A Taste of Superheavy Element Research

Alexis Diaz-Torres (University of Surrey)

Outline

- A brief history of superheavy element research
- Production of superheavy elements & beyond the Oganesson
- Concluding remarks

The Discovery of Nobelium:
a Milestone in Heavy-Element Research

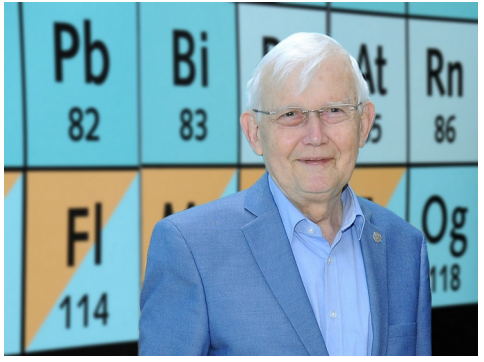
Nobelium is the first element created by *heavy ion fusion*
using a *heavy-ion accelerator*

$^{243}Am + ^{15}N \rightarrow ^{254}No + 4n$ (Donets, JINR Dubna 1966 *)

Identification by the new method of *alpha-alpha parent-daughter correlation*,
decay to known daughter nuclei guarantees safe assignment.

$^{254}No - \alpha \rightarrow ^{250}Fm - \alpha \rightarrow ^{242}Cm$

The beginning of physics with
- single atoms
- heavy-ion accelerators
- correlation technique



Courtesy of Gottfried Münzenberg

* discovery reaction, IUPAC TWG

Can shell stabilization extend the number of elements beyond the liquid-drop limit (Meitner, Frisch)?

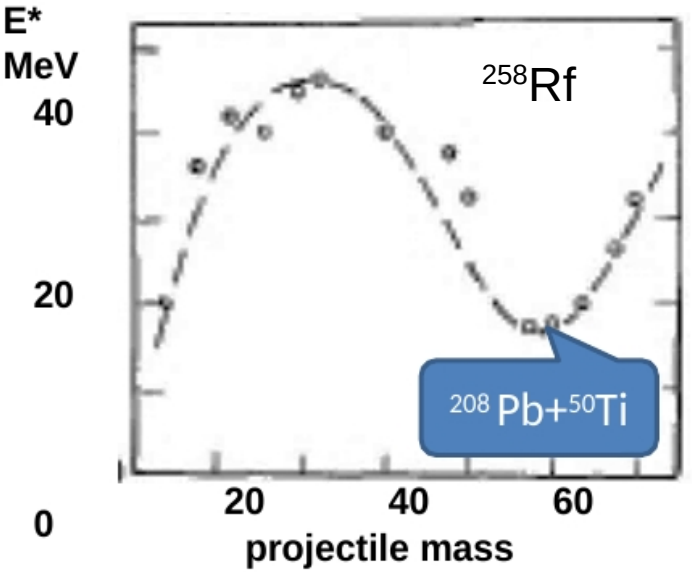
Shell model calculations say “yes” (Myers, Swiatecki semiempiric, 1966), Strutinski 1967, Nilsson 1968:

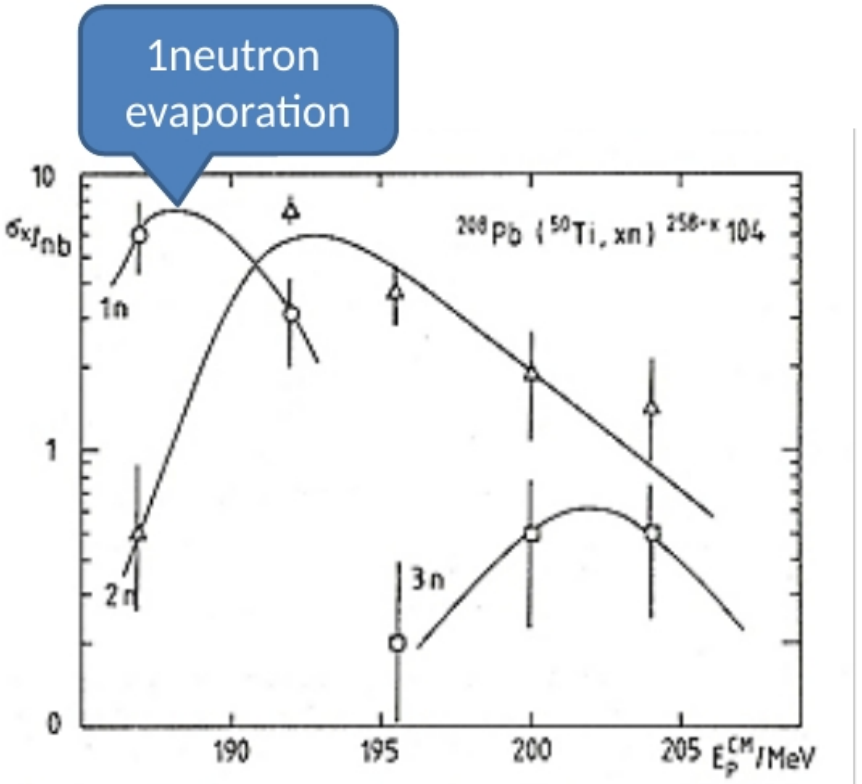
Prediction Z = 114, N=184 is the next doubly magic nucleus beyond ^{208}Pb

The birth of Super Heavy Elements (SHE)

Courtesy of Gottfried Münzenberg

Cold Fusion
paving the Way to SHE



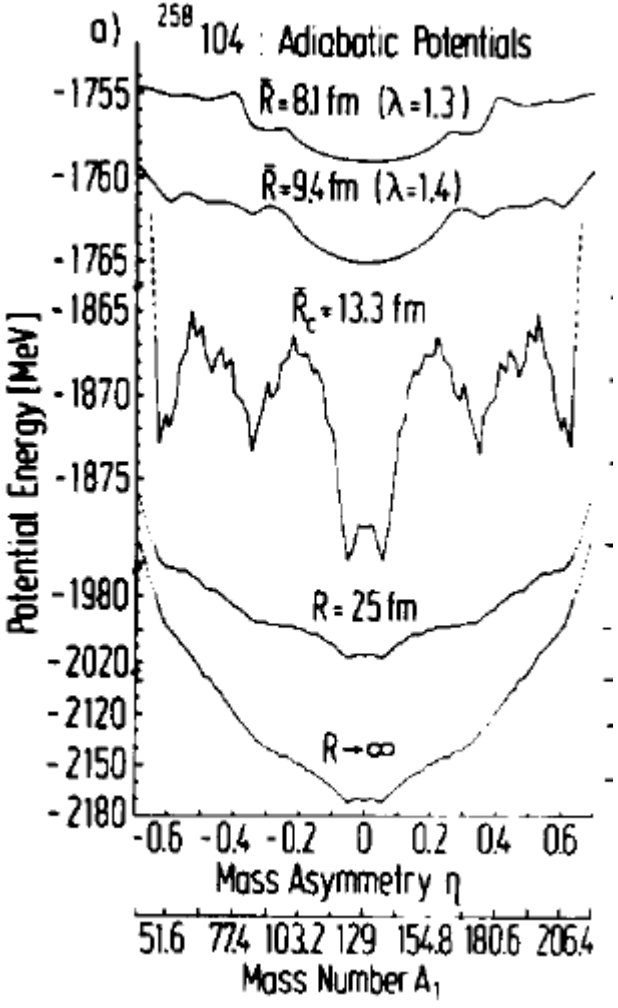


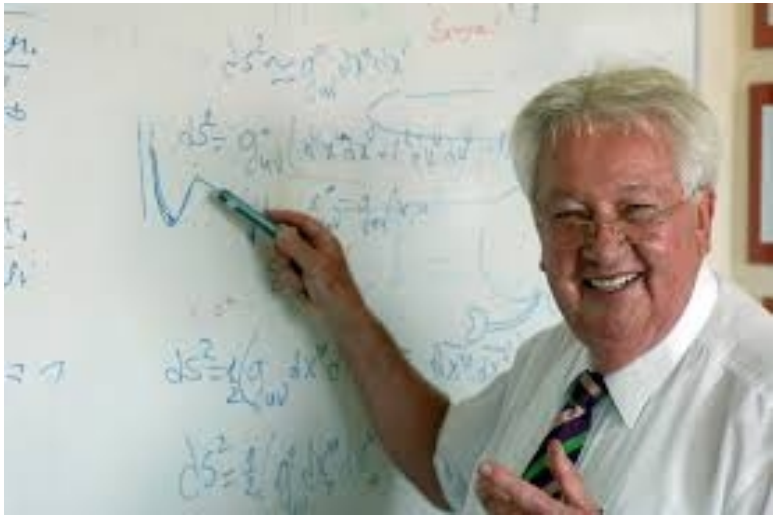
Prediction Oganessian 1974
cold fusion with doubly magic ^{208}Pb
as target

Confirmation
Measurement SHIP 1981

Courtesy of
Gottfried
Münzenberg

Cold Fusion Valleys





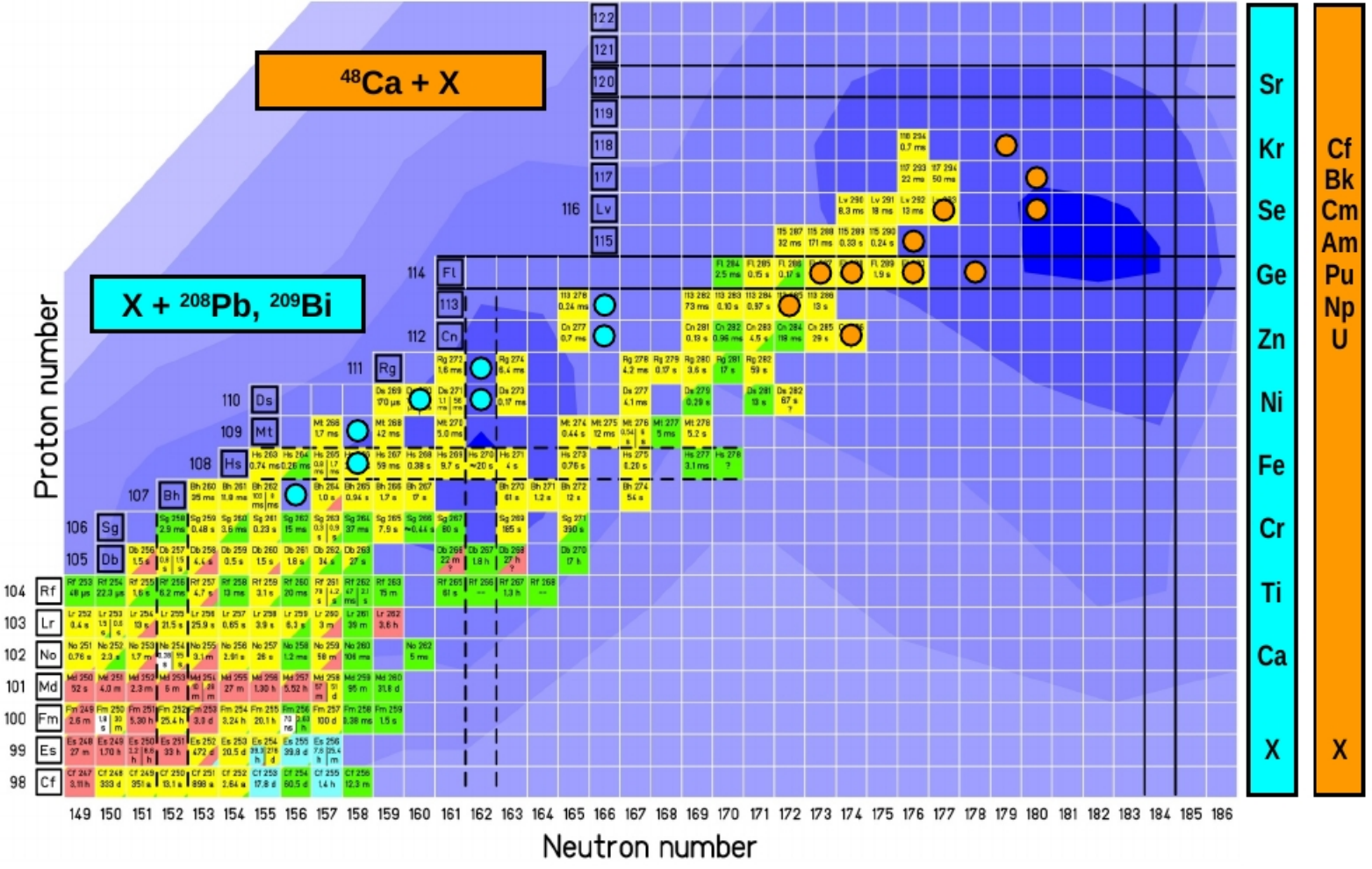
Walter Greiner

Volume 60B, number 3 PHYSICS LETTERS 19 January 1976

SYNTHESIS OF NEW ELEMENTS WITHIN THE FRAGMENTATION THEORY: APPLICATION TO $Z = 104$ and 106 ELEMENTS☆

A. SĂNDULESCU*, R.K. GUPTA**, W. SCHEID and W. GREINER
Institut für Theoretische Physik der Johann Wolfgang Goethe Universität, Frankfurt am Main, Germany

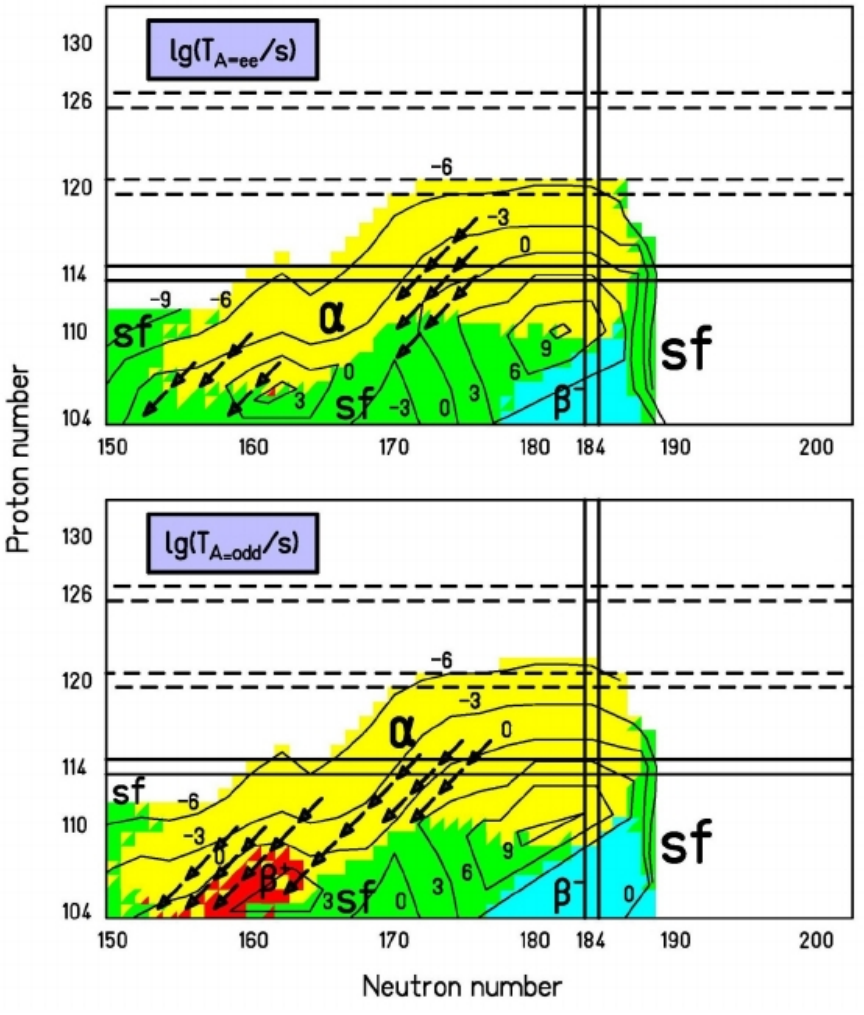
Results from cold and hot fusion





Courtesy of
Sigurd Hofmann

Dominant decay mode, agreement with experiment



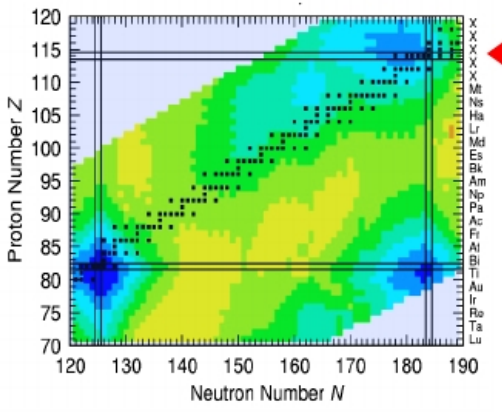
even-even

odd-A

Courtesy of
Sigurd Hofmann

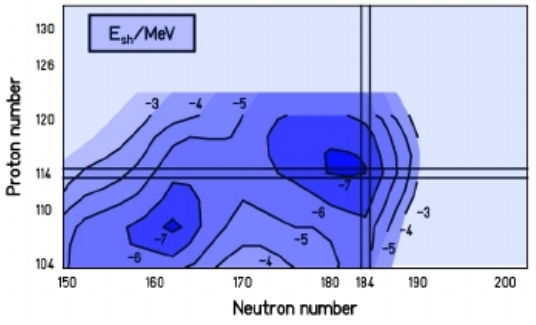
Shell effects in different models

Macroscopic-microscopic



114

P. Möller, 1995



114

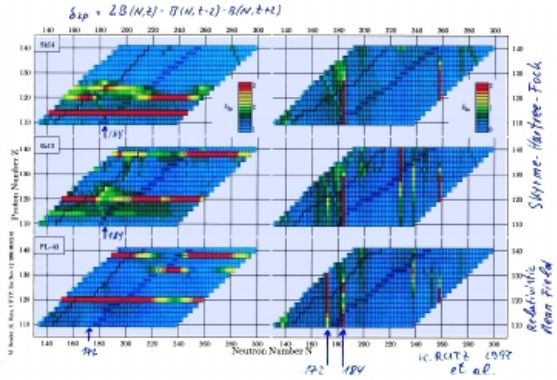
A. Sobiczewski et al., 1995

Mean field

114

120

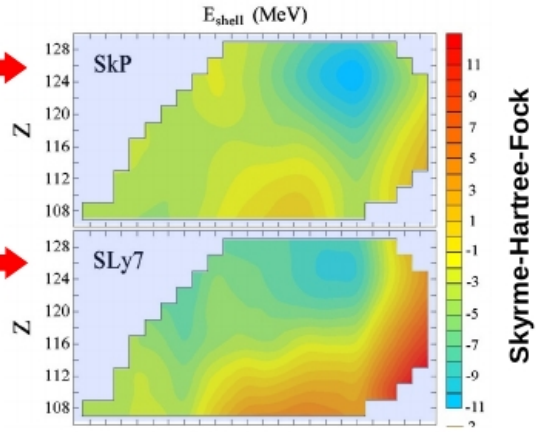
120



K. Rutz, W. Greiner et al., 1997

126

126

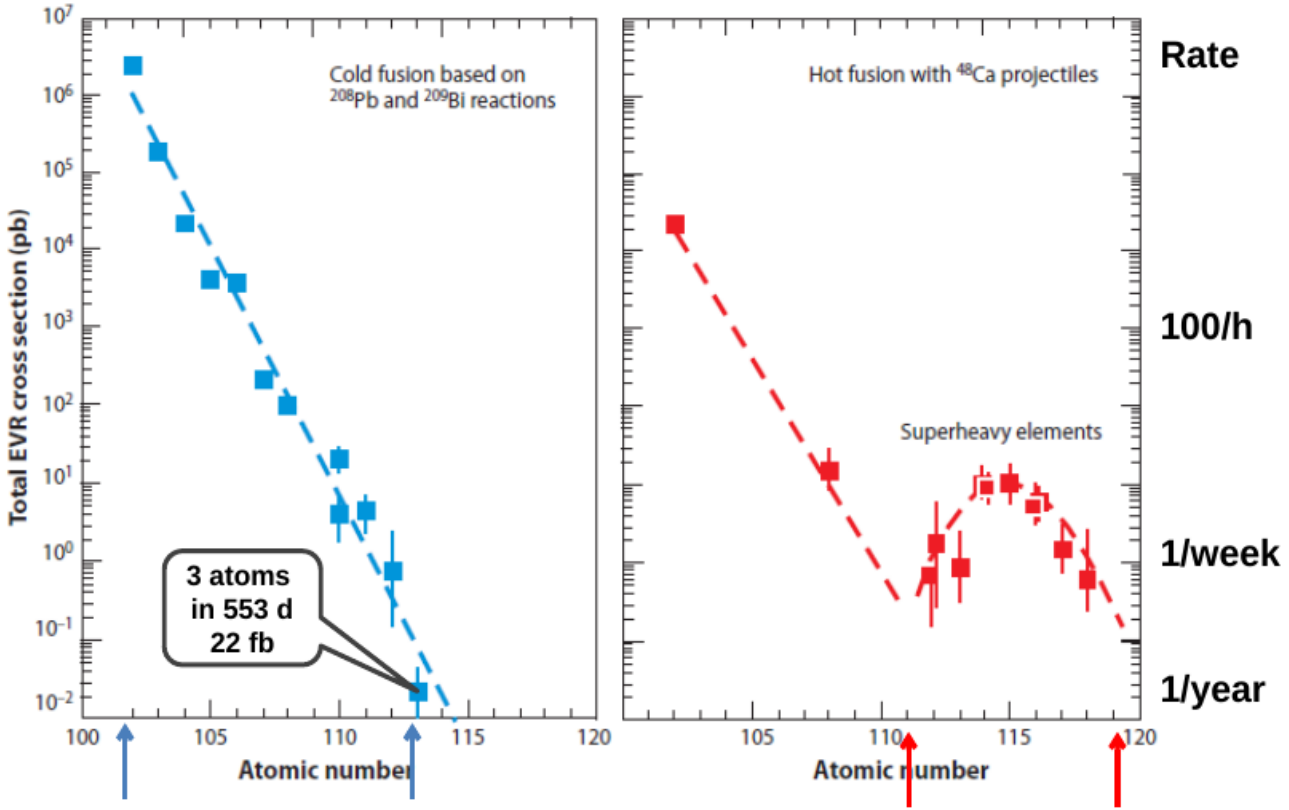


S. Cwiok et al., 1998

Courtesy of
Sigurd Hofmann

Synthesis of SHE in Cold and Hot Fusion

the influence of fusion hindrance and nuclear structure



$Z_P Z_T$ 1640 2490 1840 1960

Dominating: Fusion hindrance **Structure**

Hamilton, Hofmann, Oganessian 2013

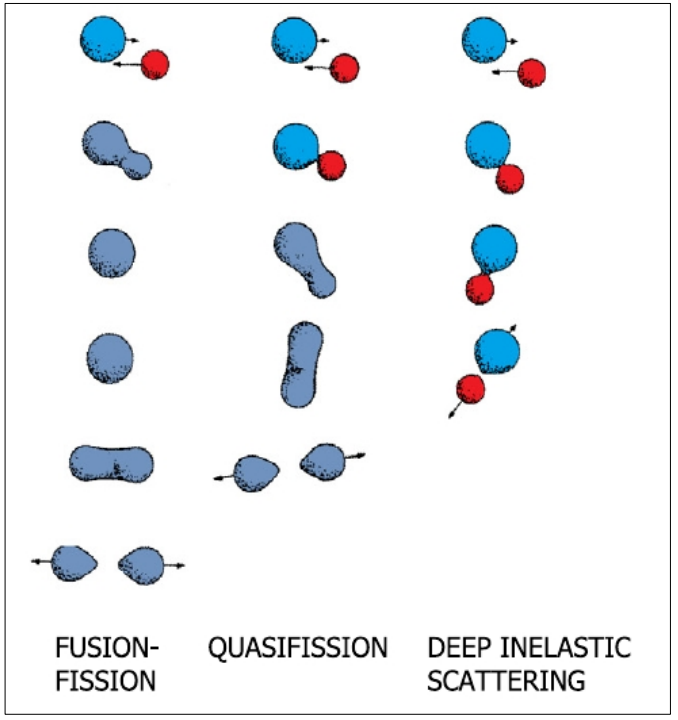
Courtesy of Gottfried Münzenberg

Evaporation Residues Cross Sections

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

capture formation survival

deep inelastic quasi-fission fission

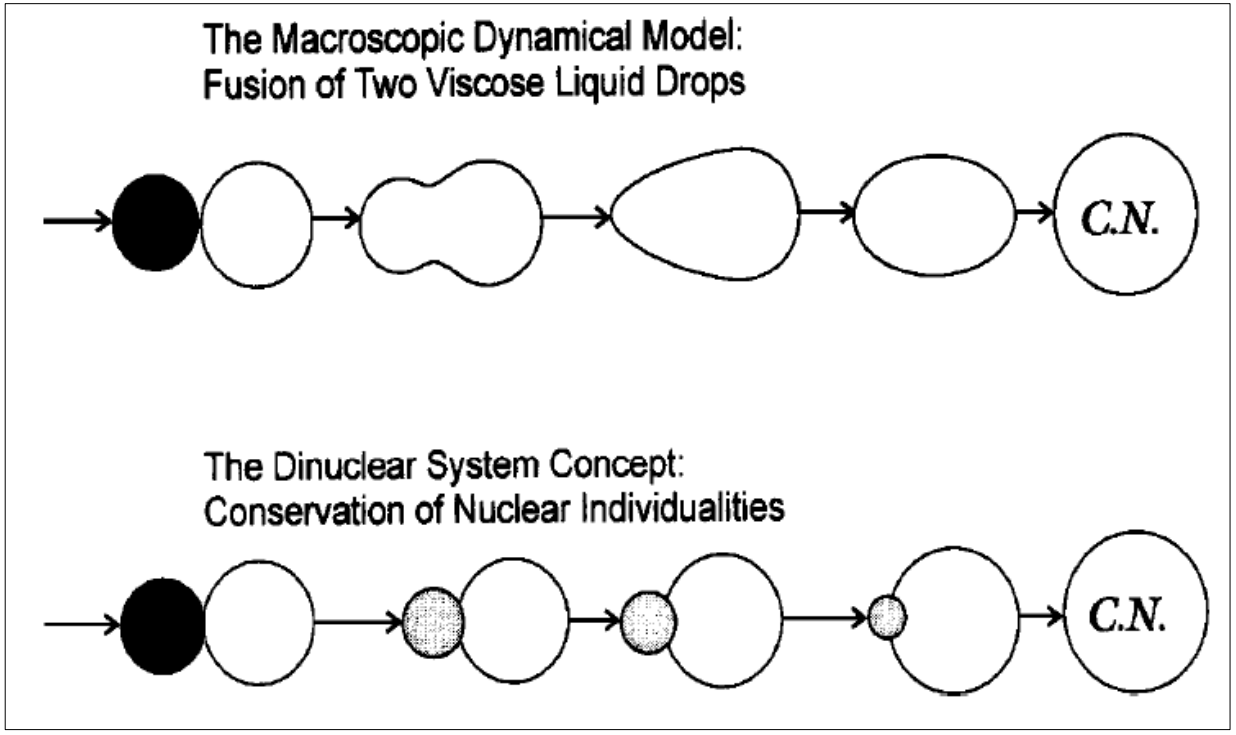


These reaction channels are only a nuisance.

The Formation of the Compound Nucleus

Adamian, Antonenko, AD-T & Heinz, EPJA **56**, 47-1-51 (2020)

AD-T, Adamian, Antonenko & Scheid, PLB **481**, 228 (2000)



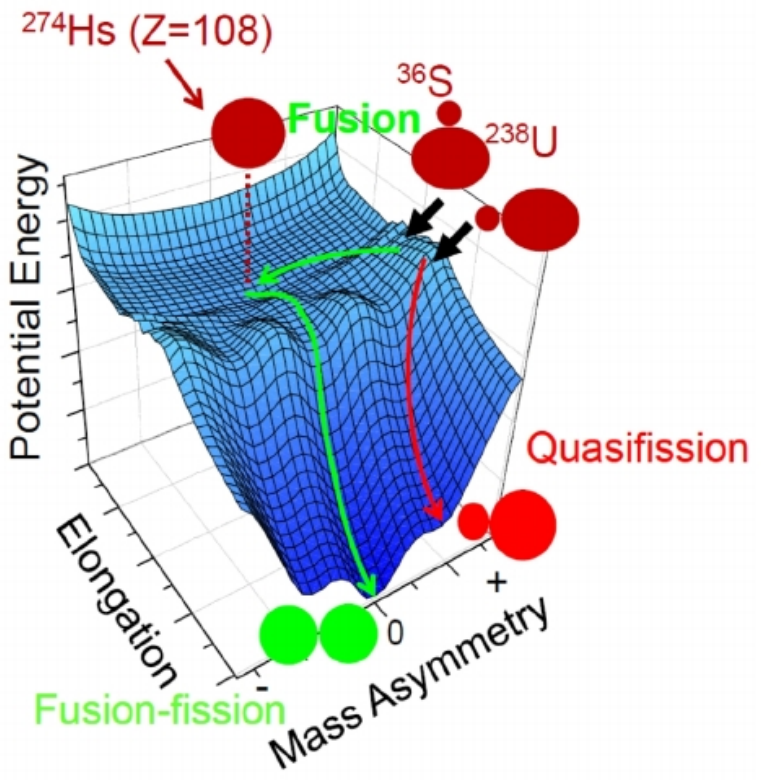


Courtesy of Vadim Volkov

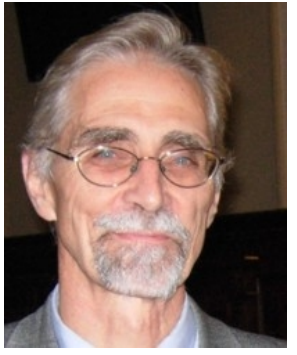
Heavy-ion reactions: Dissipation → quasifission

- Fission cross section (too large)
  - B. Heusch *et al.*, Z. Phys. A **288**, 391 (1978)
- Mass distributions (too wide)
  - B. Borderie *et al.*, Z. Phys. A **299**, 263 (1981)
- Angular distributions (too anisotropic)
  - B. B. Back *et al.*, PRL **46**, 1068 (1981)
  - B. B. Back *et al.*, PRL **50**, 818 (1983)
  - B. B. Back *et al.*, PRC **31**, 2104 (1985)
- Angle – mass correlations (not symmetric)
  - R. Bock *et al.*, NPA **388**, 334 (1982)
  - J. Toke *et al.*, NPA **440**, 327 (1985)
  - W. Q. Shen *et al.*, PRC **36**, 115 (1987)
  - B. B. Back *et al.*, PRC **53**, 1734 (1996)

- Re-arrangement of many nucleons
- Dissipation



K. Nishio, J. Phys. Conf. Ser. **282**, 012011 (2011)



Courtesy of Birger Back

Mass – angle distribution (MAD)

Compound nucleus formation:

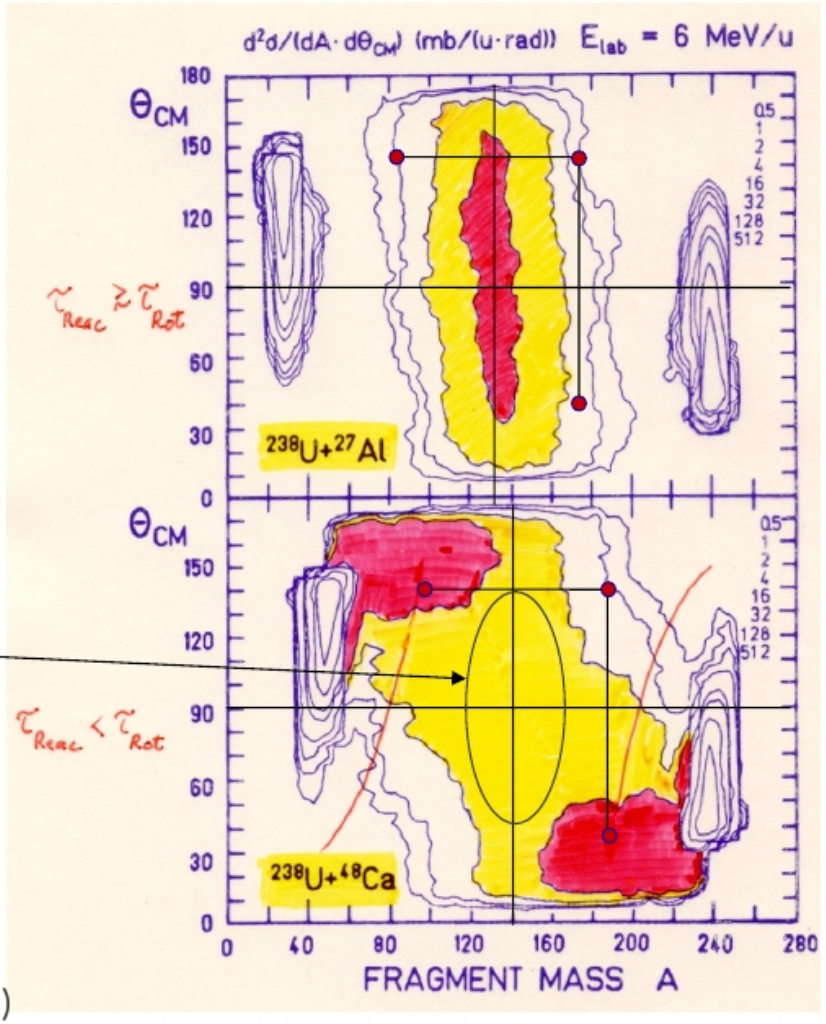
$\sigma(A,\theta)=\sigma(A,\pi-\theta)$

and

$\sigma(A,\theta)=\sigma(A_{cn}-A,\theta)$

Definite proof of dynamic process

This is where fusion-fission should appear
Buried under quasi-fission component???



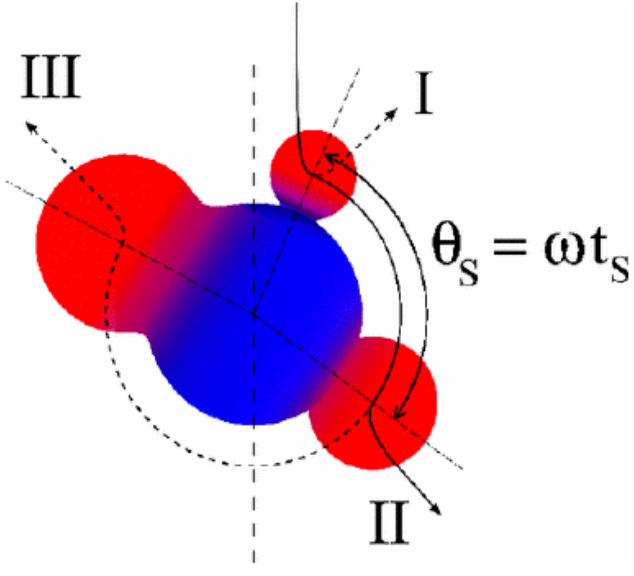
Courtesy of Birger Back

J.Toke *et al.*, Nucl. Phys. **A440**, 327 (1985)

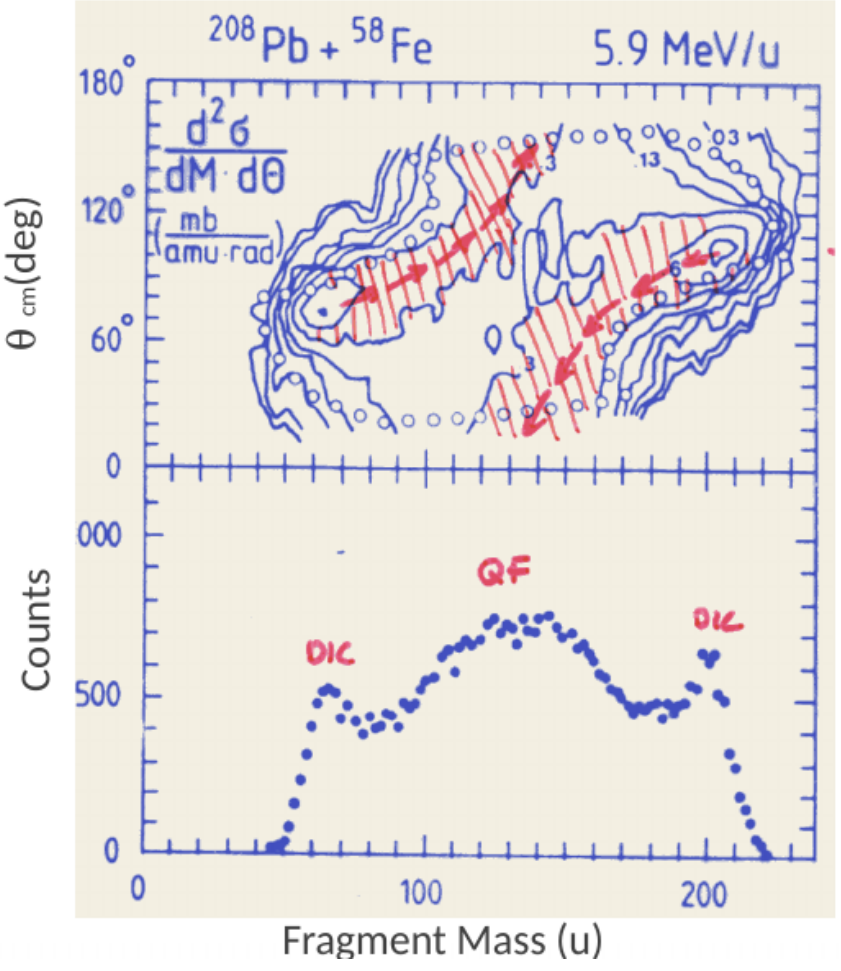
Mass drift mode

R.Bock *et al*. NPA **388**, 334 (1982)

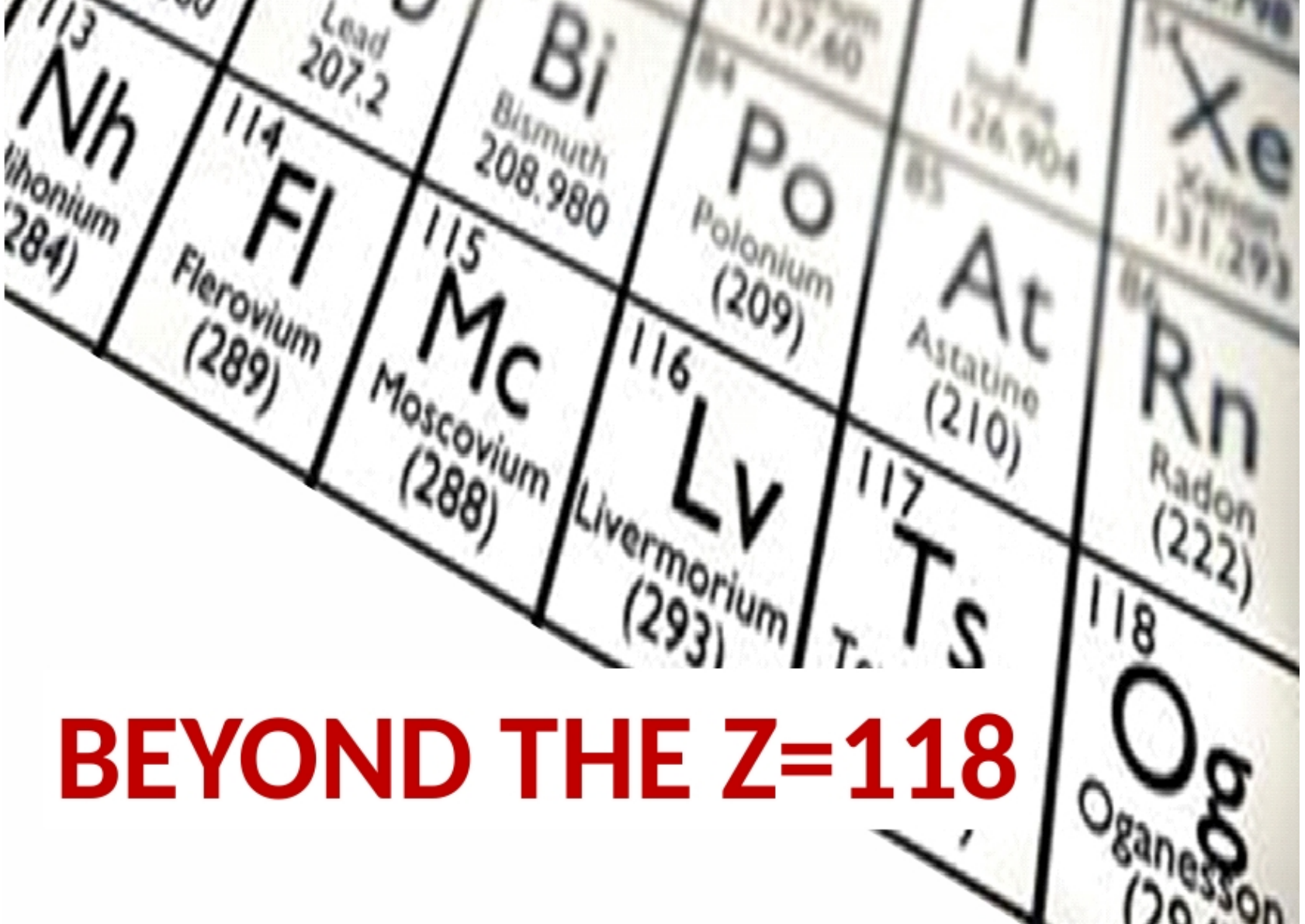
Observed early in Pb induced reactions



Du Rietz et al, PRC **88**, 054618 (2013)



Courtesy of Birger Back



BEYOND THE Z=118

2022–2025 RIKEN, Tokyo, Japan *
ORNL, Oak-Ridge Tn

2026– JINR, Dubna, Russia *
ORNL, Oak-Ridge Tn

2026? LBNL, UC Berkeley, CA
ORNL, Oak-Ridge Tn

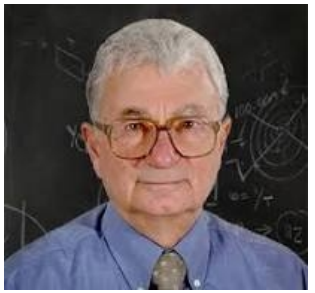
Z=119
σ ≤ 5 fb

Z=119 / 120

at SHE Factory
~ 4000 h/y beam time
25 mg/y targets Bk/Cf
3 separated exp. halls
New gas-filled separators
New condition (1st-class)

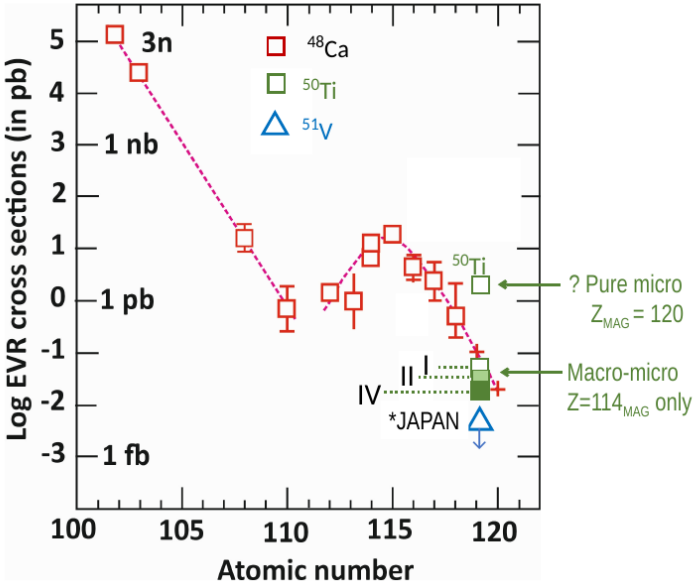
Z=120

^{50}Ti



Courtesy of
Yuri Oganessian

^{249}Bk + ^{50}Ti → ^{295,296}119 + 4n, 3n



Verification of microscopic models: MMM and RMF
Synthesis and decay properties of nuclei of elements 119 and 120

Theory

Masses of the heaviest nuclei
and
heights of fission barriers

Experiment

Energy of its alpha decay
and
the cross-section of the new SHN

Predictions of the dinuclear system model for complete fusion

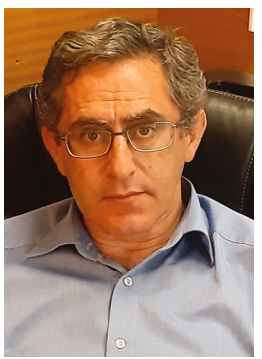
Production cross sections of 119 and 120 in $^{50}Ti + {}^{249}Bk$ and $^{50}Ti + {}^{249}Cf$ are 19 (18) fb and 8 (2) fb, respectively, within the self-consistent (MM) model

Within the TCSM(Z=120), $^{50}Ti + {}^{249}Bk$ (40 fb) and $^{50}Ti + {}^{249}Cf$ (23 fb)

The definition of the maxima of the excitation functions probably provides a good test for the predictions of the models

For $^{295-299}120$, $Q_\alpha \approx 12.0 - 11.2$ MeV, lifetimes ~3 ms −0.2 s, ~2 MeV smaller than predictions by P. Möller et al. & P. Jachimowicz *et al.*

Experimental measurement of Q_α for $Z = 120$ would help to check models and to adjust parameters to proper shell structure of SHN with $Z > 118$



Adamian & Antonenko, EPJA **58** (2022) 111

Courtesy of Gurgen Adamian

Key Messages

Science and Technology Facilities Council

There are always surprises

Superheavy nuclei: magic !!!

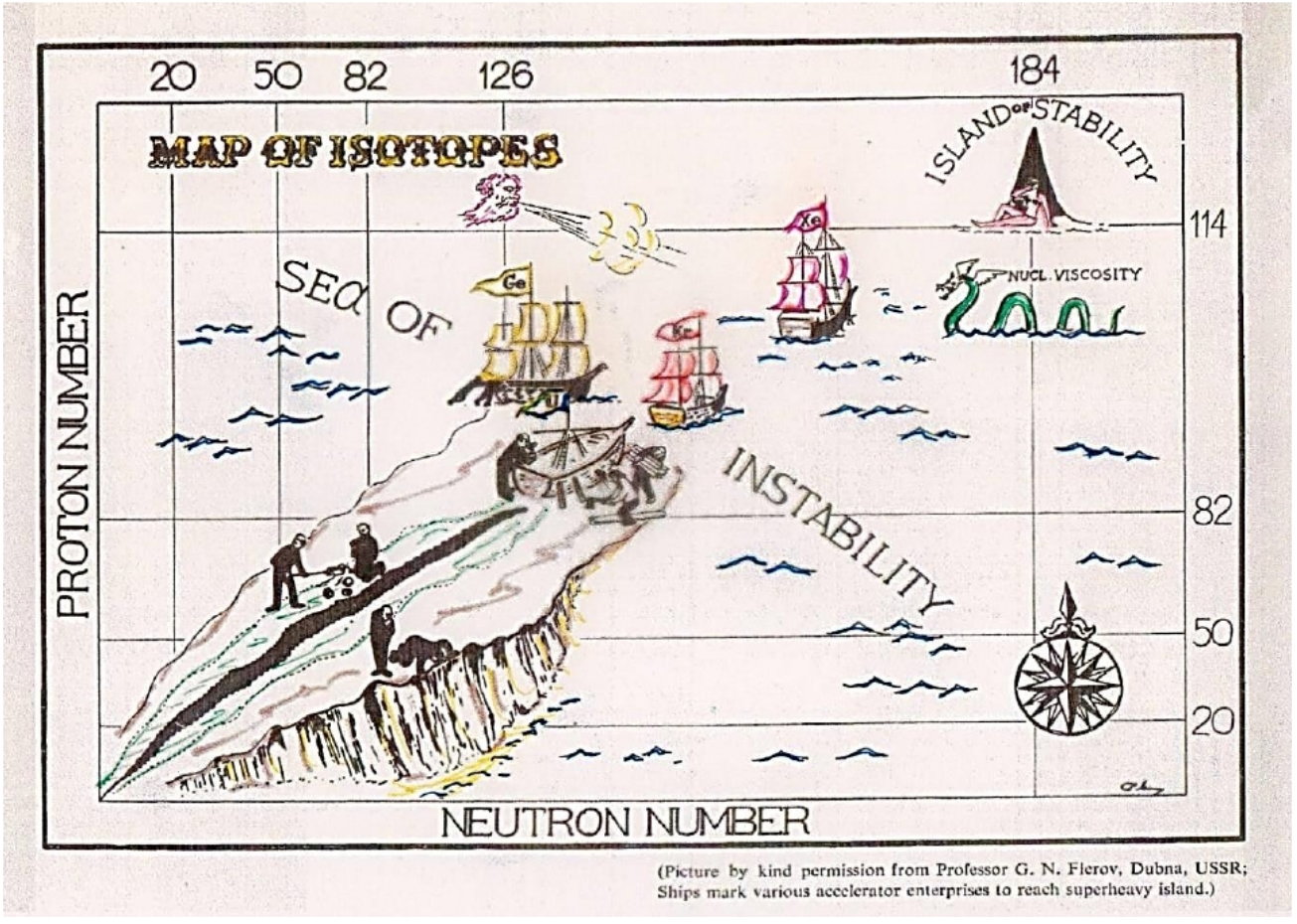
- In the fusion process,
- In the survival of the compound nucleus,
- In the stability and existence.

The Future

- Dedicated SHE facilities
- In-flight separation
- Direct identification
- Structure and Chemistry

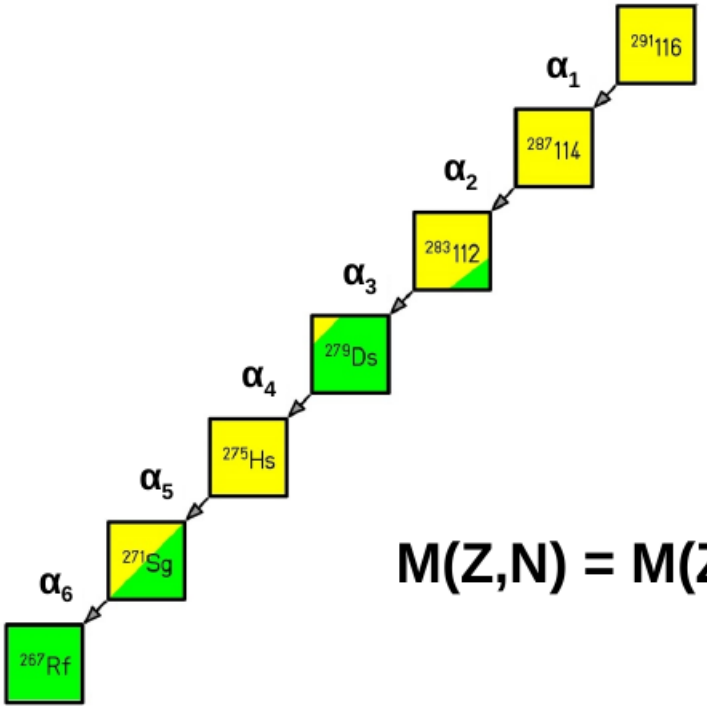
EXTRA SLIDES

Allegoric Chart of Nuclides with the Island of Stability, the Super Heavy Elements



Courtesy of Gottfried Münzenberg

Masses and shell-correction energies



$$E_{mic}/c^2 = M(Z,N) - M_{LD,theory}$$

$$M(Z,N) = M(Z-2,N-2) + M(2,2) + Q\alpha\,(Z,N)/c^2$$

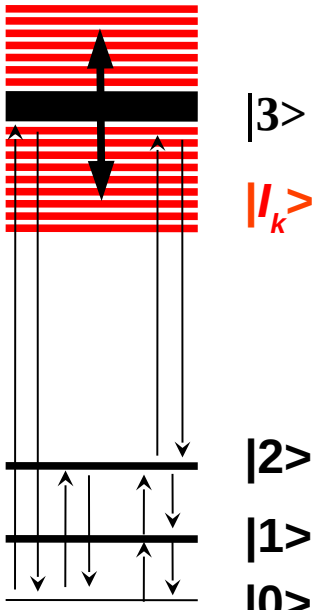
Unknown mass of end point adjusted to AME mass or to theoretical value

Courtesy of
Sigurd Hofmann

The Capture Process



relative motion



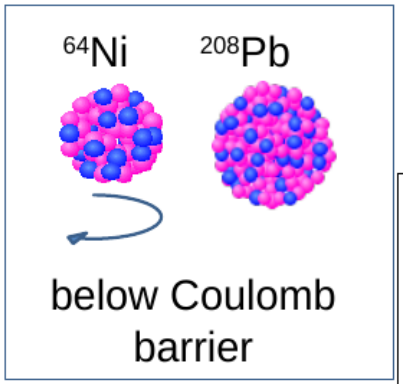
nuclear structure

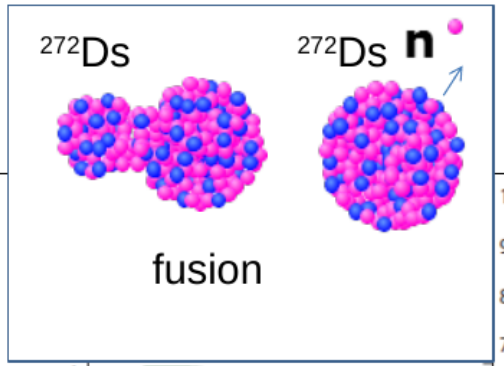
Scales

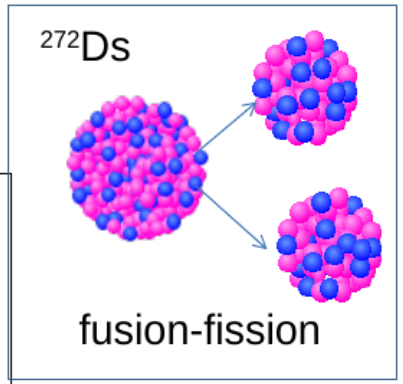
Length – 1 fm = 10^{-15} m
Time – 1 zs = 10^{-21} s
Energy – 1 MeV = 10^{6} eV

Interplay between **relative motion** and **nuclear structure** determines capture cross sections.

Heavy-Ion Fusion: creating Super-Heavy Elements





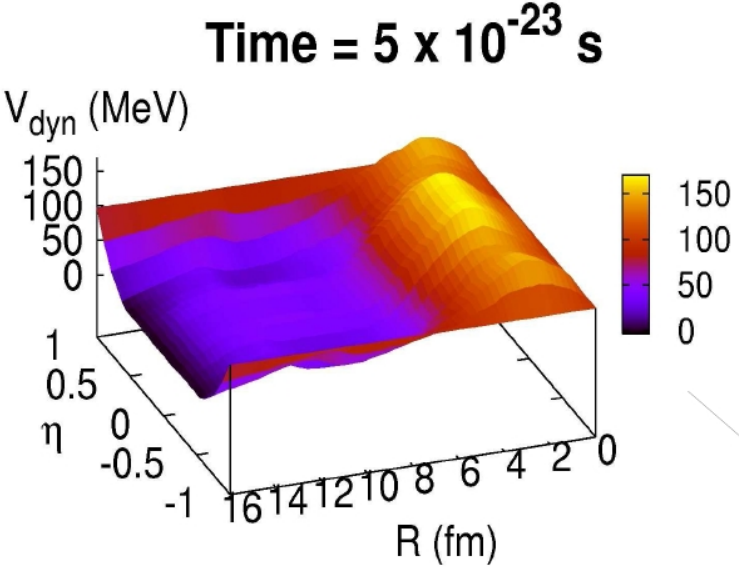


Projectile energy too low

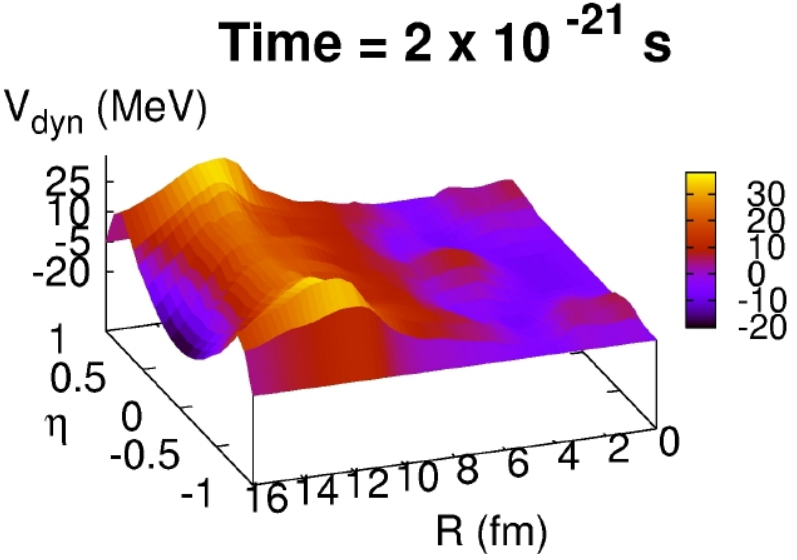
Data: Hofmann 1998
Theory: Giardina 2000

Courtesy of Gottfried Münzenberg

AD-T, PRC **74** (2006) 064601



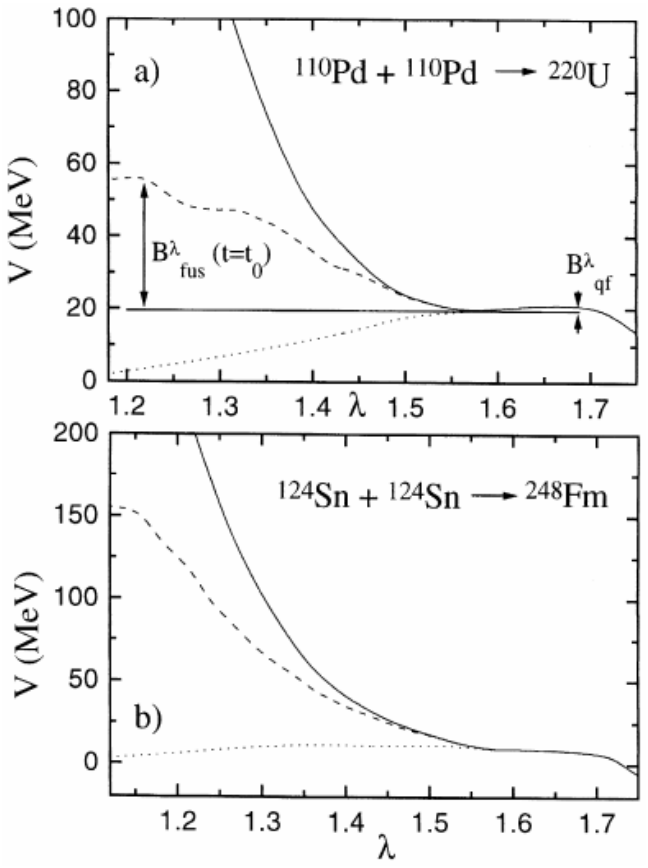
TIME



Dynamical Landscape !

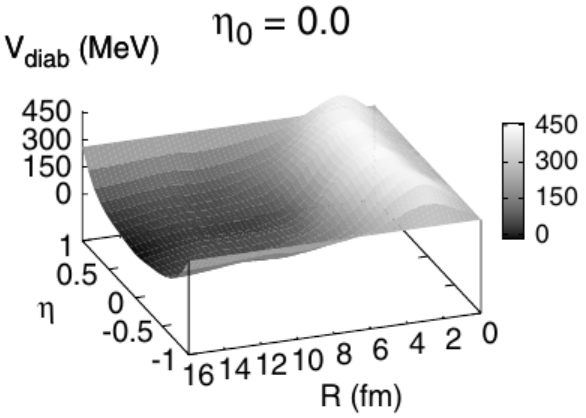
Dynamical Potential Energy Surface

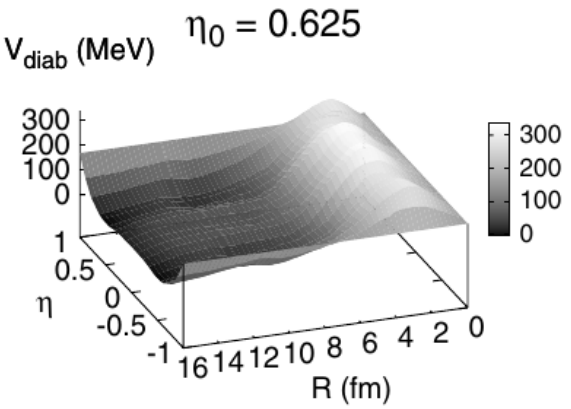
AD-T, Adamian, Antonenko & Scheid, PLB **481**, 228 (2000)

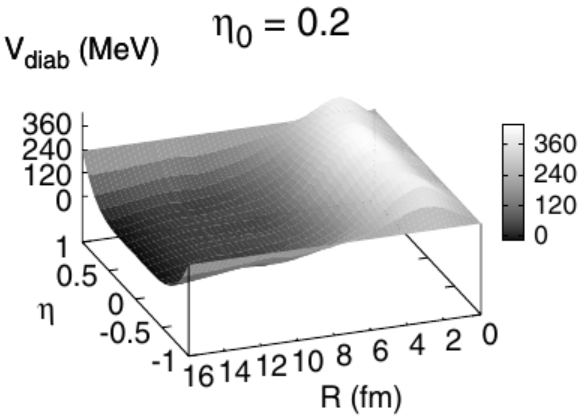


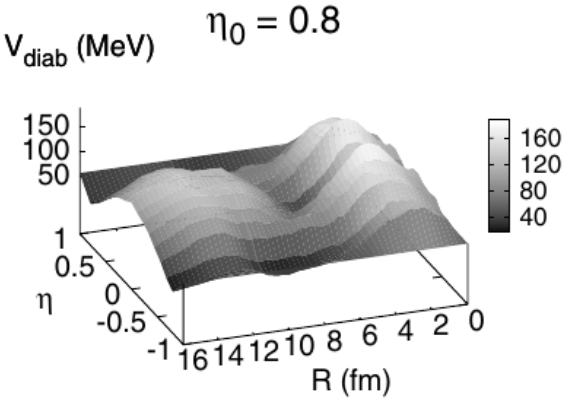
Diabatic PES in collisions forming ^{256}No

AD-T, PRC **74** (2006) 064601



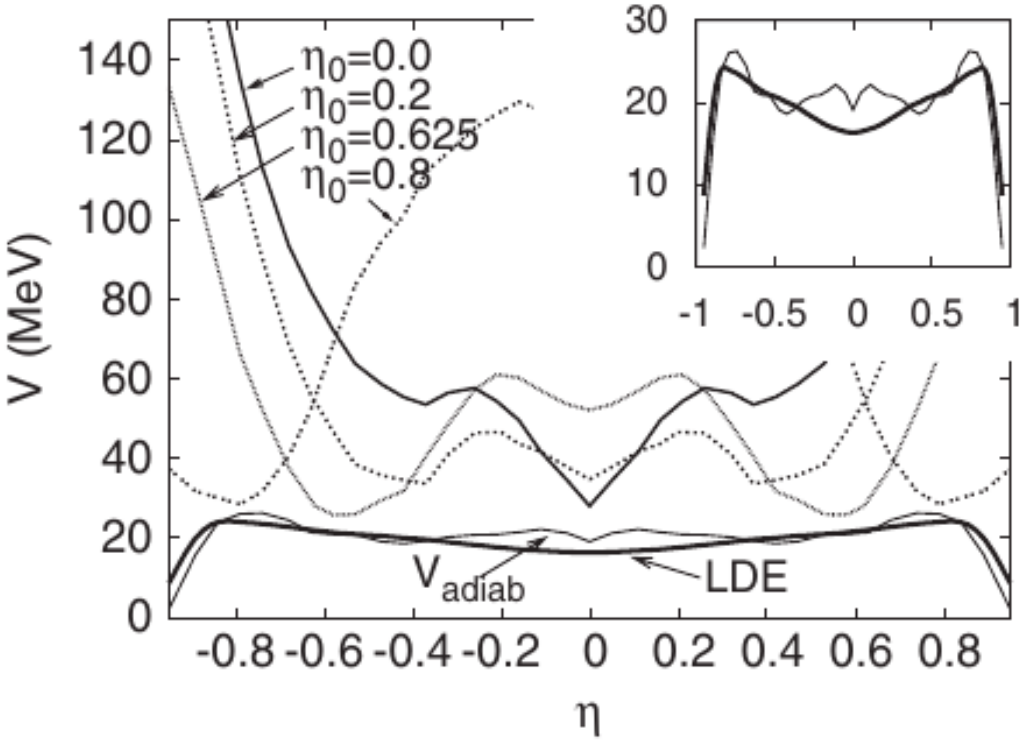






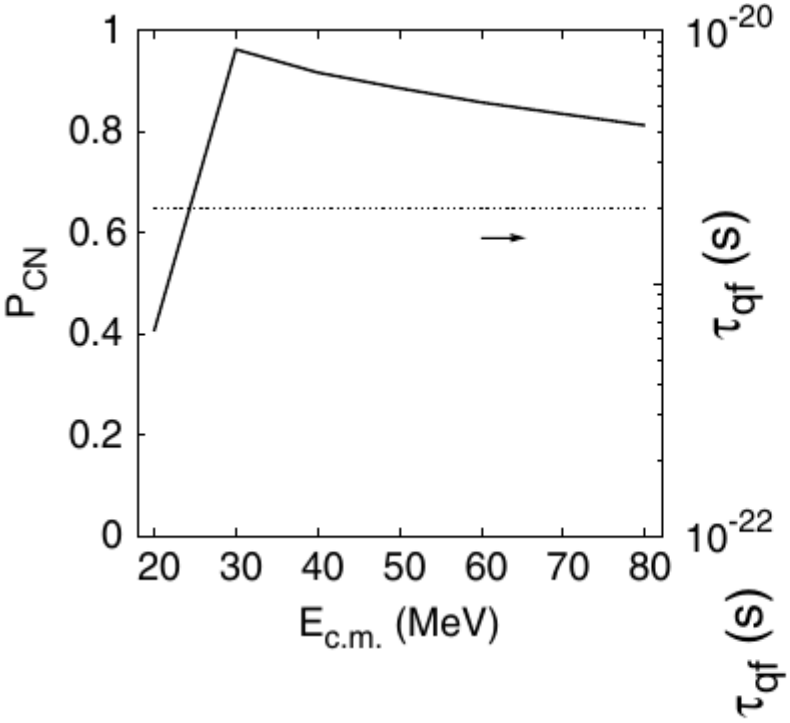
Diabatic Driving Potential in collisions forming ^{256}No

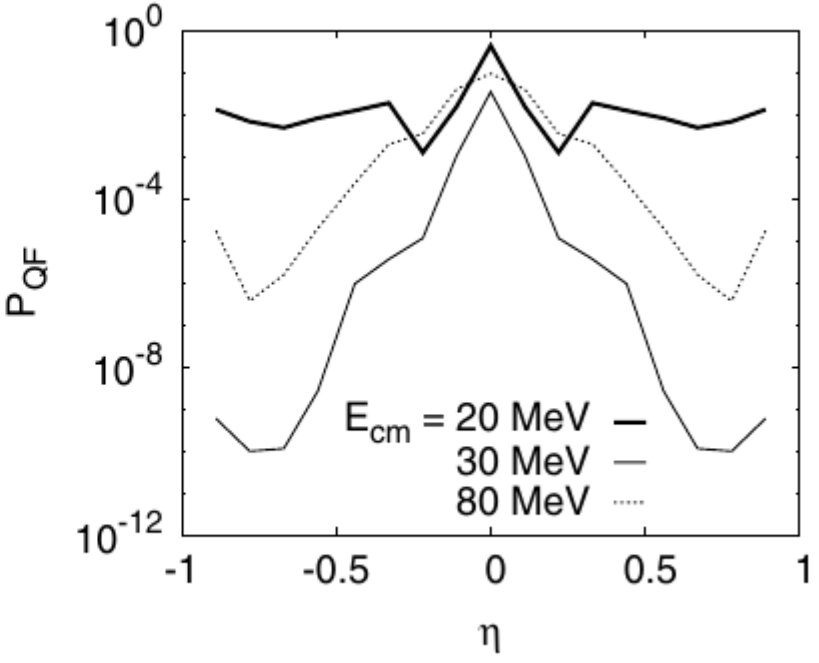
AD-T, PRC **74** (2006) 064601



Fusion & Quasi-fission Probabilities in collisions forming ^{256}No

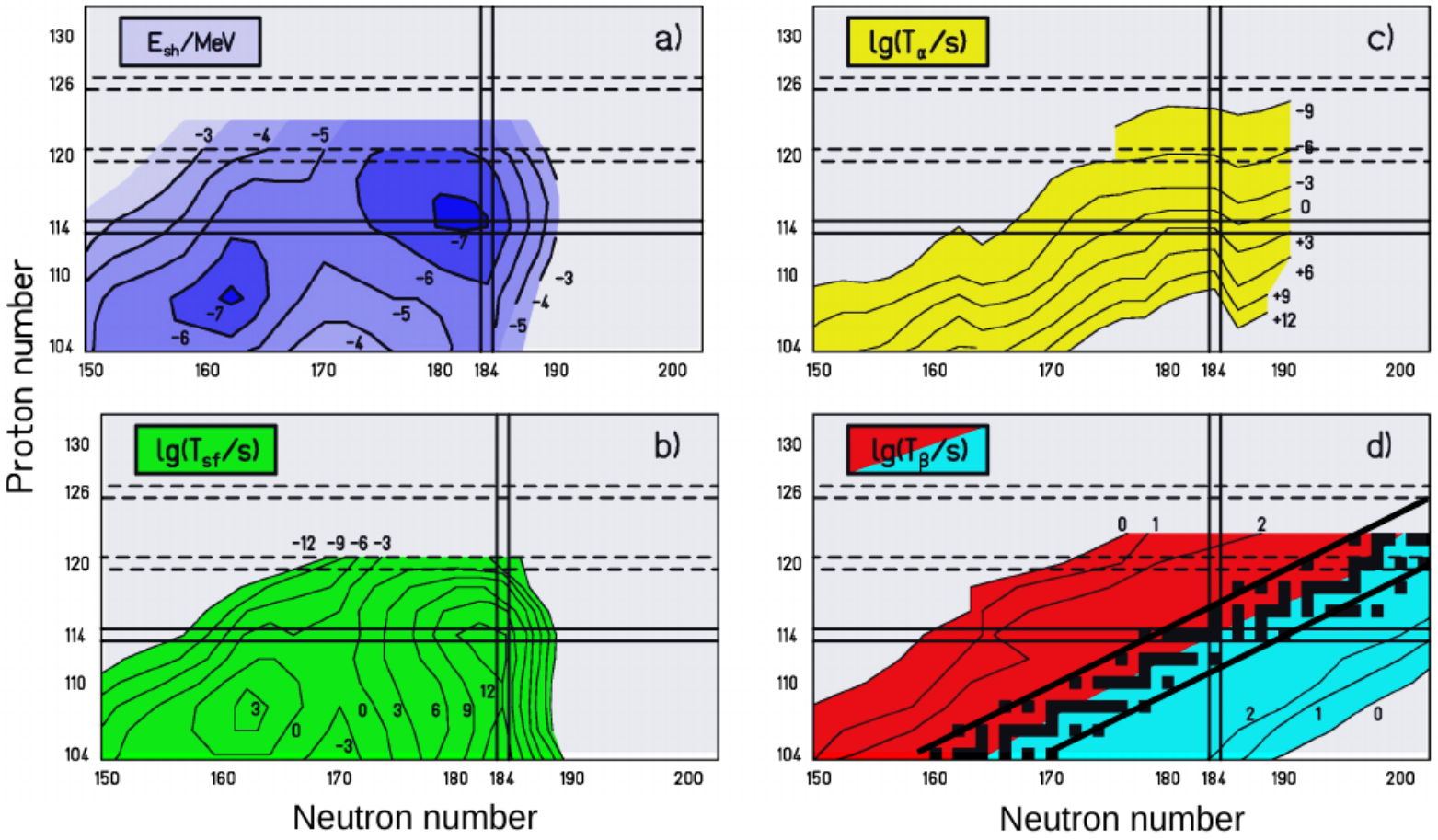
AD-T, PRC **74** (2006) 064601





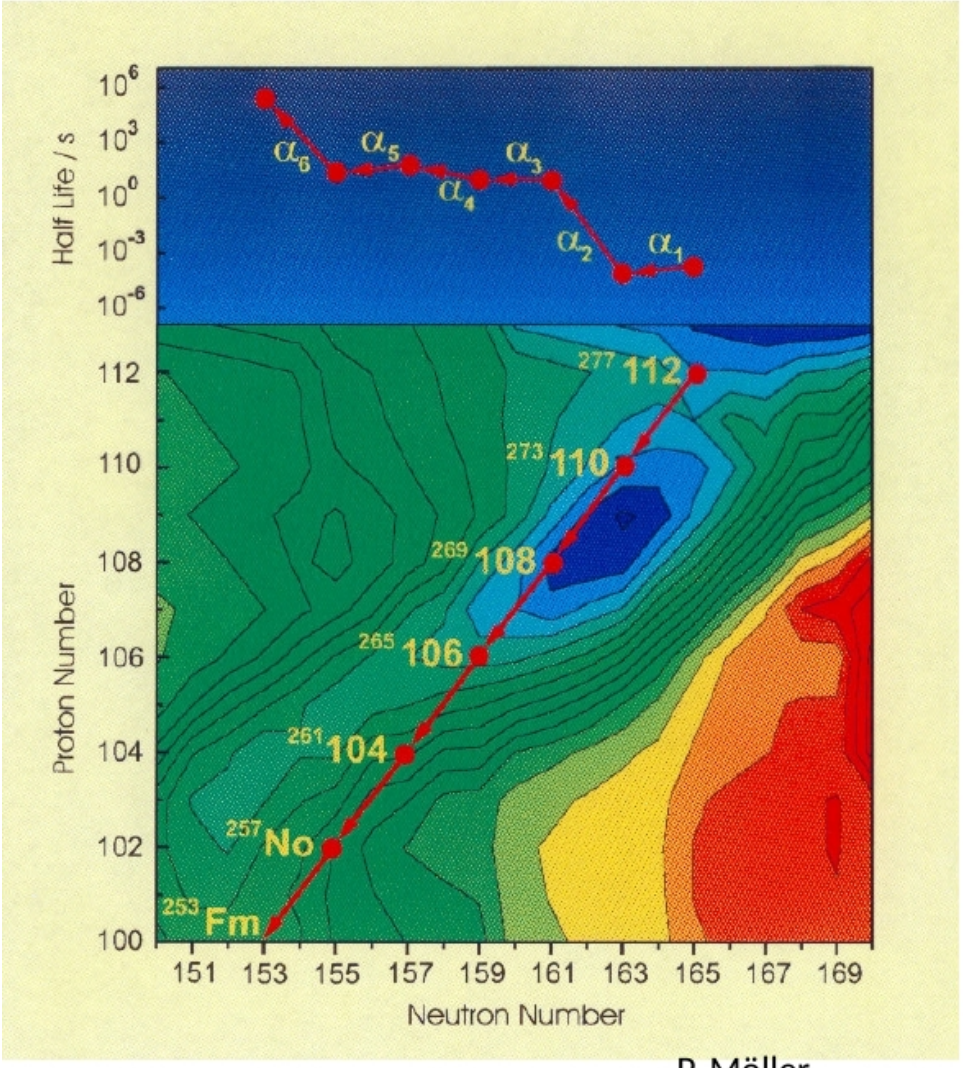
Predictions of the macroscopic-microscopic model

Calculation: R. Smolanczuk, A. Sobiczewski et al.; P. Möller et al.



Courtesy of
Sigurd Hofmann

The Shell at Z=108, N= 162



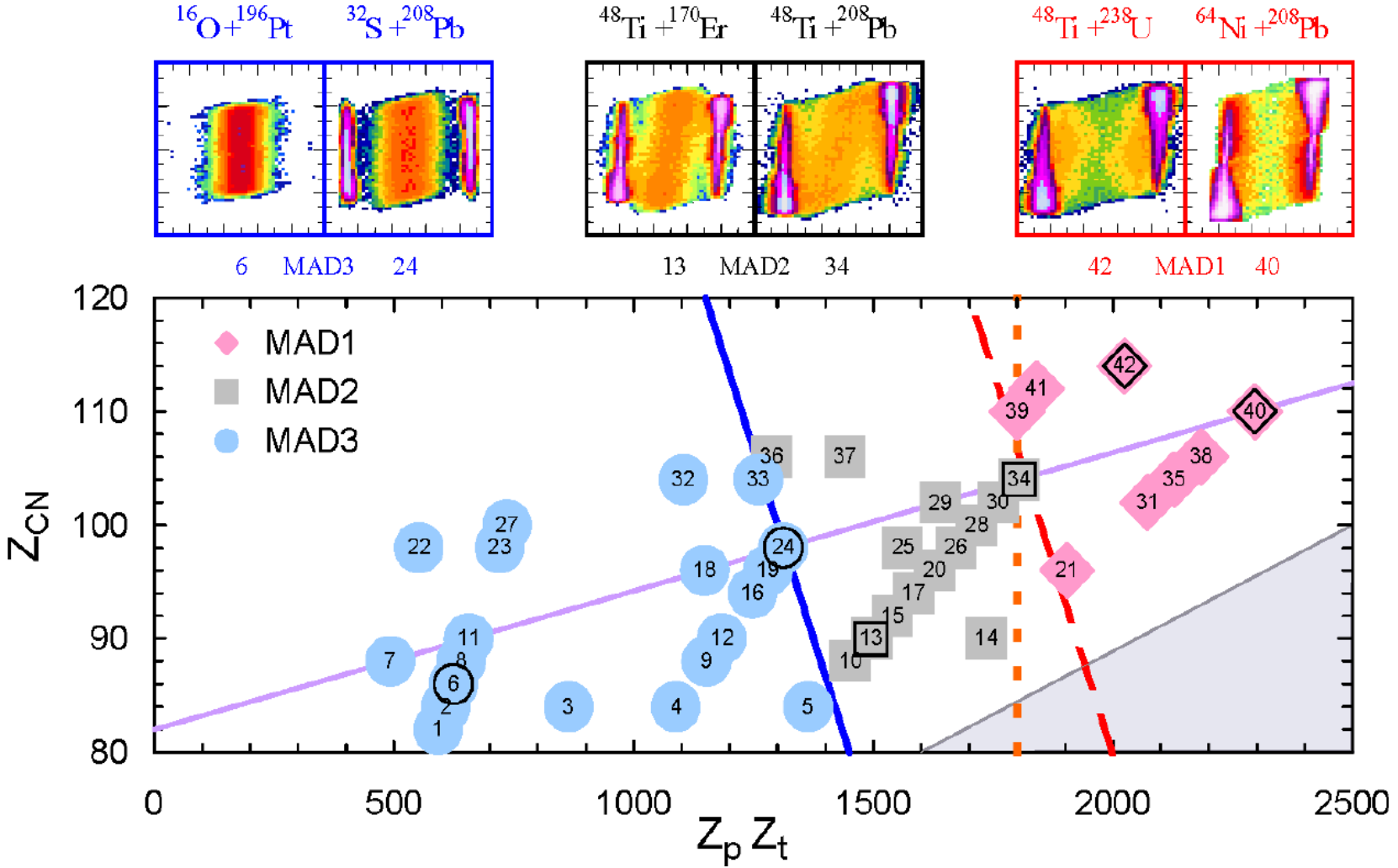
The first decay chain of element 112 (copernicium)

- Upper part: measured lifetimes
- Lower part: 112 α- chain with the calculated shell landscape

We found a deformed shell
-> Basis for the existence of elements beyond Z=104

Courtesy of Gottfried Münzenberg

Mapping Timescales of Quasi-fission

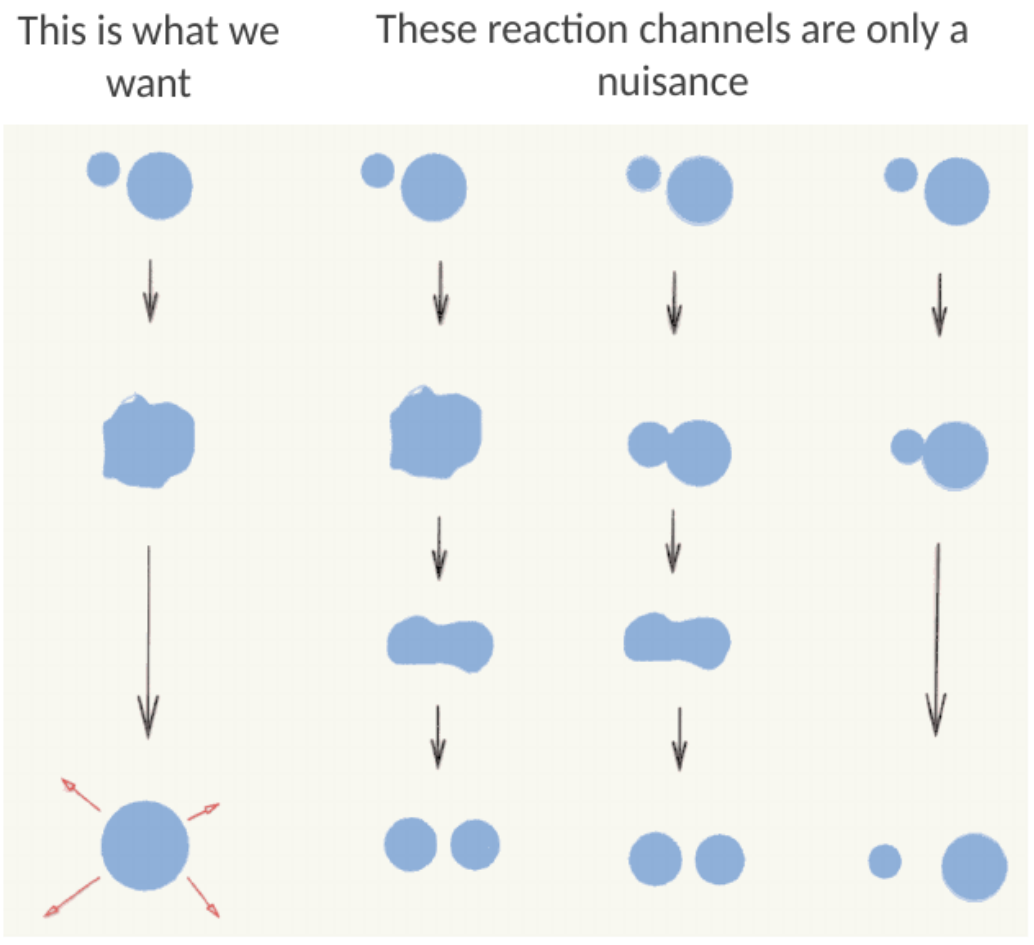


Du Rietz et al, PRC **88**, 054618 (2013)



Courtesy of David Hinde

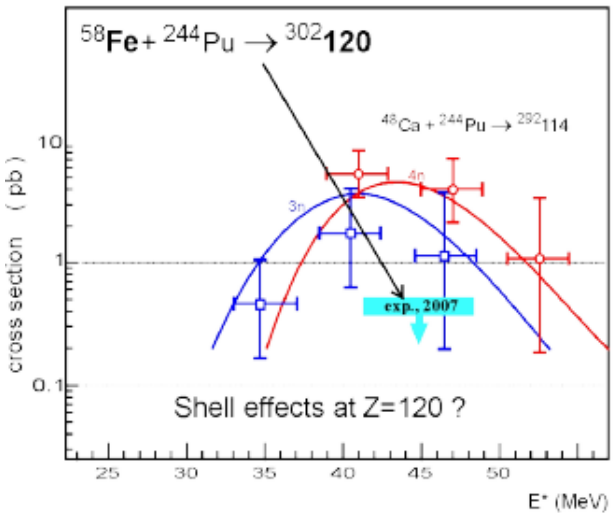
Making Super-heavy elements



Courtesy of Birger Back

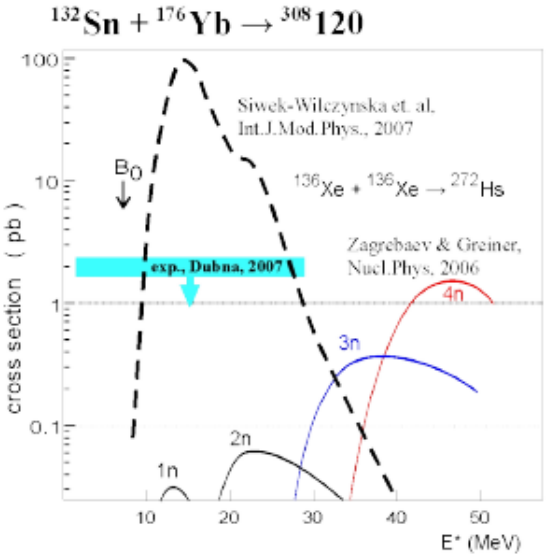
The Future: New methods for the synthesis of SHE

Heavier that ^{48}Ca projectiles



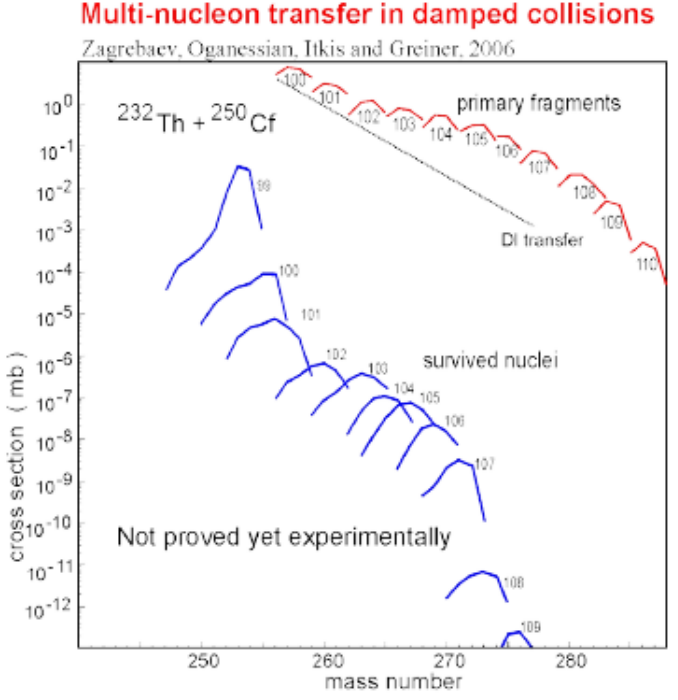
More intensive beam is needed

Fusion of accelerated fission fragments



No chances for low-intensive RI- beams of accelerated fission fragments like ^{132}Sn

Multi-nucleon transfer in damped collisions



^{160}Gd + ^{186}W is a good testing reaction

Quantum Wave-Packet Dynamics

- **Preparation:** the initial state $\Psi(t=0)$



- **Time propagation:** $\Psi(0) \rightarrow \Psi(t)$

  guided by the operator, $\exp(-i\,\hat{H}\,t/\hbar)$

  $\hat{H}$ is the model Hamiltonian



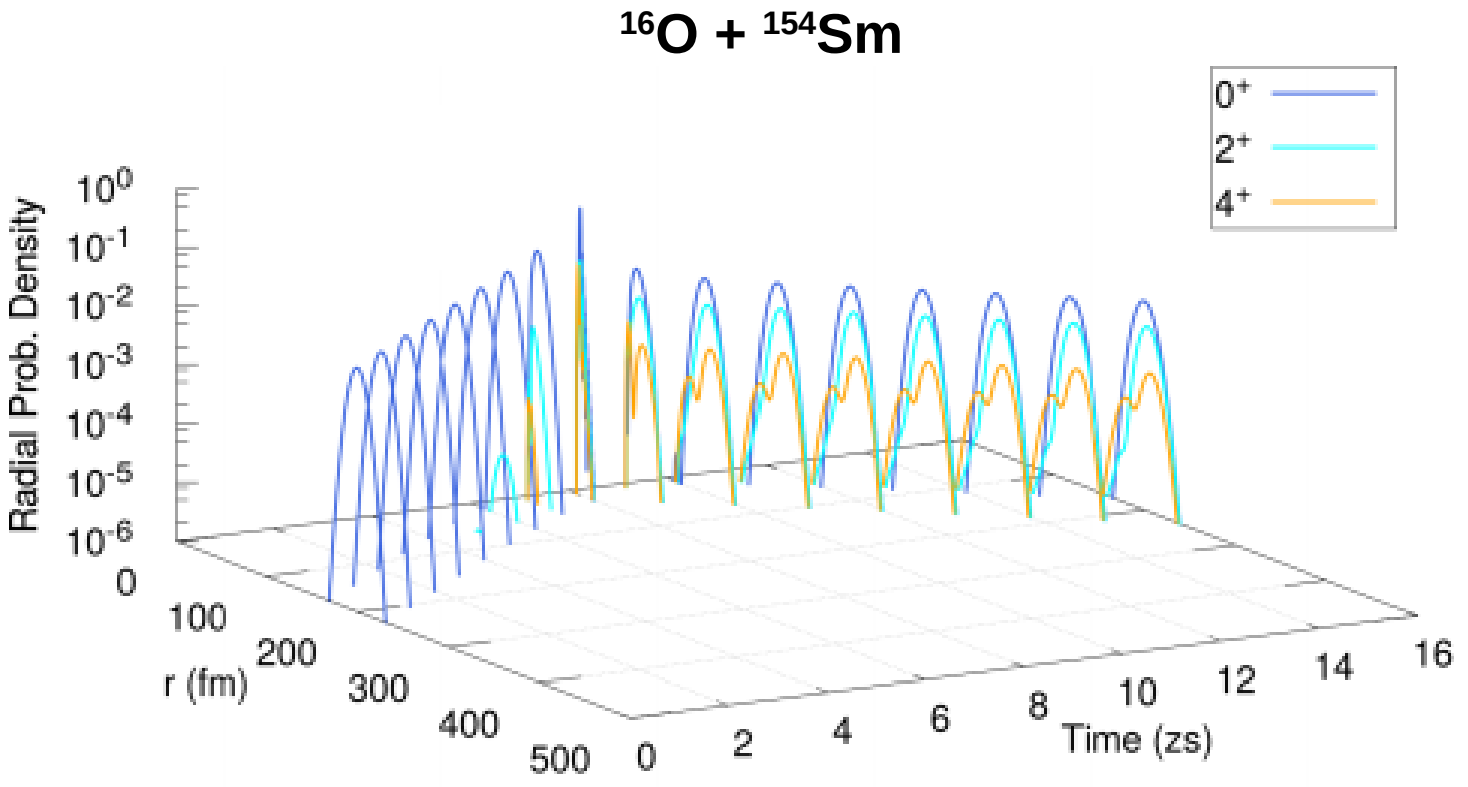
- **Analysis:** extraction of probabilities from the time-dependent wave function



Vockerodt & AD-T, PRC **104** (2021) 064601

Quantum Coupled-Channels Wave-Packet Dynamics

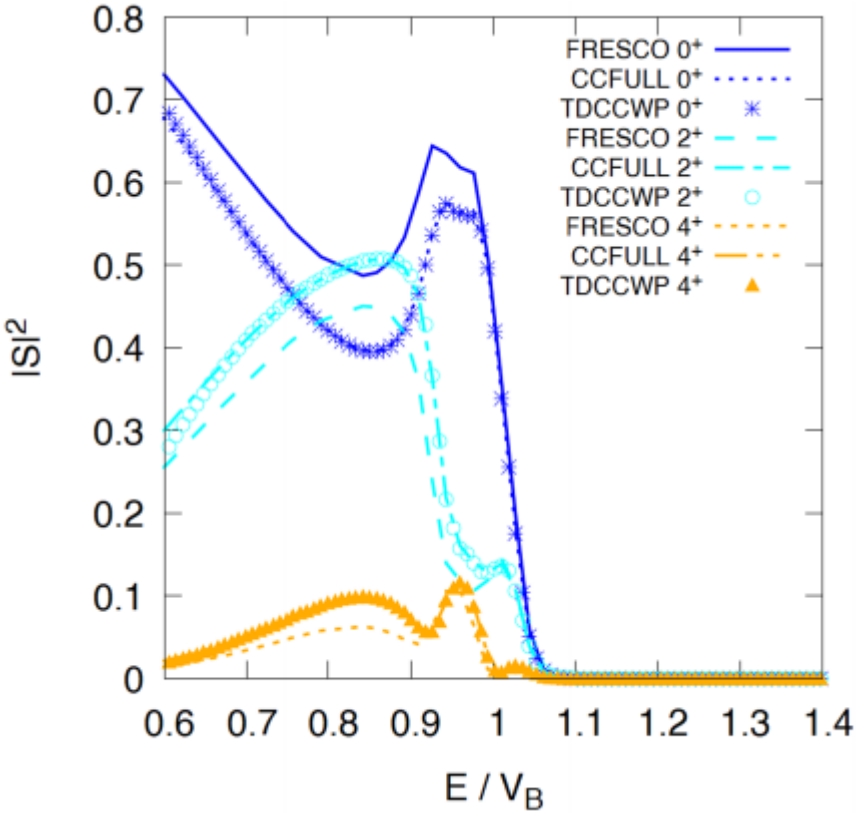
Vockerodt & AD-T, PRC **104**, 064601 (2021); PRC **100**, 034606 (2019)



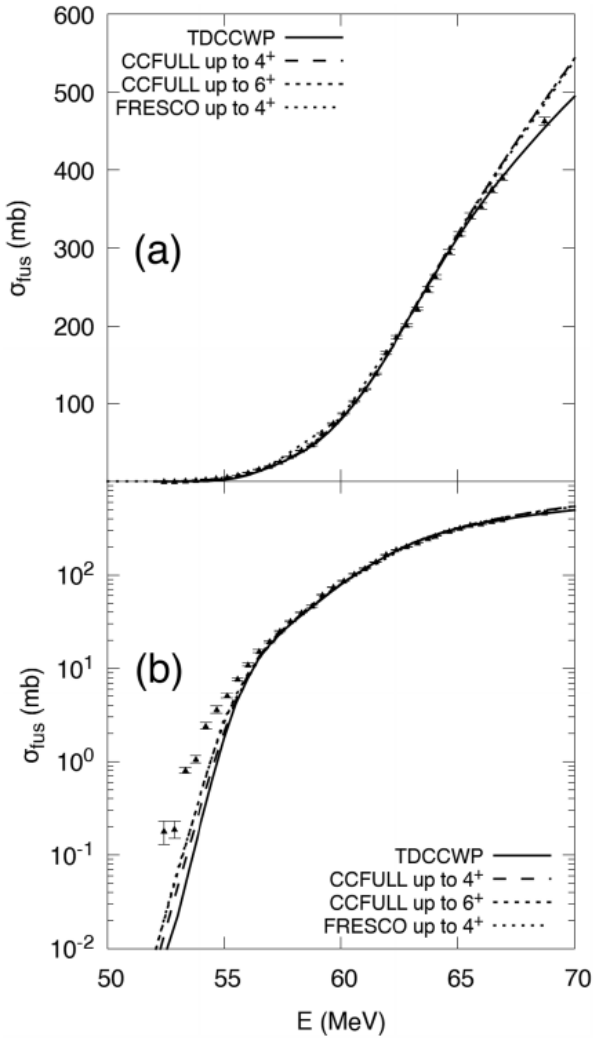
Quantum Coupled-Channels Wave-Packet Dynamics

Vockerodt & AD-T, PRC **104**, 064601 (2021)

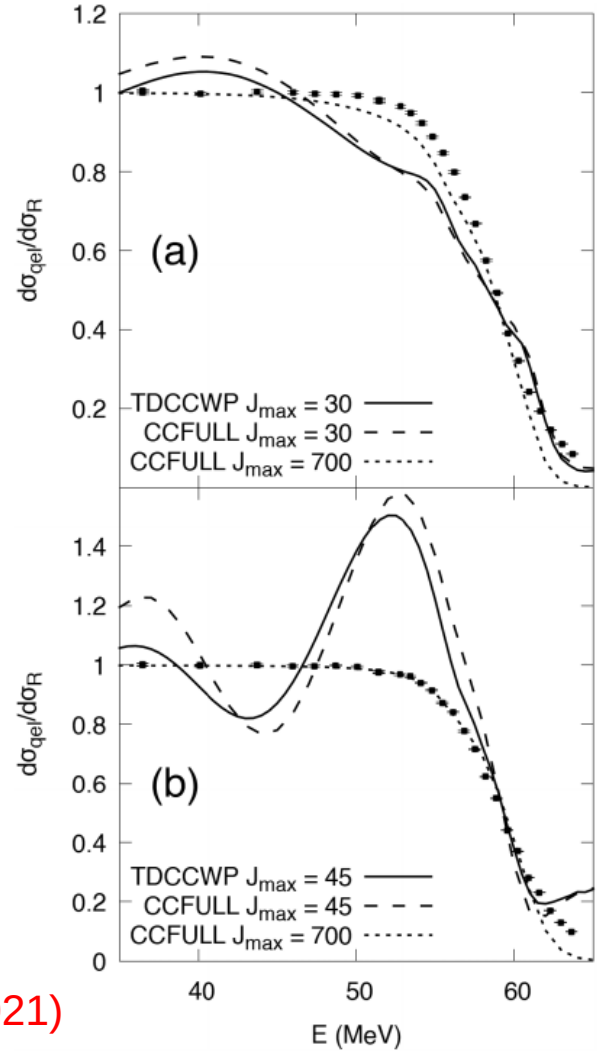
Reflection Coefficient



FUSION $^{16}O + ^{154}Sm$



QUASI-ELASTIC SCATTERING



$^{16}O + ^{154}Sm$

$\theta = 175°$

$^{16}O + ^{152}Sm$

Vockerodt & AD-T
PRC **104**, 064601 (2021)

Adiabatic and Diabatic Single-Particle Motion

Lukasiak, Cassing & Noerenberg, Nucl. Phys. A **426** (1984) 181

