Rare isotope beams production using fusion-fission reactions

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Heavy neutron-rich isotope beam production using fission reactions

- ☐ Nowadays, fission is widely used to produce rare neutron-rich nuclei.
  - * in-flight fission (abrasion-fission, Coulomb fission) ;
  - * spallation reactions (ISOL technique) at thick Uranium targets

  are used to produce such nuclei.

- ☐ Important issue of these both techniques is hardness to produce neutron-rich fragments with Z>55 due to small production abrasion-fission cross sections.

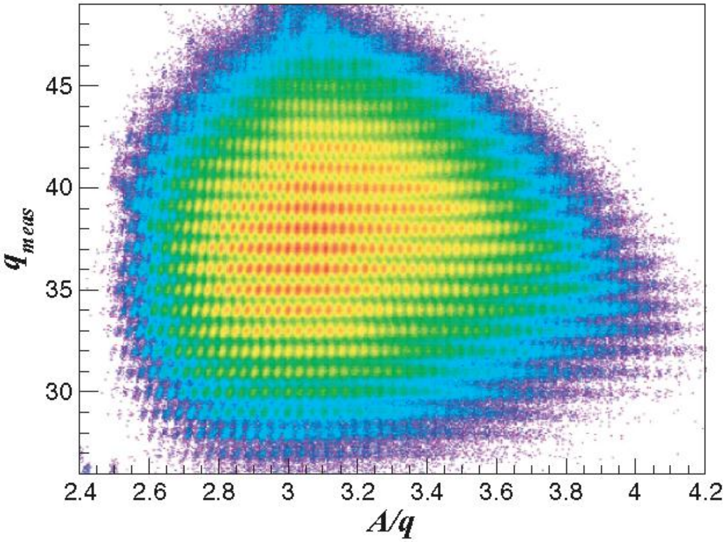
Using fusion-fission reactions, the fissile nucleus becomes heavy than projectile (so in the previous example heavy than Uranium)

Inverse kinematics of low energy reactions?

- ☐ A recent VAMOS experiment to measure fission fragment yields from the reaction of ^{238}U with ^{12}C near the Coulomb barrier demonstrated the advantages of inverse kinematics to study production mechanisms [1], and to investigate fission fragments properties [2].

1. M.Caamaño, et al., Phys. Rev. C 88, 024605 (2013)
2. A.Shrivastava et al., Phys. Rev. C 80, 051305(R) (2009)

M.Caamaño, et al., PRC88, 024605 (2013)



- ☐ However, in order to explore properties of very neutron rich isotopes produced in this way it is <u>necessary to separate isotopes of interest from undesirable products</u>.

How to produce heavy fusion-fission beams with separators ?

What beams we can expect from fusion-fission reactions?

A model[1] for fast calculations of fusion–fission fragment cross sections has been developed in LISE^{++}[2] based on already existent analytical solutions: fusion–evaporation and fission fragment production models.

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

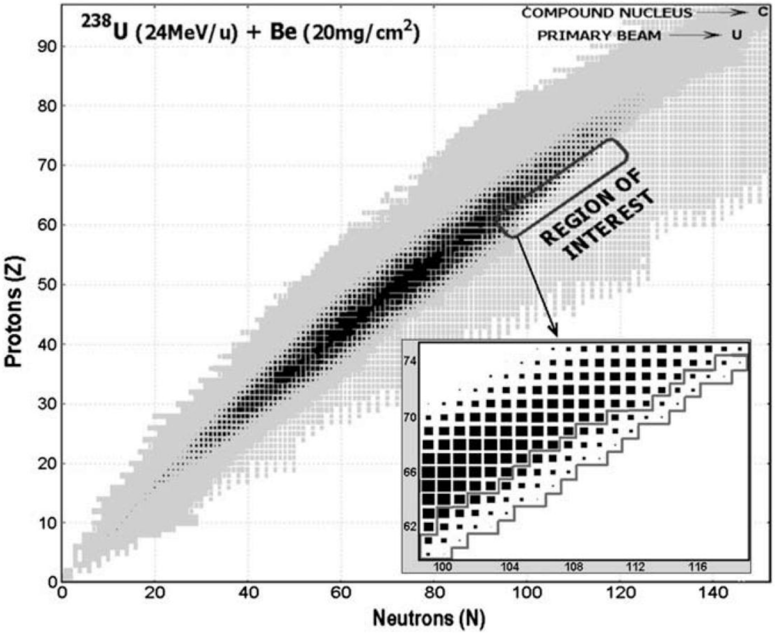
[2] O. B. T. and D. Bazin, NIM B 266, 4657 (2008).
LISE++ website: http://lise.nscl.msu.edu.

Main features of the model:

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

Using fusion-fission beams:

- *Several tens of new isotopes (in 2008) are expected to be produced in the region 55 < Z < 75 using a ^{238}U beam with light targets according to the Fusion-Fission model*
- *Properties of these new nuclei allow to test nuclear models, in particular to understand the r-process abundance patterns of element around lead as well as nuclei properties approaching closed shell N=126 (you don't need to degrade)*
- *And evidently reaction mechanism study*

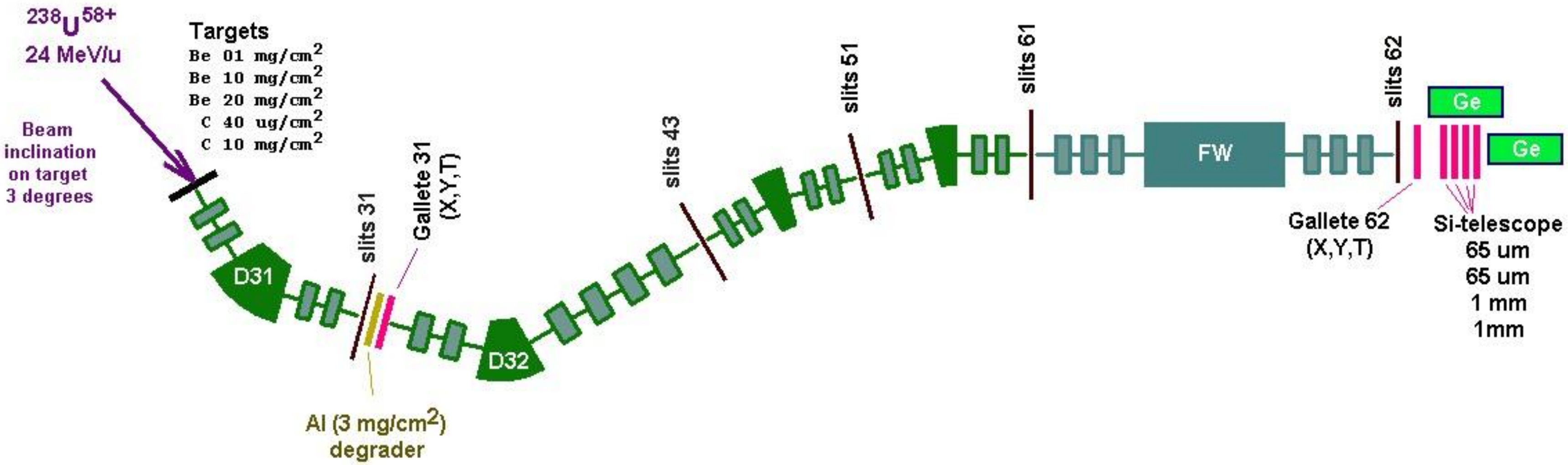


Open Questions:

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

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

Experimental set-up

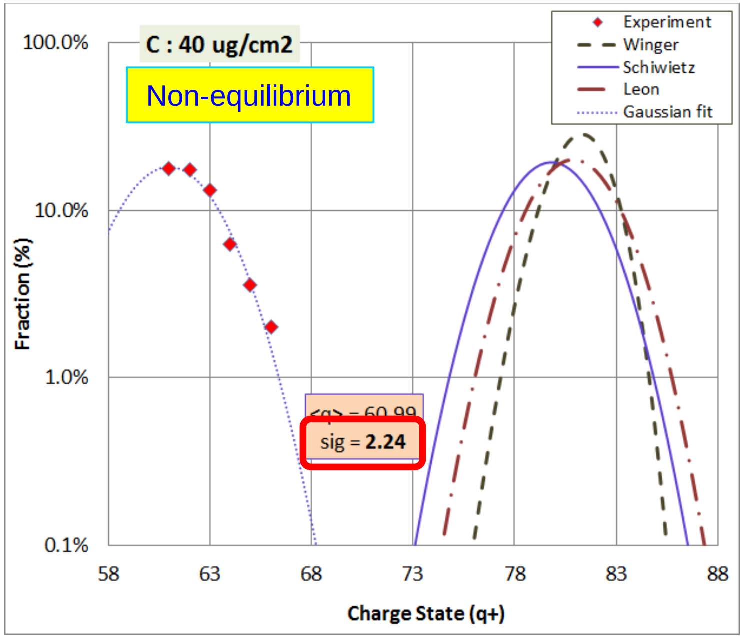


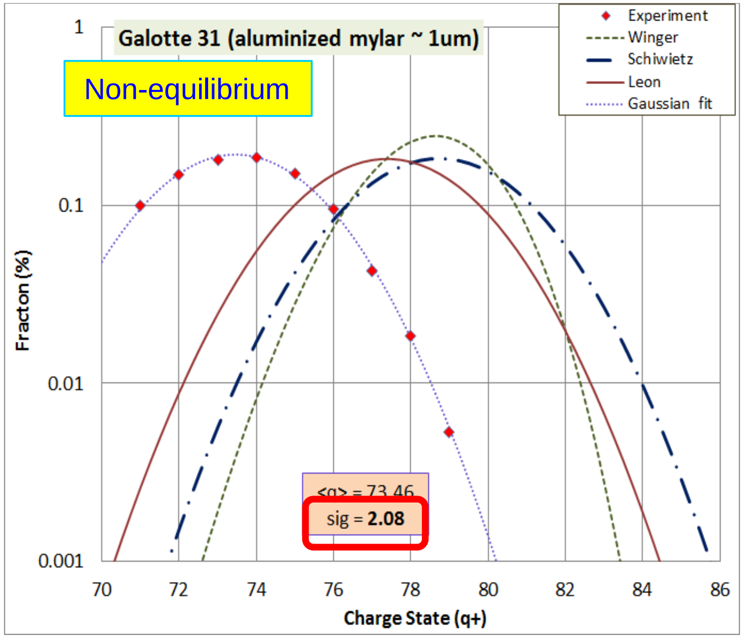
- A ^{238}U beam at 24 MeV/u with a typical intensity of 10^9 pps, was used to irradiate a series of beryllium targets and a carbon target.
- The beam was incident at an angle of 3° in order not to overwhelm the detectors with the beam charge states.
- Fragments were detected in a Silicon telescope at the end of the separator. Fission fragments produced by inverse kinematics are identified by ΔE-TKE-Bρ-ToF method.
- Two MCP detectors (gallete 31 and gallete 62) were used to measure positions and times.
- Germanium γ-ray detectors were placed near the Si telescope to provide an independent verification of the isotope identification via isomer tagging.

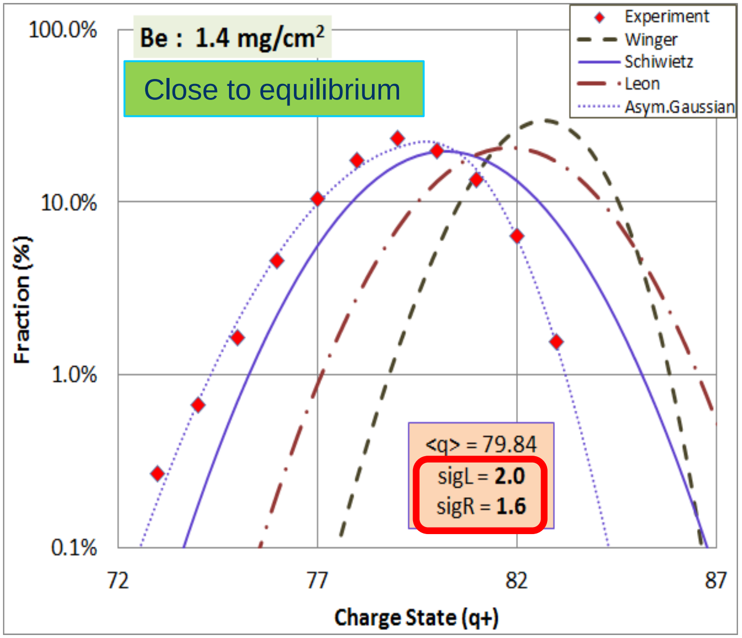
^{238}U @ 24 A MeV + ^{9}Be -> ^{247}Cm E*= 150-200 MeV

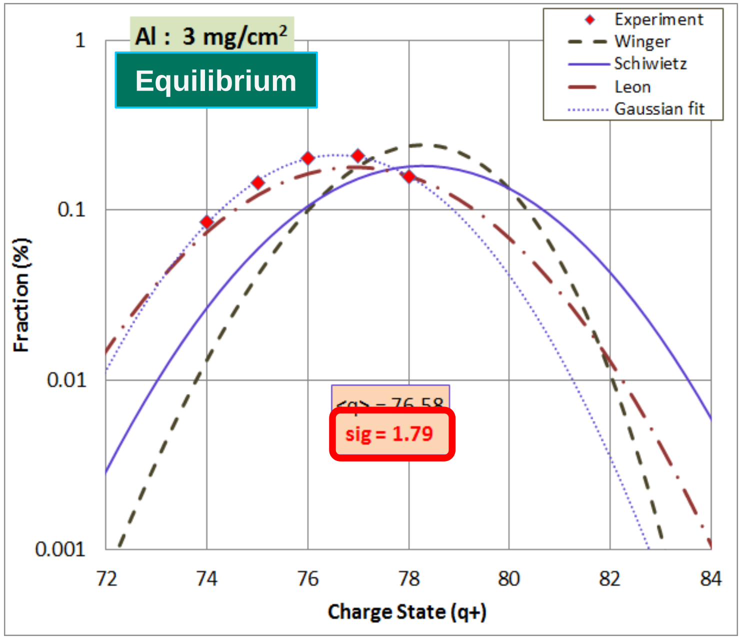
^{238}U @ 24 A MeV + ^{12}C -> ^{250}Cf E*= 180-250 MeV

$^{238}U^{58+} \rightarrow q^{+}$ (24 MeV/u) charge state distribution after …







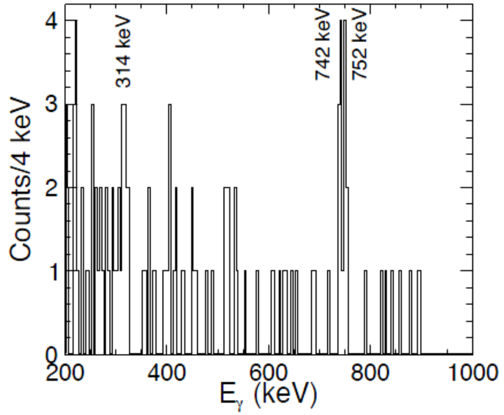


- What charge state model should be used for fragment transmission estimation?
- Based on sigma values and peak positions it is possible to conclude about reaching equilibrium thickness
- The best predictions are given for beam and fragments by A.Leon et al., AD & ND Tables 69 (1998) 217

This work was done also at GANIL

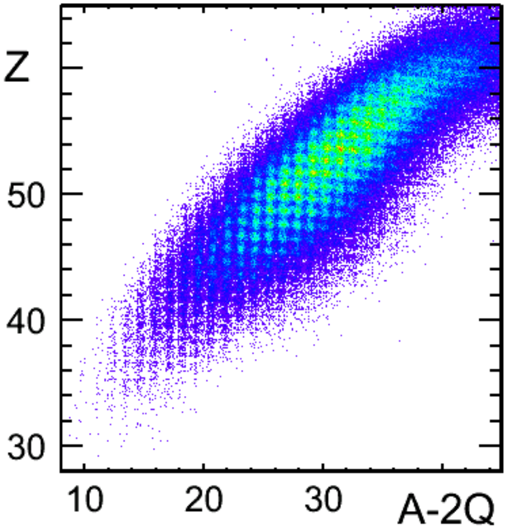
Particle Identification

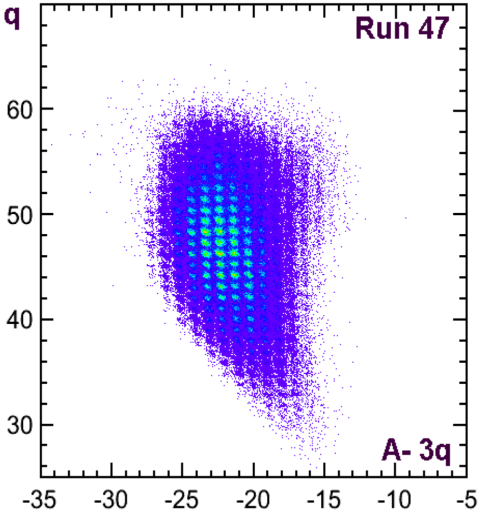
Preliminary detectors calibration with the primary beam,
Then particle identification has to be
proved by gamma from know isomers

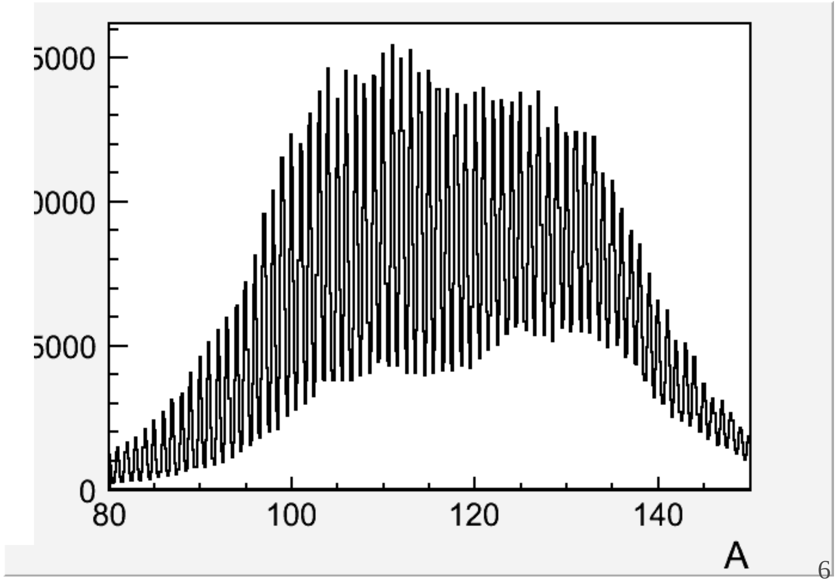


Gamma-ray spectrum observed in coincidence with ^{128}Te. The characteristic gamma lines of 314, 742 and 752 keV sign the decay of the isomeric state of $T_{\frac{1}{2}} = 370$ ns

The atomic number is determined from the combination of energy loss (ΔE) and time-of-flight (TOF) values according to the Bethe formula:	$Z \approx \sqrt{\Delta E \Big/ \left(\frac{1}{\beta^2} \ln\left(\frac{5930}{1/\beta^2 - 1} \right) - 1 \right)}$
The fragment mass can be extracted in atomic units from the relativistic formula, where TKE is calculated as a sum of the energy loss values in each of the detectors in a multilayer telescope stopping the products	$A = \frac{TKE}{931.5 \times (\gamma - 1)}$
The charge state of the ion evaluated from a relation based on the TKE, velocity and magnetic rigidity values:	$q = 3.33 \times 10^{-3} \frac{TKE \times \beta\gamma}{B\rho(\gamma - 1)}$



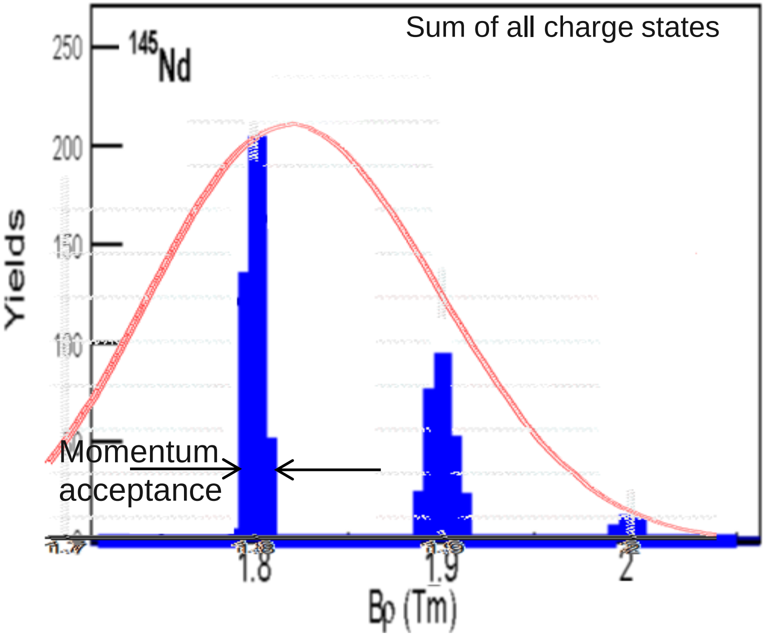




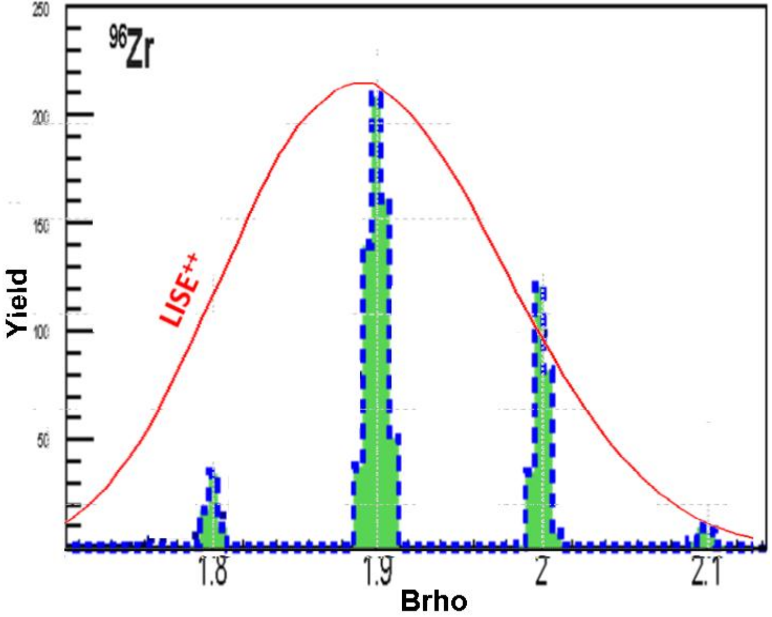
Transmission calculations

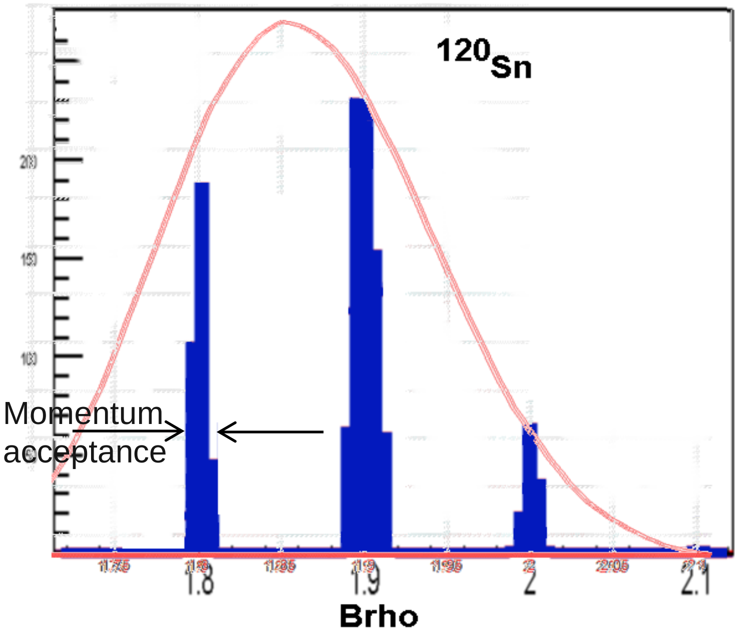
- The LISE++ code has been used for transmission calculations
- A.Leon's charge state and F.Hubert 's energy loss models were used
- Data with 15 mg/cm^2 Be & C targets have been used in analysis
- In the analysis the targets have been divided on 5 slices, results have been summed.
  It has been done because the LISE++ assumed reaction place in the middle of target

- *A lot of important updates, improvements, as well including bugs fix were done during this analysis*



^{238}U(24.1MeV/u) + C target (15mg/cm^2) → Fusion-Fission

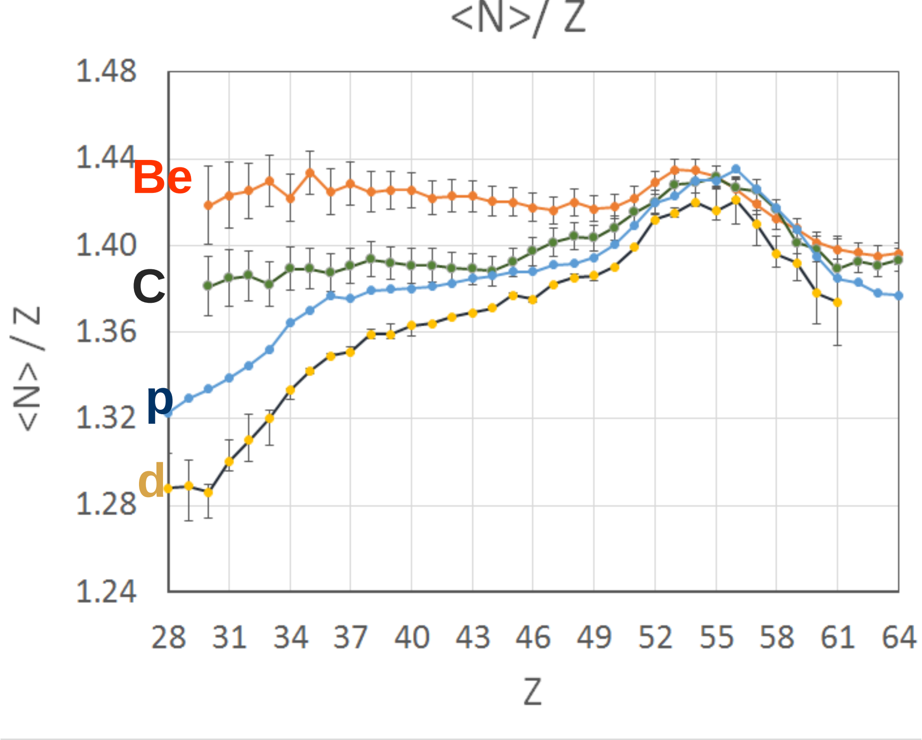




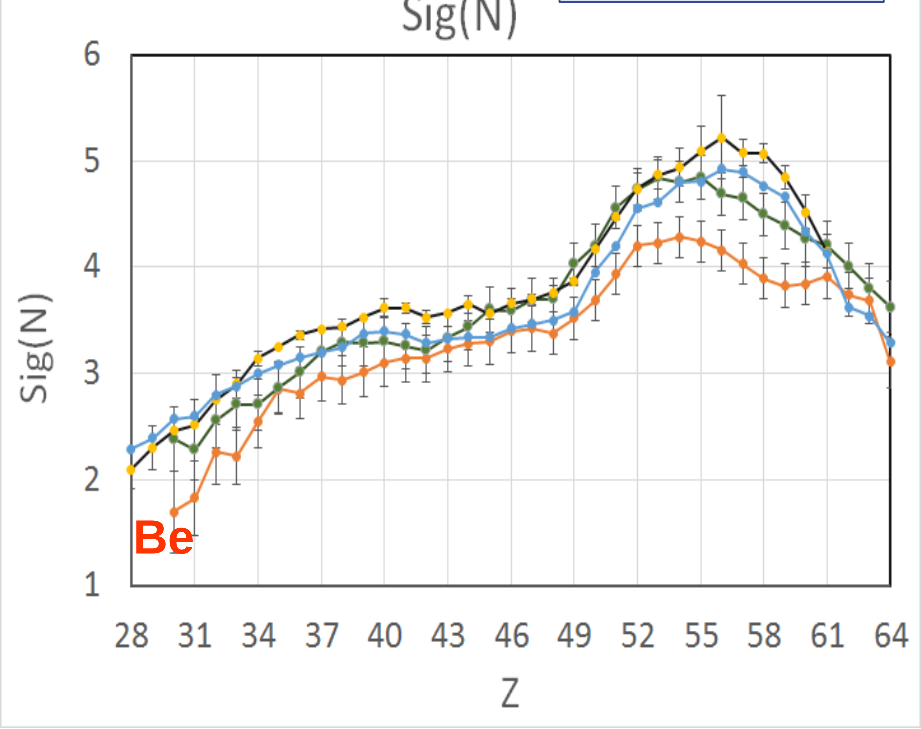
Neutron excess and width of the isotopic fission fragments produced in reactions of ^{238}U with light targets

Preliminary!!!

Neutron excess



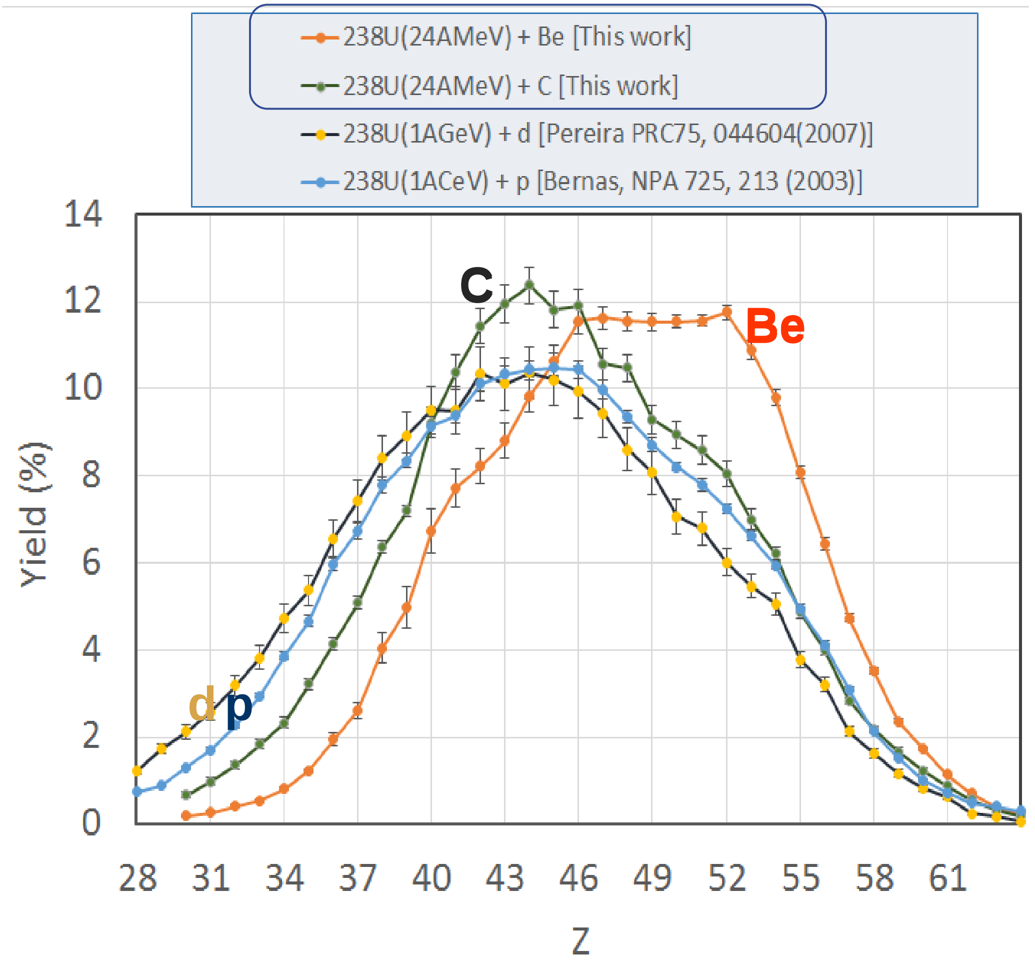
Width of isotopic distributions

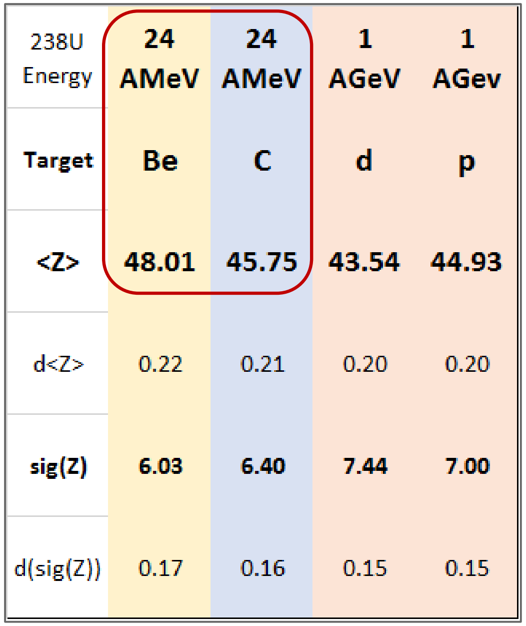


- —●— 238U(24AMeV) + Be [This work]
- —●— 238U(24AMeV) + C [This work]
- —●— 238U(1AGeV) + d [Pereira PRC75, 044604(2007)]
- —●— 238U(1ACeV) + p [Bernas, NPA 725, 213 (2003)]

Atomic number distributions of fission fragments

Preliminary!!!





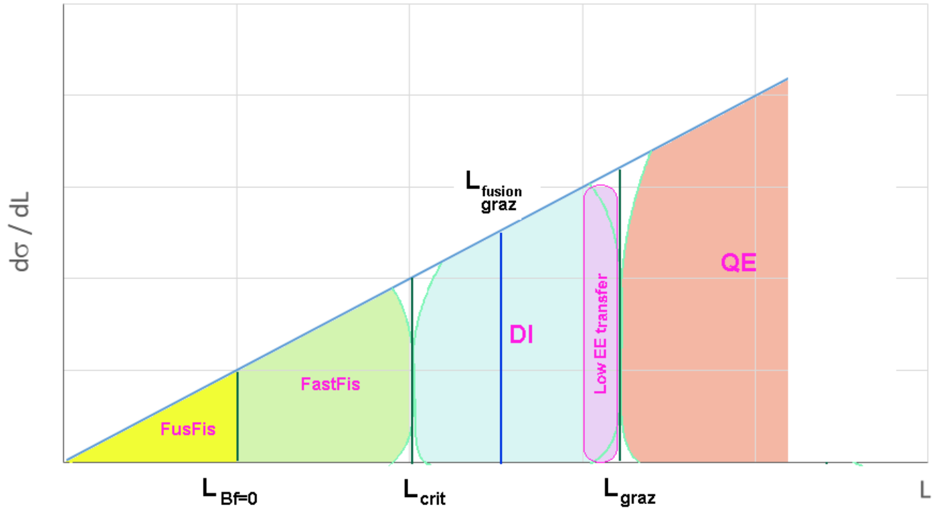
238U Energy	24 AMeV	24 AMeV	1 AGeV	1 AGev
Target	**Be**	**C**	**d**	**p**
<Z>	**48.01**	**45.75**	**43.54**	**44.93**
d<Z>	0.22	0.21	0.20	0.20
sig(Z)	**6.03**	**6.40**	**7.44**	**7.00**
d(sig(Z))	0.17	0.16	0.15	0.15

C & Be cases :

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

Reaction characteristics : ^{238}U beam on light targets

	247Cm				250Cf			
238U beam energy (MeV/u)	24	19	19-24		24	17	17-24	
Target	Be	Be			C	C		Dimension
Fusion barrier (Bass)	43.0				64.2			MeV
Center of ME	209.3	163.2			275.3	202.3		MeV
Excitation energy	202.4	156.3			251.4	178.4		MeV
Fission barrier vanishes at (from Sierk)	67	67			63	63		hbar
L_critical NRV)	71	71			81	81		hbar
L_grazing (from Wilcke)	76.2	66.5			100.7	84.3		hbar
Fusion L-grazing (PACE4)	77.0	67.5			101.8	82.0		hbar
L_max (from Wilcke)	100.2	88.4			132.1	112.6		hbar
L_minimum for Complete fusion	67	66.5			63	63		
Reaction Cross section (Lmax - Wilcke)	3468	3408	3438		3560	3211	3386	mb
Fusion cross section (Bass) - L-grazing	2194	2131	**2163**		2185	2013	**2099**	mb
Complete fusion	1634	2033	**1833**		832	1175	**1004**	mb
Fast-Fission (DIC - subsequent fission)	560	98	**329**		1353	838	**1095**	mb
Above L_grazing (QE)	1274	1277	1276		1375	1198	1287	mb
no quasi-fission for these target at these energies								

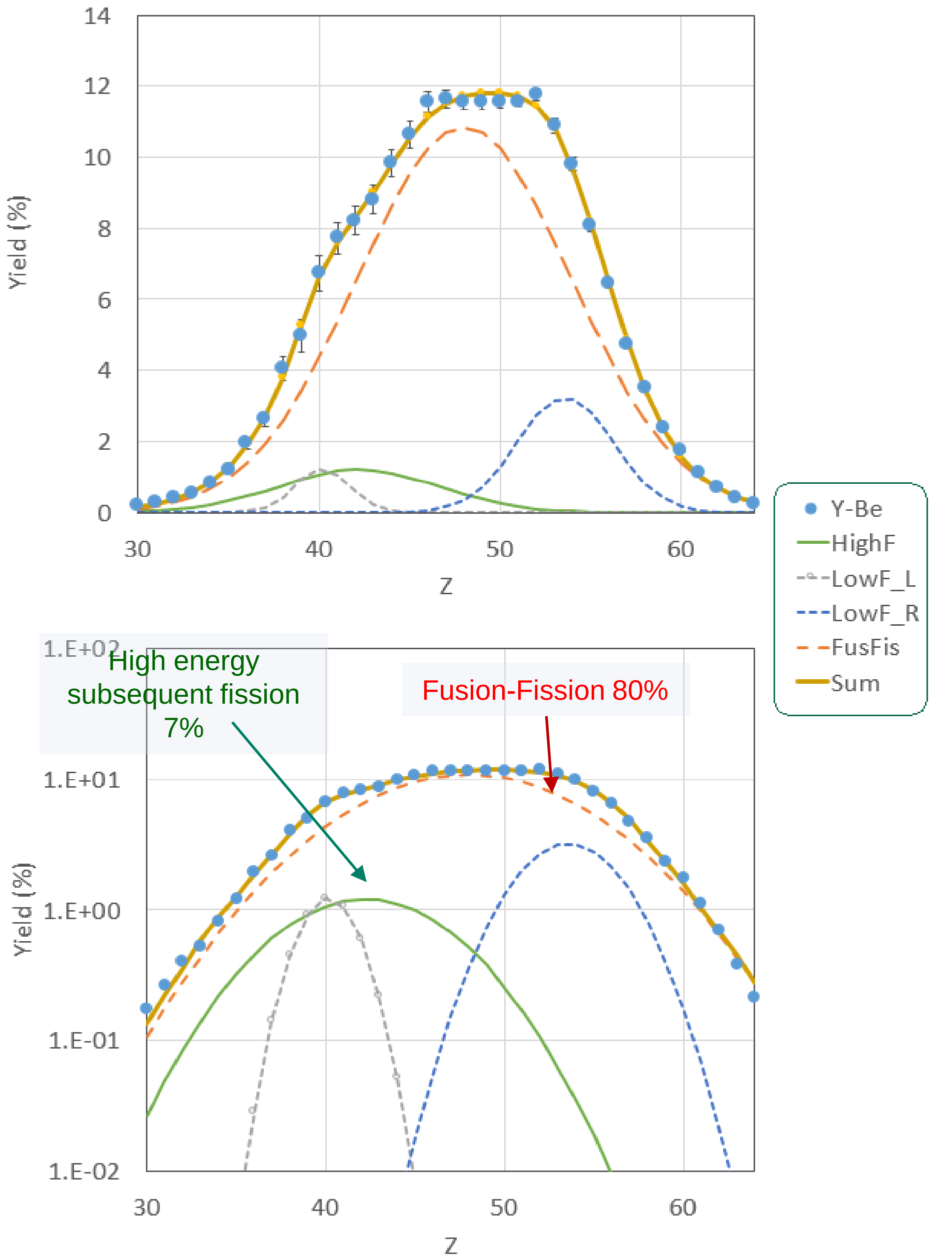


- ❖ For ^{238}U (24 MeV/u) with light targets CoulEx < 10 mb
- ❖ For ^{238}U case : Fast Fission and Deep-Inelastic give High excitation subsequent fission (DIF)
- ❖ Low excitation energy fission (|ΔA| ≤ 1) ~ 100-200 mb

Analysis of contributions

Preliminary!!!

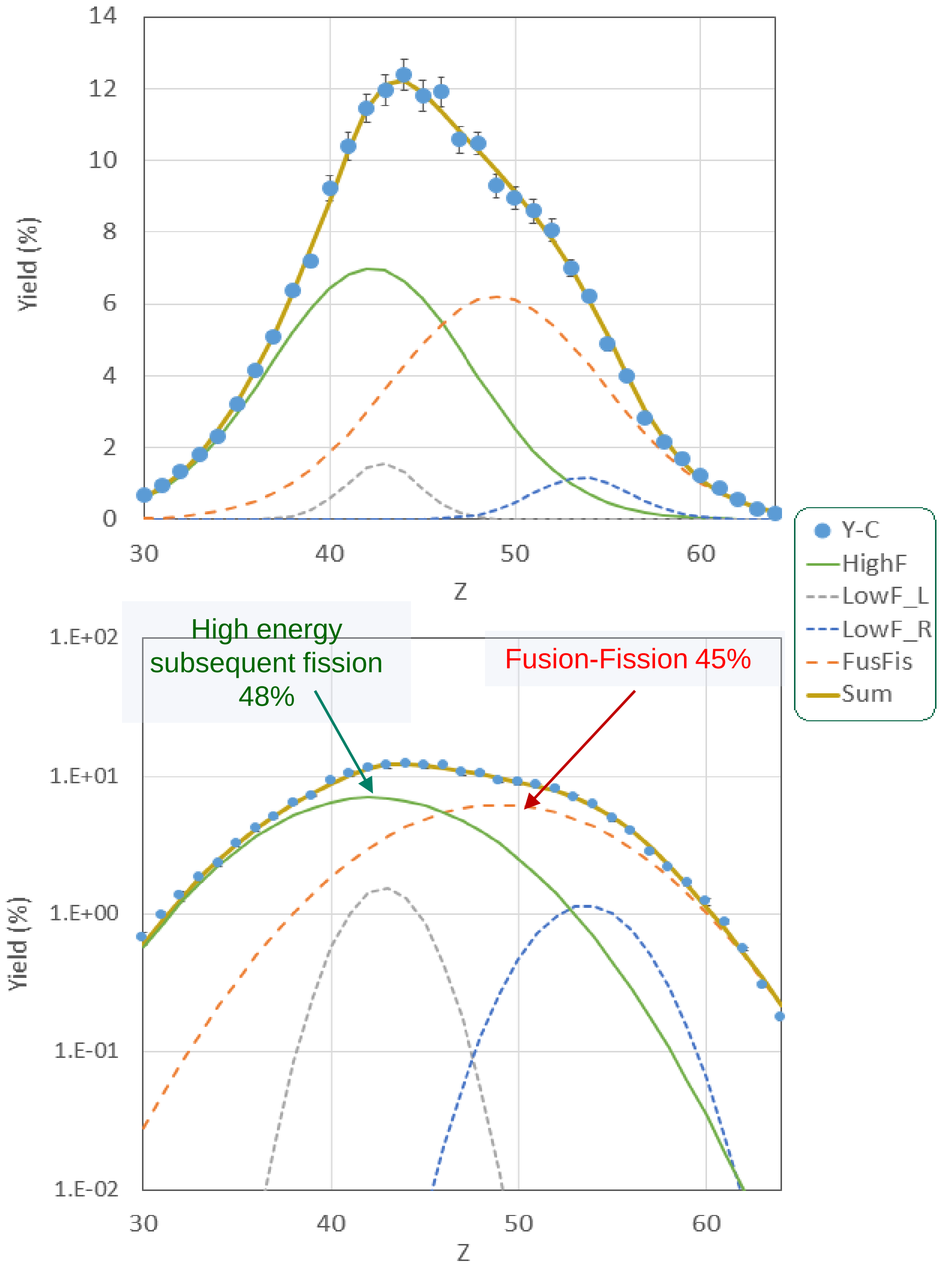
^{238}U (24 MeV/u) + Be (14 mg/cm^2)



High energy subsequent fission 7%

Fusion-Fission 80%

^{238}U (24 MeV/u) + C (15 mg/cm^2)



High energy subsequent fission 48%

Fusion-Fission 45%

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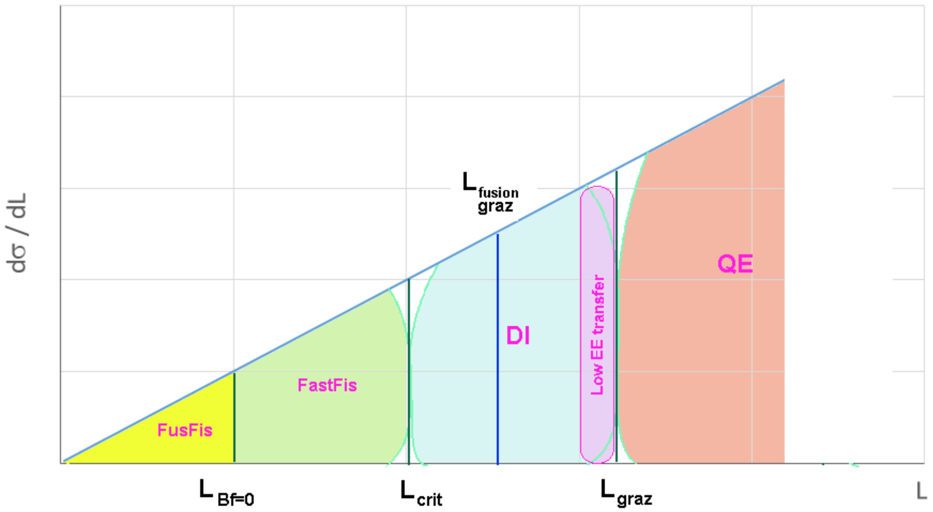
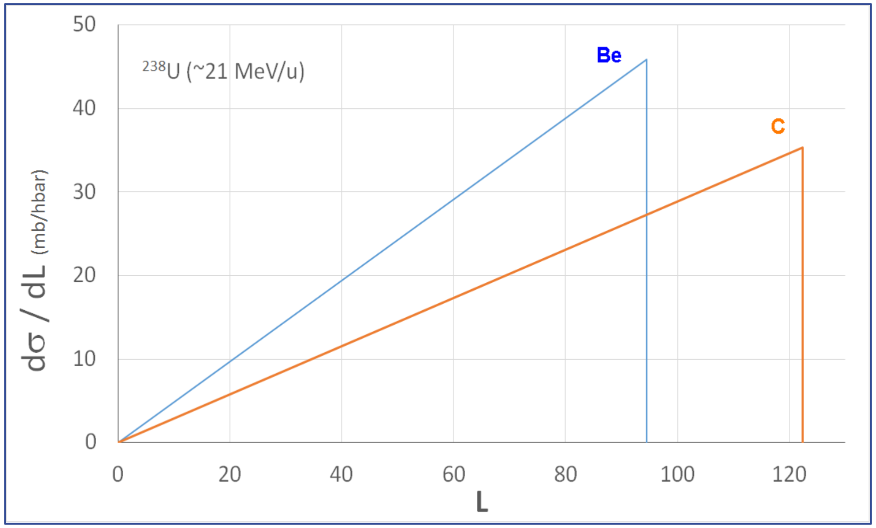
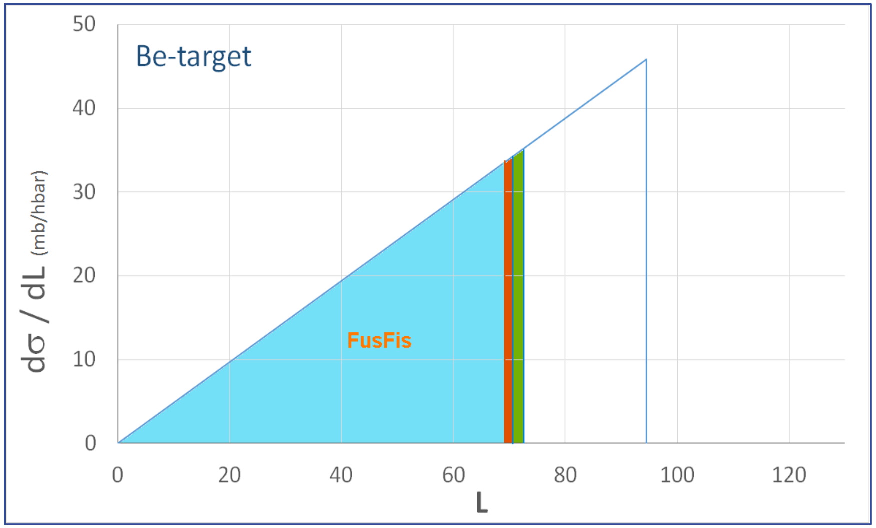
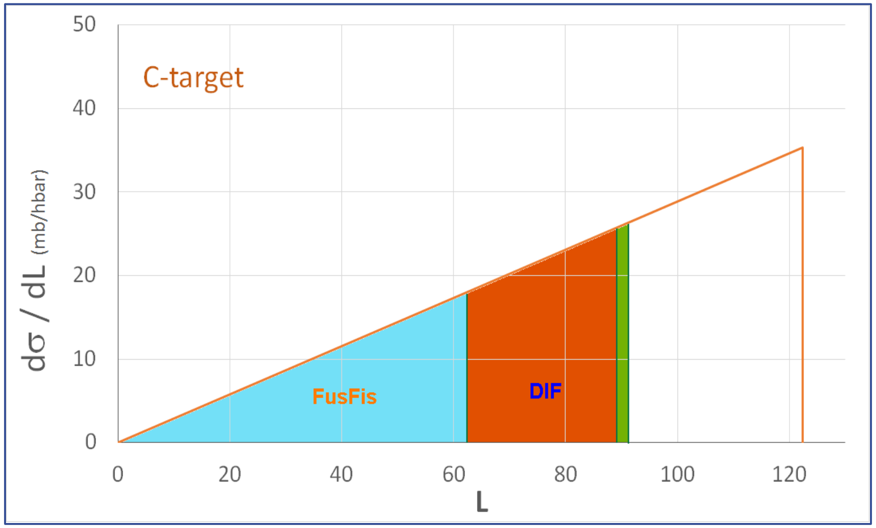


Fission mechanisms with different light targets at 21 MeV/u



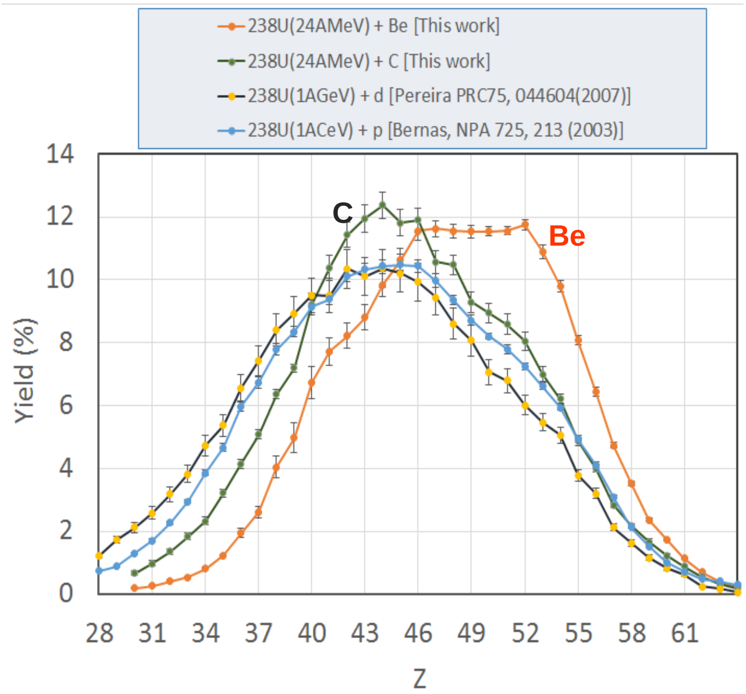


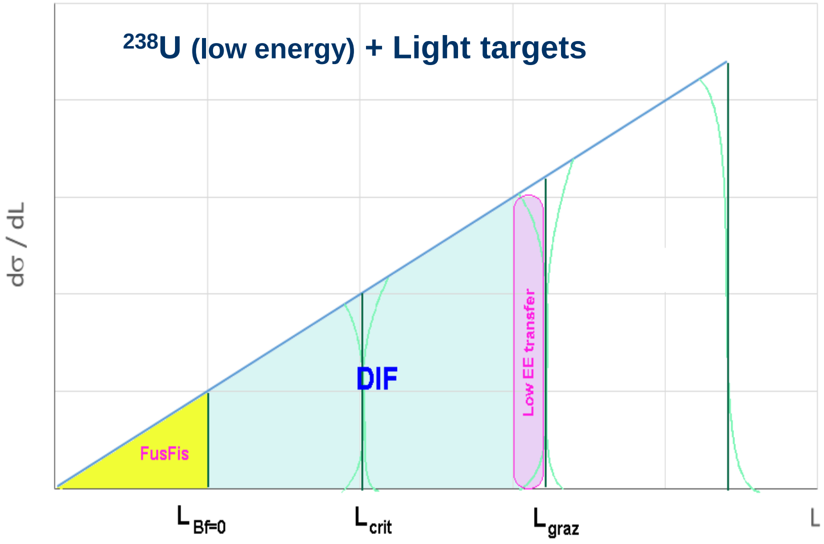


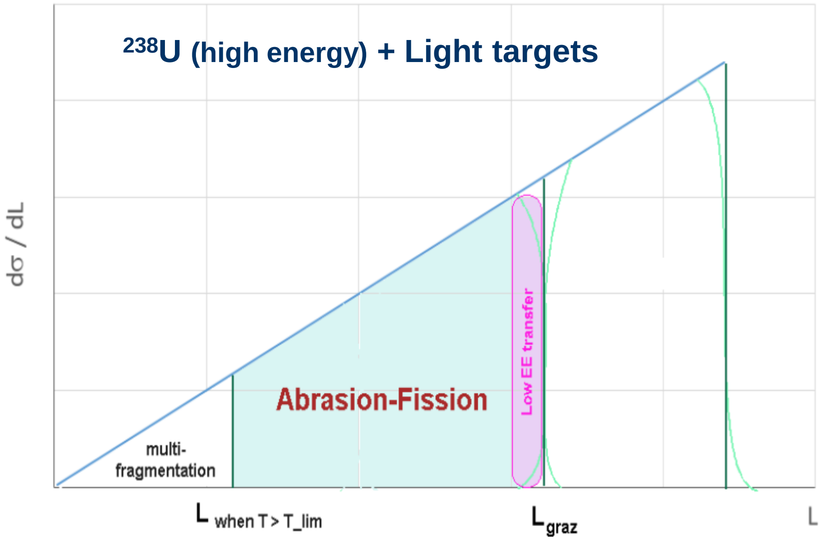
Carbon target.. 50% split… Why?

This is due to difference of moments of inertia between C+U and Be+U just above where fission barrier go to zero

Fission mechanisms on light targets vs. energy







1. No fusion-fission at high energies
2. DIF & AF both high excitation energy fission; no deep inelastic component for AF, “geometrical” cut
3. FF & AF process can be calculated with LISE^{++}

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.

- The identification of fragments was done using the d*E-TKE-Brho-ToF* method. Germanium gamma-detectors were placed in the focal plane near the Si stopping telescope to provide an independent verification of the isotope identification via isomer tagging.

- The experiment demonstrated excellent resolution, in *Z, A*, and *q*.

- The results demonstrate that a fragment separator can be used to produce radioactive beams using fusion-fission reactions in inverse kinematics, 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. Mass, atomic number and charge-state distributions are reported for the two reactions.

- 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.

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