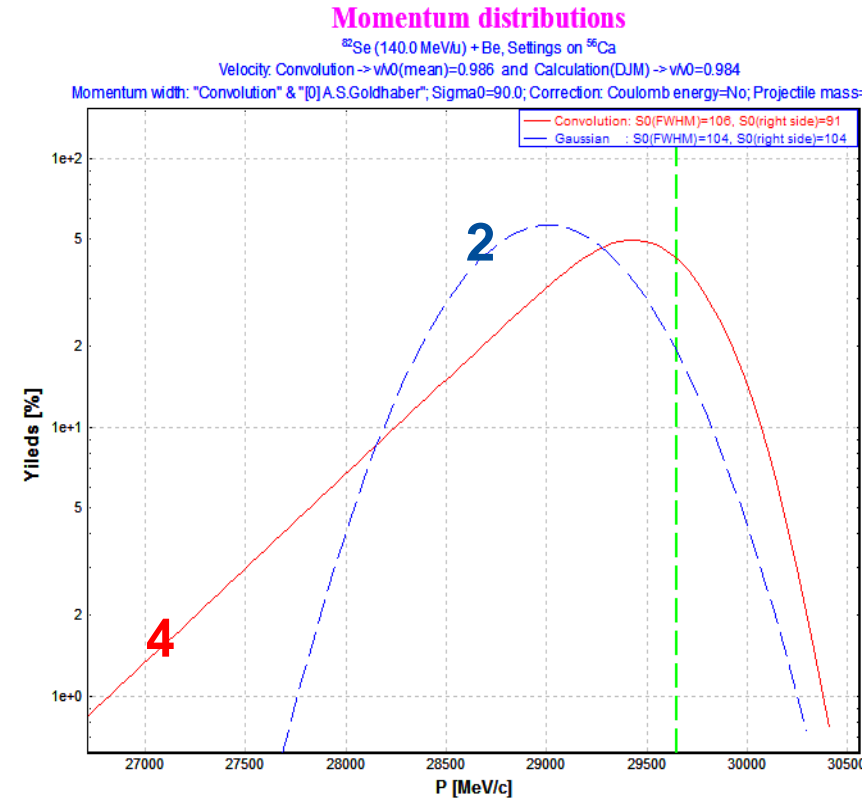
- [a] Coulomb energy correction [W.A.Friedman, PRC 27(1983) 569]  $\sigma_0^* = \sigma_0 (1 - E_B / E_{CM})^{1/2}$  Sigma0(M) corrected, [MeV/c]
- [b] Particle mass correction [R.K.Tripathi, L.W.Townsend, PRC 49(1994)2237]  $\sigma_0^* = (\sigma_0 - 20 + 2A_P / 3)$

Perpendicular momentum distribution

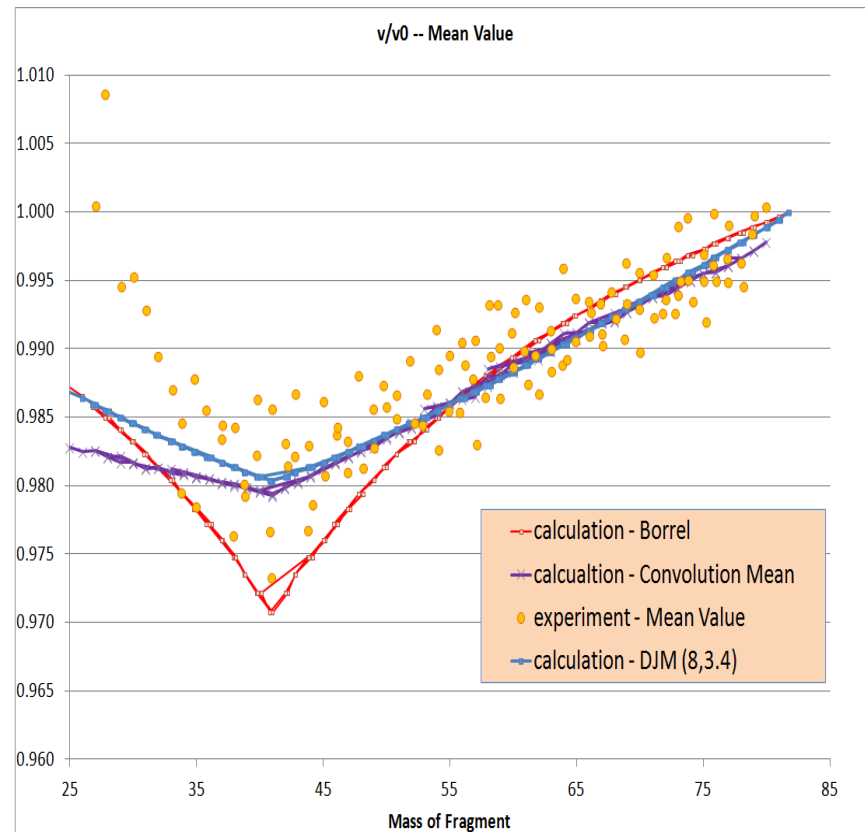
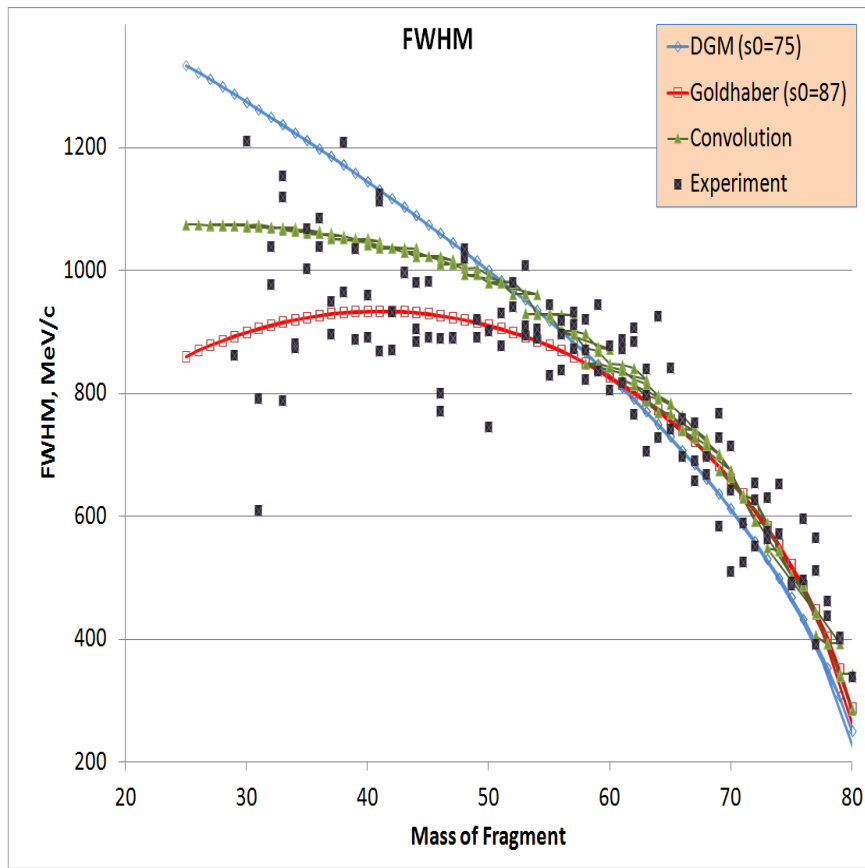
$\sigma_{\perp}^2 = \sigma_{||}^2 + \sigma_D^2 \frac{A_F(A_P - 1)}{A_P(A_P - 1)}$   $\sigma_D = 200$  MeV/c  Make default

$\sigma_{\perp} = 471.6$  MeV/c

OK Cancel ? Help



- **Models [1-3] : Gaussian distributions**
- **Model [4] : Convolution**
- **Proton rich side : low-exponential energy tails create difficulties with purity of RIBs**



O.T. et al., will be submitted to NIMA

**Projectile fragmentation**

Fragment velocity / Momentum distribution / Cross section, Excitation energy and etc

Final relation  $V_f/V_b$  been used in the program for the setting fragment: mean = 0.9865, peak = 0.9940

Reaction:  $^{82}\text{Se}(140.0 \text{ MeV/u}) + \text{Be} \rightarrow ^{56}\text{Ca}$

Mean Fragment velocity:

- Constant  $V_{\text{fragment}} / V_{\text{beam}} = 1$
- Calculation - A [V.Borrel et al., Z.Pyhs.A314(1983)191]
- Calculation - B [F.Rami et al., NPA 444(1985)349]
- Calculation - C [O.Tarasov, NPA 734(2004)536]**
- Calculation - D [from two-body reaction]
- Calculation - E [D.Morrissey, PRC 39(1989)460]

Options:

- Velocity after reaction can not exceed fragment velocity from two-body reaction kinematics (at 0 degree). It is important for pick-up reactions!
- Assume symmetric velocity distribution around  $A_{\text{proj}} / 2$ . Important for light fragment production.
- Use velocity shift for pick-up reactions [R.Piffar, D.Morrissey et al., PRC51(1995)1348]
- Exclude this shift for (p,n) and (n,p) reactions

Parameters:

- $dE/dA = 8$  at  $A_{\text{frag}} = A_{\text{proj}}$
- $V_f / V_b = 0.980$  (both default 8 MeV)  $8$  at  $A_{\text{frag}} = A_{\text{proj}} / 2$



- The fission fragment production model is at the basis of all fission reactions implemented in LISE<sup>++</sup>
- The fissile nucleus (A,Z), fission channel cross section ( $\sigma_{fis}$ ), and excitation energy ( $E^*$ ) are the input parameters
- The kinetic energy of the fissile nucleus is used for kinematics calculations in order to estimate the transmission through the separator.

**1-st step:** Calculation of an initial fission cross-section matrix of excited fragments using the semi-empirical model of Benlliure <sup>1)</sup>. This model has some similarities with previously published approaches <sup>2,3)</sup> with the added advantage of describing fission properties of a large number of fissile nuclei over a wide range of excitation energies.

**2-nd step:** Post-scission nucleon emission. The code calculates the number of post-scission nucleons with LISE evaporation cascade, which enables the user to make rapid and qualitative calculations.

*Less than 5 seconds for low-energy fission!*

Shell position (N sh.)	Strength (dU <sub>i</sub> ) (MeV)	Curvature (2C sh.) (MeV)
1 83	-2.65	0.7
2 90	-3.8	0.15

## References

1. J.Benlliure et al., Nuclear Physics A 628 (1998) 458-478.
2. M.G.Itkis et al., Yad.Fiz. 43 (1986) 1125.
3. M.G.Itkis et al., Fiz.Elem.Chastits At.Yadra 19 (1988) 701.
4. O.Tarasov and D.Bazin, NIM B204 (2003) 174-178.



Production Mechanism

Reactions: Energy Loss, Straggling / Charge states / Databases: Masses, Isomers

238U(1000.0 MeV/u) + Pb -> 130Te

Reactions:

- Settings  Projectile Fragmentation
- Settings  Fusion -> Residual
- Settings  Fusion -> Fission
- Settings  Coulomb fission
- Settings  Abrasion-Fission
- Two Body Reactions
- ISOL mode

additionally calculate yields for the next reactions

Make default  OK  Cancel  Help

Coulomb Fission

EM fission deexcitation function

- only average deexcitation energy (fast)
- 3 points of deexcitation function (qualitatively)
- manually Ex = 20 MeV CS = 1000 mb

Fission properties

Evaporation settings

Plots:

- EM excitation plots (fixed proj.energy)
- EM cross section versus proj.energy
- Fission CS plots (summary)
- Fission CS plots (partial)
- Fiss fragment excit function

Fission cross section normalization

- 1 mb (constant from Ex, Energy)
- Fission deexcitation channel of EM excitation

Make default

OK  Cancel  Help

1. The program assumes that the reaction takes place in middle of the target. Therefore the first step is the **calculation of the primary beam energy in the middle of the target.**
2. **Total fission cross-section and average excitation energy:**
  - a. Calculation of differential electromagnetic cross-section.
  - b. Deexcitation fission function  $d\sigma^f/d(E^*)$ .
  - c. Calculation of statistical parameters of the deexcitation fission function: mean value  $\langle E^* \rangle$ , and area  $\sigma^f$ .
3. **Calculation of an initial fission cross-section matrix**
4. **Post-scission nucleon emission**

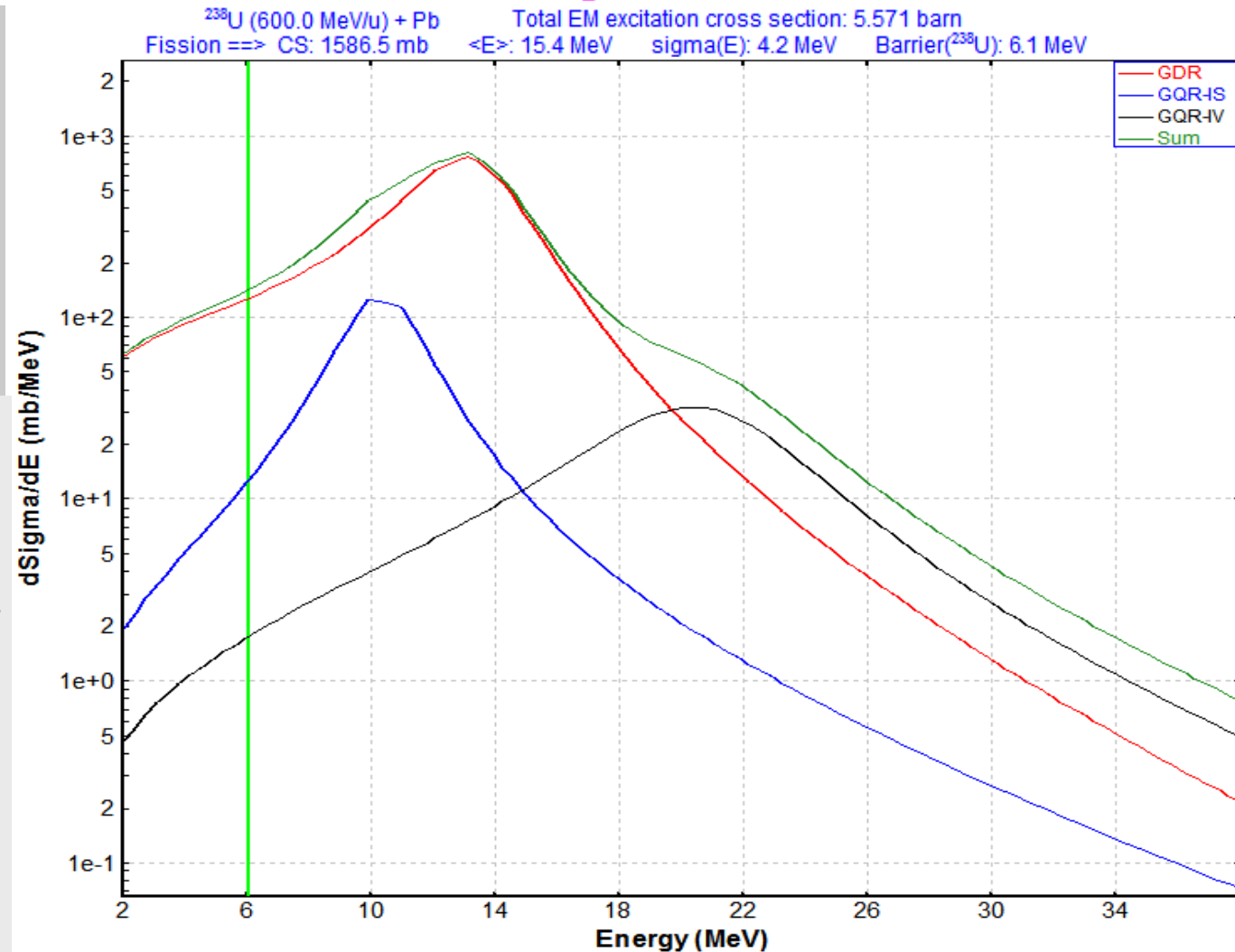
A well-known review of the processes generated by the electromagnetic interaction in relativistic nuclear, and atomic collisions, by C.Bertulani and G.Baur [Physics Report 163 (1988) 299-408] has been used to obtain the excitation energy function for fission.

The differential cross-section for electromagnetic excitation is given by:

$$\frac{d\sigma_{em}}{dE_\gamma} = \frac{n_{E1}}{E_\gamma} \cdot \sigma_\gamma^{E1} + \frac{n_{E2}}{E_\gamma} \cdot (\sigma_{\gamma,1}^{E2} + \sigma_{\gamma,2}^{E2})$$

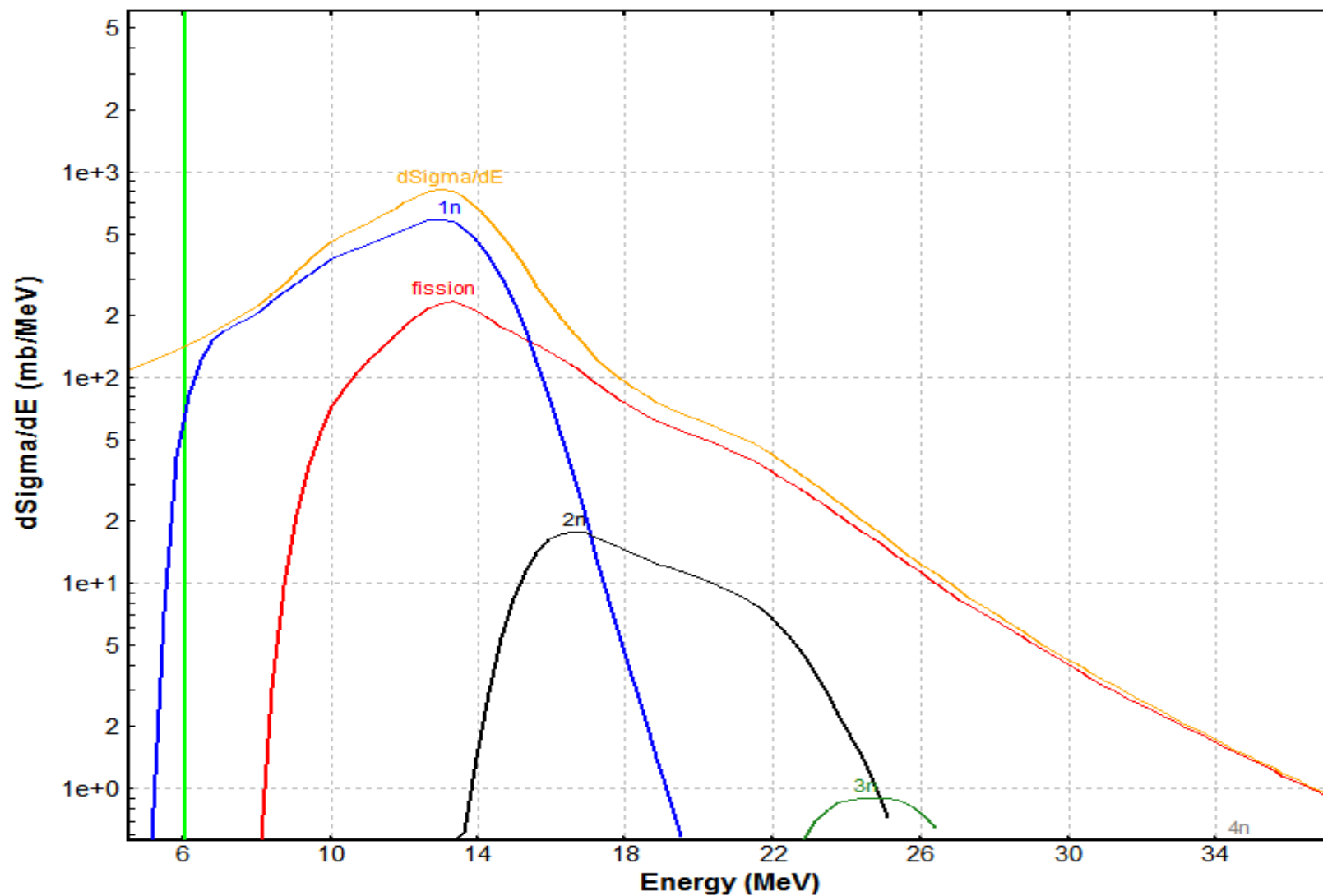
with  $n_{E1}$ ,  $n_{E2}$  being the number of equivalent photons for electric dipole and quadrupole excitations respectively.  $\sigma_\gamma^{E1}$ ,  $\sigma_{\gamma,i}^{E2}$  are the photon absorption cross-sections for giant E1 and E2 excitations, where for E2 excitations  $i=1$  denotes isoscalar and  $i=2$  denotes isovector giant quadrupole resonances. Multiple excitations of the quadrupole resonances are neglected.

## Electromagnetic excitation

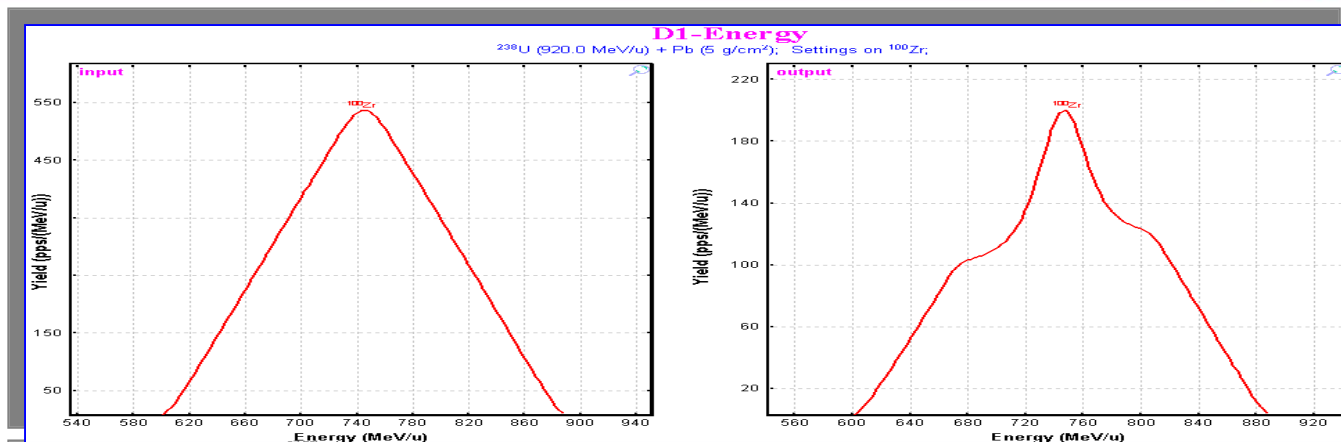


Differential cross-sections of GDR (red solid curve), GQR(IS) (blue dashed curve), and GQR(IV) (black dot curve) excitations in  $^{238}\text{U}$  as calculated from the equivalent photon spectrum representing a  $^{208}\text{Pb}$  projectile nucleus at 600 MeV/u.

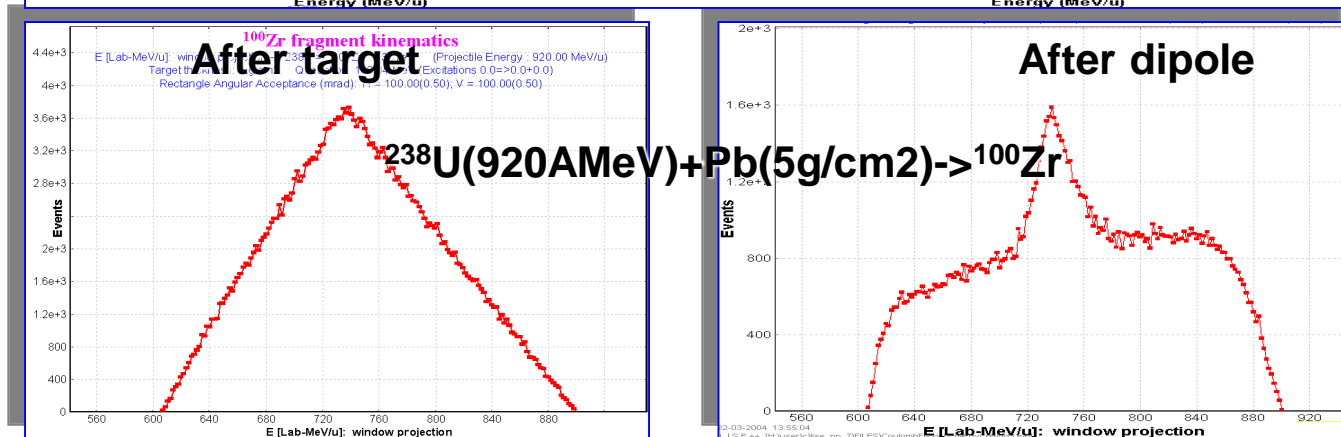
Deexcitation channels for  $^{238}\text{U}$  nuclei at 600 MeV/u excited by a lead target. The solid red curve represents fission decay. The blue dashed line represents 1n-decay channel, black dotted and green dot-dashed curves respectively 2n- and 3n-decay channels.



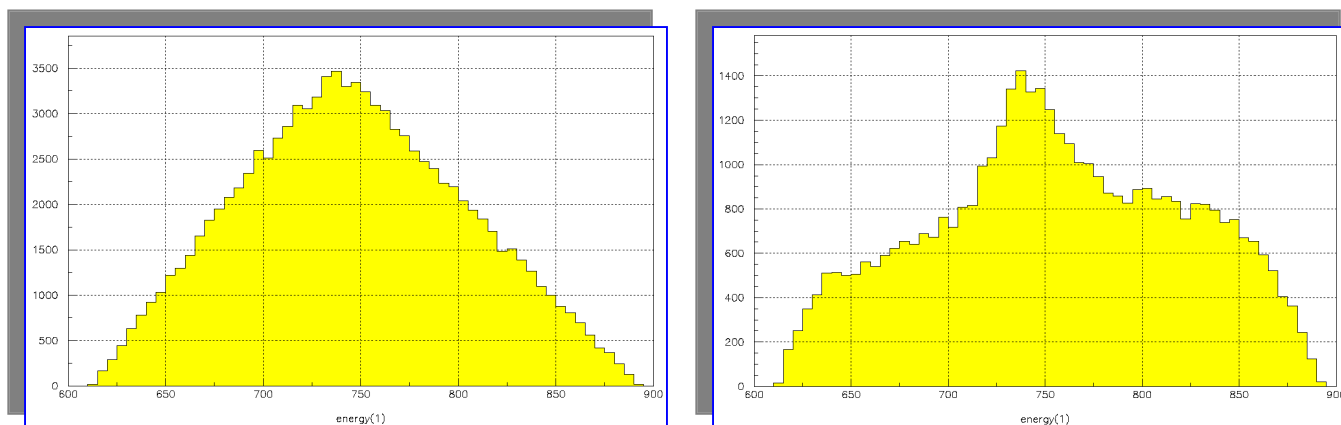
**LISE++**  
Distribution  
Method



**LISE++**  
MC method

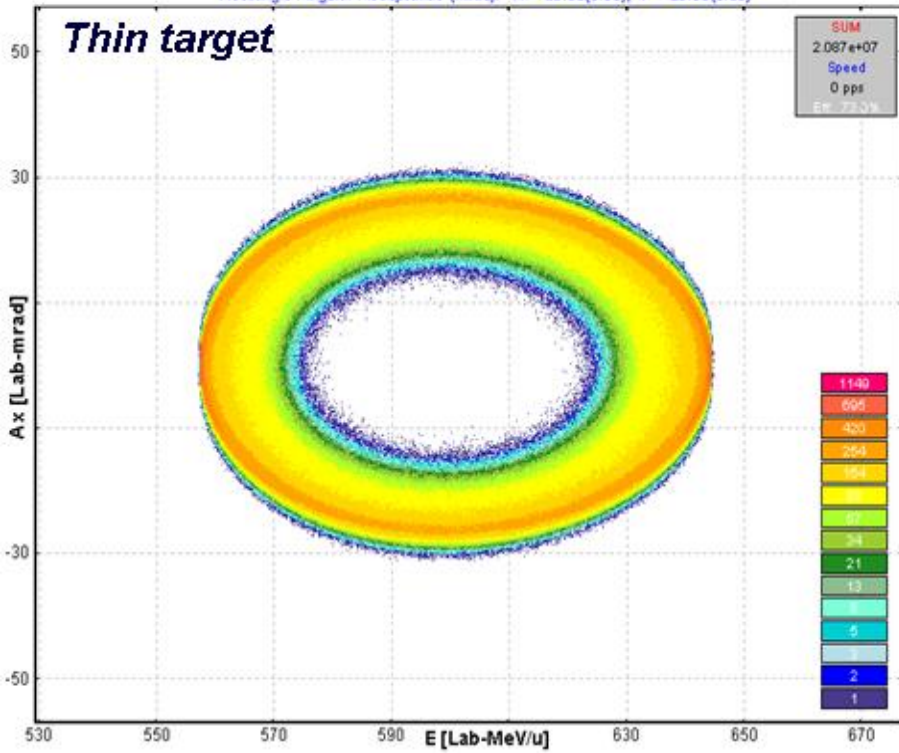


**MOCADI**



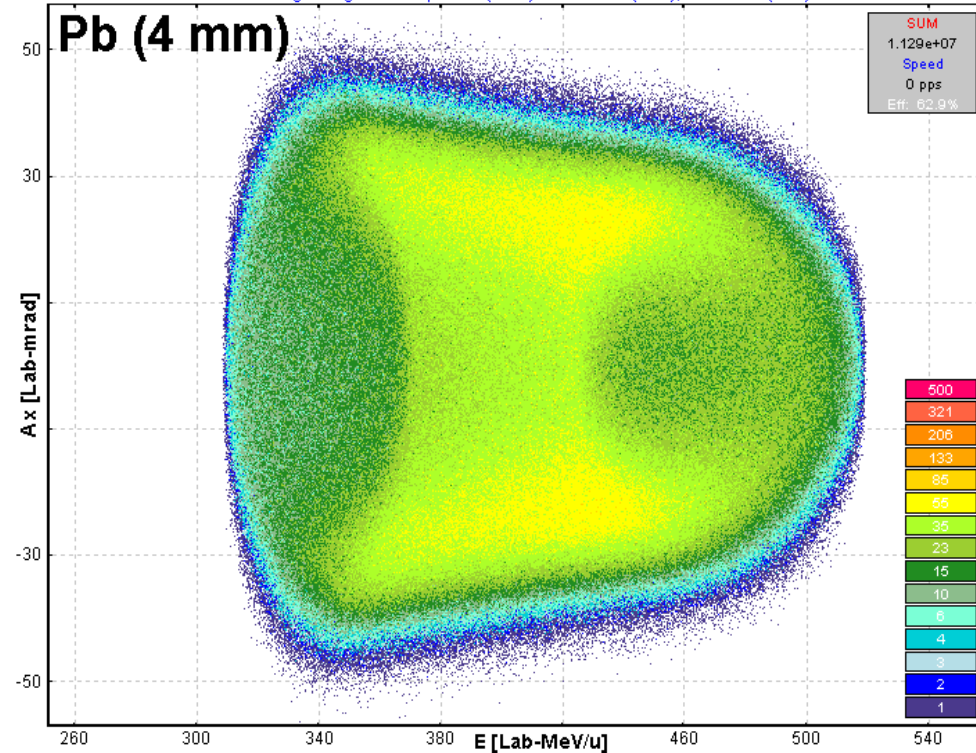
## <sup>132</sup>Sn fragment kinematics (expected final)

$^{238}\text{U} \Rightarrow ^{132}\text{Sn}(^{136}\text{Sn}^*) + ^{102}\text{Mo}^*$  (Projectile Energy : 600.00 MeV/u)  
 Q reaction: 188.79 MeV (Excitations 50.0=>24.3+24.3)  
 Rectangle Angular Acceptance (mrad): H = 60.00(0.50); V = 20.00(0.50)

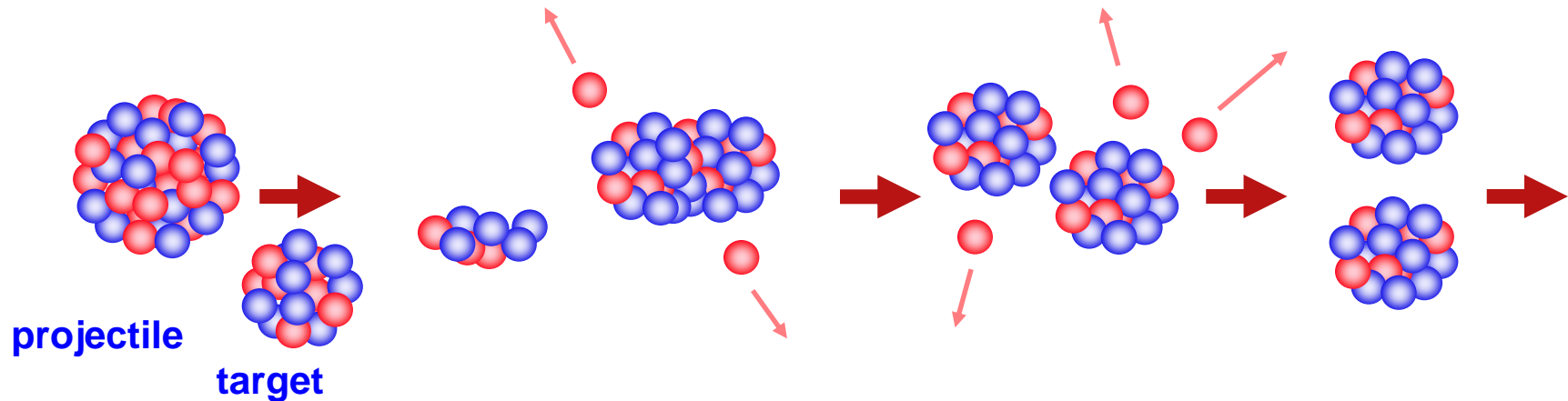


## <sup>132</sup>Sn fragment kinematics (expected final)

$^{238}\text{U} \Rightarrow ^{132}\text{Sn}(^{136}\text{Sn}^*) + ^{102}\text{Mo}^*$  (Projectile Energy : 600.00 MeV/u)  
 Target: Pb (4 mm); Q reaction: 188.79 MeV (Excitations 50.0=>24.3+24.3)  
 Rectangle Angular Acceptance (mrad): H = 60.00(0.50); V = 20.00(0.50)



2D-plots  $A_x$ (horizontal component of the angle in the laboratory frame) versus Energy per nucleon of <sup>132</sup>Sn final fragment after <sup>238</sup>U(600MeV/u,  $E_x=50$ MeV) fission. Angular acceptances  $H=60$ mrad and  $V=20$ mrad. The left plot has been produced with very thin target, the right picture represents the case of thick target (Pb 4mm).



- ❑ **ABRABLA : Abrasion-Ablation Monte Carlo**

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

- ❑ **PROFI : semi-empirical fission Monte-Carlo code**

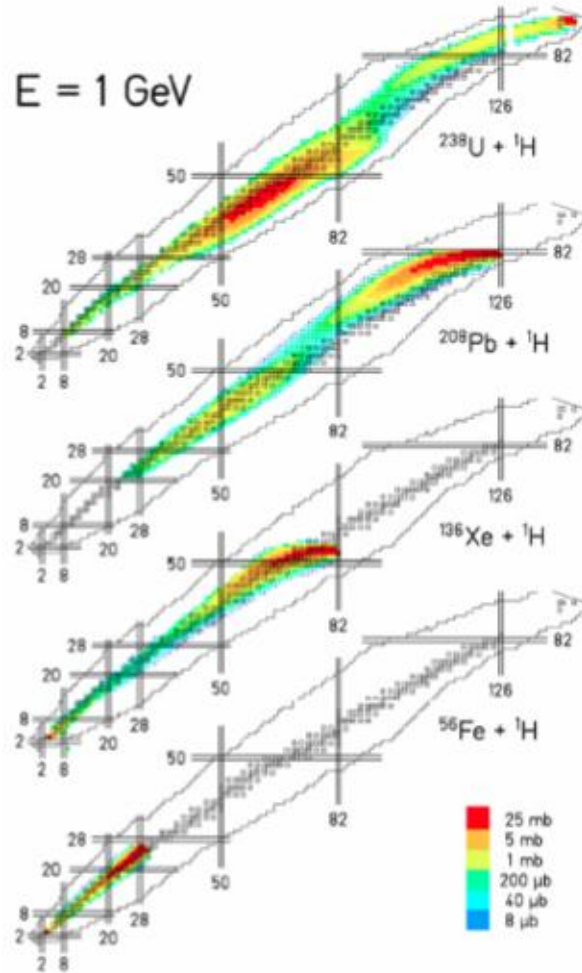
*J. Benlliure, A. Grewe, M. de Jong, K.-H. Schmidt, S. Zhdanov, Nucl. Phys. A 628 (1998) 458*

- ❑ **LISE++ 3EER Abrasion-Fission model (analytical)**

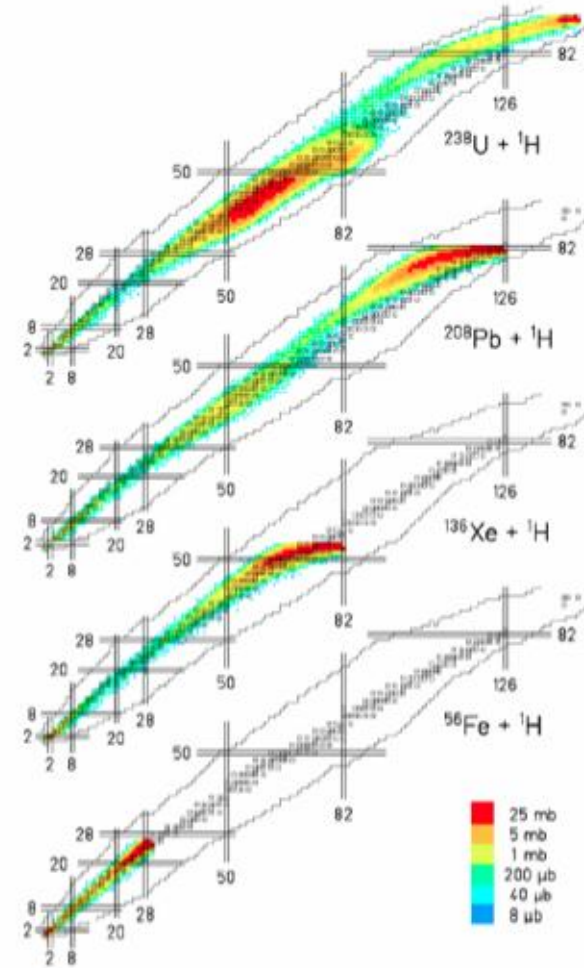
*O.T., Tech. Rep. MSUCL1300, NSCL, Michigan State University, 2005*  
[http://lise.nsl.msui.edu/7\\_5/lise++\\_7\\_5.pdf](http://lise.nsl.msui.edu/7_5/lise++_7_5.pdf)

<http://www.gsi.de/charms>

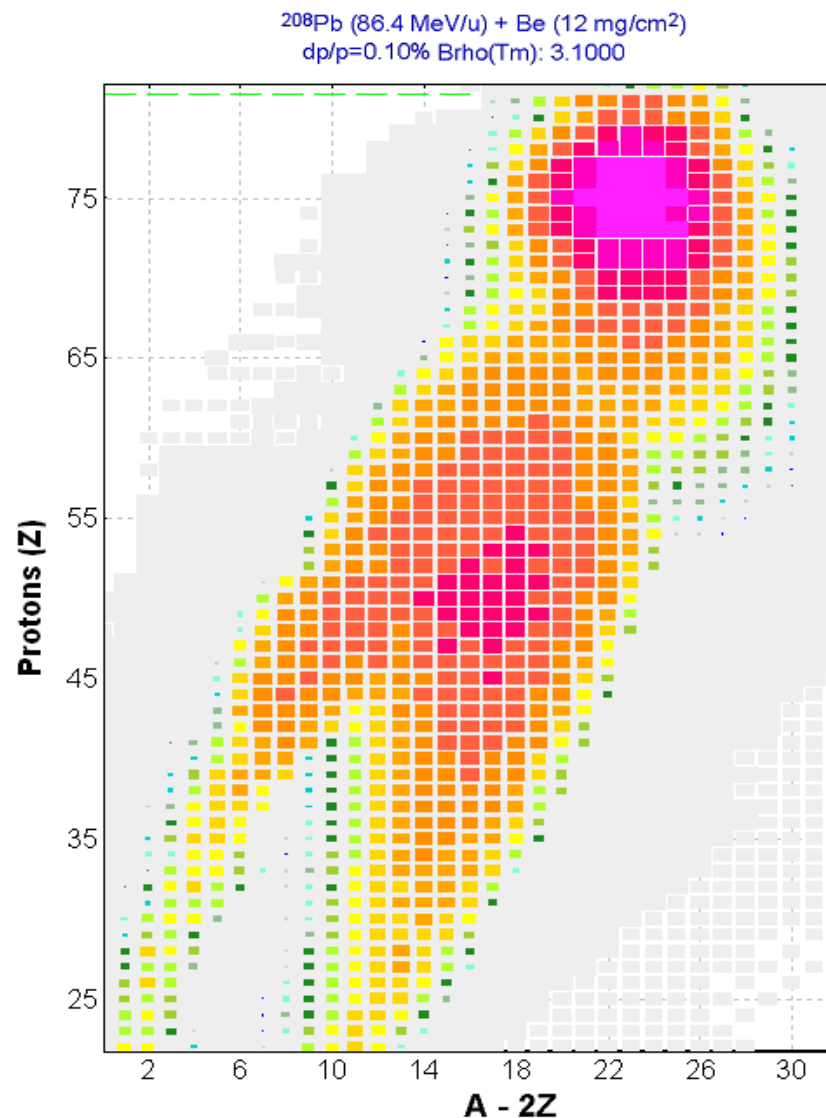
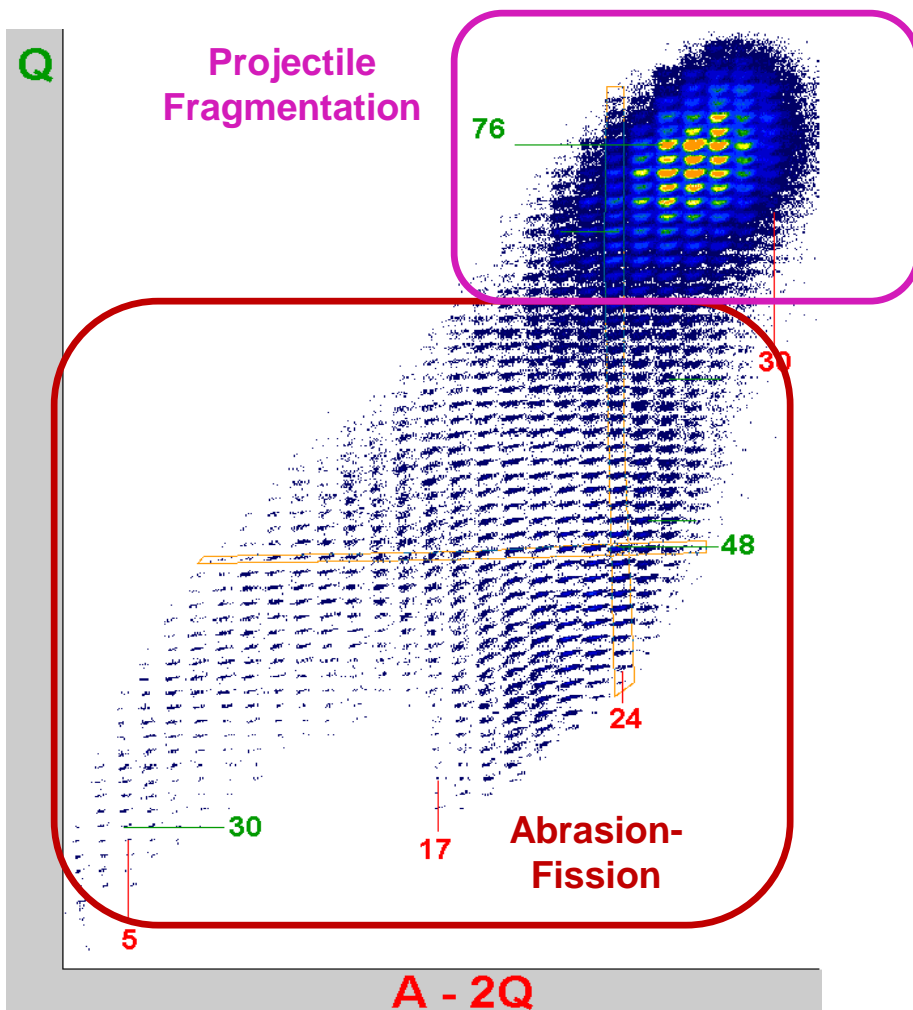
A. Kelić, S. Lukić, M. V. Ricciardi, K.-H. Schmidt



Experiment (FRS)



ABRABLA07



**Experiment #05120 @ NSCL**

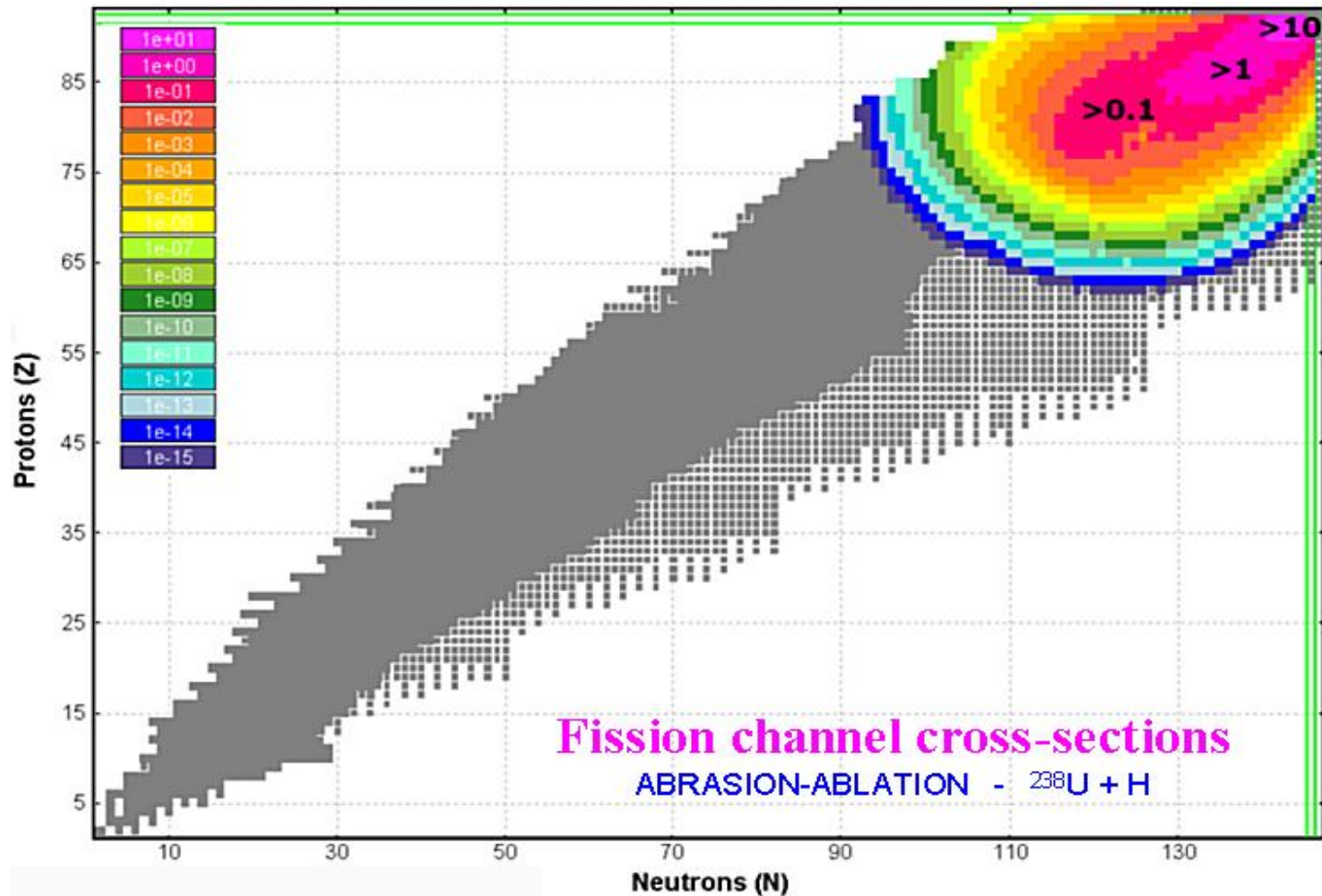
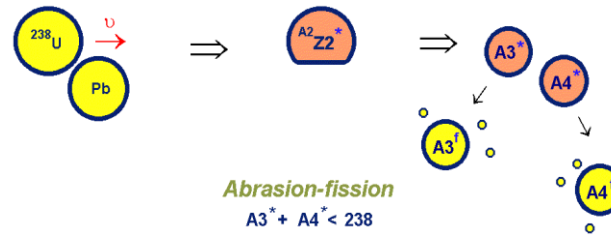
**Good qualitative agreement between experimental data & LISE++ AA & AF**

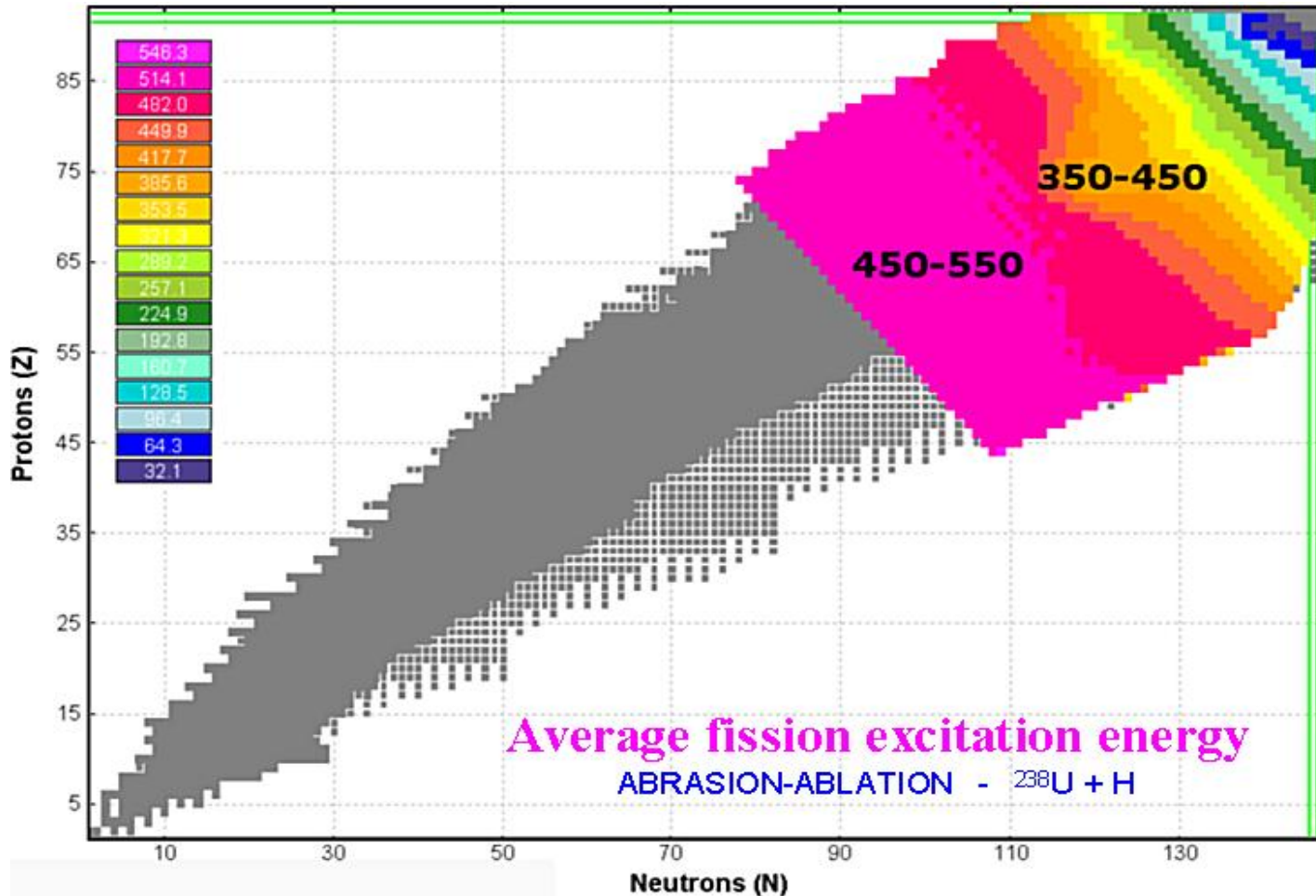
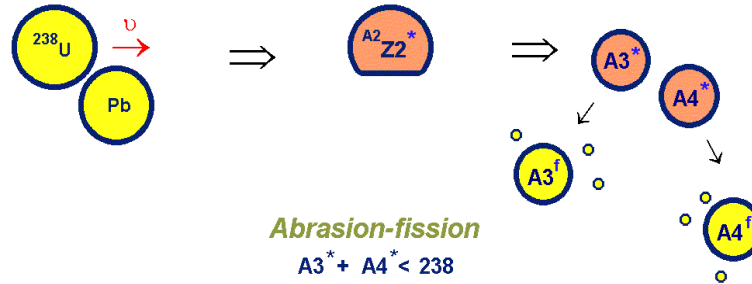
**How do we calculate?**

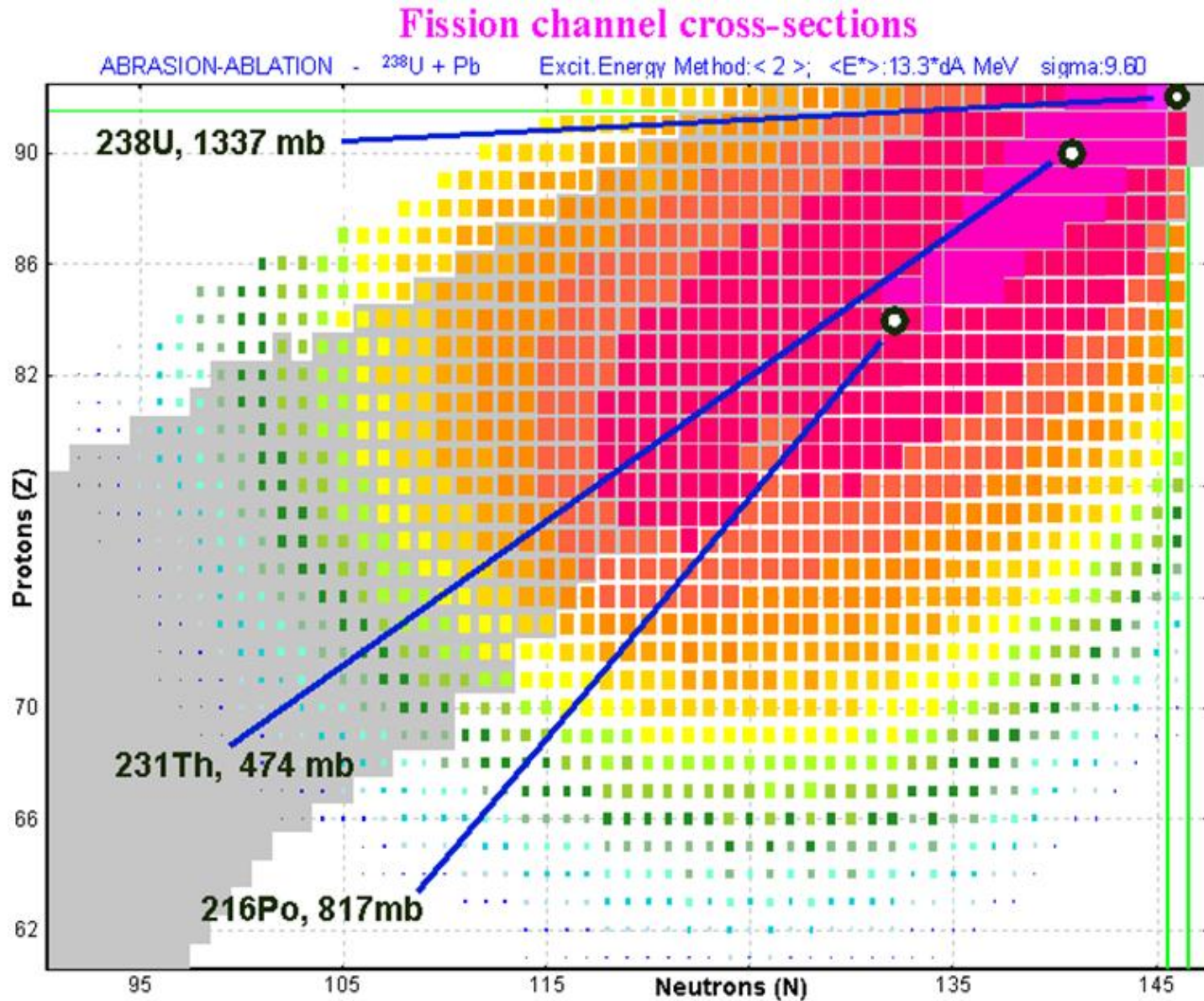
O.T. AIP Conference Proceedings Volume 1224, ISBN: 978-0-7354-0768-8 ;  
[Preprint MSUCL1409, NSCL/MSU 2009](#)



# Abrasion-Fission : ocean of fissile nuclei







### Abrasion-Fission

238U (750.0 MeV/u) + Be

Energy region definitions:

Excitation energy region	LOW	MIDDLE	HIGH
Choose a primary reaction	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Perform transmission calculations for this energy region	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
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      1. Calculate  
Evaporation settings      2. Use "All" in code  
Prefragment excit. energy      3. Plot

Make default

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

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
L+M+H	use in code **	use in code	use in code	
L+M+H+EM	1184	1191.5		

Fission barrier < LOW < 40      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

40 < MIDDLE < 180

180 < HIGH

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

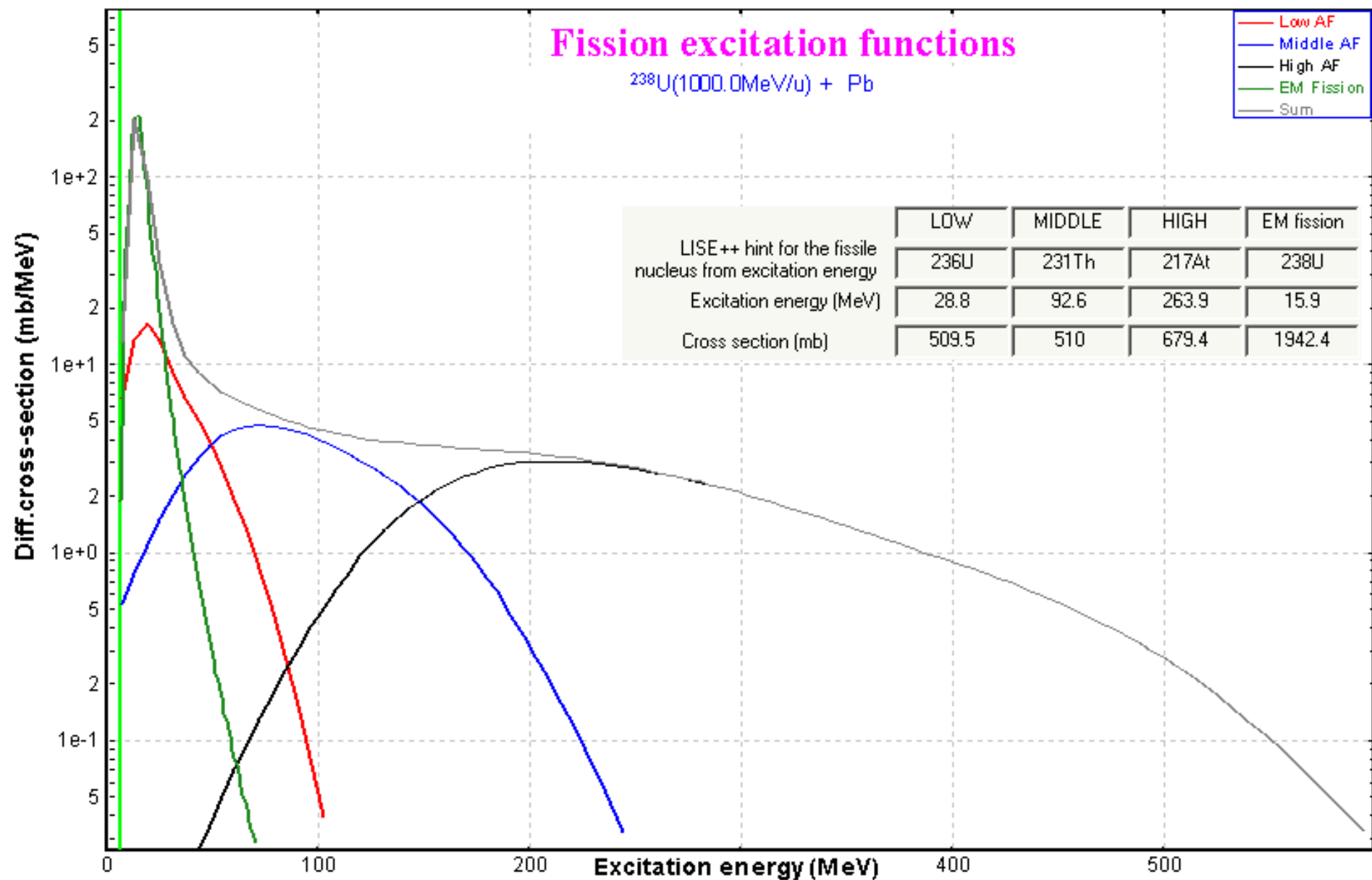
determine low Z (element number) where Abrasion-Ablation stops.  $Zstop = coef * Zbeam$

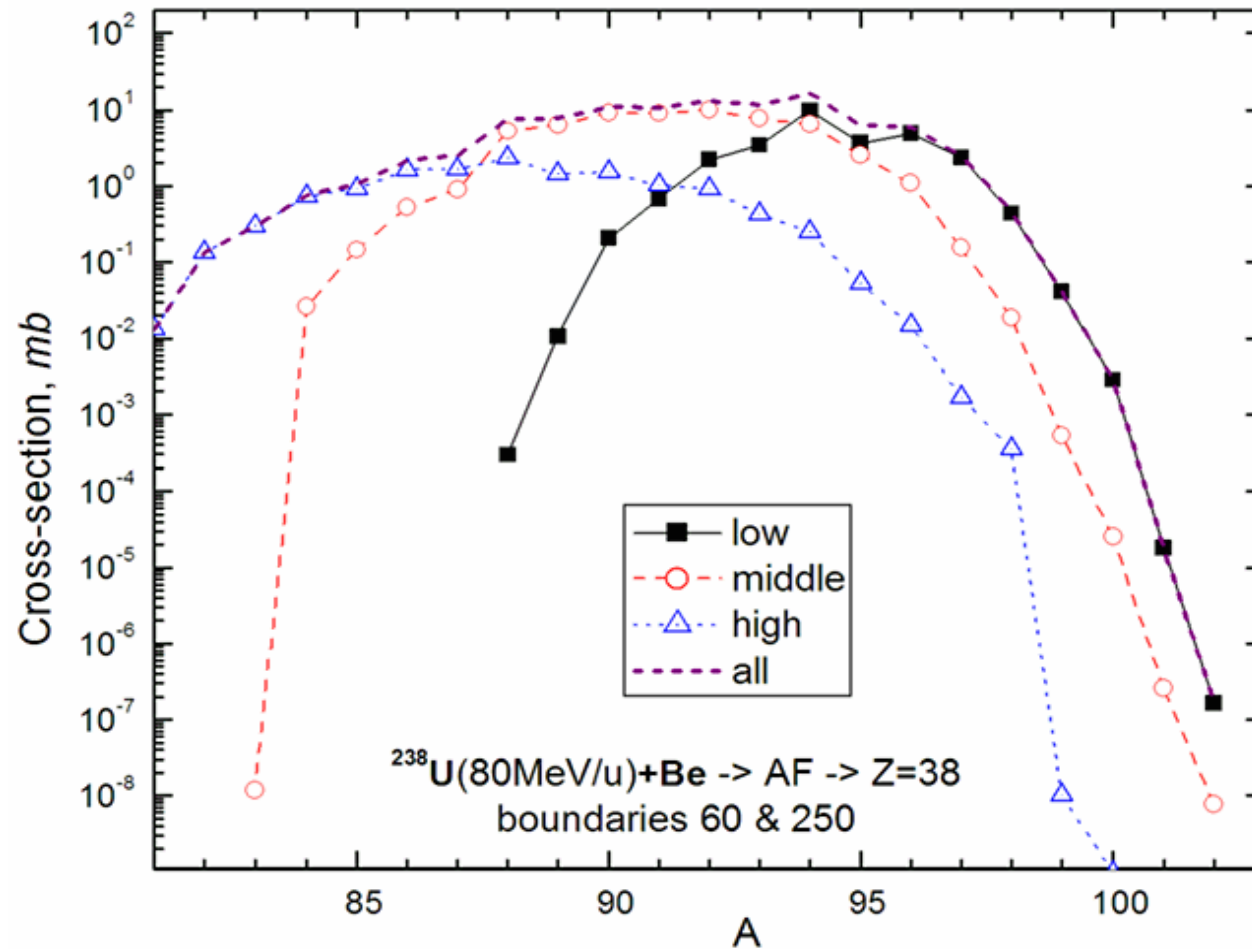
\* - takes about 0.5 - 1 minute      \*\* - Low-excitation Abrasion-Fission and EM fission results will be used together

LISE++ package:

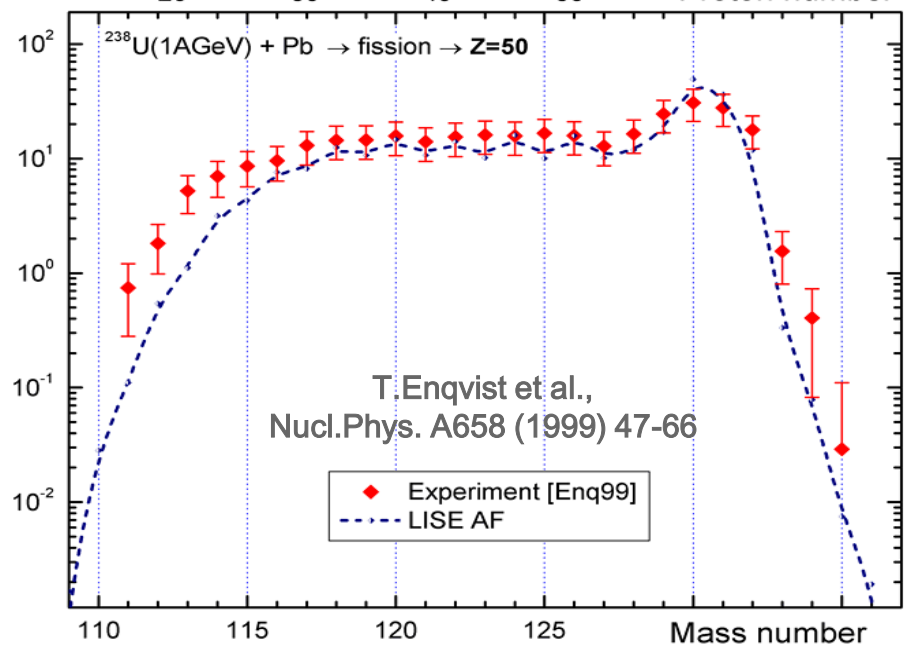
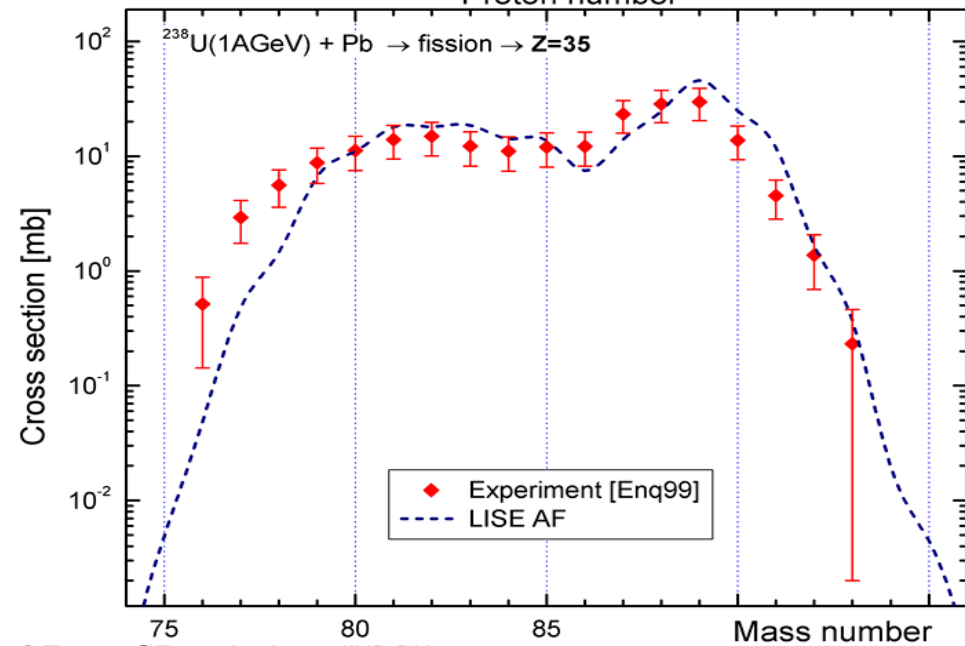
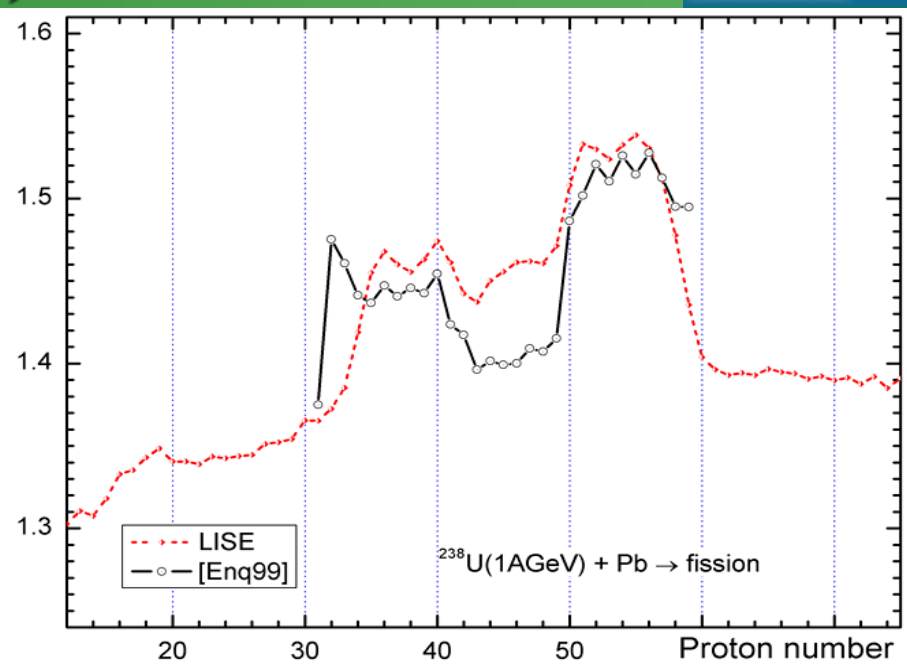
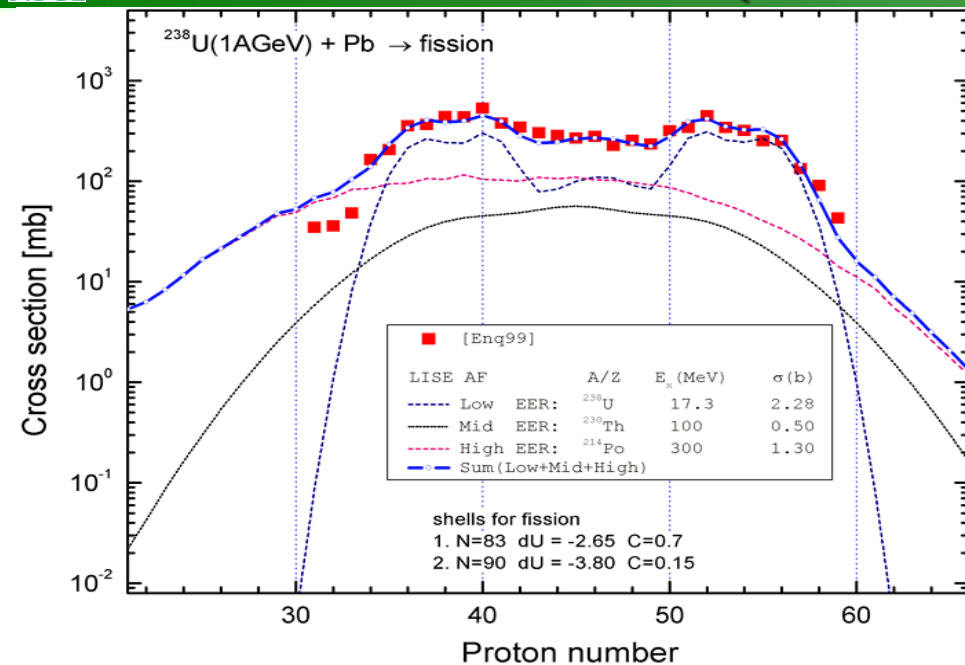
Name	Ext
[.]	
AF_238U_Pb	lpp
AF_238U_d	lpp
AF_238U_Be	lpp
AF_238U_p	lpp
AF_208Pb_p	lpp
AF_208Pb_d	lpp

Name	Ext
[.]	
238U_Pb_1AGeV_fragmentation	cs
238U_Pb_1AGeV_fission	cs
238U_p_1AGeV_spallation	cs
238U_p_1AGeV_fission	cs
238U_Be_750AMeV_fission	cs





Partial and total mass distributions of Strontium fission fragments in the reaction  $^{238}\text{U}(80\text{MeV/u})+\text{Be}$ .

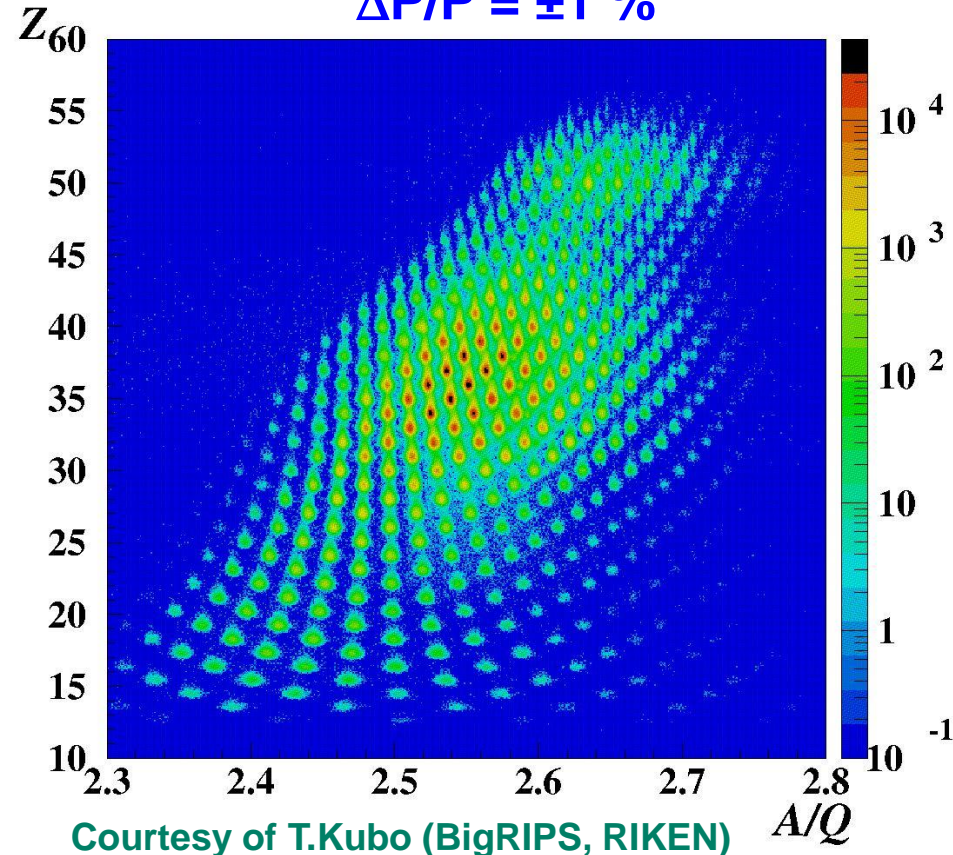


## Abrasion fission

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

Be target

$B_\rho = 7.249 \text{ Tm}$   
 F1 slit:  $\pm 21 \text{ mm}$   
 $\Delta P/P = \pm 1 \%$

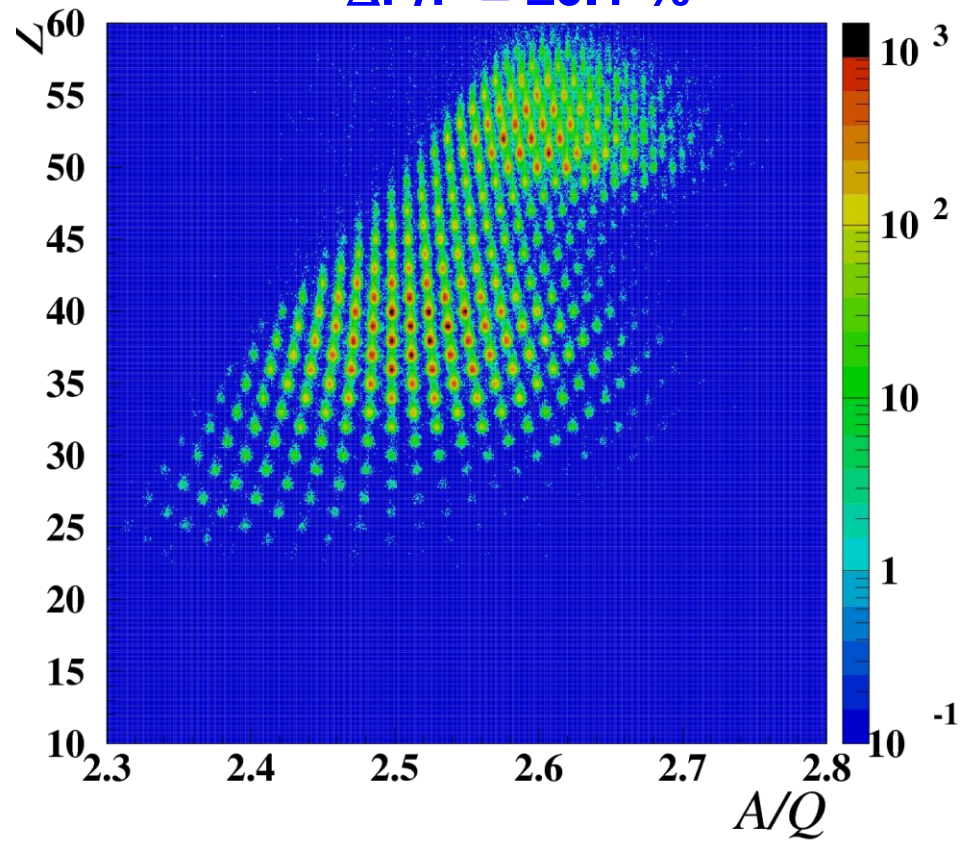


## Coulomb fission

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

Pb target

$B_\rho = 6.992 \text{ Tm}$   
 F1 slit:  $\pm 2 \text{ mm}$   
 $\Delta P/P = \pm 0.1 \%$



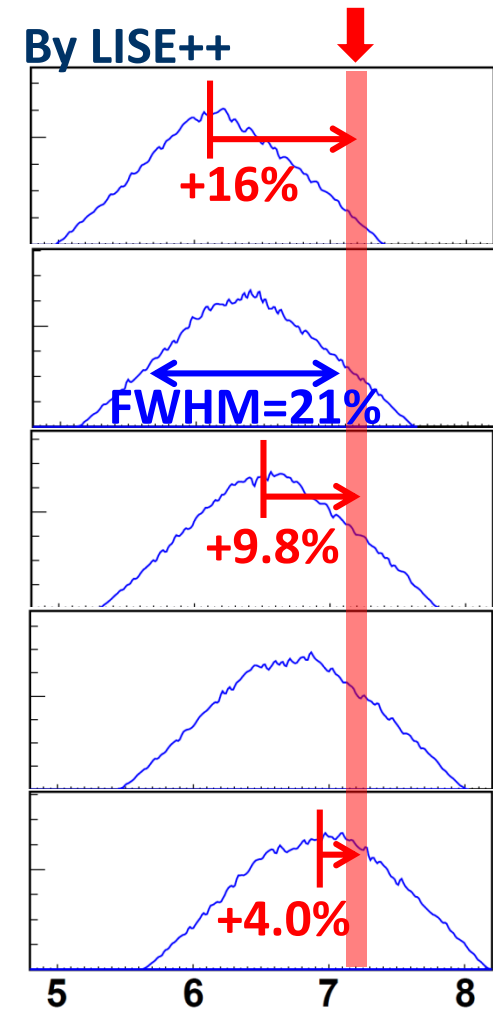
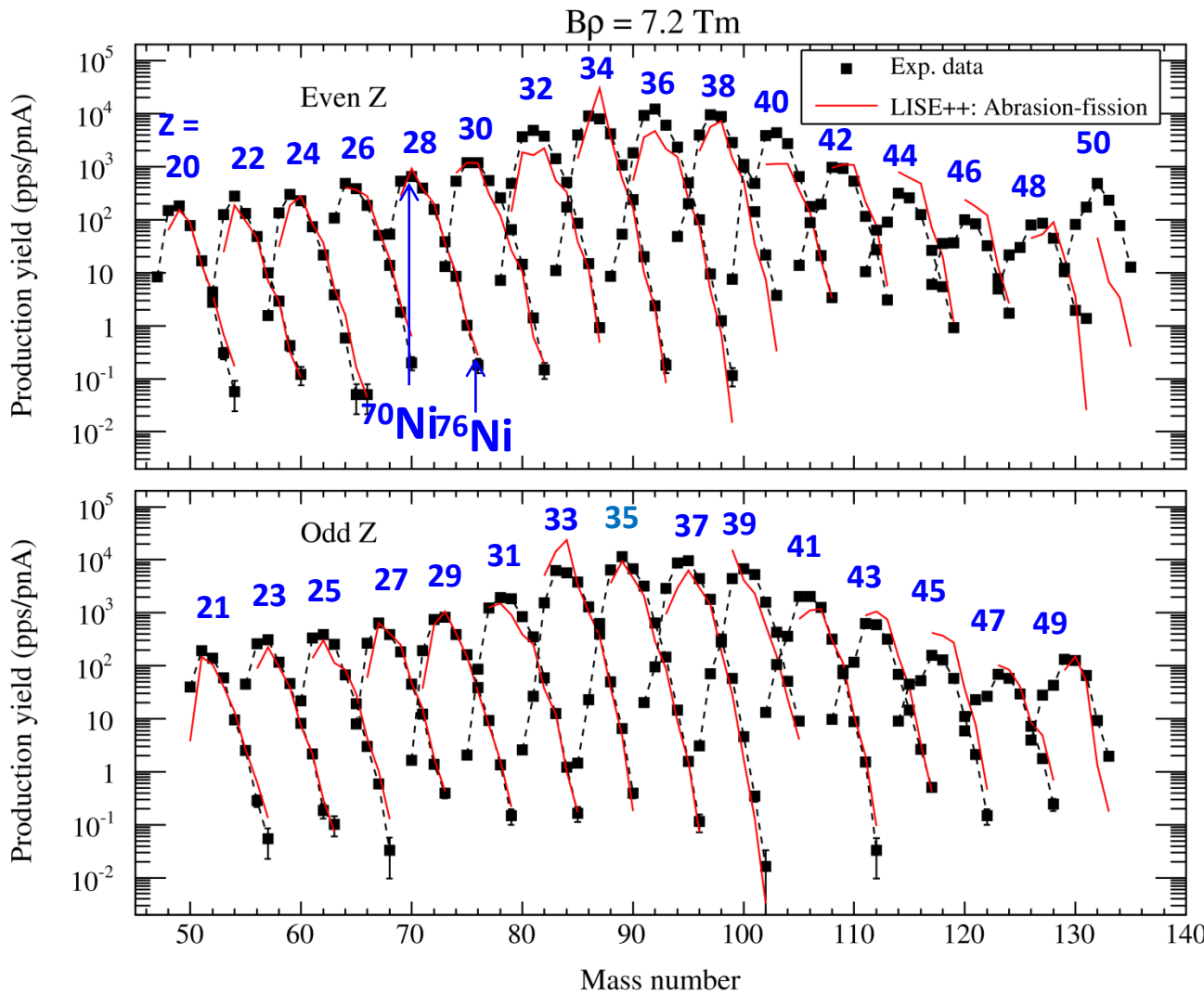


1 setting, no energy degraders used

LISE++ Abrasion-Fission

Fairly good reproduction

$B\rho = 7.2 \text{ Tm} \pm 1\%$



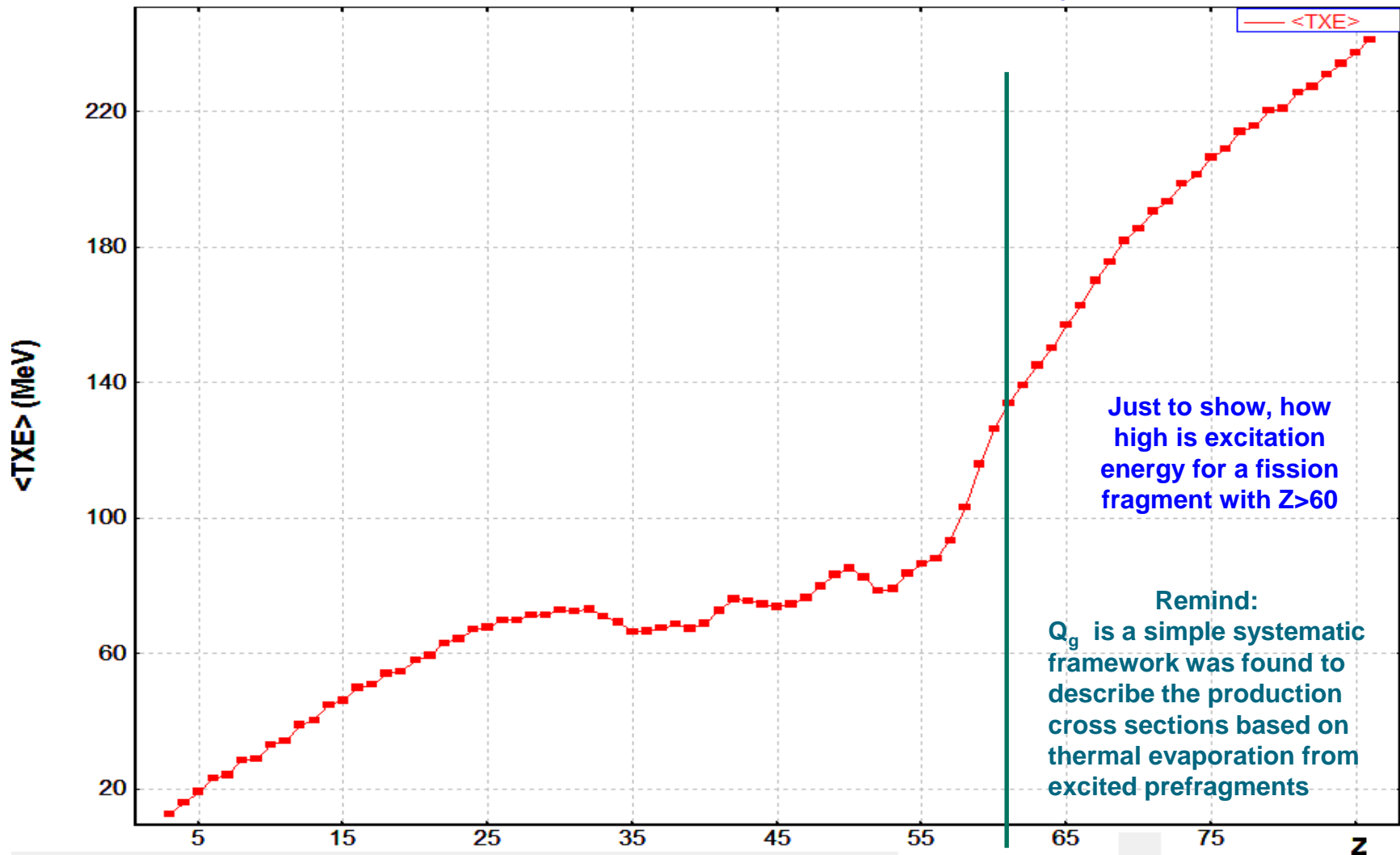
# Q<sub>g</sub>- systematics for Abrasion-Fission products (<sup>238</sup>U+Be)

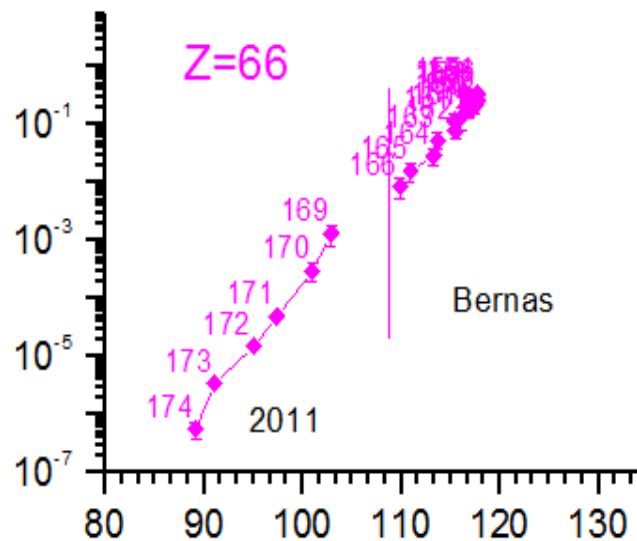
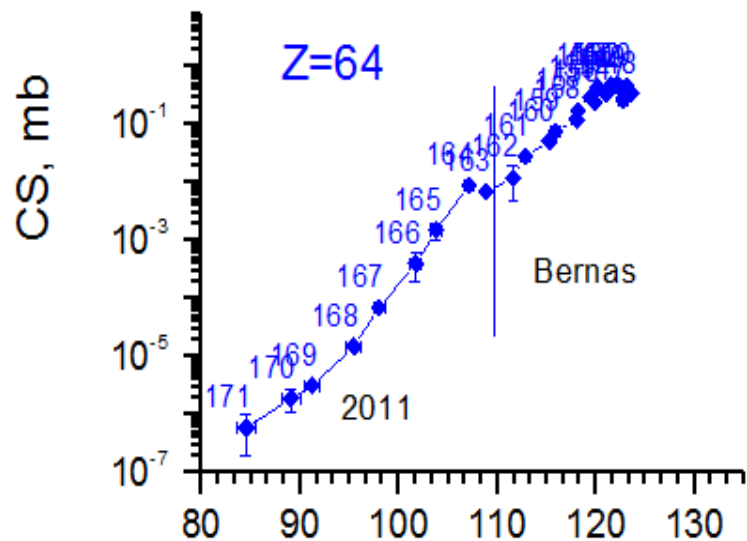
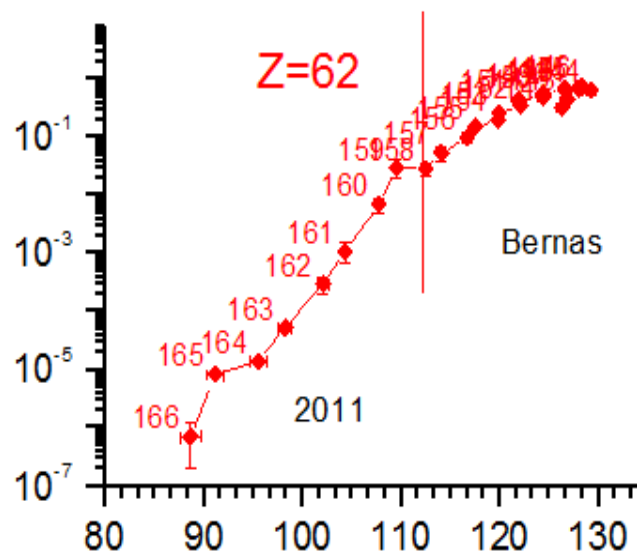
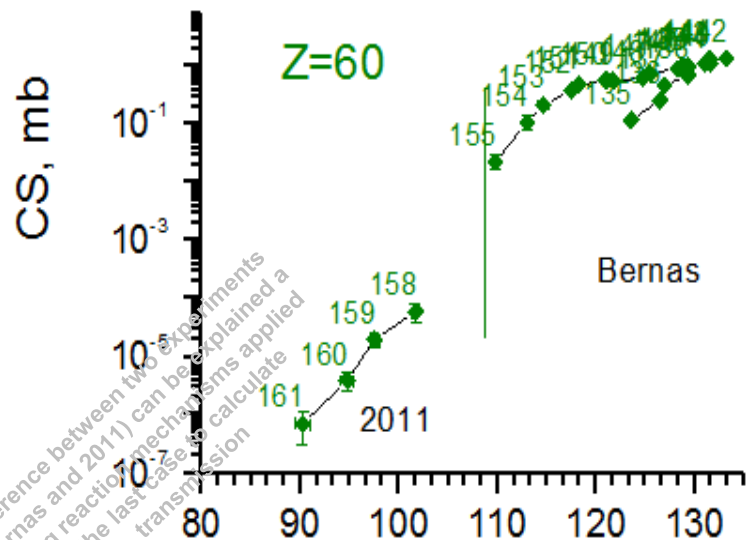
## Excitation energy of one fission fragment (LISE++ for all EERs)

— just ONE fragment — <sup>238</sup>U (750.0 MeV/u) + Be (1.01 g/cm<sup>2</sup>) → sum Z=1-200

"Average weighted" mode; TXEmethod: 1 (f=0.0045); Shells: N1={83,-2.65,0.70}, N2={90,-3.80,0.15}

Fission => Odd-Even corrections: Yes; Post-scission evaporation: Yes





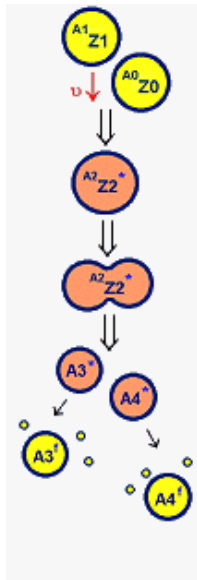
M. Bernas et al., NPA  
A765 (2006) 197

$^{238}\text{U} + p$  at 1A GeV

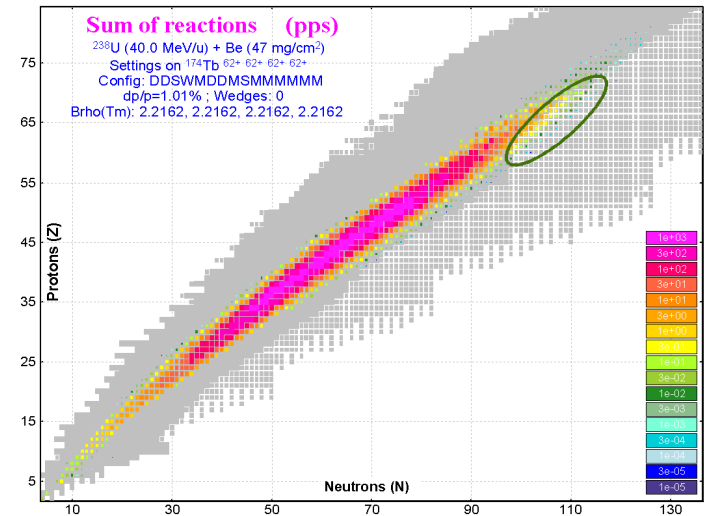
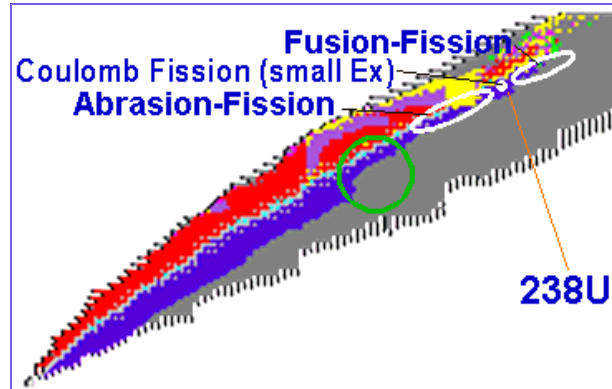
[http://arxiv.org/PS\\_cache/arxiv/pdf/1112/1112.0521v1.pdf](http://arxiv.org/PS_cache/arxiv/pdf/1112/1112.0521v1.pdf)

$^{238}\text{U} + \text{Be}$  at 1A GeV

J. Kurcewicz et al.,  
Published in PLB



O.T. and A. C. C. Villari,  
NIM B 266 (2008) 4670



## 2010: E547 @ LISE3.GANIL

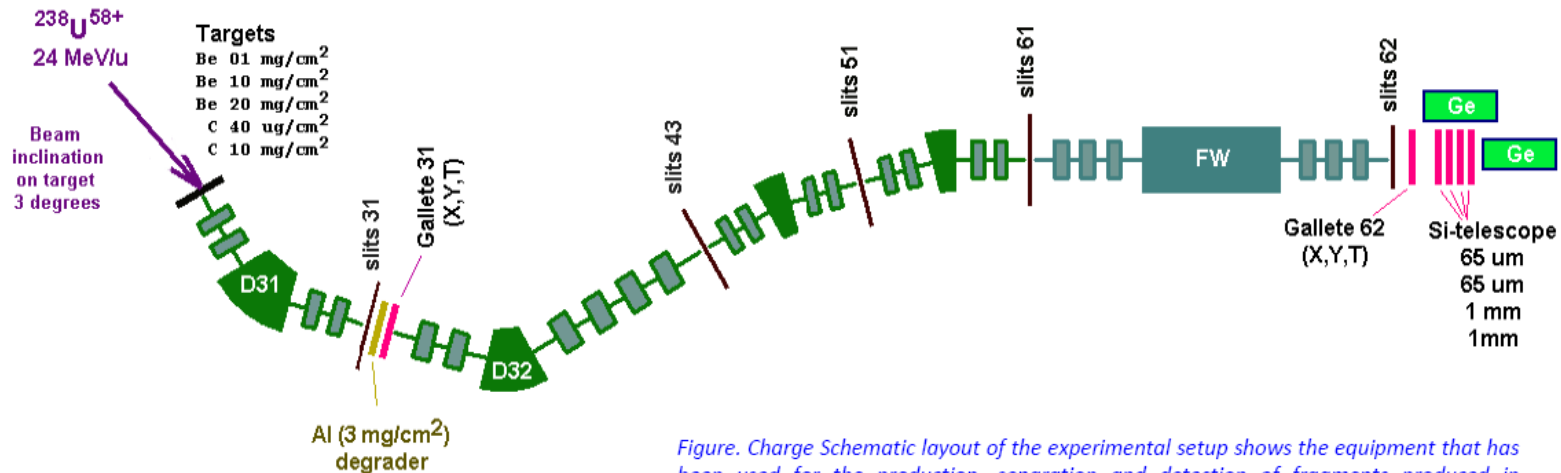
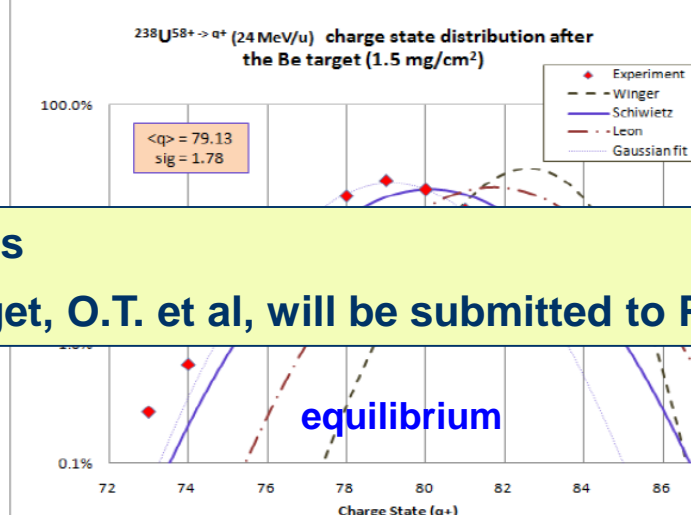
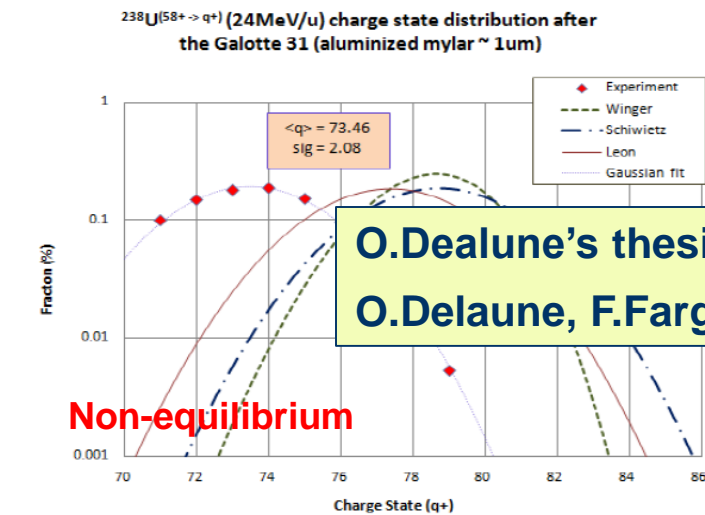
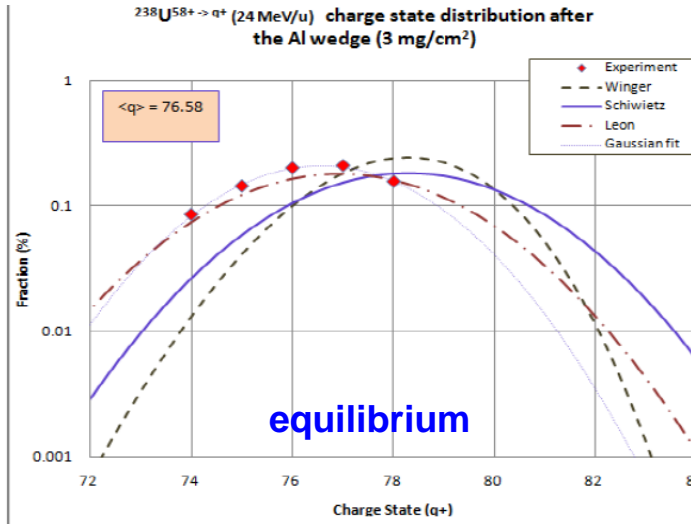
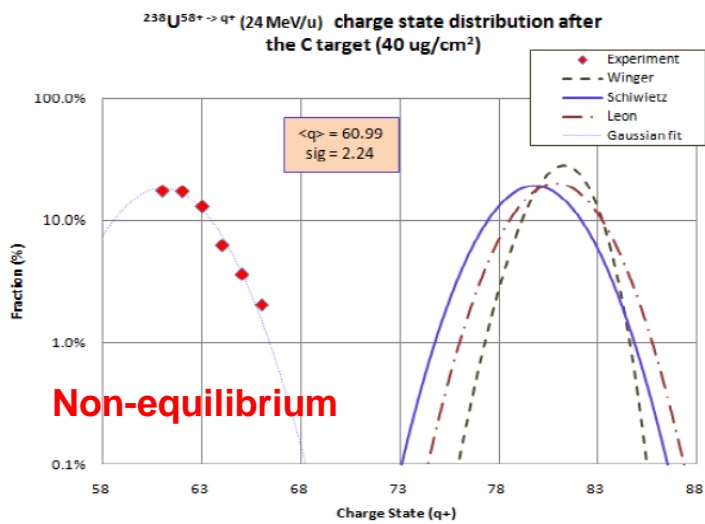
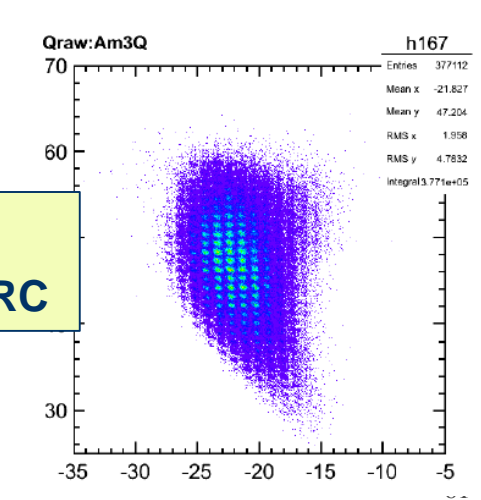
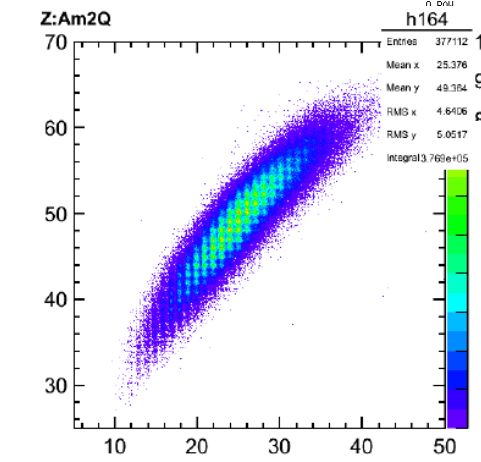
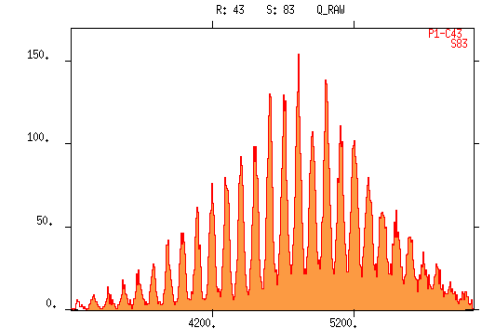


Figure. Charge Schematic layout of the experimental setup shows the equipment that has been used for the production, separation and detection of fragments produced in reactions with the <sup>238</sup>U beam.

- Handle with charge states
- Identify fragments ( $A, Z, q$ )



**O.Dealune's thesis**  
**O.Delaune, F.Farget, O.T. et al, will be submitted to PRC**



See talks this topic  
V.I. Zagrebaev  
A.G. Popeko

**Production Mechanism**

Reactions | Energy Loss, Straggling | Charge states | Databases: Masses, Isomers

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

Reactions

Settings  Projectile Fragmentation  additionally calculate yields for the next reactions

Settings  Fusion -> Residual

Settings  Fusion -> Fission

Settings  Coulomb fission

Settings  Abrasion-Fission

Two Body Reactions

ISOL mode

Make default

**Fusion-Residual**  
 $A_0 + A_1 = A_2 \geq A_3$

**Fusion -> Residual**

Evaporation settings

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)  MeV

Probability for compound nucleus formation  $P_{\{CN\}}$

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

Make default

Partner site

- Pay attention for the Fission Barrier model !
- Fusion –Evaporation code PACE 4 in the LISE++ package
- Partner site : NRV

<b>P</b> rojectile	<b><math>^{155}\text{Gd}^{64+}</math></b>
8 MeV/u 1 pA	
<b>C</b> ompound	<b><math>^{195}\text{Po}</math></b>
<b>R</b> esidual	<b><math>^{179}\text{Ir}^{48+..47+}</math></b>
<b>T</b> arget	<b>Ca</b>
5 mg/cm <sup>2</sup>	

Click "C" button

**Fusion information window**

155Gd(8.0 MeV/u) + Ca -> 195Po\* -> 179Ir

Q-value of reaction = -95.855 MeV  
 Fusion max. barrier = 147.97 MeV  
 Fusion radius = 9.55 fm

Depending on a place of reaction in the target

	beginning	middle	end
Beam energy (Lab) [MeV/u]	8.00	6.85	5.67
Beam energy (Lab) [MeV]	1239.4	1061.3	878.7
Center of mass energy [MeV]	254.01	217.51	180.09
Excitation energy [MeV]	158.16	121.66	84.23
Compound recoil energy [MeV]	985.4	843.8	698.6
Capture cross section [mb]	1.38e+03	1.13e+03	710
Probability of Compound	1.00e+00	1.00e+00	1.00e+00
Compound formation CS [mb]	1.38e+03	1.13e+03	710
Compound-Fission CS [mb]	1.28e+3	1.01e+3	583
Backup CS [mb]	0	0	0

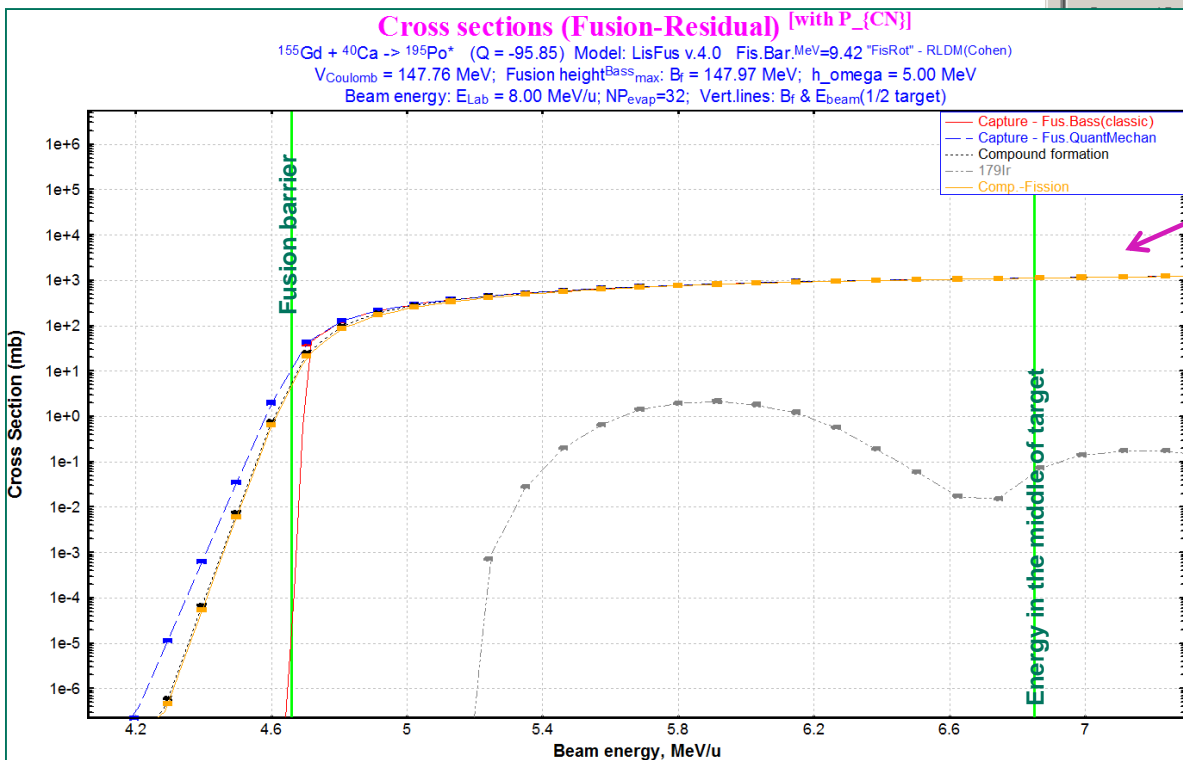
after the stripper

rapason (MeV/u)	2.596	3.580
ion charge state	45.41	49.30

Plot the excitation function

Characteristics are SS-model

Quit



**Fusion-Residue calculator**

155Gd(8.0 MeV/u) + Ca -> 195Po\* -> 179Ir

Q-value of reaction = -95.855 MeV  
 Fusion max. barrier = 147.97 MeV  
 Fusion radius = 9.55 fm

Beam energy (Lab)  8 MeV/u  
 Beam energy (Lab)  1239.4 MeV  
 Center of mass energy  254.01 MeV  
 Excitation energy  158.16 MeV  
 Compound recoil energy  985.4 MeV  
 Fusion cross section 1377.3 mb

Residue

Energy (Lab)  5.044 MeV/u  
 Corresponding ion charge state 53.47

Calculations suppose the target thickness is negligibly small

If the stripper thickness is not equal to 0 then the stripper material is used to calculate a residue charge state

Quit

**Production Mechanism**

Reactions / Energy Loss, Straggling / Charge states / Databases: Masses, Isomers /

82Se(140.0 MeV/u) + Be -> 56Ca

Reactions

Settings

- Projectile Fragmentation
- Fusion -> Residual
- Fusion -> Fission
- Coulomb fission
- Abrasion-Fission
- Two Body Reactions
- ISOL mode

additionally calculate yields for the next reactions

Make default

OK Cancel Help



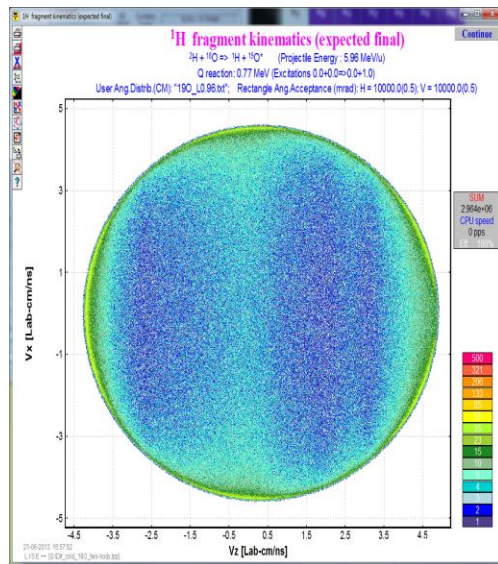
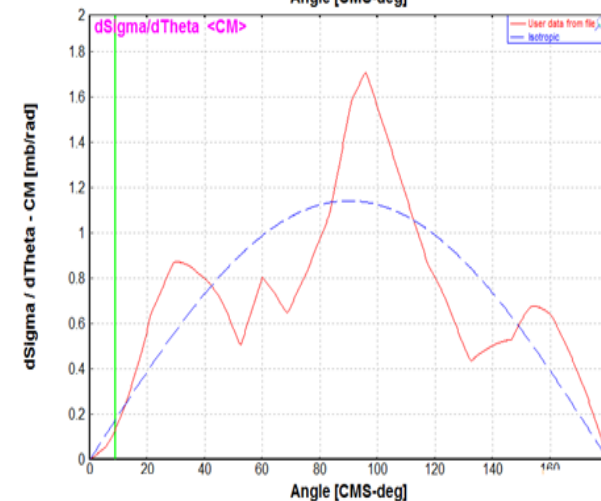
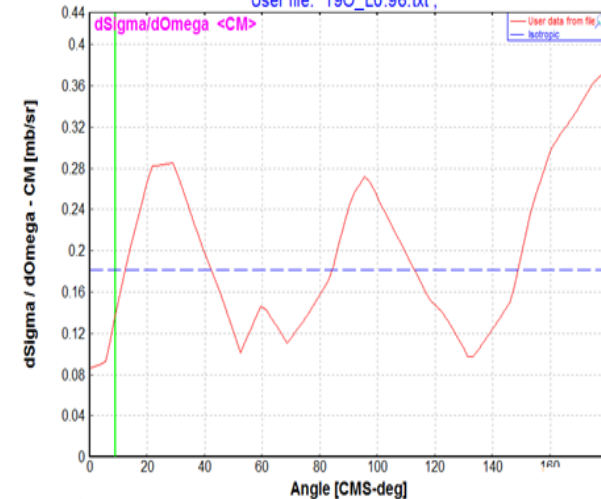
9.6.46  
24-06-13

Differential Cross Sections

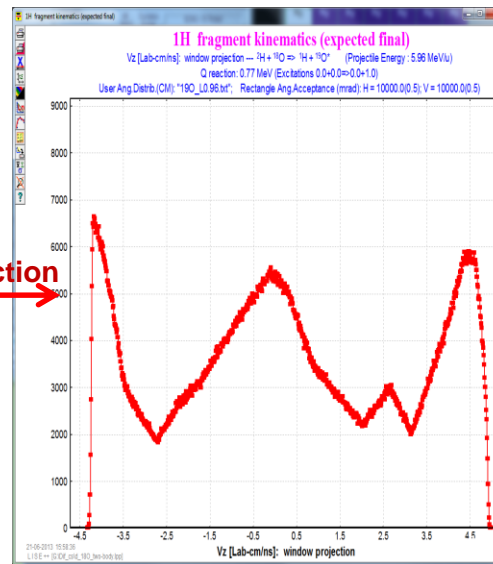
[http://lise.nsl.msui.edu/9\\_6/DifCS/9\\_6\\_44\\_DifCS.pdf](http://lise.nsl.msui.edu/9_6/DifCS/9_6_44_DifCS.pdf)

## Differential Cross Section

${}^2\text{H}$  (6.0 MeV/u) +  ${}^{18}\text{O}$  ->  ${}^1\text{H}$  (+  ${}^{18}\text{O}$ )  
User file: "190\_L0.96.txt";



X-projection



- Reaction's Characteristics
- Differential Cross Sections ; LAB <-> CM converter
  - Electromagnetic excitation plots
  - Create an initial file for nucleon pick-up (beta)
  - User cross-sections analysis using Abrasion-Ablation model



O.T., D. Bazin,  
Nucl. Instr. and Meth. in  
Phys. Res. B 266 (2008)  
4657–4664

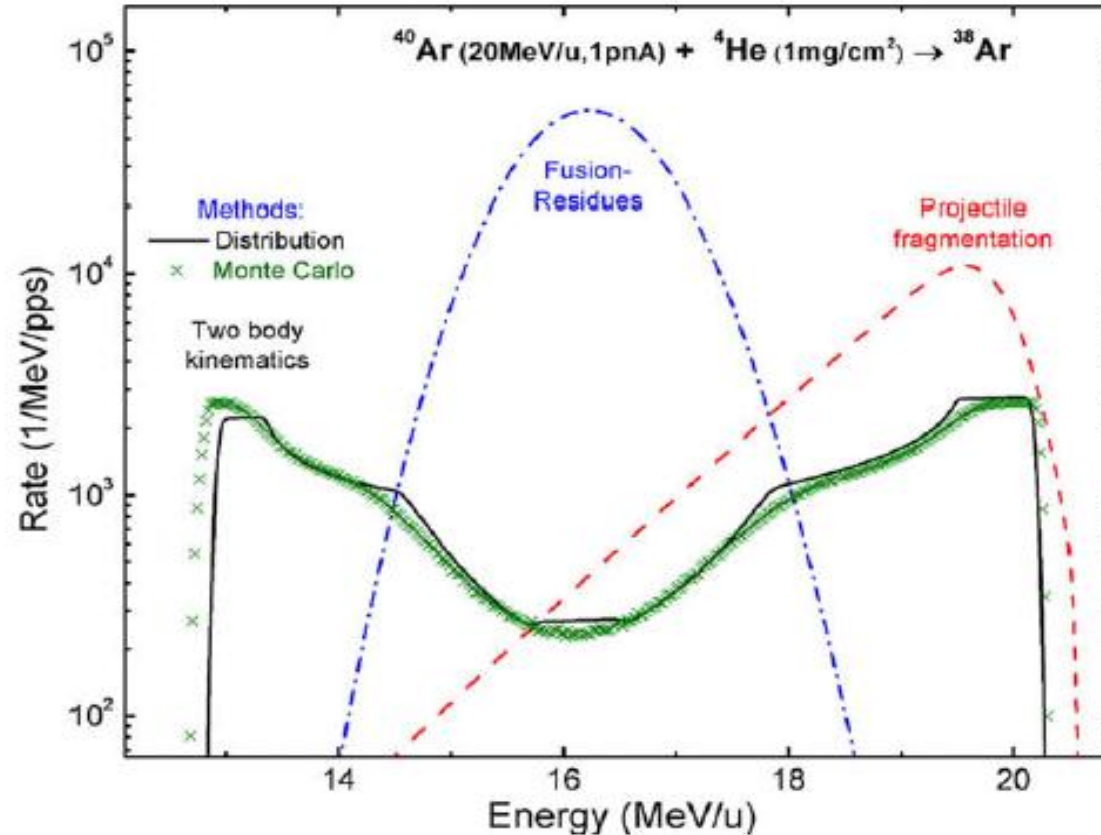
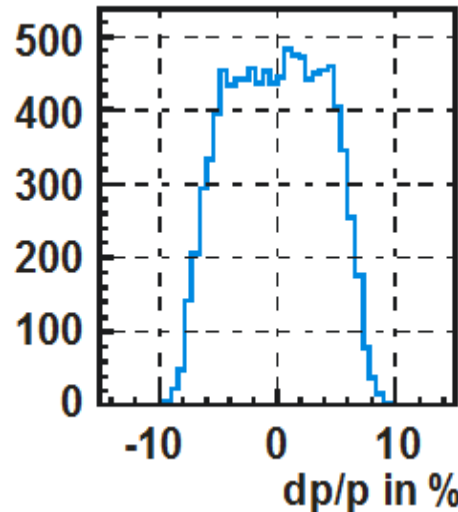
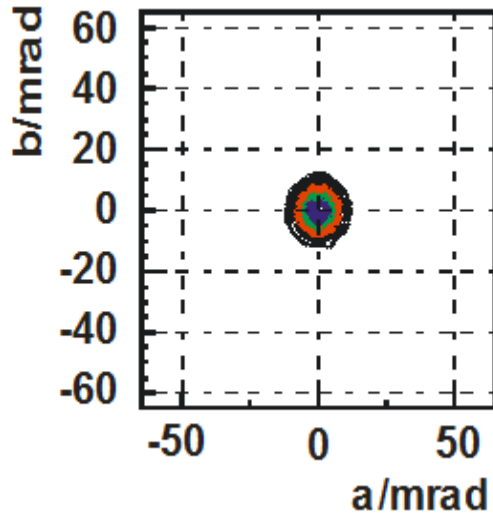


Fig. 6. Energy spectra calculated by the “Distribution” method of  $^{38}\text{Ar}$  fragments produced by different reaction mechanisms, using an  $^{40}\text{Ar}$  beam at 20 MeV/u on a  $^4\text{He}$  target ( $1\text{ mg/cm}^2$ ) and gated by a rectangular angular acceptance  $X' = \pm 100\text{ mrad}$ ,  $Y' = \pm 60\text{ mrad}$ . The Monte-Carlo calculation of the energy spectrum of  $^{38}\text{Ar}$  fragment produced in two body reaction is also shown. The default LISE++ production cross-sections EPAX 2.15 and LisFus model were used to estimate the rates.

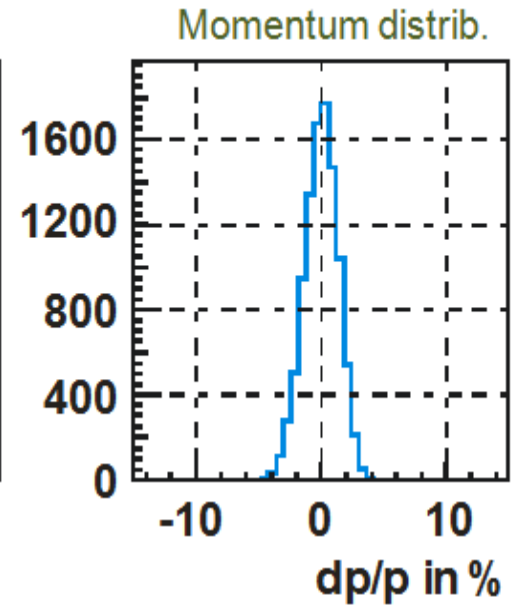
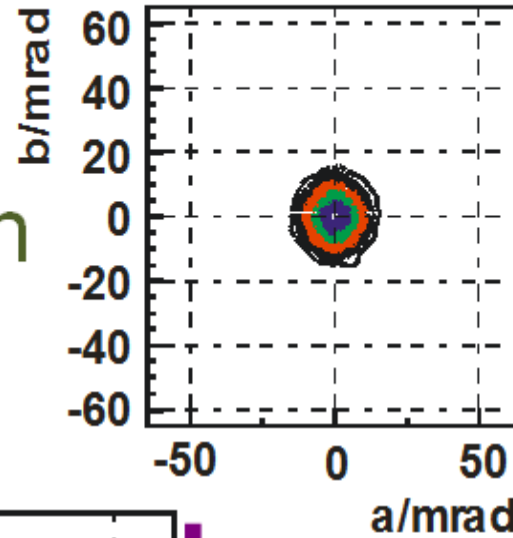
• LISE++ Simulation for  $^{124}\text{Xe}$  and  $^{208}\text{Pb}$  fragmentation

Relatively 'easy' to collect due to small phase space

$^{200}\text{W}$



$^{100}\text{Sn}$

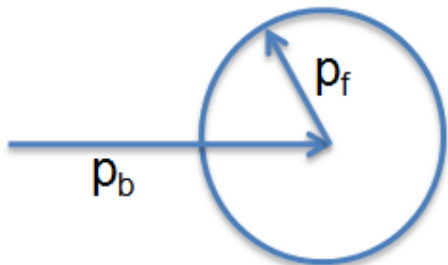


- Angles  $\leq \pm 20$  mrad
- Momentum  $\pm 3 - 8 \%$

M. Hausmann, T. Nettleton

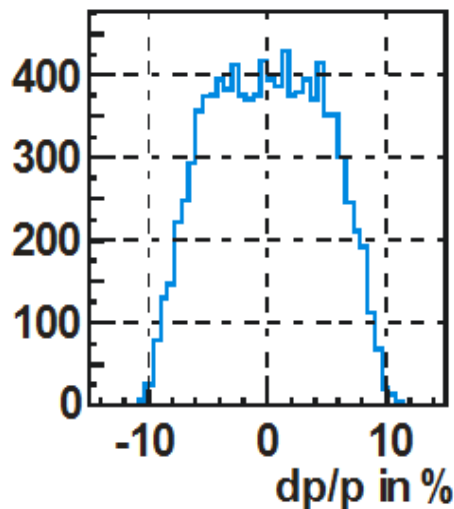
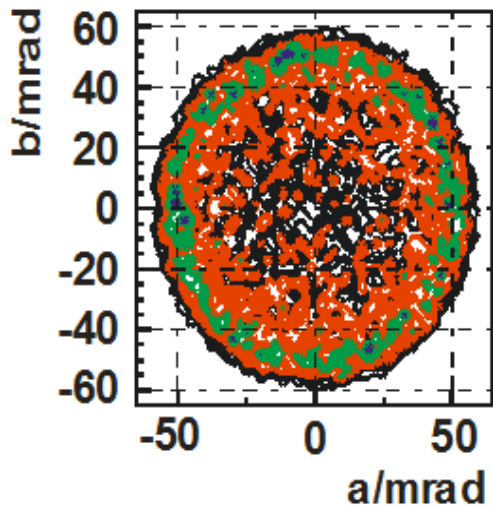
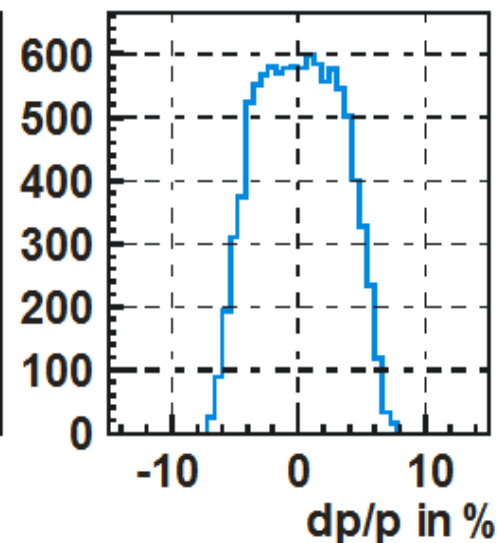
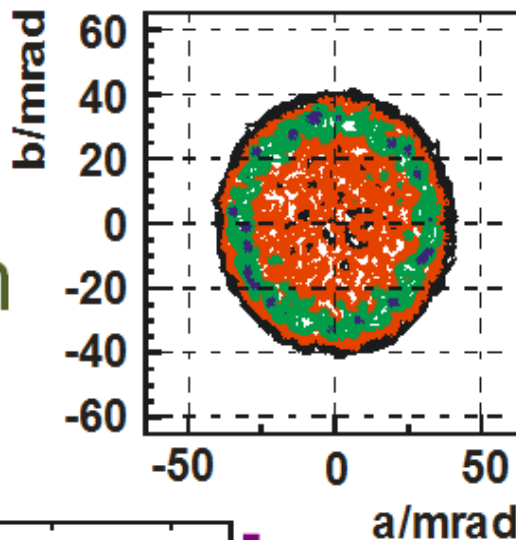
Courtesy of B.Sherrill

- LISE++ Fission model for  $^{238}\text{U}$



$^{76}\text{Ni}$

$^{132}\text{Sn}$



- Angles  $\pm 40 - 60$  mrad
- Rigidity  $\pm 6 - 10$  %
- Plus correlations due to fission kinematics

M. Hausmann, T. Nettleton

Courtesy of B.Sherrill

$\epsilon_t$

## efficiency transmission at target

- lost of primary beam and fragments of interest due to reaction in target and stripper
- Charge state factor after target (stripper)
- Gain due to secondary reactions



Clicking the right button of mouse on the  $^{125}\text{Ag}$  cell in the table of nuclides

Let's consider the following case :



statistics: 125Ag

125Ag	Beta- decay (Z=47, N=78)	Silver
Q1 (Dipole 1)	47	45
Q2 (Dipole 2)	47	45
Q3 (Wien)	47	45
Q4 (D6)	47	45
Production Rate (pps)	7.73e+0	6.71e-1
Sum of charge states (pps)	8.41e+0	8.41e+0
Reaction	Fragmentn	Fragmentn
Sum of all reactions (pps)	8.41e+0	8.41e+0
CS in the target (mb)	1.35e-5	1.35e-5
Total transmission (%)	68.521	5.954
Target (%)	68.52	0.124
Unreacted in mater. (%)	71.17	71.17
Q (Charge) ratio (%)	91.85	7.98
Unstopped in mater. (%)	100	100
Secondary Reactions (coef)	1.05	1.05

FaradayCup 1

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Total transmission includes blocks from Target up to FaradayCup 1



Questions ?

Haben Sie Fragen?

Вопросы ?

有問題嗎？

¿Preguntas?

Demandoj?

質問？

Pytania?

Domande?

Sorular?