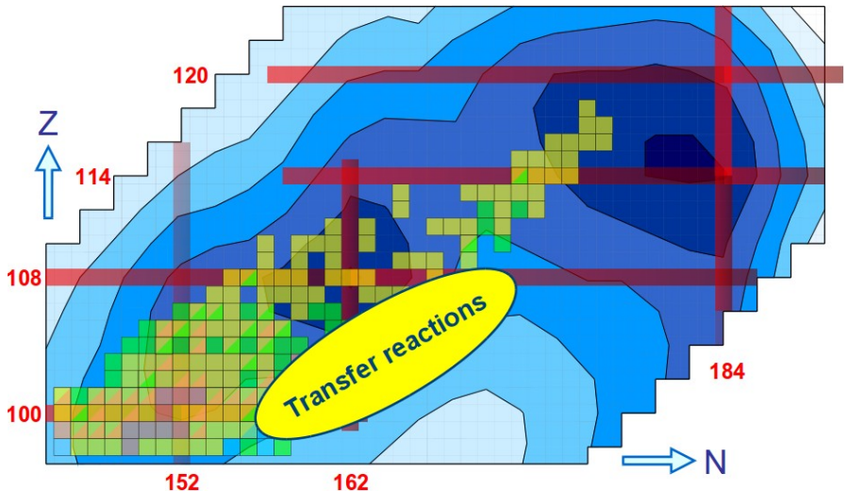
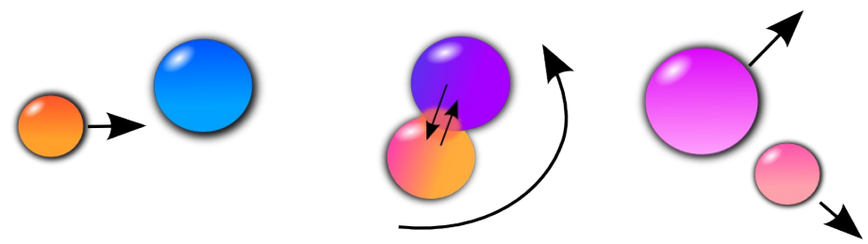
IRiS
HEAVY ELEMENTS





Reaction Properties

Working Group report

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Jan Dvorak
Helmholtz Institute Mainz

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Outline

- Design Reactions
- Reaction channels:
  - Elastic scattering
  - Quasi-elastic and few-nucleon transfer channels
  - Multi-nucleon transfer channels
  - Fusion
- Preparatory experiment

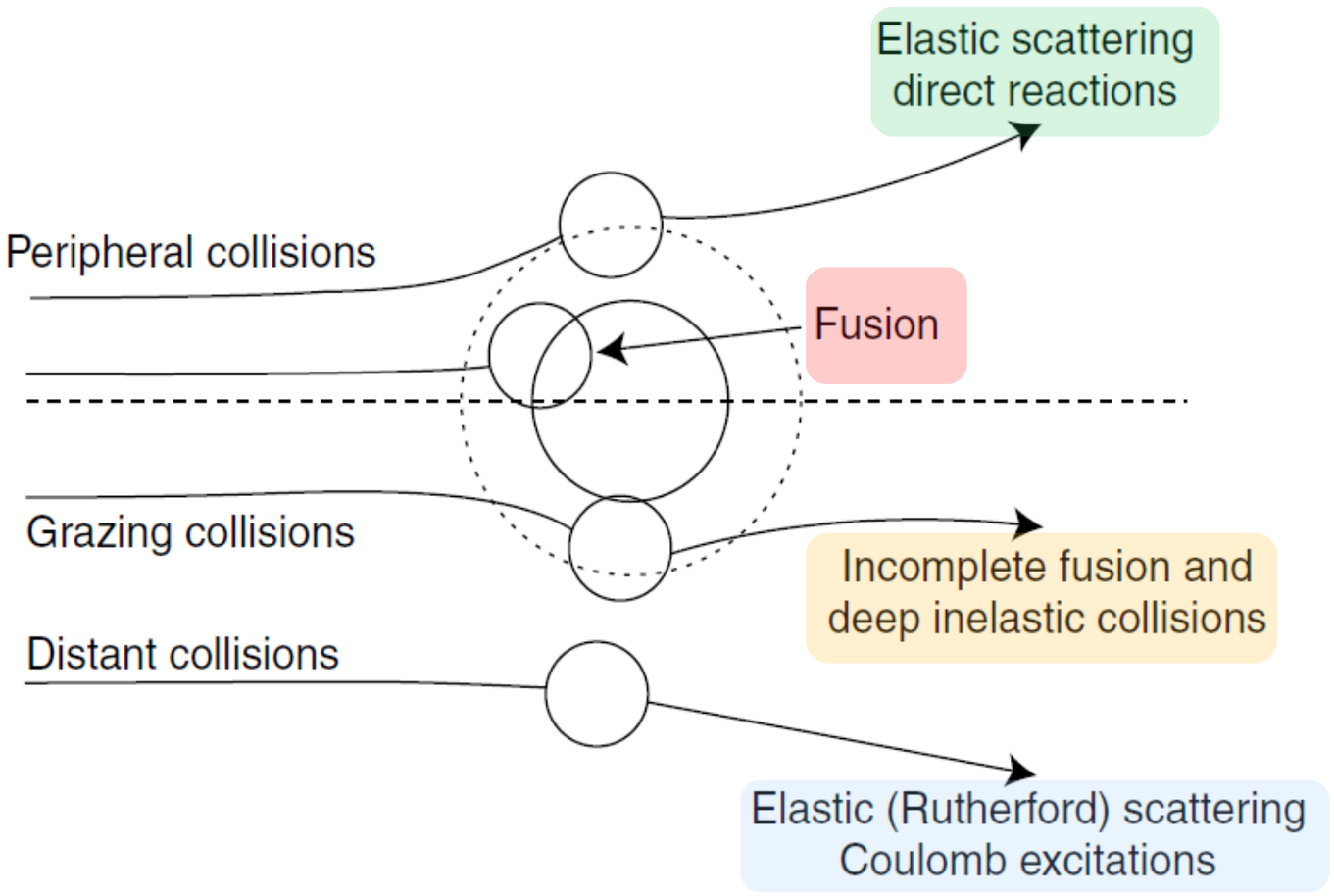
Design Reactions

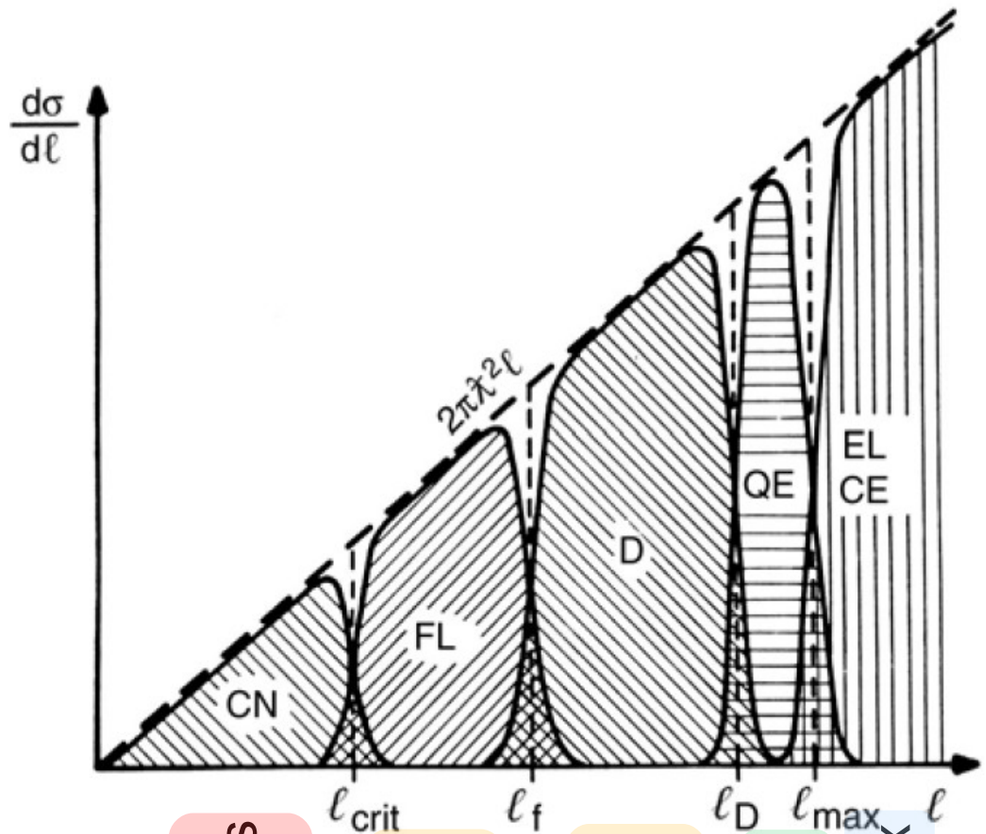
Design reactions chosen at IRiS 10 (Spring) workshop:

- Various projectiles + Actinide targets
- $^{136}Xe + ^{208}Pb$
- Energy < 10 % above the Coulomb Barrier

Reaction	E_{LAB} [MeV]
$^{22}Ne + ^{238}U$	125
$^{40}Ar + ^{238}U$	228
$^{48}Ca + ^{238}U$	255
$^{136}Xe + ^{238}U$	799
$^{238}U + ^{238}U$	1606
$^{136}Xe + ^{208}Pb$	789

Classification of collisions





Compound Nucleus

Fusion Like

Deep-Inelastic

Quasi-elastic

Elastic and Coulex

Loveland, W. D.; Morrissey, D. & Seaborg, G. T. Modern Nuclear Chemistry

Elastic scattering

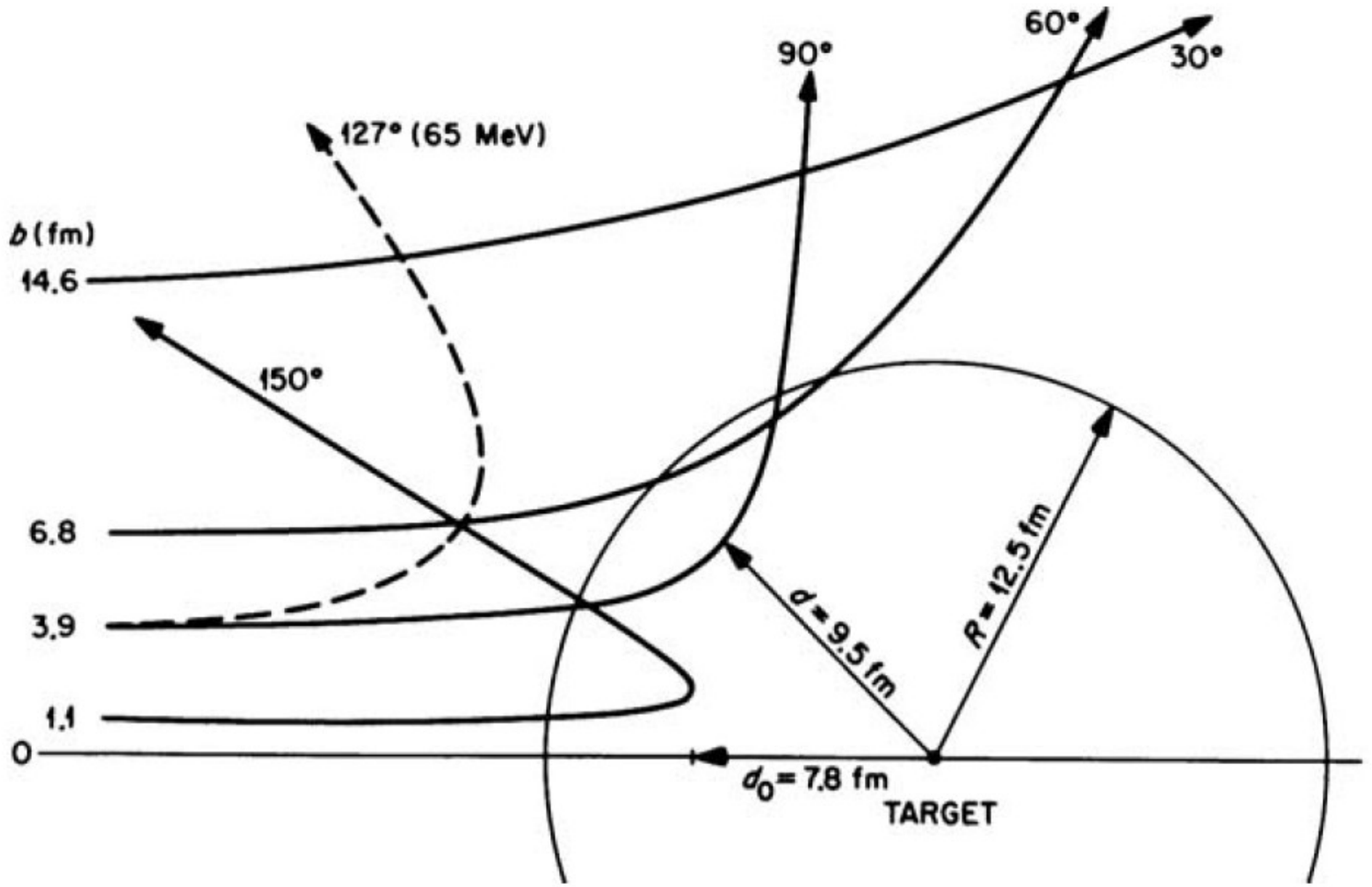


Figure 10.13 Diagram showing some representative projectile orbits for the interaction of 130 MeV ^{16}O with ^{208}Pb. [From Satchler (1990).]

Loveland, W. D.; Morrissey, D. & Seaborg, G. T. Modern Nuclear Chemistry

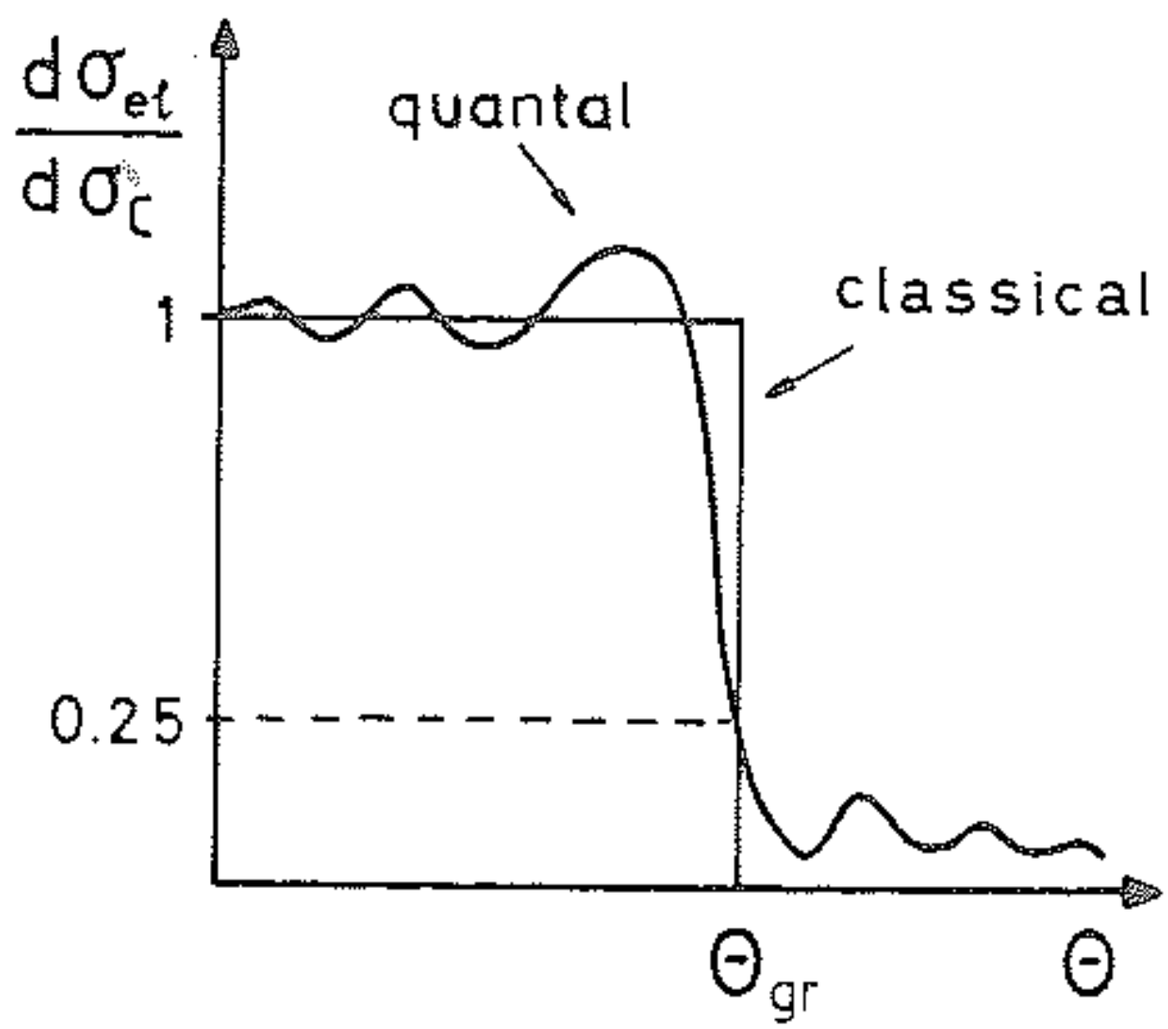
Elastic scattering – differential cross section

- Up to θ_{gr} Rutherford cross section

$$\frac{d\sigma}{d\Omega} = \frac{dI}{I_0}\frac{1}{d\Omega} = \left(\frac{d_0}{4}\right)^2 \frac{1}{\sin^4(\theta/2)} = \left(\frac{Z_1 Z_2 e^2}{4T_P^{cm}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

$$\theta_{gr} = 2\,asin\left(\frac{V_C}{2E_{CM} - V_C}\right)$$

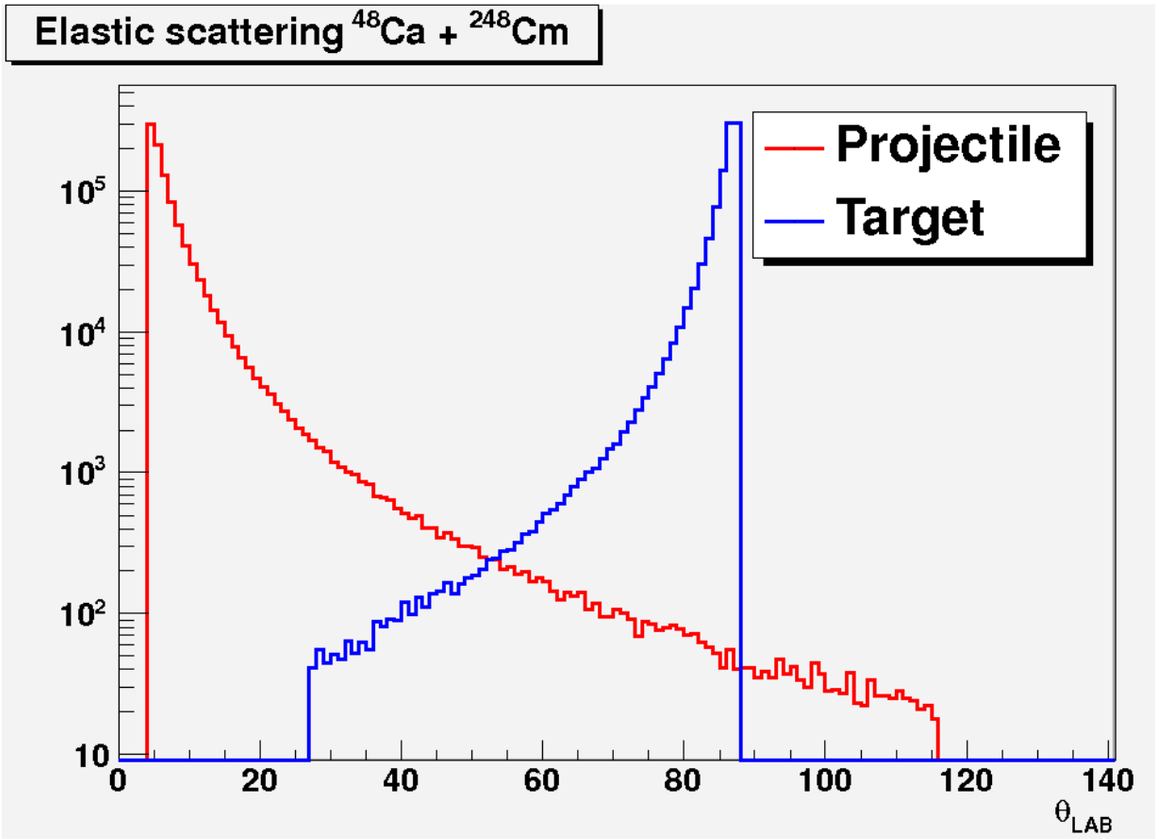
- $E_{CM} = 1.1V_C \rightarrow \theta_{gr} = 110°$
- Below that σ_{el} drops



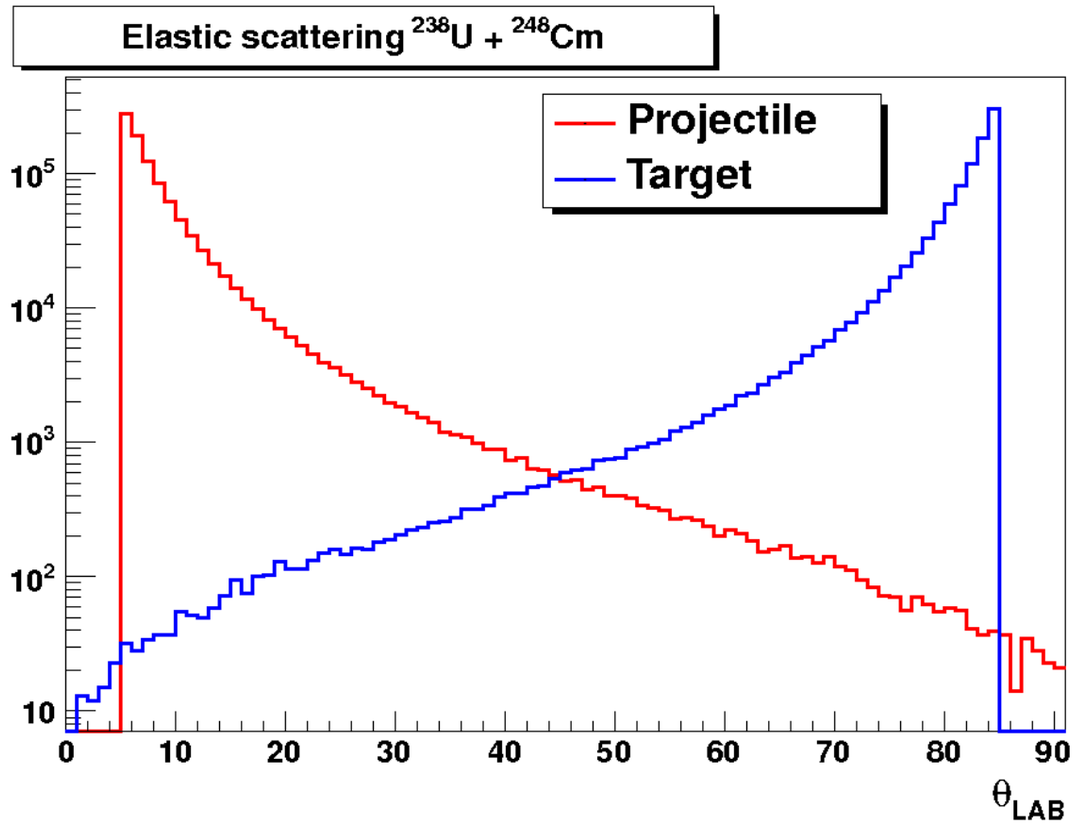
R. Bass, Nuclear Reactions With Heavy Elements

Elastic scattering – differential cross section

$^{48}Ca + ^{248}Cm$ @ 209 MeV CM (1.07 V_C)



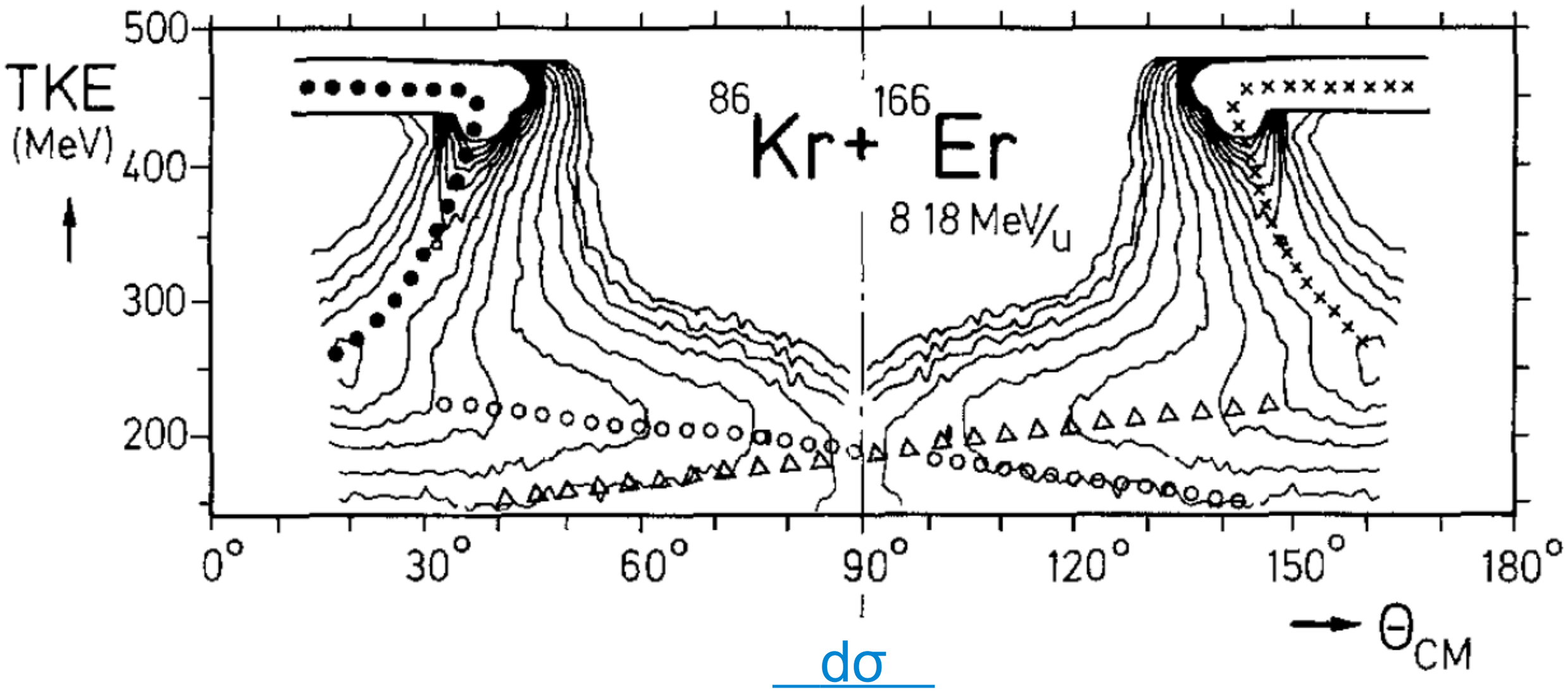
$^{238}U + ^{248}Cm$ @ 750 MeV CM (~ V_C)



$\frac{d\sigma}{d\theta}$ Arbitrary scale

Inelastic collisions

$^{86}Kr+^{166}Er$ at 8.18 MeV/u



$$\frac{d\sigma}{dE\, d\theta}$$

Gobbi, Nuclear Physics A, 1981, 354, 337 - 374

Inelastic collisions – angular distribution

Behavior scales with "modified Sommerfeld parameter" η'

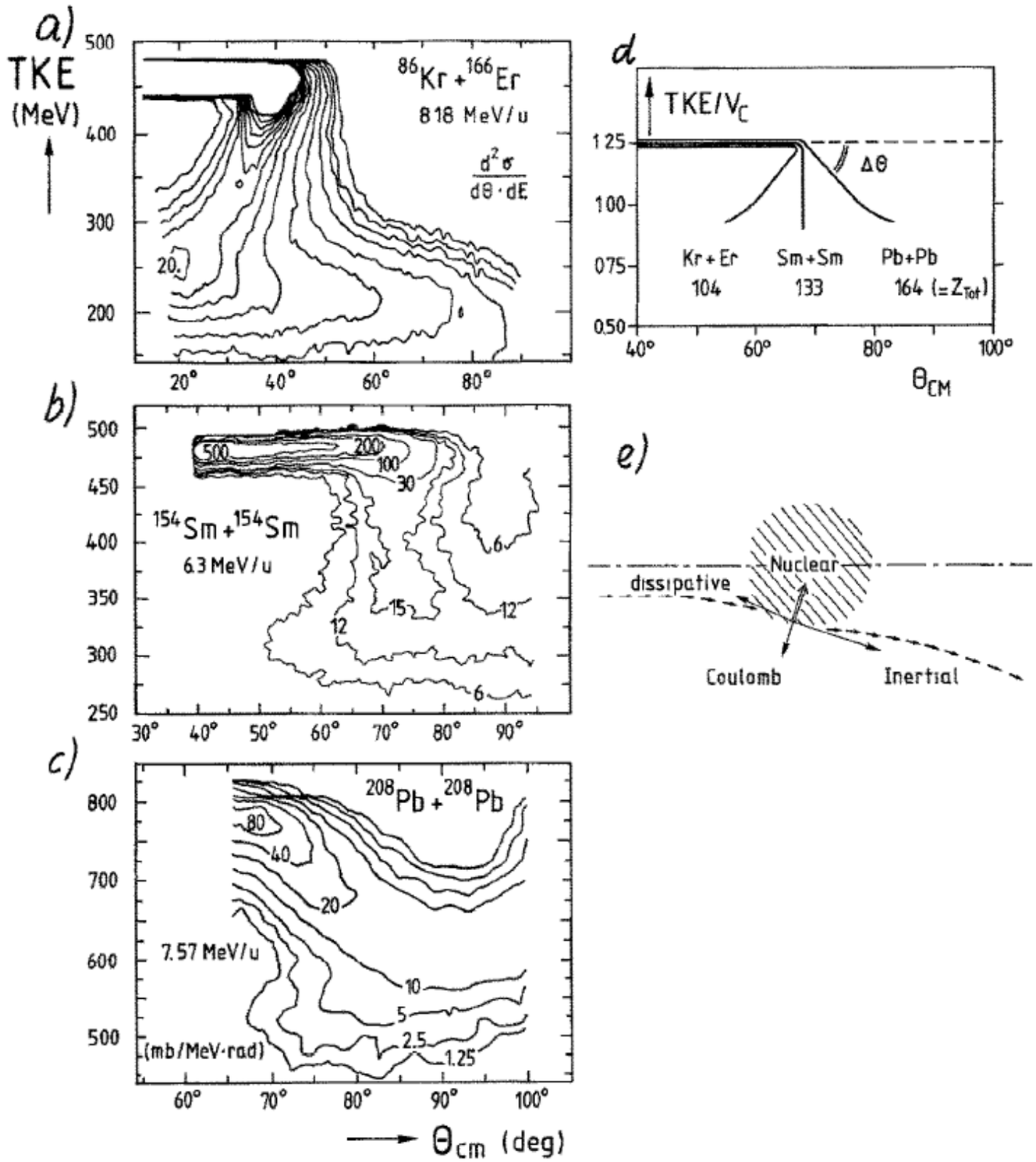
$$\eta' = \frac{Z_1 . Z_2 . e^2}{\hbar . v_B}$$

V_B - *relative velocity at interaction barrier*

a) Orbiting η' < 150

b) Focusing 250 < η' < 400

c) Coulomb trajectory 500< η'



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Angular distribution for design reactions

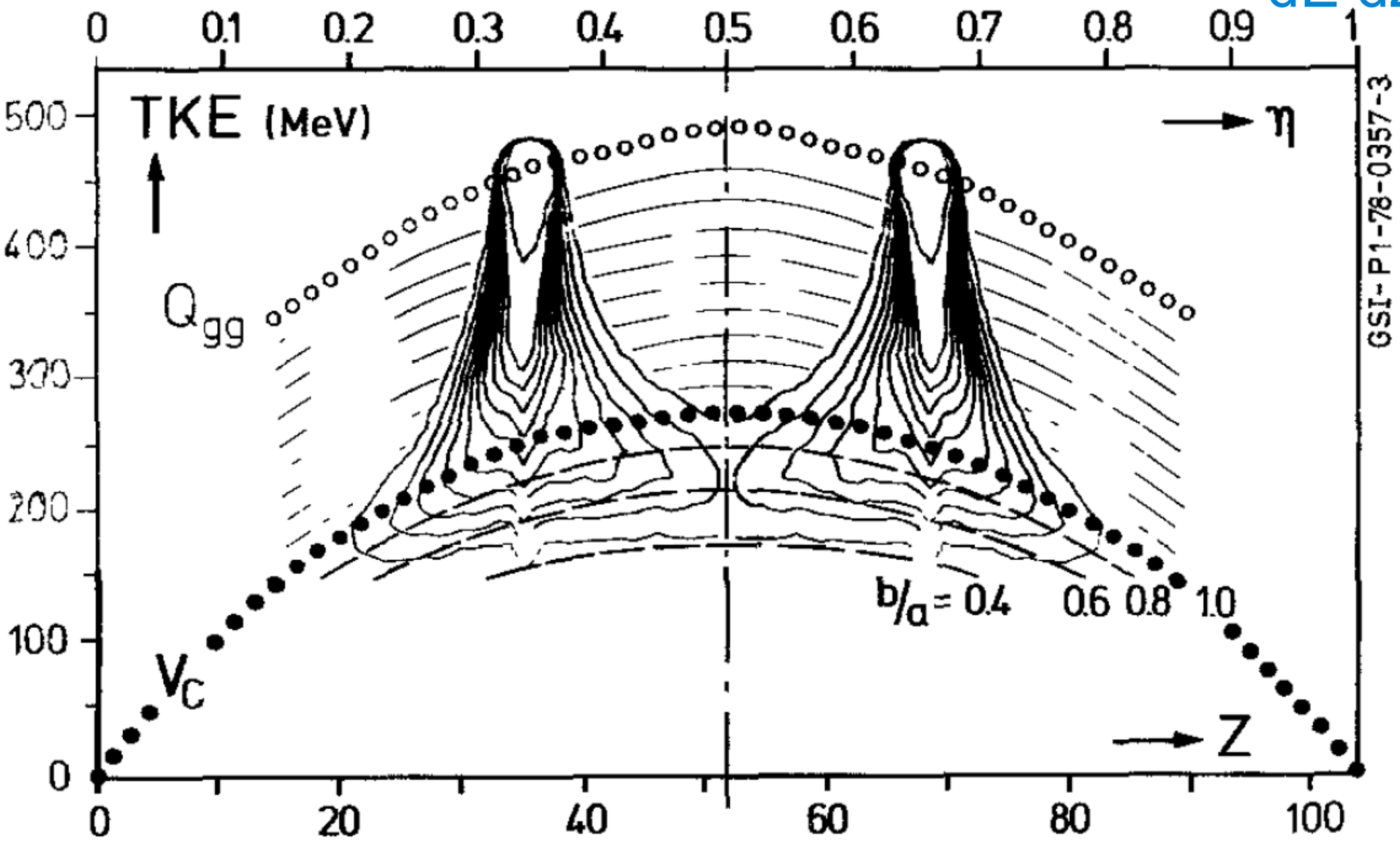
Reaction	E_{LAB} [MeV]	η'	Type
$^{22}Ne + ^{238}U$	125	200	Focusing
$^{40}Ar + ^{238}U$	228	357	Focusing
$^{48}Ca + ^{238}U$	255	418	Focusing
$^{136}Xe + ^{238}U$	799	1071	Coulomb
$^{238}U + ^{238}U$	1606	1700	Coulomb
$^{136}Xe + ^{208}Pb$	789	802	Coulomb

^{48}Ca and $^{238}U + ^{238}U$ (^{248}Cm) are representative reactions

Deep inelastic collisions

$^{86}Kr+^{166}Er$ at 8.18 MeV/u

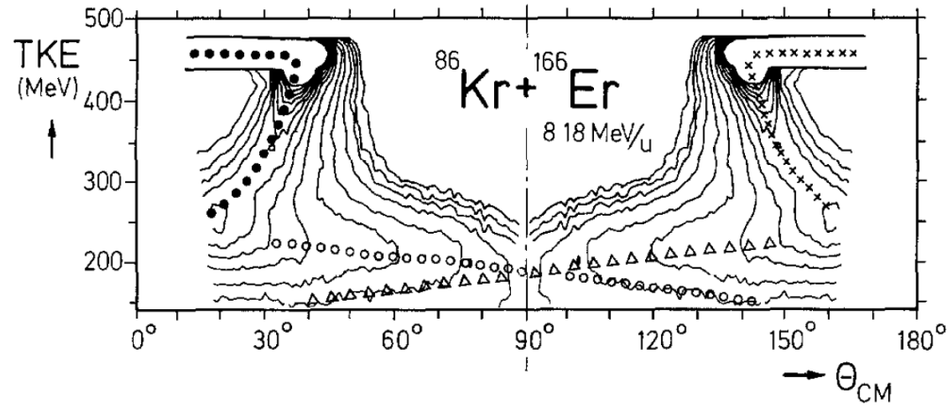
$\frac{d\sigma}{dE\,dZ}$

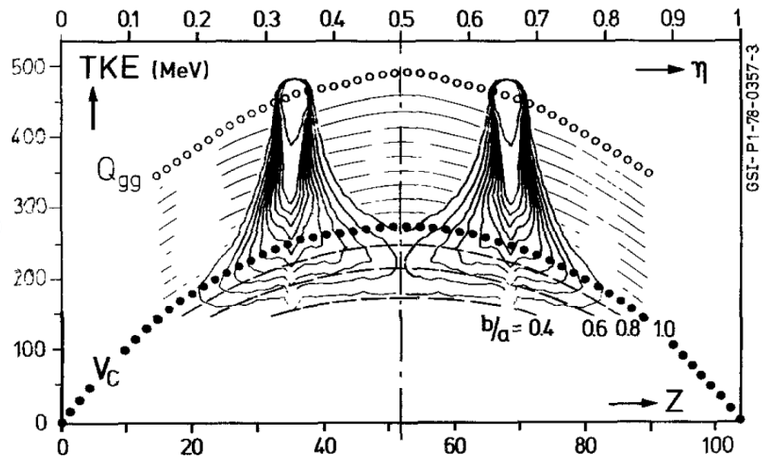


Gobbi, Nuclear Physics A, 1981, 354, 337 - 374

GRAZING

- Deep-inelastic reactions are complex
- Luckily we have GRAZING
  - coupled channels calculations
  - G. Polarollo





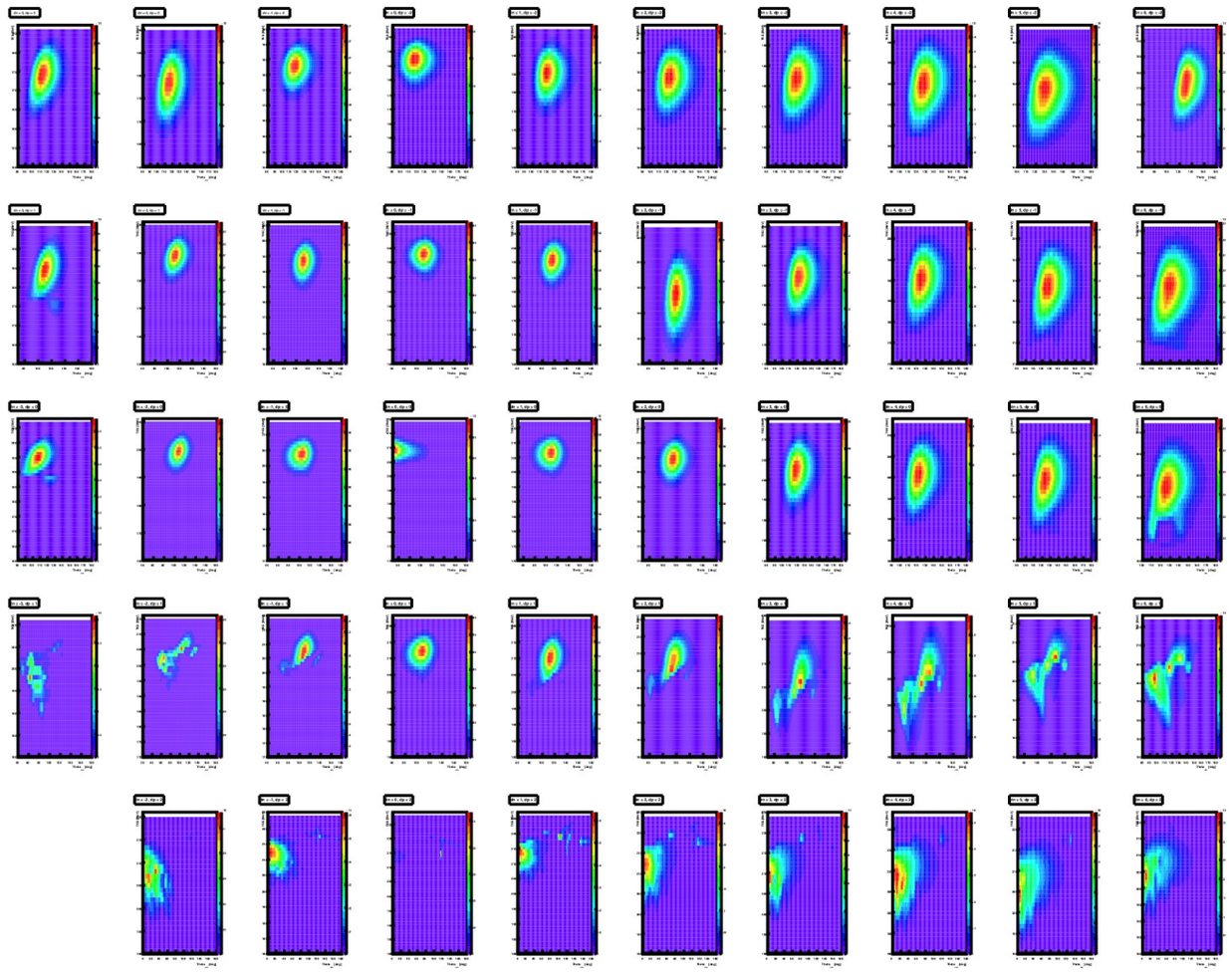
- See his presentation from the last IRiS workshop

http://www-win.gsi.de/iris10/contributions/IRiS10_contribution_Pollarolo.pdf

http://personalpages.to.infn.it/~nanni/grazing/

GRAZING calculation for ^{48}Ca + ^{248}Cm @ 209 MeV

- dσ/(dE.dθ) for different exit channels
- Reliable for quasi-elastic and few-nucleon transfer channels
  - The strongest channels



Many-nucleon transfer reactions

- Two detailed theoretical calculations:
  - $^{48}Ca + ^{248}Cm$ @ 209 MeV CM (1.07 V_C) by Adamian and Antonenko
  - $^{238}U + ^{248}Cm$ @ 750 MeV CM (~ V_C) by V. Zagrebaev

$^{48}Ca + {}^{248}Cm$ @ 209 MeV CM (1.07 V_C)

- Calculated by Adamian and Antonenko
  - Diffusion of dinuclear system in the charge and mass asymmetry coordinates
  - Long contact times → isotropic angular distribution
  - Excitation energy of the system shared between fragments by their mass

Ref e.g.: Adamian, G. G., Antonenko, N. V., Sargsyan, V. V. & Scheid, W., Phys. Rev. C, 2010, 81, 024604

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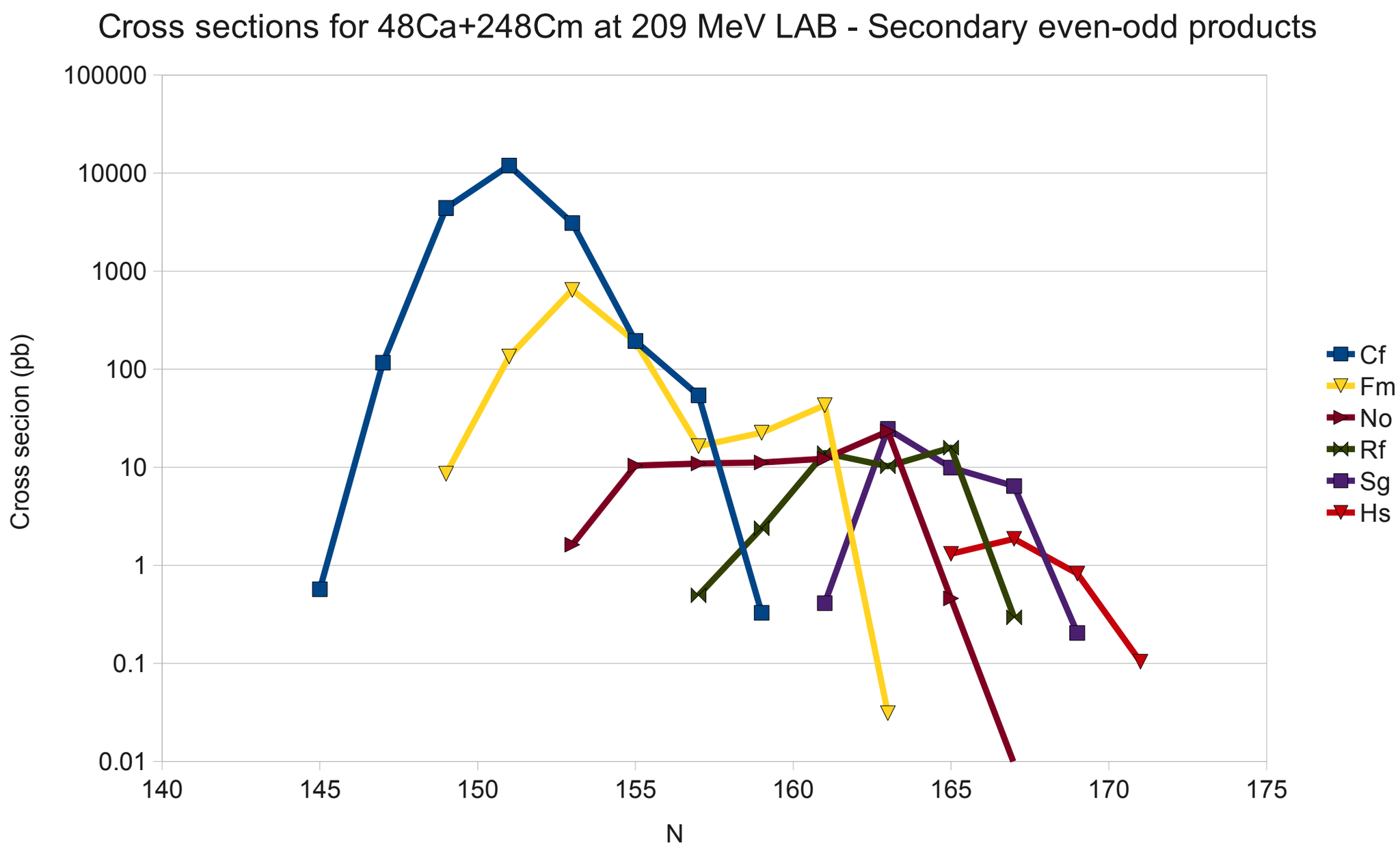
$^{48}Ca + {}^{248}Cm$ @ 209 MeV CM



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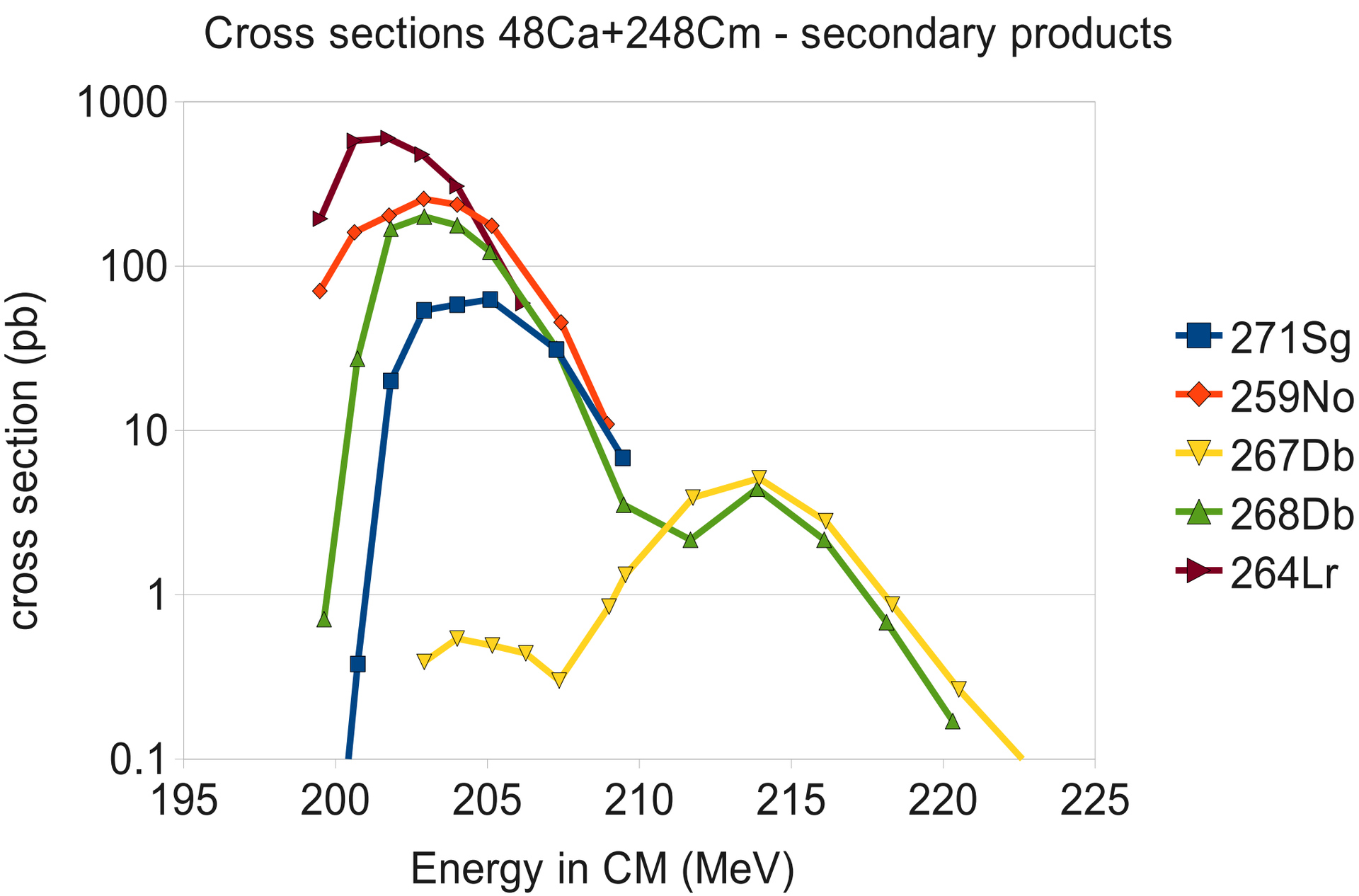
$^{48}Ca + {}^{248}Cm$ @ 209 MeV CM



$^{238}U + ^{248}Cm$ @ 750 MeV CM (~ V_C)

- Calculation by V. Zagrebaev
  - Dynamical model based on Langevin-type dynamical equations of motion
  - Promising results presented at the last IRiS workshop

    http://www-win.gsi.de/iris10/contributions/IRiS10_contribution_Zagrebaev.pdf
  - Meanwhile new calculations

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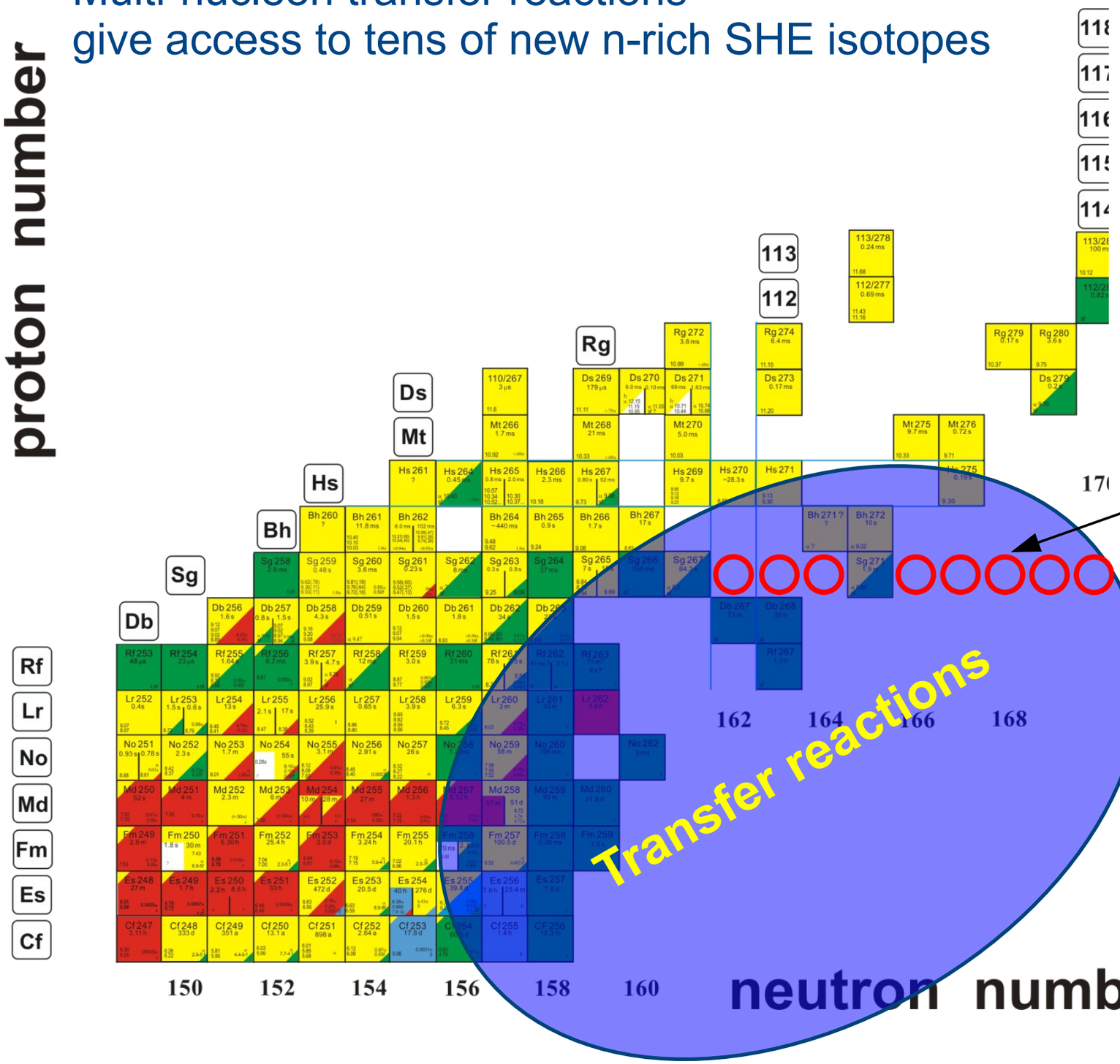
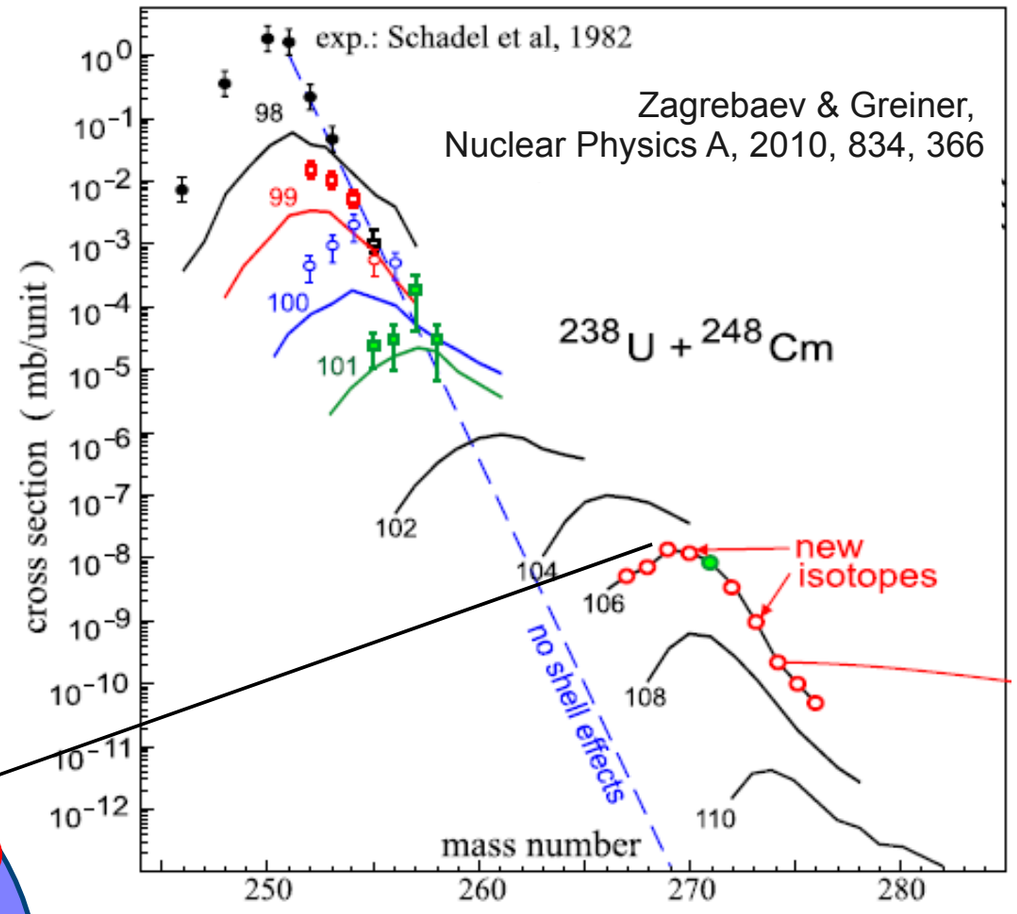
Chart of Nuclides

Multi-nucleon transfer reactions give access to tens of new n-rich SHE isotopes





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What is missing in the picture?

- ✓ Design Reactions – concentrate on ^{48}Ca,^{238}U + ^{248}Cm
- ✓ Reaction kinematics

  Reaction channels:
  - ✓ – Elastic scattering
  - ✓ – Quasi-elastic and few-nucleon transfer channels – GRAZING
  - ✓ – Multi-nucleon transfer channels – Calculations by experts
  - – Fusion – especially fusion-fission
- Preparatory experiments

Fusion-fission

- Fusion-fission – reactions with lighter projectiles
- Rather simple (comparing to other channels)
- Experimental data exist

Itkis at al., Fusion-fission of Superheavy Nuclei,

J. of Nuclear and Radiochemical Sciences, 2002, 3, 57–61

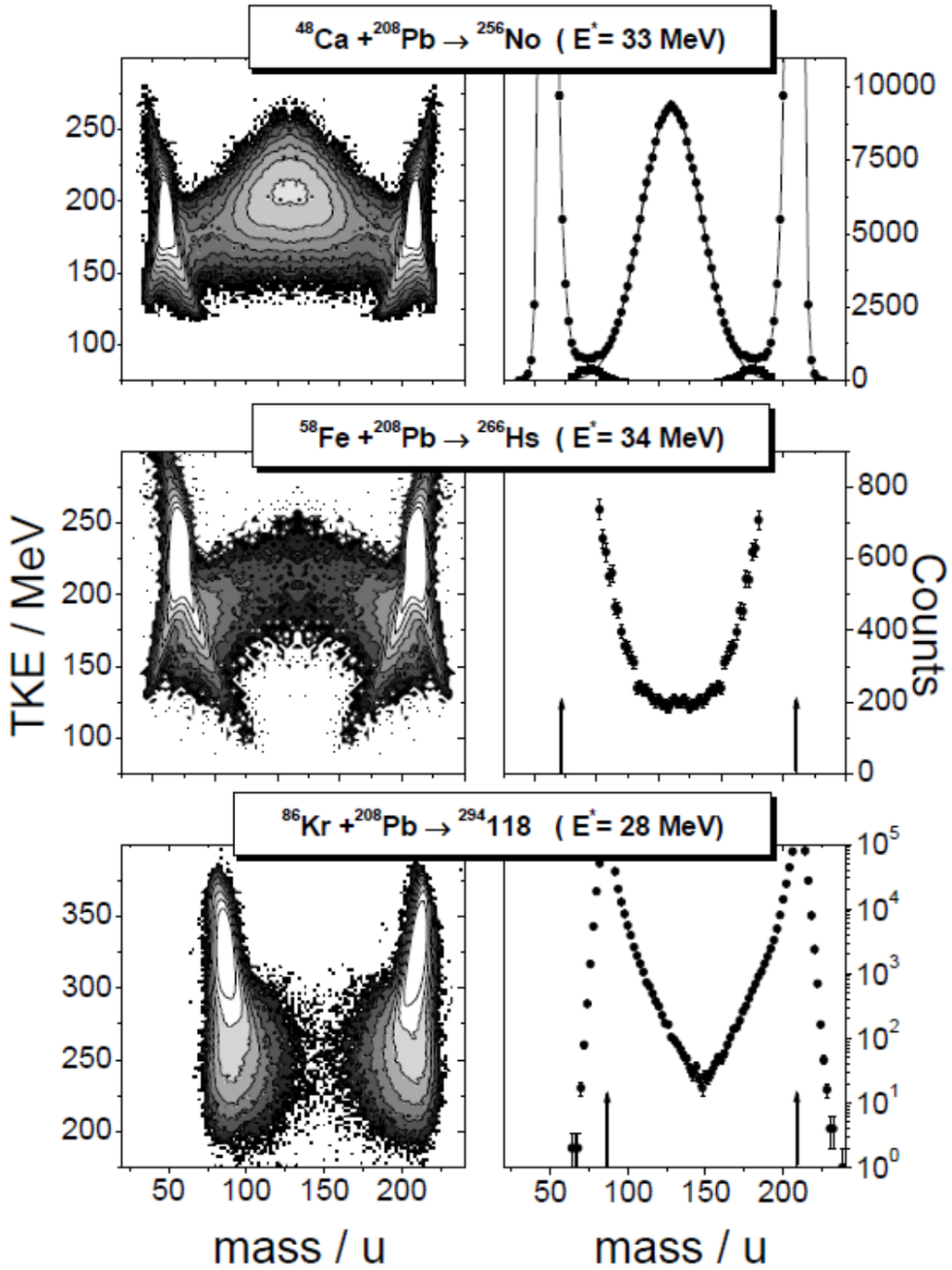
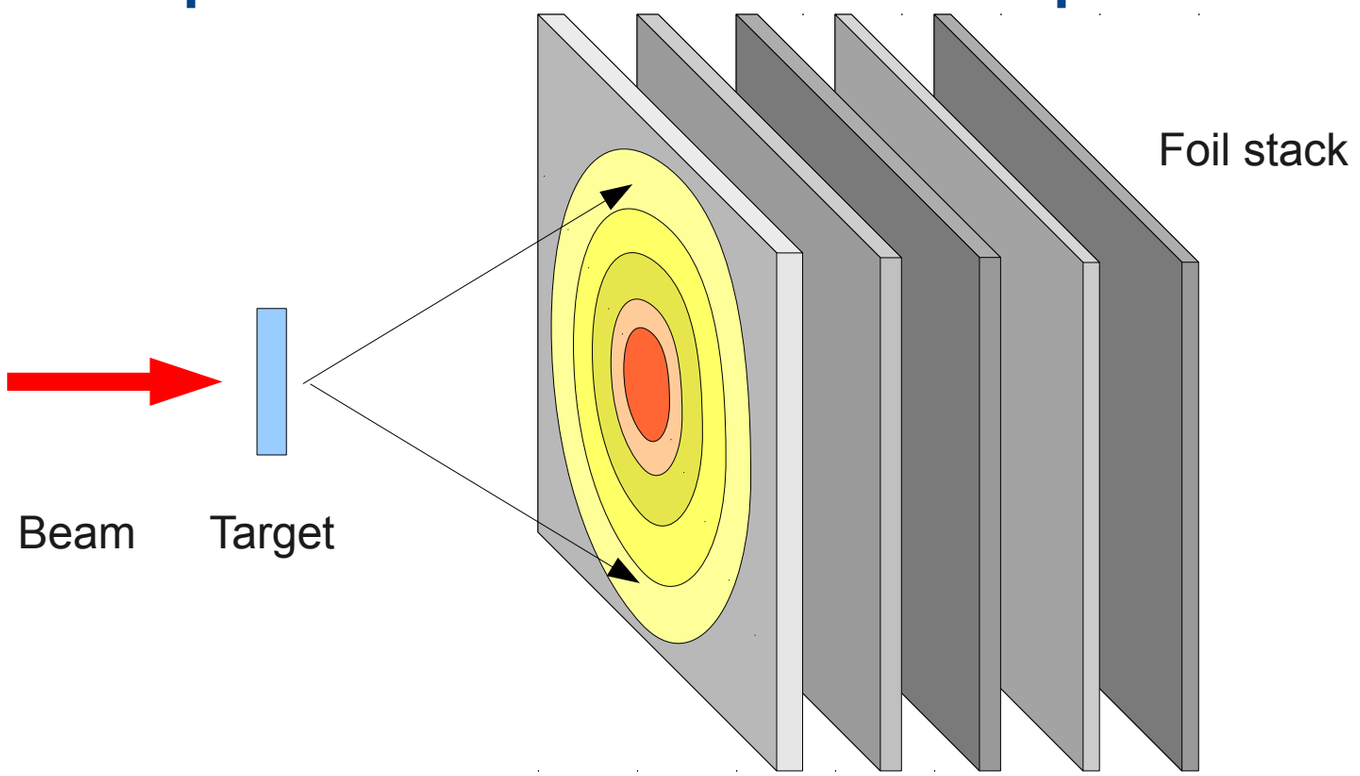


Figure 5. Two-dimensional TKE-Mass matrices and mass yields of fission fragments for the reactions $^{48}Ca + ^{208}Pb$, $^{58}Fe + ^{208}Pb$, $^{86}Kr + ^{208}Pb$ at an excitation energy of 28–34 MeV.

Preparatory experiments

- Angular distribution of SHE fragments
  - The biggest unknown
  - Critical for separator simulations
  - Experimental data missing
  - A simple radiochemical experiment would help



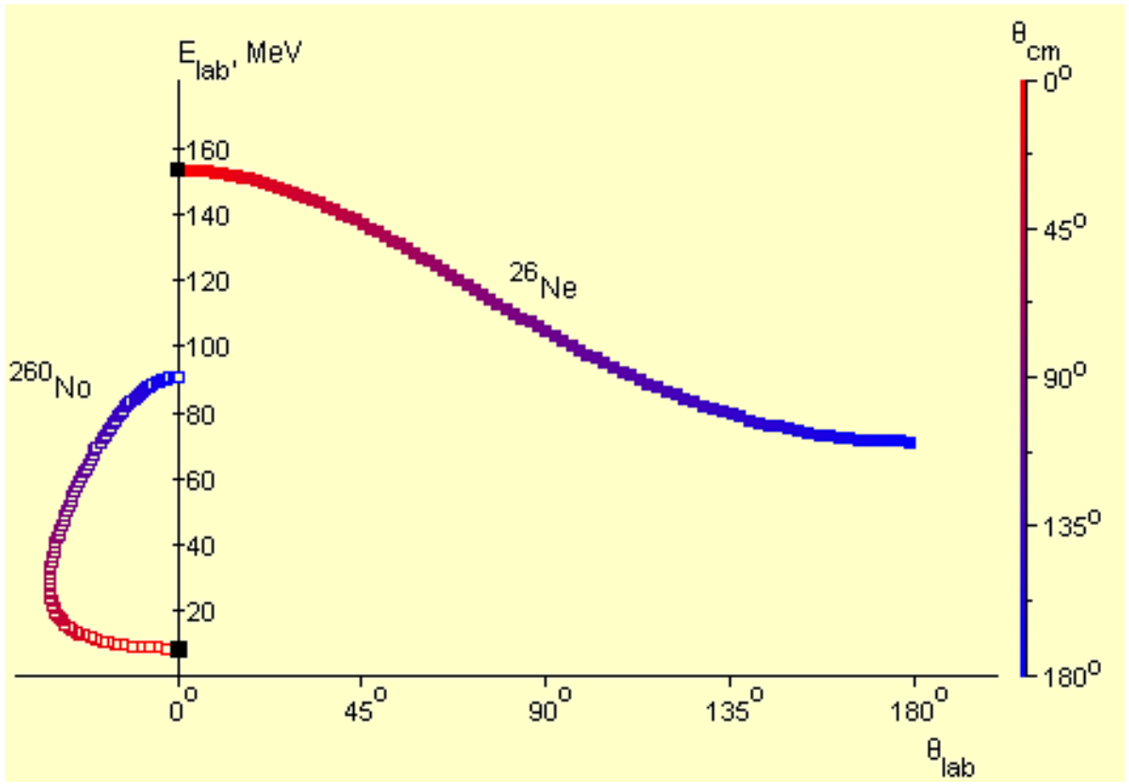
IRIS
Heavy Elements

Thank you for your attention!

2 body kinematics

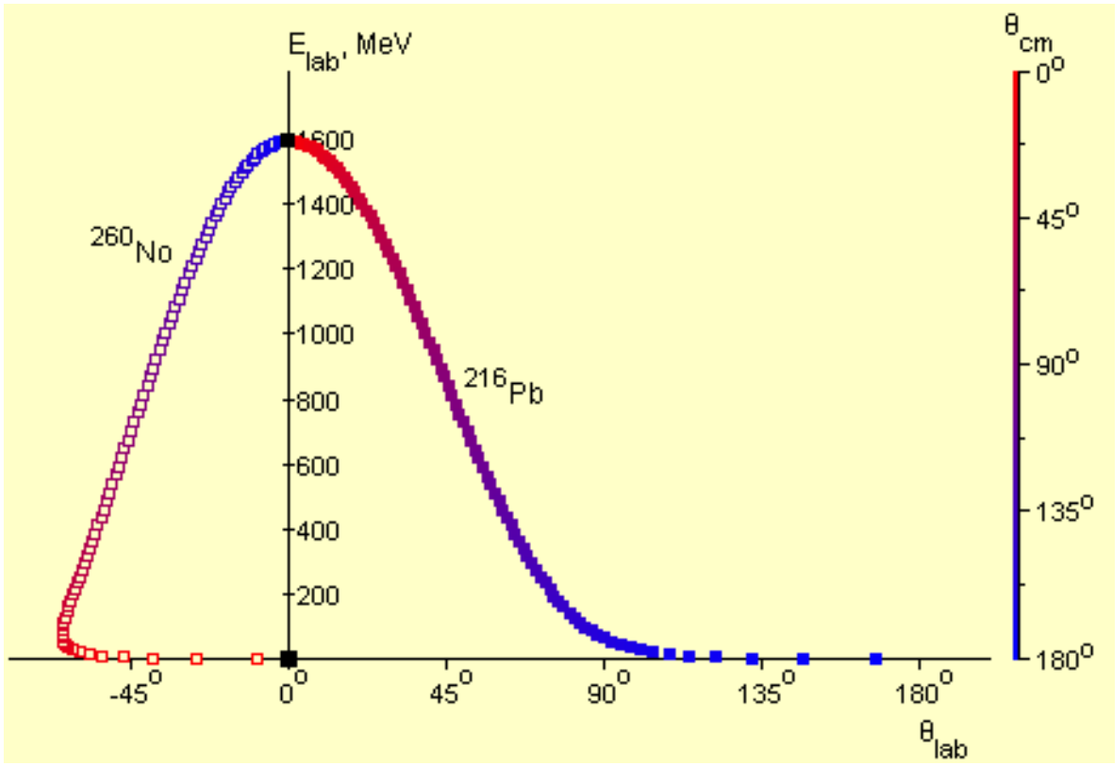
- http://nrv.jinr.ru/nrv/webnrv/kinematics/two_body.php

$^{48}Ca+^{238}U \rightarrow {}^{26}Ne + {}^{260}No$ at 255 MeV LAB



$\Theta_{LAB}(^{260}No) < 32°$, $8.7 < E_{LAB}(^{260}No) < 90$ MeV

$^{238}U+^{238}U \rightarrow {}^{216}Pb + {}^{260}No$ at 1606 MeV LAB



$\Theta_{LAB}(^{260}No) < 65°$, $3.9 < E_{LAB}(^{260}No) < 1594$ MeV