Fission reactions to produce rare isotopes

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@ Sakura-2019 "Nuclear Fission and Structure of Exotic Nuclei"

In-flight rare isotope beams production

- **Beam optics** (2nd order calculations & 5th order use, ..)
- **Atomic physics** (energy loss, charge state distribution, ...)
- **Production mechanism** (projectile fragmentation, fusion, fission....)

LISE++

yields calculation

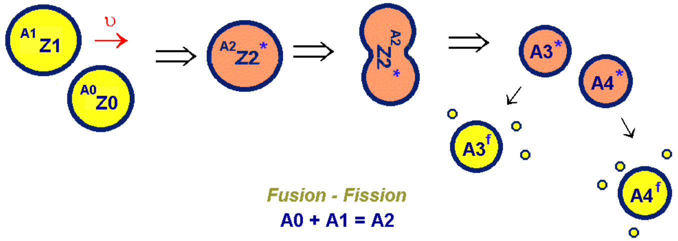
Production mechanism & exotic nuclei

- **GANIL: Fusion-Fission (24 MeV/u)** ✓
  O.T. et al., Eur. Phys. J. A (2018) 54: 66
- **MSU: Abrasion-Fission (80 MeV/u)** ✓
  analysis almost finished
- **RIKEN: new isotopes in ^{60}Ca region**
  O.T. et al., PRL 121, 022501 (2018)
- **Collaboration with BNL-JLAB**
  exotic nuclei production through fission
  at e-HI collider (E = confidential)

Secondary beams production with Fusion-Fission reactions

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

Nowadays, in-flight fission is widely used to produce rare neutron-rich nuclei



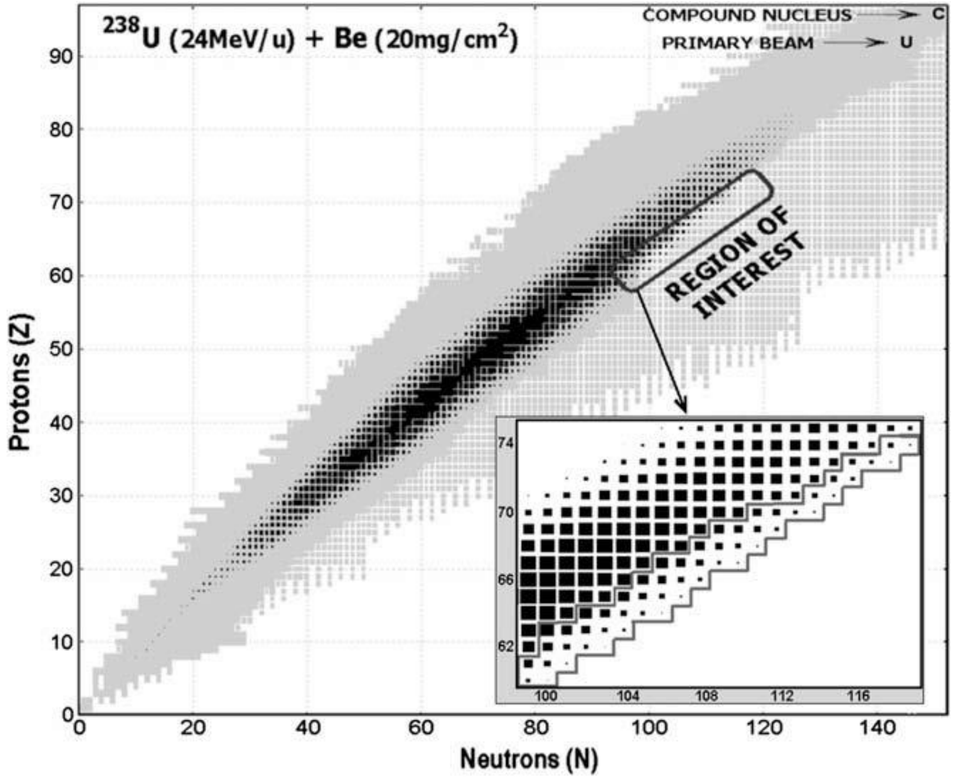
Advantages of in-flight fusion-fission in inverse kinematics to explore neutron-rich 55 < Z < 75 region are comparing to AF & CF:

- *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.*

LISE^{++} Fusion-Fission model [1,2] features:

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

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



Open Questions:

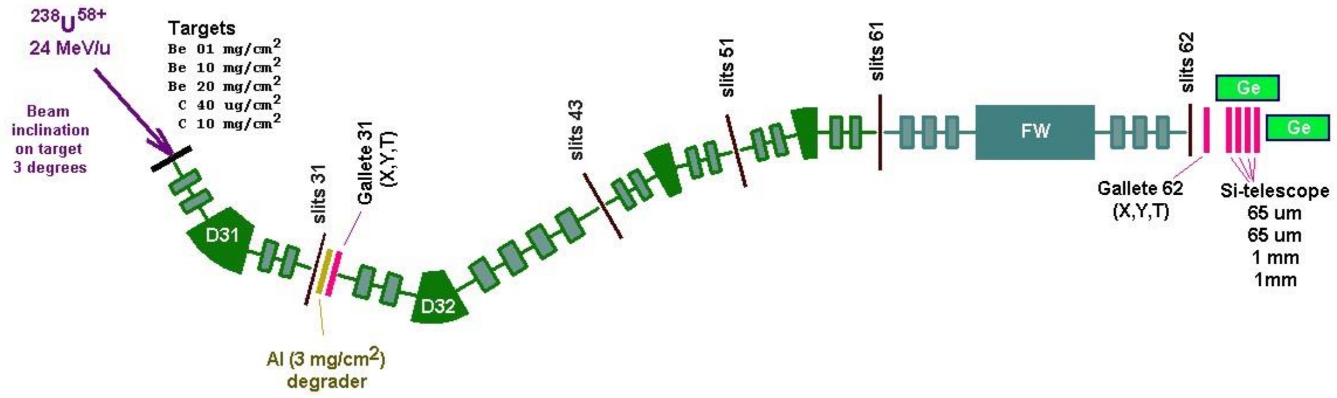
- *What is optimal conditions (energy, target material, thickness and so on)?*
- *How reliable are simulations? Intensities, purification?*
- *What are contributions from other reaction mechanisms?*
- *Separation, Identification, Resolution?*

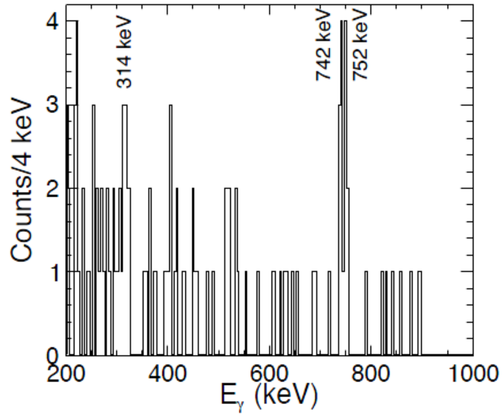
A experiment to show separation and identification of fusion-fission products has been performed using the LISE3 fragment-separator at GANIL.

[1] O. B. T. and A. C. C. Villari, NIM B 266 (2008) 4670-4673
[2] O. B. T. and D. Bazin, NIM B 266, 4657 (2008).

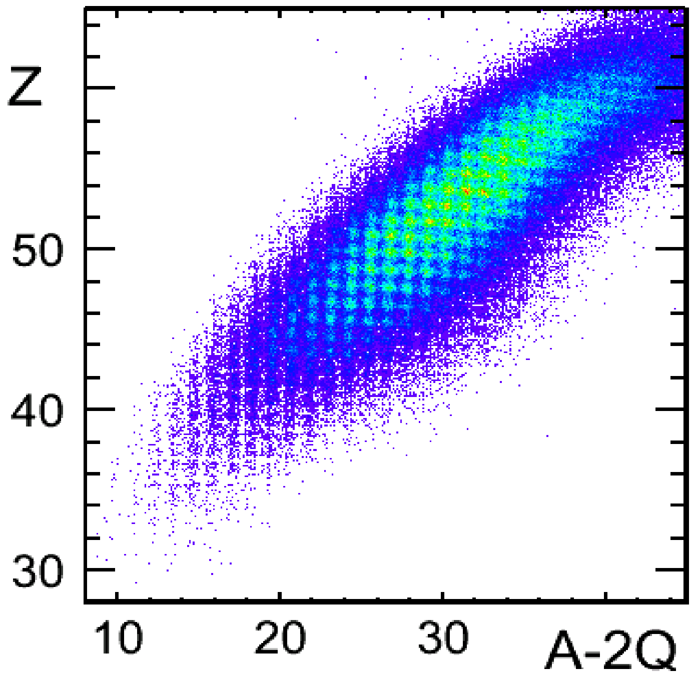
^{238}U(24MeV/u) + Be, C

LISE3 @ GANIL



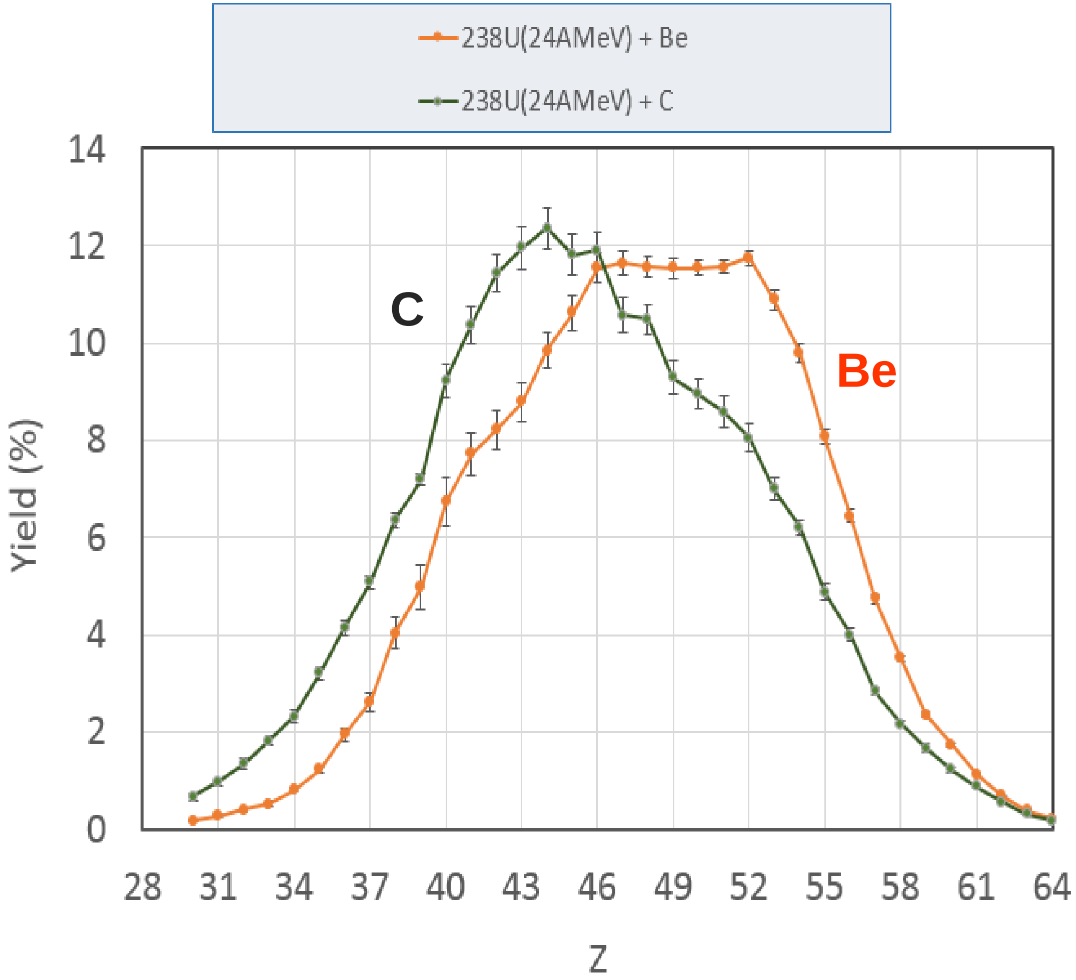


Gamma-ray spectrum observed in coincidence with ^{128}Te. The characteristic gamma lines of 314, 742 and 752 keV sign the decay of the isomeric state of $T_{\frac{1}{2}} = 370$ ns



- A ^{238}U beam at 24 MeV/u with a typical intensity of 10^9 pps, was used to irradiate a series of beryllium targets and a carbon target.
- The beam was incident at an angle of 3° in order not to overwhelm the detectors with the beam charge states.
- Fragments were detected in a Silicon telescope at the end of the separator. Fission fragments produced by inverse kinematics are identified by ΔE-TKE-Bρ-ToF method.

Elemental distributions of fission fragments with Be & C targets



^{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^{++} : channels analysis

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

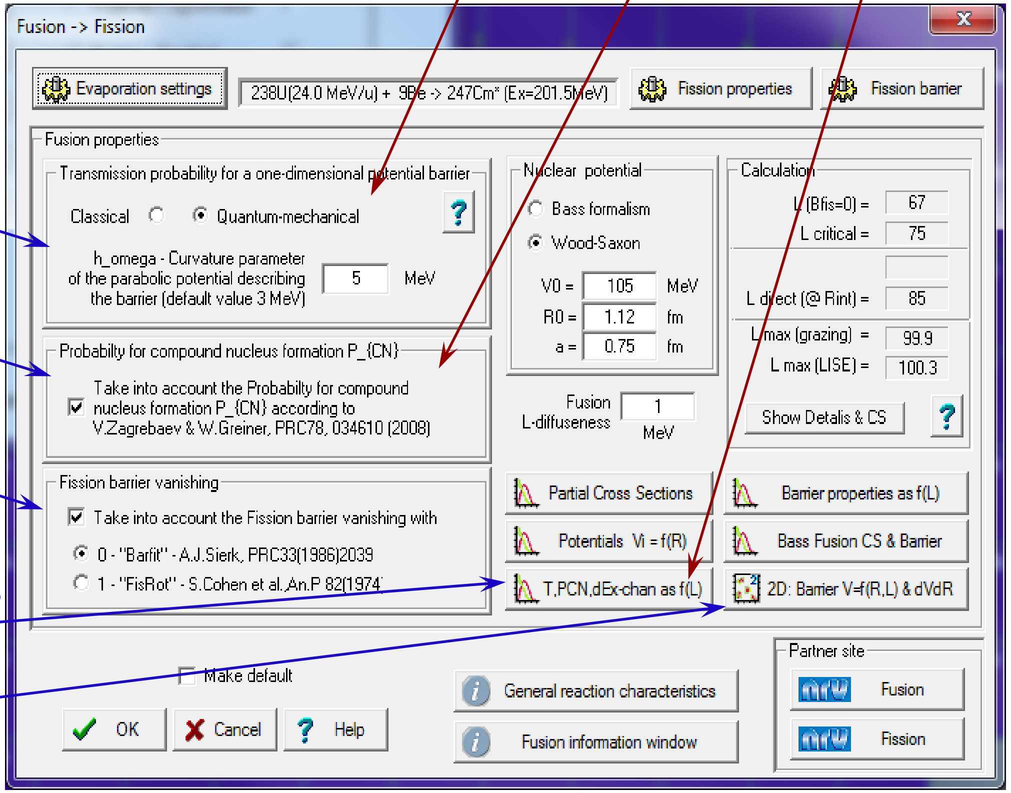
Fusion or Quasi-Elastic?

Compound or Quasi-Fission?

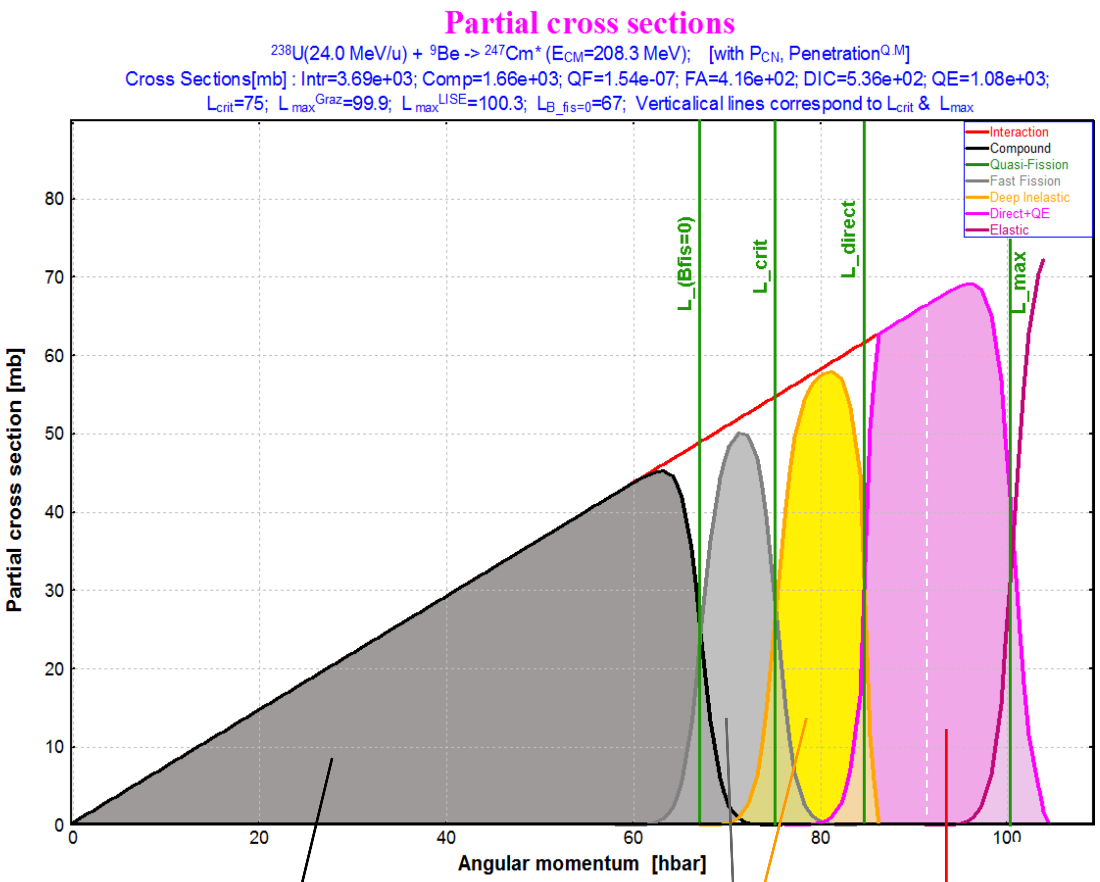
Capture or Fast Fission?

Fusion-Evaporation or Fusion-Fission?

Capture or Deep-Inelastic?



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



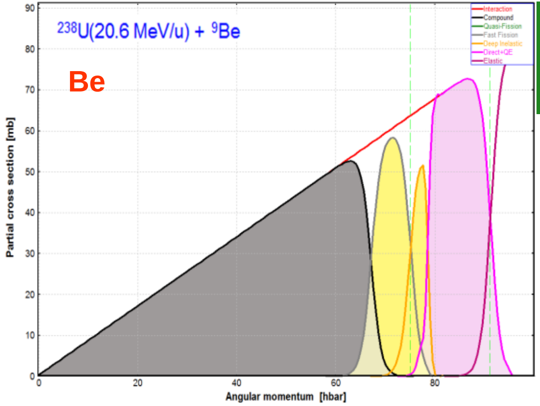
Sequential fission after DIC
Fissile Z < 92
High Excitation Energy

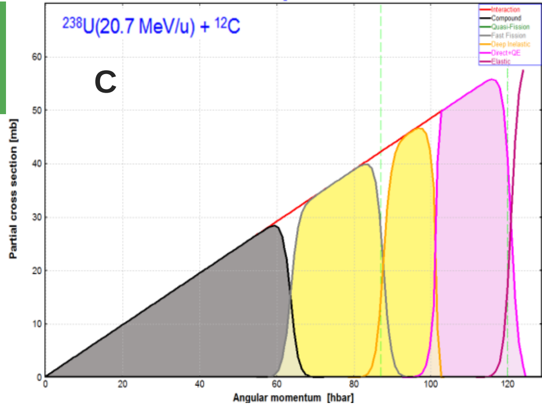
Compound fission ~100%
Fissile Z = 96
High Excitation Energy

Partially go to fission
Fissile Z~92
Low Excitation Energy

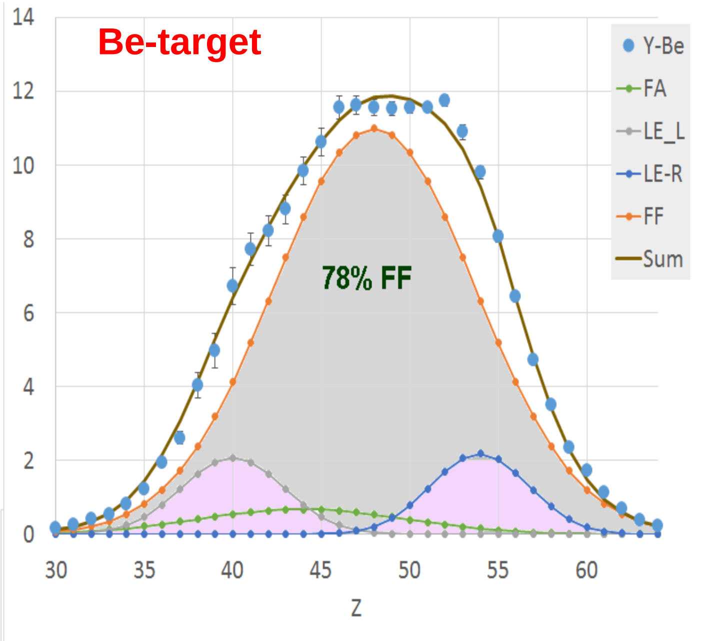
1. http://lise.nscl.msu.edu/9_10/9_10_Fusion.pdf
2. OT et al., Eur. Phys. J. A (2018) 54: 66

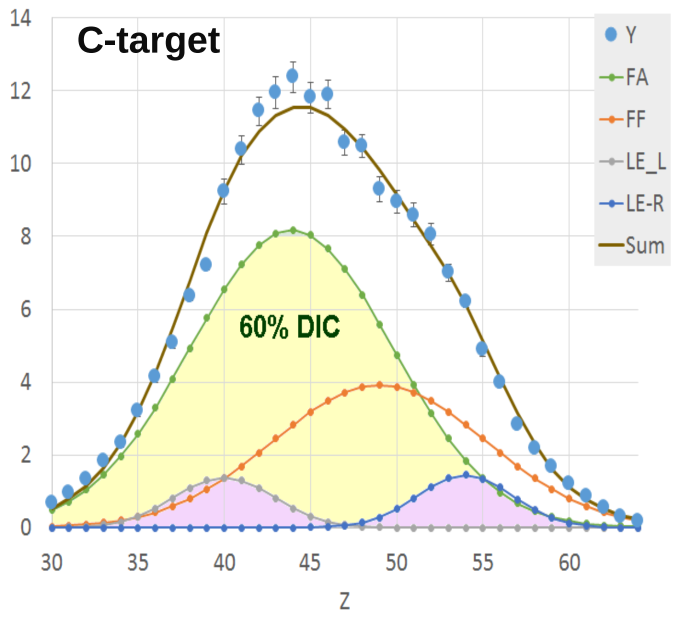
e547 experiment: results interpretation





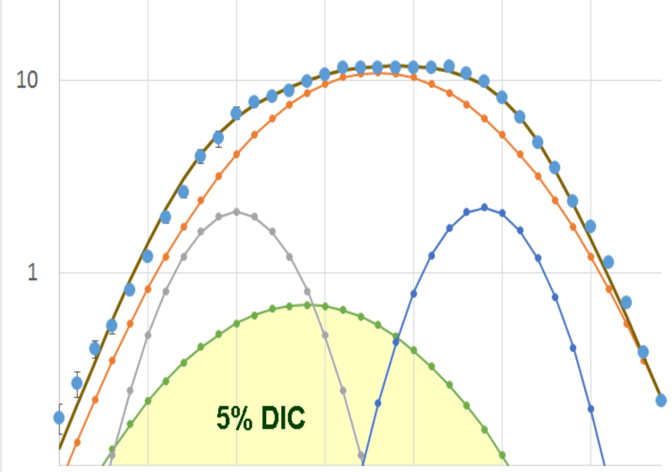
	$L\ (B_{fis}=0)$	L critical	L direct	L max ("grazing")
Be-target	67 $\hbar$	75 $\hbar$	78 $\hbar$	89.2 $\hbar$
C-target	63 $\hbar$	87 $\hbar$	99 $\hbar$	117.1 $\hbar$

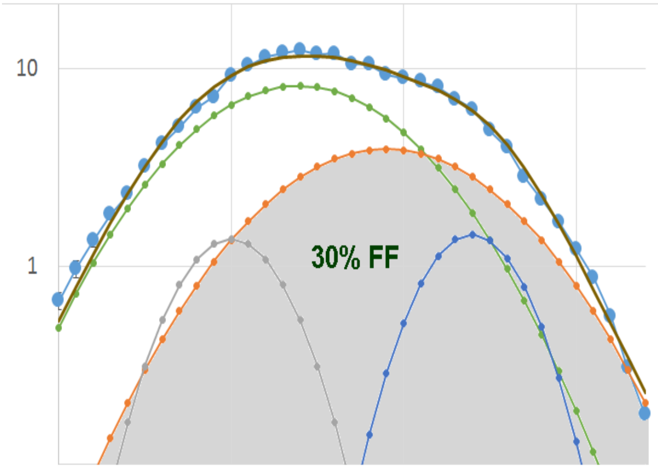




- Three main channels with earlier discussed parameters were used in fitting

- Reaction positions and widths were used the same in both case during fitting process except FF positions (48 and 49)



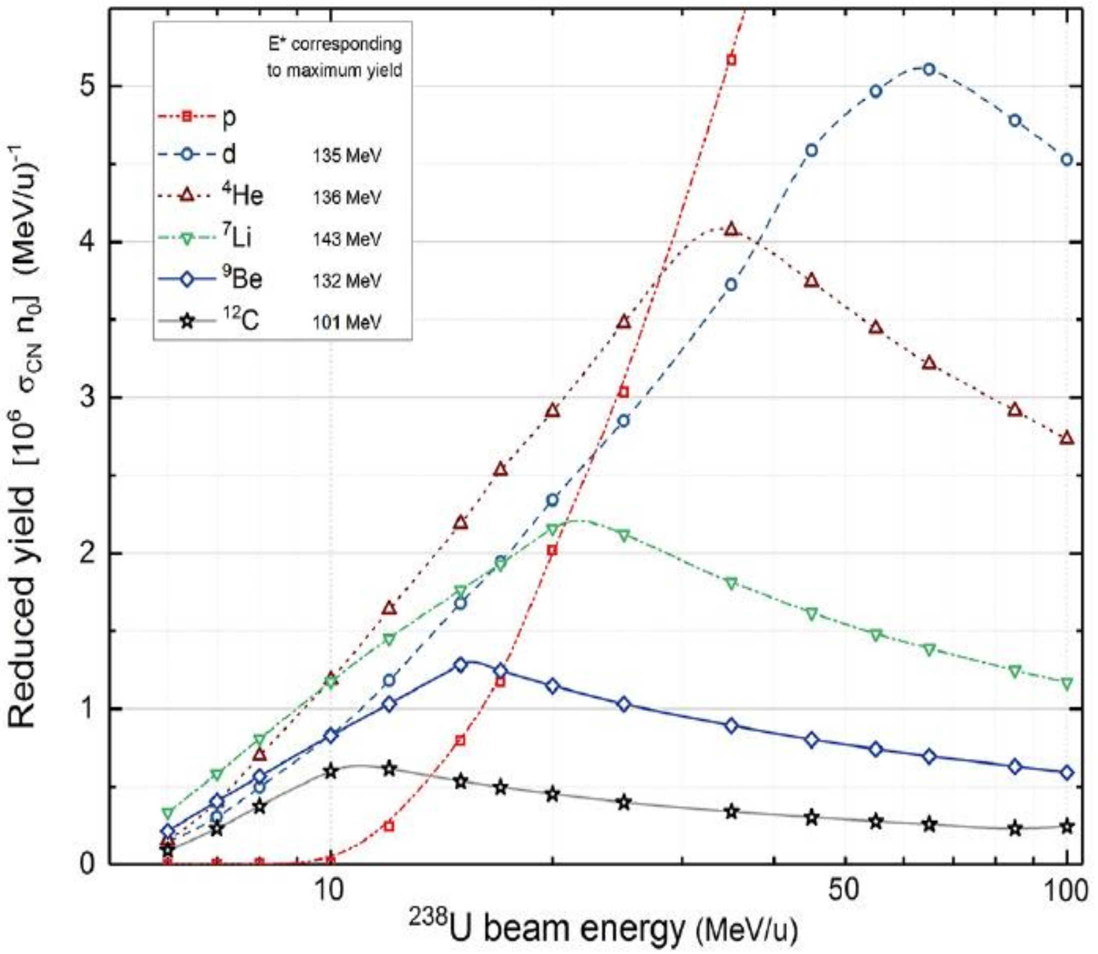


- From fitting results it follows, that Fusion-fission dominates in the case of Be-target, and sequential fission in the case of C-target

- **Fusion-Fission mechanism is responsible in both cases for High-Z isotope production (Z>60)**

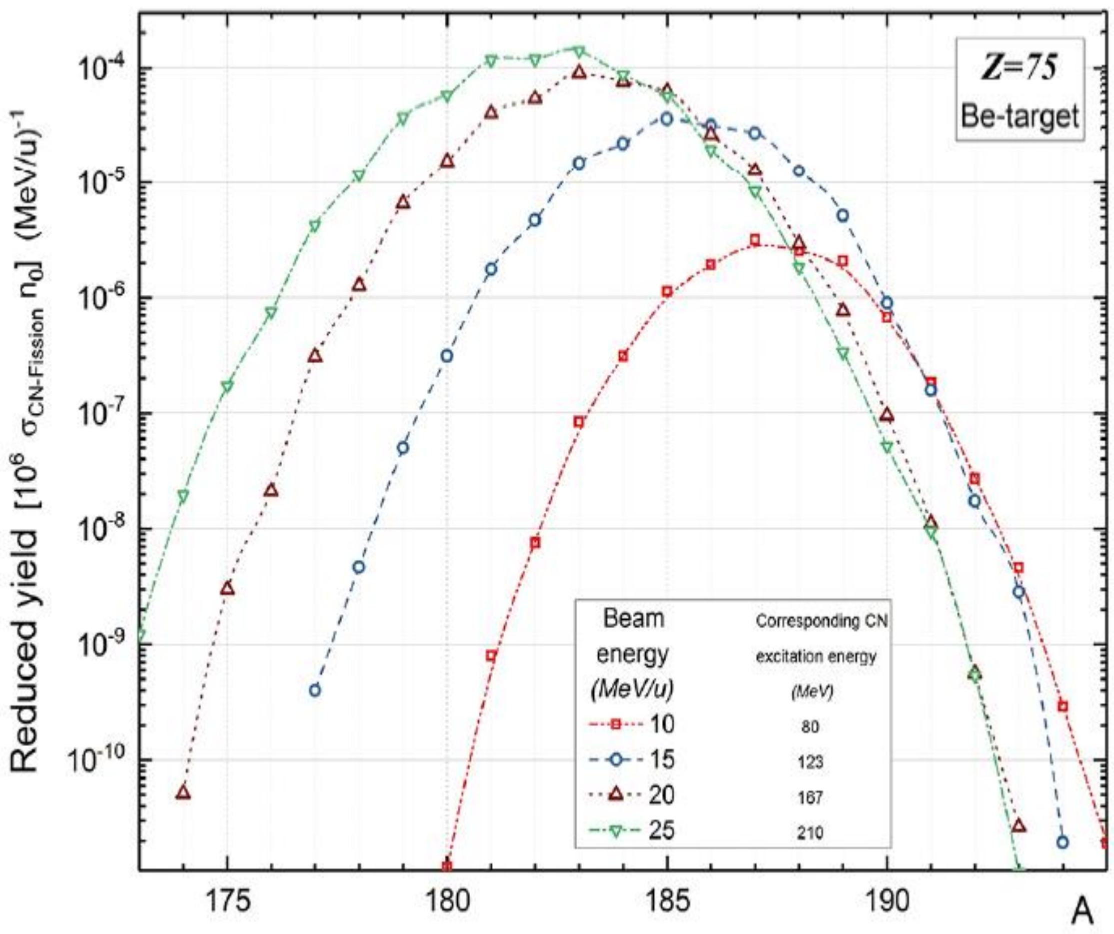
Rare Isotopes with Fusion-Fission Reactions

Calculated CN formation rates in reaction of ^{238}U projectiles with various light targets as function of a primary beam energy



- thickness corresponds to a 1 MeV/u loss of primary beam energy
- a beam fluence of 10^6

Reduced yield of rhenium (Z = 75) isotopes calculated for fusion-fission fragments produced in reaction of the ^{238}U ions with a Be target



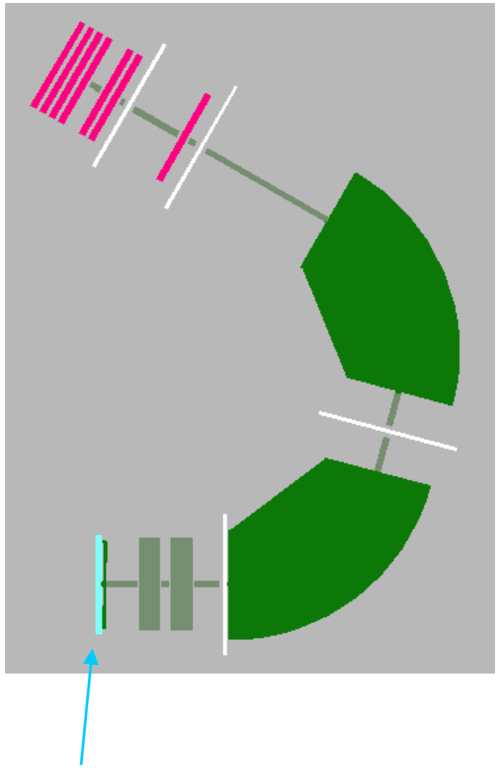
- Complicated secondary bam productions regarding to charge states (beam and fragments)

OT et al., Eur. Phys. J. A (2018) 54: 66

Abrasion-Fission

^{238}U (80MeV/u) + C @ S800

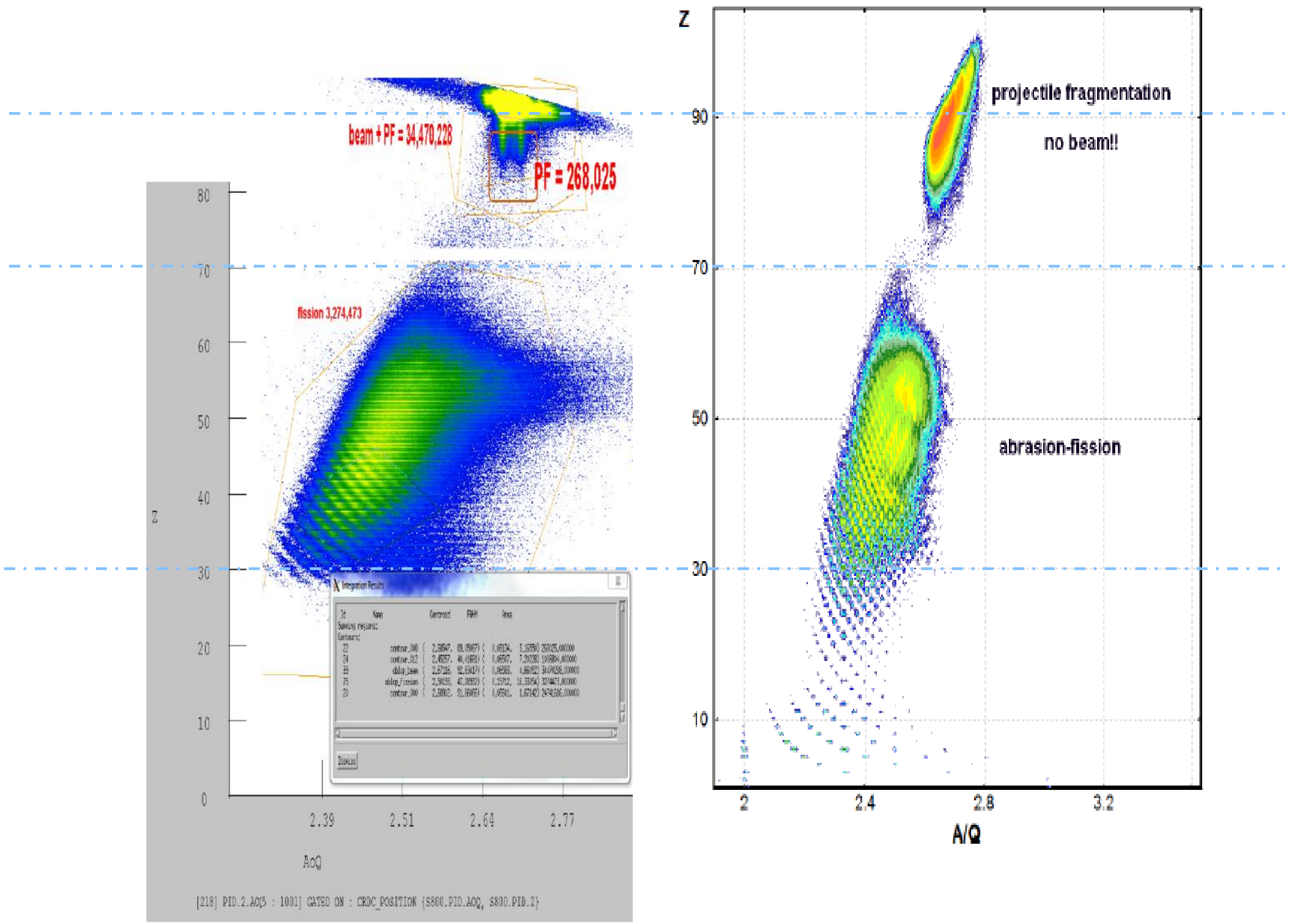
S800 @ NSCL / MSU



- Diamond target
  * ToF start

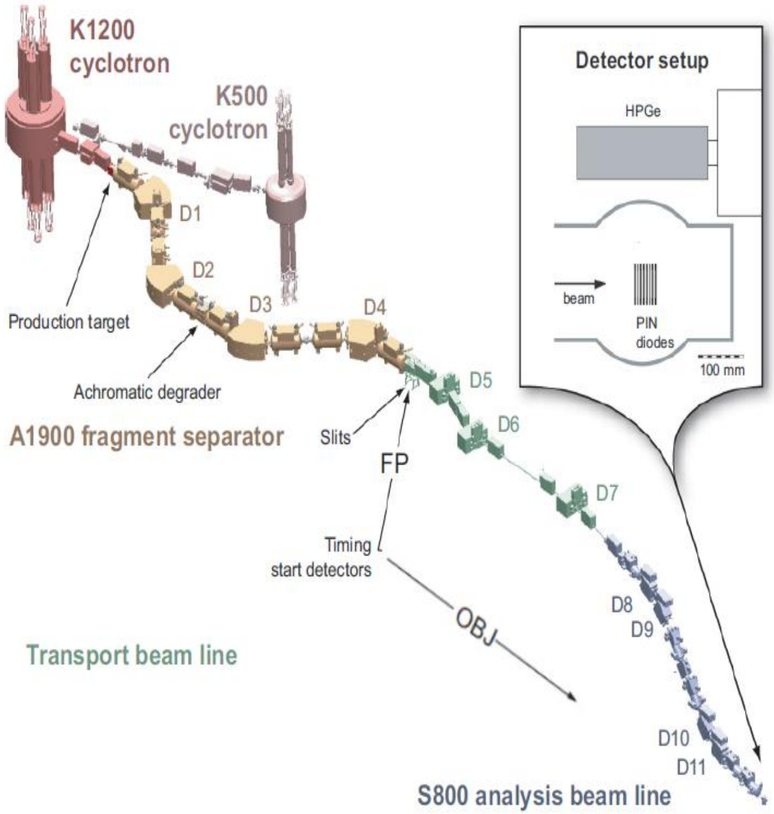
- Large Angular Acceptance
  * 24 msr

Experiment *LISE++ simulation*

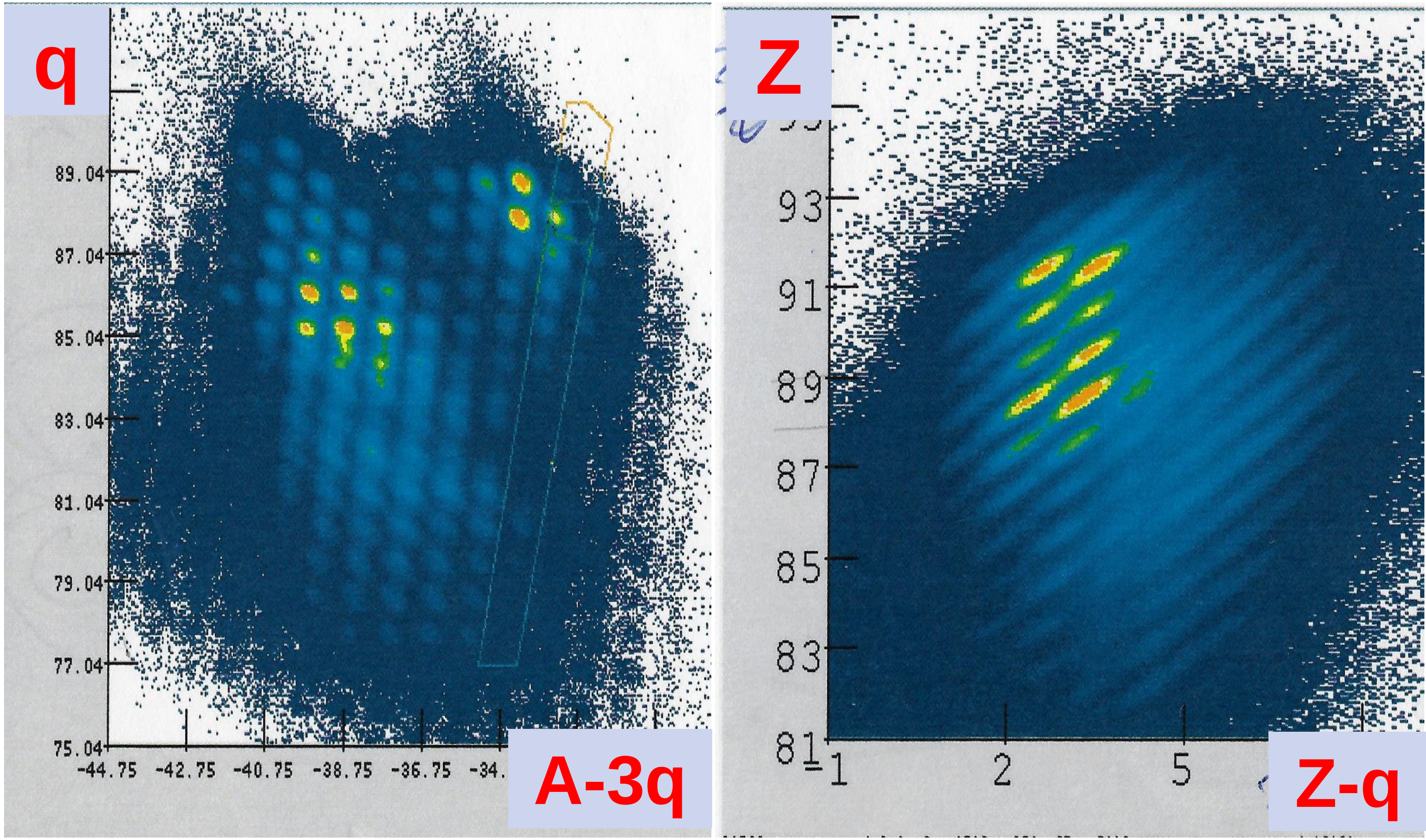


OFF TOPIC!

E.Kwan, O.T. et al.,
will be published soon



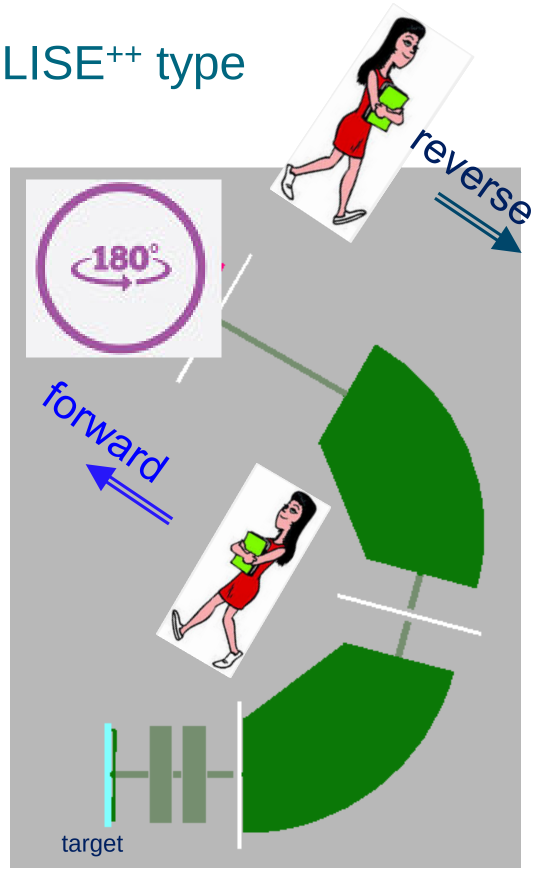
A,Z,q – separation in the Z=92 region



Long ToF-base
Non-cooled PIN-diodes (50x50 mm^2 0.5mm)

Trajectory Reconstruction Methods in LISE^{++}

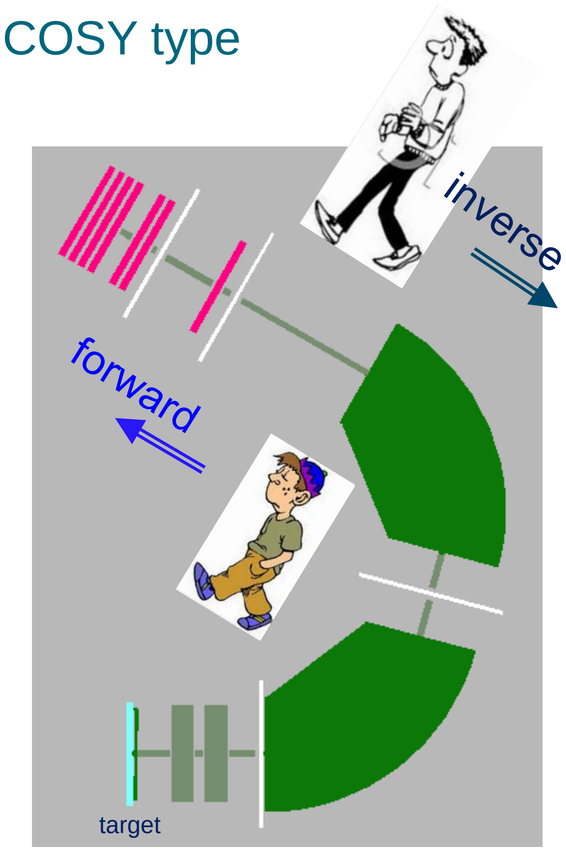
LISE^{++} type



turn around & go forward

- *The coordinate system is changed (x_n = -x, y'_n= -y_n, L_n= -L)*
- *Matrices are calculated by LISE^{++}*
- *Up to 2nd order*

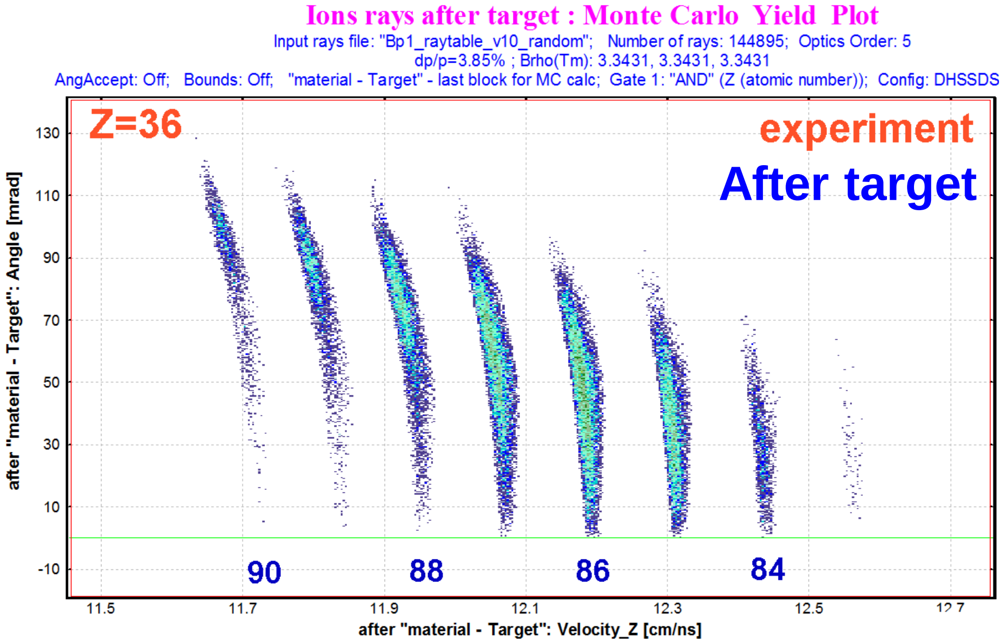
COSY type



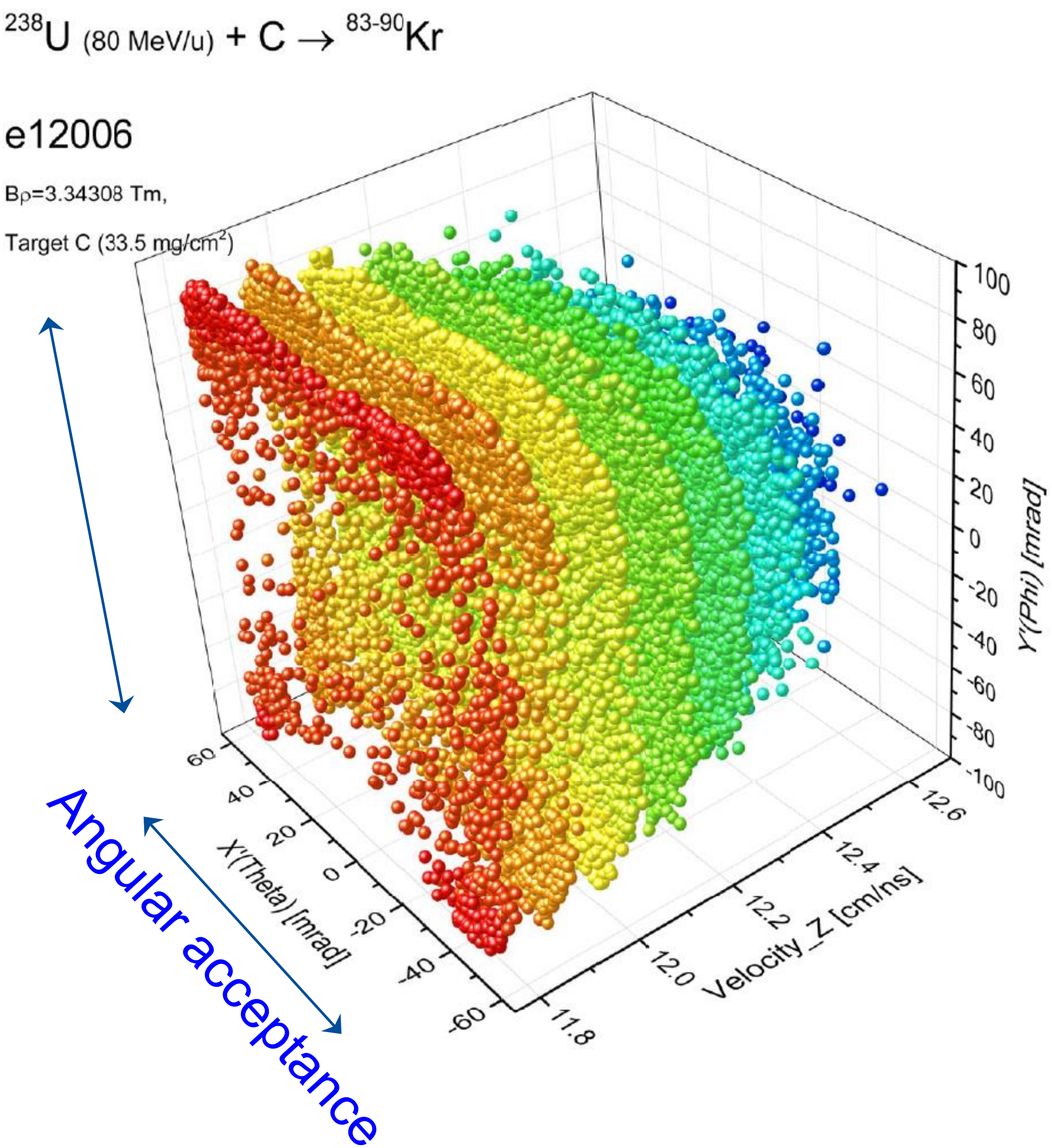
go backwards

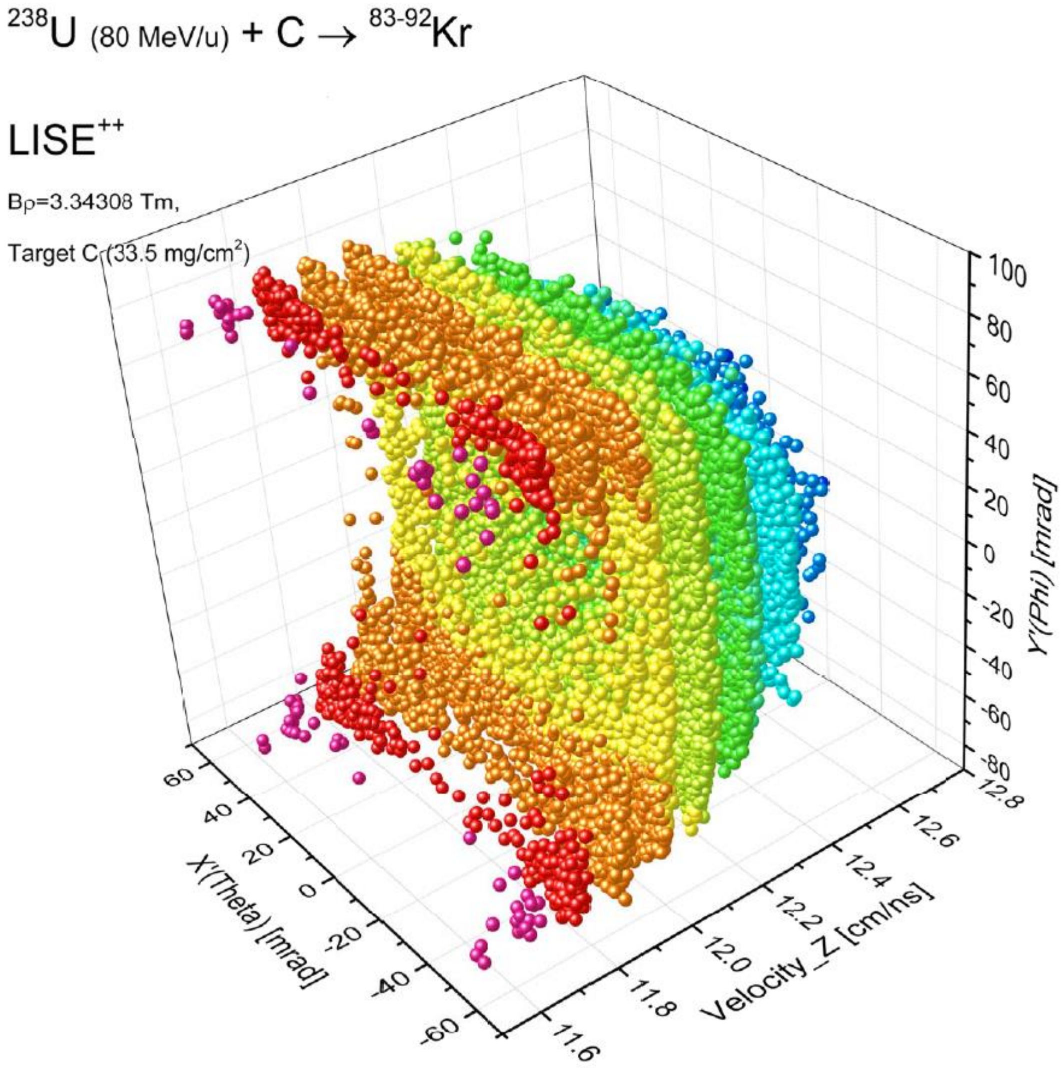
- *The coordinate system is not changed*
- *COSY matrices are imported (linked)*
- *Up to 5th order*

- Using reconstruction LISE^{++} technique allows fragment vectors measured at the final plane of a spectrometer to be replayed through in the backward direction of the spectrometer to reconstruct their trajectories in order to deduce the reaction place and momentum vector.
- The COSY-type 5th order inverse separator technique developed in the LISE^{++} package* and coupled with the S800 configuration has been used to study fission mechanism properties.



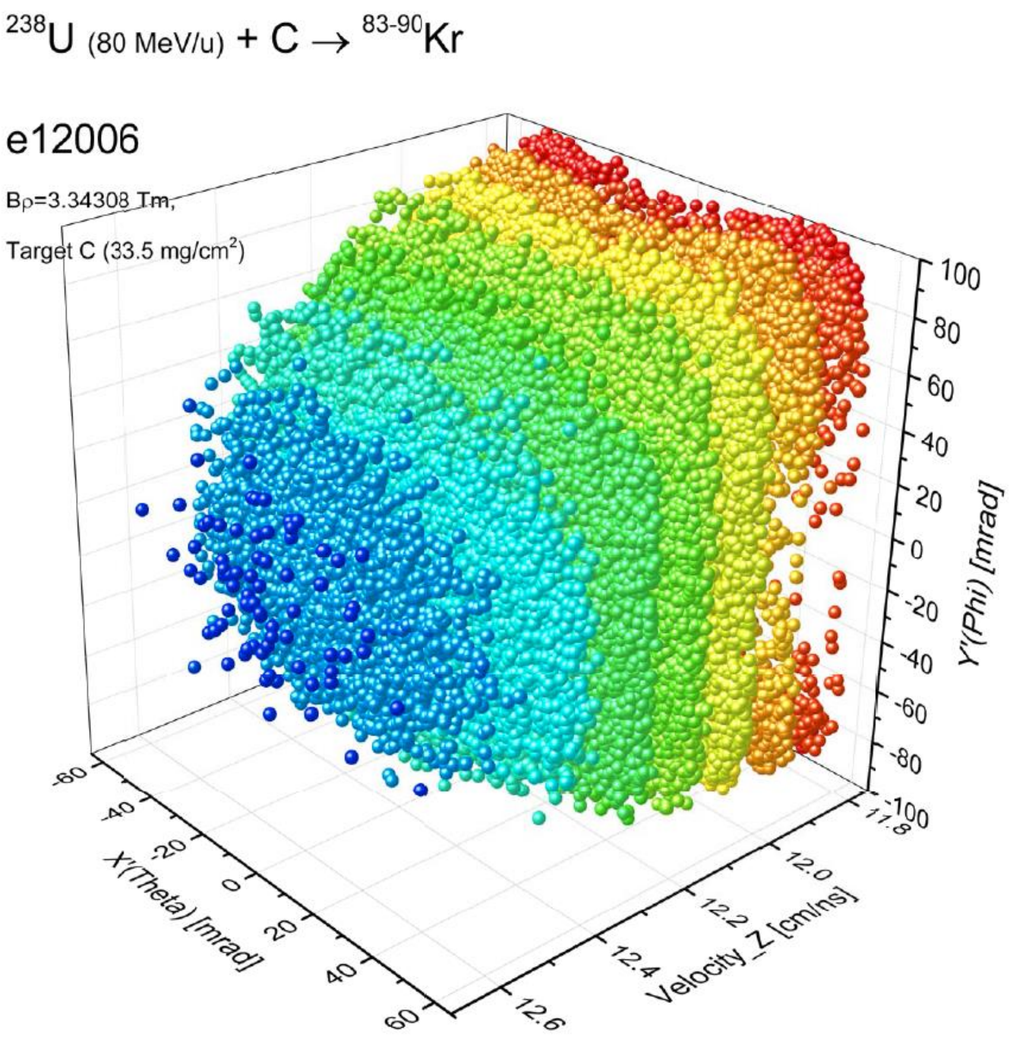
Velocity-Z vs X,Y-Angles 3D-plots @ S800 Target position

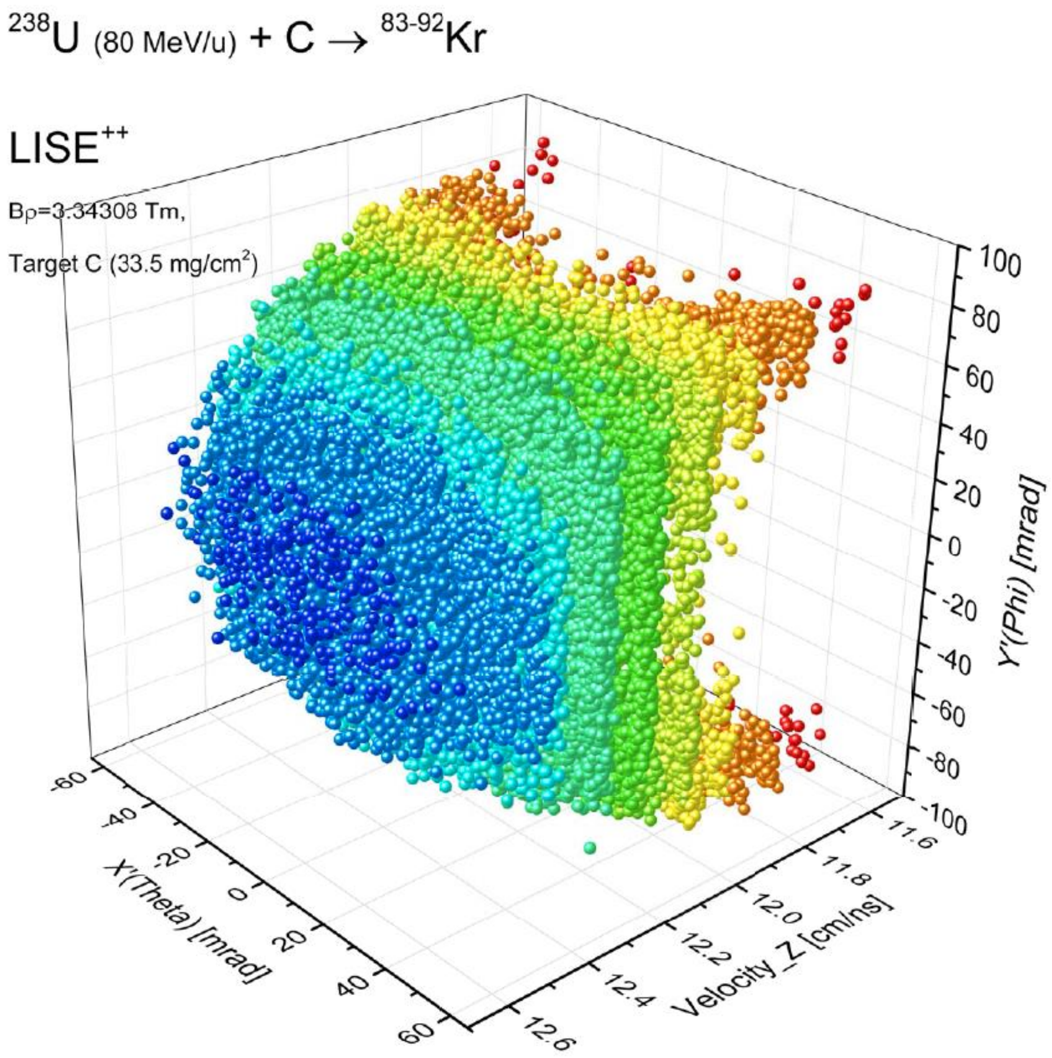




LISE++ direct calculations are gated on the Scintillator position

LISE++ calculations the isotope range is 83-92 instead experimental 83-90

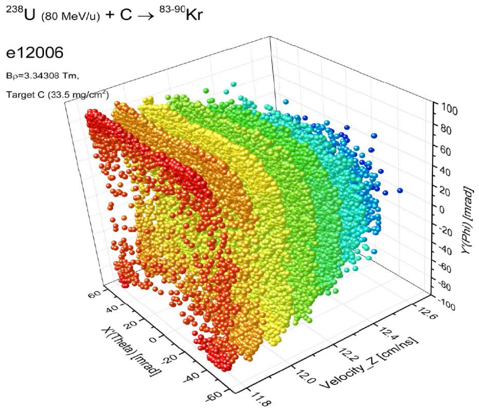




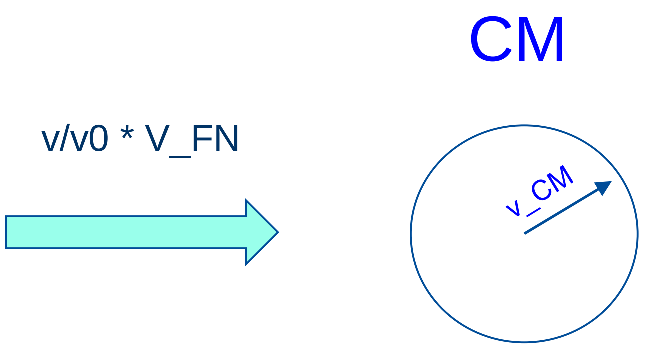
LISE^{++} direct calculations are gated on the Scintillator position

LISE^{++} calculations the isotope range is 83-92 instead experimental 83-90

Krypton isotope CM velocities as function of fissile nucleus velocity

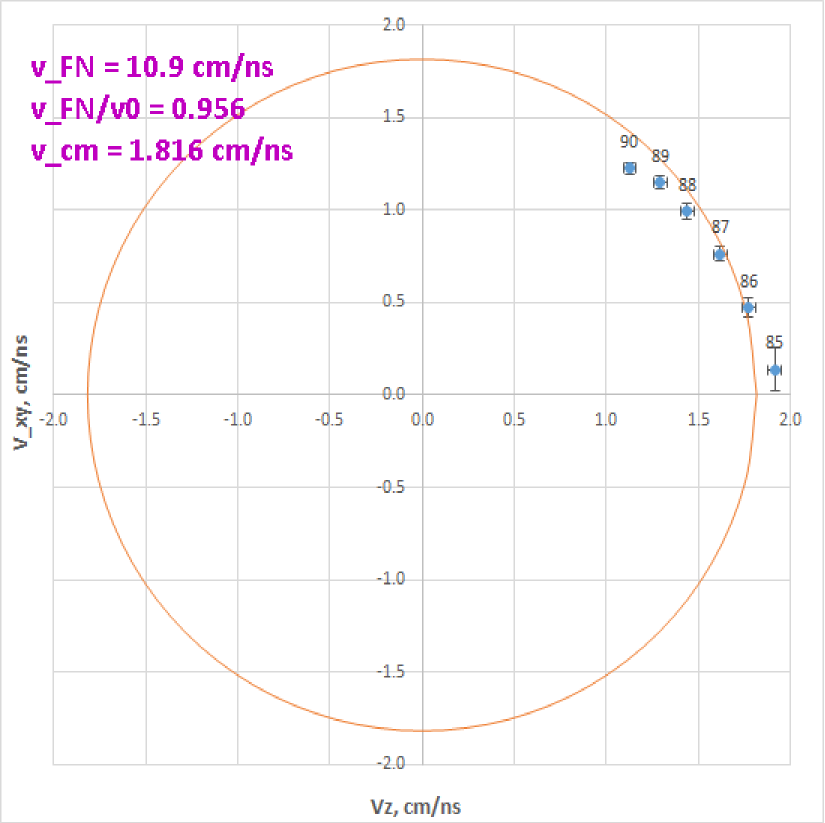


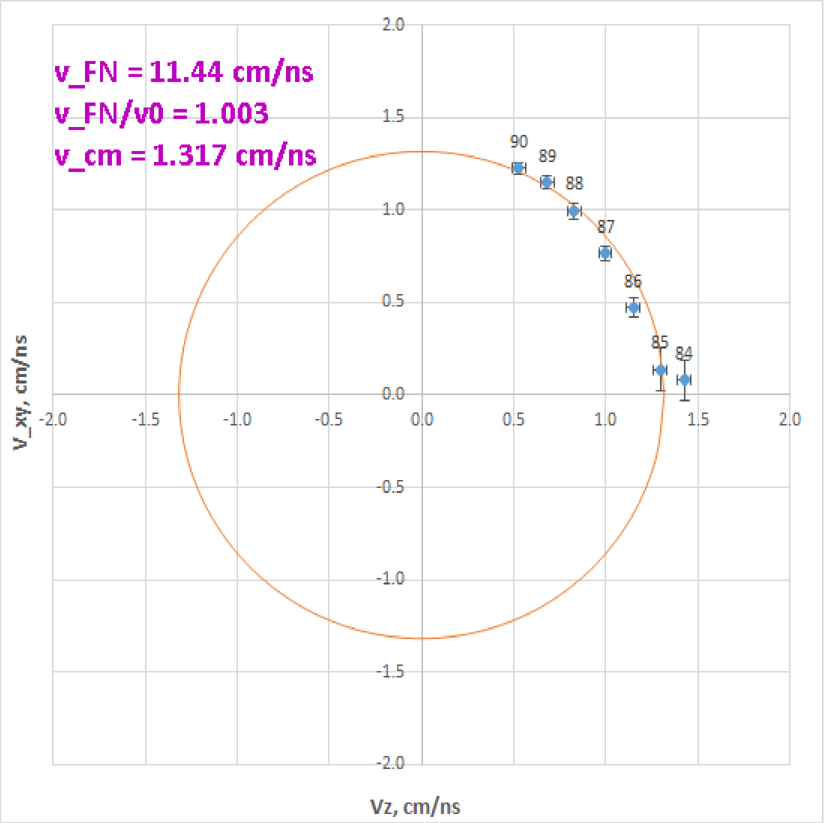
v/v0 * V_FN

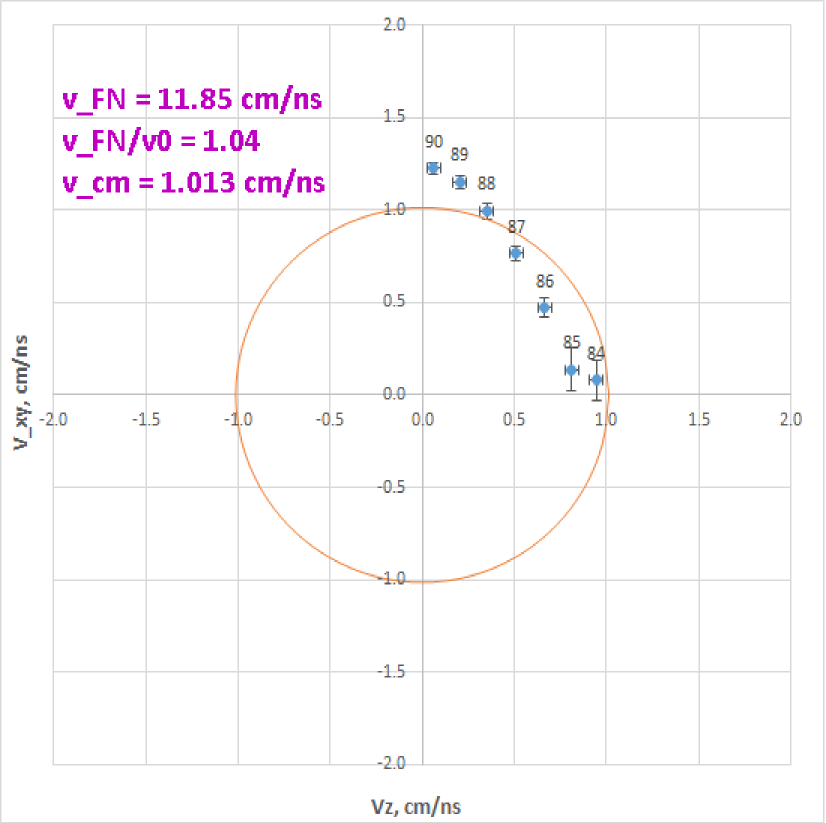


v/v0 : velocity ratio between the fissile nucleus and the primary beam (1 ≤ v/v0)

V_FN : velocity of the fissile nucleus
(variable value for fitting)







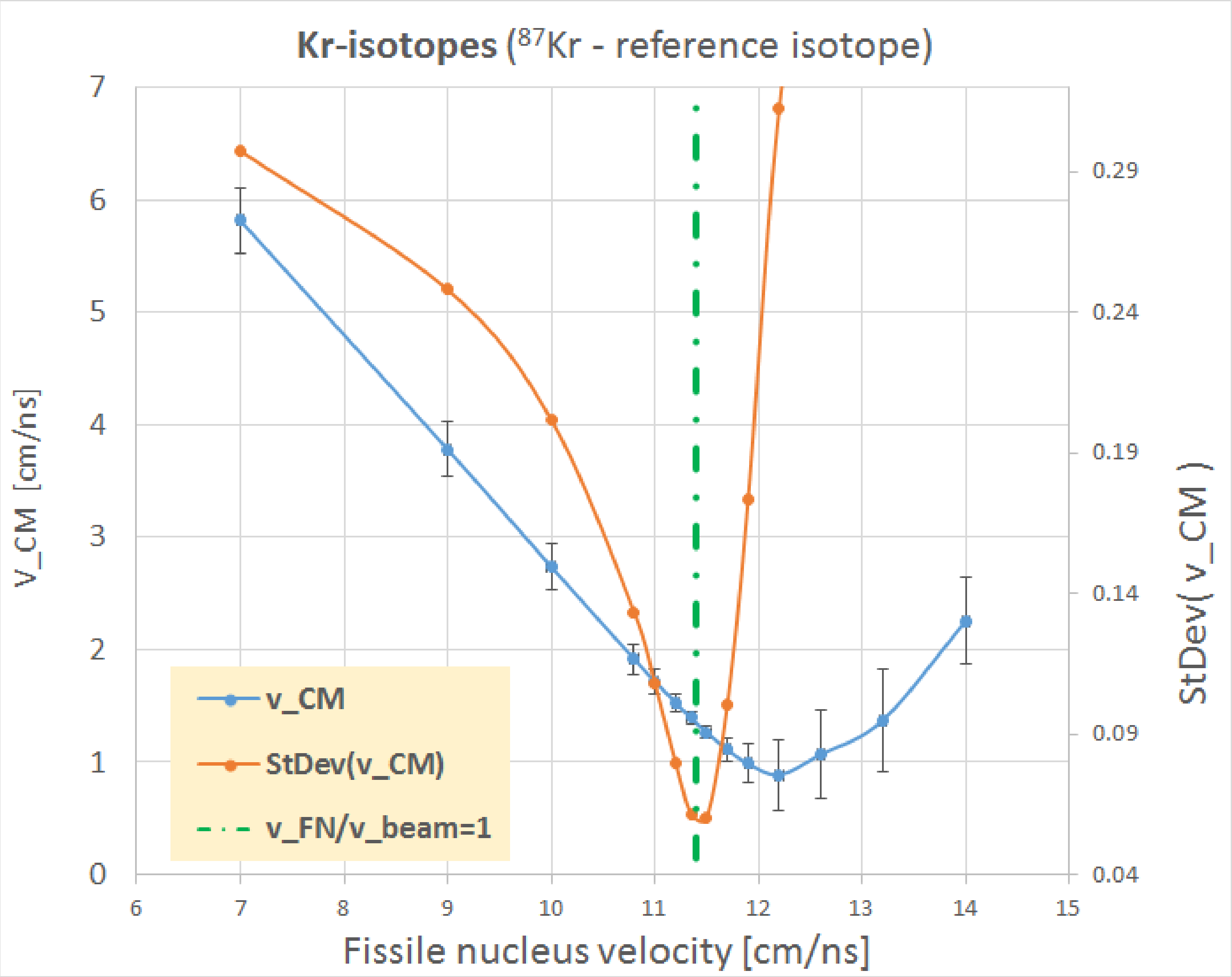
The “circle” condition is minimum of the **StDev**(v_cm) distribution

v_CM : deduced velocity of krypton isotopes in CMS

StDev(v_CM) : Standard Deviation of the deduced v_CM

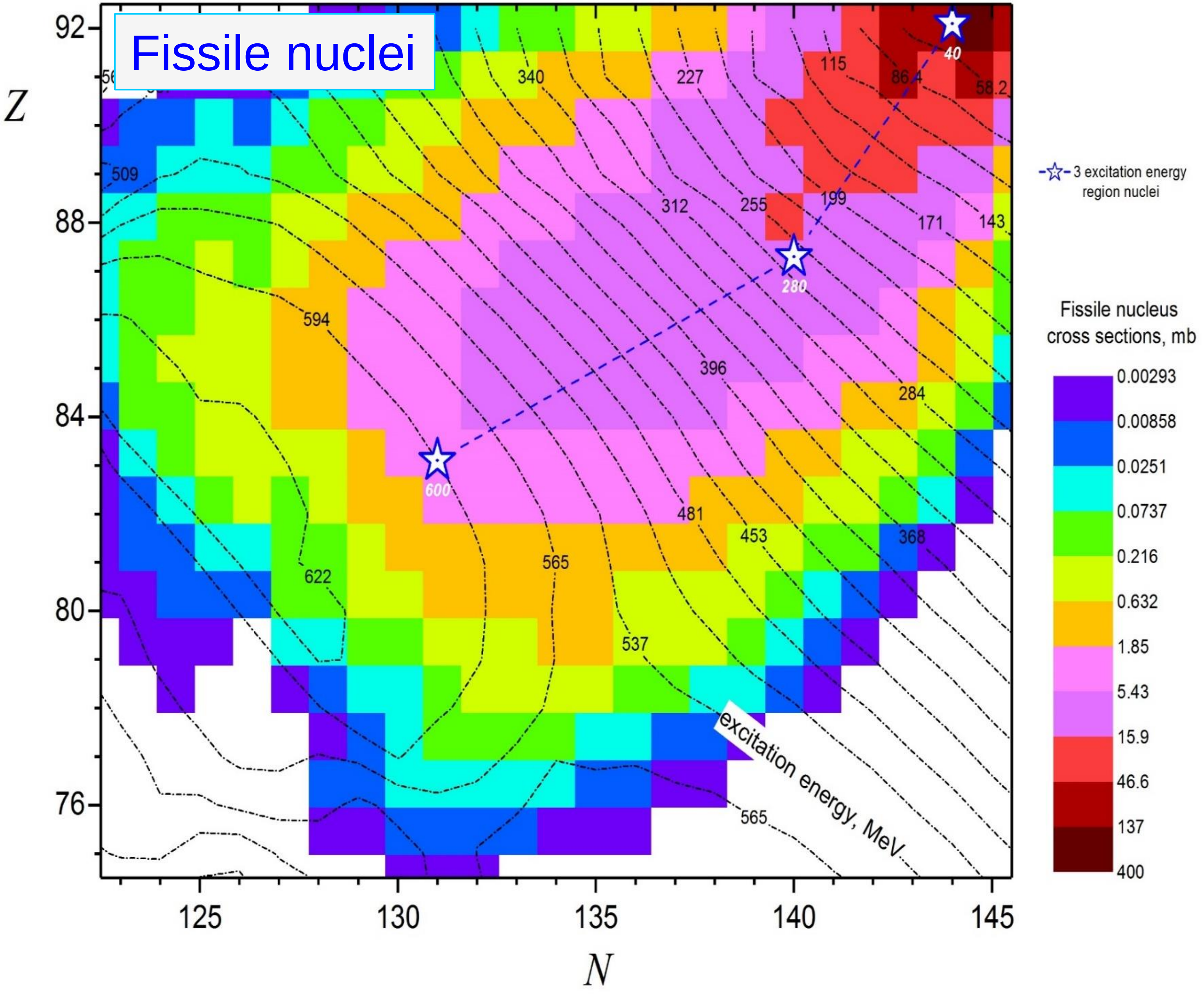
v_FN : velocity of the fissile nucleus *(variable value for fitting)*

v_beam : velocity of the primary beam at the middle of target



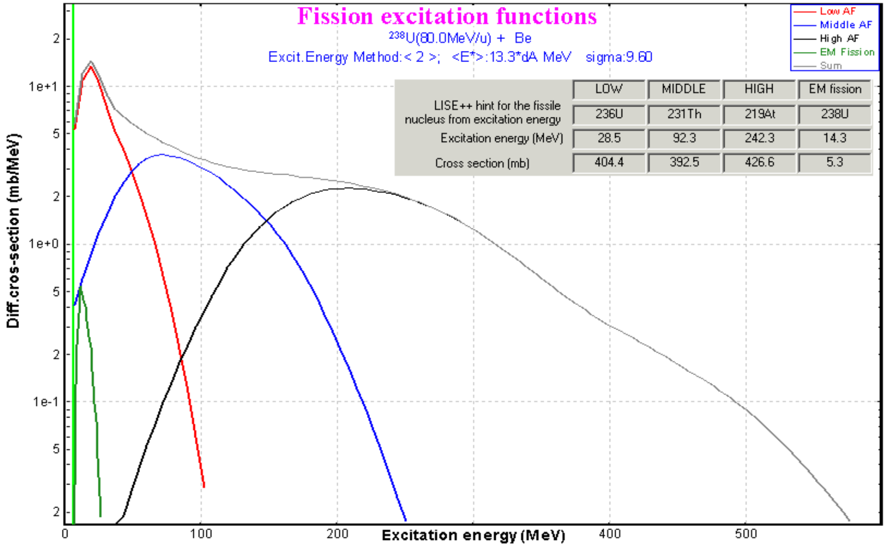
Why we would like to know v_{CM}?

Abrasion-Fission : Three Excitation-Energy regions model



Abrasion - Fission

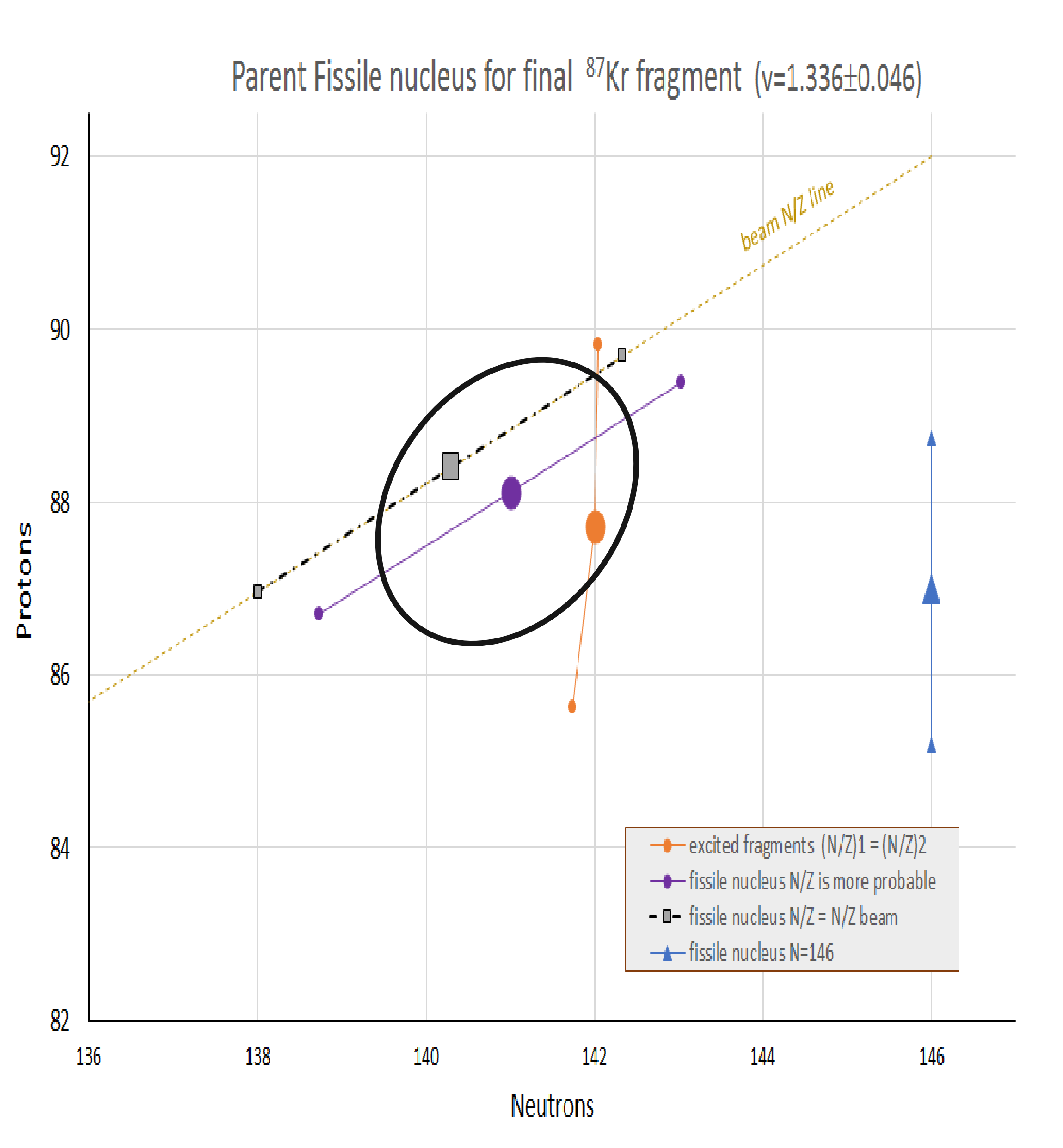
> *LISE++ 3EERs (excitation energy region) model:*
>
> Simple approximation to substitute about 1400 fissile nuclei by 3 nuclei based on excitation energy

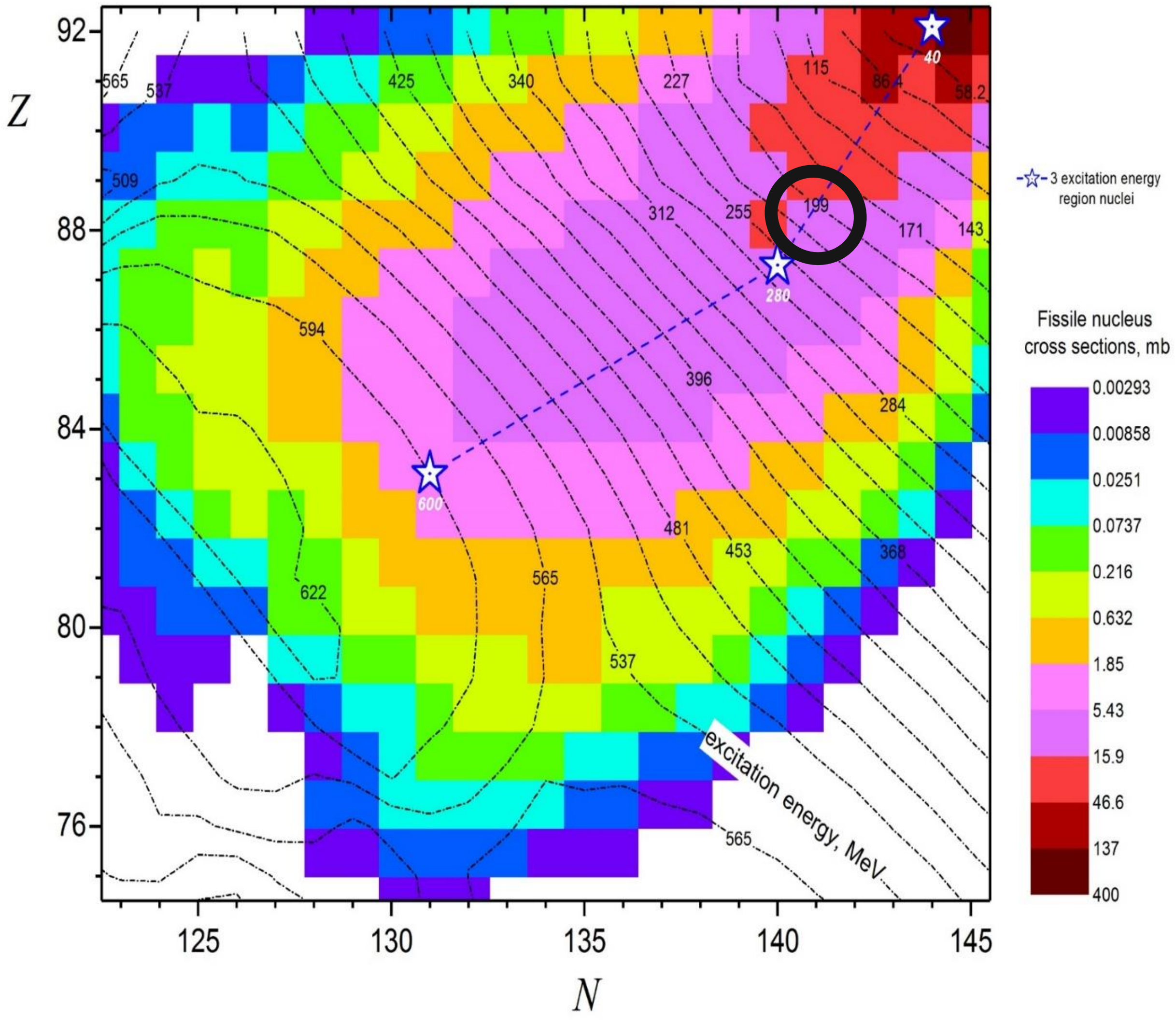


	LOW	MIDDLE	HIGH	EM fission
LISE++ hint for the fissile nucleus from excitation energy	236U	231Th	219At	238U
Excitation energy (MeV)	28.5	92.3	242.3	14.3
Cross section (mb)	404.4	392.5	426.6	5.3

http://lise.nscl.msu.edu/7_5/lise++_7_5.pdf

Parent fissile nucleus for final ^{87}Kr fragment (experiment)





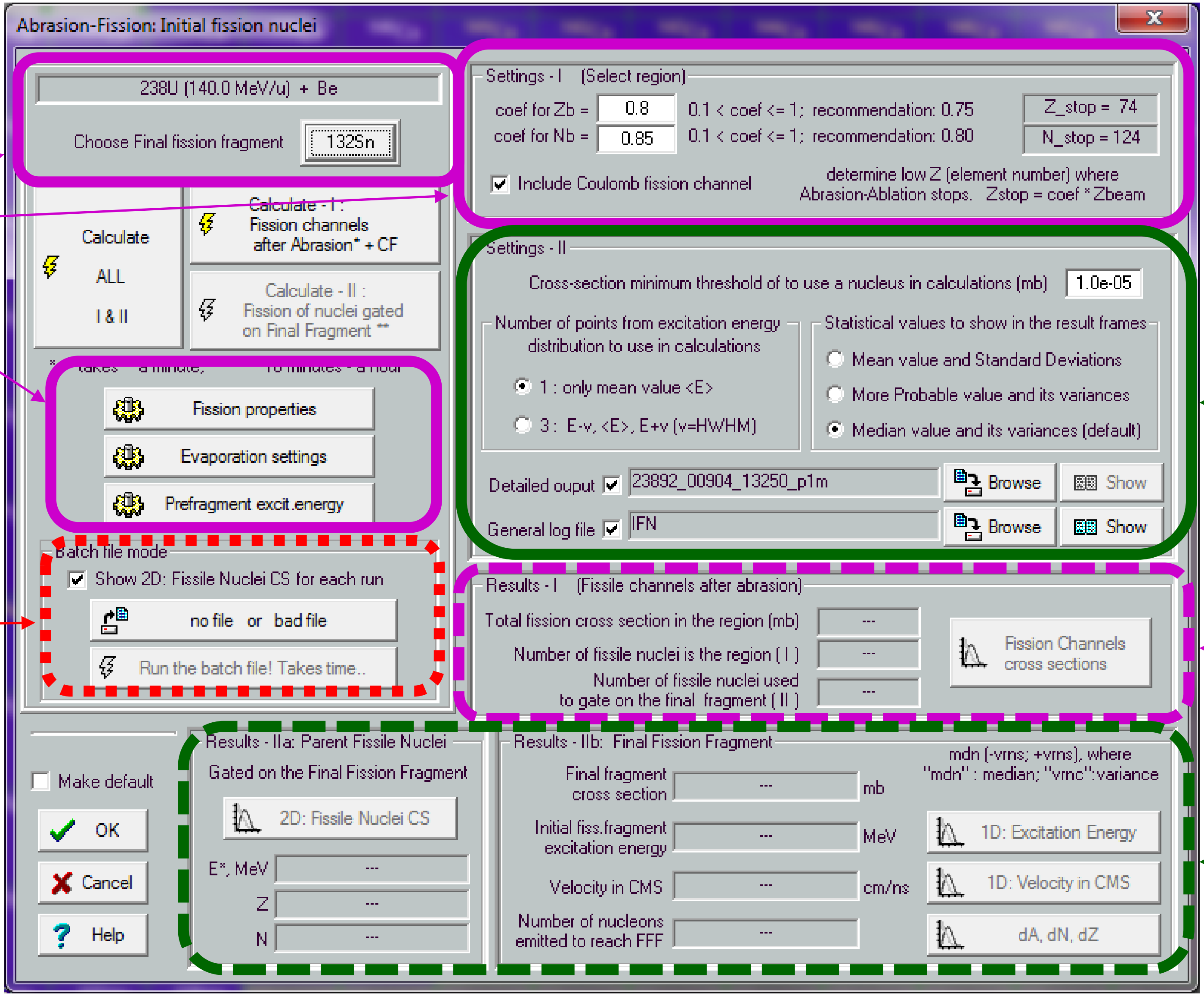
2019 LISE^{++} :

Initial Fissile Nuclei Analysis

Initial Fissile Nuclei (IFN) Analyzer

1st step settings

Bath mode settings and run



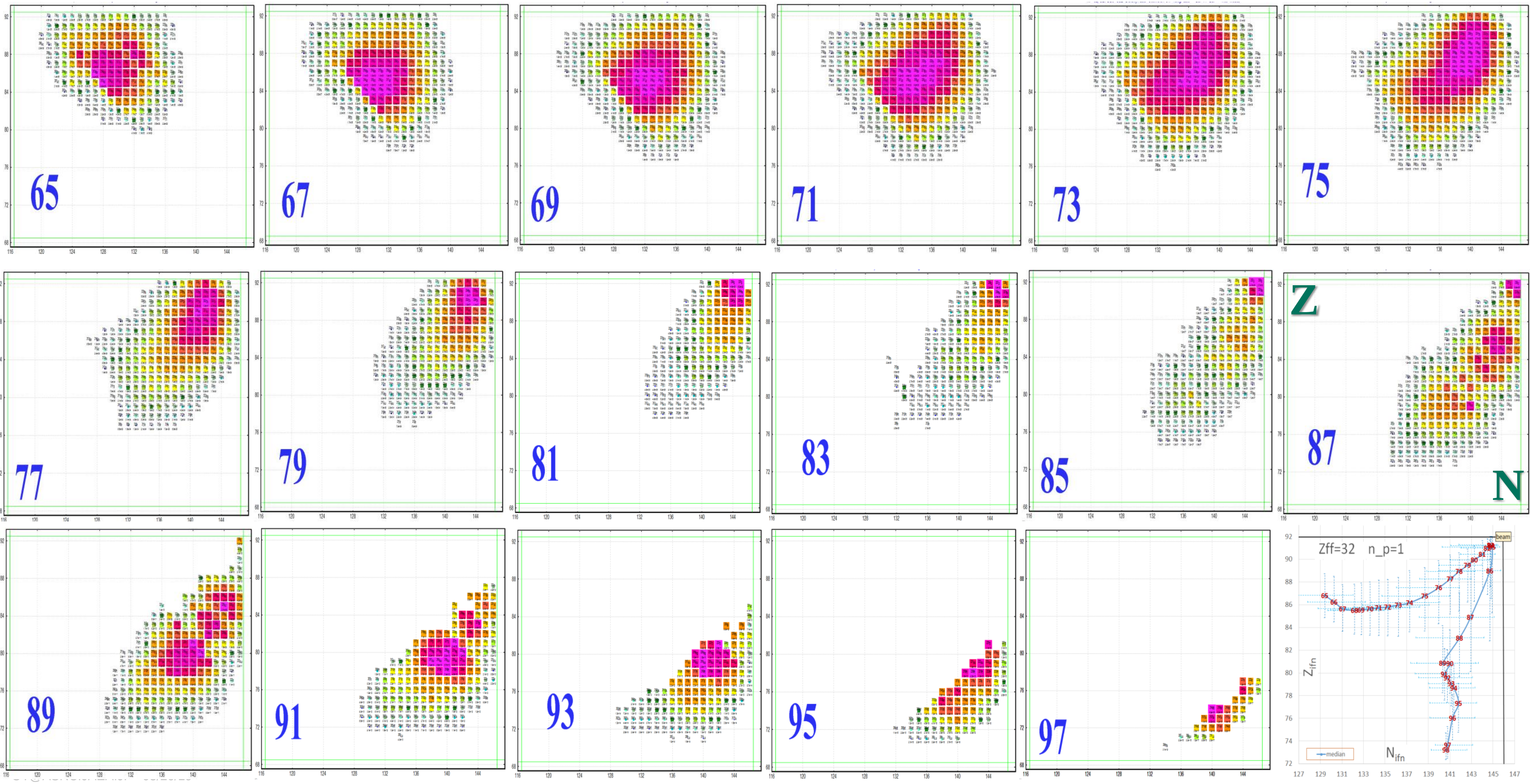
2nd step settings

1st step results

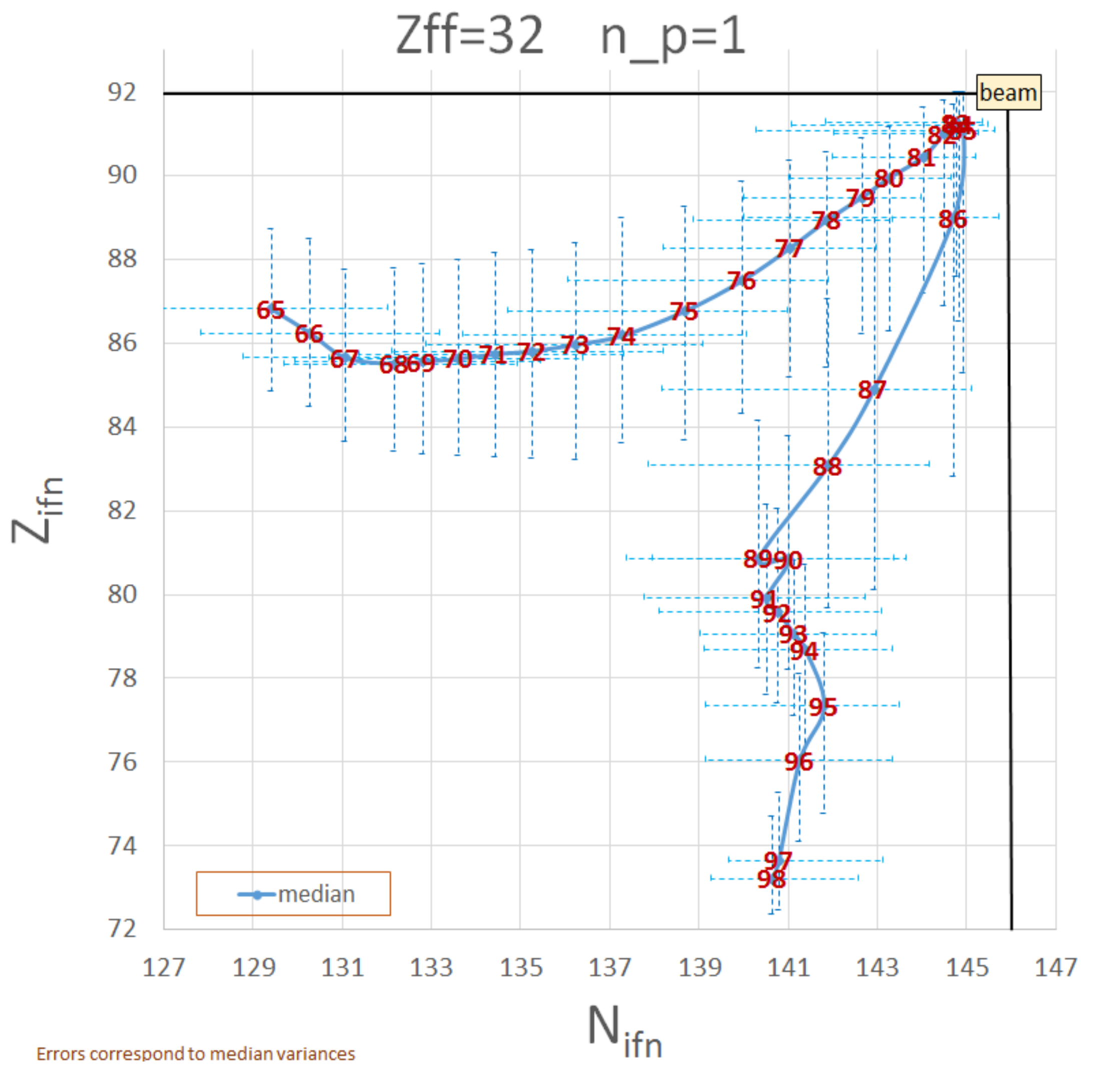
2nd step results

http://lise.nscl.msu.edu/10_1/11_0_28_IFN_search.pdf

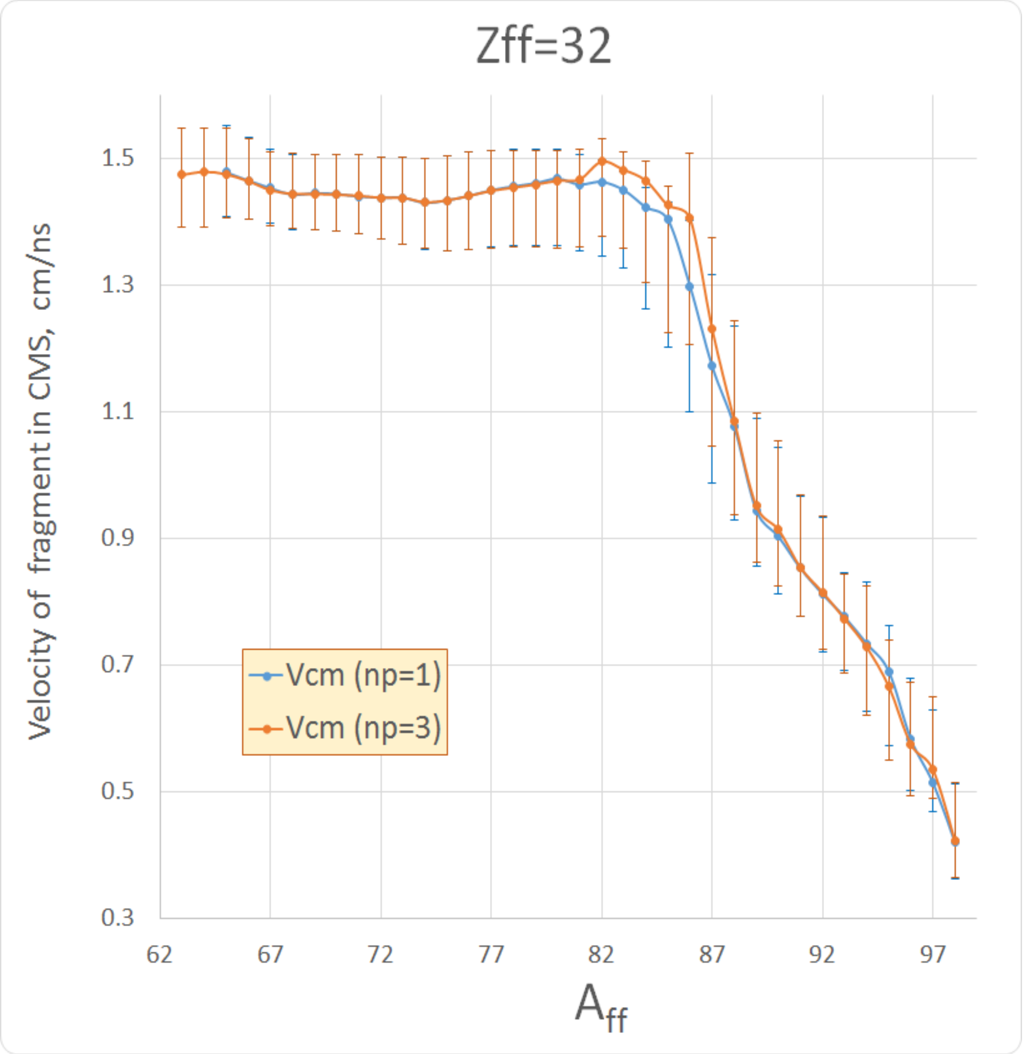
Initial Fissile Nuclei (IFN) for final Ge-isotopes (Z=32)



IFN-analysis for final Ge-isotopes (Z=32)

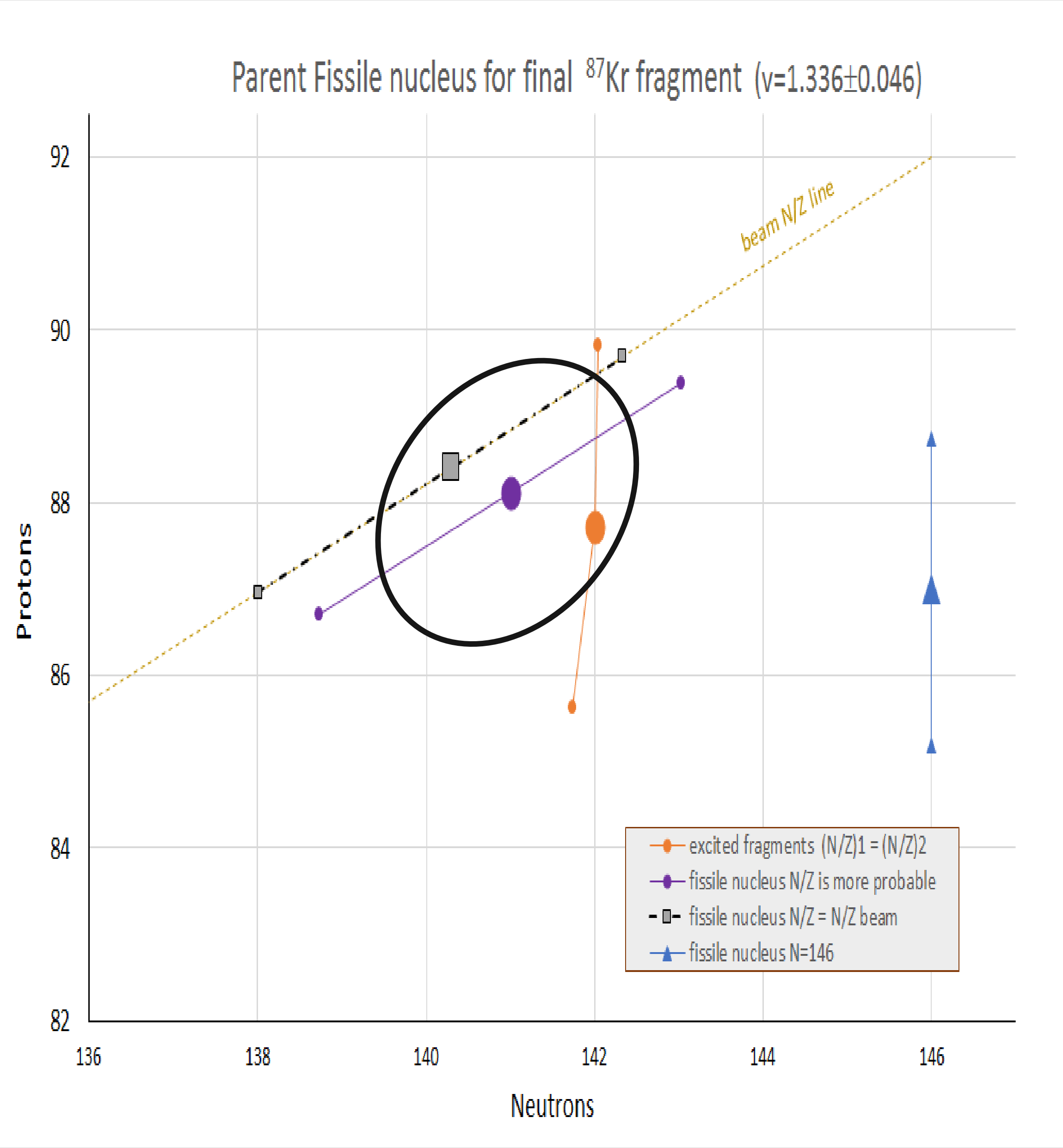


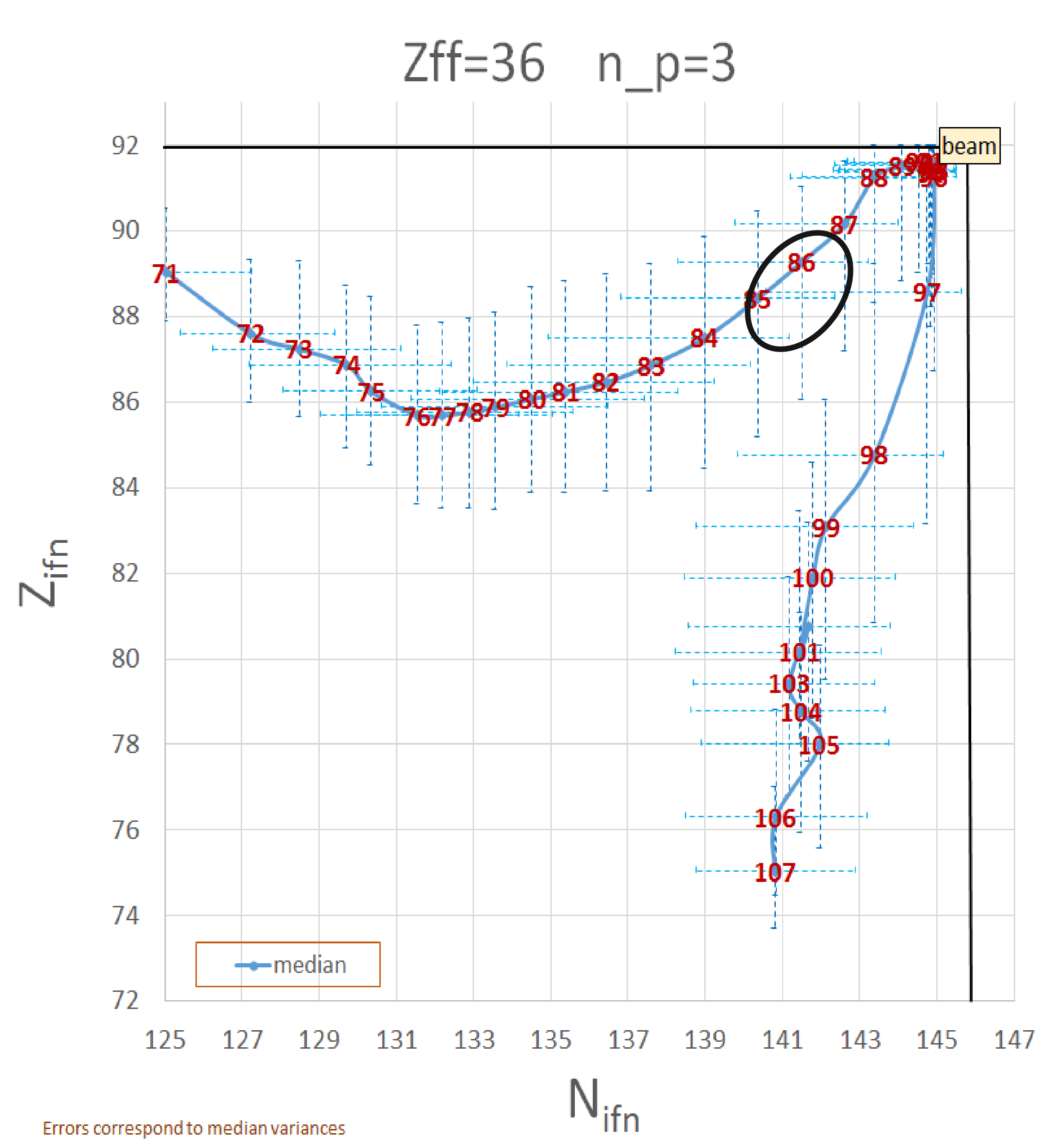
Errors correspond to median variances



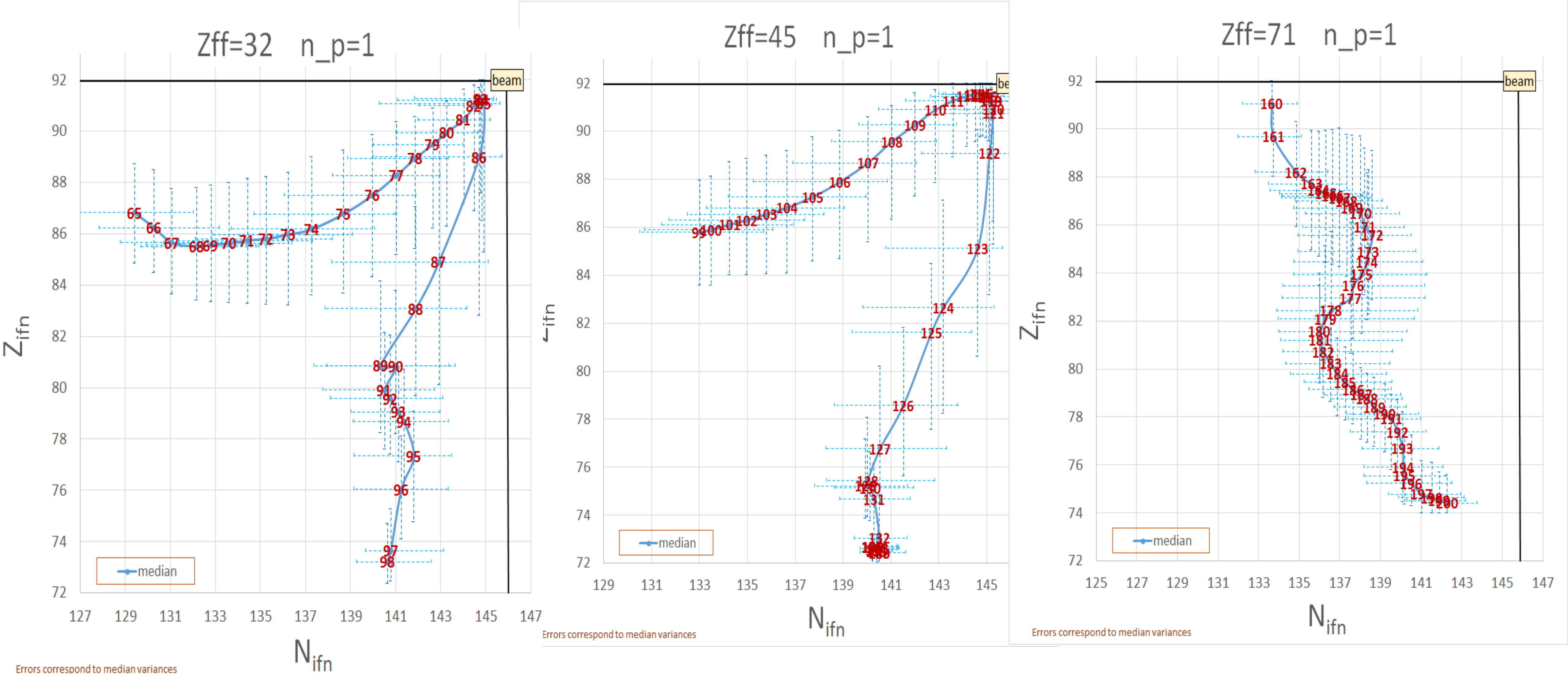
- Velocity of fragment as indicator of Z $_{\text{fissile nuclei}}$

Parent fissile nucleus for final ^{87}Kr fragment (experiment)





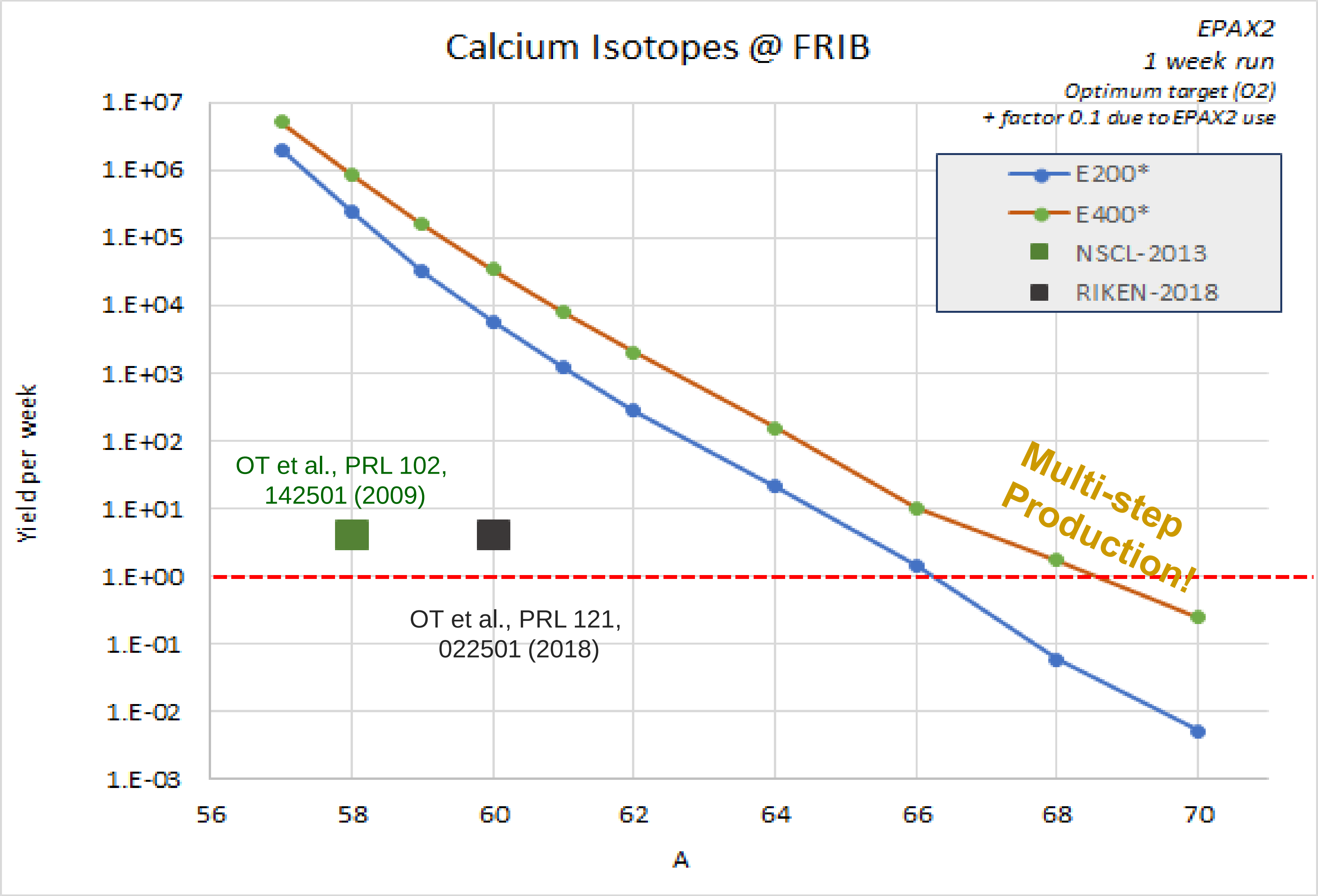
IFN-analysis: Z=32, 45, 71



- The high excited region becomes responsible for one-step super-neutron-rich isotopes production
- Develop new Abrasion-Fission mode to use IFN tables, that provides more fast and qualitative fission yield calculations

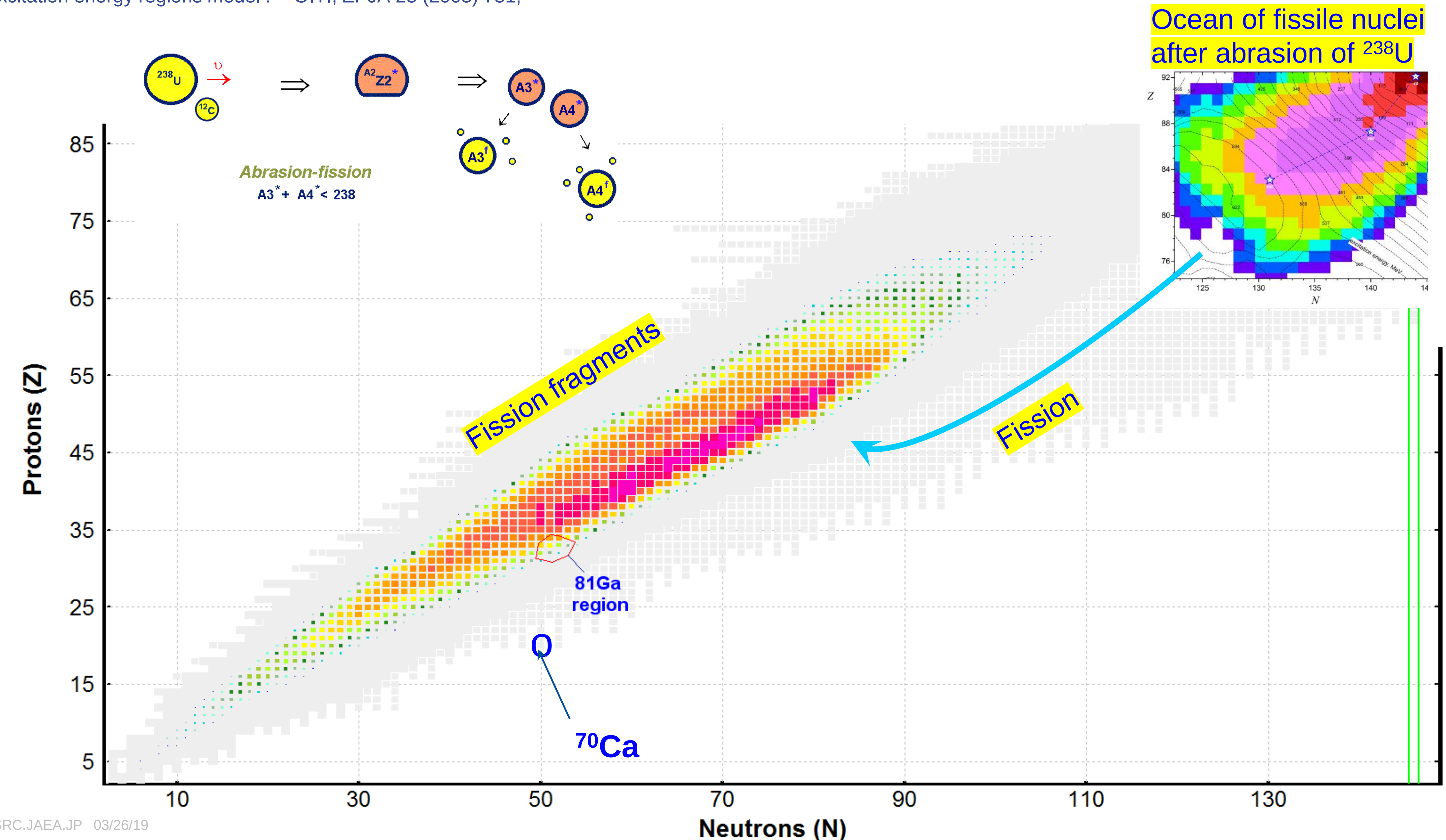
Super-Heavy Calcium isotopes production: multi-step production in one target

Super-Heavy Calcium isotopes production per week

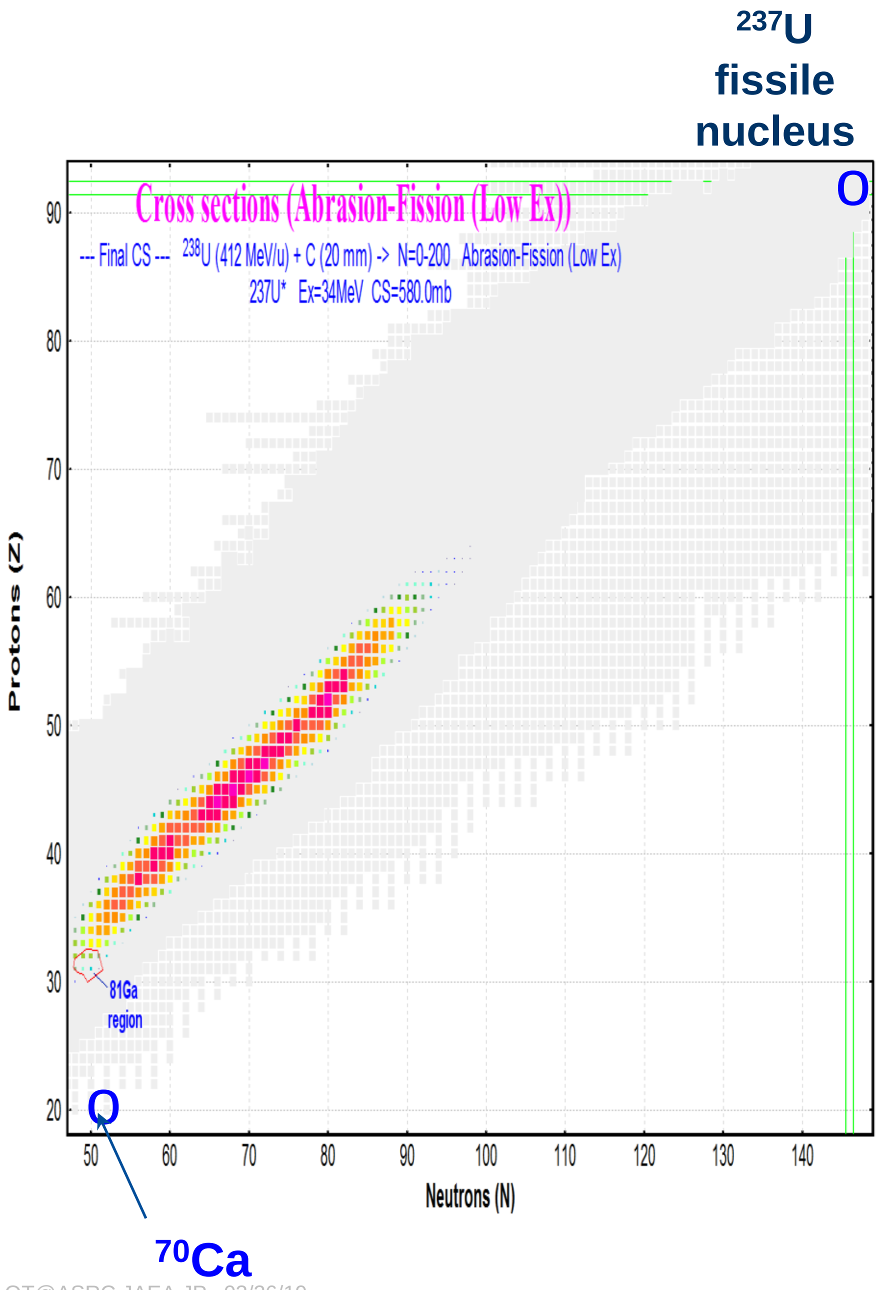


1st step : Abrasion-Fission

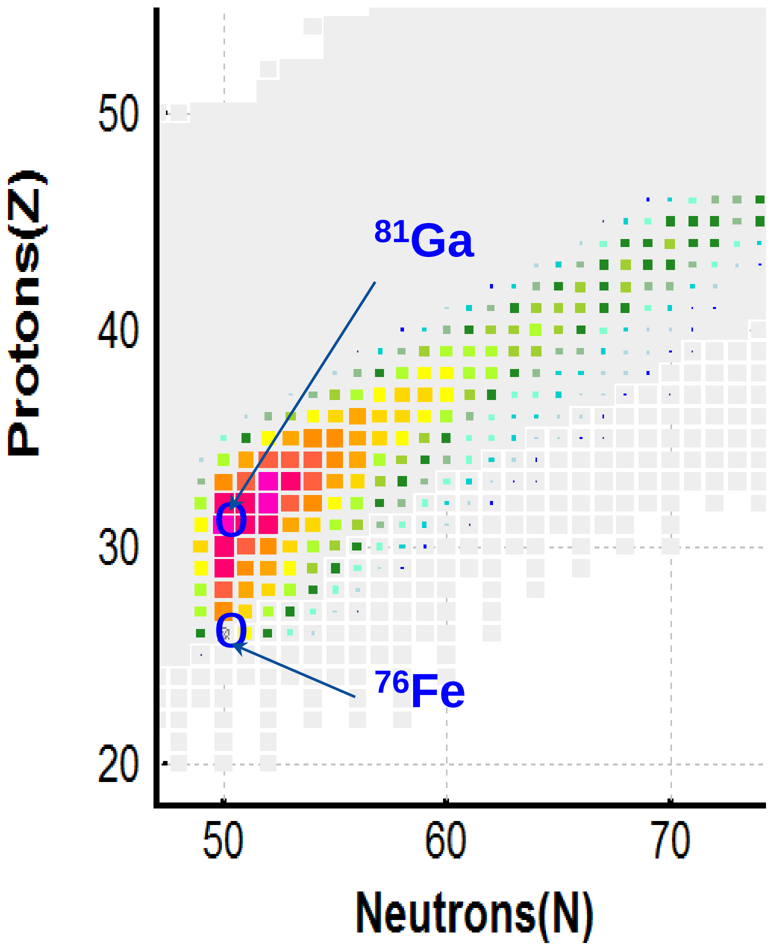
3 Excitation energy regions model : O.T., EPJA 25 (2005) 751;



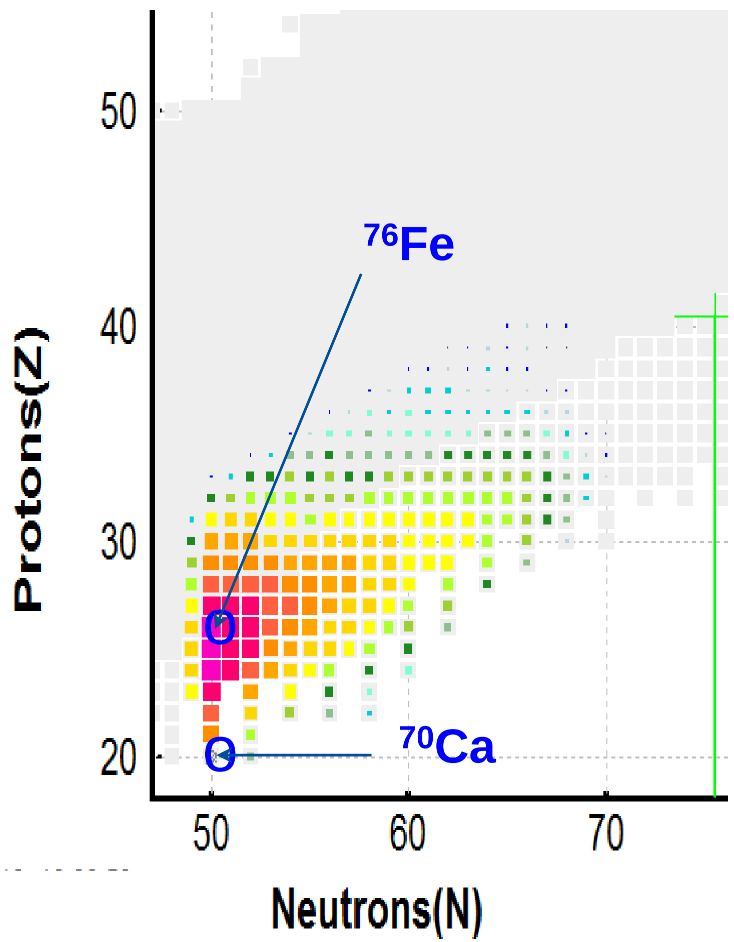
Fission of ^{237}U (E*=34 MeV), Projectile fragmentation steps



More probable parents of ^{76}Fe



More probable parents of ^{70}Ca



Multi-step reactions: different techniques

Production of very neutron-rich Pd isotopes around N = 82 by projectile fragmentation of a RI beam of ^{132}Sn at 280 MeV/u

SUZUKI Hiroshi
BigRIPS team
Nishina Center for Accelerator-Based Science
RIKEN

Oct. / 27 / 2018 @ HAWAII2018

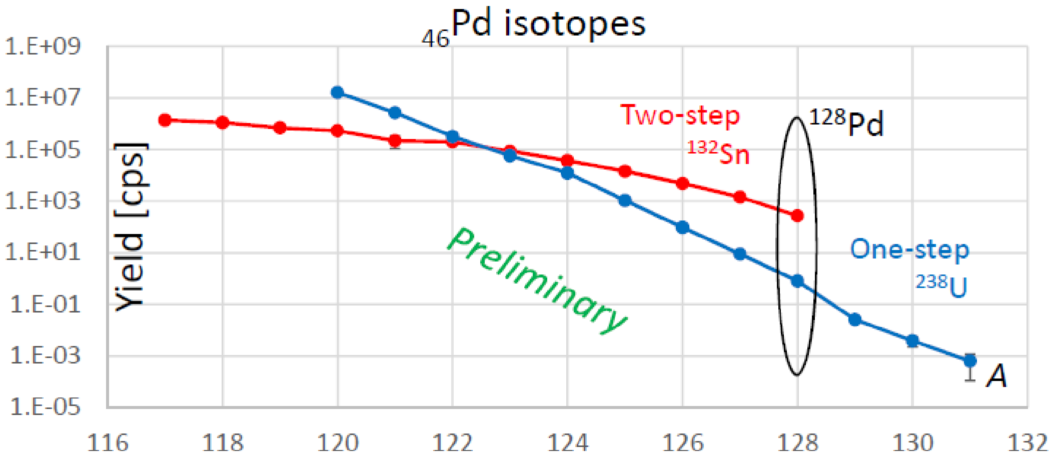
Yield comparison in two- vs one-step

Assumption

	Beam int.	Target	Transmission
Two-step: this work, [GSI] ^{132}Sn fragmentation	3×10^{10} cps (EURISOL)	4-mm Be	80%
One-step: [RIBF1-3] ^{238}U in-flight fission	1 pμA (RIBF) (6×10^{12} cps)		30%

[GSI] D. Pérez-Loureiro *et al.*, Phys. Lett. B **703** (2011) 552
[RIBF1] T. Ohnishi *et al.*, J. Phys. Soc. Jpn **77** (2008) 083201
[RIBF2] T. Ohnishi *et al.*, J. Phys. Soc. Jpn **79** (2010) 073201
[RIBF3] Y. Shimizu *et al.*, J. Phys. Soc. Jpn **87** (2018) 014203

- The yields by two-step decrease more gently (two step: 1/3, one step: 1/10 @ ^{128}Pd).
- The yields of Pd isotopes by two-step is higher than the ones by one-step at A > 123 when using the ^{132}Sn as the primary beam.
- For the production of nuclei with N > 82 region, ^{133}Sn or more neutron-rich Sn isotope with the two-step production may give more yields than the one-step production.



ex.) Production of ^{129}Pd

	ISOL	frag.
• ^{238}U → ^{132}Sn → ^{129}Pd	1	1/100
• ^{238}U → ^{133}Sn → ^{129}Pd	1/20	1
• ^{238}U → ^{132}Sn → ^{128}Pd (ref.)	1	1

Figure of merit: x5

Conclusion

- Fusion-Fission reaction products produced by a ^{238}U beam at 24 MeV/u on Be and C targets were measured in inverse kinematics by use of the LISE3 fragment separator, and fission and fragmentation products at 80 MeV/u by use the S800.
- The GANIL experiment results demonstrate that a fragment separator can be used to produce radioactive beams using fusion-fission reactions in inverse kinematics, and further that in-flight fusion-fission can become a useful production method to identify new neutron-rich isotopes, investigate their properties and study production mechanisms.
- The comparison of the experimental atomic-number and mass distributions combined with the analysis of the isotopic-distributions properties show that between the ^{9}Be and the ^{12}C target, the reaction mechanism changes substantially, evolving from a complete fusion-fission reaction to incomplete fusion or fast fission.
- It has been demonstrated, that the reverse tracking technique can be used as a precise tool to get information for reaction mechanism characteristics.
- It has been shown that Velocity of fissile nuclei is close to primary beam velocity in the case of ^{87}Kr, that corresponds to the small number of abraded nucleons from the projectile (that belongs to the middle excitation energy region (EER) and correspond to LISE^{++} calculations).
  - **The new Abrasion-Fission mode with IFN tables use will be developed**, that provides more fast and qualitative fission yield calculations.
    - **Measurement of Velocity CM of fission fragment can be used to deduce reaction mechanism properties**.
- **The analysis shows that high excited fissile nuclei are responsible for one-step super-neutron-rich isotopes production.**
- **Multi-step reactions, combination of different reaction mechanisms are future tools to explore the neutron drip-line.**
- **Reaction mechanisms involved in rare isotope production are required more attention from the nuclear reaction community.**

Collaborators

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