Super Heavy Elements
and the Limits of Nuclear Stability

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Outline

1. Introduction
2. Reaction Mechanism of Heavy Ion Collisions at the Coulomb Barrier
3. Synthesis and Investigation of Superheavy Nuclei
4. Nuclear Structure of Heavy and Superheavy Nuclei
5. Additional Methods

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Geschichte der Entdeckung und Synthese Schwerer Elemente

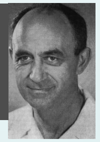
1898
Polonium (Z=84)
Radium (Z=88)

1899
Actinium (Z=89)

1896
Endeckung der Radioaktivität durch A.H. Becquerel

1908
Radon (Z=86)

1934
Enrico Fermi schlägt die Bestrahlung von Uran mit Neutronen vor zur Synthese schwererer Elemente



1917
Protactinium (Z=91)

1938
Otto Hahn und Fritz Straßmann entdecken die n-induzierte Kernspaltung

1939
Francium (Z=87)

1896 — **1940**

1940
Astat (Z=85)
Neptunium (Z=93)

1941
Plutonium (Z=94)

1944
Americium (Z=95)
Curium (Z=96)

1939
60-inch-Zyklotrongruppe:
Cooksey, Corson, Ernest O. Lawrence
Thornton, Backus, Salisbury,
Luis Alvarez und Edwin McMillan

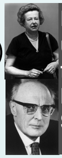
1949
Berkelium (Z=97)

1950
Californium (Z=98)

1940 — **1952**

1952
Einsteinium (Z=99)
Fermium (Z=100)

1955
Mendelevium (Z=101)



Ende der 40er Jahre wird von M. Goeppert-Mayer und J.H.D. Jensen das Schalenmodell entwickelt, für das sie 1963 den Nobelpreis erhalten. Es Motivation und Grundlage für die nun beginnende Suche nach der Insel der Stabilität.

1965
Nobelium (Z=102)
Lawrencium (Z=103)

1969
Rutherfordium (Z=104)

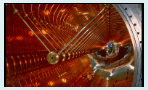
1970
Dubnium (Z=105)

1974
Seaborgium (Z=106)

1952 — **1974**

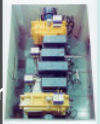
1981
Bohrium (Z=107)

1982
Meitnerium (Z=109)



Der Linearbeschleuniger UNILAC und das Geschwindigkeitsfilter SHIP bei GSI ermöglichten die Synthese der Elemente mit Z=107-112.

1984
Hassium (Z=108)



1994
Darmstadtium (Z=110)
Roentgenium (Z=111)

1996
Element 112

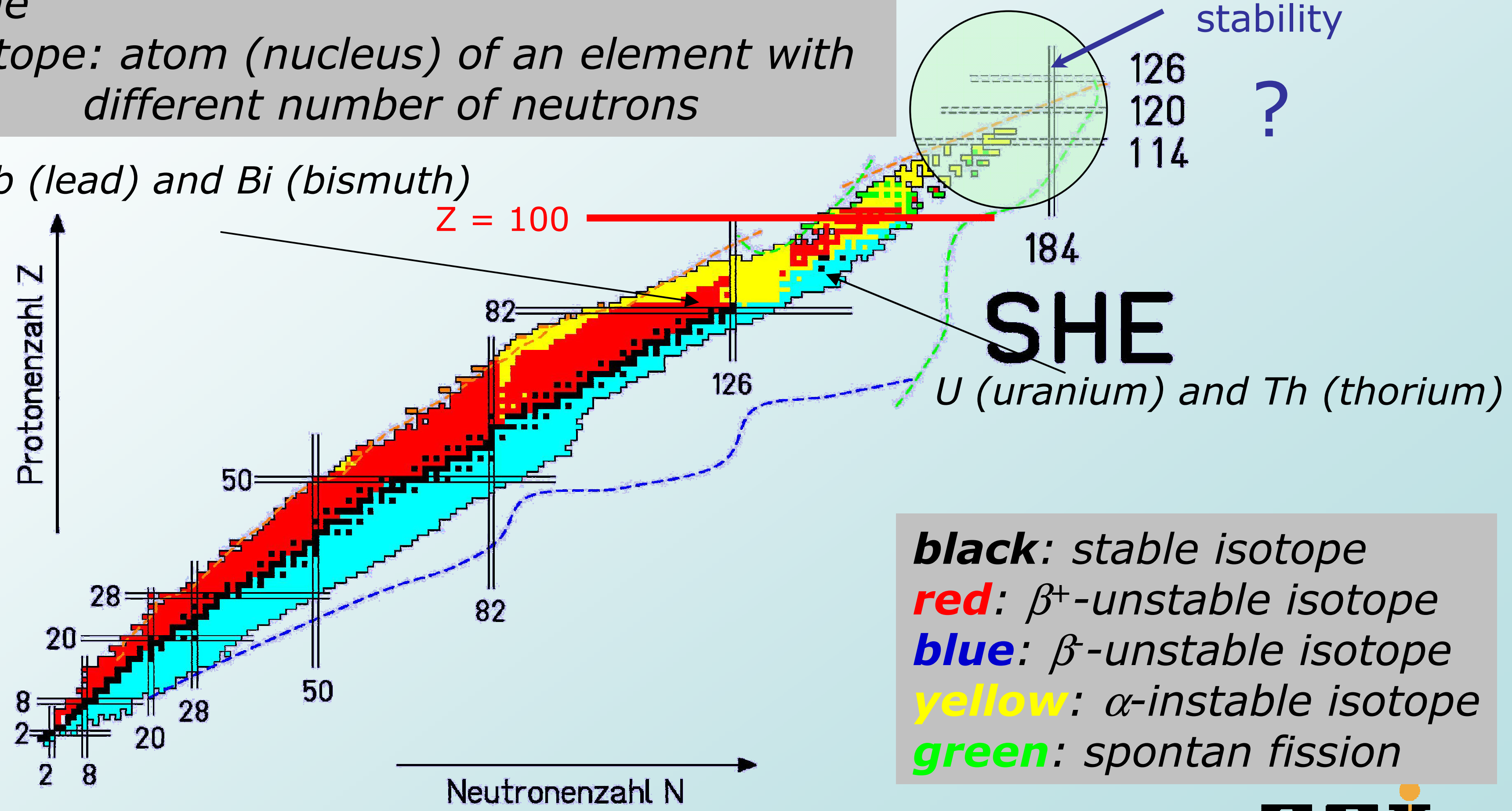
Element 112-116, 118
Dubna, Rußland

2004
Element 113
RIKEN, Japan

1974 — **2005**

The Chart of Nuclides
– the "Playground" for Nuclear Physics I

chart of nuclides:
-representation of the isotopes in the Z-N-plane
-isotope: atom (nucleus) of an element with different number of neutrons

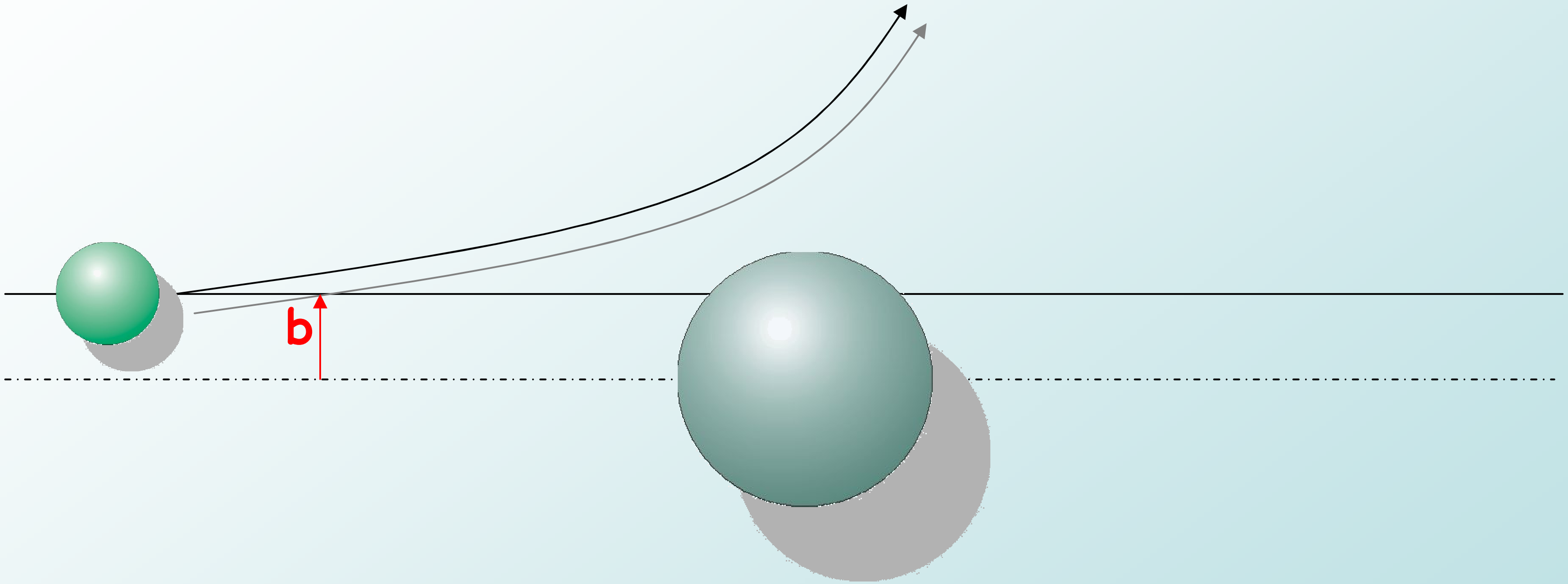


***black**: stable isotope*
***red**: β^+-unstable isotope*
***blue**: β^--unstable isotope*
***yellow**: α-instable isotope*
***green**: spontan fission*

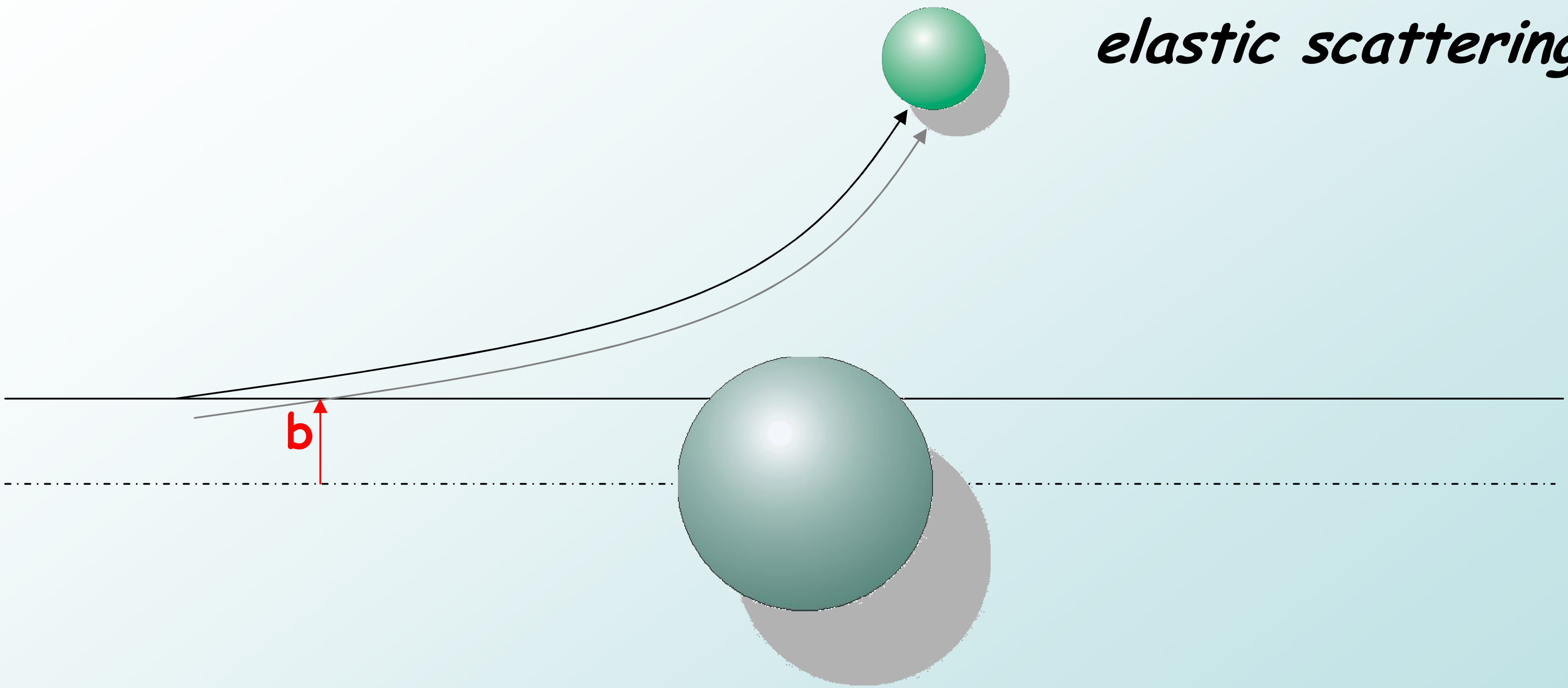
Outline

1. Introduction
2. **Reaction Mechanism of Heavy Ion Collisions at the Coulomb Barrier**
   - **Competing reaction channels**
   - **Fusion excitation function**
   - **The concept of barrier distribution**
   - **The compound nucleus spin distribution**
3. Synthesis and Investigation of Superheavy Nuclei
4. Nuclear Structure of Heavy and Superheavy Nuclei
5. Additional Methods

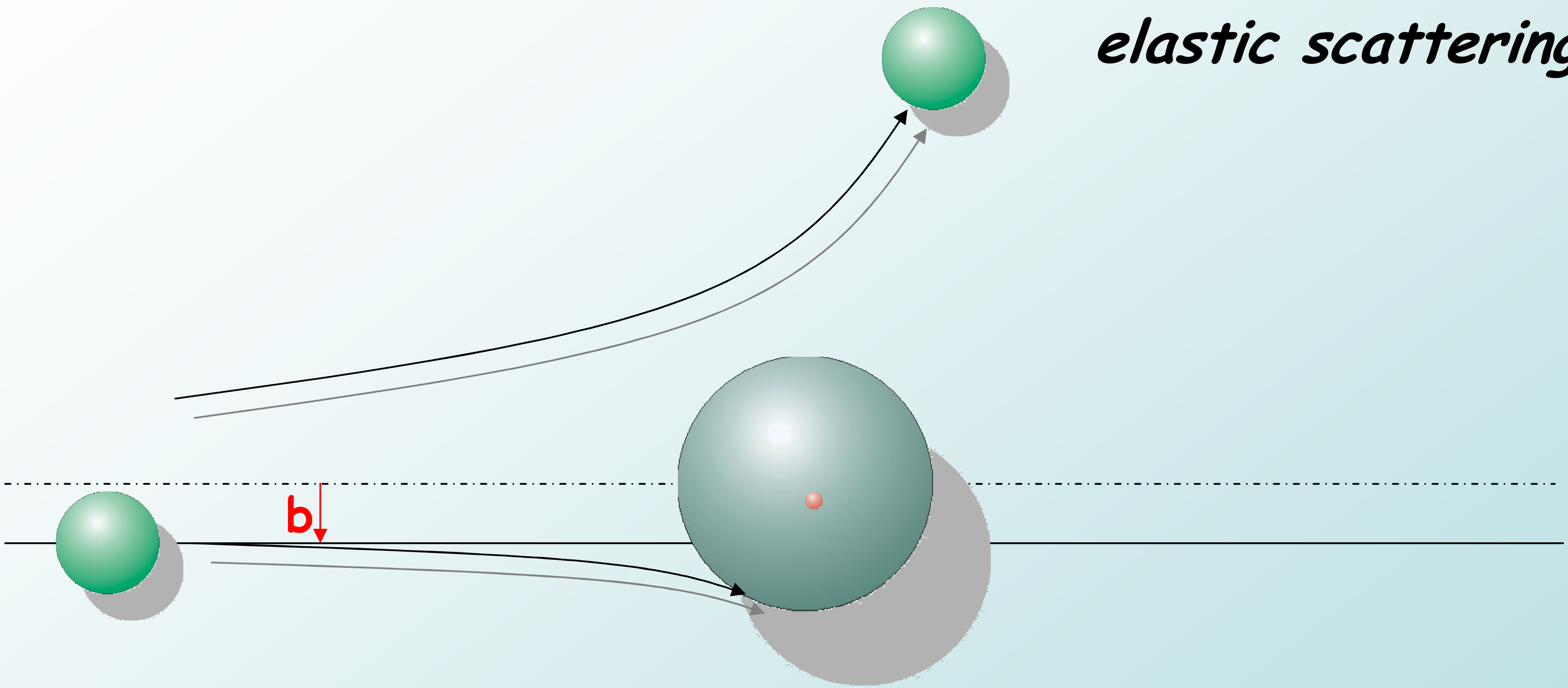
elastic scattering



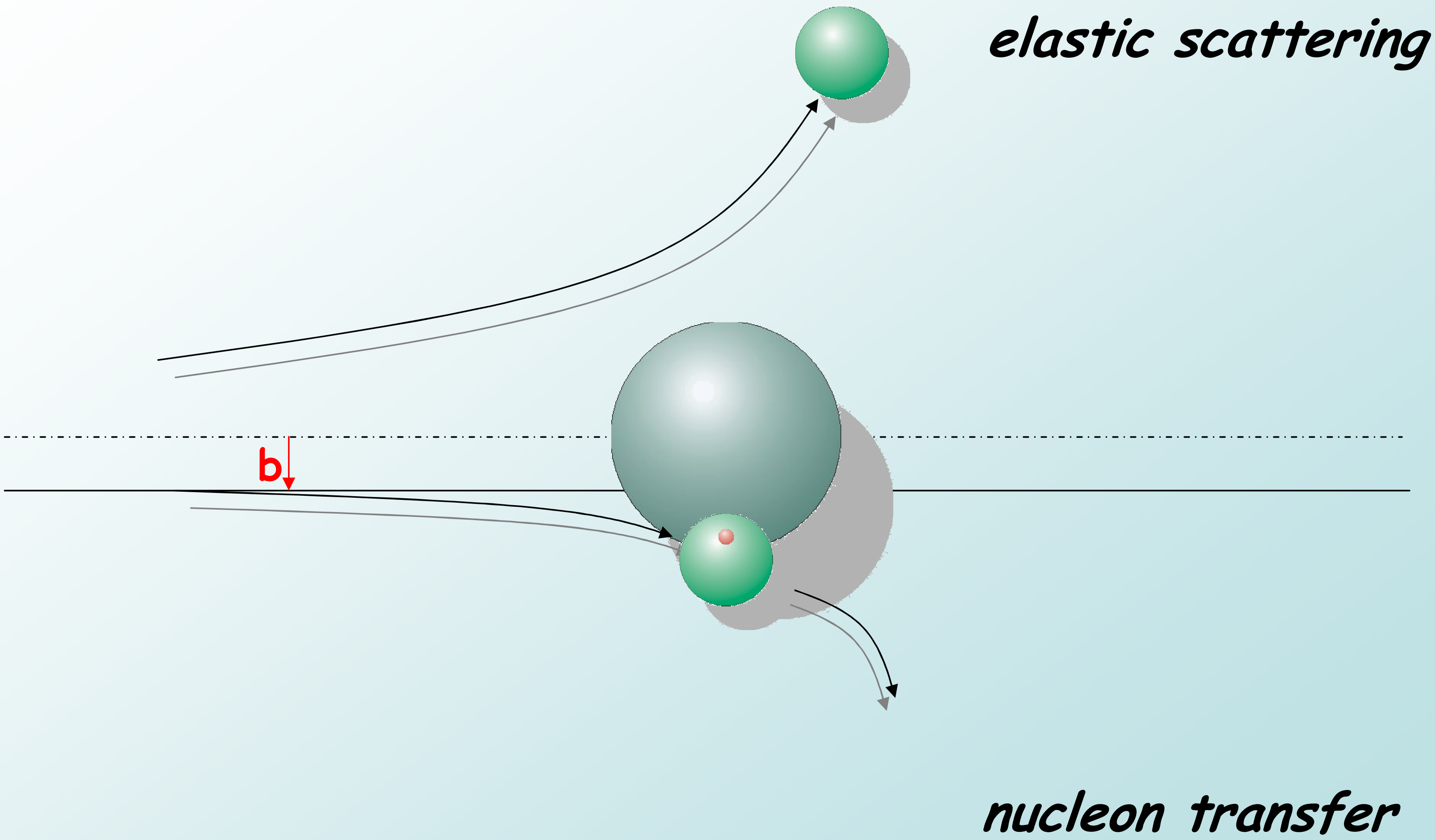
elastic scattering

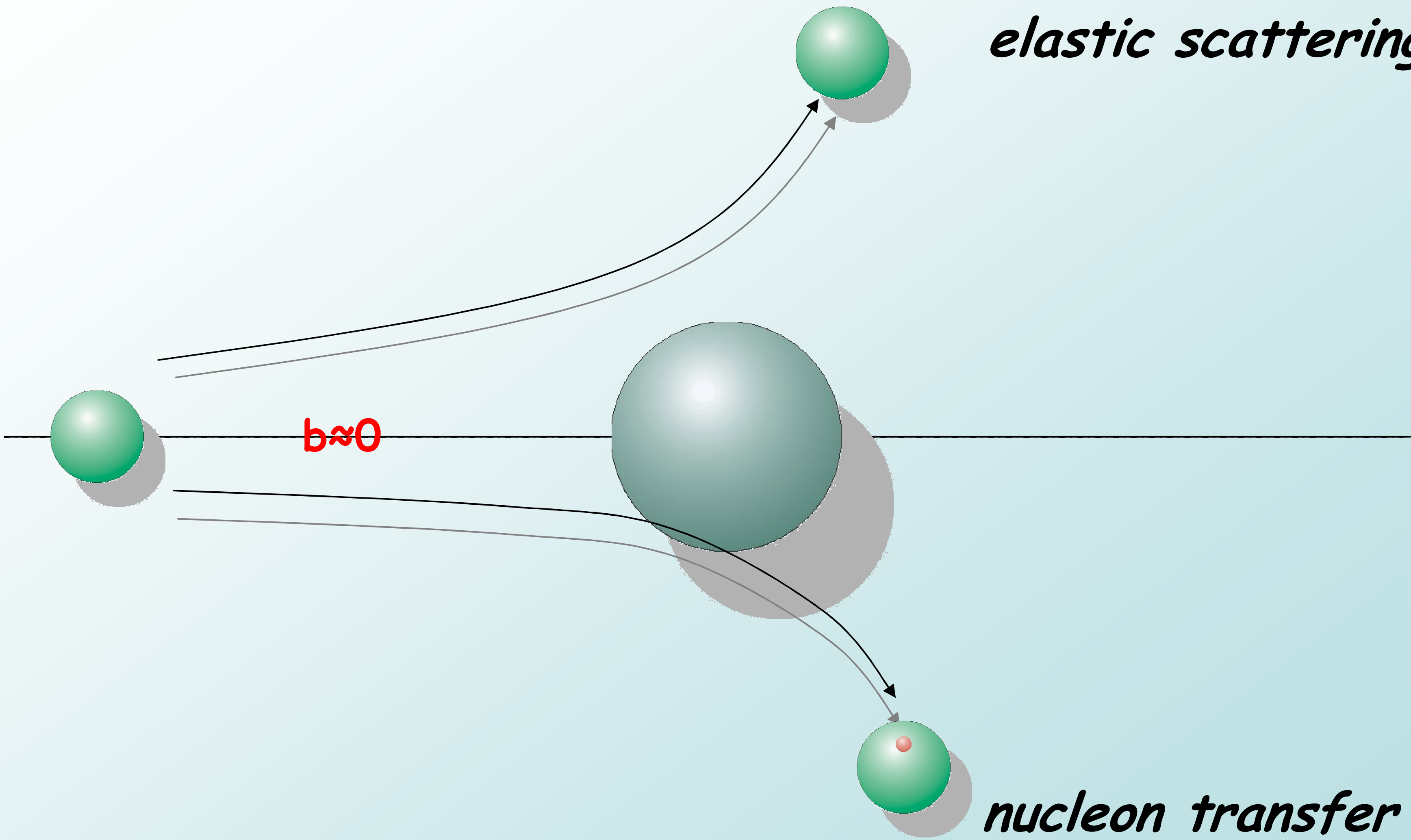


elastic scattering

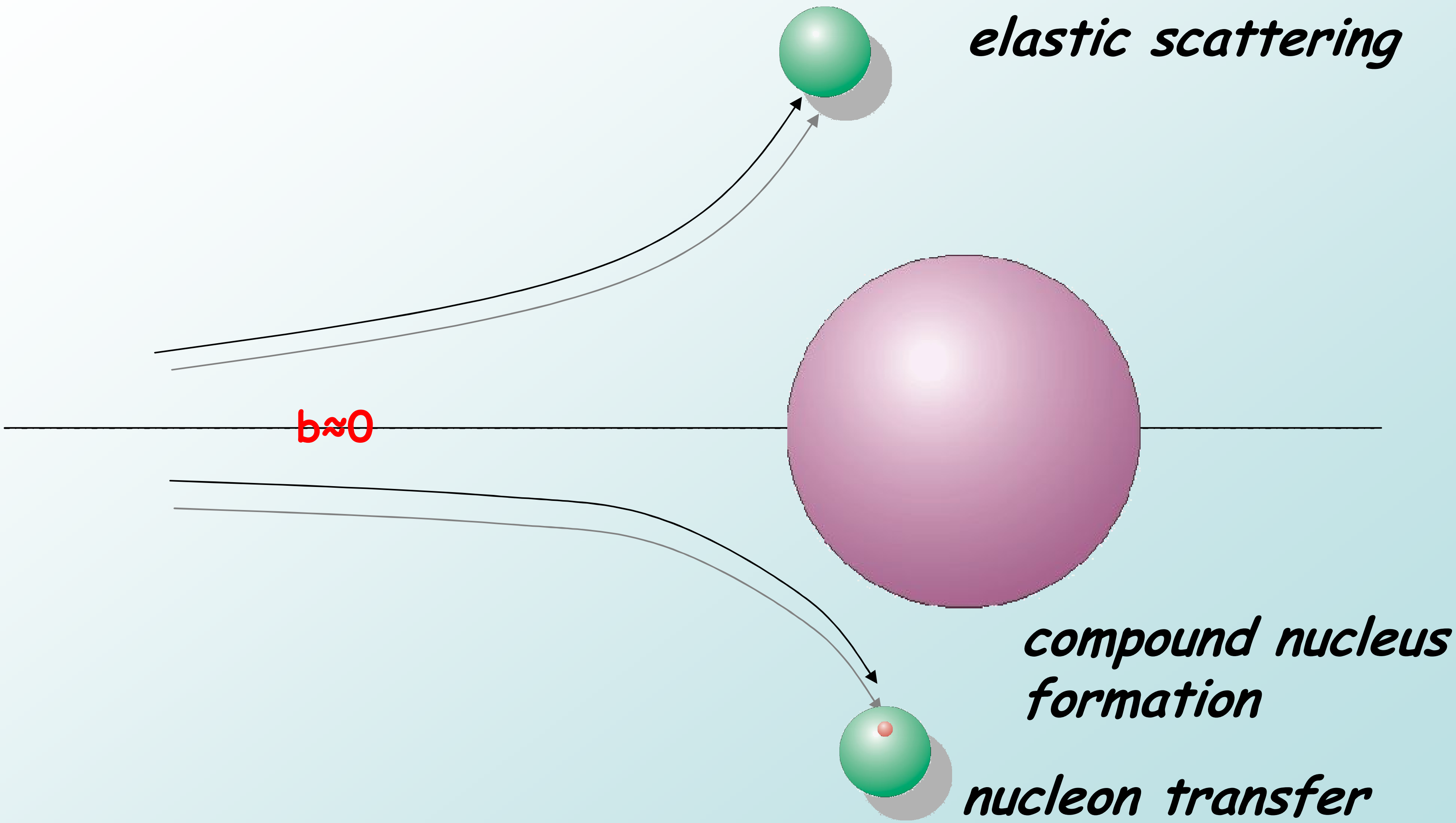


Heavy Ion Reactions @ the Coulomb Barrier

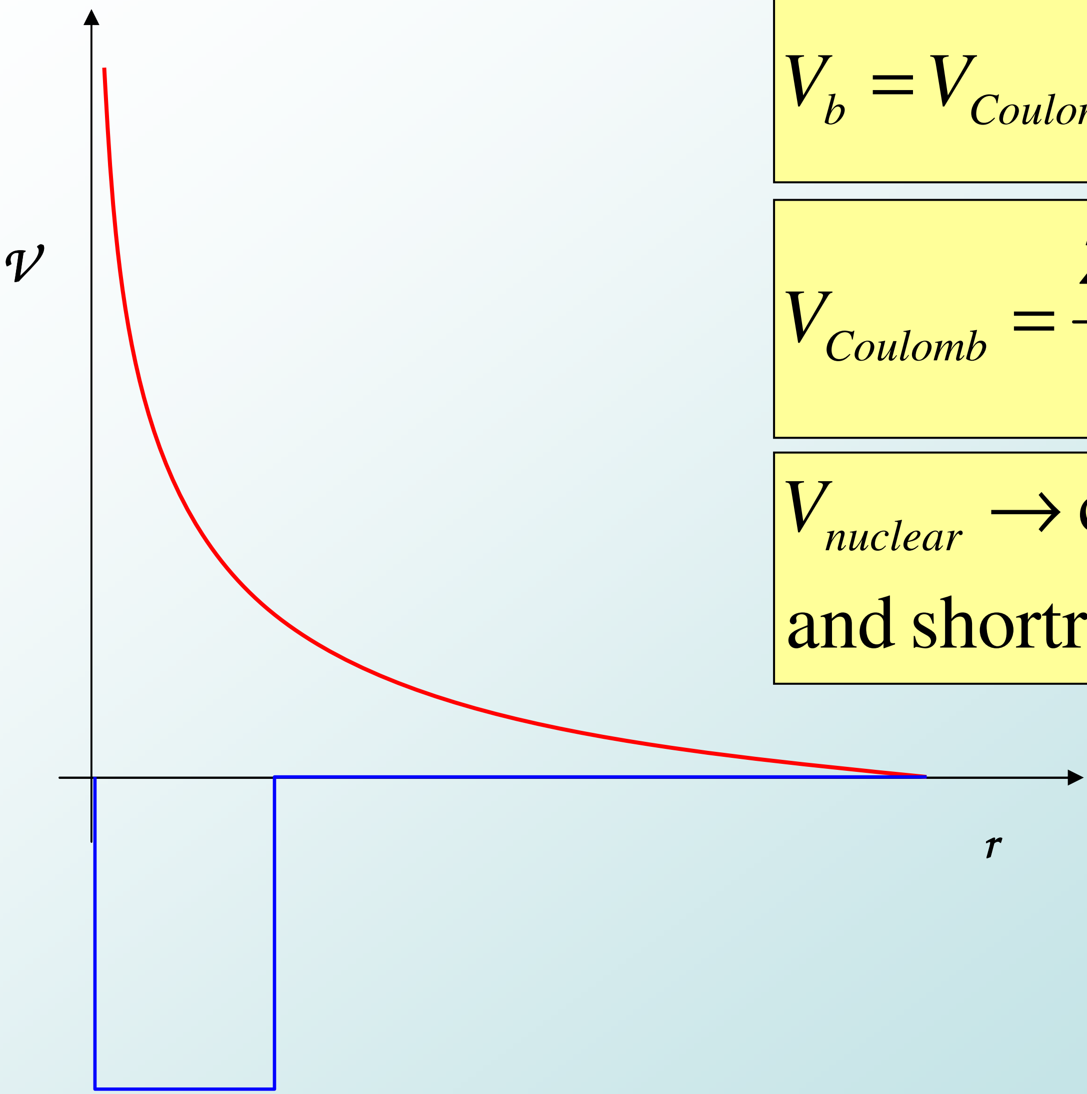



elastic scattering
b≈0
nucleon transfer

Heavy Ion Reactions @ the Coulomb Barrier



The Nuclear Potential

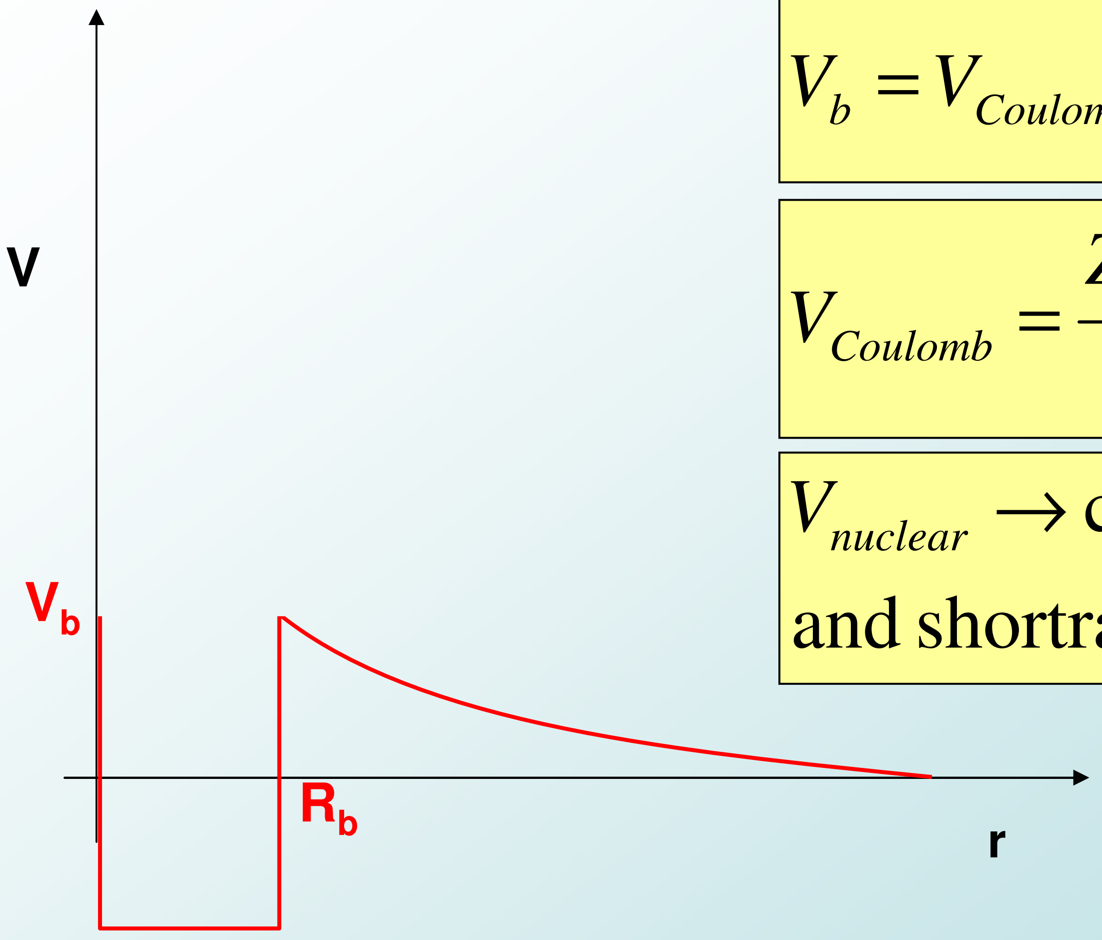


$$V_b = V_{Coulomb} \propto \frac{1}{r} + V_{nuclear} + V_{rotational}$$

$$V_{Coulomb} = \frac{Z_p Z_t e^2}{R_b} \propto \frac{1}{r}$$

$V_{nuclear} \rightarrow$ constant, attractive and shortrange $\rightarrow$ rectangular

The Nuclear Potential



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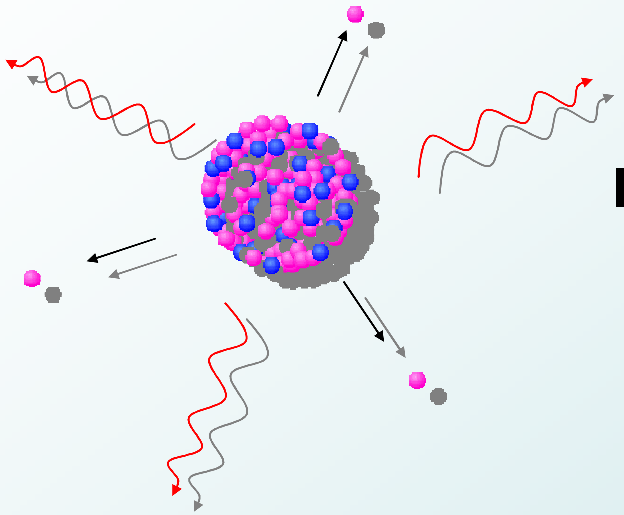
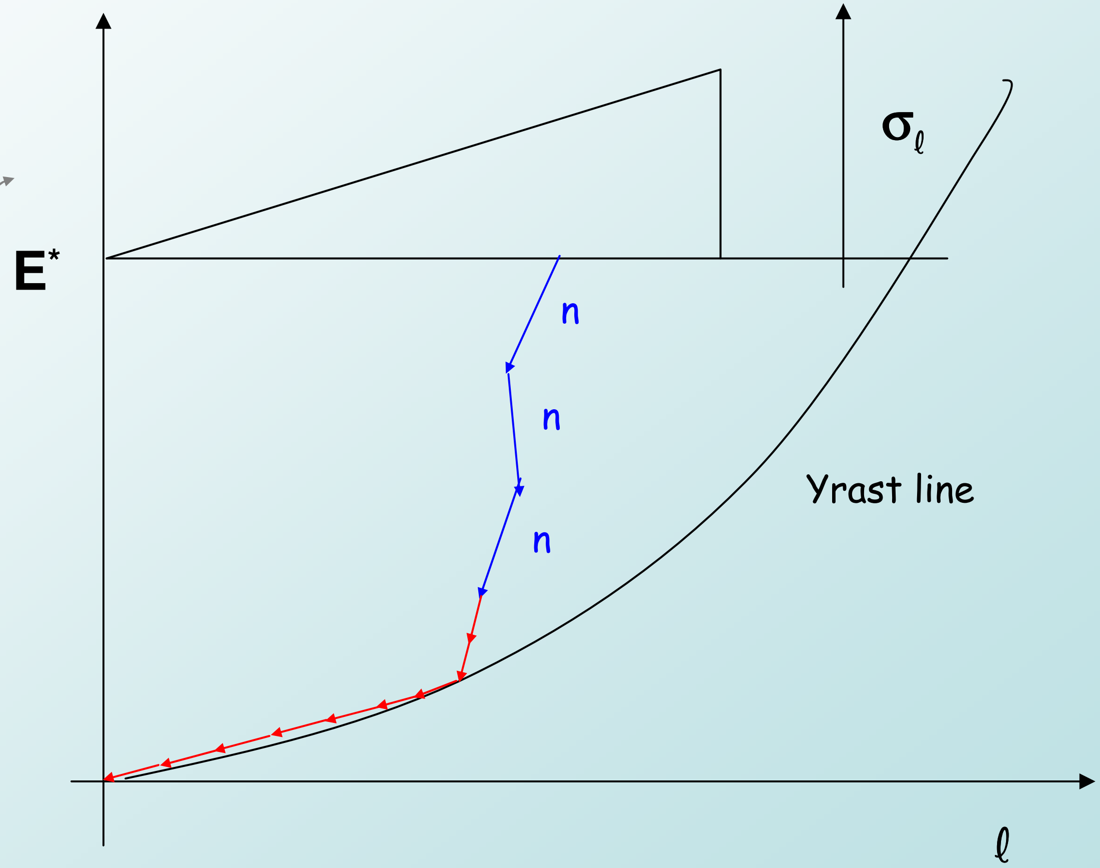
$$V_{Coulomb} = \frac{Z_p Z_t e^2}{R_b} \propto \frac{1}{r}$$

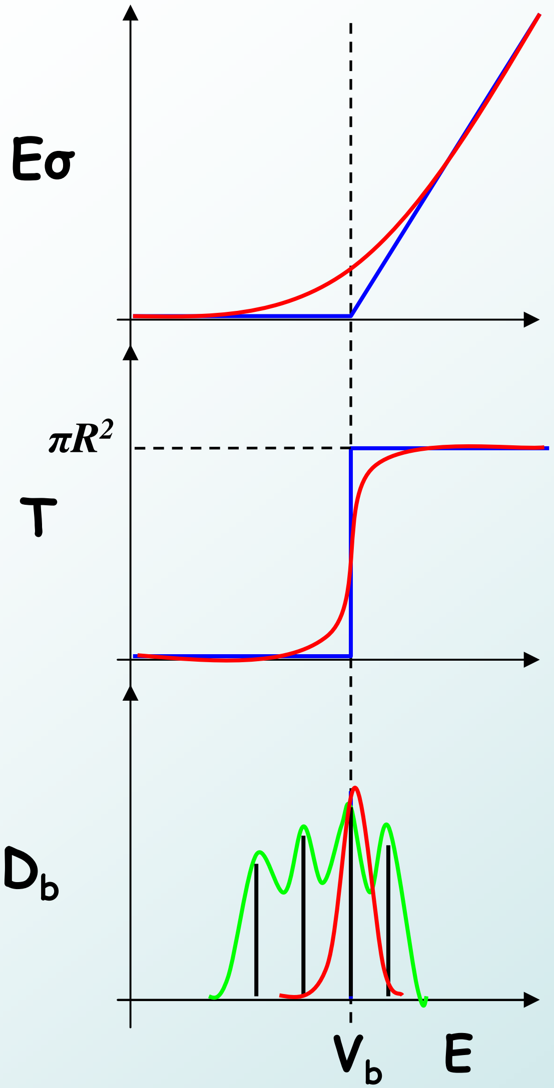
$V_{nuclear} \rightarrow$ constant, attractive and shortrange $\rightarrow$ rectangular

The Statistical Model
- de-excitation of the Hot Compound System





Fusion Barrier Distribution
- the Concept

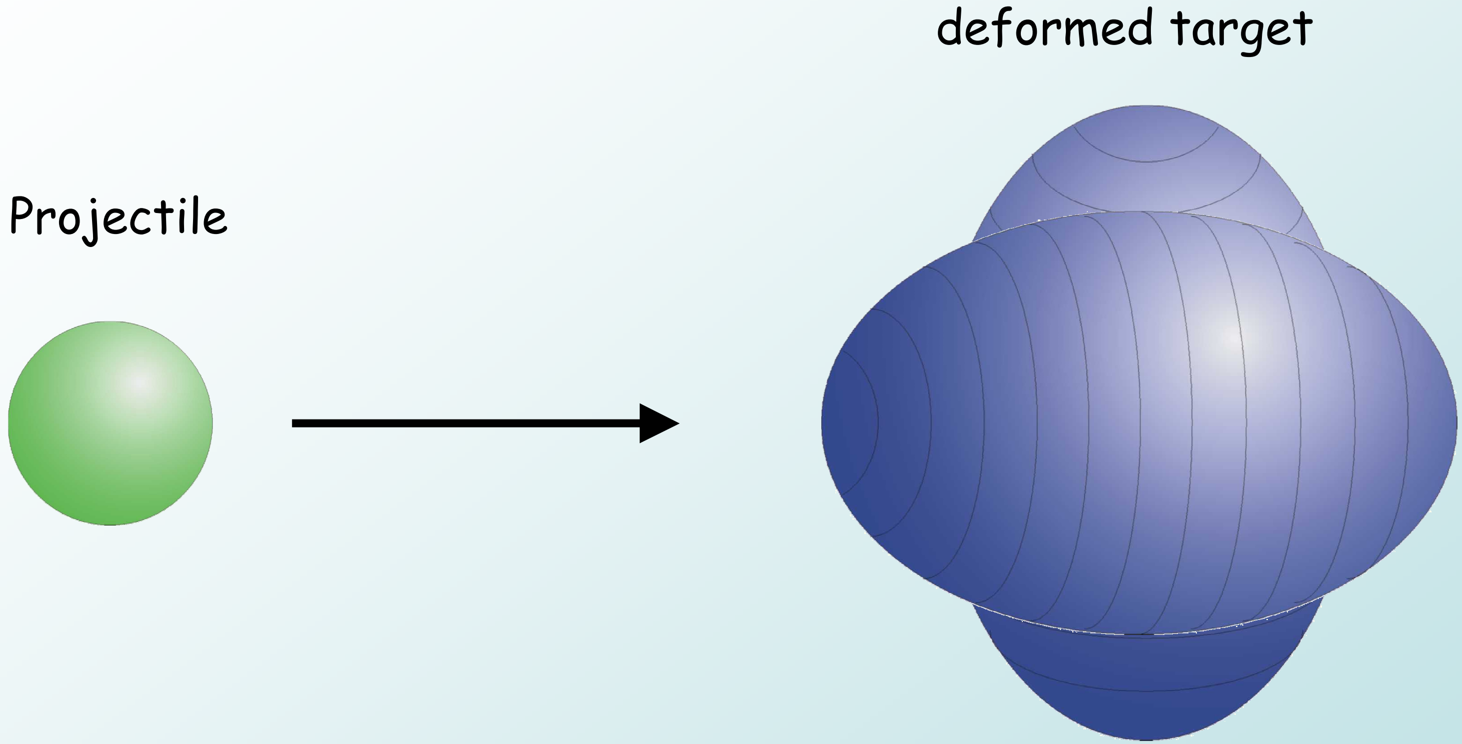


$$\sigma E(E,V_b) = \pi R^2\left(1-\frac{V_b}{E}\right) \quad , E > V_b$$
$$\sigma E(E,V_b) = 0 \quad , E < V_b$$

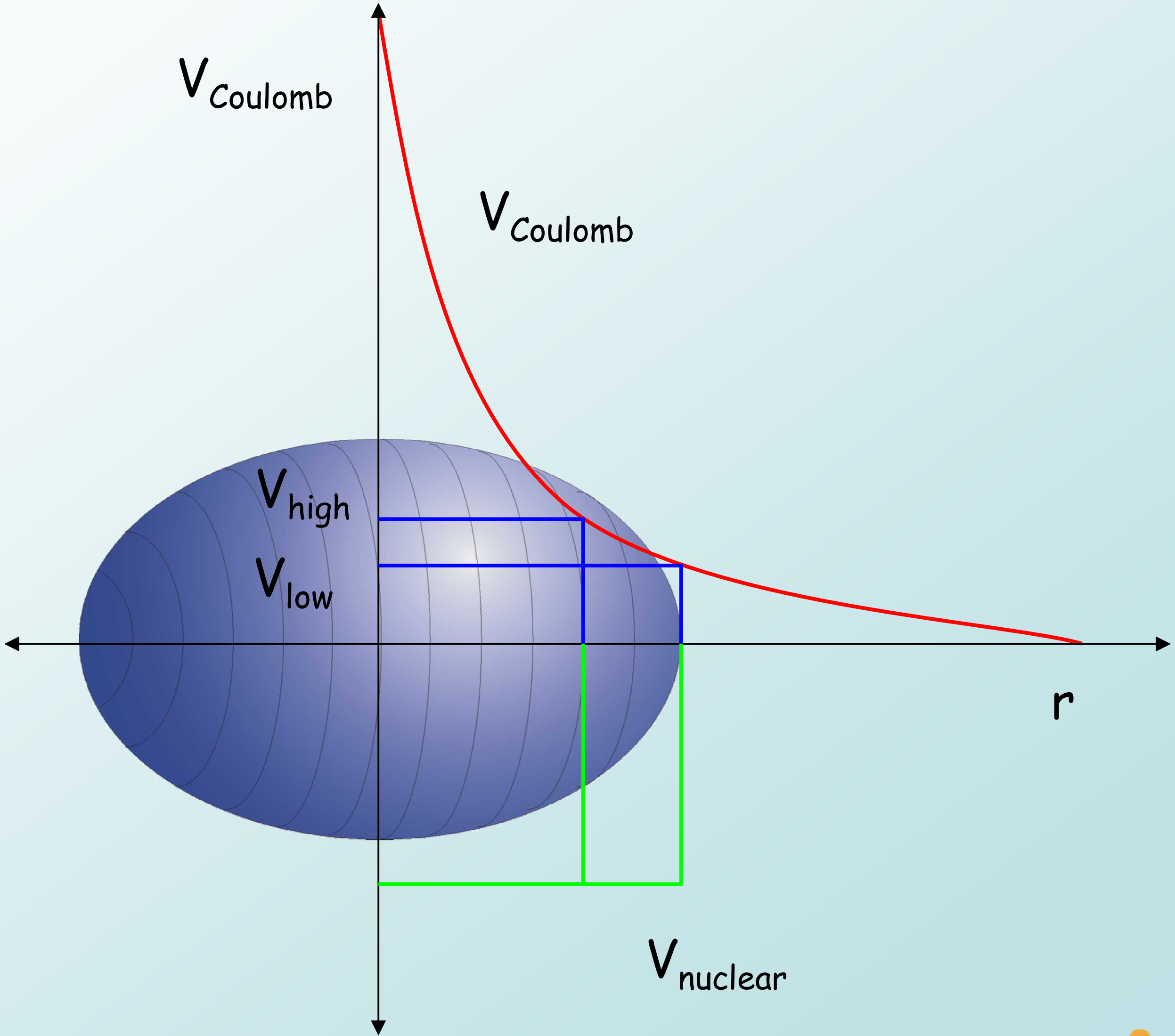
$$\frac{d(E\sigma(E,V_b))}{dE} = \pi R^2 \quad , E > V_b$$
$$\frac{d(E\sigma(E,V_b))}{dE} = 0 \quad , E < V_b$$

$$\frac{d^2(E\sigma(E,V_b))}{dE^2} = \pi R^2 \delta(E\text{-}V_b)$$

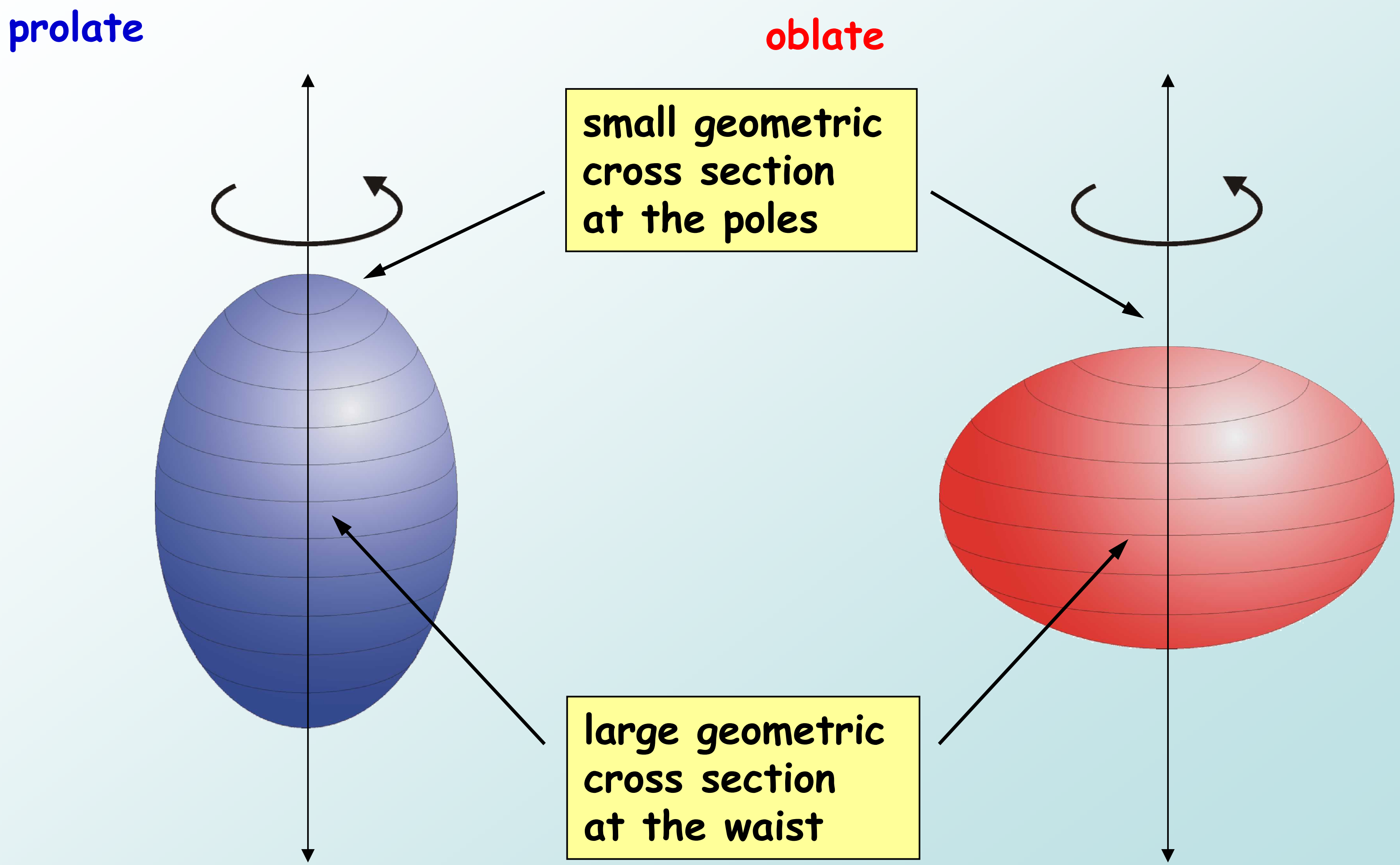
Fusion Barrier Distribution
- Deformed Nuclei



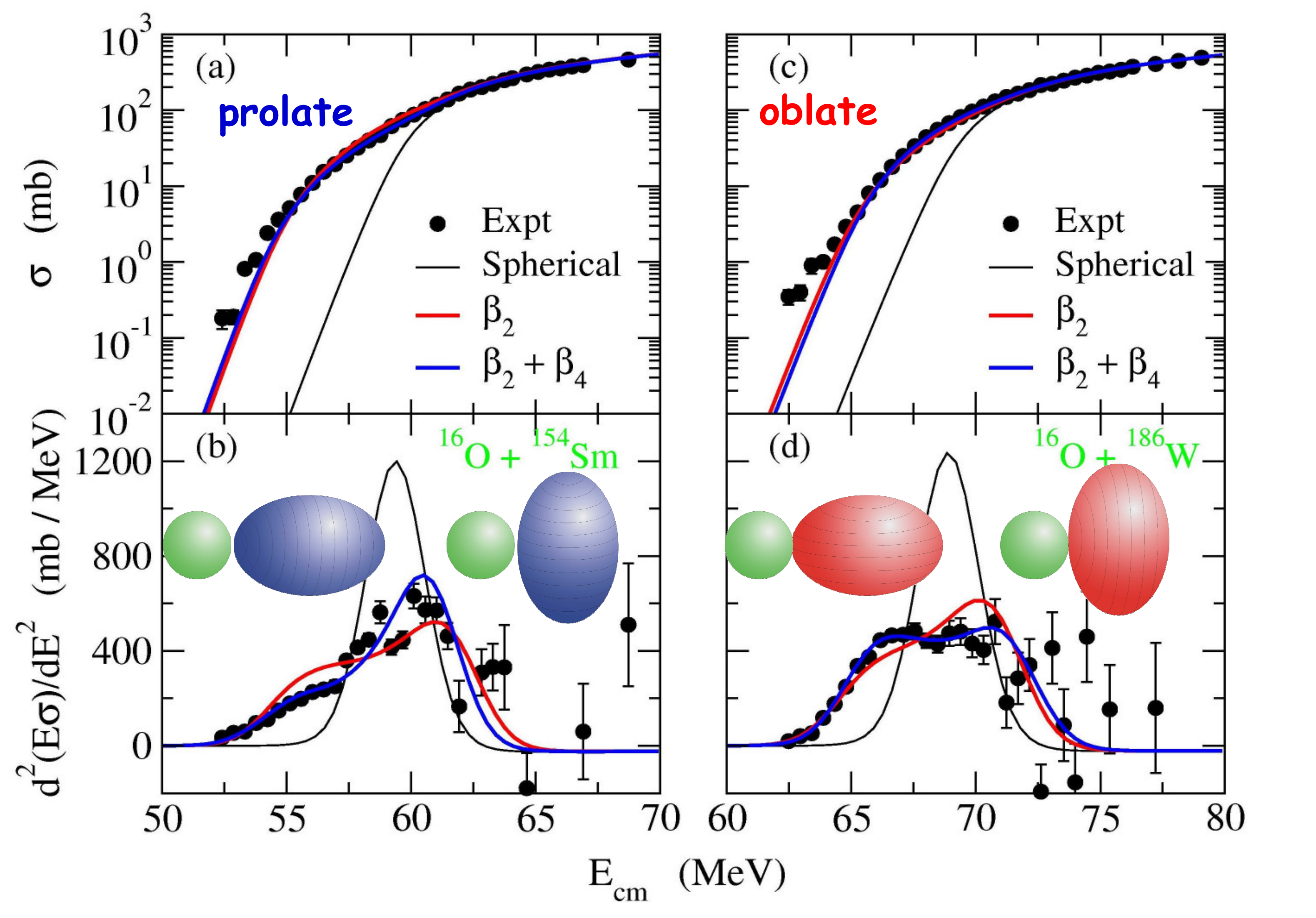
Fusion Barrier Distribution
- Deformed Nuclei and the Potential



Fusion Barrier Distribution
- Deformed Nuclei: prolate and oblate

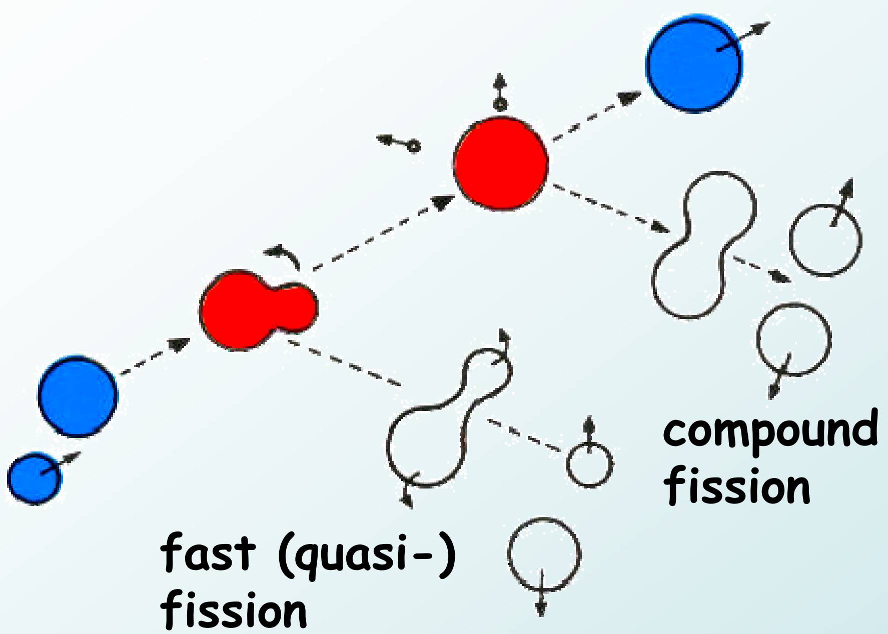


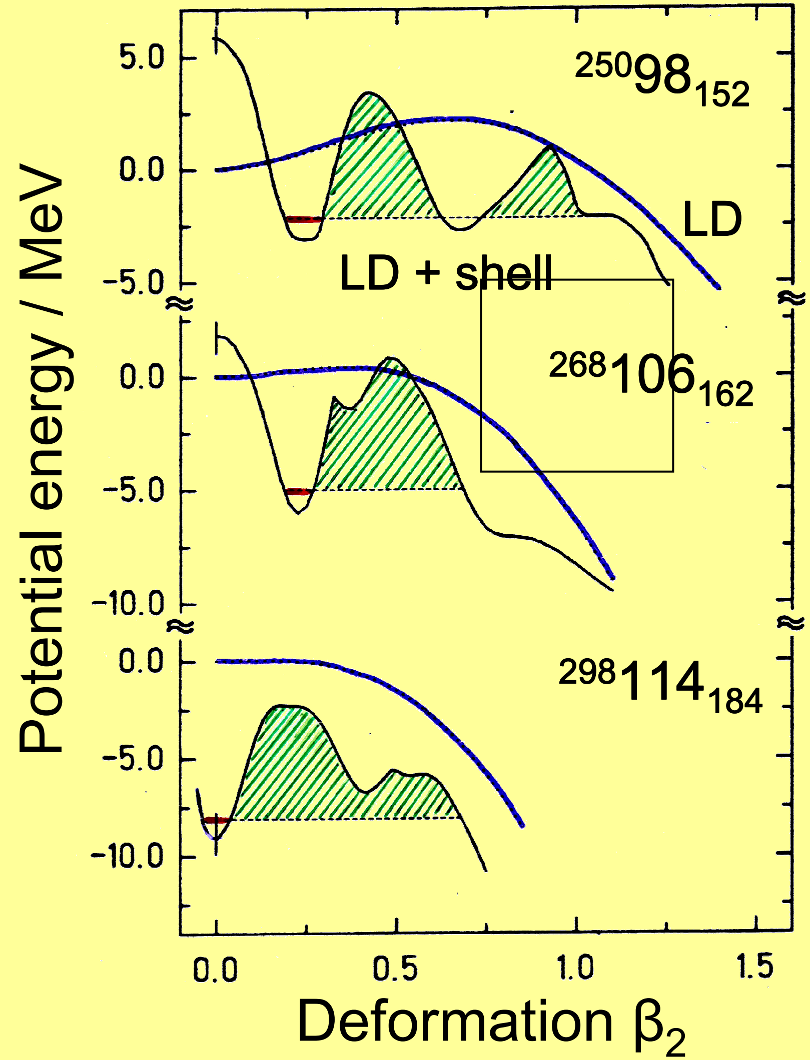
Fusion Barrier Distribution
- Deformed Nuclei: prolate and oblate



Fusion/Fission Competition for SHE

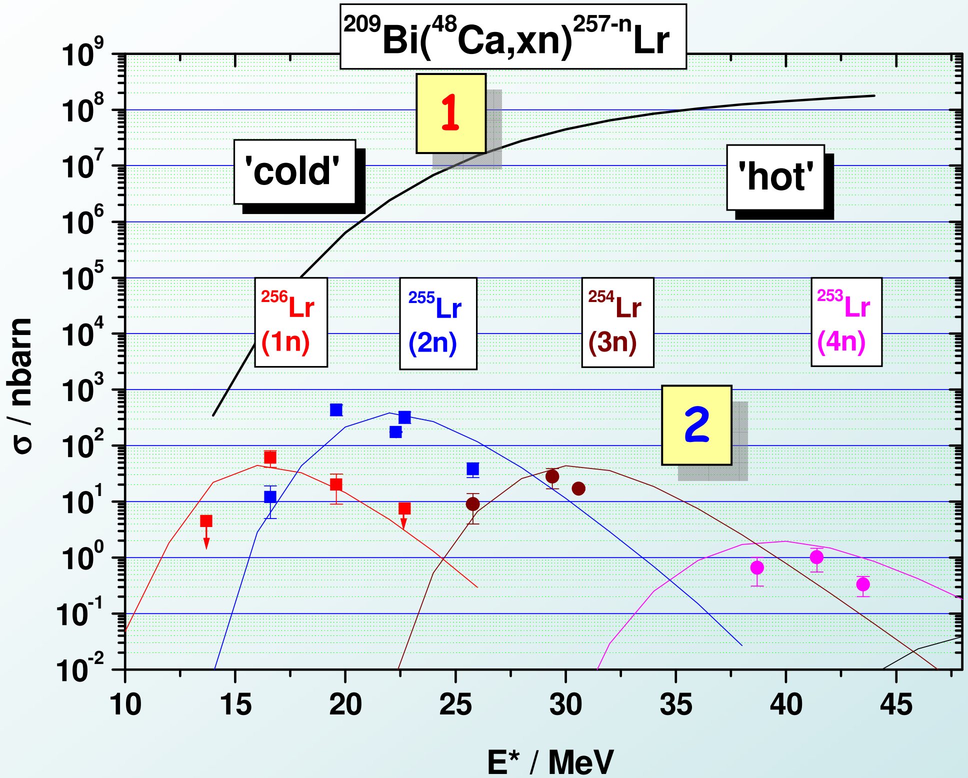
- Liquid Drop + Shell Corrections





A. Sobiczewski et al.

The 2-step process Fusion - Evaporation



F.P.Heßberger 2.5.2005

1. CN formation
   - entrance channel properties (nuclear structure, deformation…)

2. ER formation
   - survival
   - fission competition

probes:
- Fusion-fission excitation function (fission and ER-production)
- l-distribution

...

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1. Introduction
2. Reaction Mechanism of Heavy Ion Collisions at the Coulomb Barrier
3. **Synthesis and Investigation of Superheavy Nuclei**
   - **Predictions of the next closed p and n shells**
   - **Separation and identifcation**
   - **"cold" and "hot" fusion**
4. Nuclear Structure of Heavy and Superheavy Nuclei
5. Additional Methods

Theoretical Models I
- Microscopic-Macroscopic Model

The nucleus is treated as a classical liquid drop (macroscopis part) with quantum mechanical corrections (microscopic part):

$$E_{bind}(Z,N) = E_{macro}(Z,N) + E_{micro}(Z,N)$$

Macroscopic part (Bethe-Weiszäcker formula, 1935):

$$E_{macro}(Z,N) = a_c \frac{Z^2}{A^{\frac{1}{3}}} + a_I \frac{(N-Z)^2}{A} + a_V A + a_S A^{\frac{2}{3}}$$

Terms: Coulomb, Asymmetry, Volume, Surface

Coulomb and Surface: deformation dependent

Microscopic part :

$$E_{micro}(Z,N) = E_{shell} + E_{pairing}$$

Theoretical Models IIa

- Self-consistend Models: Hartree Fock Bogoliubov

Schrödinger equation for the nuclear many body system:

$$H\Psi = E_o\Psi$$

H:	the nuclear Hamiltonian
E_0:	the total binding energy
Ψ:	fully antisymmetric wave function

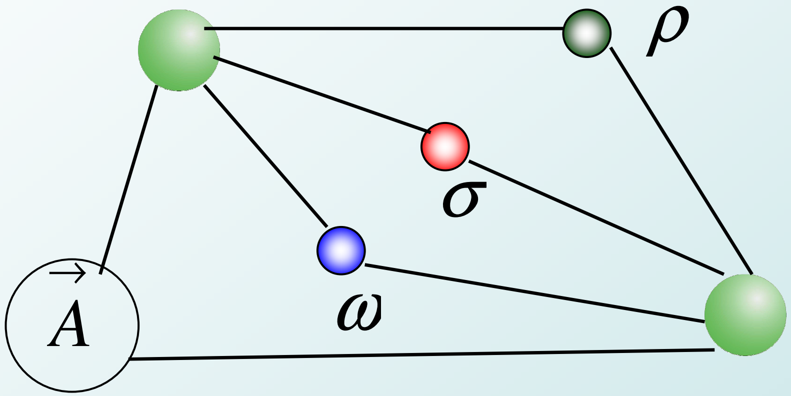
$$H = \sum T + \sum V(i,j)$$

$V(i,j)$:	nucleon-nucleon interaction (Gogny force, Skyrme force, ...)

Theoretical Models IIb

- Self-consistend Models: Relativistic Mean Field

The nucleon-nucleon interaction is mediated by mesons

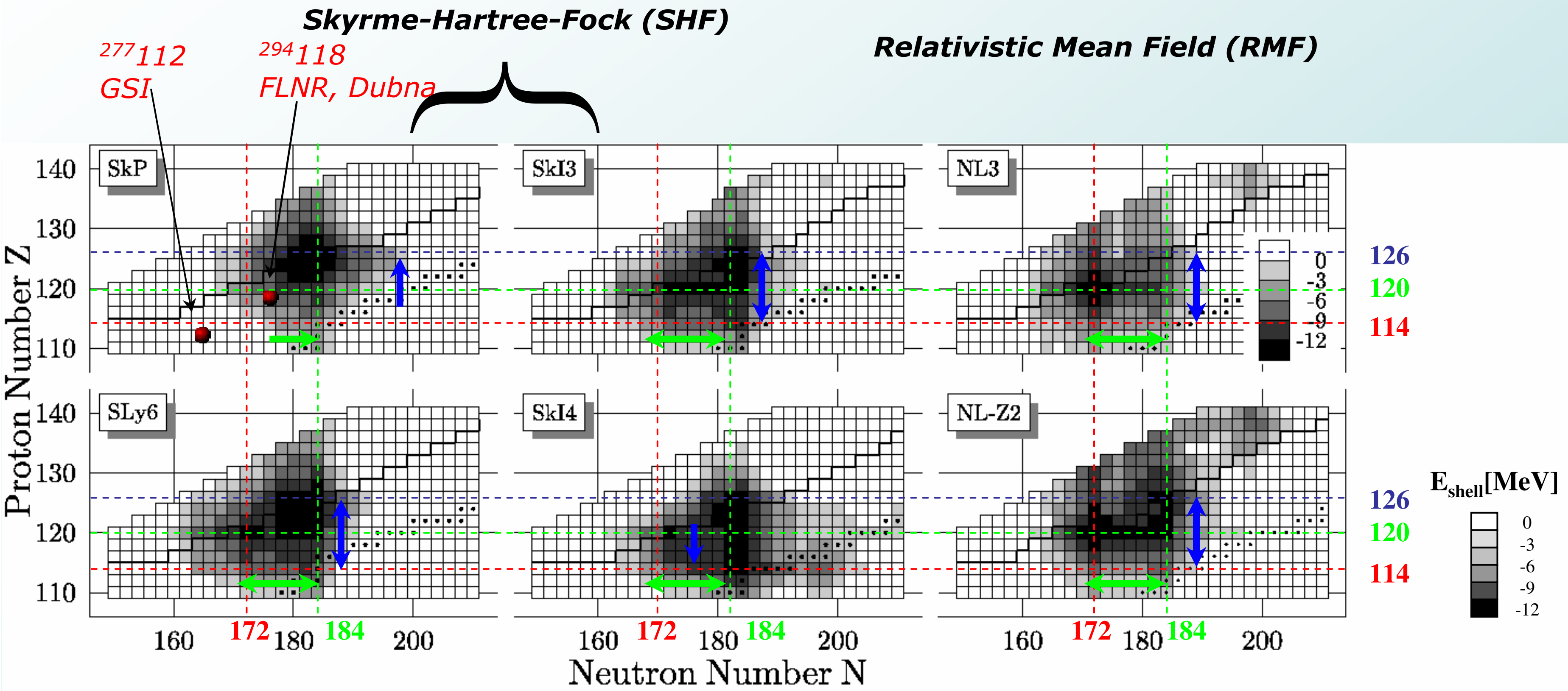


$L(nucleon,\rho,\sigma,\vec{\omega},A)$ (Lagrangian density)
$\rightarrow$ Dirac equation + Klein-Gordon equations (for mesons and photons)

Method: solve the system of coupled Dirac equations for the nucleons and Klein-Gordon equations for mesons and photons to obtain the ground state energy of the nucleus and its wave function.
The pairing energy should be added

Selbstkonsistente Rechnungen: Stabilitätsbereiche

- M. Bender, W. Nazarewicz, P.-G. Reinhard et al.



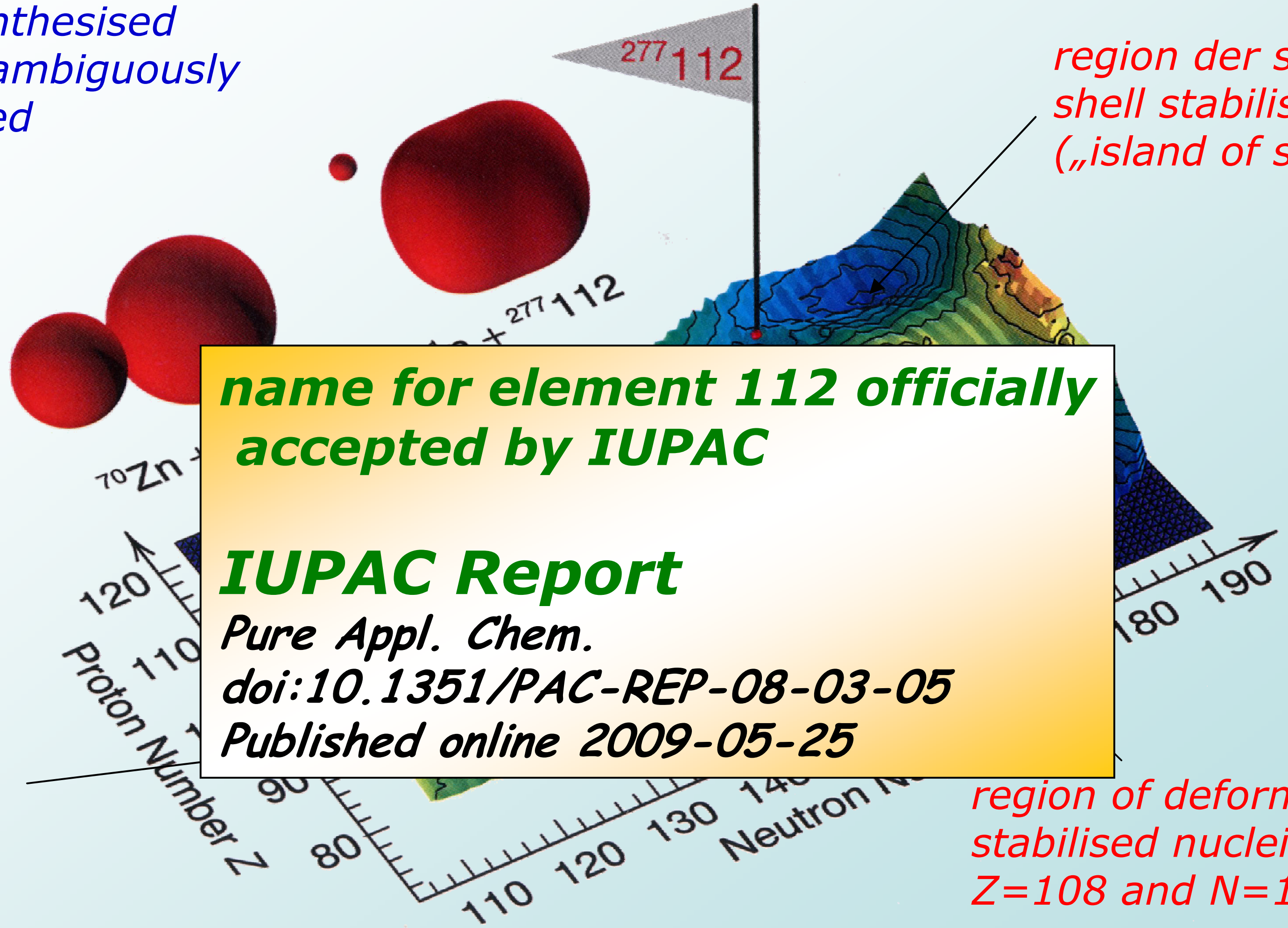
Shell Correction Energies E_{shell} in the Region of Superheavy Elements

- P. Möller et al.: microscopic-macroscopic model

at GSI: *Elements 107-112*
first synthesised
and unambiguously
identified

107 – Bh
108 – Hs
109 – Mt
110 – Ds
111 – Rg

region der spherically shell stabilised nuclei („island of stability")



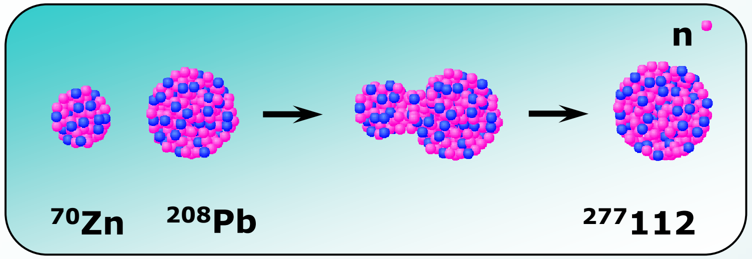
name for element 112 officially accepted by IUPAC

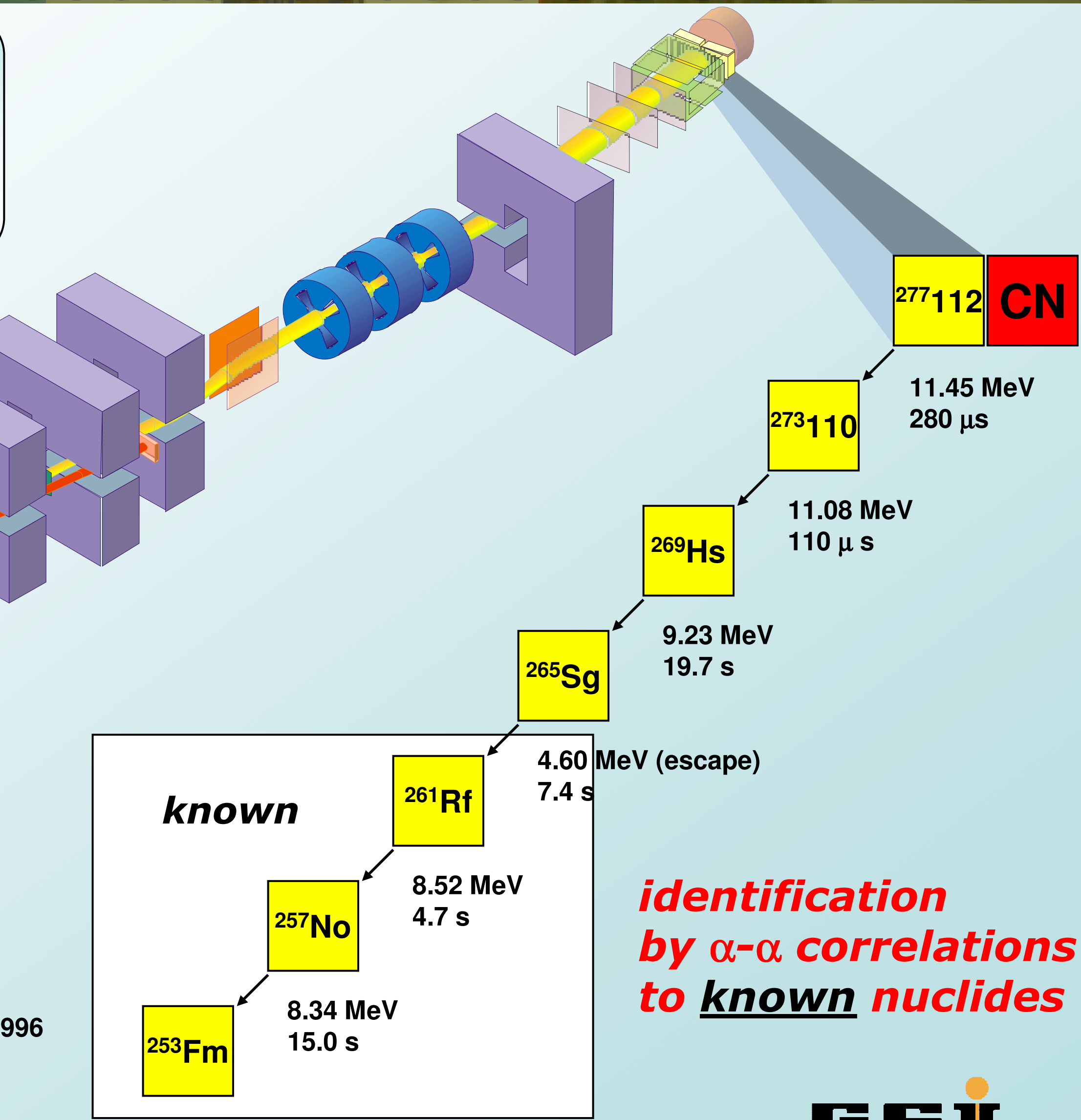
IUPAC Report
Pure Appl. Chem.
doi:10.1351/PAC-REP-08-03-05
Published online 2009-05-25

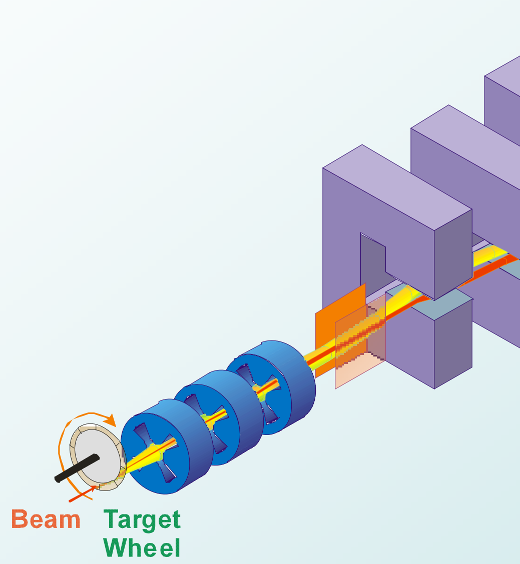
^{208}Pb

region of deformed shell stabilised nuclei around Z=108 and N=162

Synthesis and Identification of SHE at SHIP







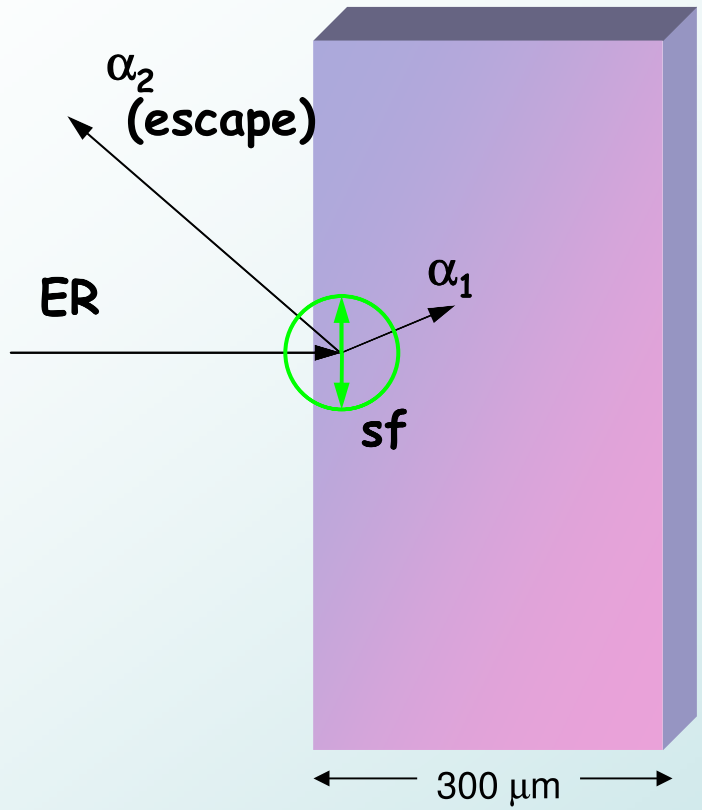
kinematic separation in flight

identification by α-α correlations to __known__ nuclides

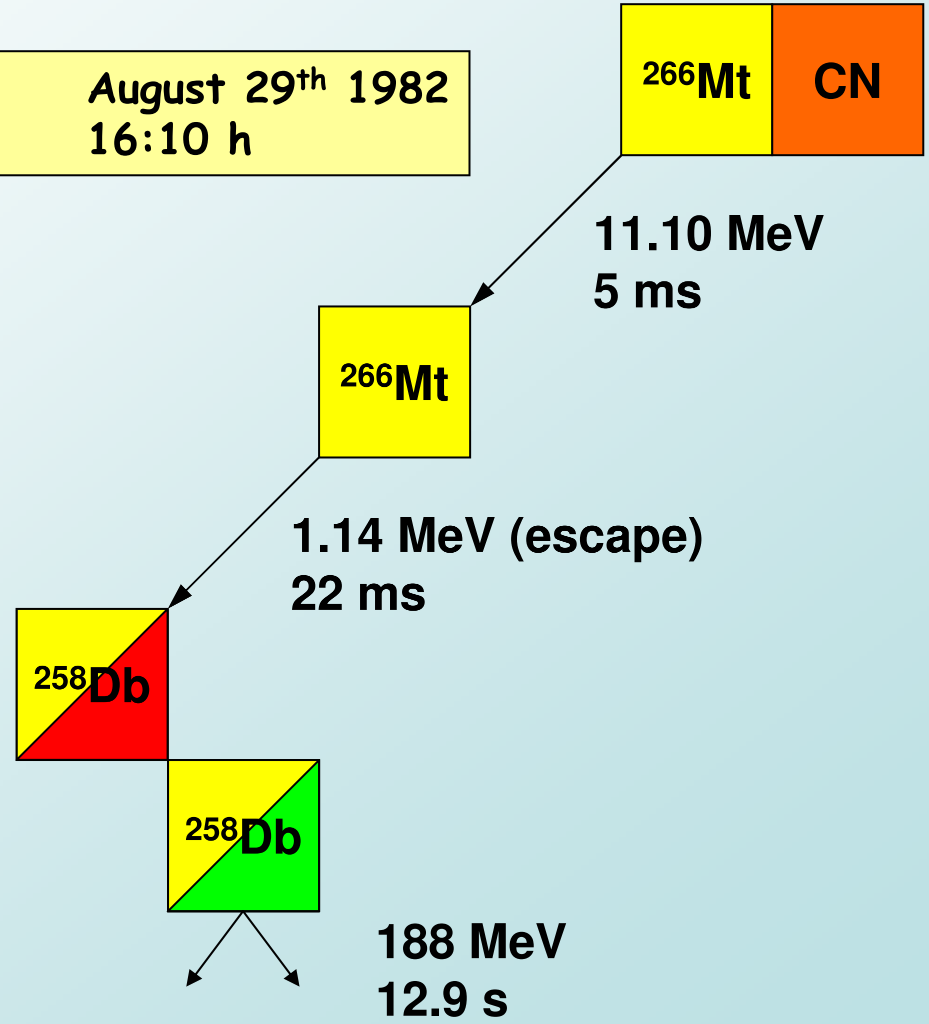
ER-α Correlation method

- Example: $^{58}Fe + ^{209}Bi \rightarrow ^{266}Mt + 1n$

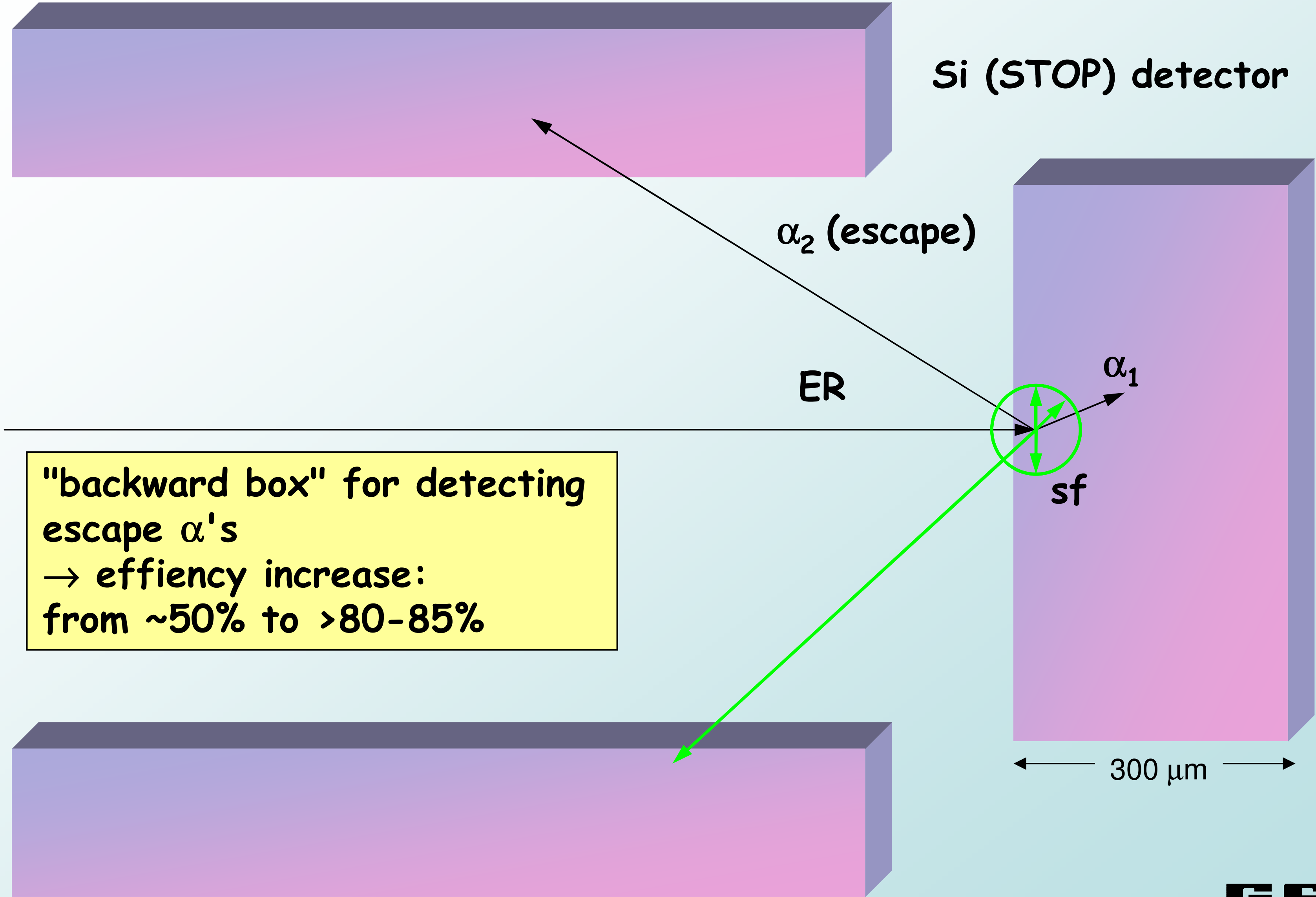
Si (STOP) detector



date: August 29th 1982
time: 16:10 h



Revelation of escape α's
- "Backward Box" SI detector array



"backward box" for detecting escape α's
→ effiency increase:
from ~50% to >80-85%

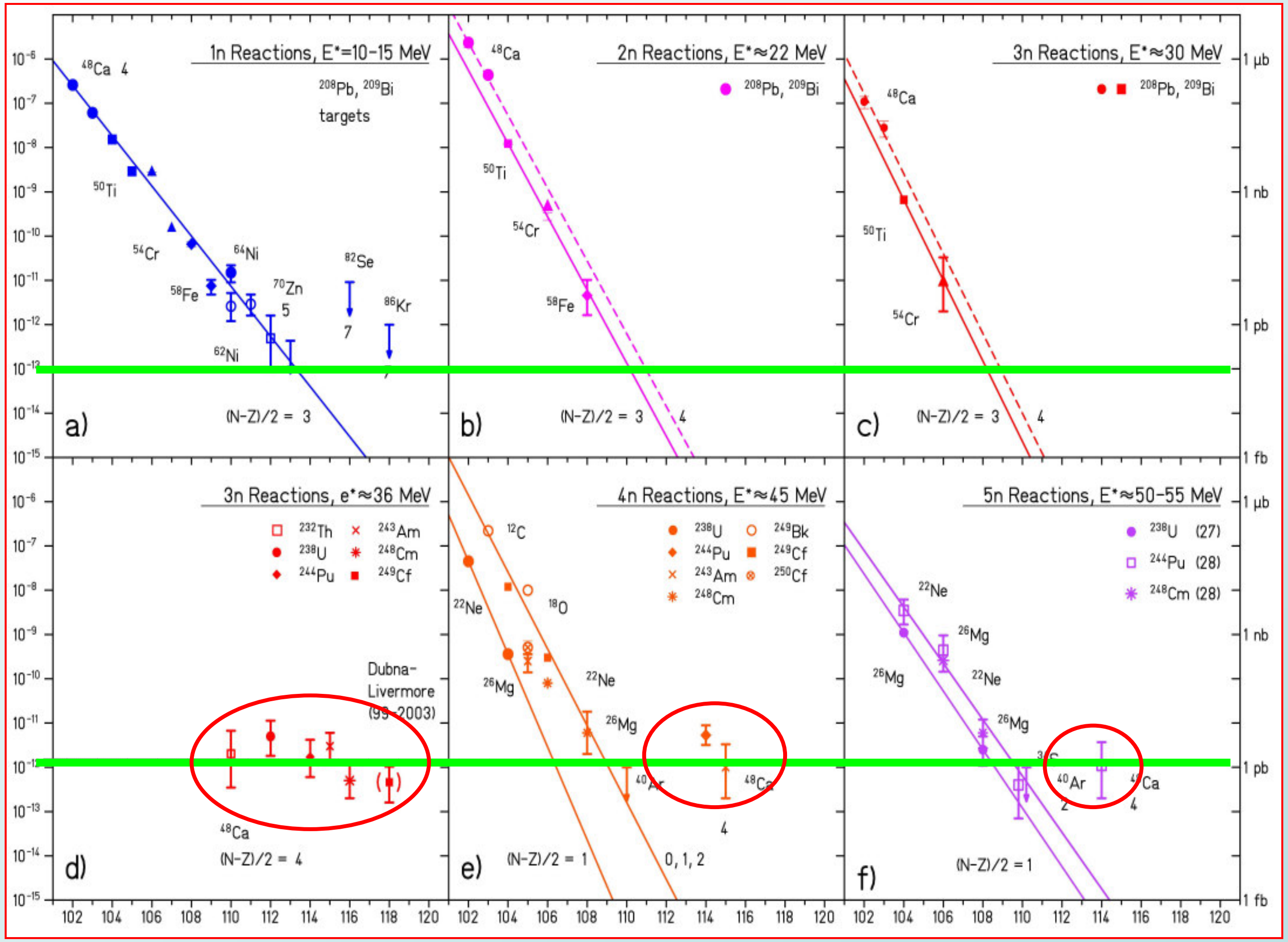
Cross Section Systematics

Cold fusion (GSI)
→ based on
Pb and Bi targets

1 pb

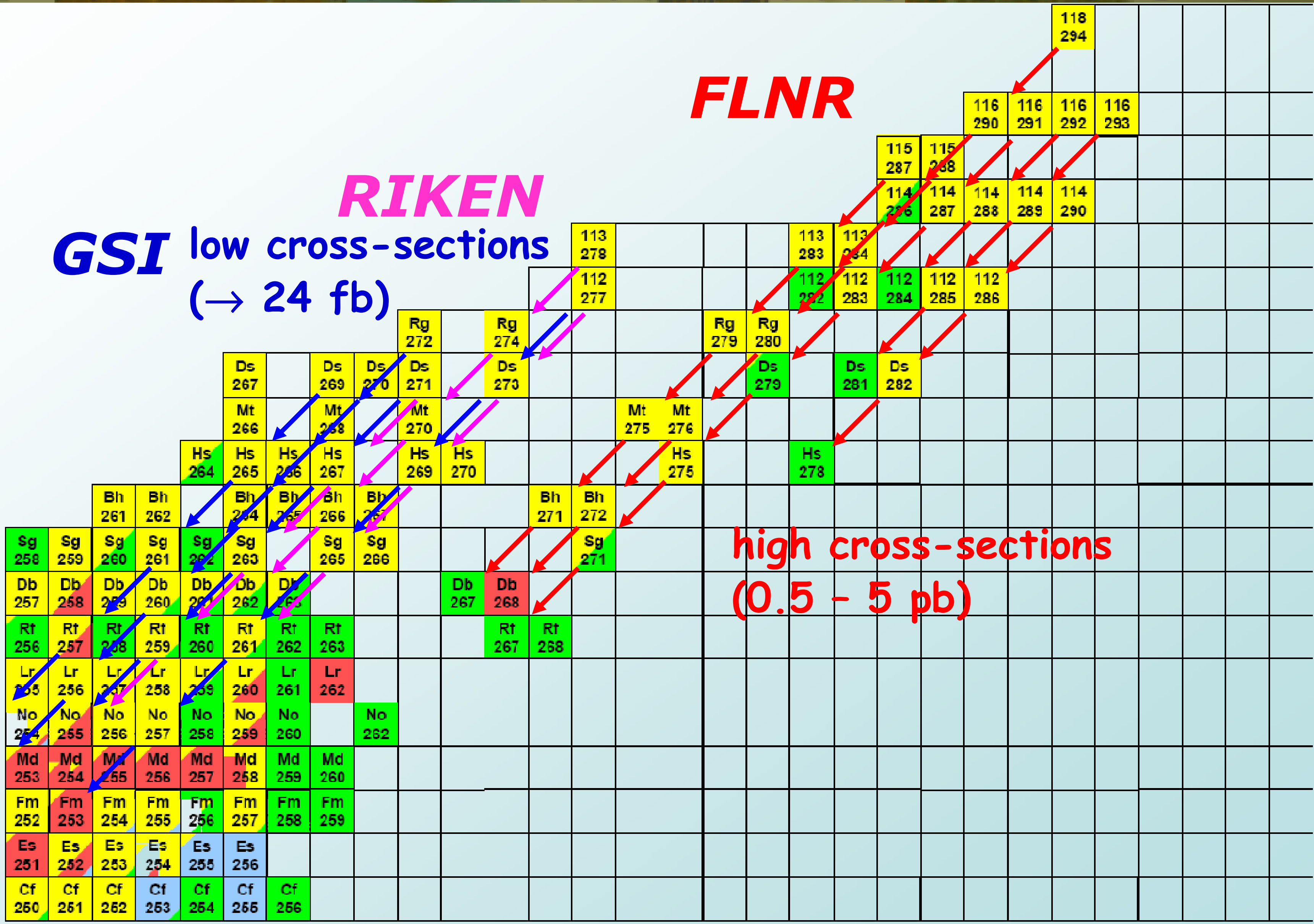
Hot fusion (JINR)
→ based on
actinide targets

1 pb



Surprising high cross-sections (0.5 – 5 pb) for synthesis of spherical SHE

SHE Synthesis – Present Status



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2. Reaction Mechanism of Heavy Ion Collisions at the Coulomb Barrier
3. Synthesis and Investigation of Superheavy Nuclei
4. **Nuclear Structure of Heavy and Superheavy Nuclei**
   - **The shell model – Maria Goeppert Mayer**
   - **Single particle levels and deformation**
   - **Decay spectroscopy – ER-α-γ(-γ) correlations**
   - **Isomeric states**
   - **Nuclear structure in the vicinity of closed shells**
5. Additional Methods

The Shellmodel

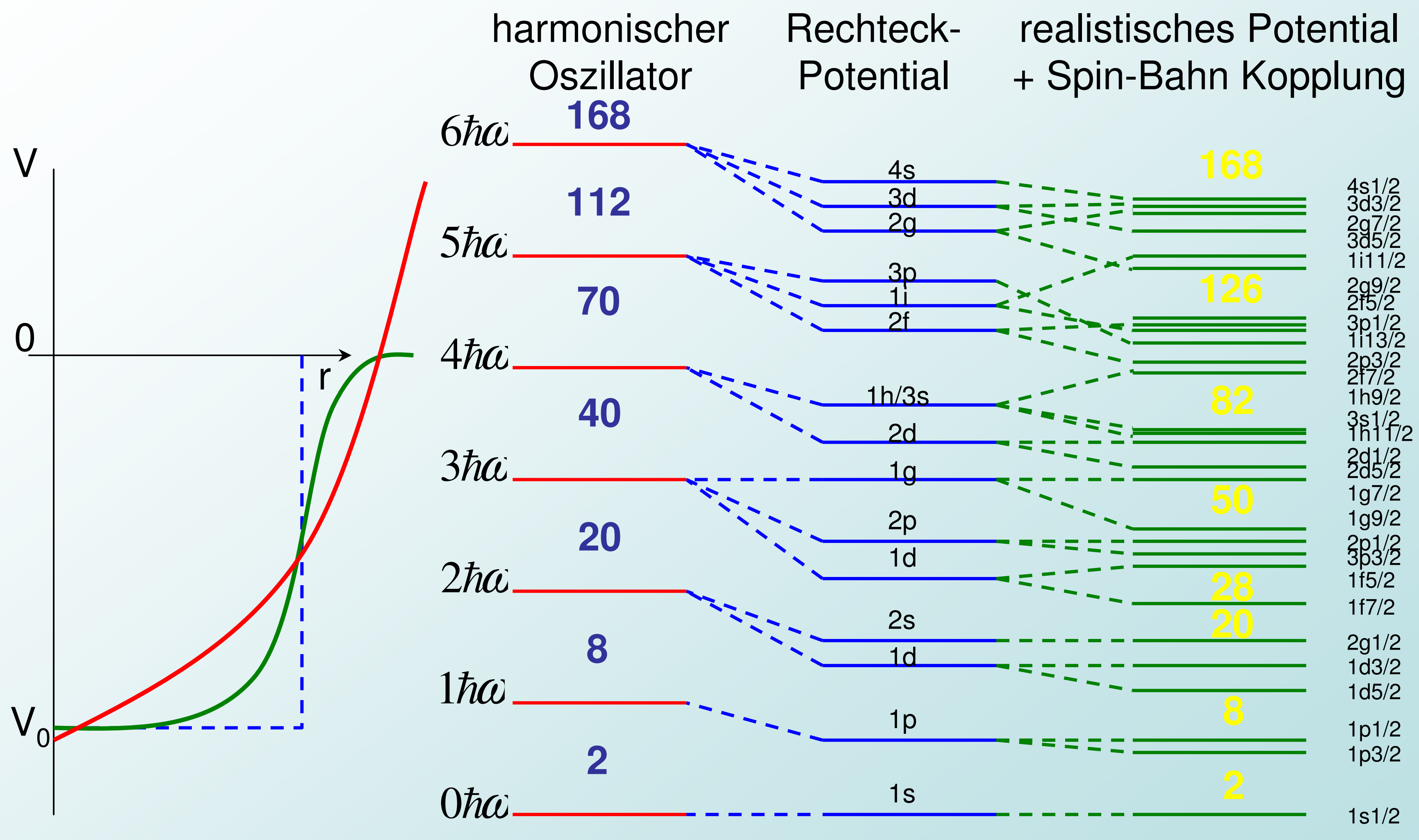
- Maria Goeppert-Mayer and J. Hans D. Jensen

The Shell modell:
Harmonic oscillator and spin orbit coupling → shell structure of single particle levels (Maria Goeppert Mayer and J. Hans D. Jensen)

Table 1 -- Nuclear Shell Structure (from *Elementary Theory of Nuclear Shell Structure*, Maria Goeppert Mayer & J. Hans D. Jensen, John Wiley & Sons, Inc., New York, 1955.)

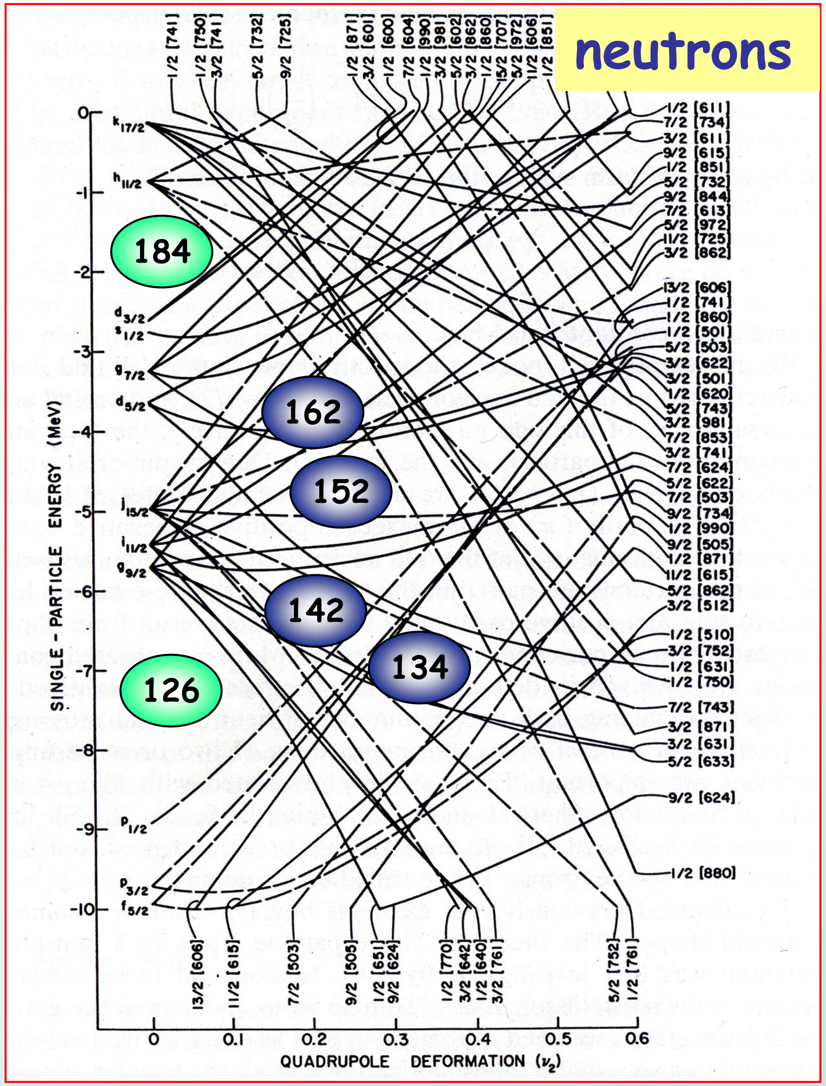
Angular Momentum ($\hbar\Omega/2\pi$)		Spin-Orbit Coupling (1/2, 3/2, 5/2, 7/2...)	Number of Nucleons Shell	Total	Magic Number
7	1j				
		1j 15/2	16	[184]	{184}
		3d 3/2	4	[168]	
6	4s	4s 1/2	2	[164]	
6	3d	2g 7/2	8	[162]	
		1i 11/2	12	[154]	
6	2g	3d 5/2	6	[142]	
		2g 9/2	10	[136]	
6	1i				
		1i 13/2	14	[126]	{126}
		3p 1/2	2	[112]	
5	3p	3p 3/2	4	[110]	
		2f 5/2	6	[106]	
5	2f	2f 7/2	8	[100]	
		1h 9/2	10	[92]	
5	1h				
		1h 11/2	12	[82]	{82}
4	3s	3s 1/2	2	[70]	
		2d 3/2	4	[68]	
4	2d	2d 5/2	6	[64]	
		1g 7/2	8	[58]	
4	1g				
		1g 9/2	10	[50]	{50}
		2p 1/2	2	[40]	{40}
3	2p	1f 5/2	6	[38]	
		2p 3/2	4	[32]	
3	1f				
		1f 7/2	8	[28]	{28}
		1d 3/2	4	[20]	{20}
2	2s	2s 1/2	2	[16]	
2	1d	1d 5/2	6	[14]	
		1p 1/2	2	[8]	{8}
1	1p	1p 3/2	4	[6]	
0	1s	1s 1/2	2	[2]	{2}

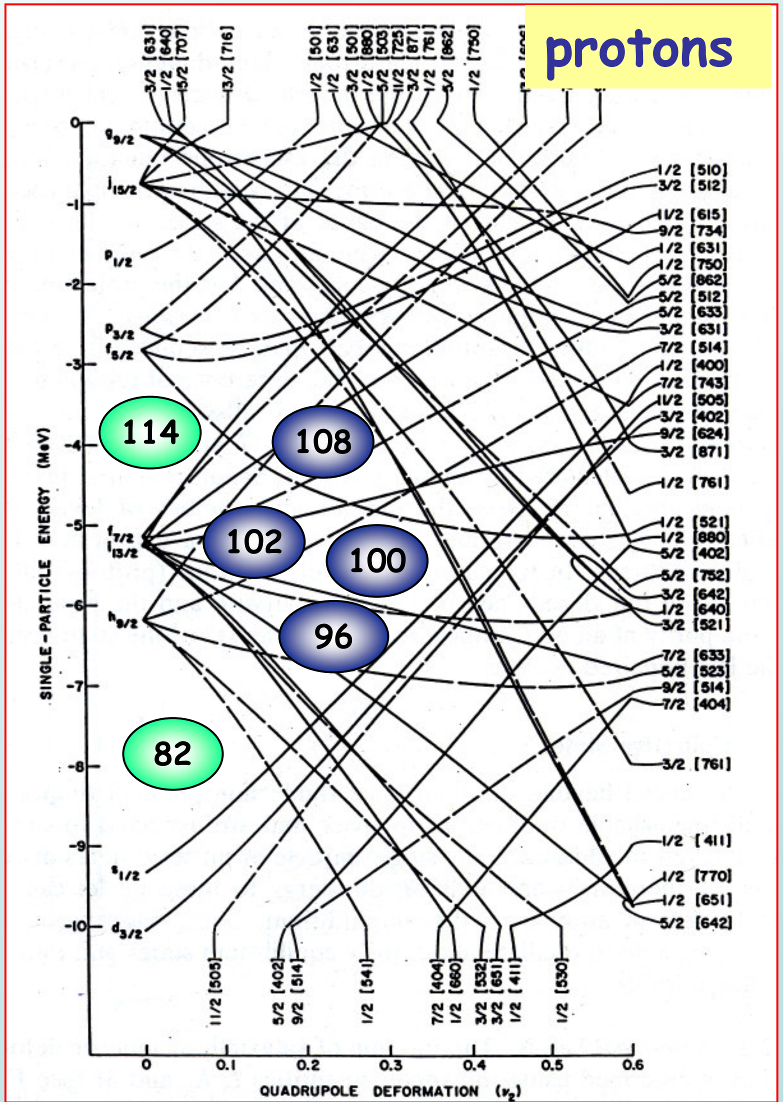
The Shell Model
- Maria Goeppert-Mayer and J. Hans D. Jensen



Nuclear Structure of Heavy Nuclei

- Single Particle Levels and Deformation





Nuclear Structure of Heavy Nuclei

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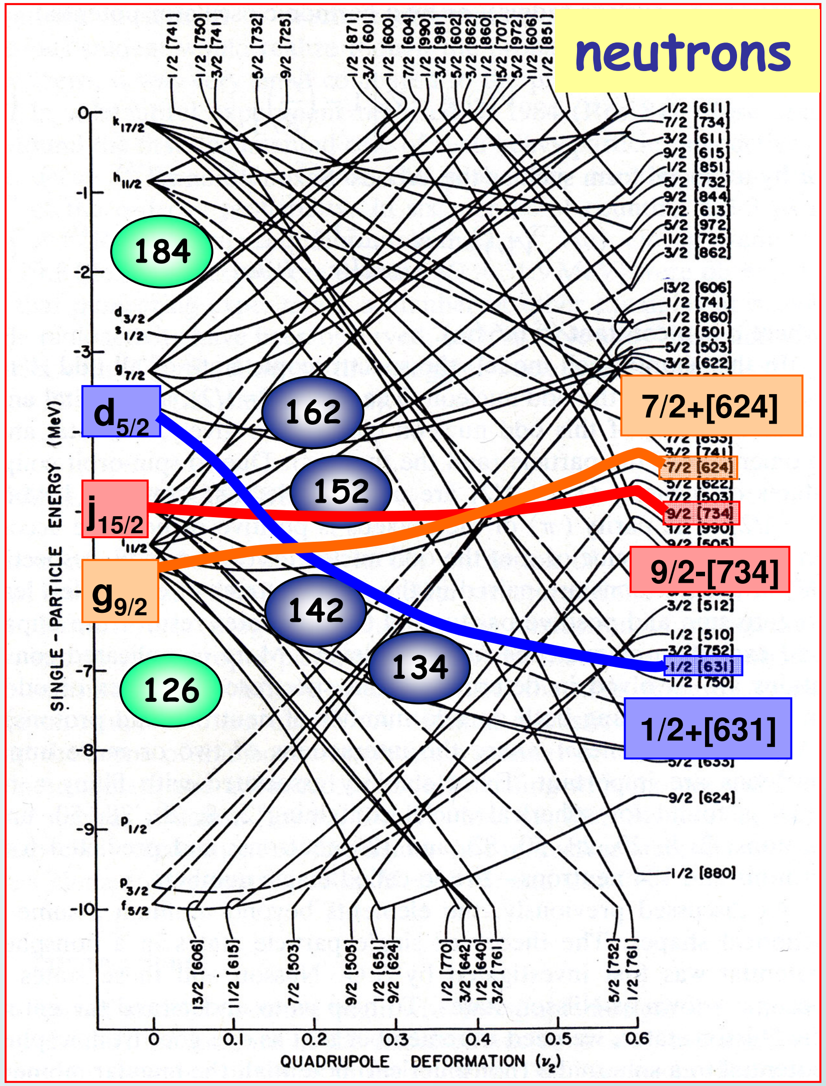
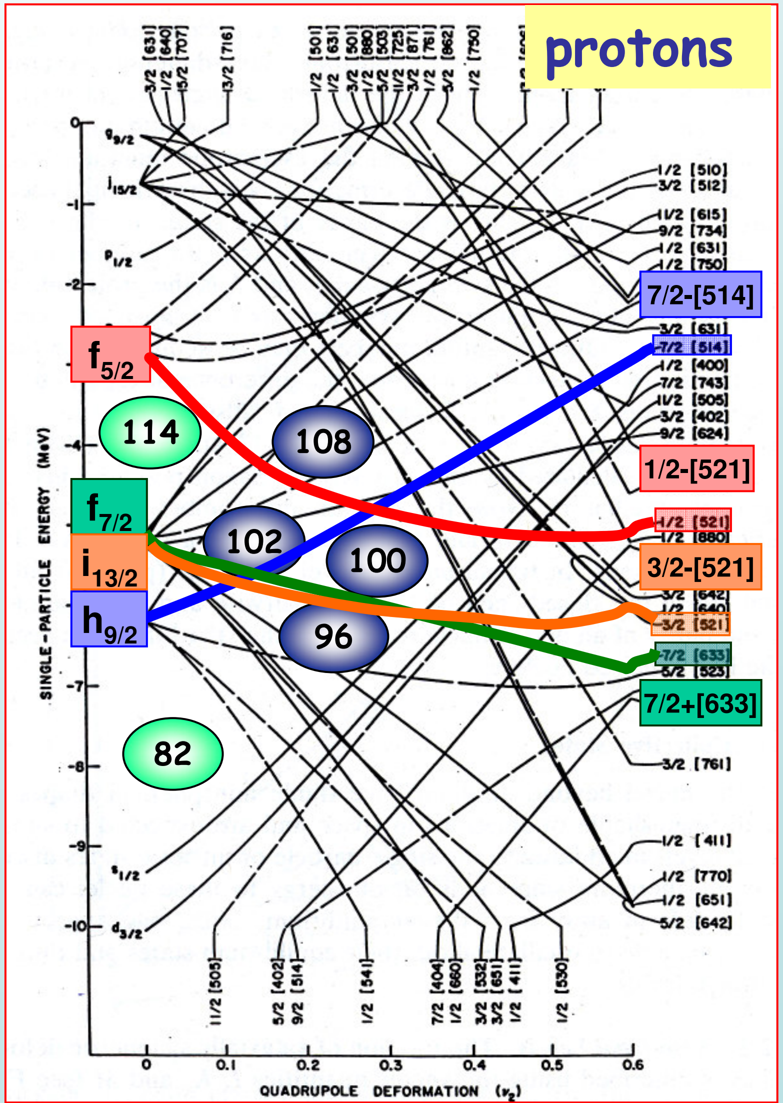
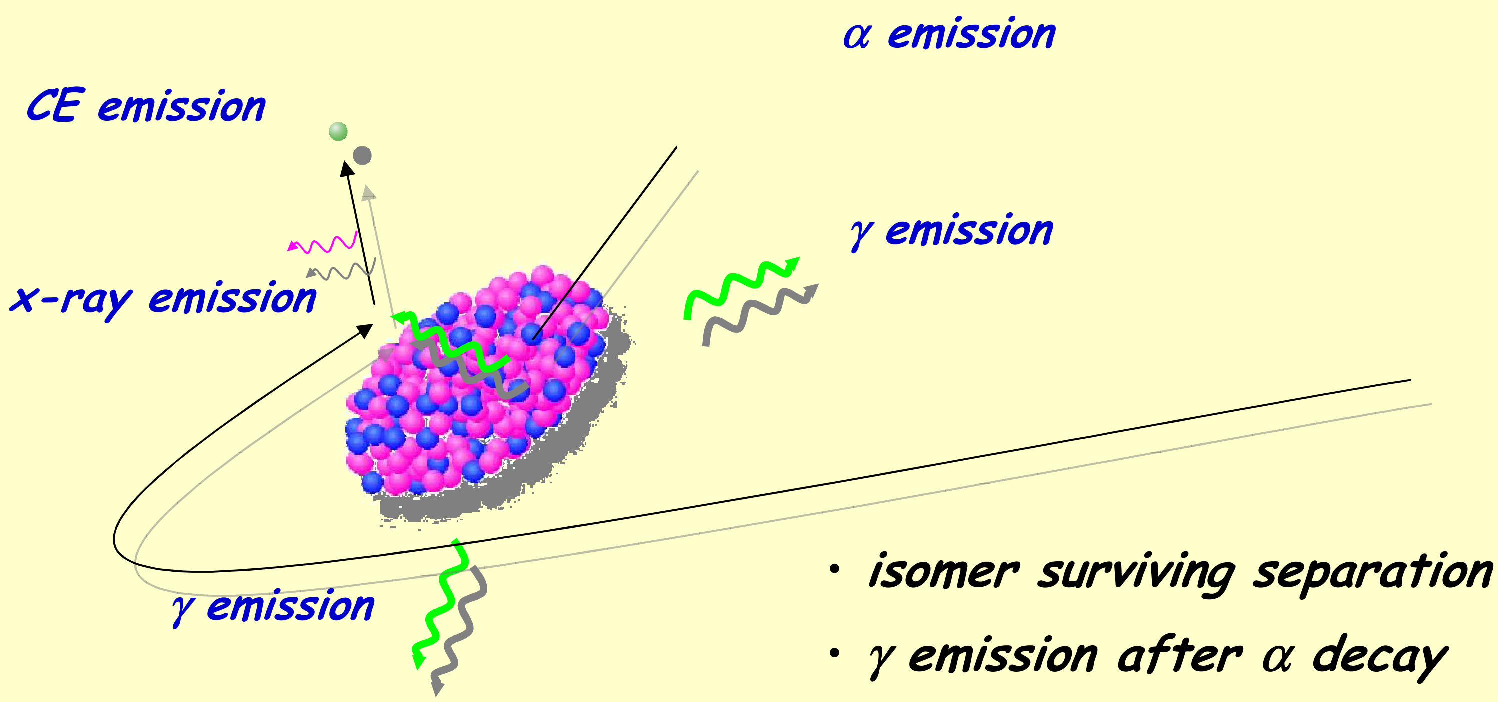




Nuclear Structure of SHE

- Decay Spectroscopy at SHIP/TASCA

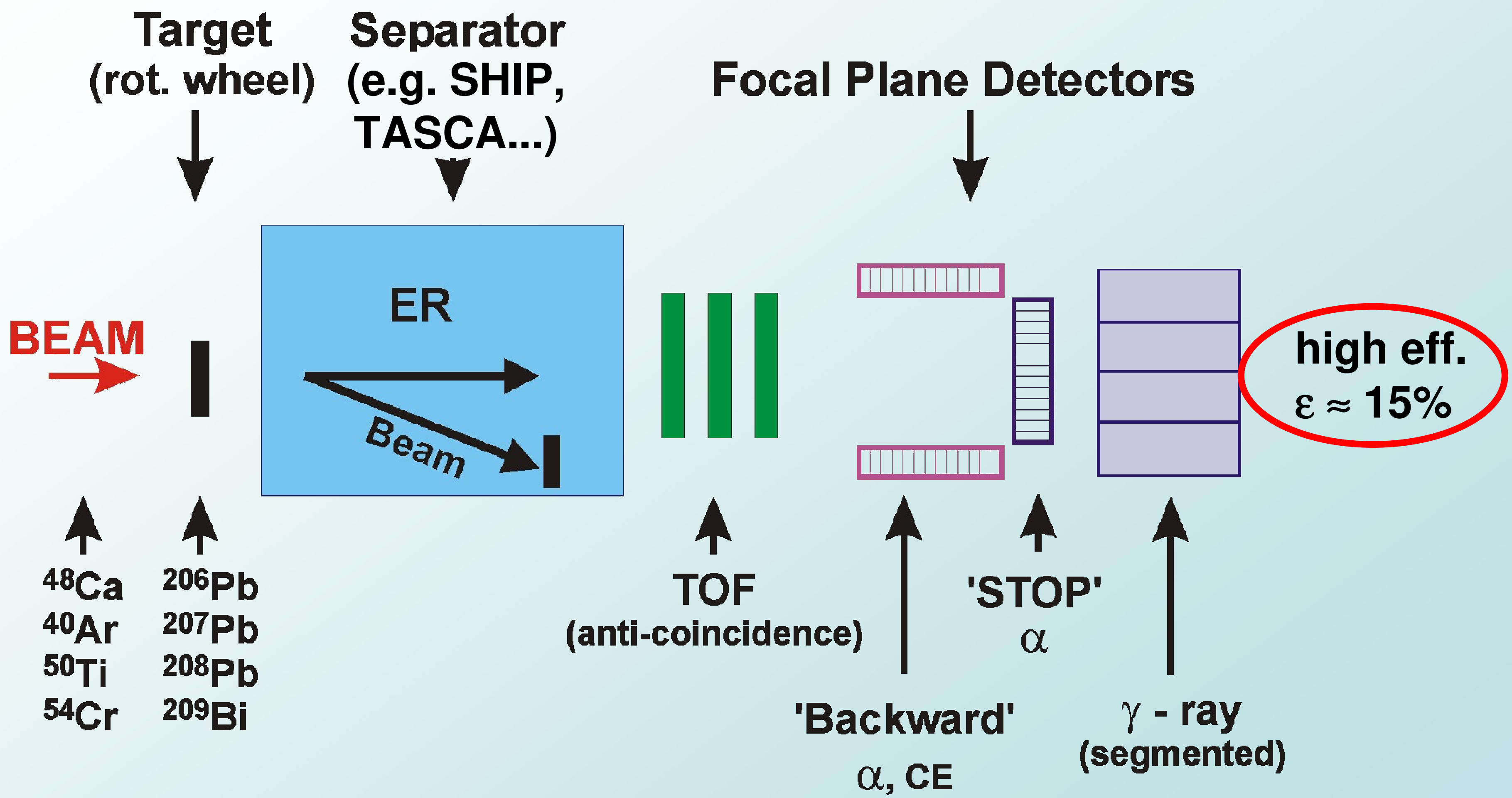


evaporation residue after separation

- isomer surviving separation
- γ emission after α decay
- CE for highly converted transitions
  + X-ray emission

Nuclear Structure of SHE

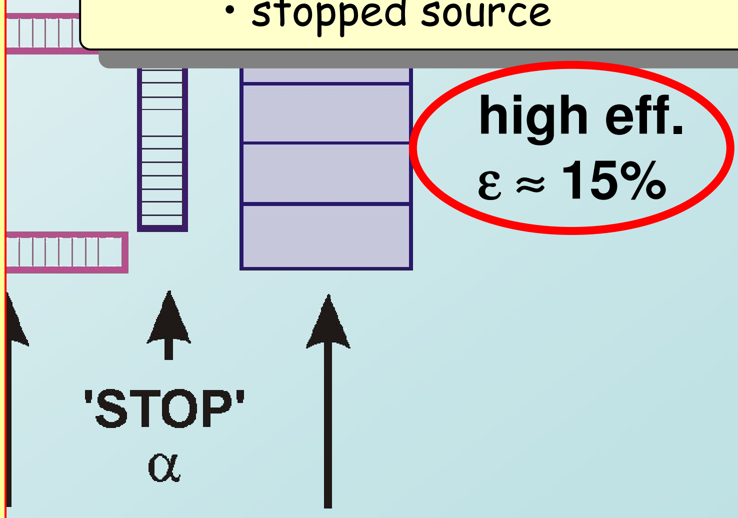
- Decay Spectroscopy at SHIP/TASCA

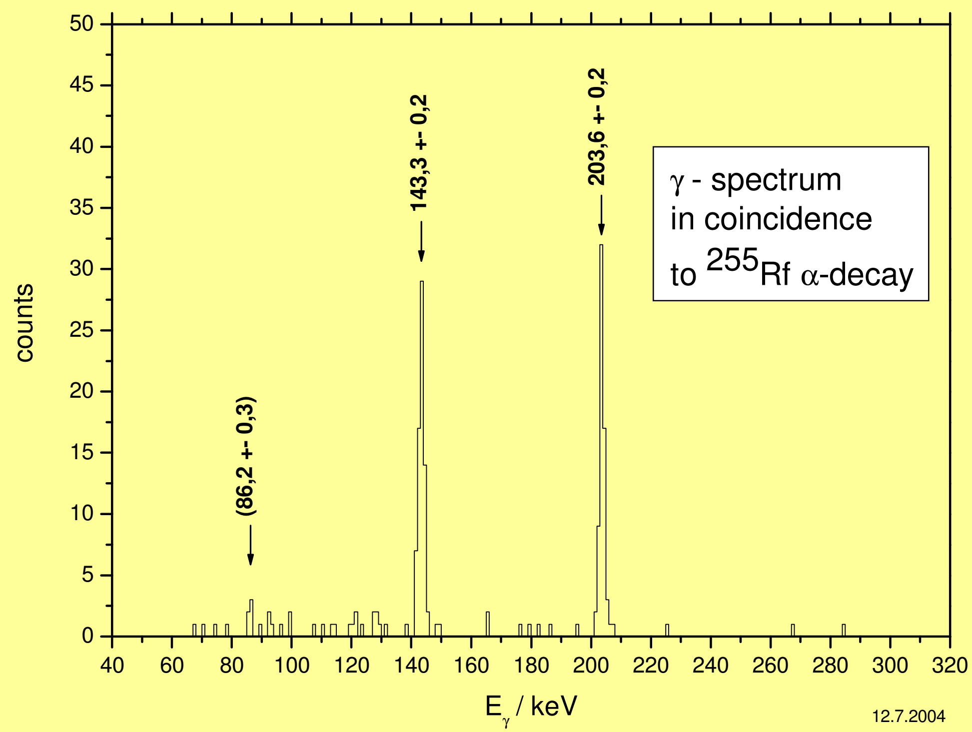


Nuclear Structure of SHE

- Decay Spectroscopy at SHIP/TASCA

- **inclusive measurement**
  - ER, α's, γ's <u>and e⁻</u>
- **clean**
  - particle discrimination
  - ER-α-γ correlations
- **highly efficient**
  - close geometry
  - stopped source

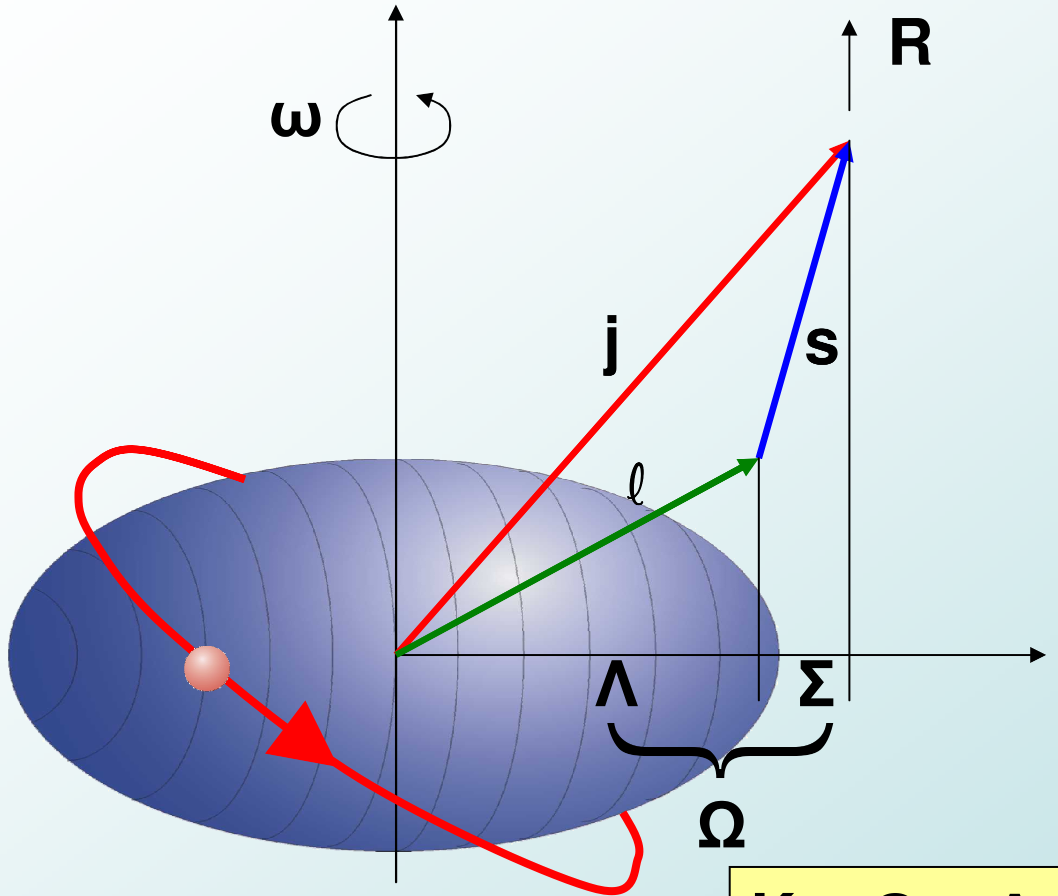


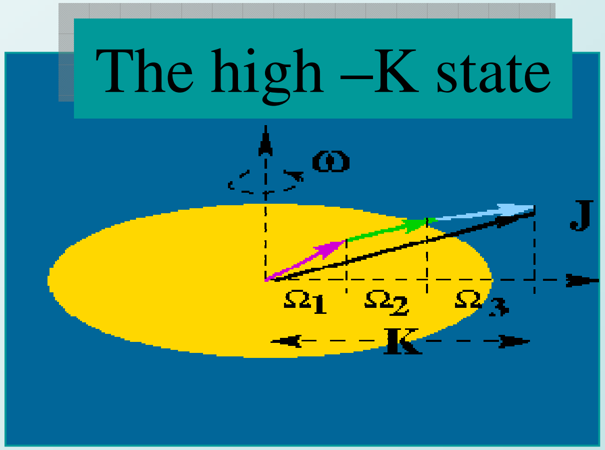


F.P. Heßberger et al, EPJ A 30, 561 (2006)

K-Quantum number

- the Definition





$$K = \Omega = \Lambda + \Sigma$$

K-isomers for Z = 96 - 110

- Experimental Information

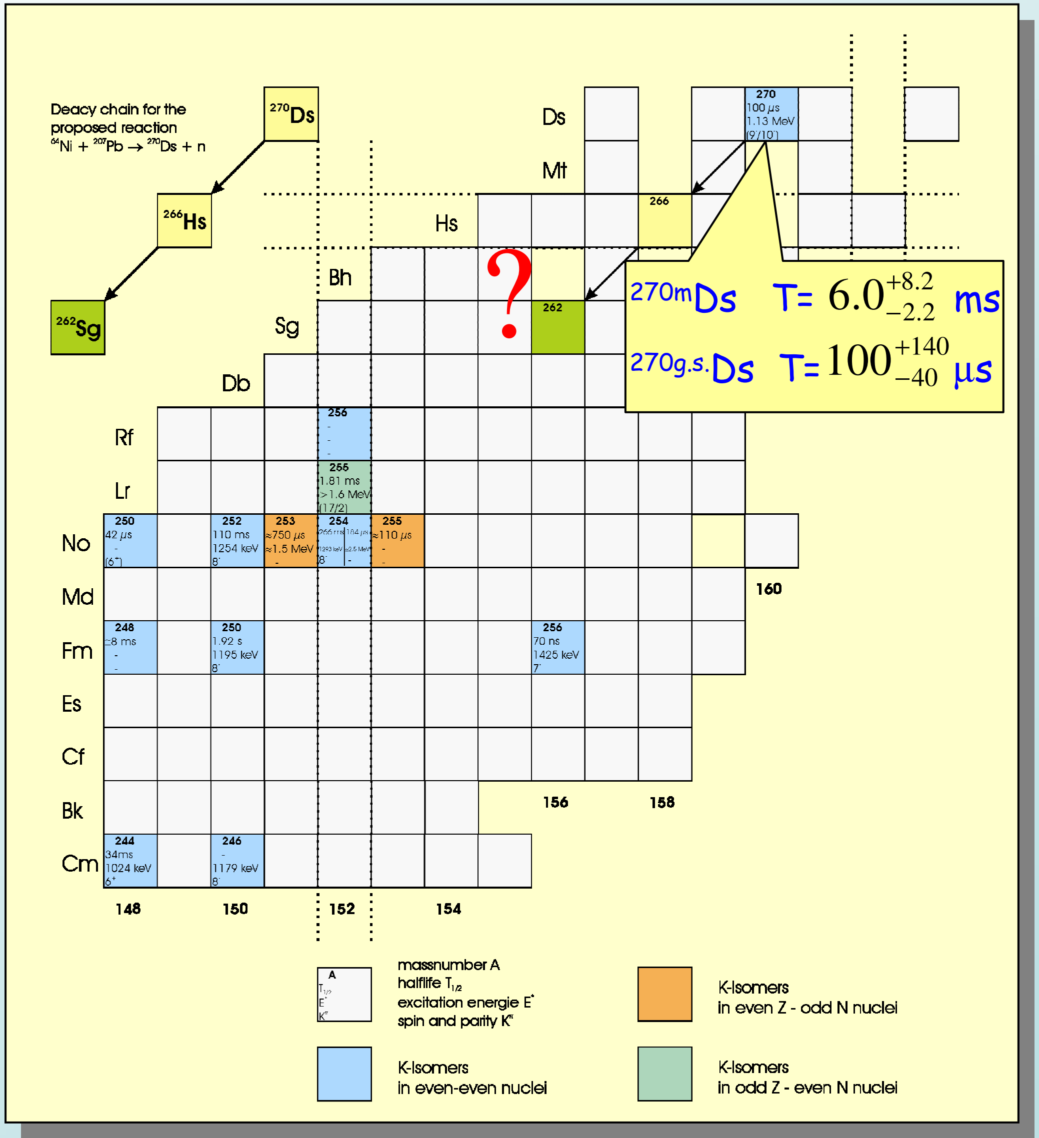
14 cases:

even-even:	11
even-odd:	2
odd-even:	1

Sg and Hs isotopes?

$T_{1/2}$: 70 ns (^{256}Fm) – 1.92 s (^{250}Fm)

E*: 1-1.5 MeV (2.5 MeV for ^{254m2}No)



K-isomers for Z = 96 - 110

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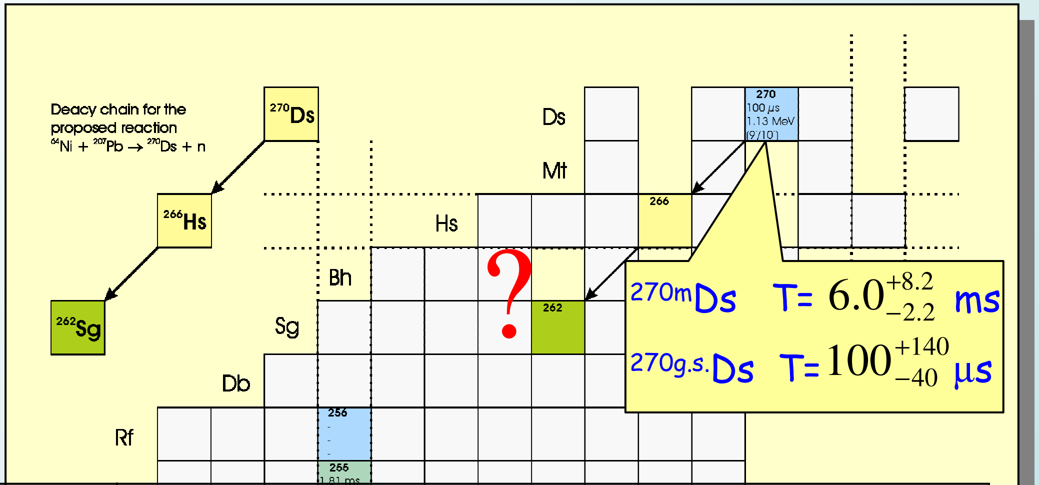


Table 1
Table of known *K*-isomers in even–even nuclei in the heavy and superheavy elements

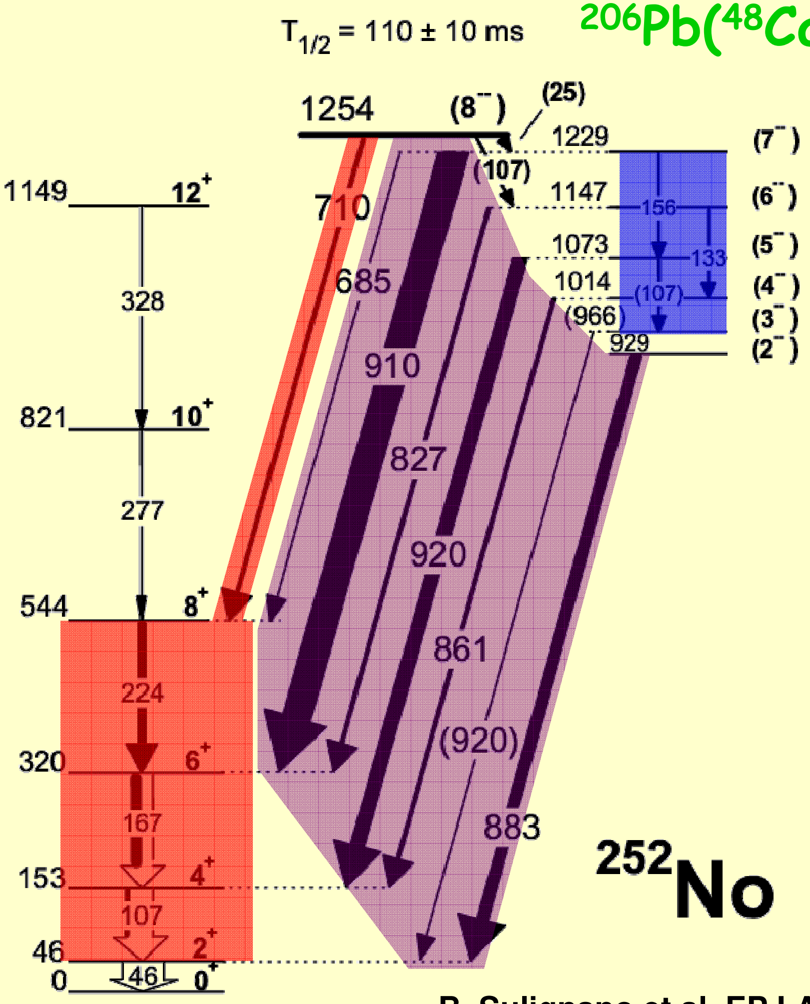
Nucleus	K^π	$T_{1/2}$	E_x	Decay Mode	Configuration	Reference
^{244}Cm	6^+	34 ms	1.040 MeV	γ	$5/2^+[622]_\nu \otimes 7/2^+[624]_\nu$	[135,171]
^{246}Cm	8^-	–	1.179 MeV	γ	$7/2^+[624]_\nu \otimes 9/2^-[734]_\nu$	[138]
^{248}Fm	–	≃8 ms	–	γ	–	[148]
^{250}Fm	8^-	1.92 s	1.195 MeV	γ	$7/2^+[624]_\nu \otimes 9/2^-[734]_\nu$	[82]
^{256}Fm	7^-	70 ns	1.425 MeV	γ,SF	$7/2^+[633]_\pi \otimes 7/2^-[514]_\pi$	[69]
^{250}No	(6^+)	42 µs	–	SF,γ?	$(5/2^+[622]_\nu \otimes 7/2^+[624]_\nu)$	[118]
^{252}No	8^-	110 ms	1.254 MeV	γ	$7/2^+[624]_\nu \otimes 9/2^-[734]_\nu$	[169]
^{254}No	8^-	266 ms	1.293 MeV	γ	$7/2^-[514]_\pi \otimes 9/2^+[624]_\pi$	[77,78]
^{254}No	–	184 µs	≃2.5 MeV	γ	–	[77,78]
^{270}Ds	$9^-,10^-$	6 ms	≃1.13 MeV	α	$11/2^-[725]_\nu \otimes 7/2^+[613]_\nu$ $11/2^-[725]_\nu \otimes 9/2^+[615]_\nu$	[22]

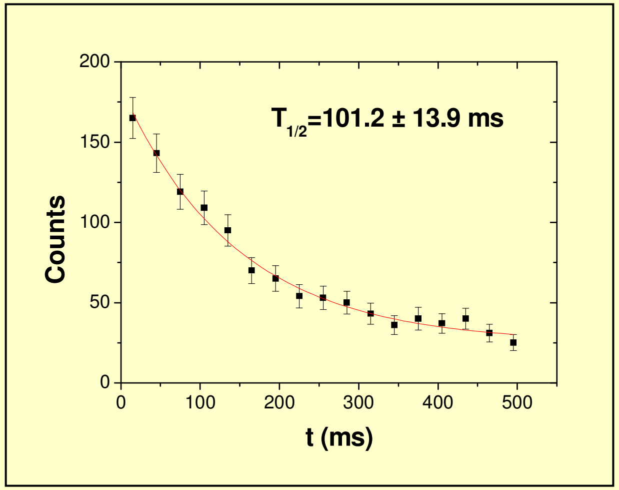
In some cases the K^π or configuration assignments are tentative and have not been made on the basis of unambiguous experimental data. See relevant references for details.

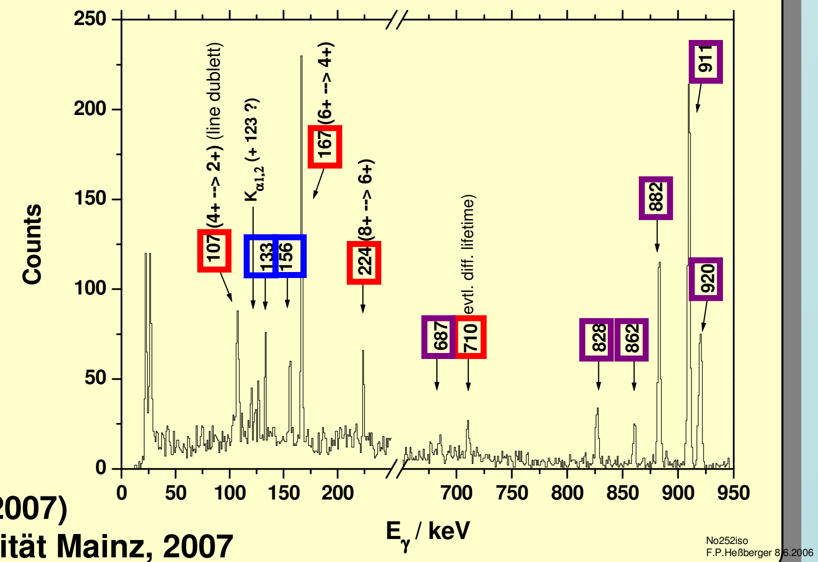
Nuclear Structure of the Heaviest Nuclei:

Isomeric states – ^{252}No (Ph.D. Thesis B. Sulignano)

$^{206}Pb(^{48}Ca,2n)^{252}No$



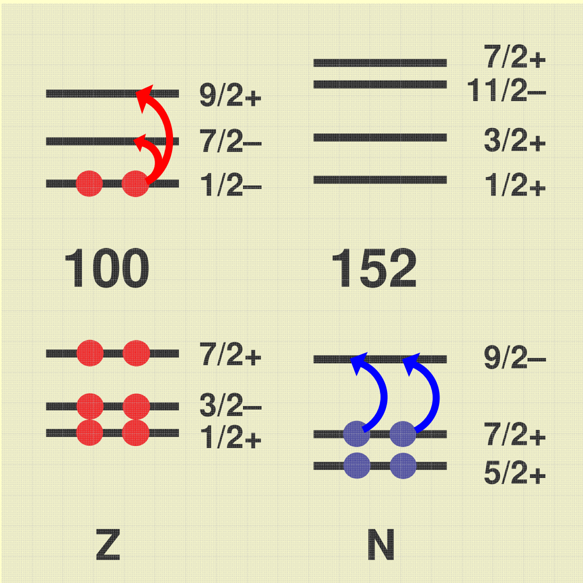




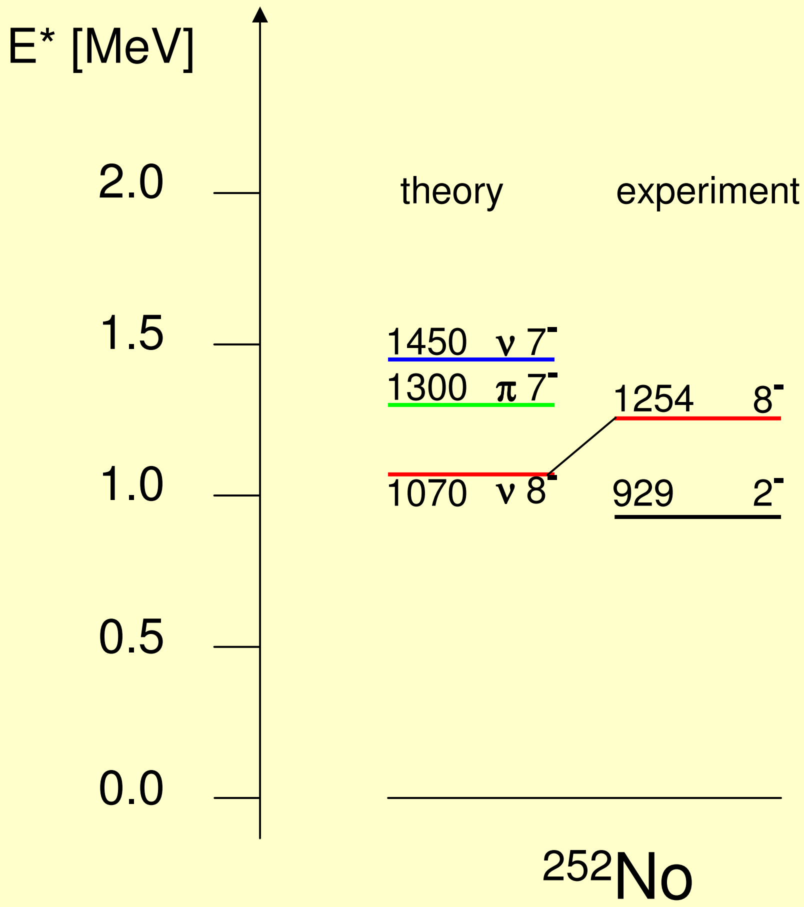
B. Sulignano et al. EPJ A33, 327 (2007)
B. Sulignano, PHD thesis, Universität Mainz, 2007

Nuclear Structure of the Heaviest Nuclei:
– ^{252}No Hartree Fock Bogolyubov/Gogny D1S

4+, 5–, 8–   8–



^{252}No



2-quasineutron state

$\{\nu[624]_{7/2+} \otimes \nu[734]_{9/2-}\}_{8^-}$

β_2 = 0.25

J.P. Delaroche et al., Nucl. Phys. A 771, 103 (2006)

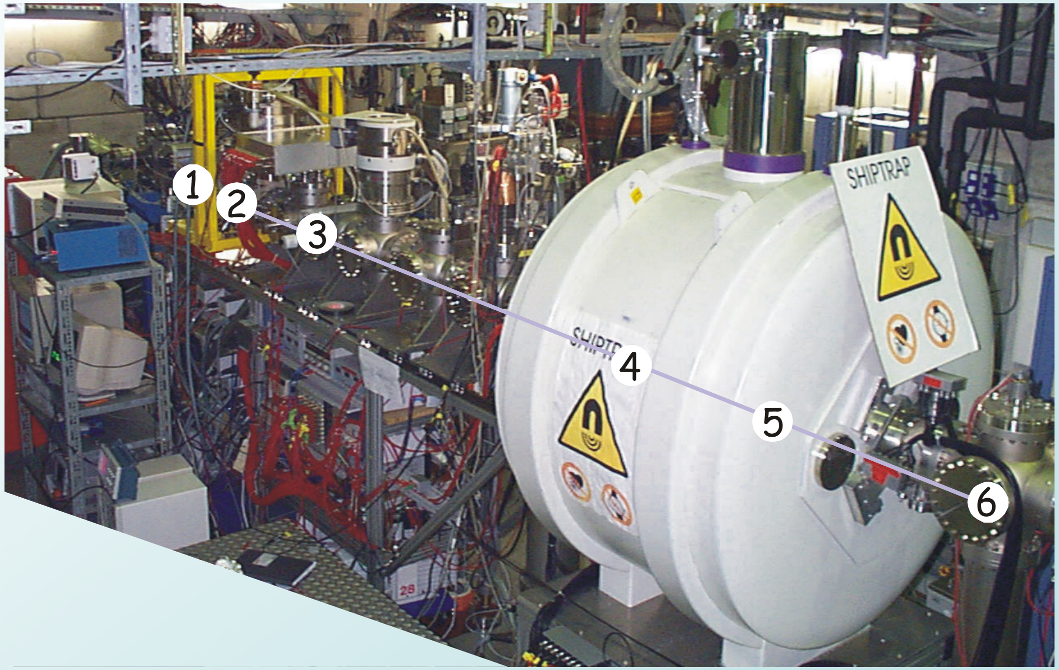
Additional Methods

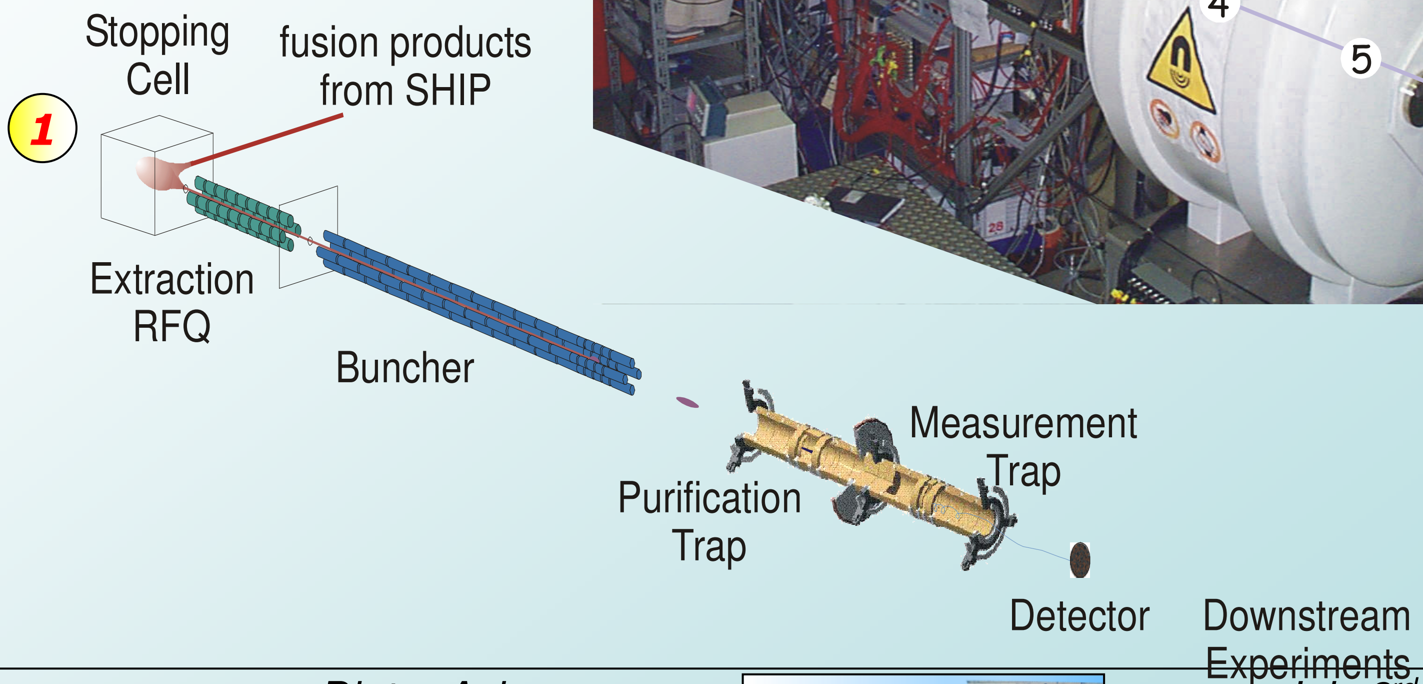
Outline

1. Introduction
2. Reaction Mechanism of Heavy Ion Collisions at the Coulomb Barrier
3. Synthesis and Investigation of Superheavy Nuclei
4. Nuclear Structure of Heavy and Superheavy Nuclei
5. **Additional Methods**
   - **Precision mass measurements**
   - **Chemistry**

SHIPTRAP

1. deceleration





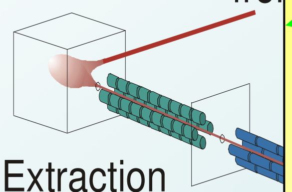
SHIPTRAP

1. decelerati

Stopping Cell

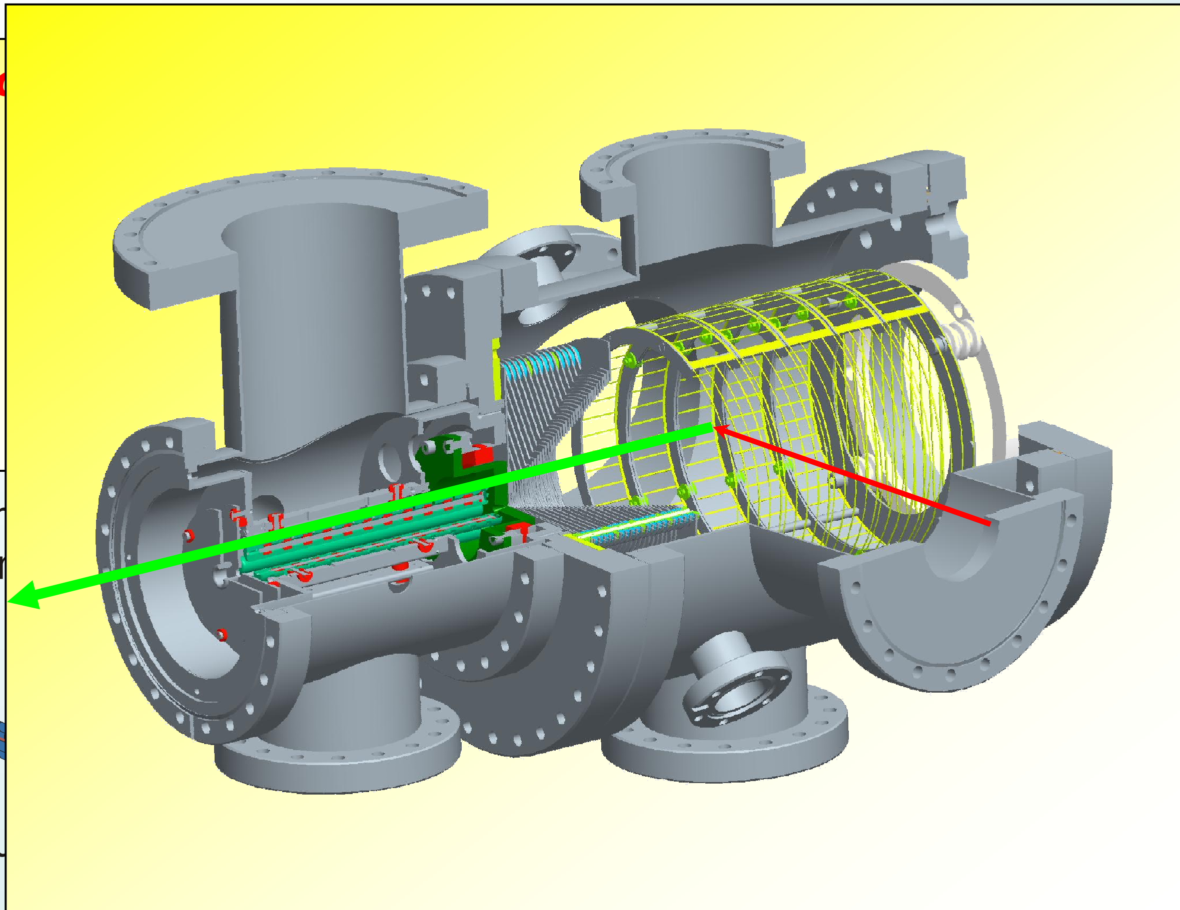
fusion fro

1



Extraction RFQ

Bu



Purification Trap

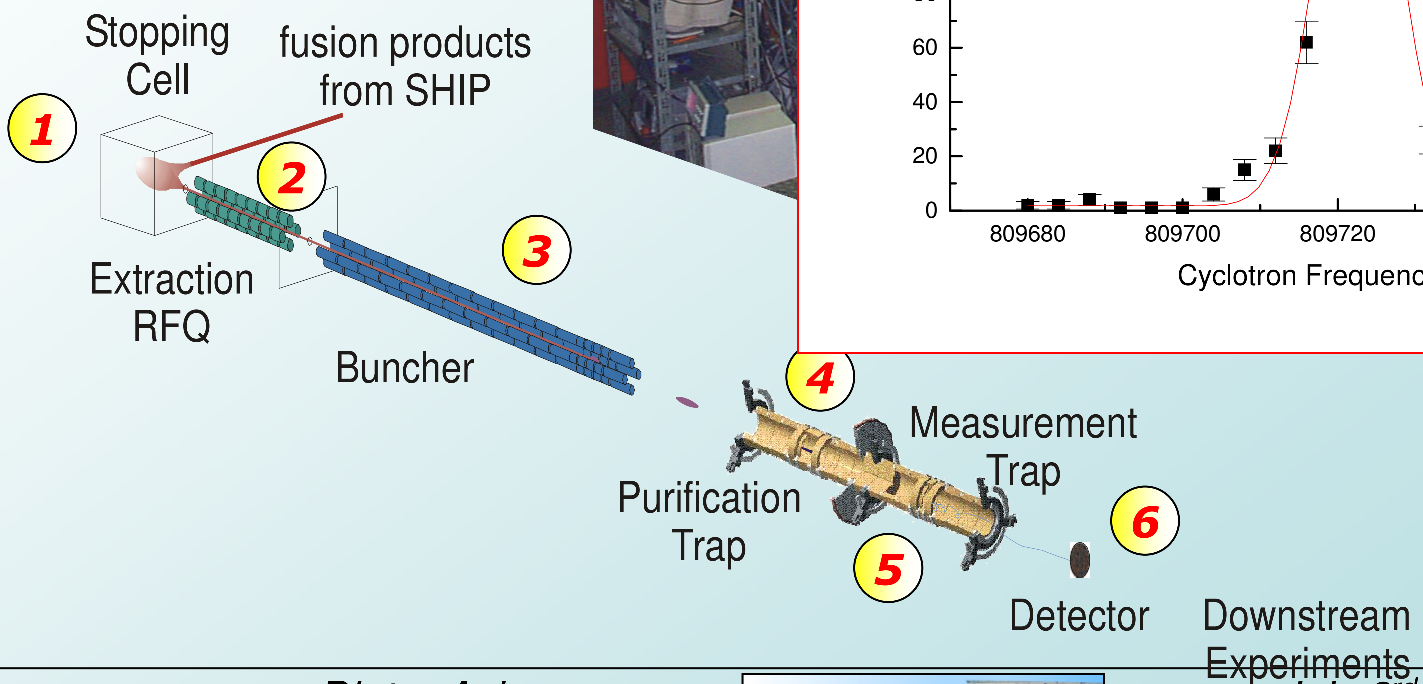
Trap

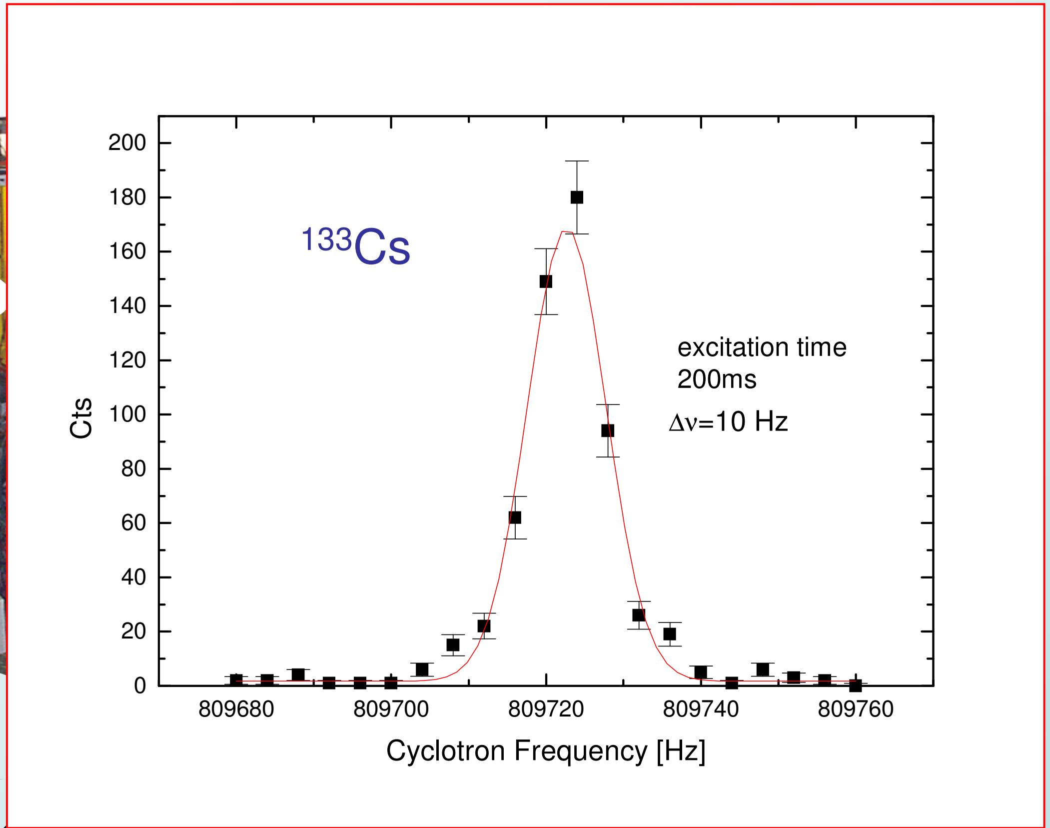
Detector

Downstream Experiments

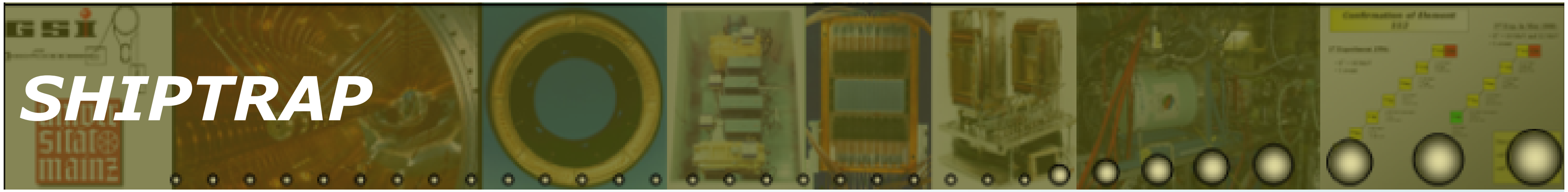
SHIPTRAP

1. ***deceleration***
2. ***cooling***
3. ***accumulation***
4. ***purification***

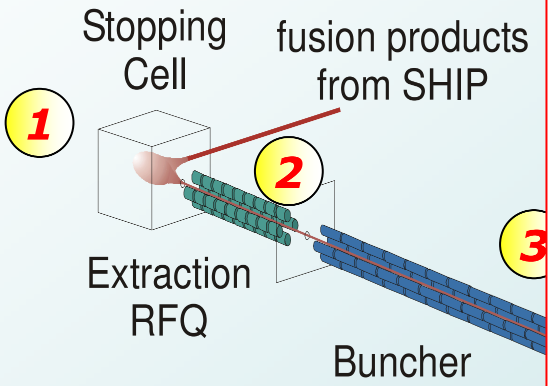


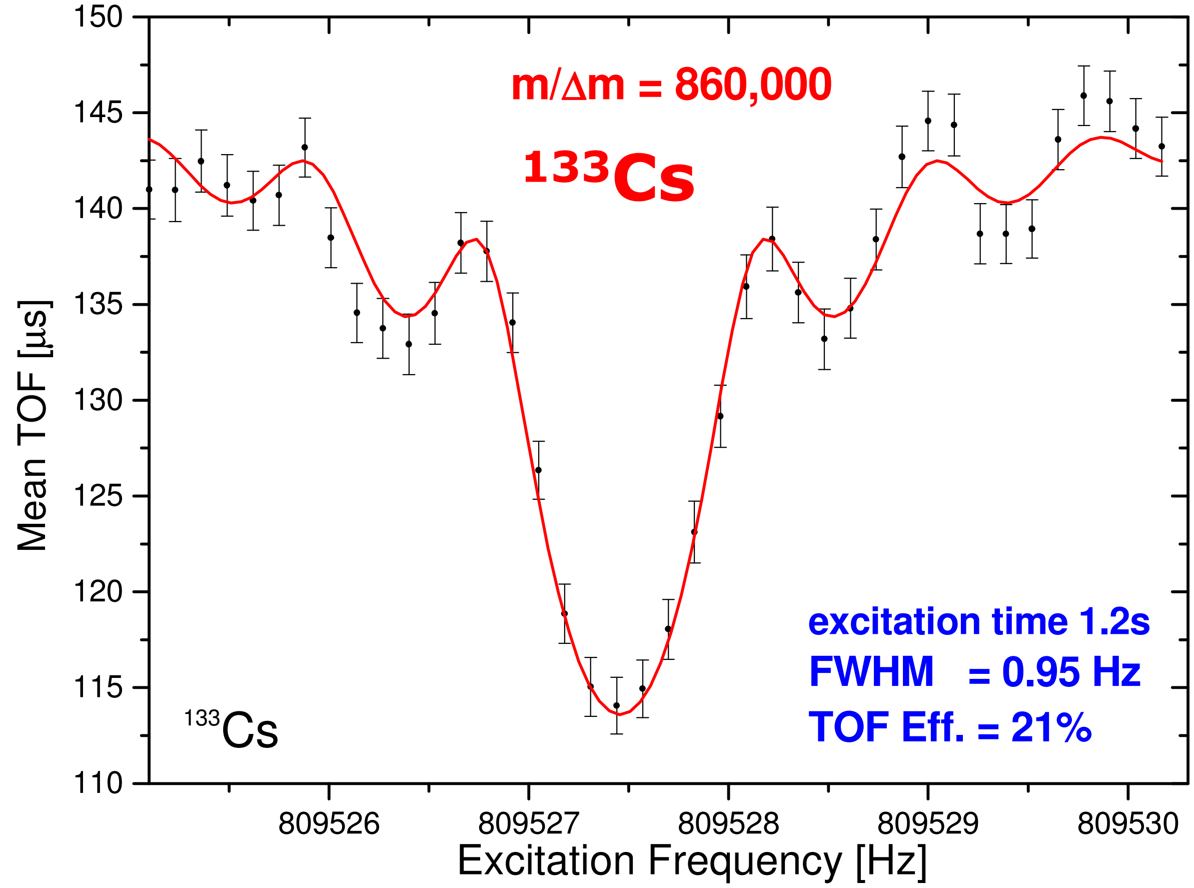


SHIPTRAP



1. *deceleration*
2. *cooling*
3. *accumulation*
4. *purification*
5. *storage*
6. *detection…*





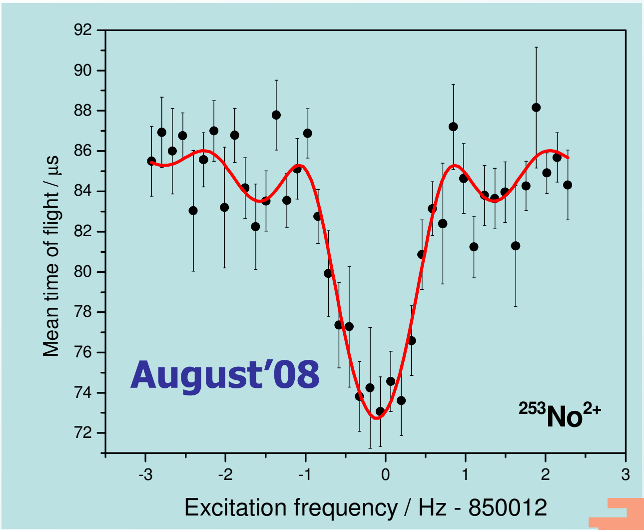
Detector

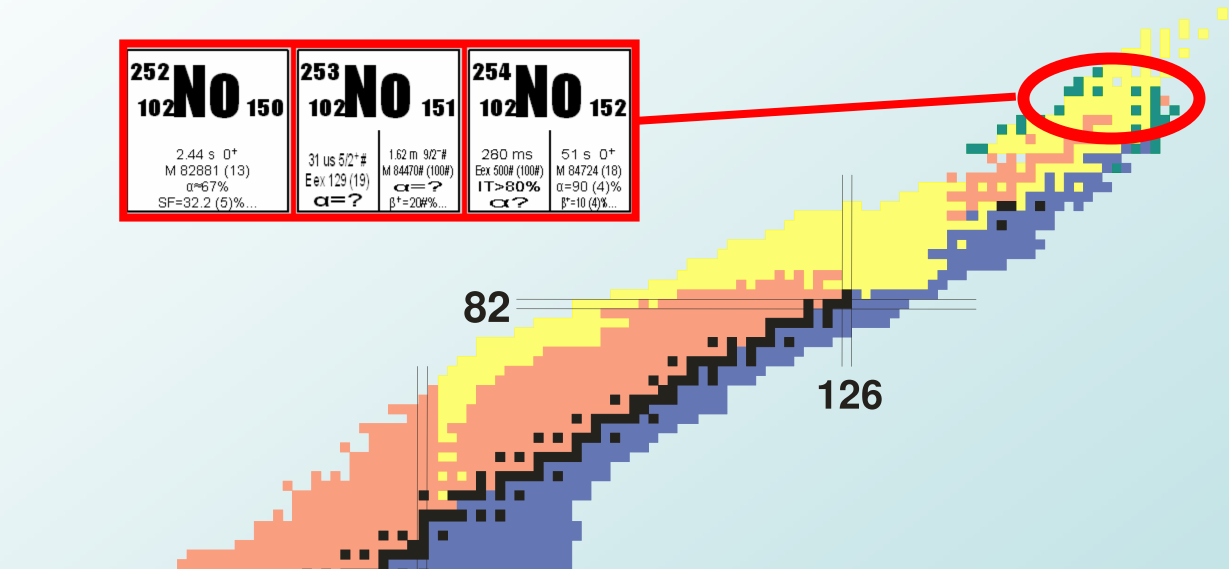
Downstream Experiments

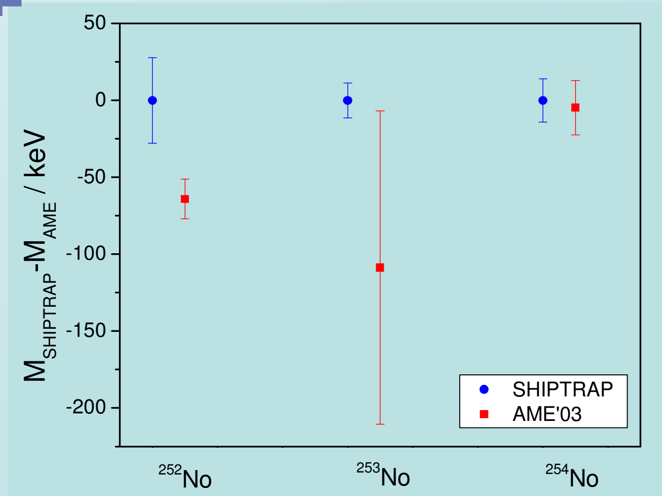
First direct mass measurements of $^{252-254}$No @ SHIPTRAP

Incoming particles for ^{252}No:

only ~0.6 ions/s







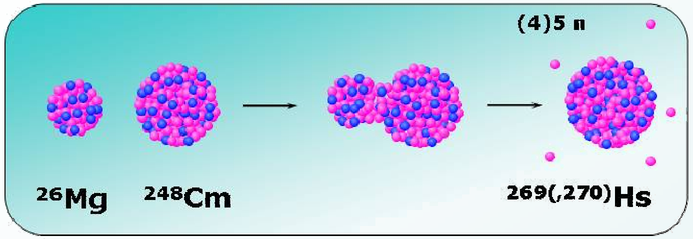
Periodic Table of the Elements: forms Hs a gaseous molecule with oxygen?

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112	113	114	115	116		118

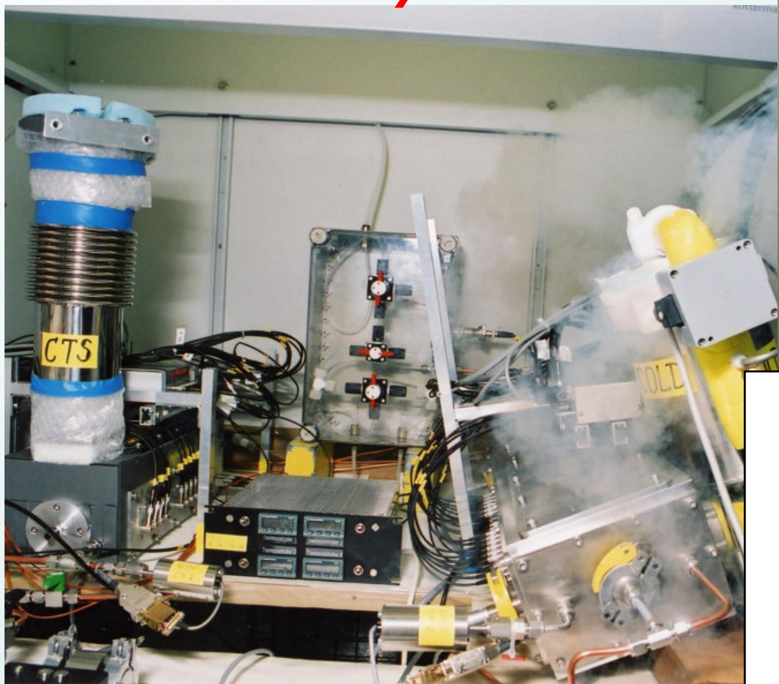
Lanthanides	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

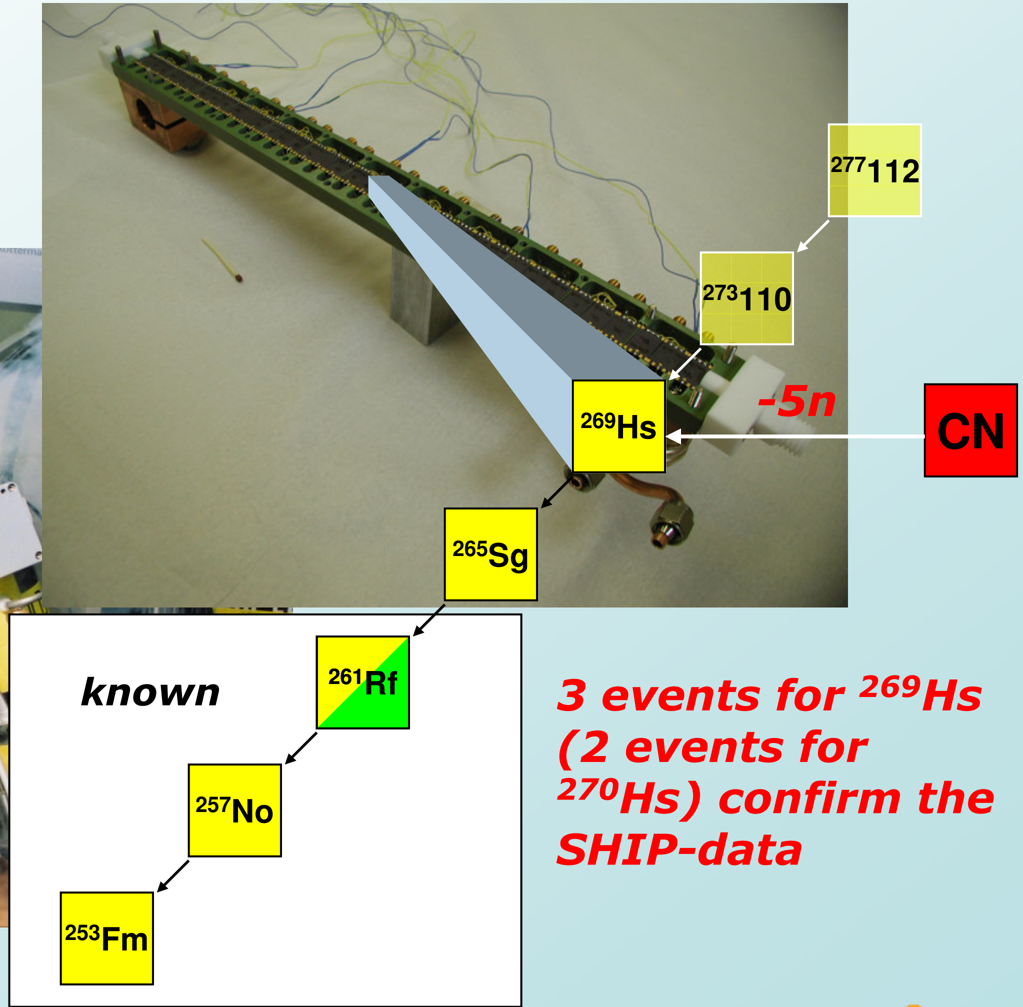
(courtesy of A.Türler, H. Gäggeler, M. Schädel et al.)

Chemistry of Hassium
- Thermochromatography



+ chemistry

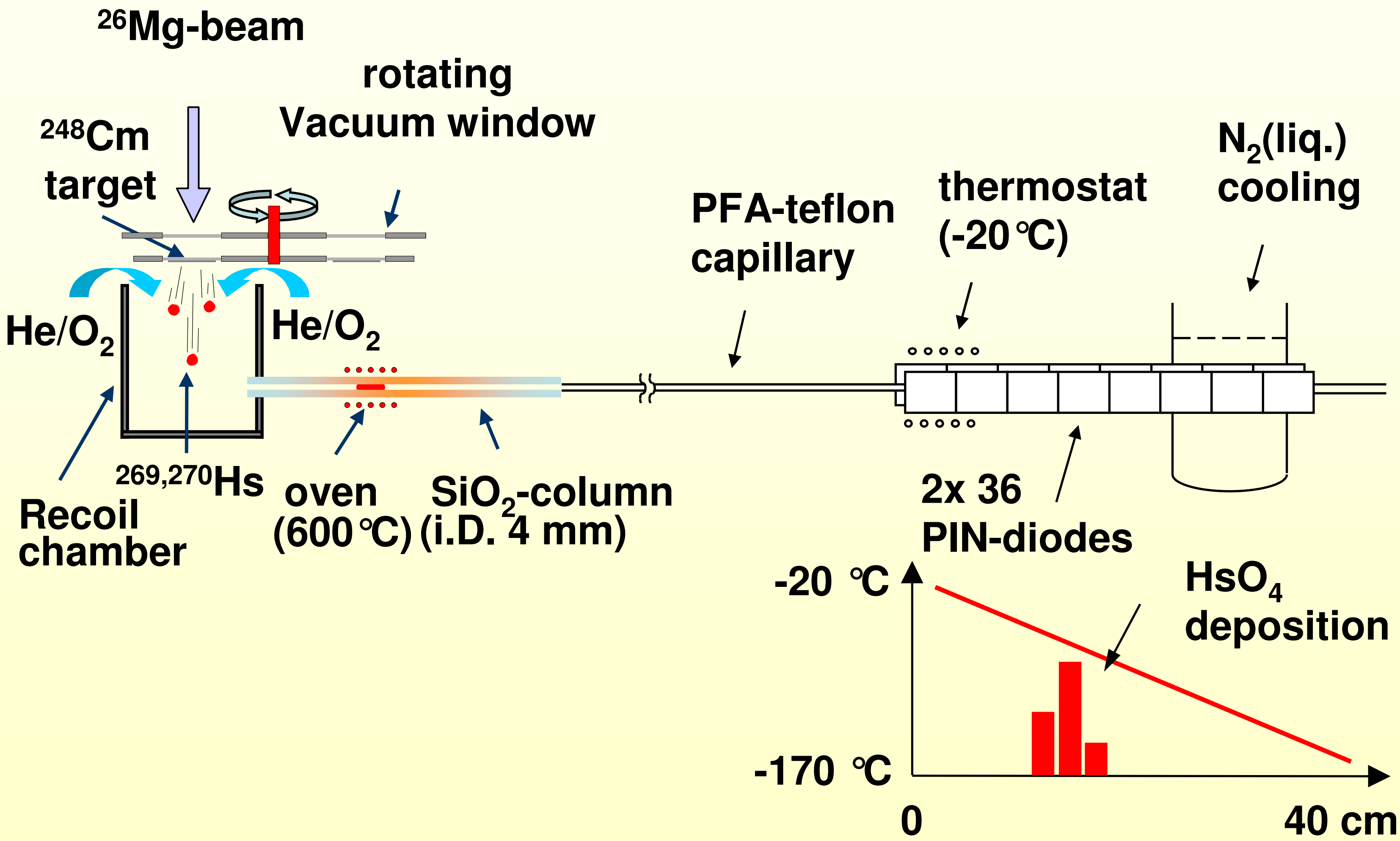




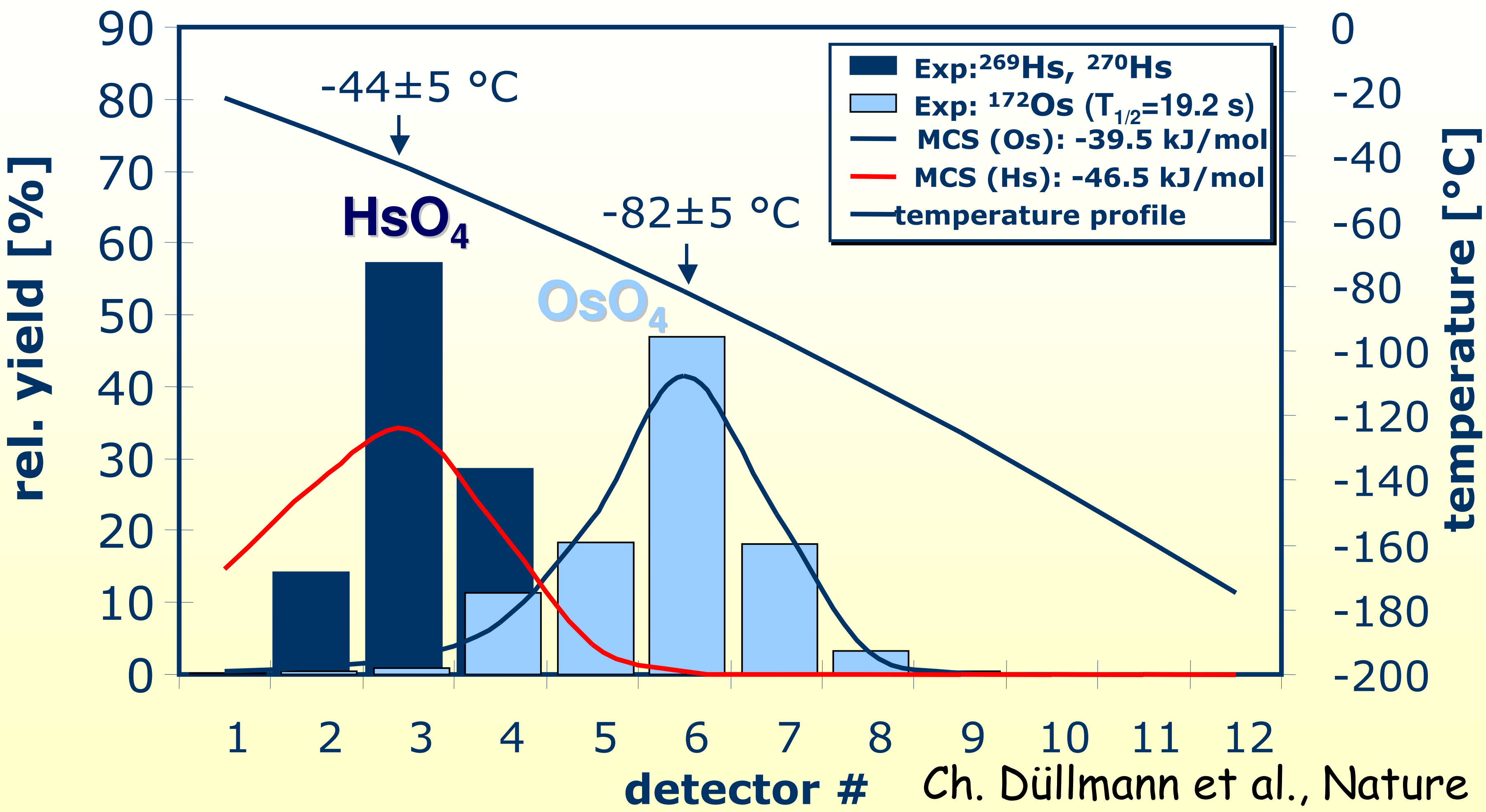
3 events for ^{269}Hs (2 events for ^{270}Hs) confirm the SHIP-data

determination of the chemical Properties of Hassium

In-Situ Volatilization and On-line detection - IVO



Thermochromatography of OsO_4 and HsO_4



Ch. Düllmann et al., Nature

Periodic Table of the Elements: is E112 like Hg?

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
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37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
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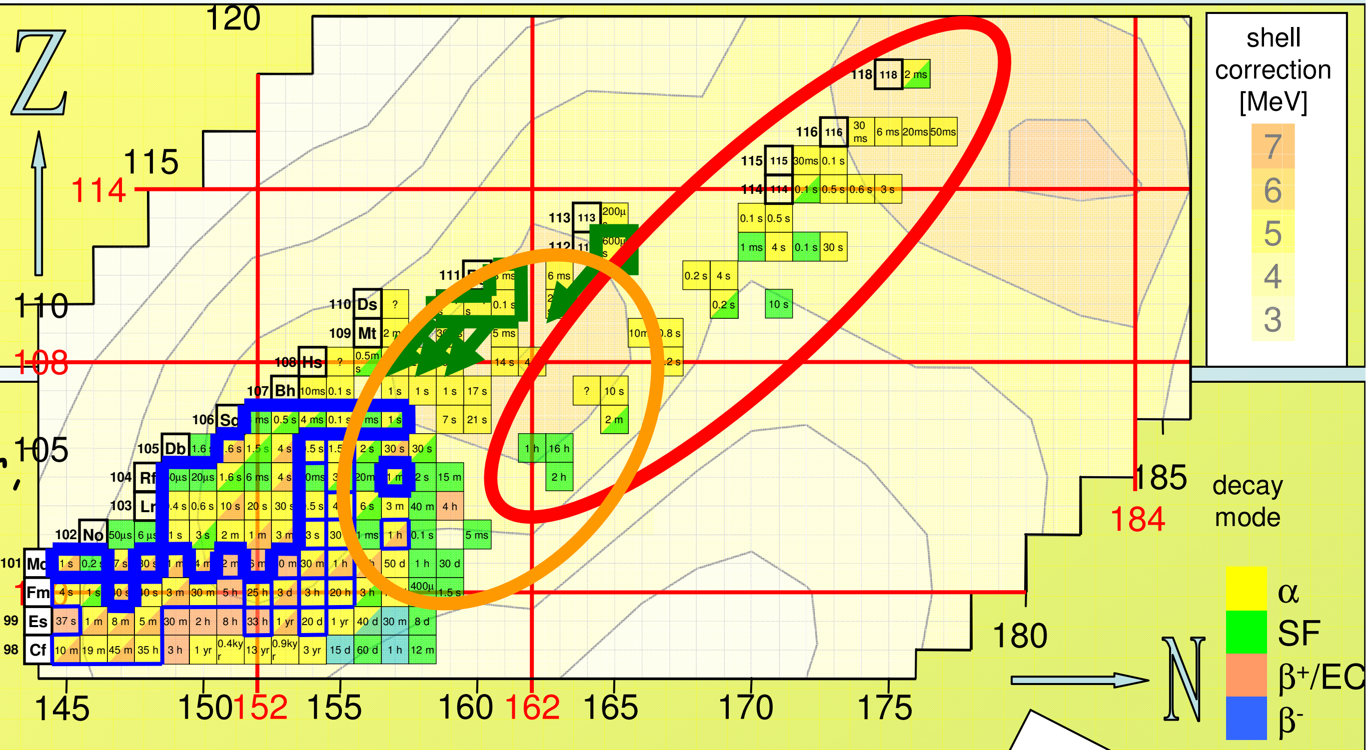
SHE Synthesis and Nuclear Structure of SHE

- Roadmap/Long Term

- cold fusion at SHIP
- hot fusion at FLNR
- spectroscopy from transactinides to SHE



- reaction mechanism systematics (transfer, incomplete fusion, spin distribution, …)
- efficiency upgrade
- mass measurement /determination
- employment of all available technology and methods (ER-α-γ correlations, chemistry, traps, mass determinati…

- "rare isotopes"? – yes for systematic investigations
  - maybe(???) for SHE synthesis (low beam intensity!!!)

→ localisation of the region of spherical shell-stabilized SHE

The End