Resent study of fission in inverse kinematics

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Heavy neutron-rich isotope beam production

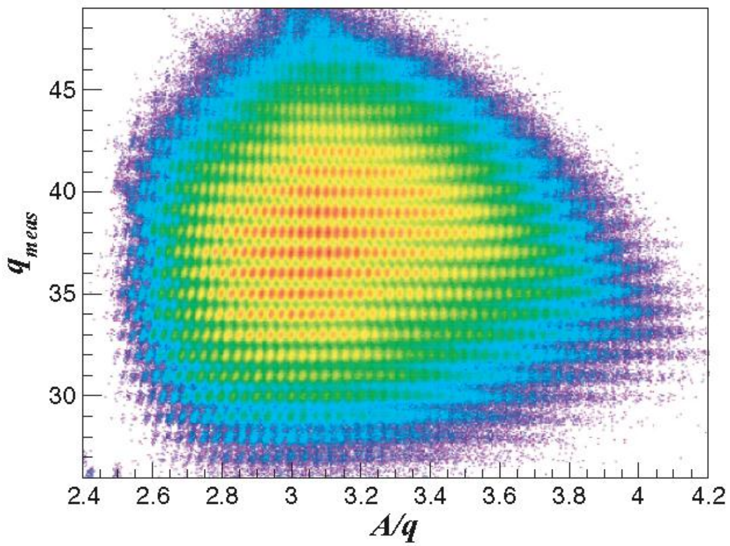
- Nowadays, fission is widely used to produce rare neutron-rich nuclei. :
  - * in-flight fission (abrasion-fission, Coulomb fission)
  - * spallation reactions (ISOL technique) at thick Uranium targets

- Important issue of these both techniques is the inability 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 (Uranium)

Inverse kinematics of low energy reactions?

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



- VAMOS experiments 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].

- 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>.

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

How to produce heavy fusion-fission beams with separators ?

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

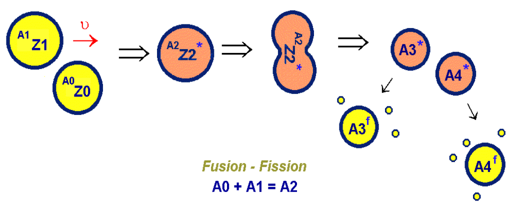
A model [1] for fast calculations of fusion–fission fragment cross sections has been developed in LISE++ [2] based on already existent analytical solutions: fusion–evaporation and fission fragment production models.

[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).

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)*



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

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

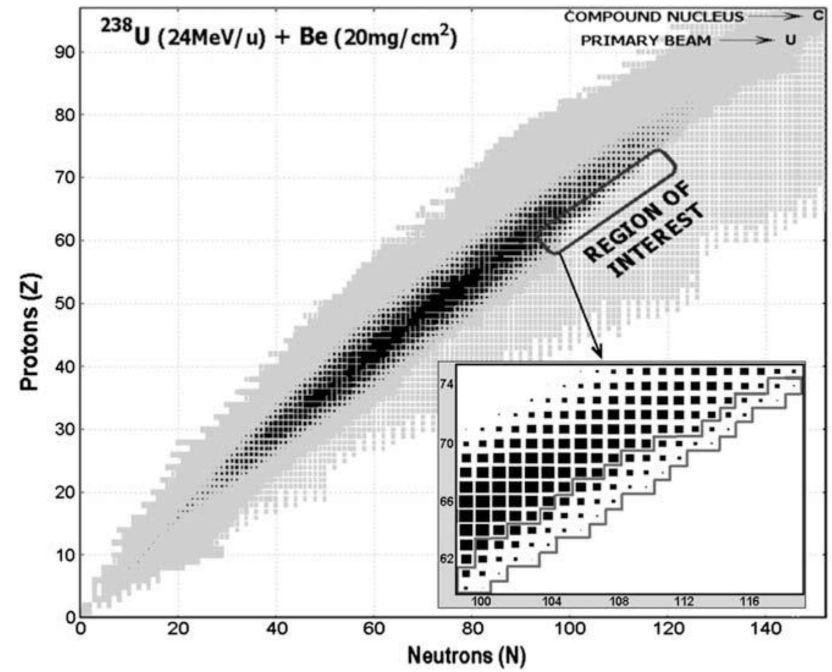


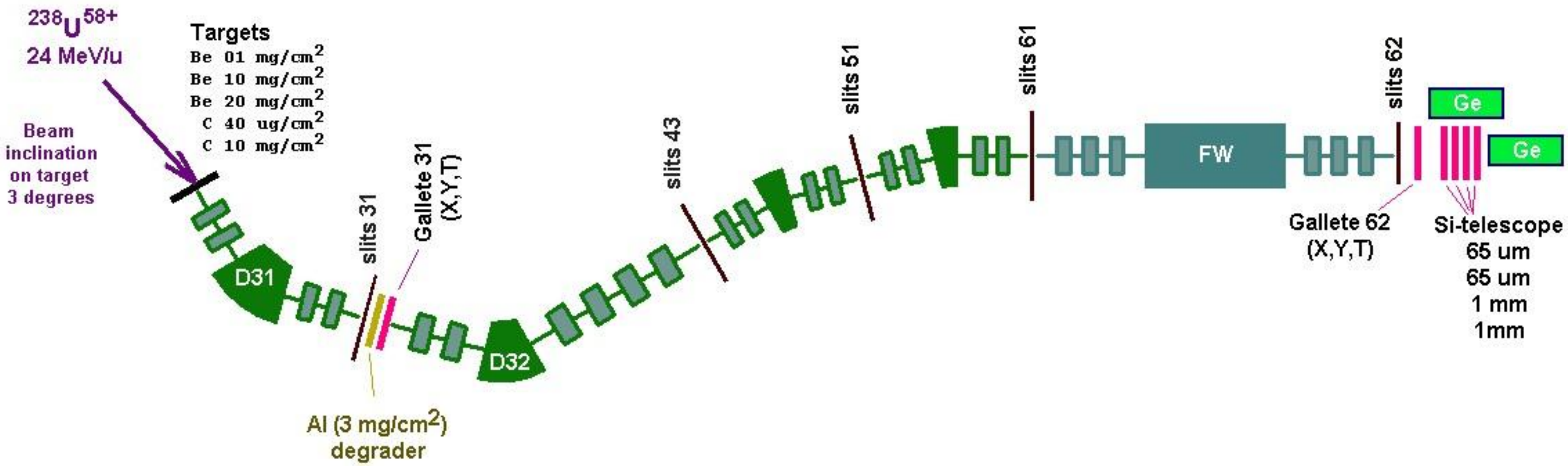
Fig. Two-dimensional yield plot for fragments produced in the ^{238}U (20 MeV/u,1pnA) + D (12 mg/cm^2) reaction and separated by SISSI + Alpha

Open Questions:

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

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

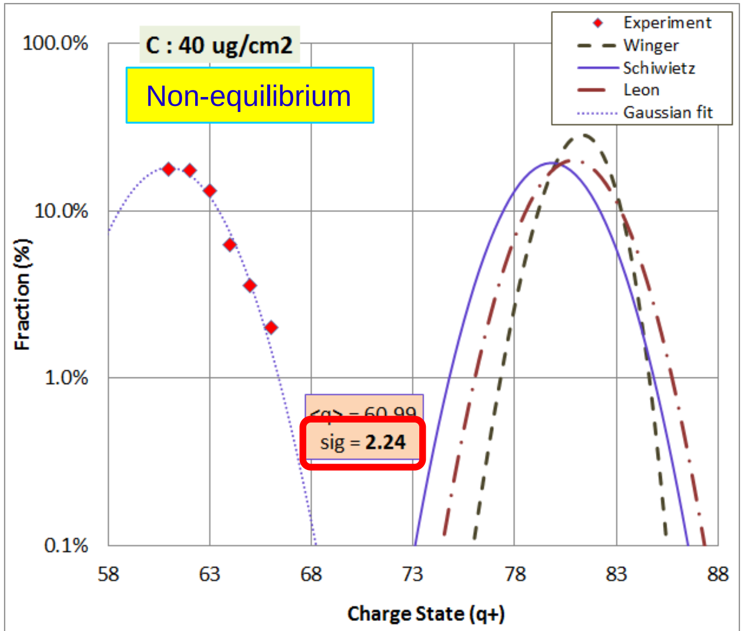
Experimental set-up

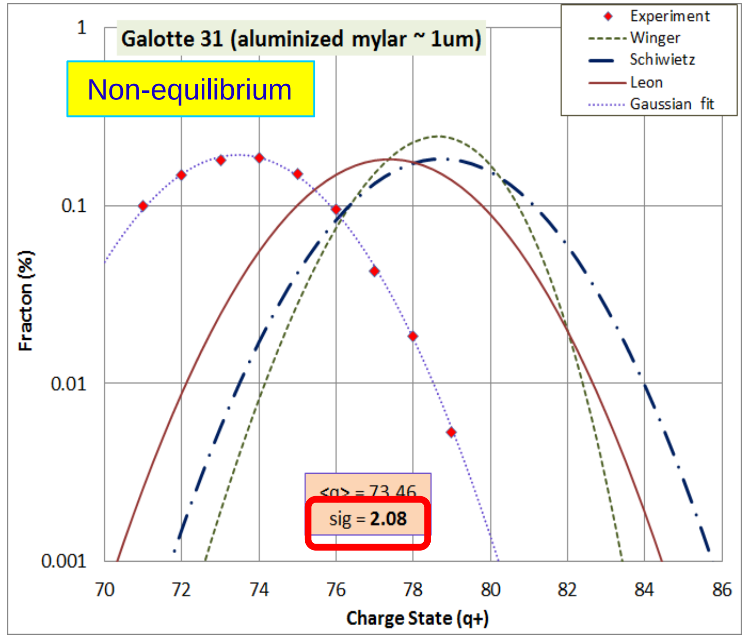


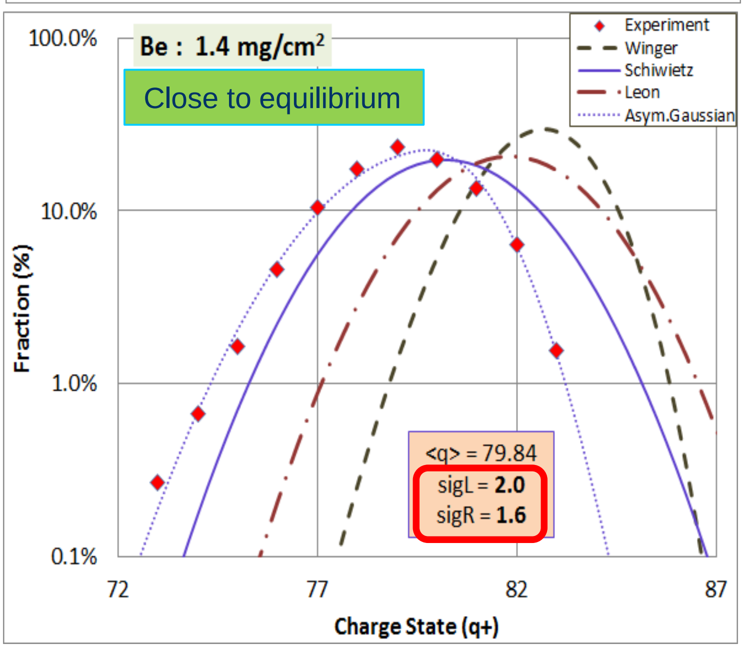
- A ^{238}U beam at 24 MeV/u with a typical intensity of 10^9 pps, was used to irradiate a series of beryllium targets and a carbon target.
- The beam was incident at an angle of 3° in order not to overwhelm the detectors with the beam charge states.
- Fragments were detected in a Silicon telescope at 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.

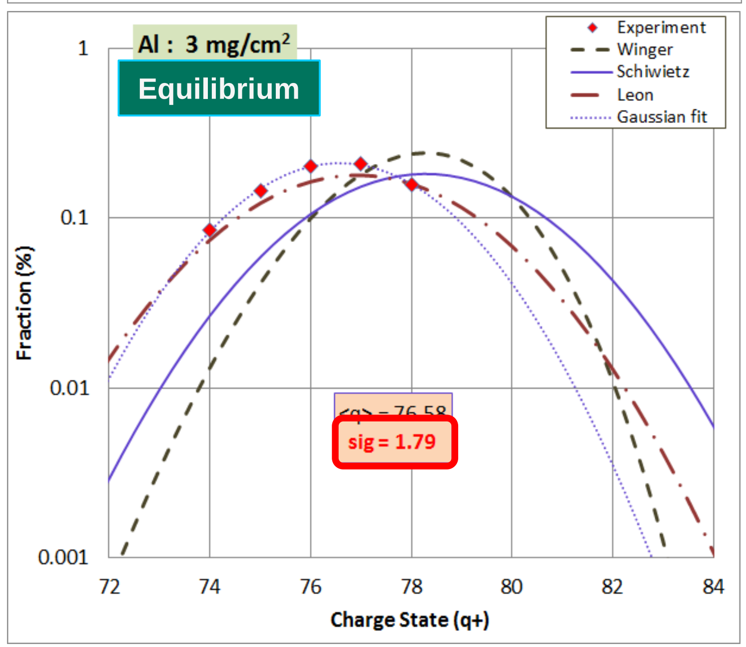
^{238}U @ 24 A MeV + ^{9}Be -> ^{247}Cm E*= 150-200 MeV
^{238}U @ 24 A MeV + ^{12}C -> ^{250}Cf E*= 180-250 MeV

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





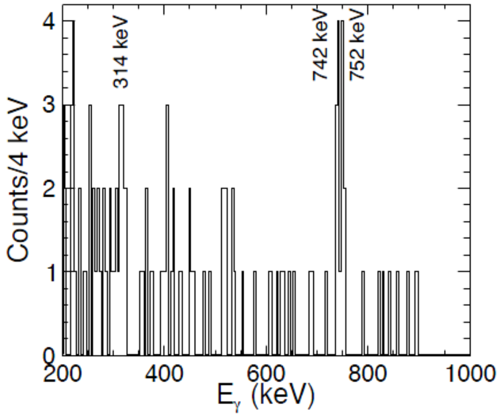




- What charge state model should be used for fragment transmission estimation?
- Based on sigma values and peak positions it is possible to conclude about reaching equilibrium thickness
- The best predictions are given for beam and fragments by A.Leon et al., AD & ND Tables 69 (1998) 217

This work was done also at GANIL

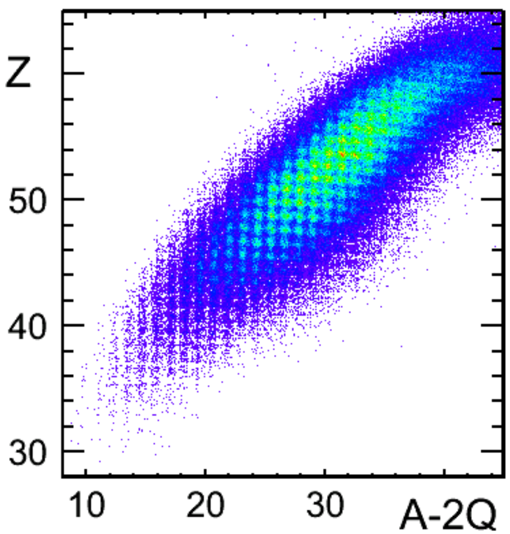
Particle Identification

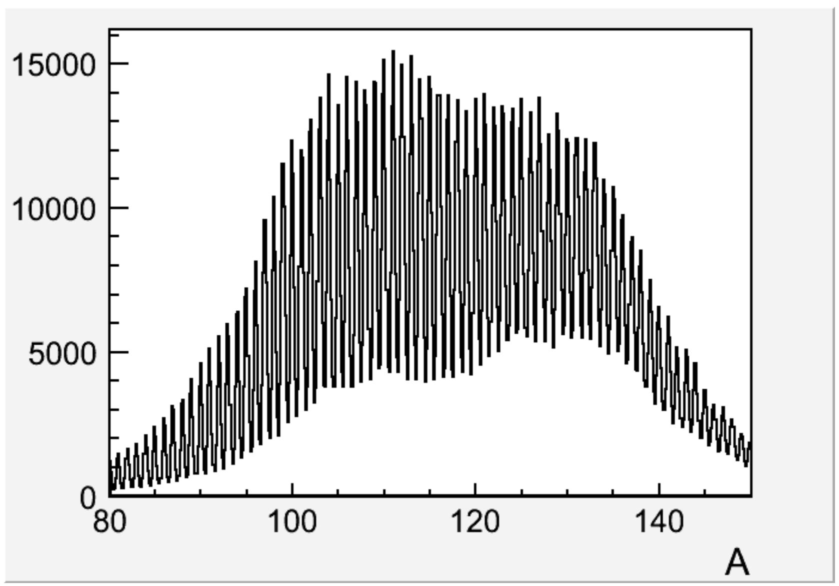


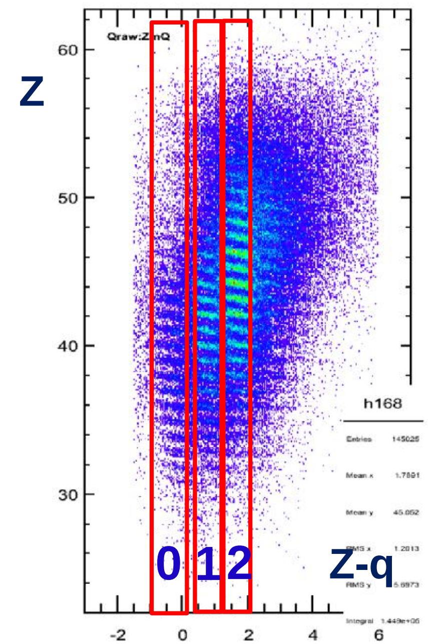
Gamma-ray spectrum observed in coincidence with ^{128}Te. The characteristic gamma lines of 314, 742 and 752 keV sign the decay of the isomeric state of $T_{\frac{1}{2}} = 370$ ns

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

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:	$q = 3.33 \times 10^{-3} \frac{TKE \times \beta\gamma}{B\rho(\gamma - 1)}$



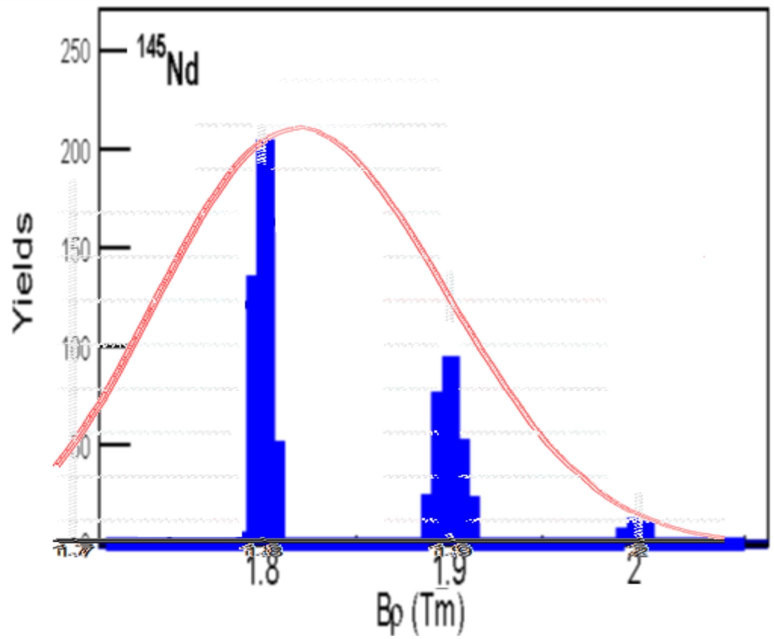




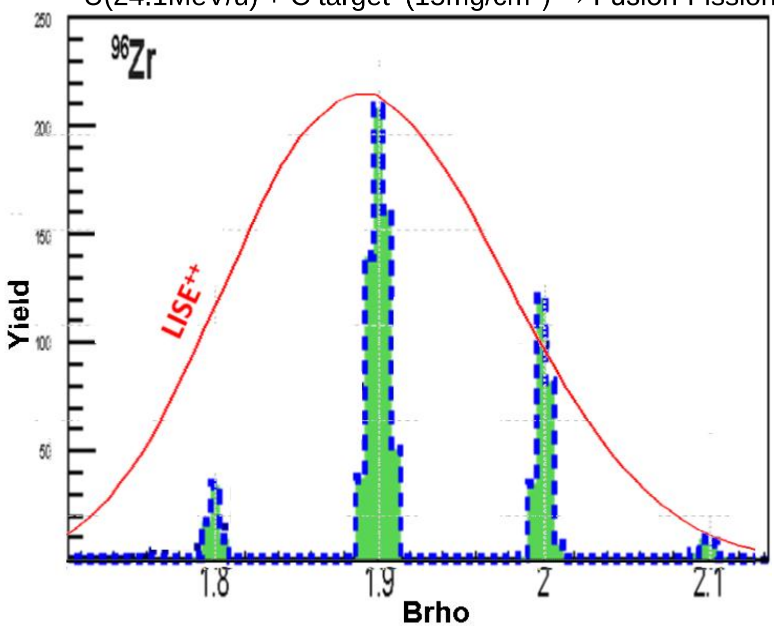
Transmission calculations

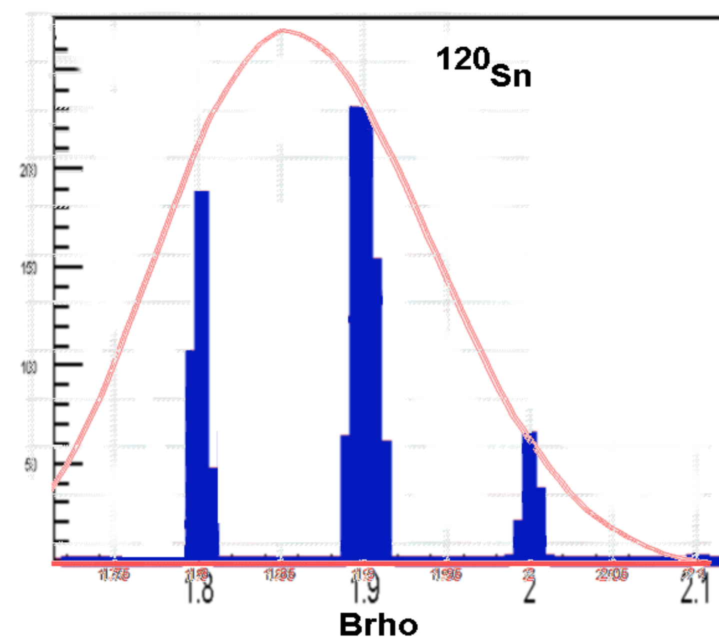
- The LISE^{++} code has been used for transmission calculations
- A.Leon's charge state and F.Hubert 's energy loss models were used
- Data with 15 mg/cm^2 Be & C targets have been used in analysis
- In the analysis the targets have been divided on 5 slices, results have been summed.
  It has been done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

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

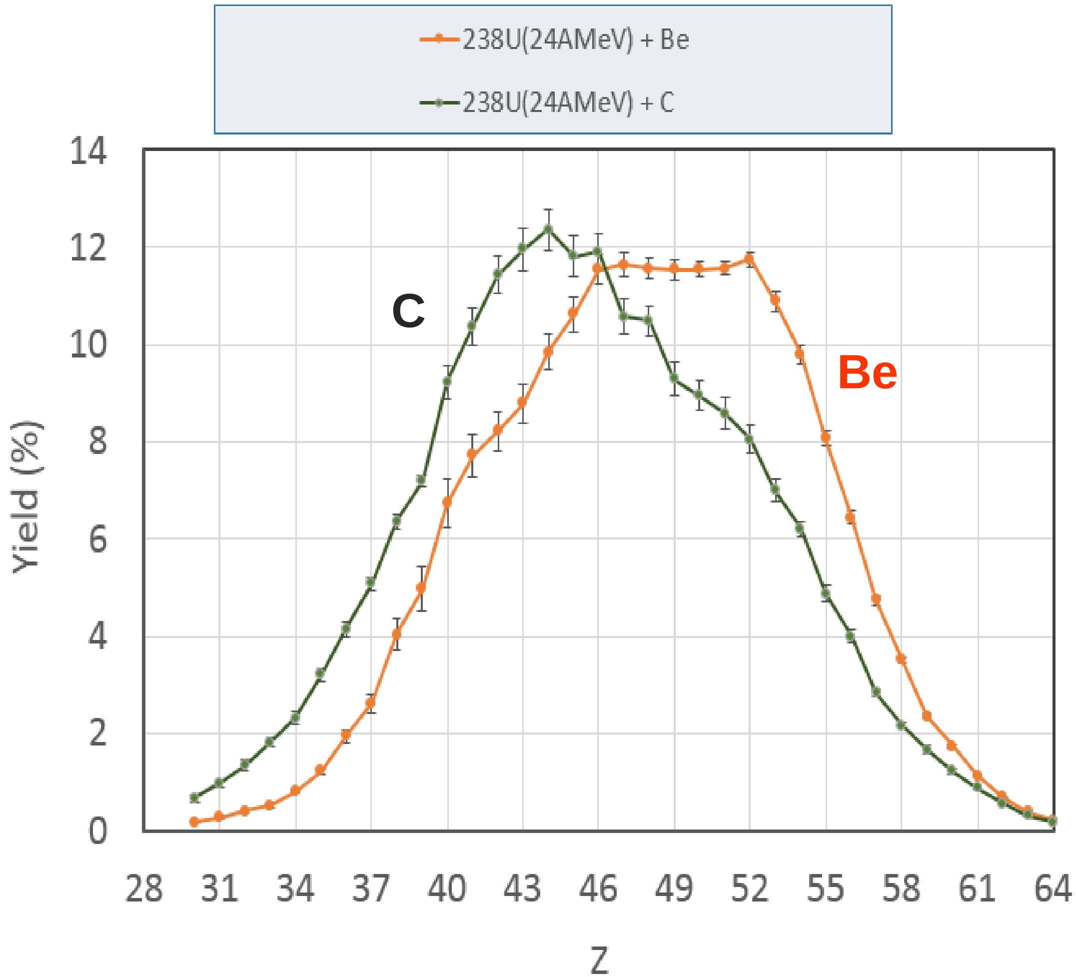


^{238}U(24.1MeV/u) + C target (15mg/cm^2) → Fusion-Fission





Elemental distributions of fission fragments



^{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^{++}

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

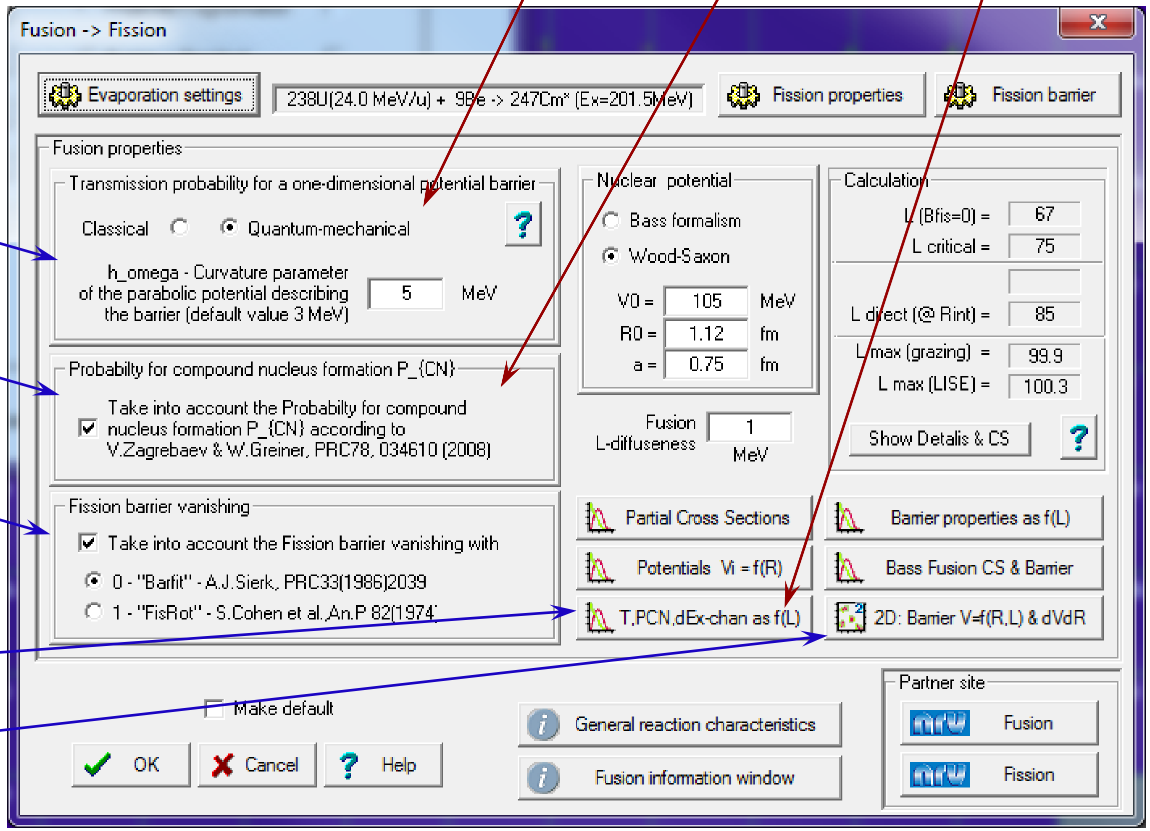
Fusion or Quasi-Elastic?

Compound or Quasi-Fission?

Capture or Fast Fission?

Fusion-Evaporation or Fusion-Fission?

Capture or Deep-Inelastic?

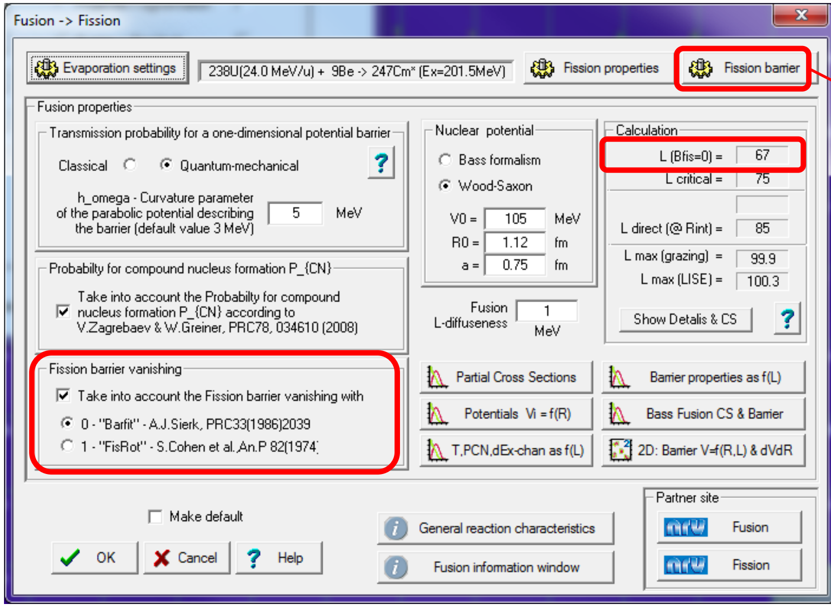


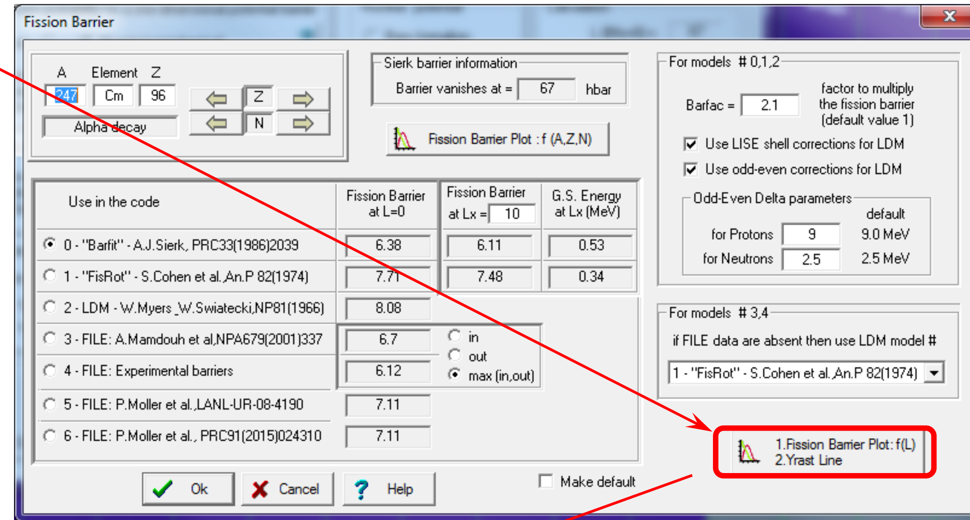
A recent update of low-energy reaction mechanism was performed to simulate the dependence of different reaction channels from angular momentum and qualitatively estimate production cross sections in the case of Fusion-Fission and Fusion- Residue.

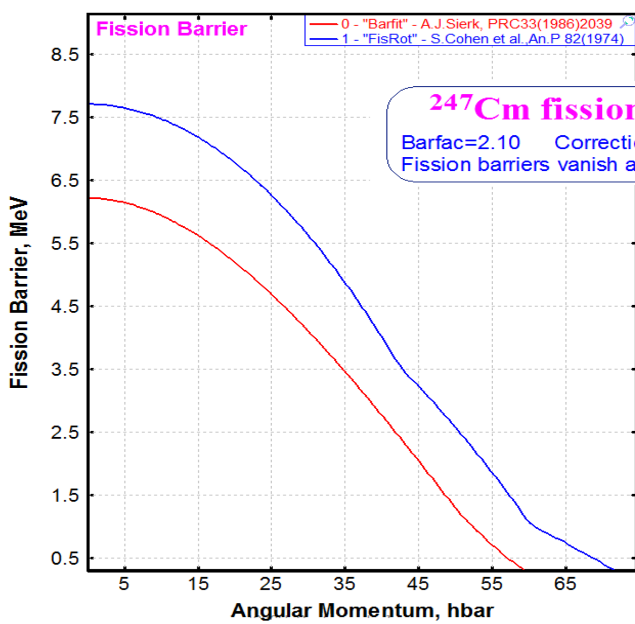
Projectile Fragmentation and Abrasion-Fission are dominated reaction mechanisms in LISE^{++} for rare beam production, where we are developing our own models

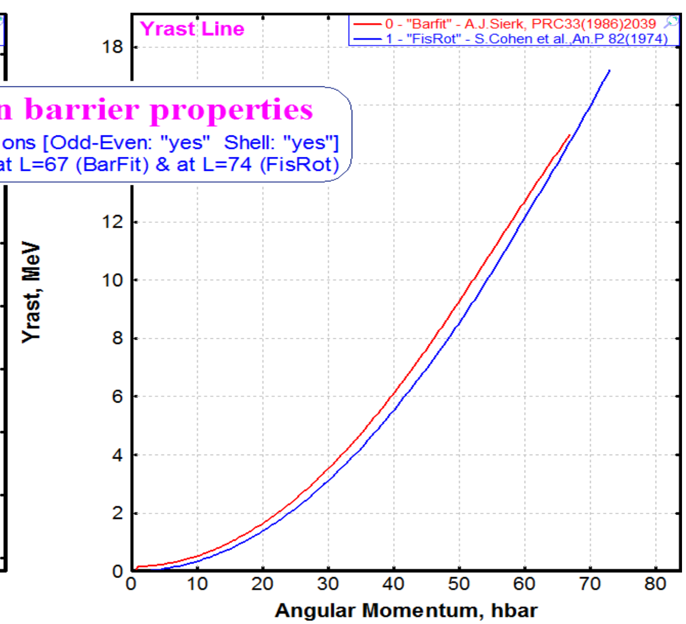
Do not hesitate to use Low-Energy reaction computing centers as NRV for more sophisticated solutions with Channel Coupling, Langevin equations and so on

Fission Barrier Vanishing as f(L)







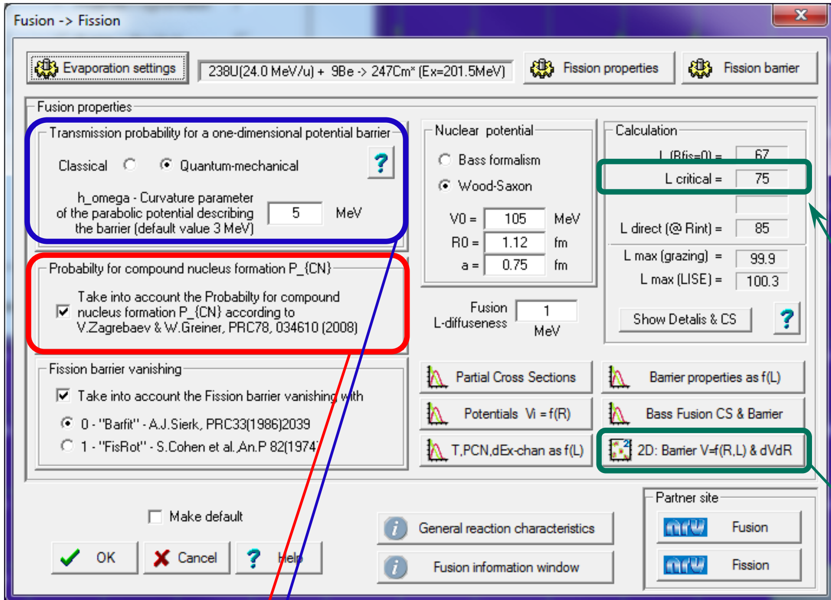


^{247}Cm fission barrier properties

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

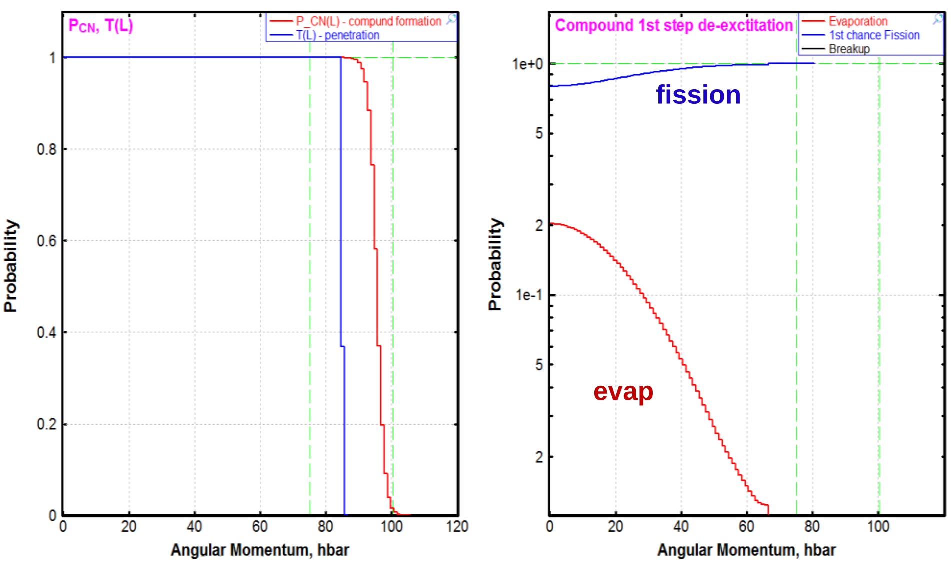
Fission barriers vanish at L=67 (BarFit) & at L=74 (FisRot)

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



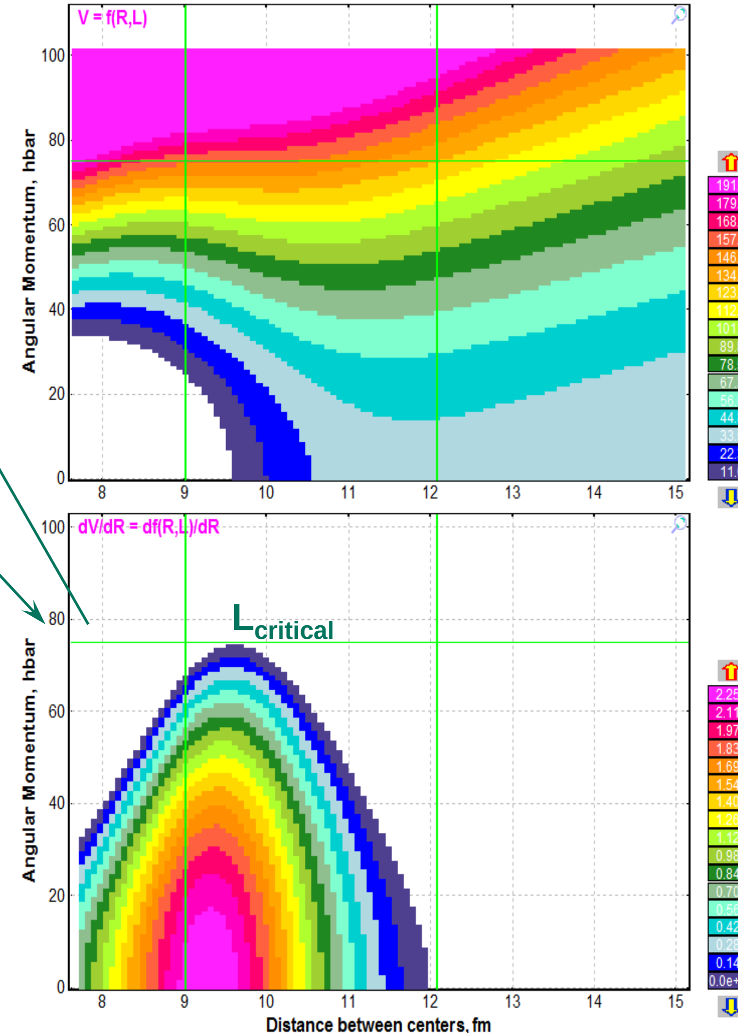
Probabilities as f (L)

^{238}U(24.0MeV/u) + ^{9}Be -> ^{247}Cm* (E_{CM}=208.3 MeV); h_omega=5.0
L_{crit}=75; L_{max}^{Graz}=99.9; L_{max}^{LISE}=100.3; Nuclear potential: WoodSaxon
Vertical lines correspond to $L_{critical}$ & $L_{maximum}$

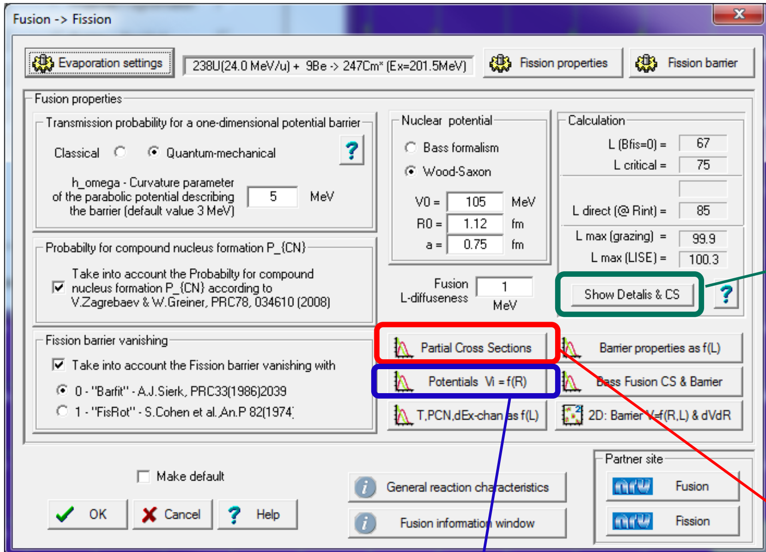


2D Potential plots as f(R,L) & df(R,L)/dR

^{238}U(24.0 MeV/u) + ^{9}Be -> ^{247}Cm* (E_{CM}=208.3 MeV)
L_{crit}=75; L_{max}^{Graz}=99.9; L_{max}^{LISE}=100.3; Nuclear potential: WoodSaxon; WS params: 105.0,1.12,0.75
Vertical lines correspond to (C_p + C_t) and $R_{interaction}$, Horizontal line to $L_{critical}$



Potential energy and Partial cross sections

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Cross sections (mb)

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

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

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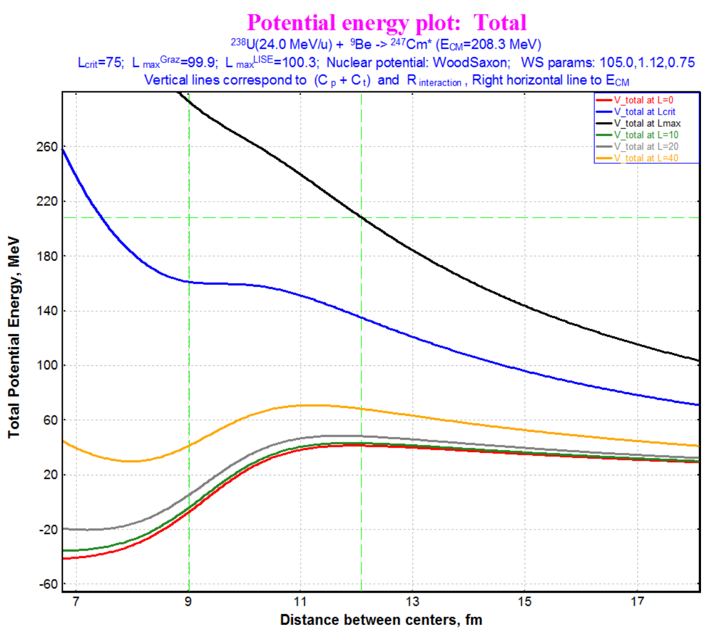
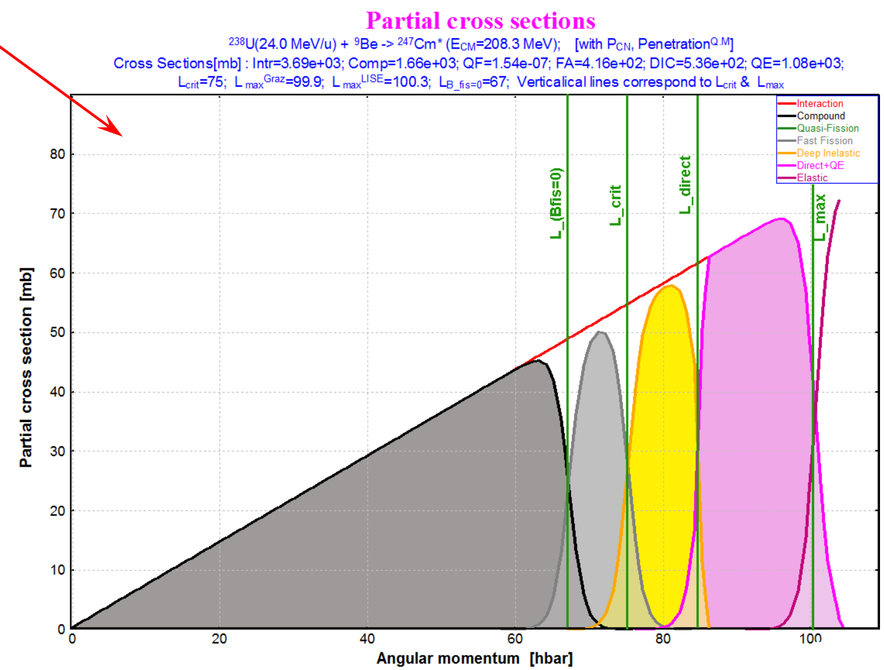
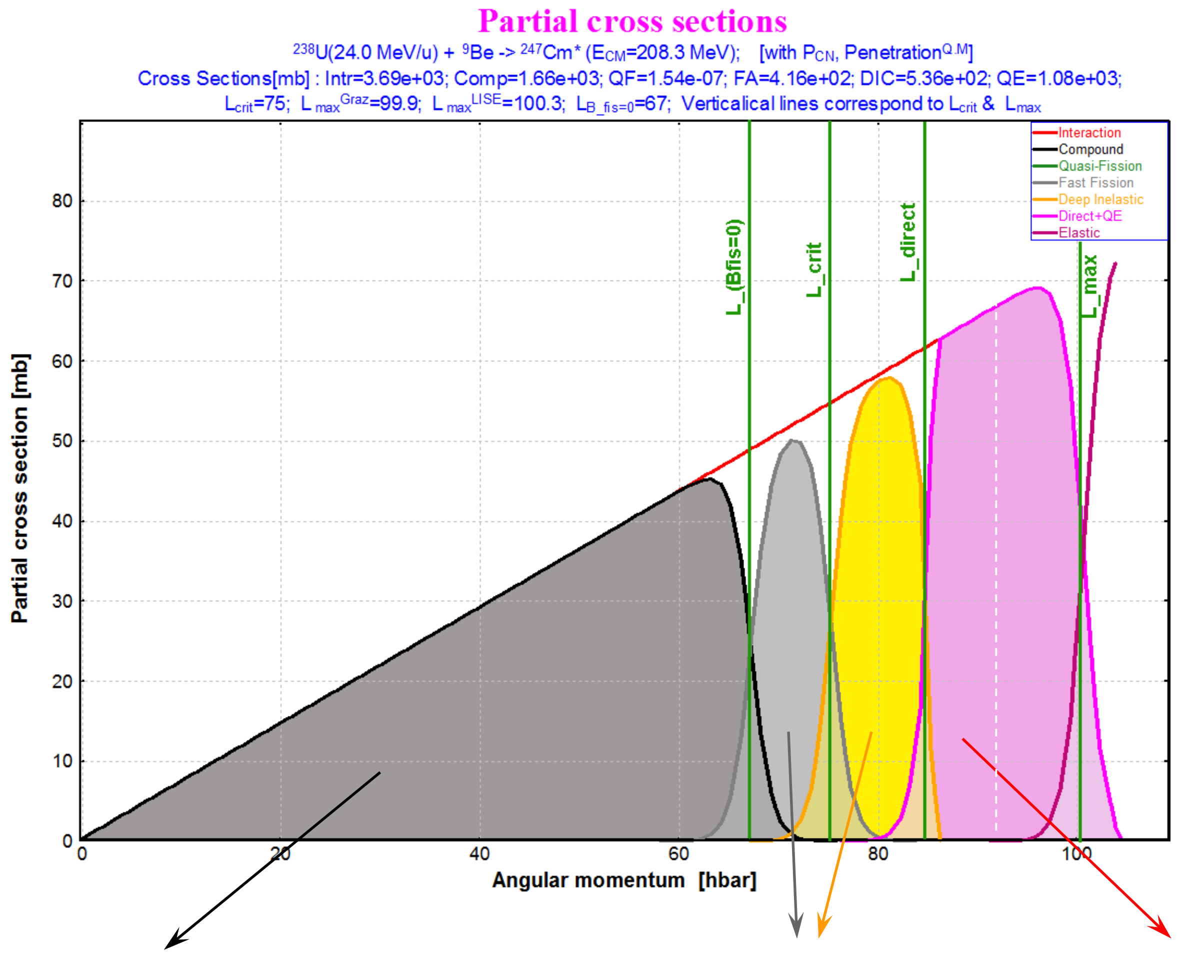




Output channels in the e547 experiment : ^{238}U (24 MeV/u)

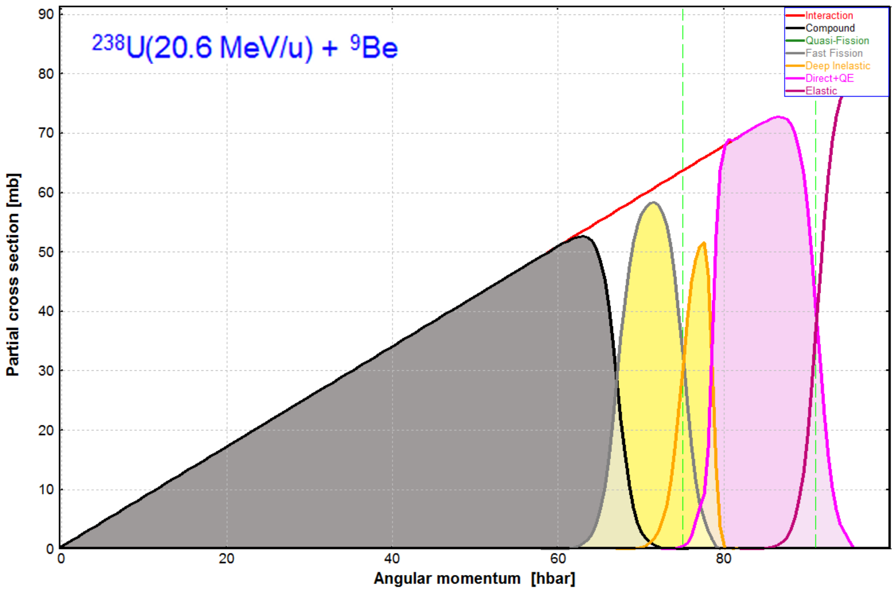


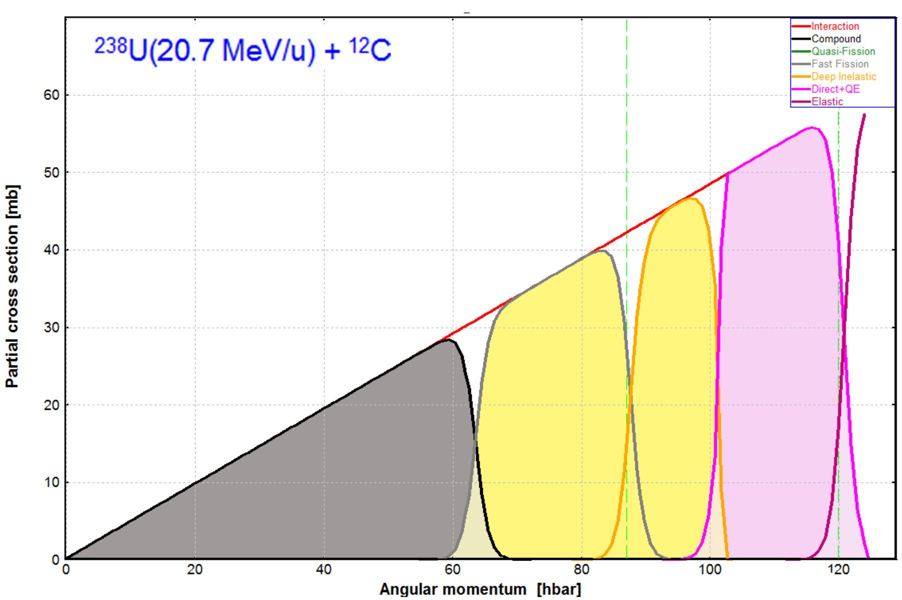
Compound fission ~100%
Fissile Z = 96
High Excitation Energy

Sequential fission after DIC
Fissile Z < 92
High Excitation Energy

Partially go to fission
Fissile Z~92
Low Excitation Energy

e547 experiment : Be vs. C targets

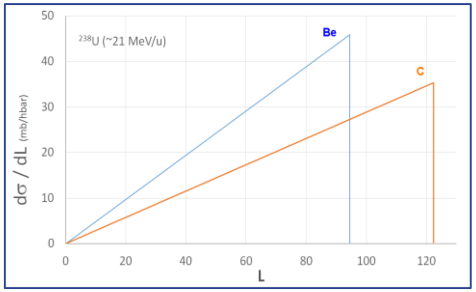




average for 17-24 MeV/u range

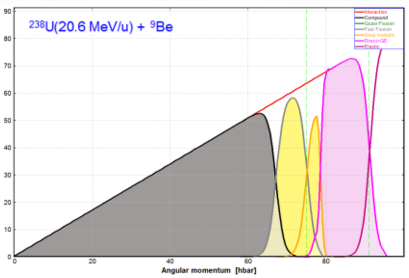
Fission Barrier Vanishing	Reactions	Targets: Be	Targets: C
Sierk	DIC+FA	19%	42%
	Fusion-Fission	56%	29%
	QE	25%	29%
Cohen	DIC+FA	8%	29%
	Fusion-Fission	66%	41%
	QE	25%	29%

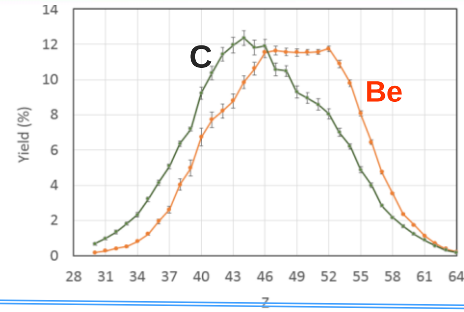
Momentum (hbar)	Be	C
L (Bfis=0)	67	63
L critical	75	87
L direct @ Rint	79 (12)	101 (38)
L max (grazing)	90.5	118.9
L max (LISE)	91.0	119.5



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

e547 experiment: results interpretation





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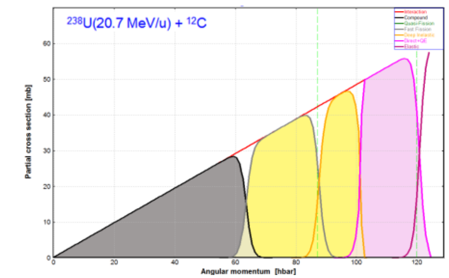
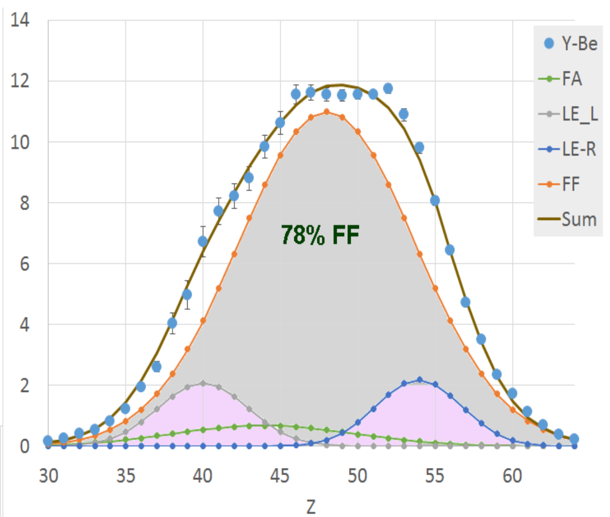
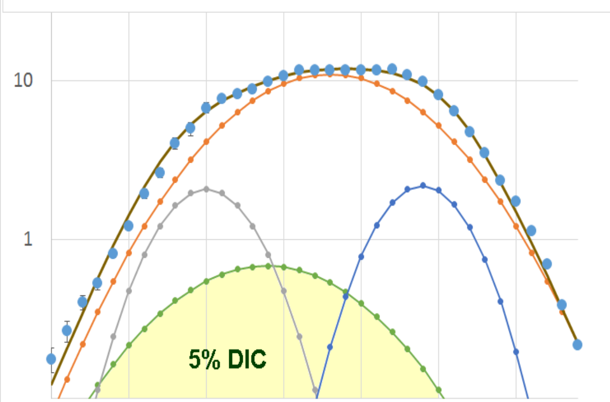
QE-channel partially goes to Low-excitation fission

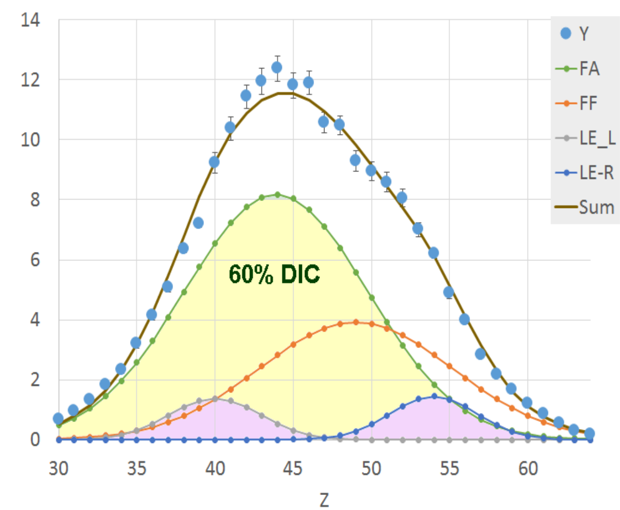


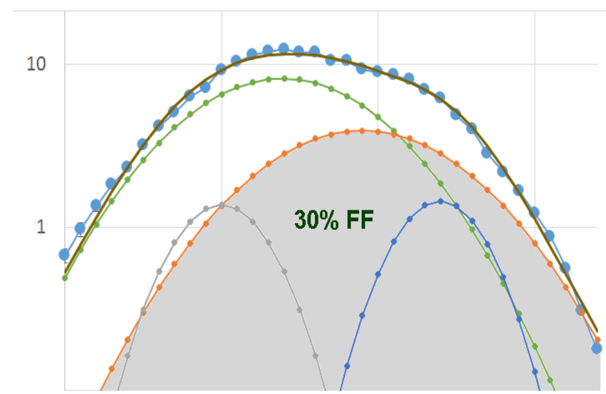
Be-target





C-target





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

Still under analysis … and again transmission….

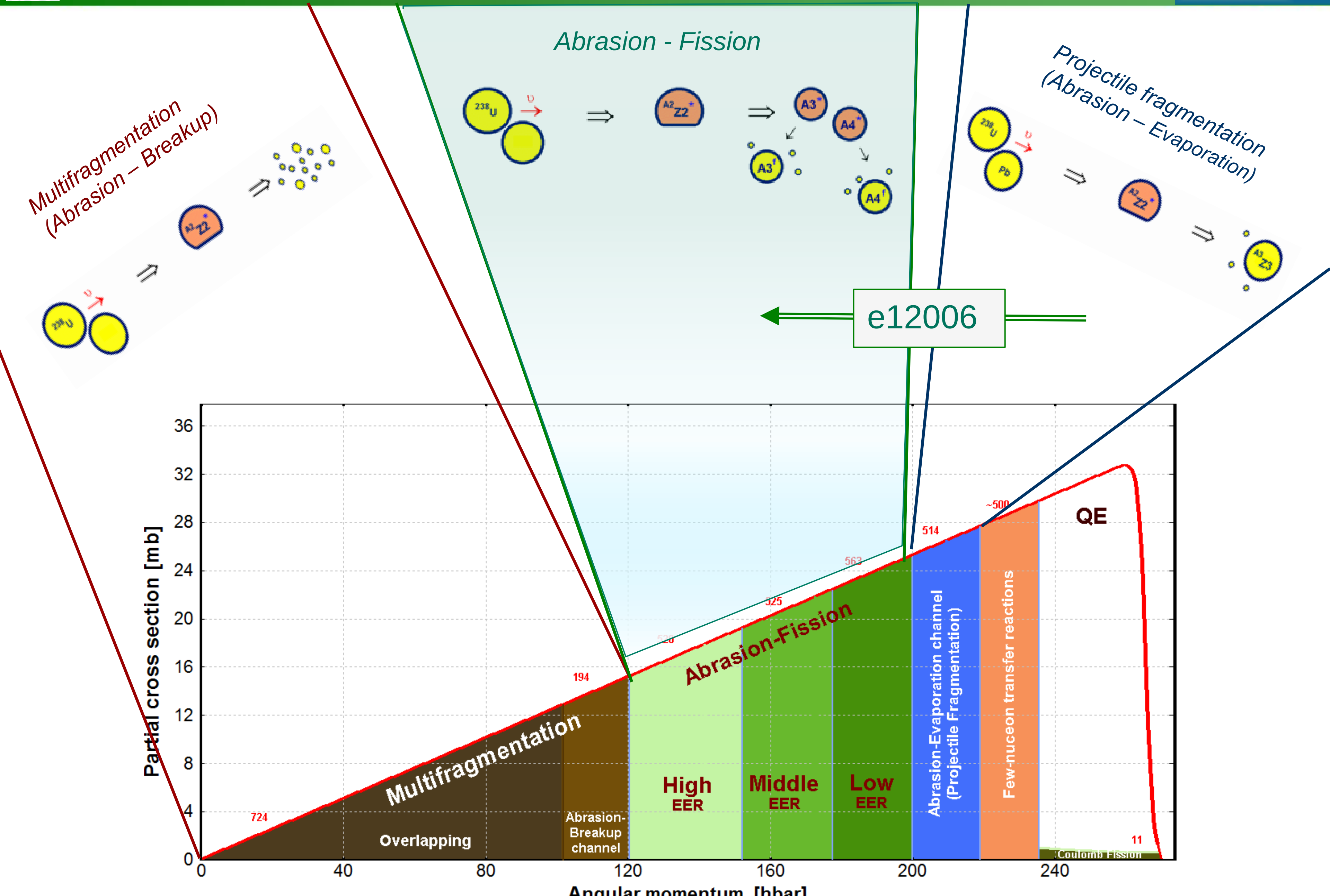
Main reaction channels for ^{238}U (20 MeV/u) on Be & C targets as function of angular momentum

	L (B_{fis}=0)	L critical	L direct	L max
L-definition	Fission barrier vanishes	Potential energy pocket vanishes	Corresponds to the interaction radius (max. s-wave barrier position)	Corresponds to the distance of minimum approach at grazing angle
Be-target	67	75	78	89.2
C-target	63	87	99	117.1
Reaction from previous L up to current L	Complete Fusion-Fission	Fast Fission with HE sequential fission	Deep-Inelastic Collisions with HE sequential fission	Some part of Direct reactions go to sequential LE fission
Z of Fissile nucleus	Z of compound for targets Be: 96; C: 98	Below projectile 85 < Z < 92		Around Z-projectile (92)
Fissile nucleus velocity	Compound velocity	Between compound and projectile velocities		Close to Projectile velocity
Excitation Energy of Fissile nucleus	C: 204.3 MeV Be: 166.6 MeV	Very broad energy range (30 MeV– Compound nucleus excitation energy)		Low energy range : 6-30 MeV
Z-distribution of fission fragments	1 peak : Broad for Be: <Z>=48 C: <Z>=49	broad distribution with peak @ Z~42-45		Two narrow peaks with Z around 38-40 and 52-54
Reaction channel designation	FF (fusion-fission)	IF (incomplete fusion-fission, inelastic sequential fission)		DF (sequential fission after direct reactions)
FOR INTERNAL INFORMATION				
Yield Experimental (preliminary)				
Be-target	79.6%	15.4%		10%
C-target	30%	60%		10%
Fission cross sections [mb] calculated by LISE++				
Be-target	1990	494	153	874
C-target	1020	913	542	1013

Quasi-Fission -> 0 for these light targets

- Next transmission analysis should be done, even reaction channel contributions are expected to be close the same
- Previous analysis : yields -> cross sections -> contribution factors
- Next analysis : yields & transmission -> factors -> cross sections

^{238}U(80MeV/u) + C reaction scheme



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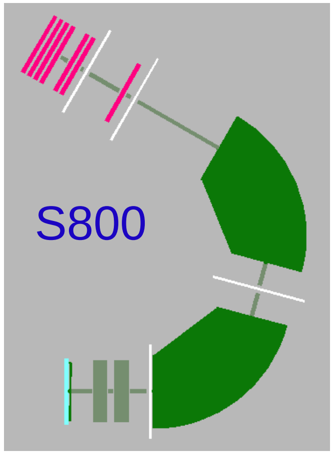
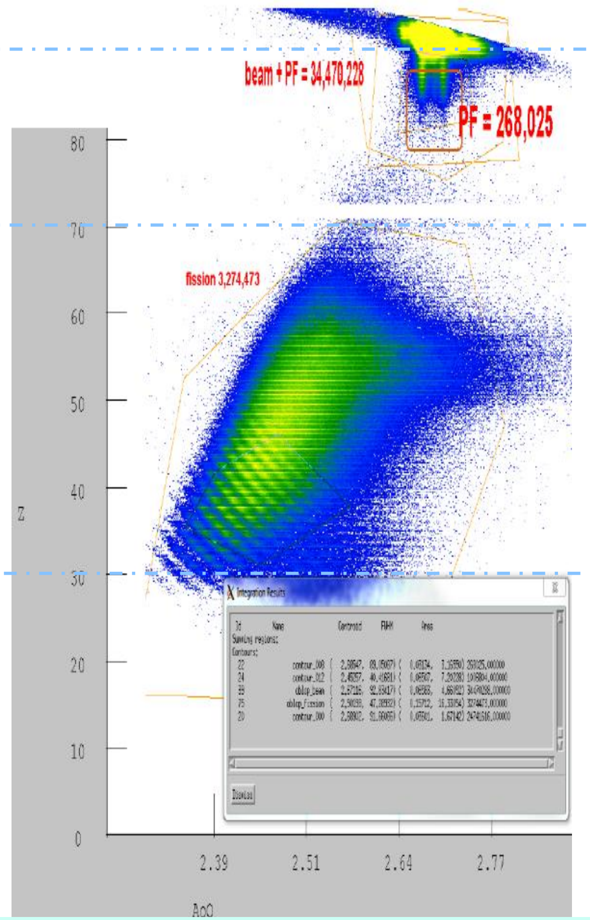


Diamond target:
ToF start

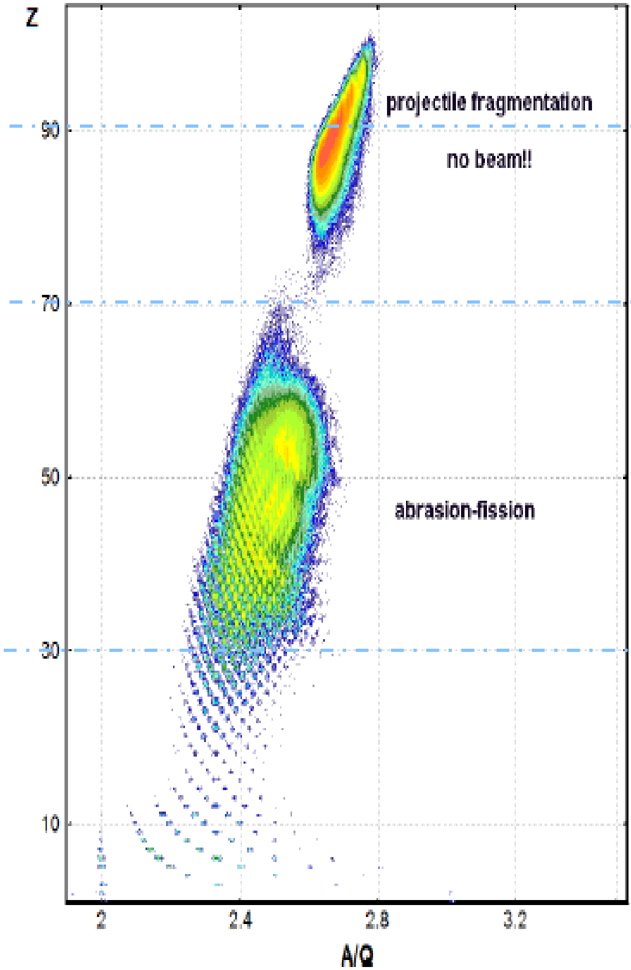
Experiment

No *A,Z,q* separation

No *q* separation

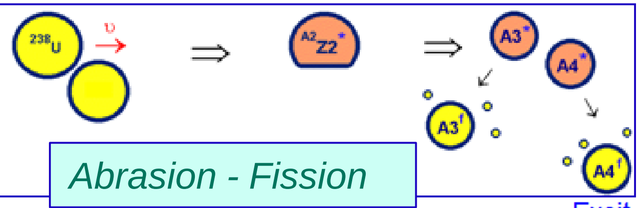


LISE++ *simulation*

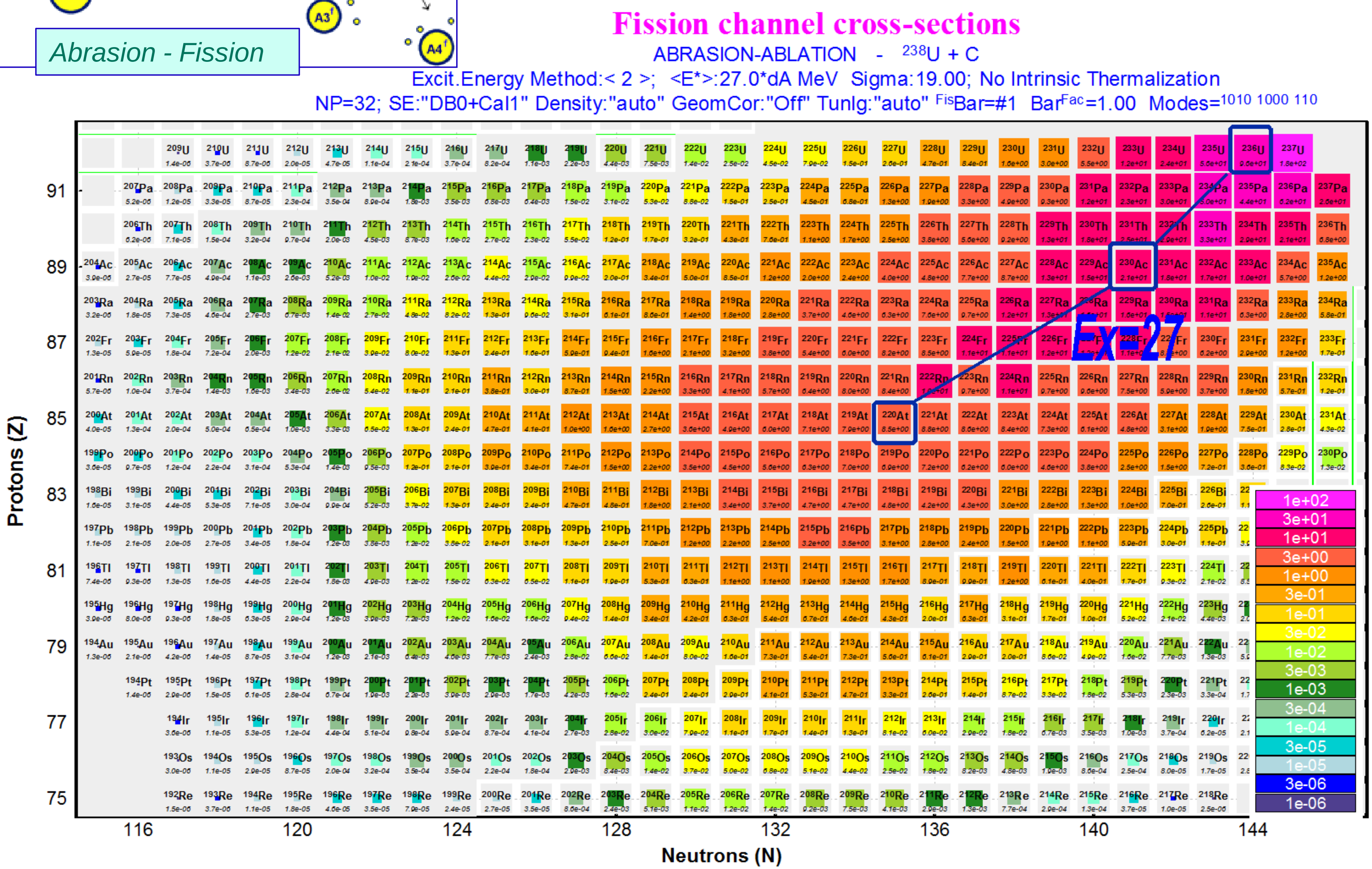


1. Initial purpose: Projectile fragmentation products
2. Finally working under in-flight fission mechanism

Abrasion-Fission : Three Excitation-Energy regions model



Fission channel cross section plot for E* = 27.0*dA MeV



Fission kinematics and Abrasion excitation energy

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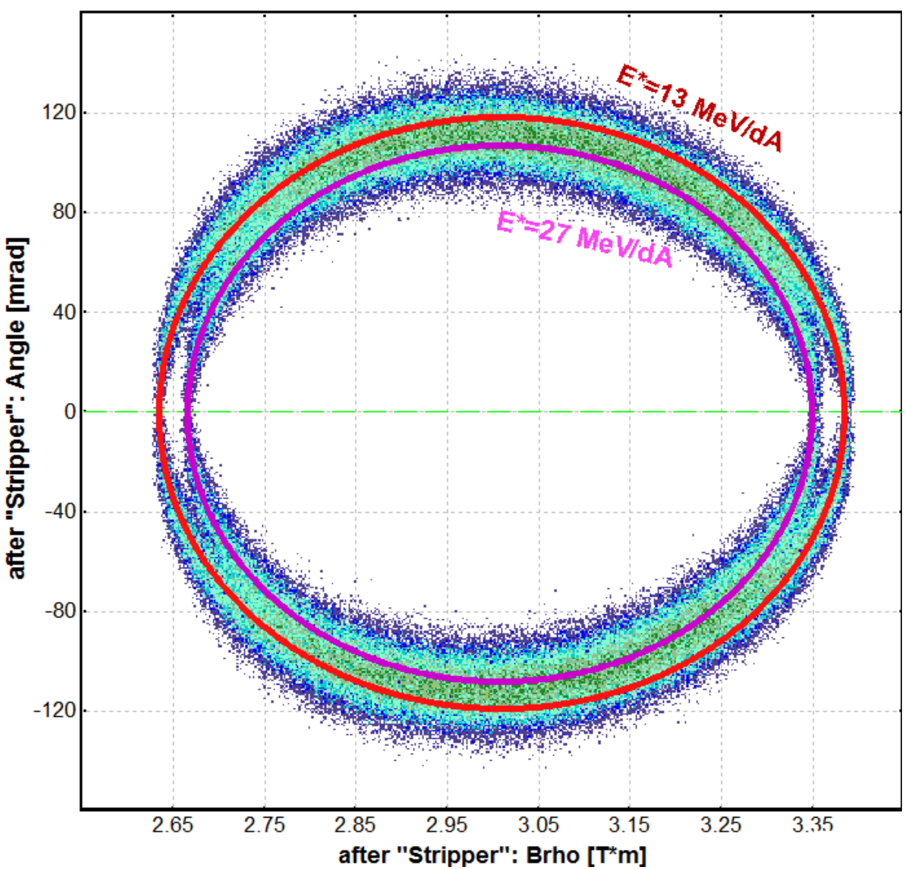
LISE^{++} Abrasion-Fission model

Monte Carlo method

^{238}U (79.56 MeV/u) + C
Transmitted Fragment ^{83}Kr (AFmid)

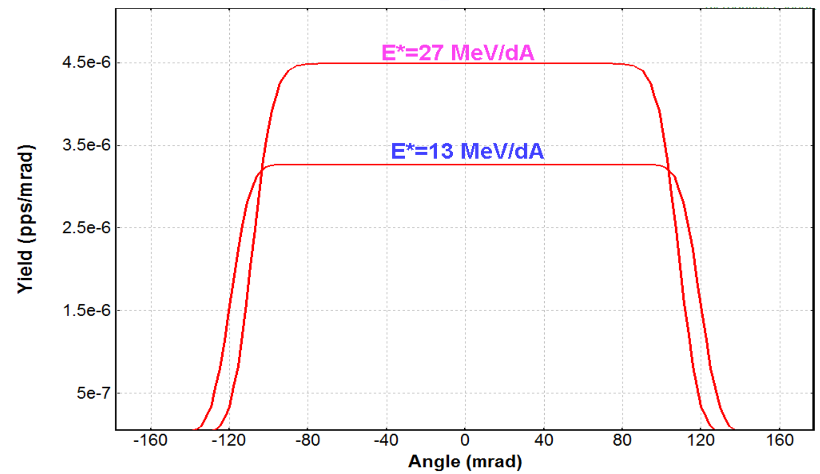
special case: d(E*)=0 & thin target



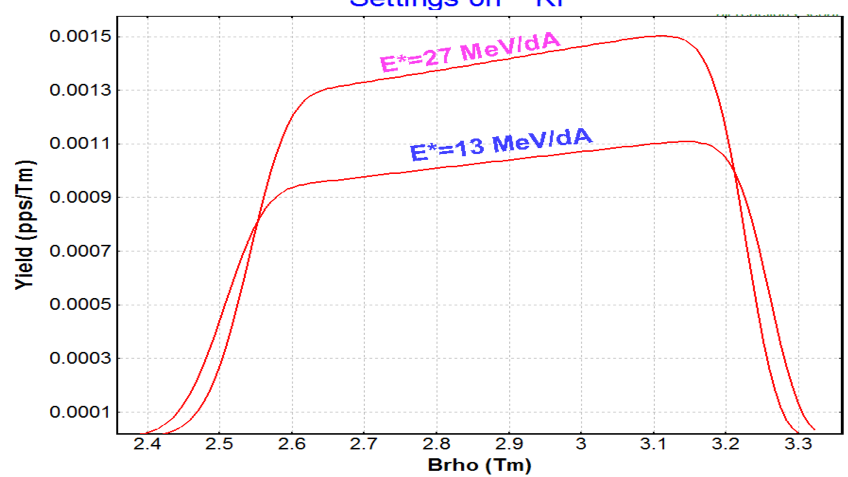
E* = 27 * dA (27 MeV per abraded nucleon)

Distribution method

Stripper: x'angular
^{238}U (79.56 MeV/u) + C (33.5 mg/cm^2)
Settings on ^{83}Kr



Stripper: Momentum
^{238}U (79.56 MeV/u) + C (33.5 mg/cm^2)
Settings on ^{83}Kr



3D fission kinematics

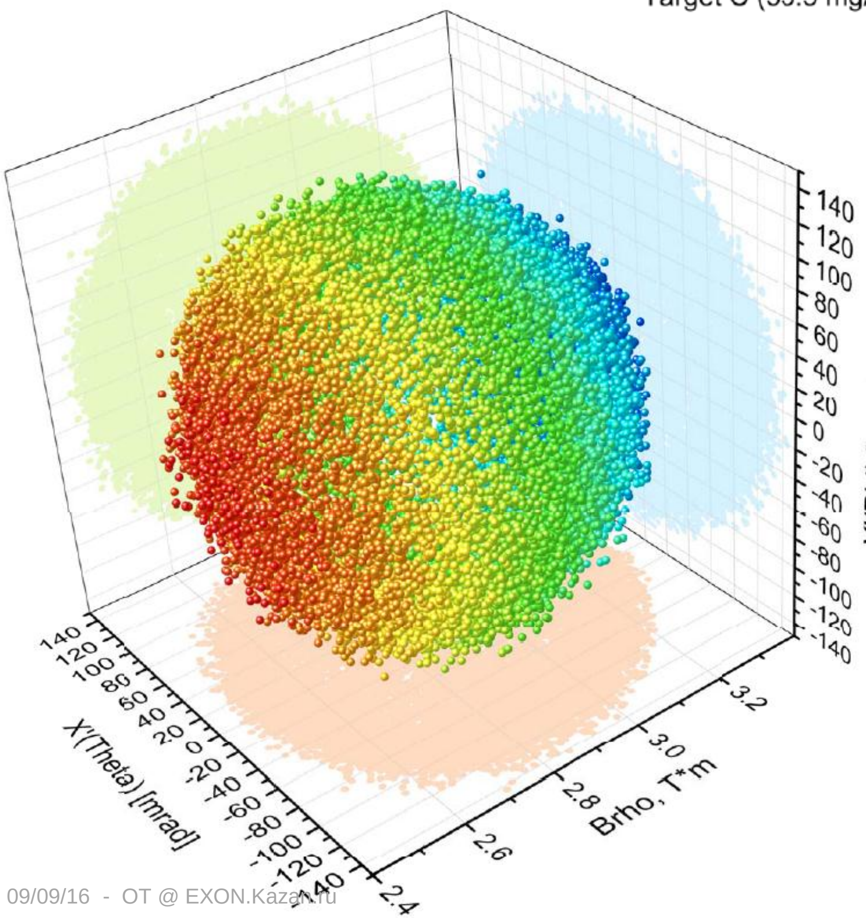
^{238}U (80 MeV/u) + C → ^{83}Kr $_{Mid\ EER}$

after target

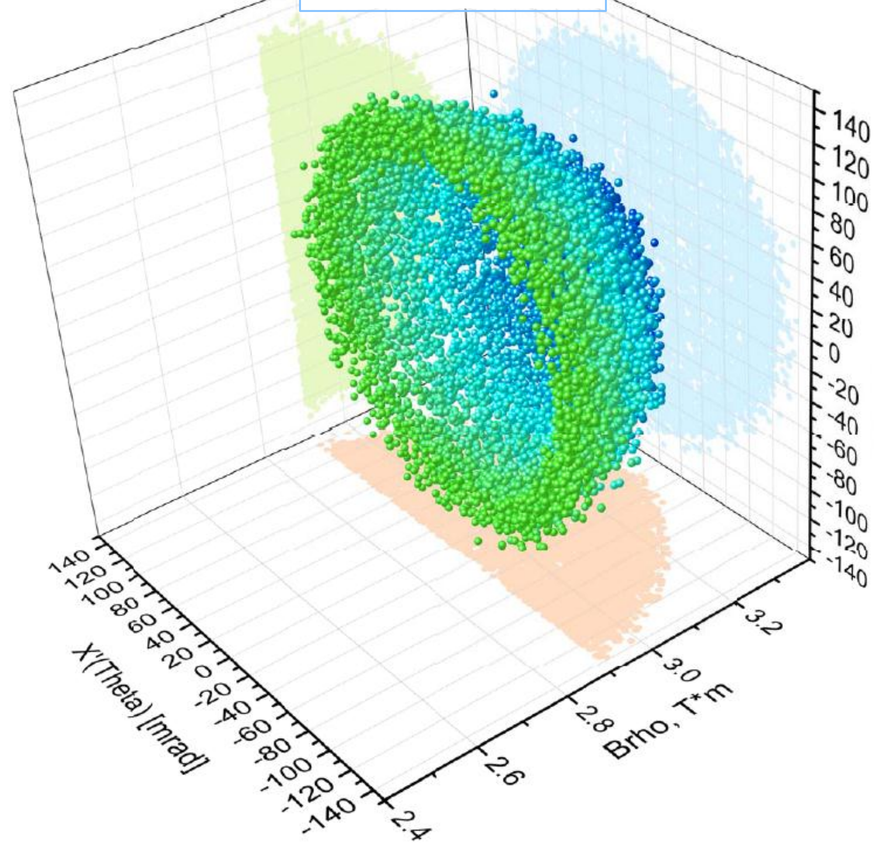
LISE^{++}

Bρ=3.1743 Tm,

Target C (33.5 mg/cm^2)



Fast Half



3D fission kinematics

^{238}U (80 MeV/u) + C → ^{83}Kr $_{\text{Mid EER}}$

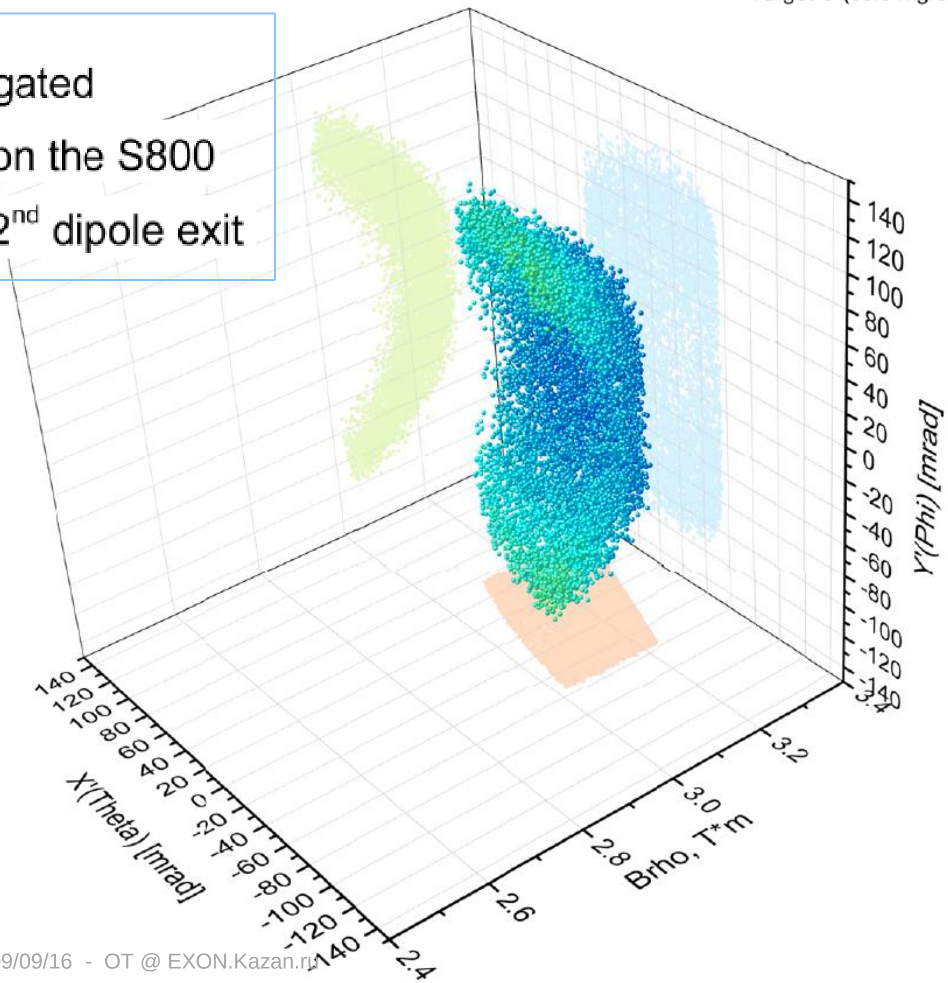
after target

LISE^{++}

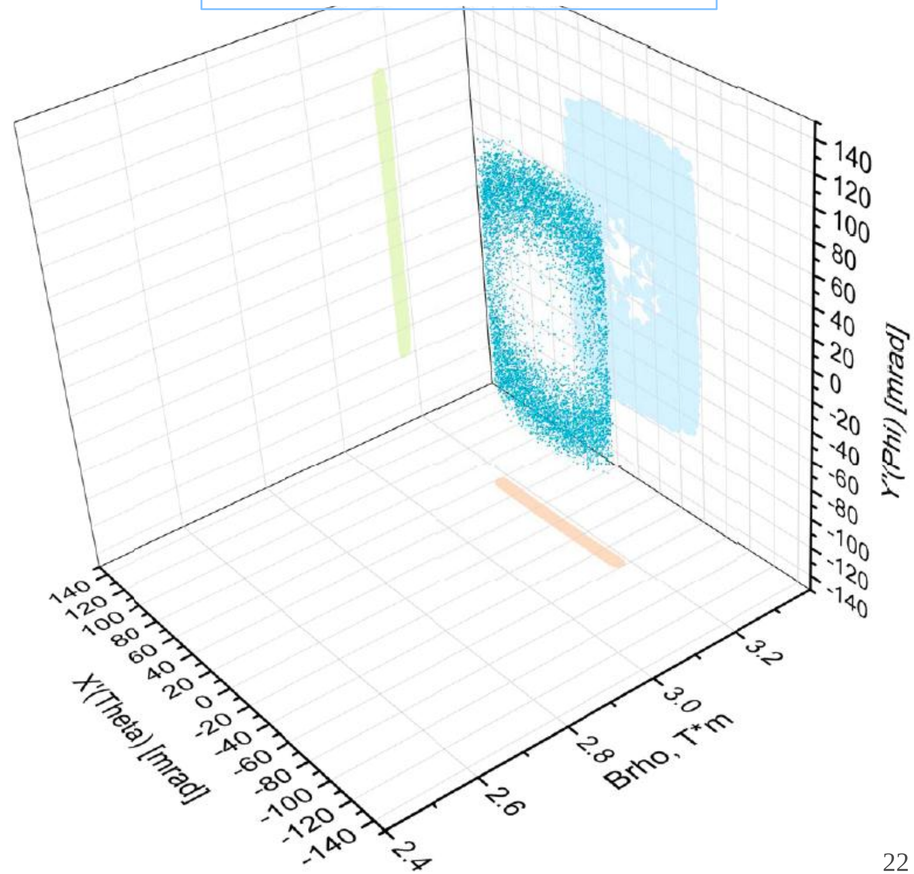
Bρ=3.1743 Tm,

Target C (33.5 mg/cm^2)

gated on the S800 2nd dipole exit



gated on the FP slits (±10mm)



Reverse technique and its application

- The Reverse technique sending experimental data back through a spectrometer to get a momentum vector at the target (Trajectory reconstruction)

- Momentum vector after reaction in target (for example standard S800 technique)
  - Reaction mechanism study
  - Beam spot
  - Angular acceptance vs emittance
- Beam emittance measurement (X,A,Y,B,E)
  - Study of correlations between beam emittance components
- Determination of location of new ions production
  - BigRIPS case : production in the beam-dump

- Benchmarks based on LISE^{++} MC apparatus and spectrograph segmentation
  - Beam dynamics visualization
  - Beam optics calculation verification
  - Experimental analysis and calibrations test
- Experiment set-up feedback with LISE^{++}
  - Obtaining experimental information by detecting devices in some (or one) locations
  - Retracing up-stream (or down-stream) from detection locations based
  - Analysis, minimization

Velocity-Z vs Theta plot

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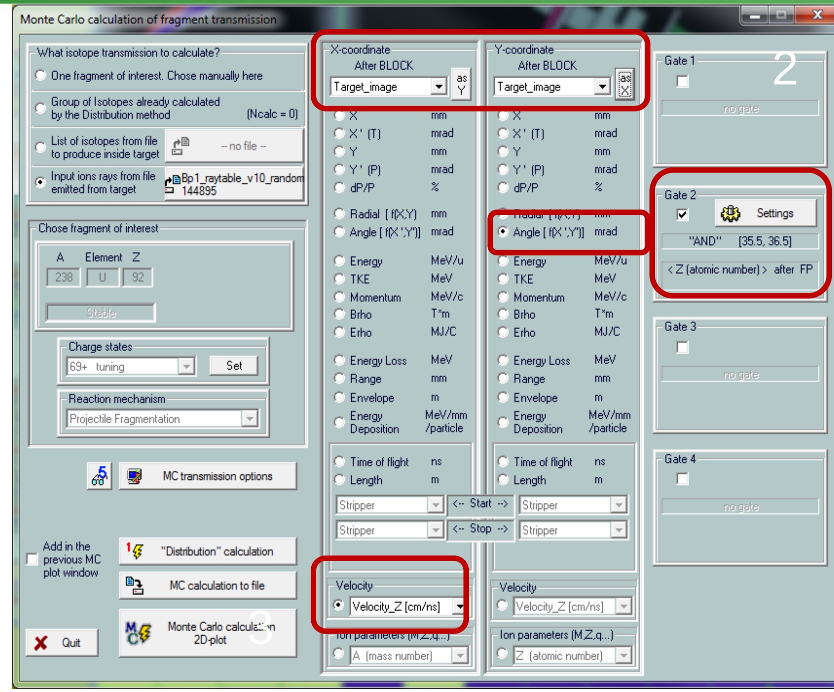
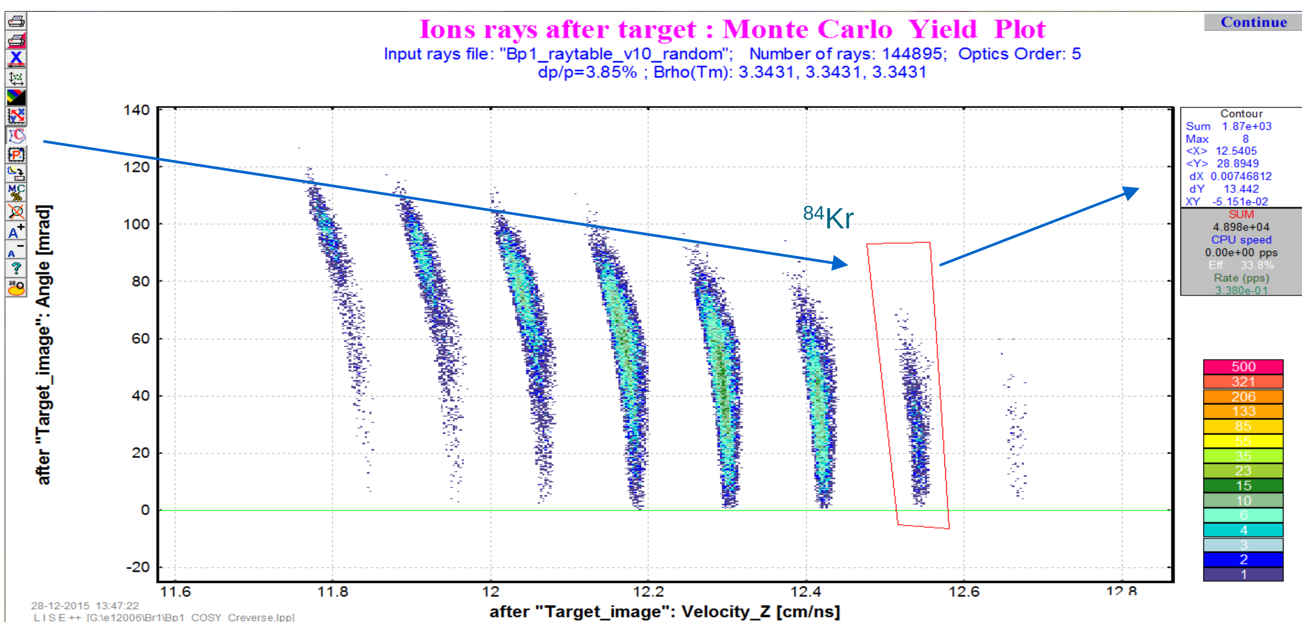
- The reverse separator technique developed in the LISE^{++} package* and coupled with the S800 configuration has been used to study fission mechanism properties.
- Using LISE^{++} technique allows fragment vectors measured at the final plane of a spectrometer to be replayed through in the backward direction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

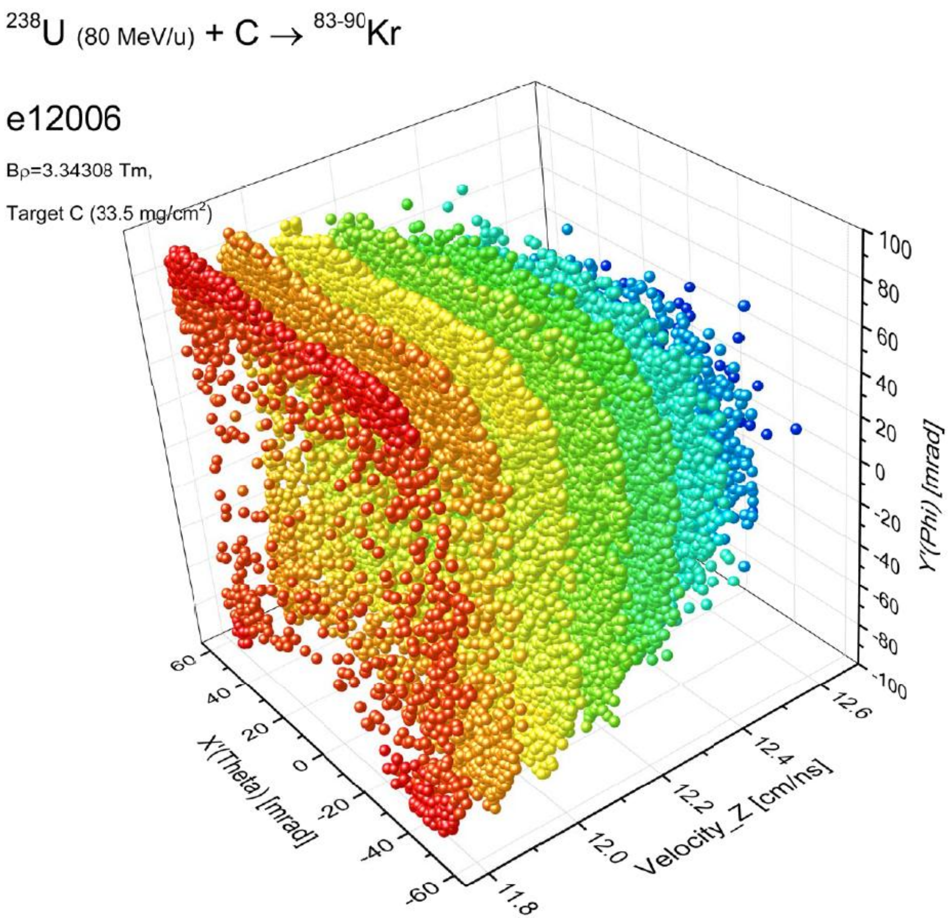


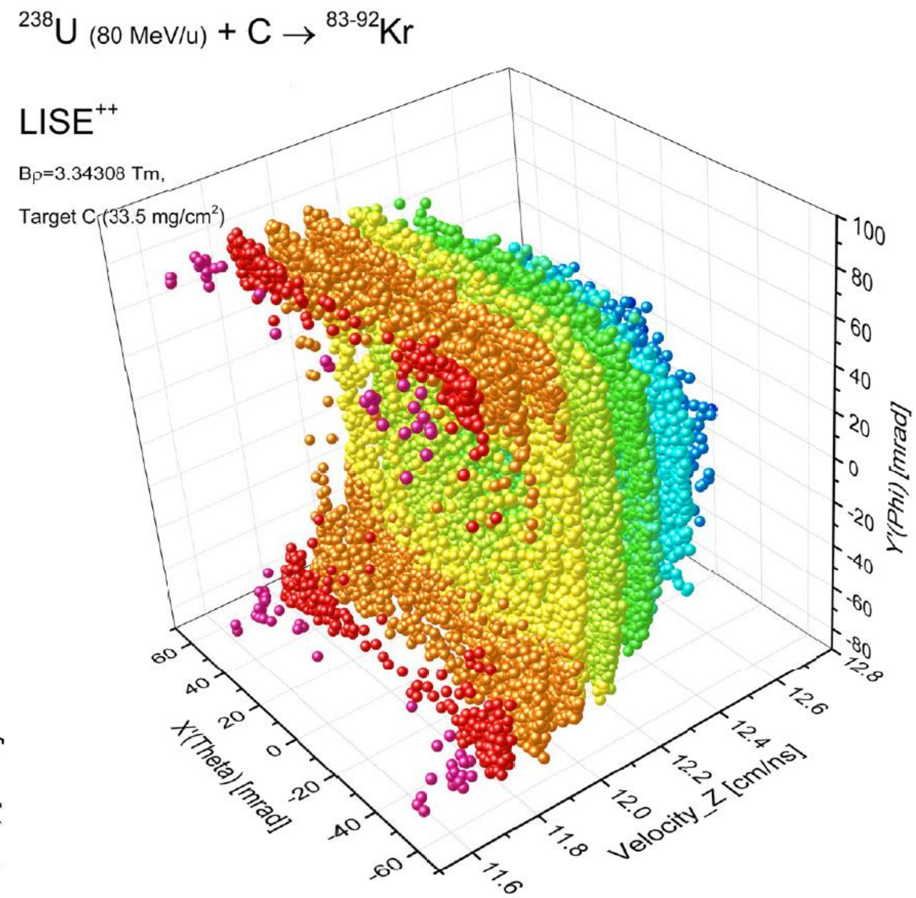
Gate for Kr isotopes

contour



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



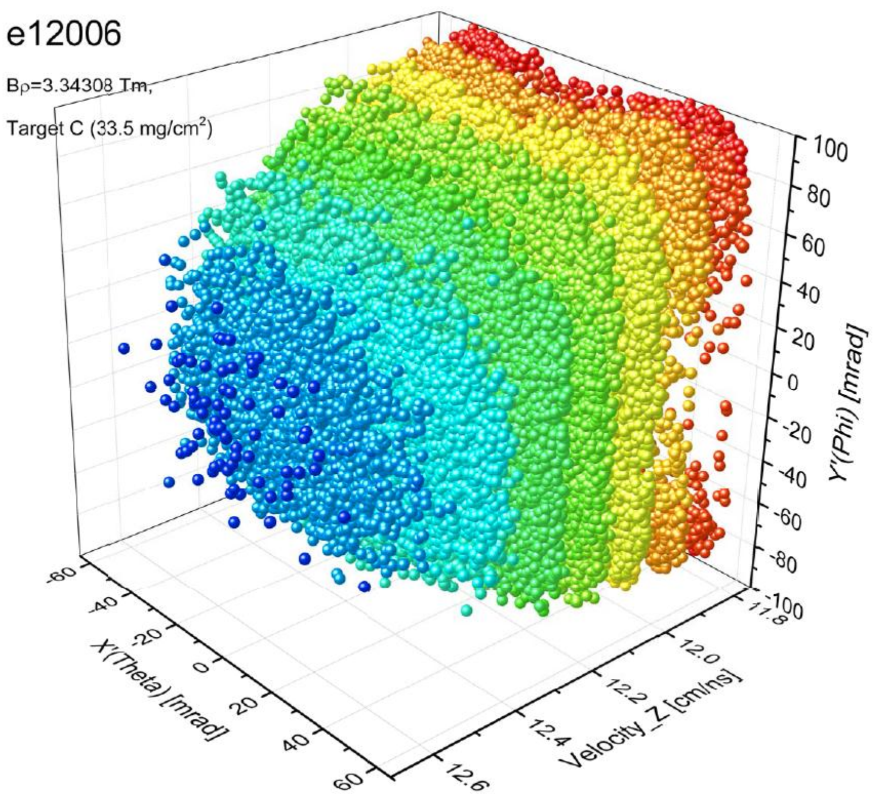


LISE++ direct calculations are gated on the Scintillator position

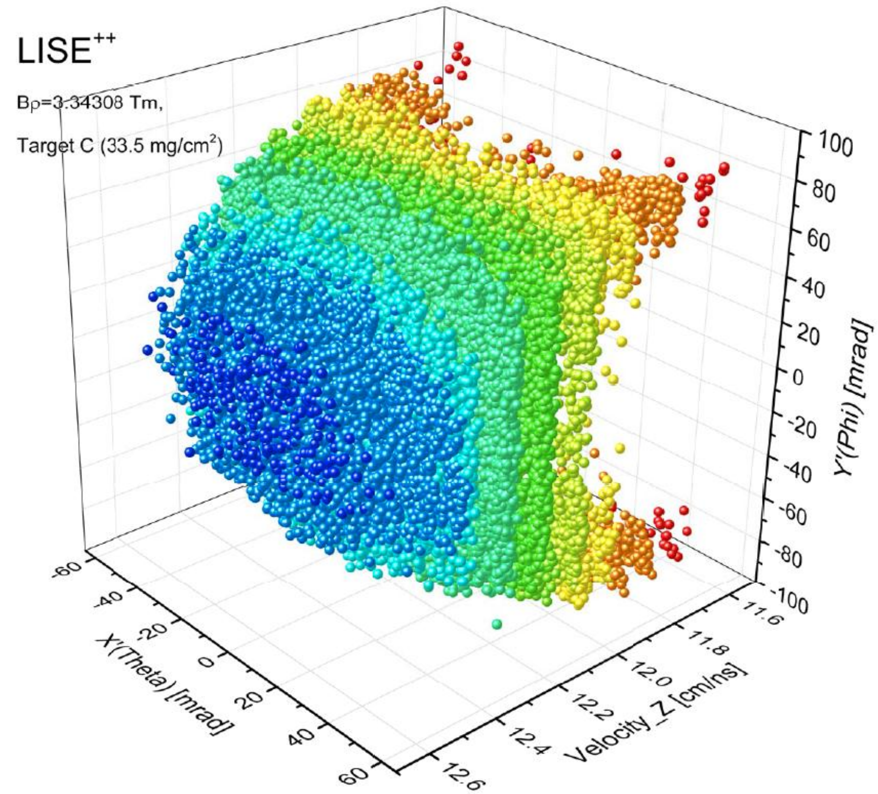
Pay attention that in LISE++ calculations the isotope range is 83-92 instead experimental 83-90

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

^{238}U (80 MeV/u) + C → $^{83\text{-}90}Kr$



^{238}U (80 MeV/u) + C → $^{83\text{-}92}Kr$

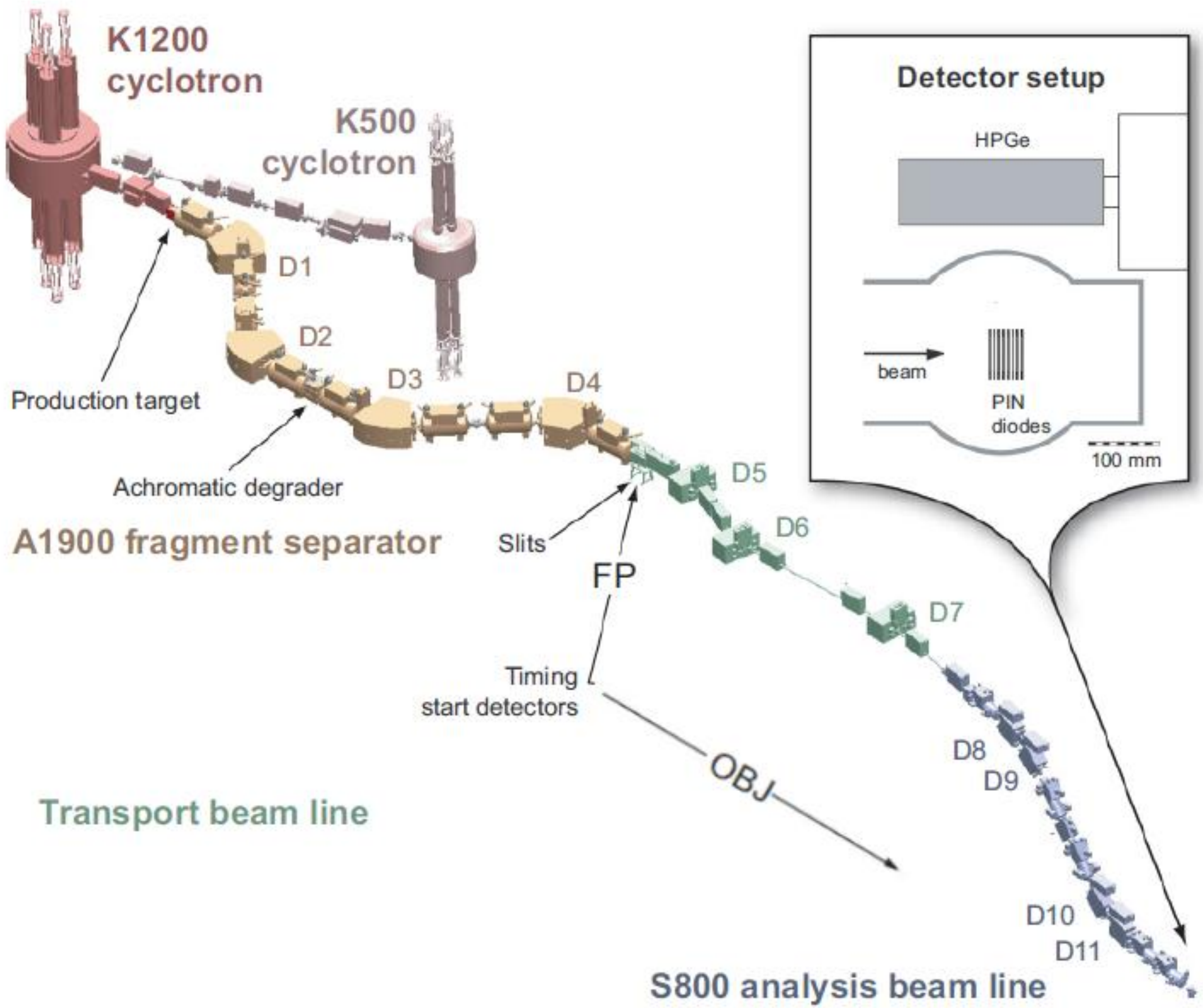


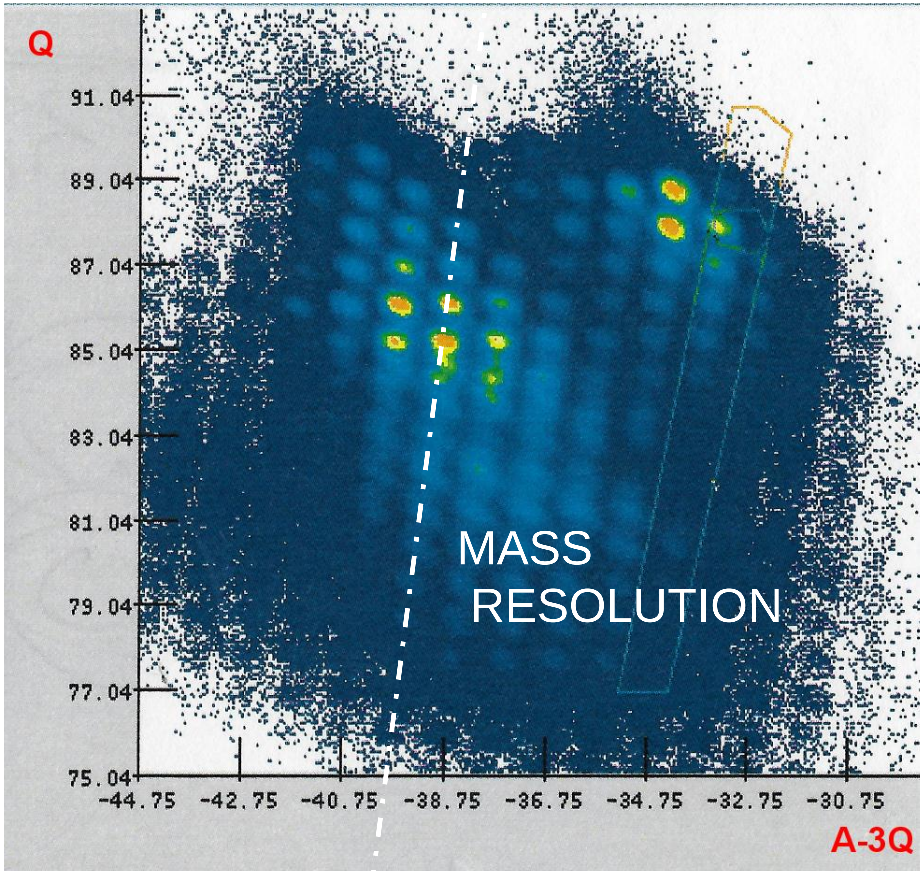
LISE^{++} direct calculations are gated on the Scintillator position

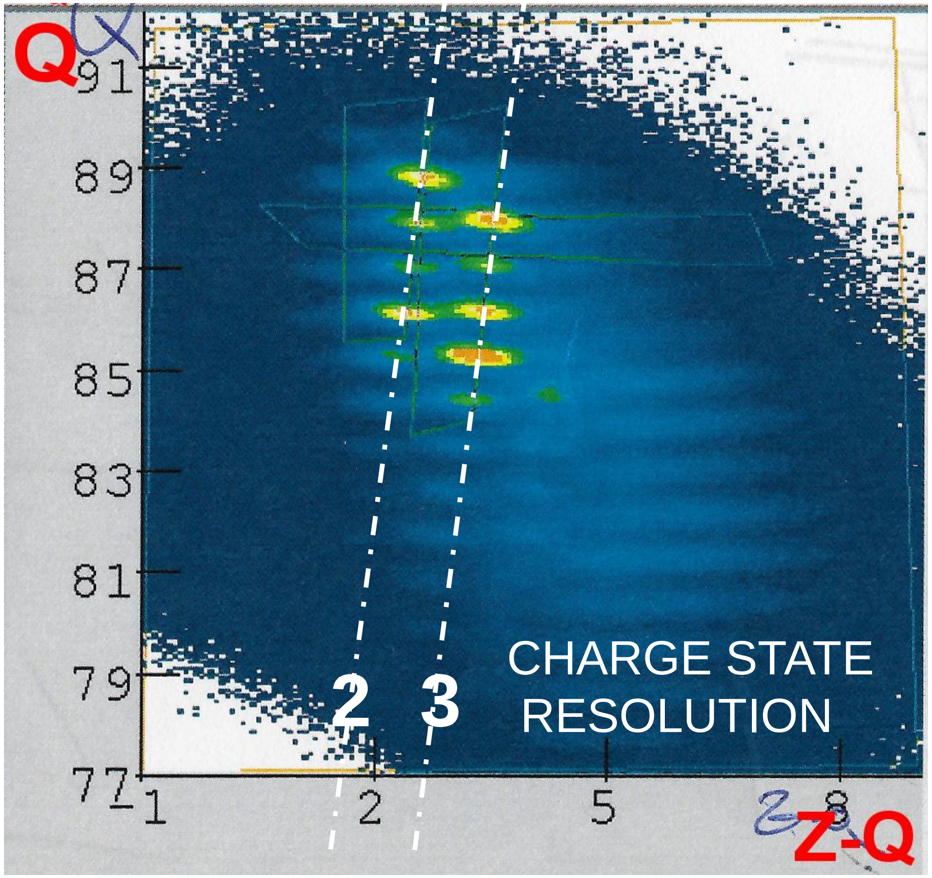
Pay attention that in LISE^{++} calculations the isotope range is 83-92 instead experimental 83-90

e09063 : Projectile fragmentation of ^{238}U

End of June, 2016
E.Kwan – current spokesperson

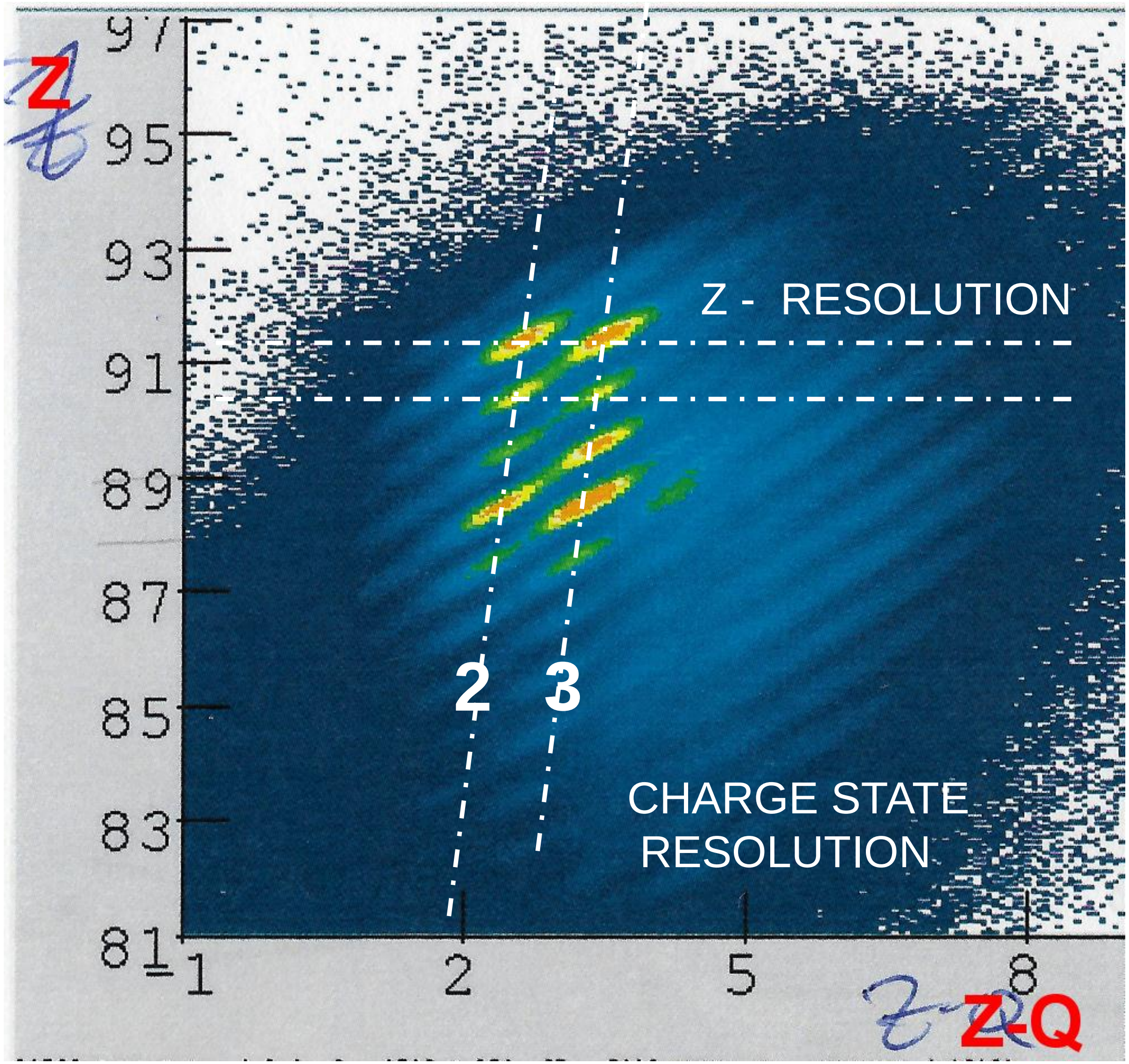






Small Momentum acceptance
Non-cooled PIN-diodes (50x50 mm^2 0.5mm)

e09063 : Projectile fragmentation of ^{238}U



Several words for…. LISE++ Development (since last 2014 EXON)

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LISE++ : EXOTIC BEAM PRODUCTION WITH FRAGMENT SEPARATORS AND THEIR DESIGN O.B.Tarasov, D.Bazin	**30**
FUTURE PERFORMANCE AND MODEL IMPROVEMENTS IN THE LISE++ SOFTWARE SUITE O.B.Tarasov, D.Bazin, M.P.Kuchera, B.M.Sherrill, K.V.Tarasova	**31**

v.9.9

- Optics: S & E construction methods
- Extended configurations in LISE++
- Compensating dipole
- Multipole : Quadrupole & Sextupole superposition
- TRANSPORT code file import to LISE++
- Range Optimizer (Gas cell utility) update

- Extended Configurations

- Regular support routine:
  - user requests, calculation optimization, fix of bugs, interface improvement, Databases and other updates

v.9.10.345

- Update of Fusion reaction mechanism
- Optics minimization (up to 2nd order)
- Reverse configurations: ray trajectory reconstruction
- Radiation Residue Calculator
- ETACHA4 (GUI) (still under construction)

- Others notable
  - Decay Branching Database
  - Ionization energy database & Ion mass calculator
  - Utility "Angular Straggling & Rutherford scattering probabilities in compound“
  - Rutherford scattering of primary beam in target in MC mode
  - FRIB mass tables in the LISE++ package
  - Second order optics calculations of electric dipole

Next official <u>version 10</u> will be released soon : October 2016

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 spectrograph and A1900+S800BL separation system.
- 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 experiments demonstrated excellent resolution, in *Z, A*, and *q* *(fusion-fission Z<60), projectile fragmentation (Z~92)*.
- 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.
- It has been demonstrated, that the reverse tracking technique can be used as a precise tool to get information for reaction mechanism characteristics.

Collaborators

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