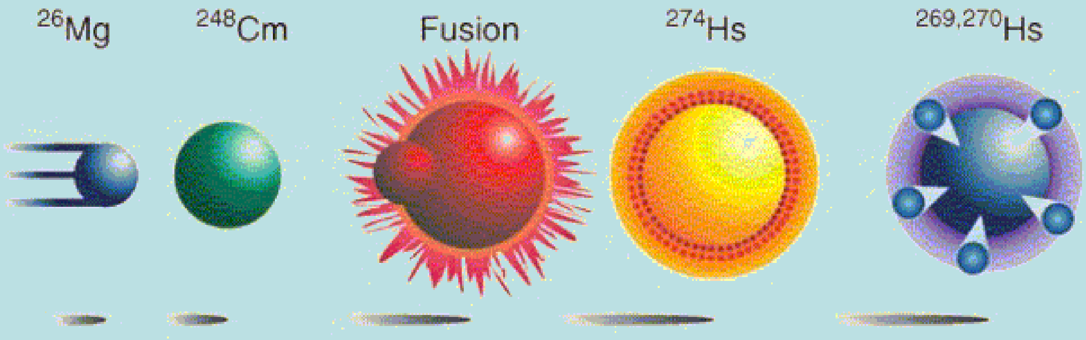
"Hot Fusion"



$5 \cdot 10^{15}$ ⟶ $5 \cdot 10^{8}$ ⟶

projectiles on target — compound nuclei — 1 atom

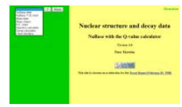
Hot fusion (1961 – 1974)

successful up to element 106 (Seaborgium)

- **Coulomb barrier V_C** between projectile and target nucleus has to be exceeded

$$V_C = \frac{Z_p \cdot Z_t \cdot e^2}{R_{int}} = 126.2\ MeV \quad (^{26}Mg + {}^{248}Cm)$$

- reaction: a + A → C^* → B + b



http://nuclear.lu.se/database/masses/

$$\Delta m = m_a + m_A - m_{CN}$$

$$\Delta m = (25.983 + 248.072 – 274.143) * 931.478\ MeV/c^2$$

$$= -82.153\ MeV/c^2$$

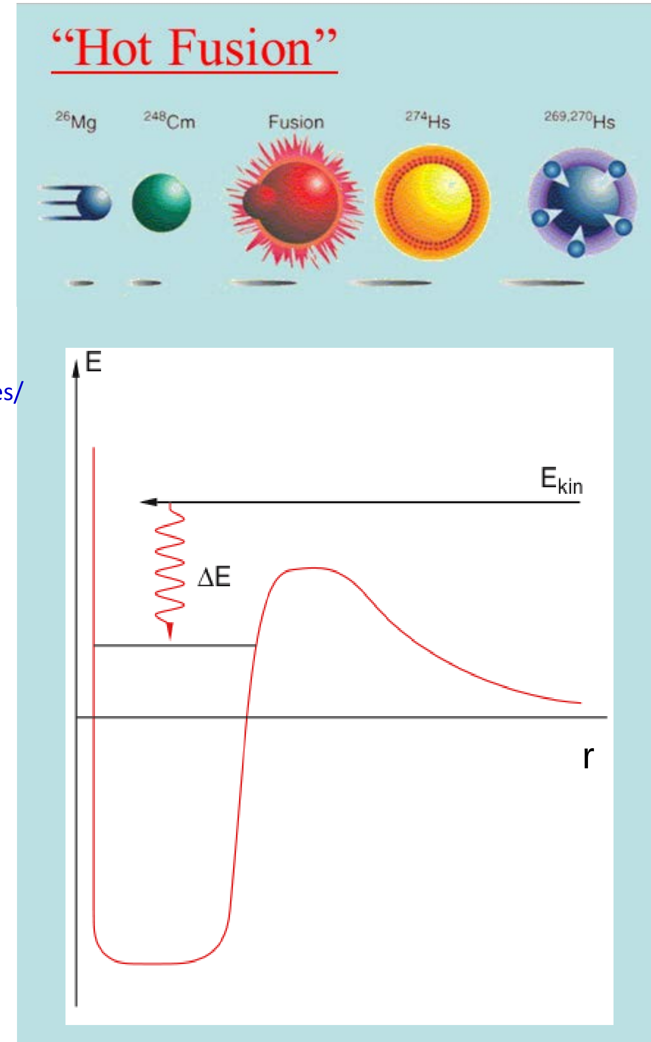
- excitation energy of compound nucleus

$$E^* = E_{kin} + \Delta m \cdot c^2$$

$$= 126.2\ MeV – 82.2\ MeV$$

= 44.0 MeV

- approximate 4 neutrons will be evaporated to avoid fission

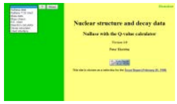


Cold fusion (1981 – 1996)

- **Coulomb barrier V_C** between projectile and target nucleus has to be exceeded

$$V_C = \frac{Z_p \cdot Z_t \cdot e^2}{R_{int}} = 223.3\ MeV \quad (^{58}Fe + {}^{208}Pb)$$

- reaction: a + A → C* → B + b



http://nuclear.lu.se/database/masses/

$$\Delta m = m_a + m_A - m_{CN}$$

$$\Delta m = (57.933 + 207.977 - 266.130) * 931.478\ MeV/c^2$$

$$= -205.092\ MeV/c^2$$

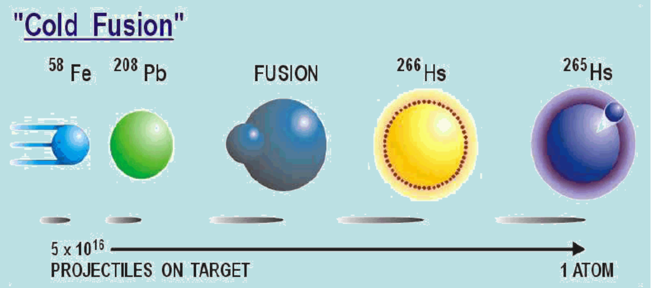
- excitation energy of compound nucleus

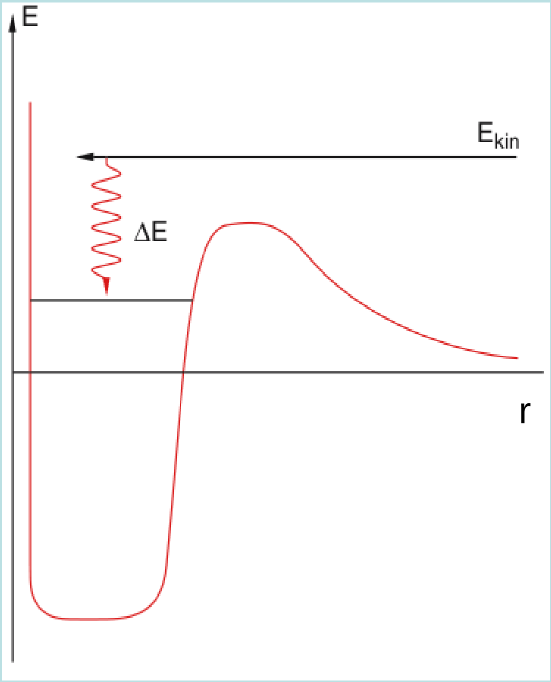
$$E^* = E_{kin} + \Delta m \cdot c^2$$

$$= 223.3\ MeV - 205.1\ MeV$$

$$\mathbf{= 18.2\ MeV}$$

- approximate 1-2 neutrons will be evaporated to avoid fission



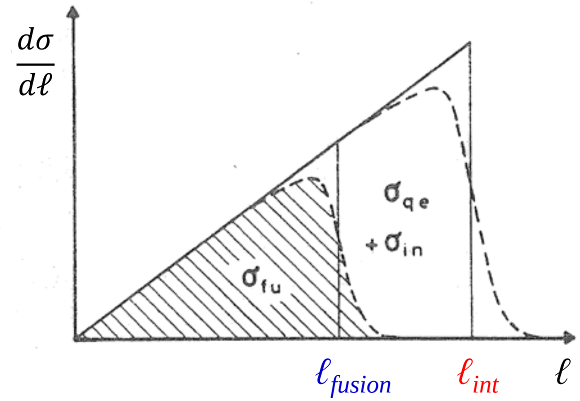


Fusion cross section

Radius for fusion barrier:

$$R_{fusion} = R_{int} - \begin{cases} 0.3117 \cdot (Z_p \cdot Z_t)^{0.2122} & Z_p \cdot Z_t < 500 \\ 1.096 + 1.391 \cdot Z_p \cdot Z_t/1000 & Z_p \cdot Z_t \geq 500 \end{cases} \quad [fm]$$

<table>
<tr><th></th><th>R_i [fm]</th><th>C_i [fm]</th><th>R_{int} [fm]</th><th>$V_C(R_{int})$ [MeV]</th><th>R_{fusion} [fm]</th><th>$V_C(R_{fusion})$ [MeV]</th></tr>
<tr><td>^{58}Fe</td><td>4.40</td><td>4.17</td><td rowspan="2">13.75</td><td rowspan="2">223.3</td><td rowspan="2">12.36</td><td rowspan="2">248.4</td></tr>
<tr><td>^{208}Pb</td><td>6.96</td><td>6.82</td></tr>
</table>



Total cross section for fusion:

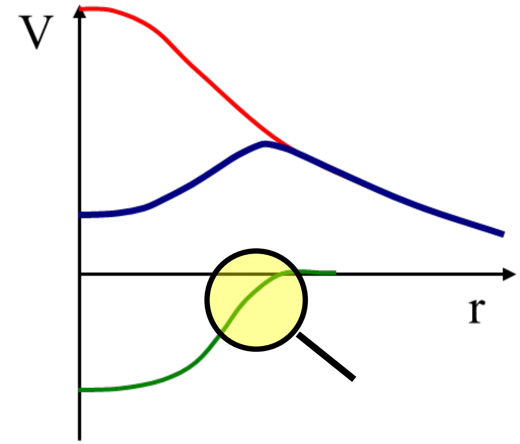
$$\sigma_{fusion} = \pi R_{fusion}^2 \cdot \left[1 - \frac{V_C(R_{fusion})}{E_{cm}}\right] \qquad with \quad E_{cm} = \frac{A_t}{A_t + A_p} \cdot E_{lab}$$

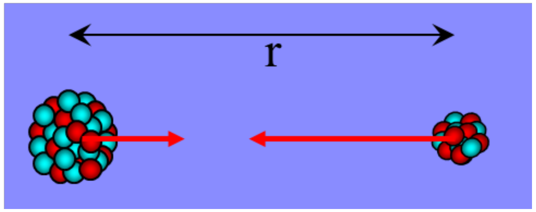
$$\sigma_{fusion} = \frac{\pi}{k_\infty^2} \cdot \ell_{fusion} \cdot (\ell_{fusion} + 1) \qquad with \quad k_\infty = 0.2187 \cdot \frac{A_t}{A_t + A_p} \cdot \sqrt{A_p \cdot E_{lab}} \quad [fm^{-1}]$$

The potential between projectile and target nucleus is given by a function of the relative distance between them

$$V(r) = V_N(r) + V_C(r)$$

nuclear potential + Coulomb potential





$$V_C(r) = \begin{cases} \dfrac{Z_1 Z_2 e^2}{2 \cdot R_C}\left(3 - \dfrac{r^2}{R_C^2}\right) & r < R_C \\ \dfrac{Z_1 Z_2 e^2}{r} & r \geq R_C \end{cases}$$

$$V_N(r) = 4\pi \cdot \gamma \cdot \frac{C_p \cdot C_t}{C_p + C_t} \cdot b \cdot \Phi(\xi)$$

$$\Phi(\xi) = \begin{cases} -0.5 \cdot (\xi - 2.54)^2 - 0.0852 \cdot (\xi - 2.54)^3 & \xi \leq 1.2511 \\ -3.437 \cdot exp(-\xi/0.75) & \xi \geq 1.2511 \end{cases}$$

$$\xi = (r - C_p - C_t)/b$$

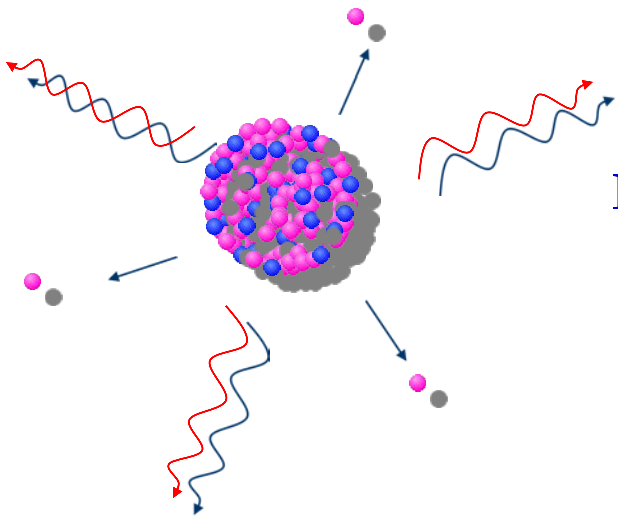
$$b = \frac{\pi}{\sqrt{3}} \cdot a \cong 1\, fm \quad with\ a = 0.55\, fm$$

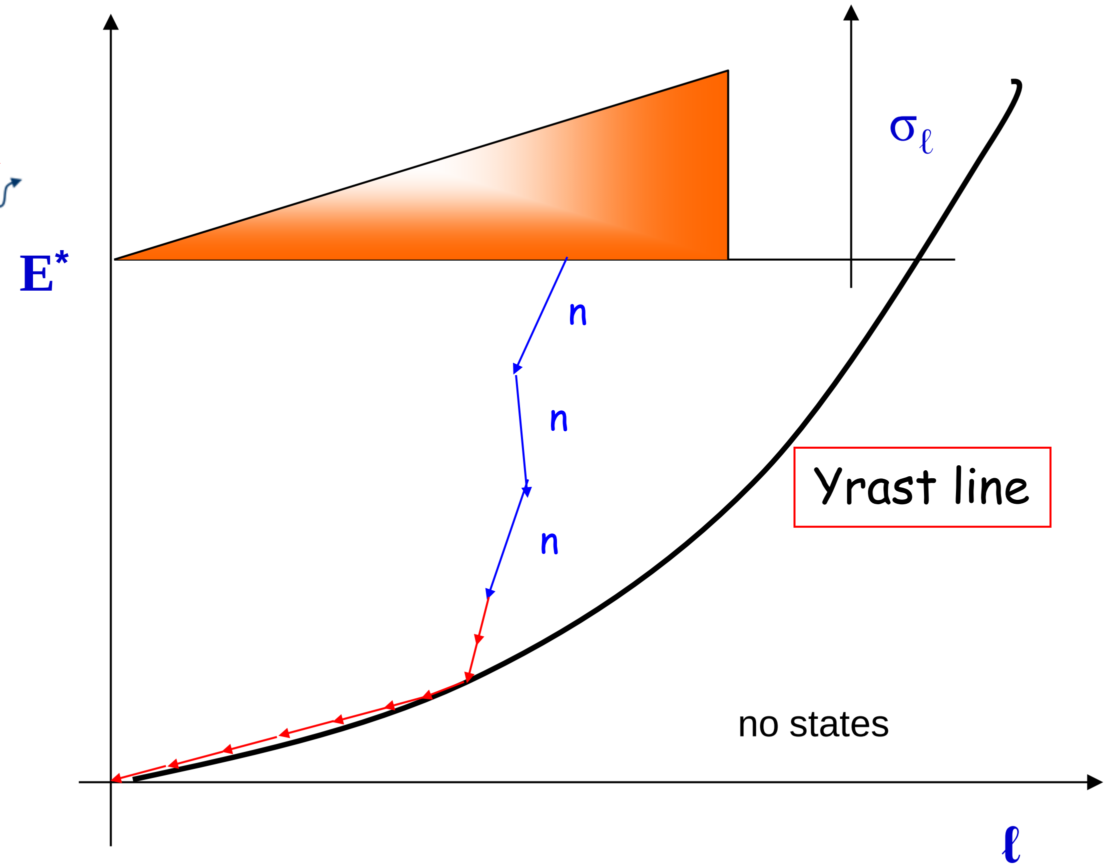
$$\gamma = 0.9517 \cdot \left\{1 - 1.7826 \cdot \left(\frac{N_c - Z_c}{A_c}\right)^2\right\} \quad \frac{MeV}{fm^2}$$

$$C_i = R_i \cdot \left(1 - R_i^{-2}\right) \quad [fm] \qquad R_i = 1.28 \cdot A_i^{1/3} - 0.76 + 0.8 \cdot A_i^{-1/3} \quad [fm]$$

The Statistical Model

de-excitation of the hot compound system

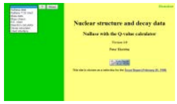




$$E^* = E_{kin} + \Delta m \cdot c^2$$

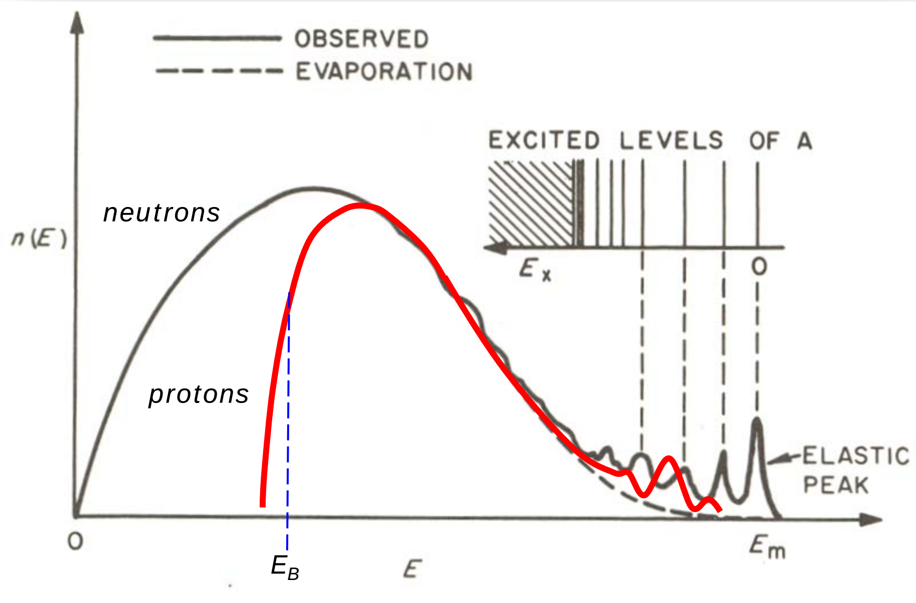
$$E_{kin} > V_C = \frac{Z_a \cdot Z_A \cdot e^2}{R_{int}}$$

$$\Delta m = m_a + m_A - m_{CN}$$



http://nuclear.lu.se/database/masses/

Evaporation particles



compound nucleus reactions

direct reactions

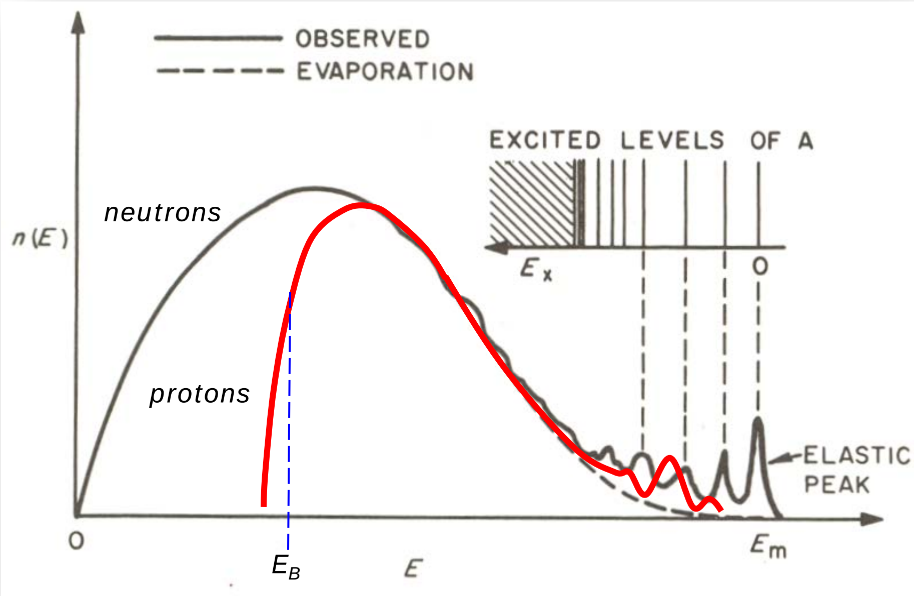
cm-spectra of particles statistically emitted from CN (evaporation) are of Maxwell Boltzmann type

$$\frac{dN}{dE} \propto (E - E_B) \cdot e^{-E/T}$$

E_B = Coulomb barrier
T = effective nuclear temperature

Typical energy spectrum of nucleons emitted at a fixed angle in inelastic nucleon-nucleon reactions.

Evaporation particles



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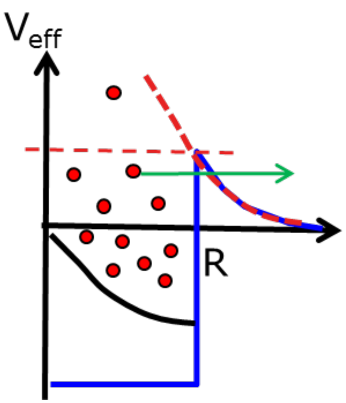
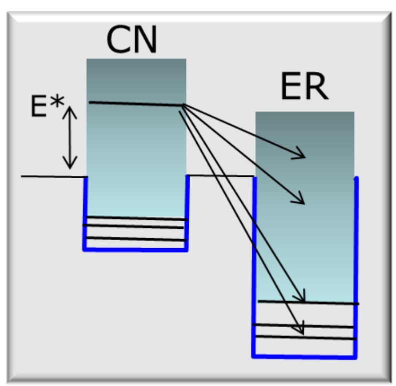
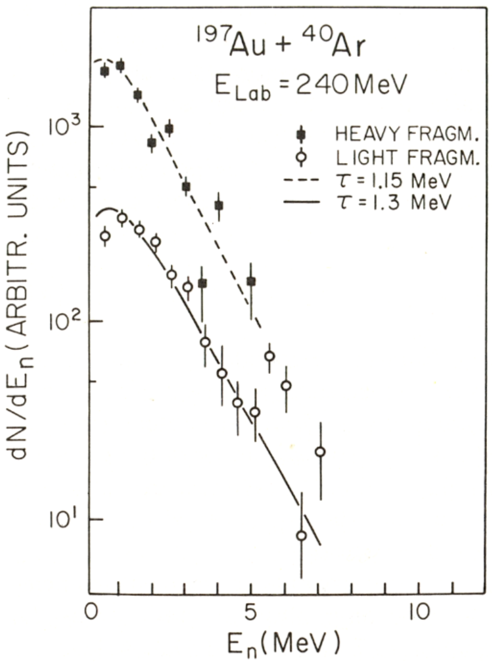




Even for fixed E^* the particle spectrum is continuous (Maxwell Boltzmann), except for transitions to discrete spectrum at low $E_{ER}{}^*$

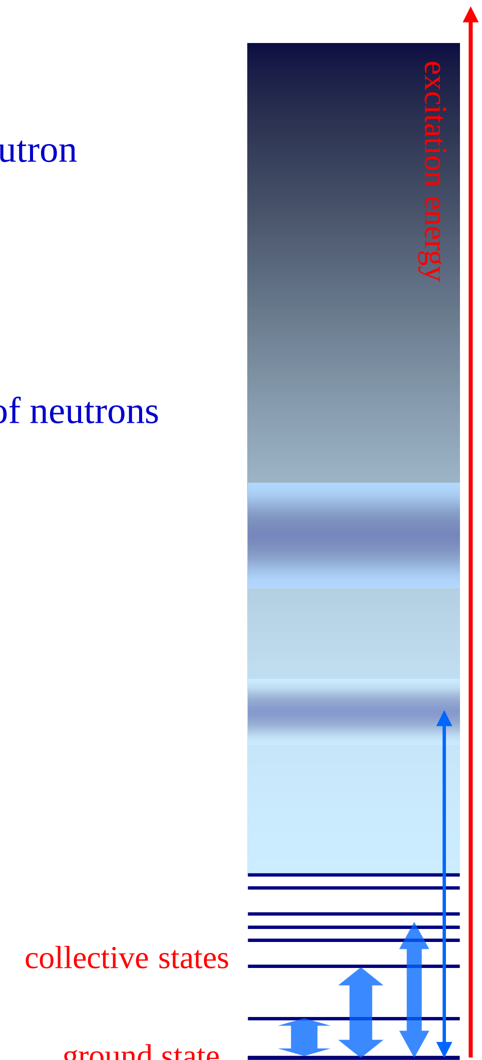


$$\frac{dN}{dE_n} \propto E_n \cdot e^{-E_n/T}$$ spectrum of single neutron

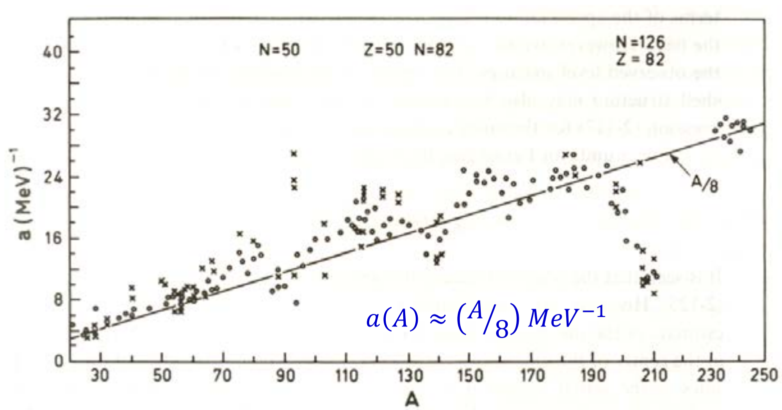
$$\langle E_n \rangle = 2T \qquad \max \frac{dN}{dE_n} \ @\ E_n = T$$

$$\frac{dN}{dE_n} \propto \sqrt{E_n} \cdot e^{-E_n/T_{eff}}$$ spectrum of cascade of neutrons

$$\langle E_n \rangle = 1.5T \qquad T_{eff} \approx 0.92 \cdot T \quad (1^{st}\ daughter)$$



deviations at shell closures

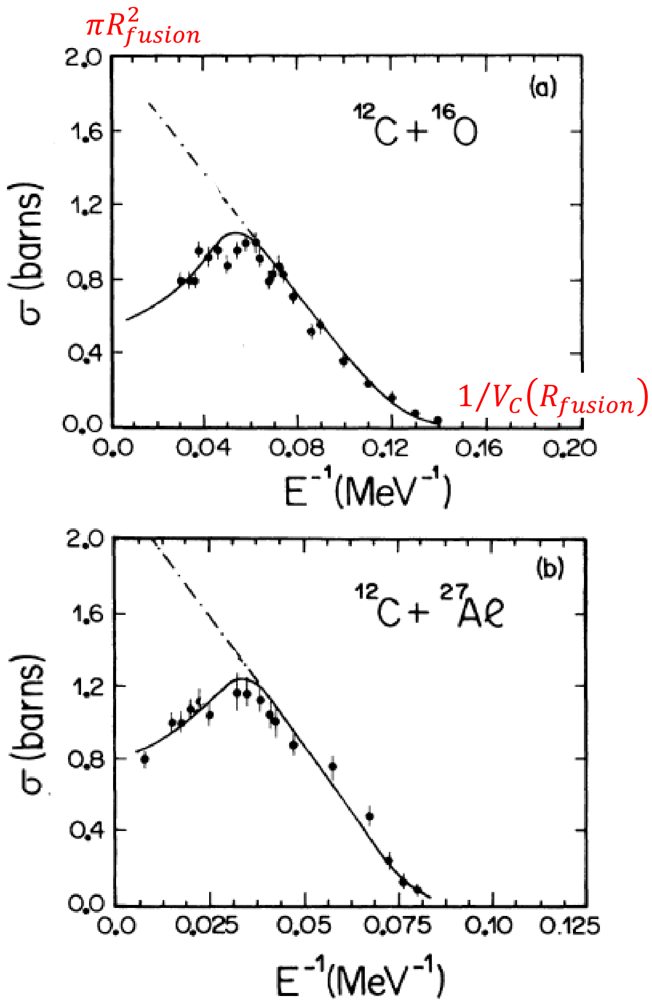


Fermi gas relations:

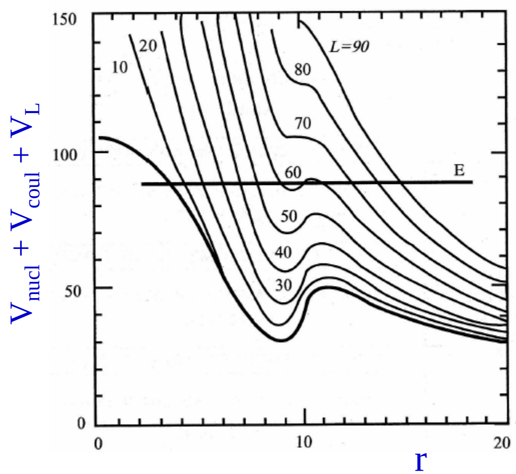
$$E^* = a \cdot T^2 \quad \text{"little – a"}$$

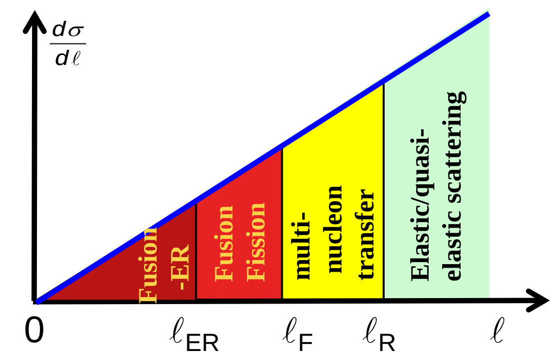
$$S = \int \frac{dE^*}{E^*} = 2\sqrt{a \cdot E^*}$$

$$\rho\left(E^*\right) = \rho_0 \cdot e^{2\sqrt{a \cdot E^*}}$$



maximum ℓ_{fusion} due to nuclear centrifugal stability





A limiting nuclear angular momentum

rotating charged liquid drop

surface energy:

$$E_S^{(0)} = 17.9439 \cdot \left[1 - 1.7826 \cdot \left(\frac{N-Z}{A}\right)^2\right] \cdot A^{2/3} \quad [MeV]$$

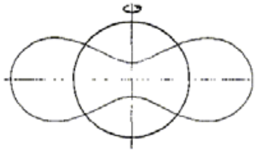
Coulomb energy:

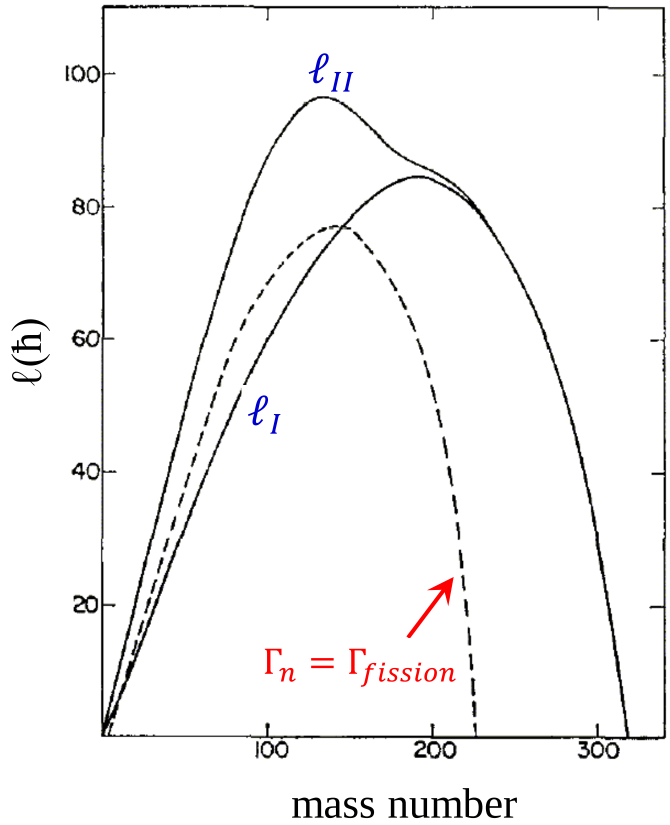
$$E_{Coul}^{(0)} = 0.7053 \cdot \left(Z^2/A^{1/3}\right) \quad [MeV]$$

rotational energy:

$$E_{Rot}^{(0)} = \frac{1}{2}\frac{\hbar^2 \cdot \ell^2}{(2/5) \cdot A \cdot m \cdot R^2} = 34.54 \cdot \frac{\ell^2}{A^{5/3}} \quad [MeV]$$

change of the nuclear shape





$$\frac{E_{Rot}^{(0)}}{E_S^{(0)}} = \begin{cases} 0.2829 - 0.3475 \cdot X - 0.0016 \cdot X^2 + 0.0501 \cdot X^3 & 0 \le X \le 0.75 \\ (7/5) \cdot (1-X)^2 - 4.5660 \cdot (1-X)^3 + 6.7443 \cdot (1-X)^4 & 0.75 \le X \le 1.0 \end{cases}$$

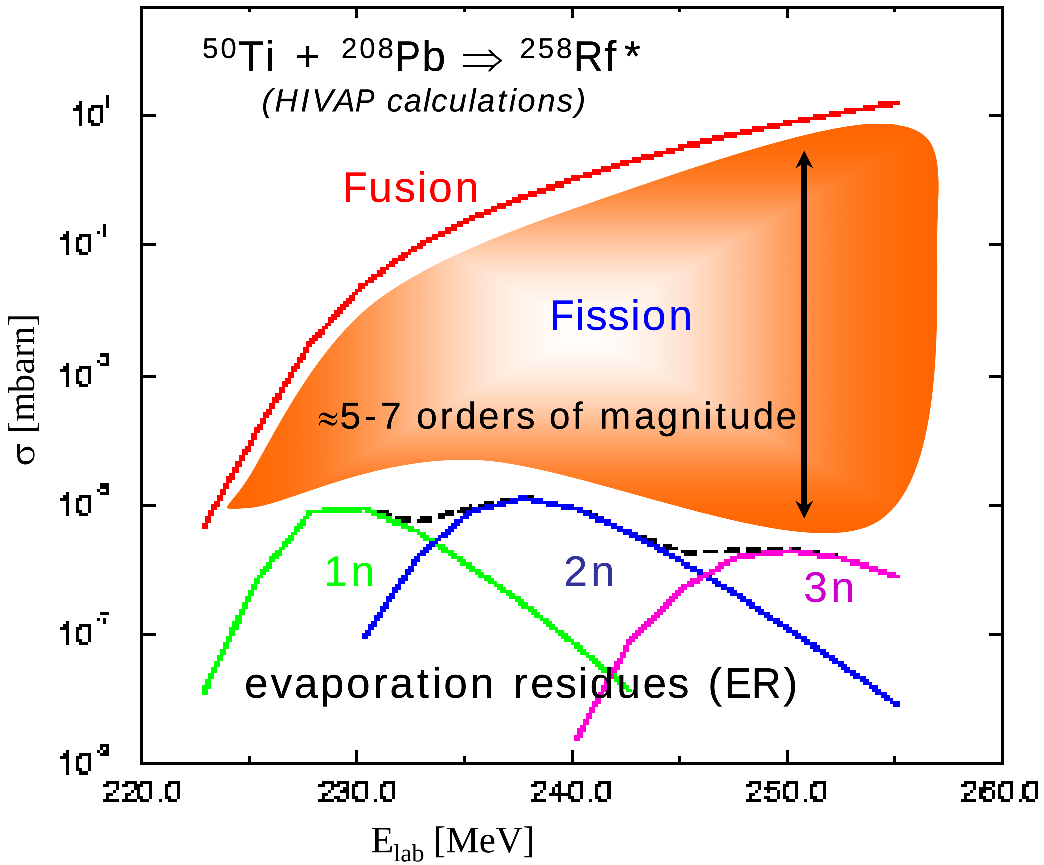
with $X = \frac{E_{Coul}^{(0)}}{2 \cdot E_S^{(0)}}$ "fissility parameter"

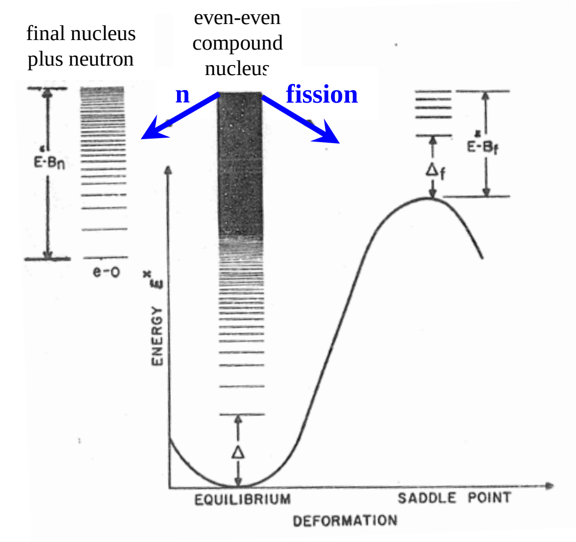
example: ${}^{127}_{57}La$ $E_S^{(0)} = 444.9\ [MeV]$ $E_{Coul}^{(0)} = 455.9\ [MeV]$ $X = 0.512$ $E_{Rot}^{(0)}/E_S^{(0)} = 0.1112$ $E_{Rot}^{(0)} = 49.48\ [MeV]$ $\ell_I = 67.8\ [\hbar]$

Cohen, Plasil, Swiatecki; Ann. Phys. 82, 557 (1974)

Fusion and evaporation

cold fusion





Both decay processes are determined by the level density, either from the residual nucleus or at the saddle point.

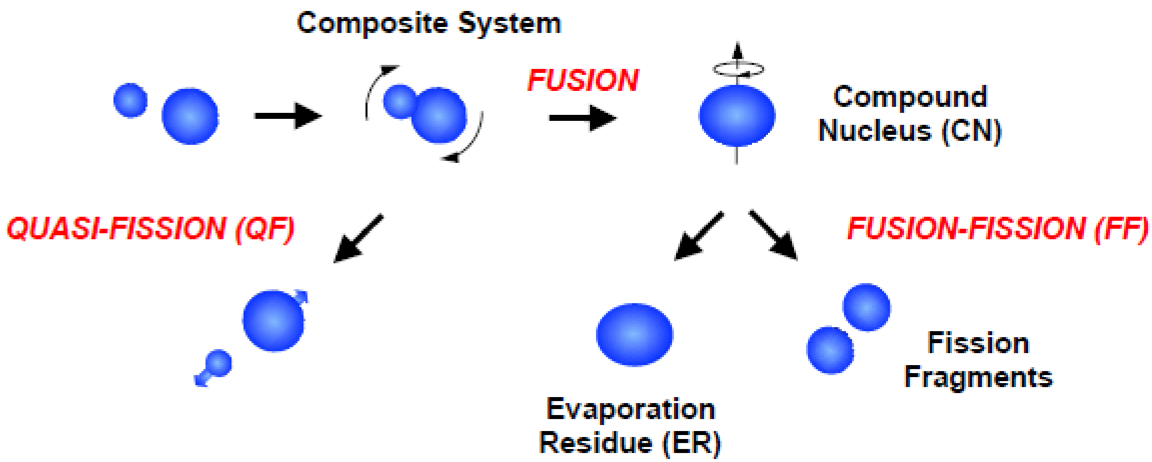
level density: $\rho(E^*) = const \cdot \exp(E^* / T)$

$$\frac{\Gamma_n}{\Gamma_f} = \frac{2 \cdot T \cdot A_{CN}^{2/3}}{K_0} \cdot \exp[(B_f - B_n)/T]$$

$K_0 = \hbar^2 / 2 \cdot m \cdot r_0^2 \approx 11.4 MeV$ $\qquad$ $T = \sqrt{8 \cdot E^* / A_{CN}}$

Fusion / Fission competition

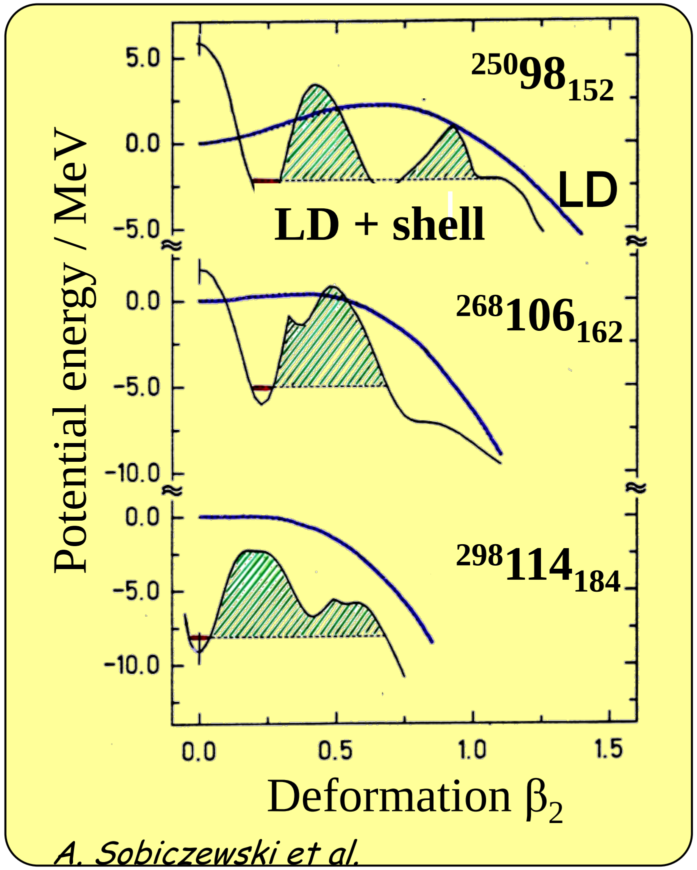
liquid drop + shell corrections



$$\sigma_{ER} = \sigma_{capture} \cdot P_{CN} \cdot P_{survival}$$

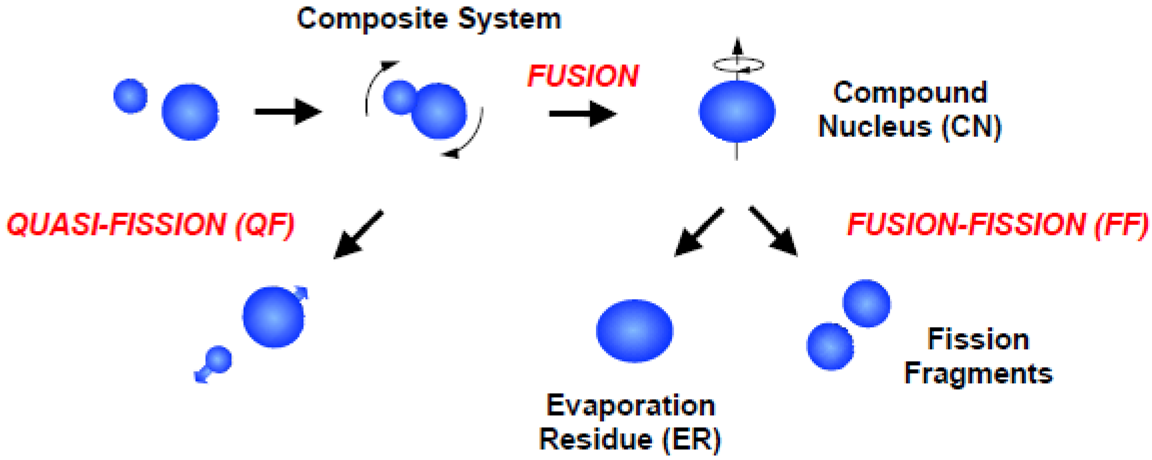
$$\sigma_{ER}^{xn}(E) = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{max}} (2\ell+1) \cdot \underbrace{P_{CN}(E^*,\ell)}_{\text{formation}} \cdot \underbrace{P_{xn}(E^*,\ell)}_{\text{survival}}$$

Superheavy system: $\sigma_{ER} \ll \sigma_{capture}$



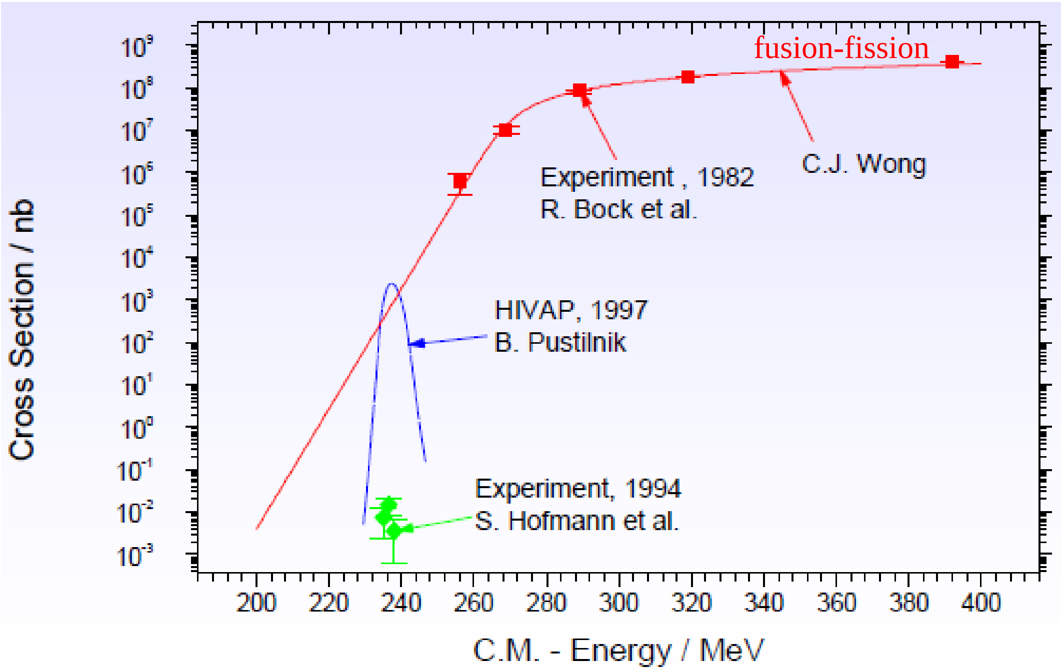
Fusion / Fission competition

liquid drop + shell corrections

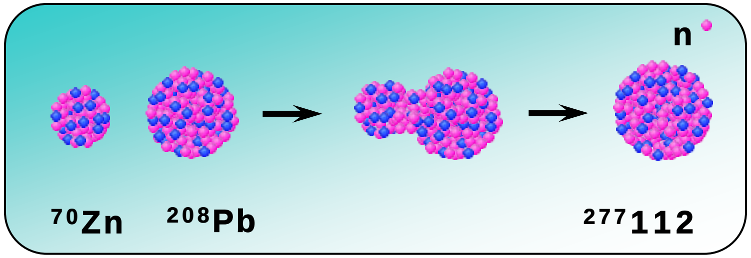


$^{64}Ni + ^{208}Pb \longrightarrow ^{271}Ds + 1n \quad V_C(R_{int}) = 238\ MeV$

$$\sigma_{ER} = \sigma_{capture} \cdot P_{CN} \cdot P_{survival}$$

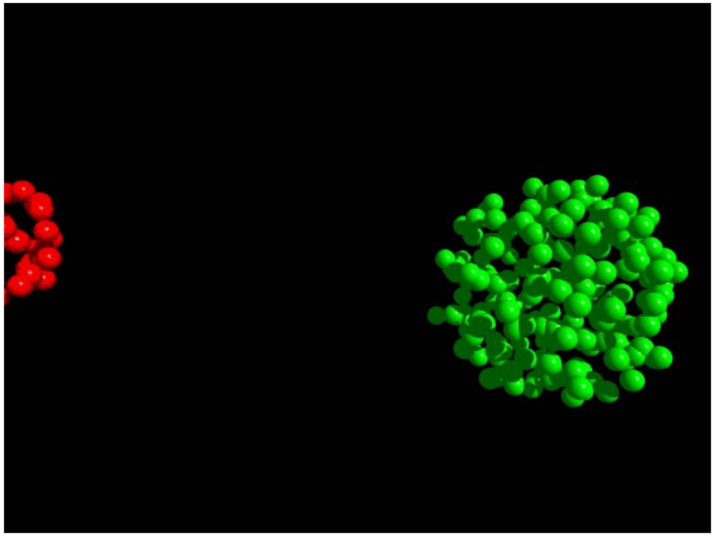


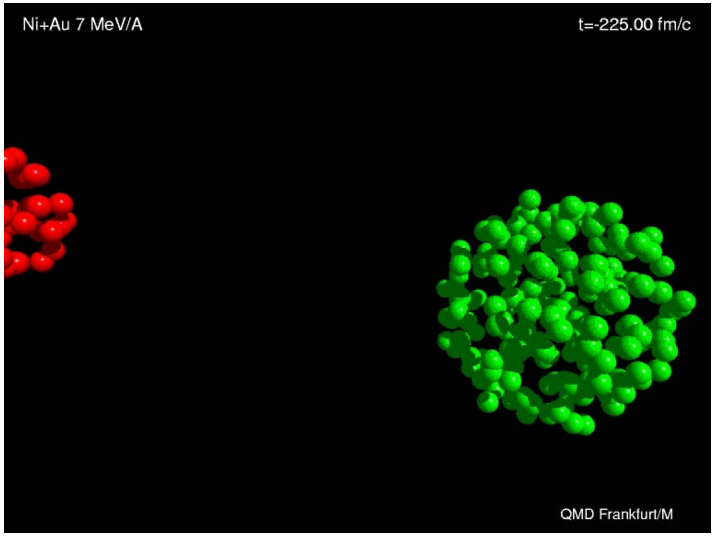
Synthesis of heavy elements



Fusion

$\frac{1}{10^{12}}$





The production cross section

fusion cross section and survival probability

Nucleus:

1 barn = 10^{-24} cm^2 = 10^{-28} m^2

fusion cross section:

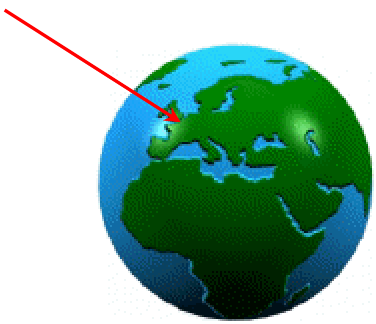
< 1 barn

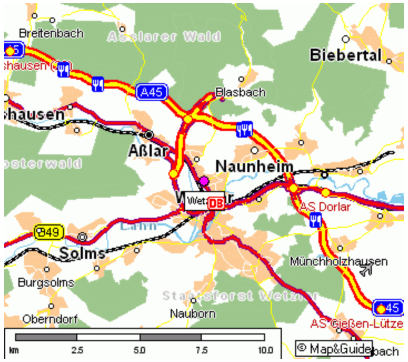
1:10^{12}

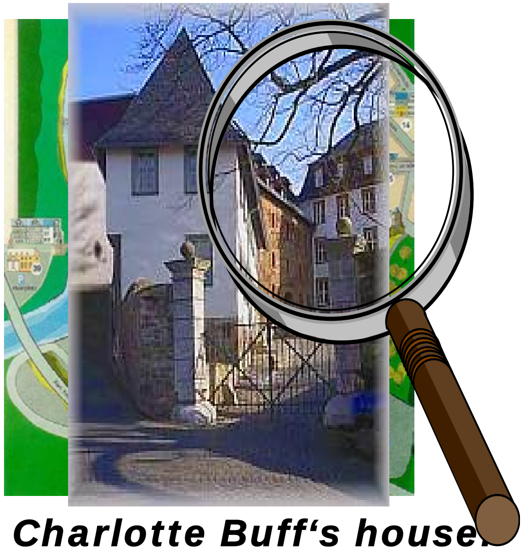
Production cross section

^{277}112:

≈ 1 pbarn = 10^{-12} barn







Earth:

∅-Area 1.3x10^8 km^2

1.3x10^{14} m^2

1:10^7

Wetzlar:

Area 75.67 km^2

≈1.3x10^7 m^2/2

1:10^5

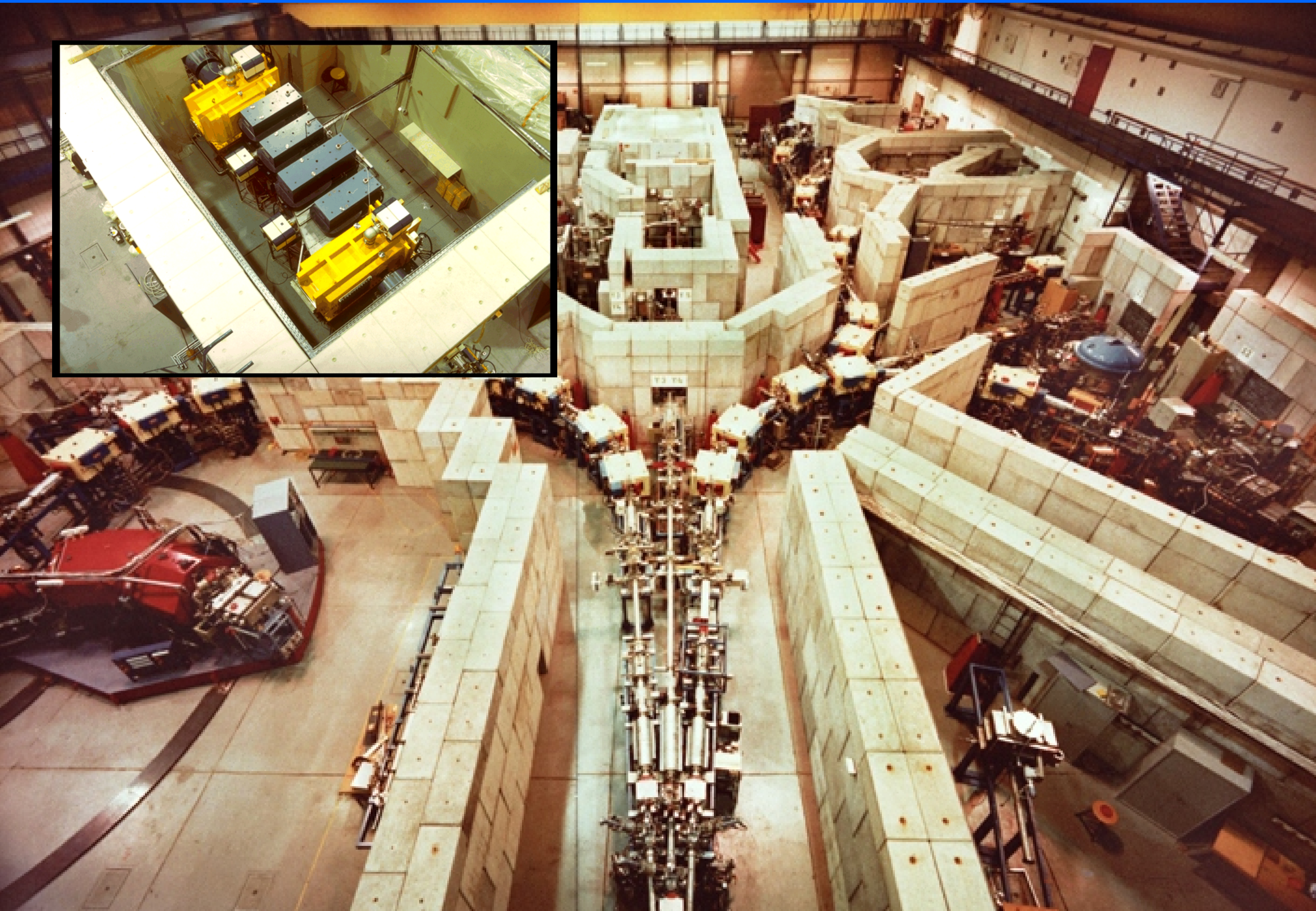
Charlotte Buff's house:

Area x 130 m^2

1.3x10^2 m^2

1:10^{12}

Separator for Heavy Ion Products (SHIP)



Separator for Heavy Ion Products (SHIP)

- Fusion products are slower than scattered or transfer particles

$$v_{CN} = [m_p/(m_p + m_t)] \cdot v_p$$

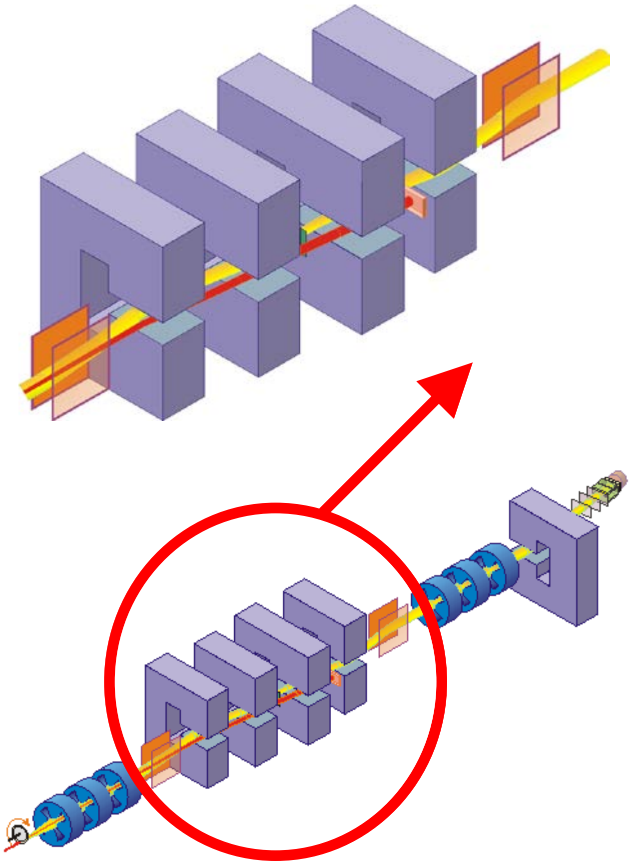
$$e.q.\, v_p \approx 10.3\% \quad \rightarrow \quad v_{CN} \approx 2.2\%$$

- E- and B-field are perpendicular to each other

$$B \cdot \rho = \frac{m \cdot v}{e \cdot q}$$

$$E \cdot \rho = \frac{m \cdot v^2}{e \cdot q}$$

$$F_{mag} = F_{el} \Rightarrow F_{tot} = 0$$



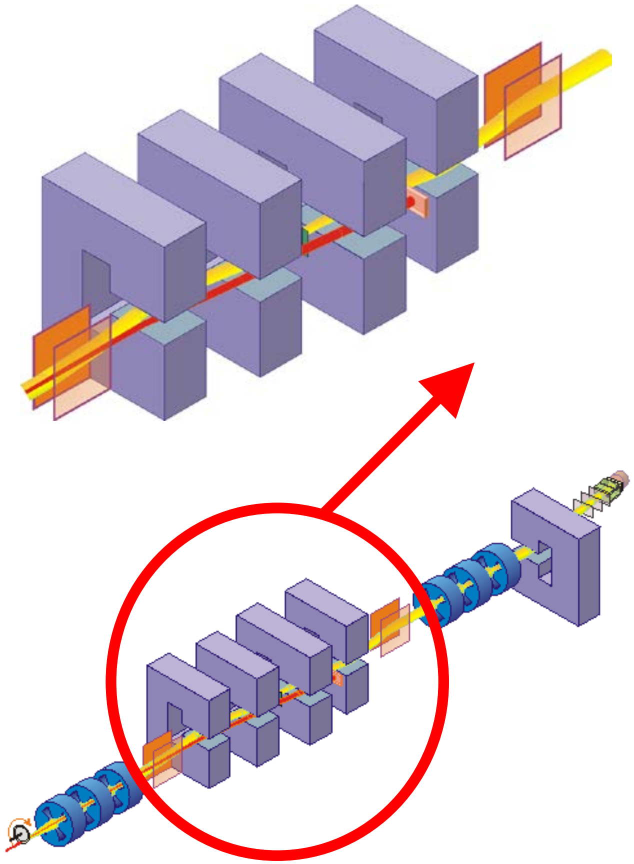
electric deflectors: ±330 kV   dipole magnets: 0.7 T max

Separator for Heavy Ion Products (SHIP)

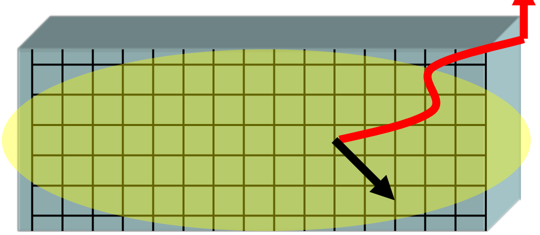
- The choice of E and B determines the transmitted velocity

$$v = \frac{E}{B}$$

- The rejected beam will be stopped on a cooled Cu plate



SHIP – stop detector



SHE will be measured in a pixel

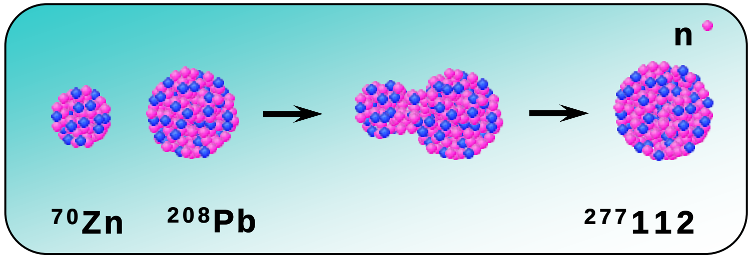
- position sensitive Silicon detector determines the position an energy of SHE and α, β, ...

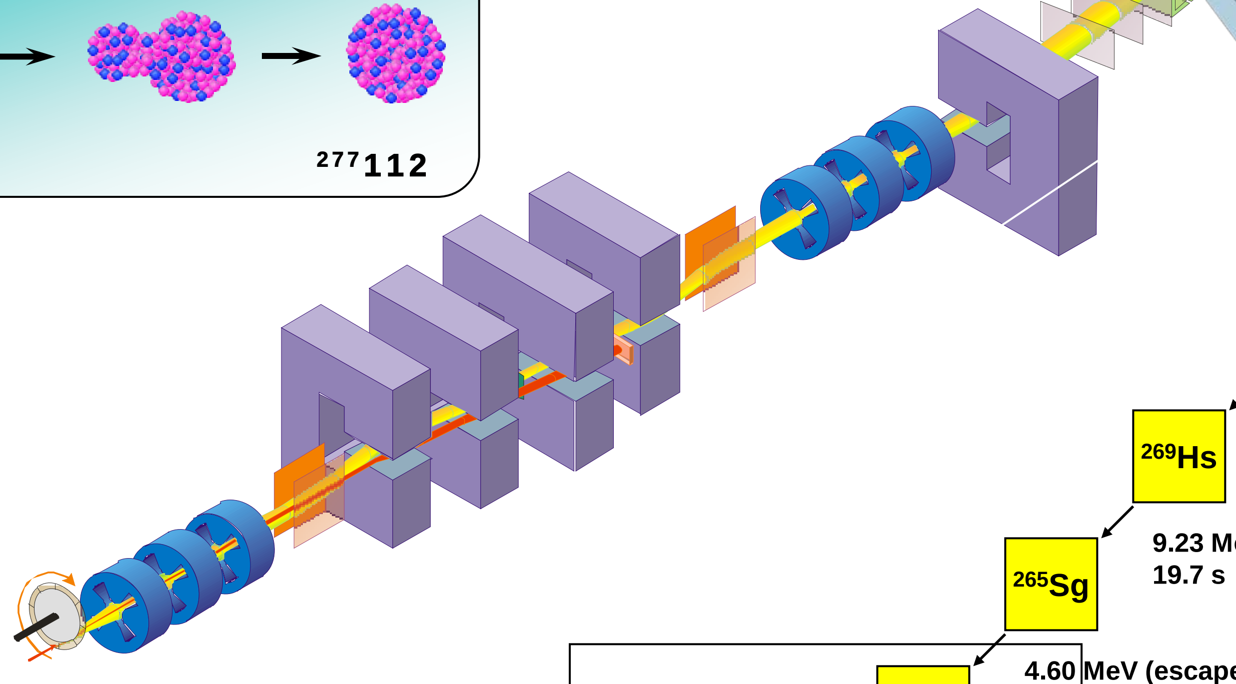
area: 27*87mm², thickness: 0.3mm, 16 strips
energy resolution ΔE=18-20 keV @ E_α> 6MeV (cooling 260K)
position resolution Δx=0.3mm (FWHM)

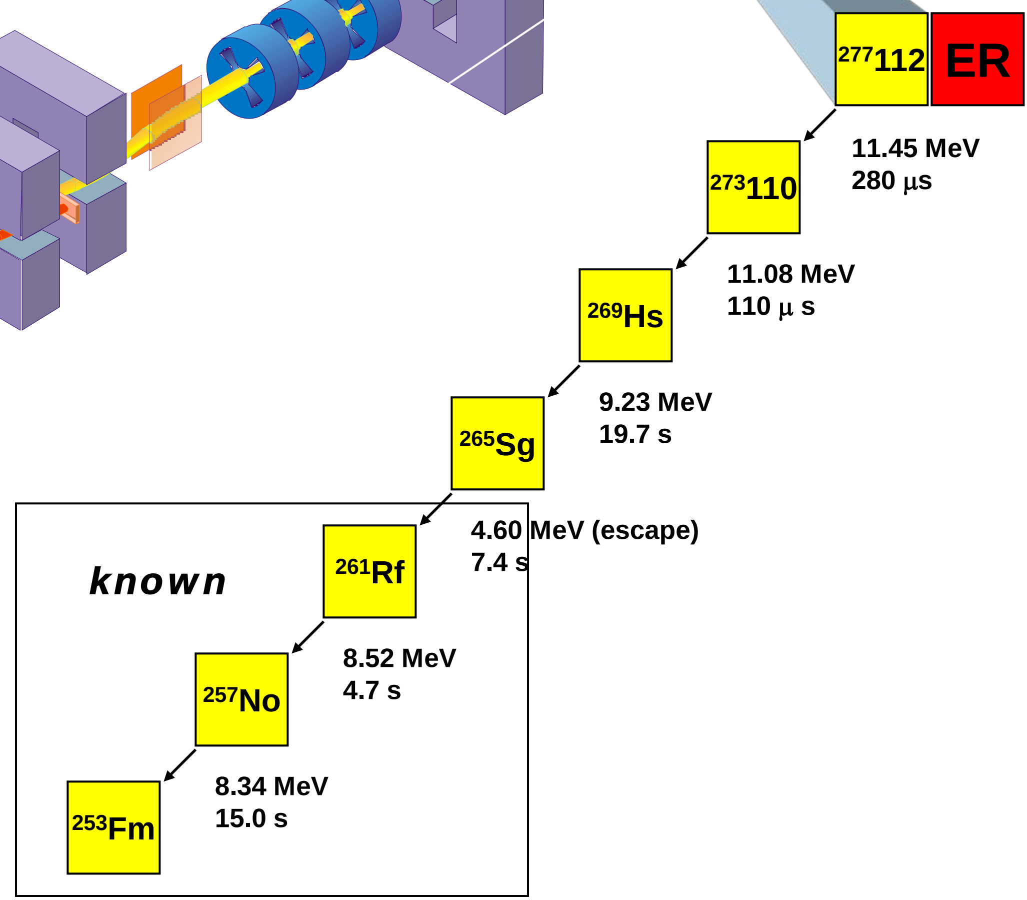
Wait for the emission of an α-particle
(or β-particle)

correlation method: implantation and decay event in the same pixel

Synthesis and identification of heavy elements with SHIP







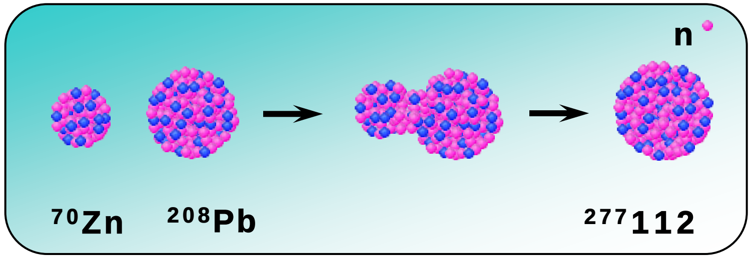
Date: 09-Feb-1996
Time: 22:37 h

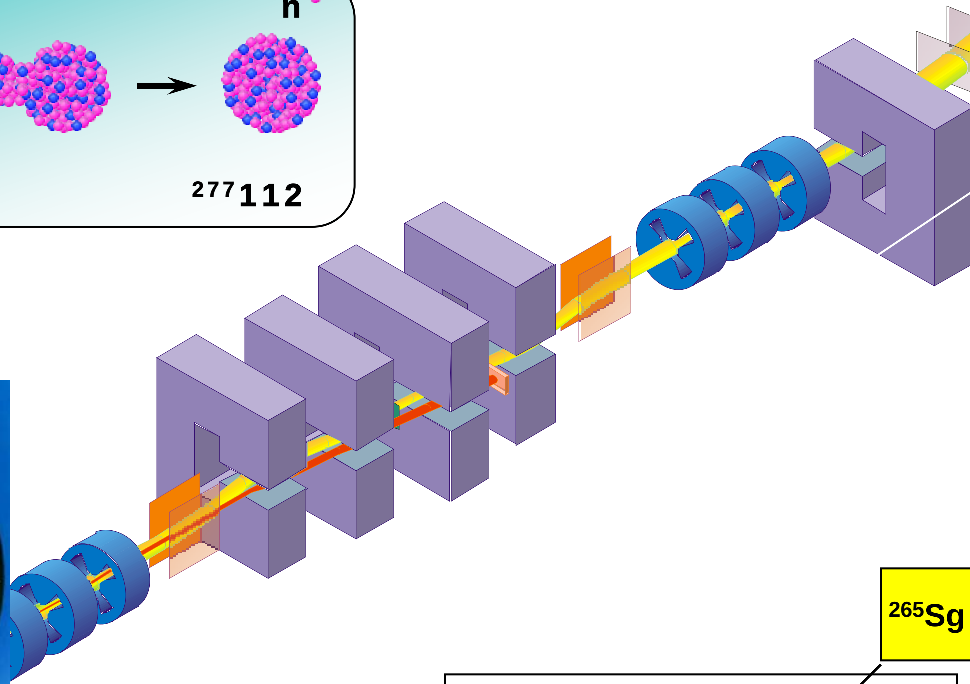
***kinematical separation** (in flight)*

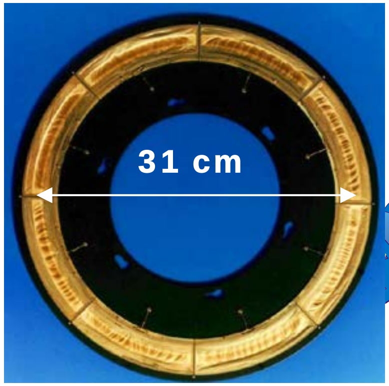
using electric deflectors
and dipole magnets

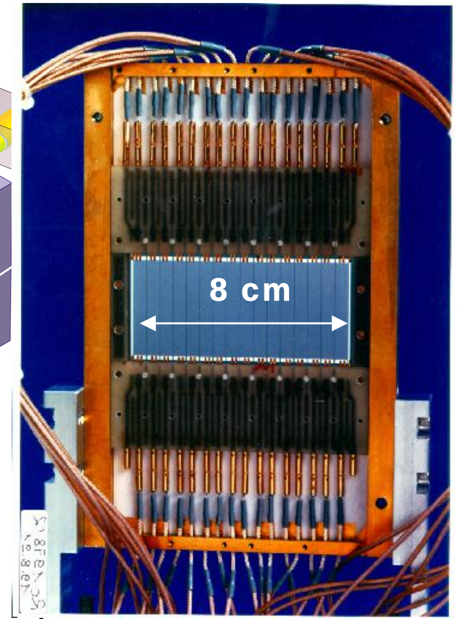
$v = {}^{E}/_{B}$ → ***velocity filter***

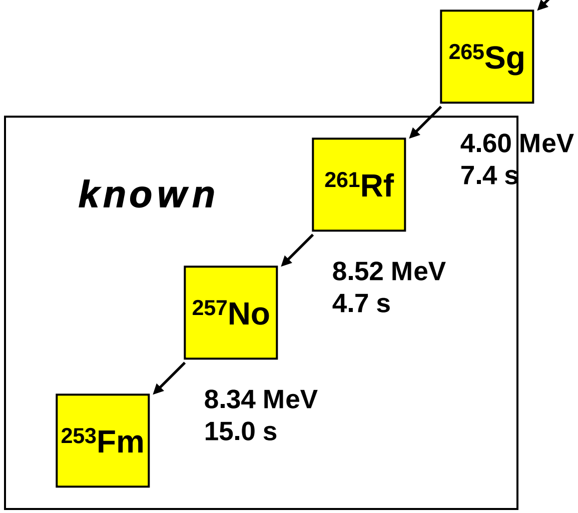
Synthesis and identification of heavy elements with SHIP











Date: 09-Feb-1996
Time: 22:37 h

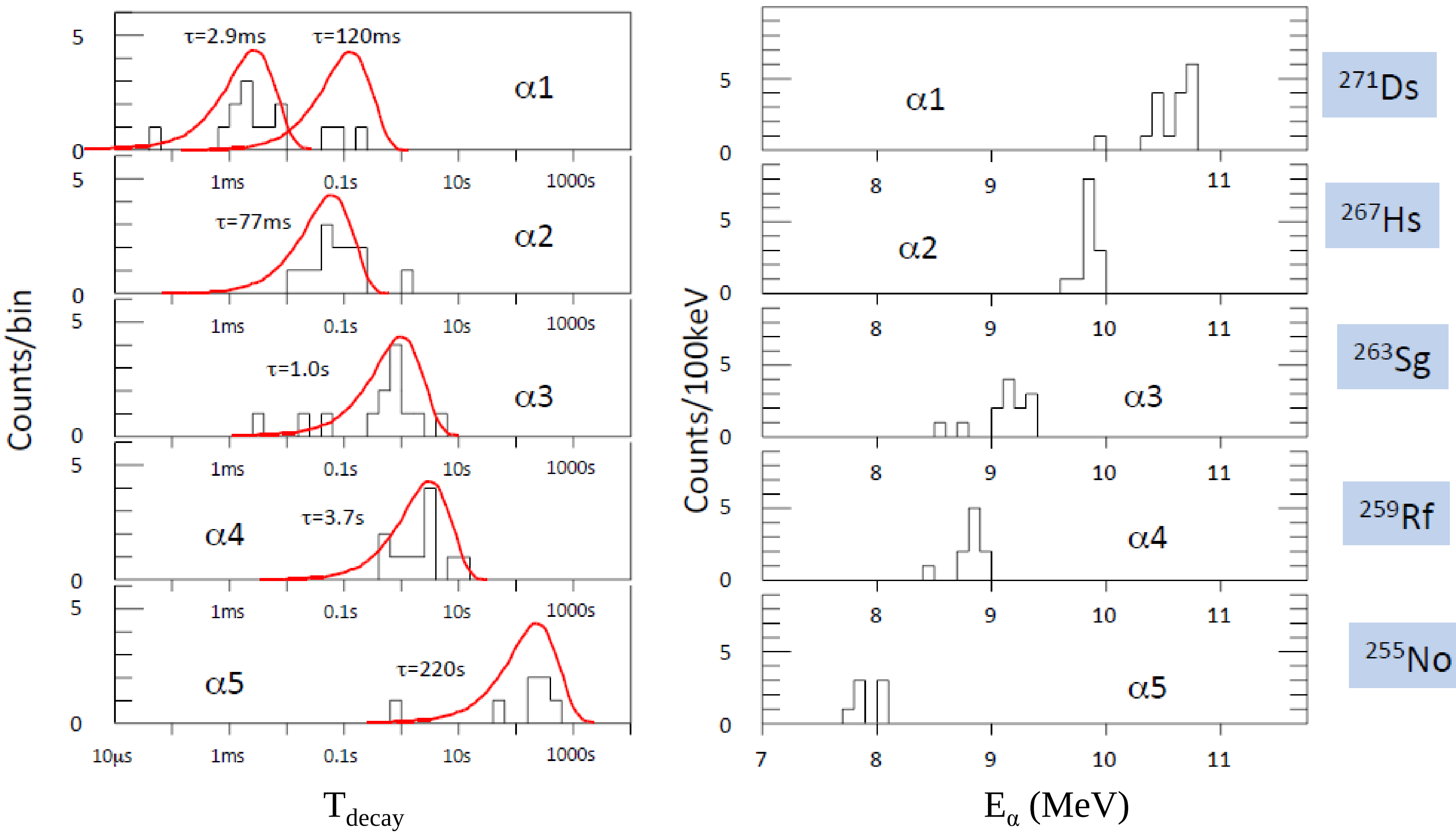
*Identification by α-α correlations down to **known** isotopes*

kinematical separation (in flight)

using electric deflectors and dipole magnets

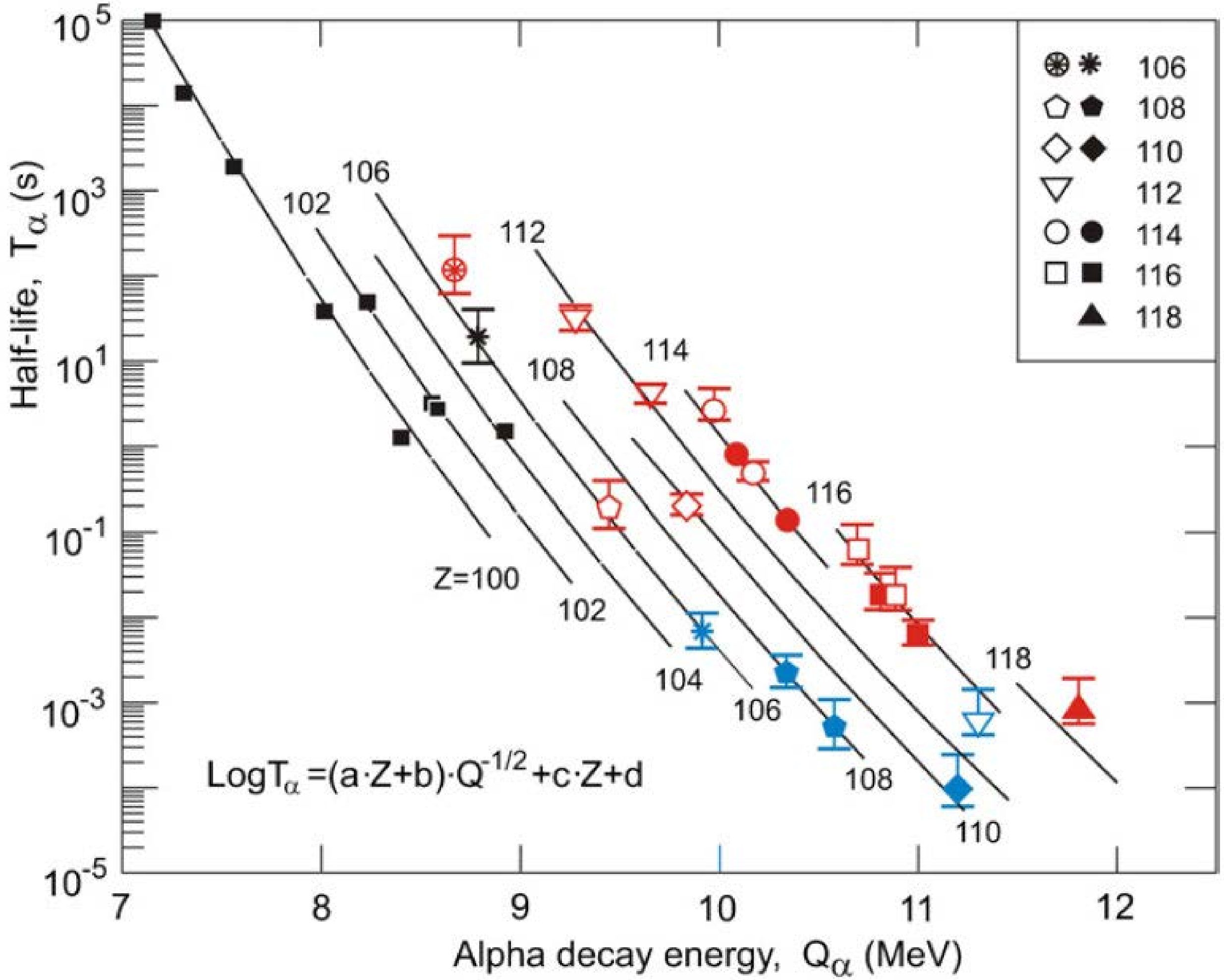
$v = E/B \quad \rightarrow$ *velocity filter*

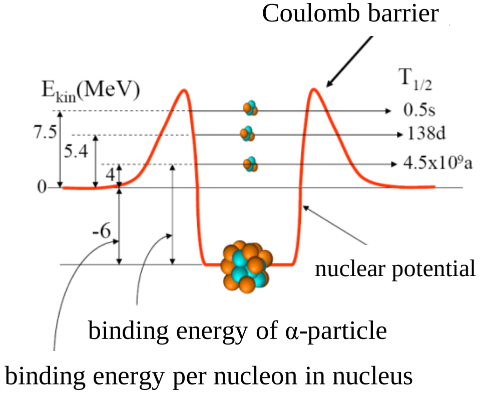
$^{208}Pb + ^{64}Ni \rightarrow ^{272}Ds^*$



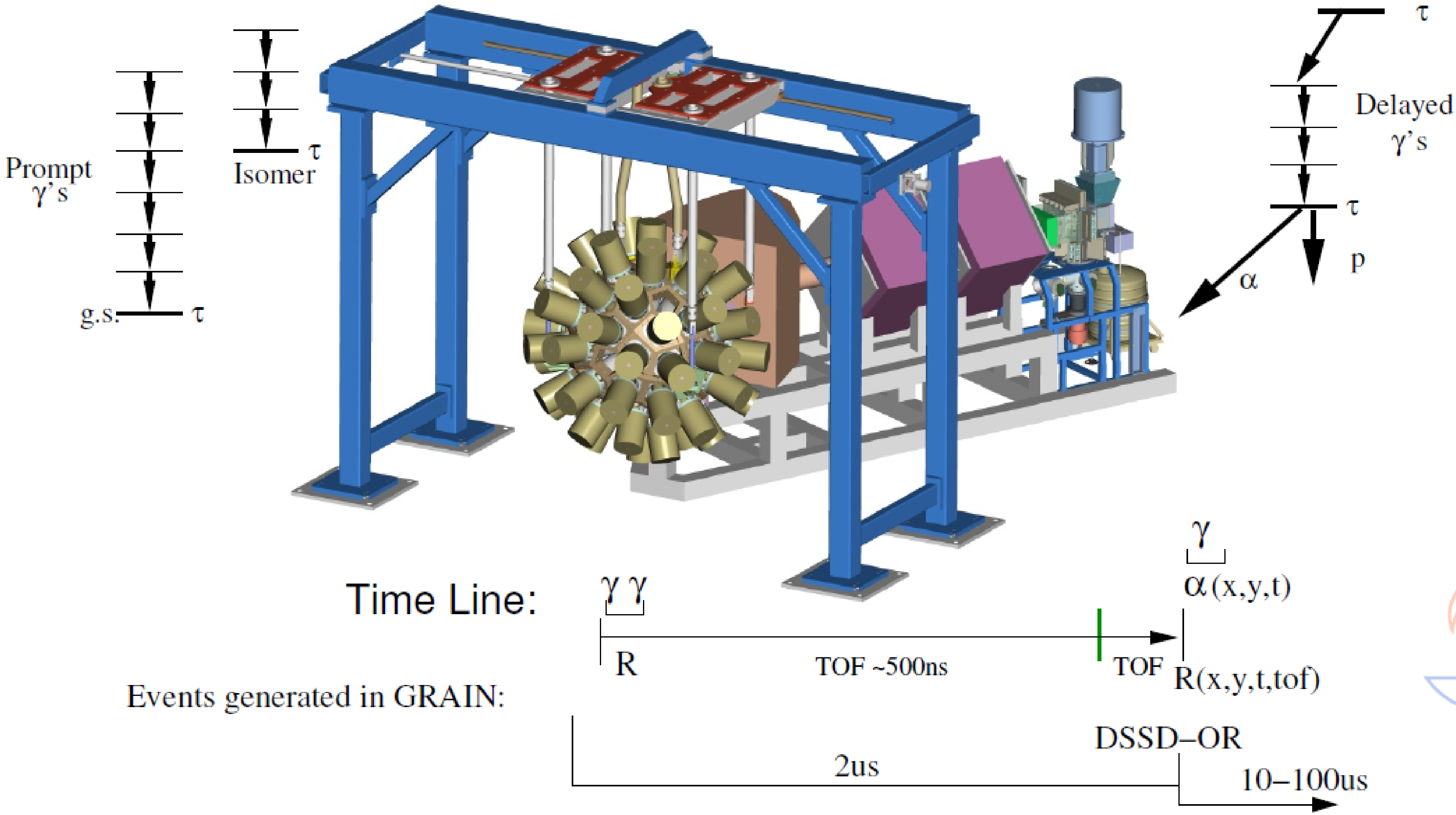
Geiger-Nuttall relationship

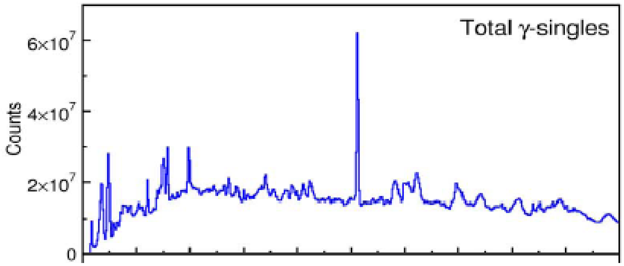
❖ The average decay properties of even mass decay chains match the Geiger-Nuttall relationship

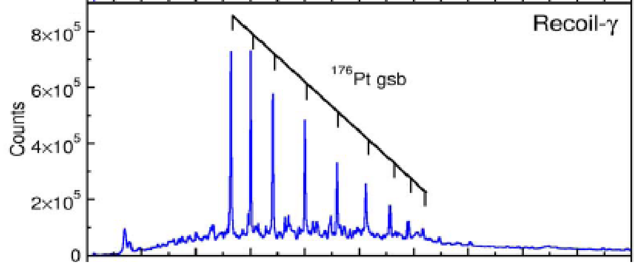


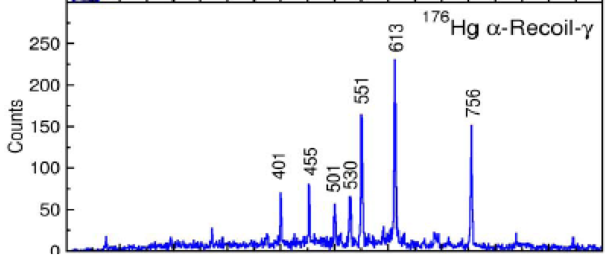


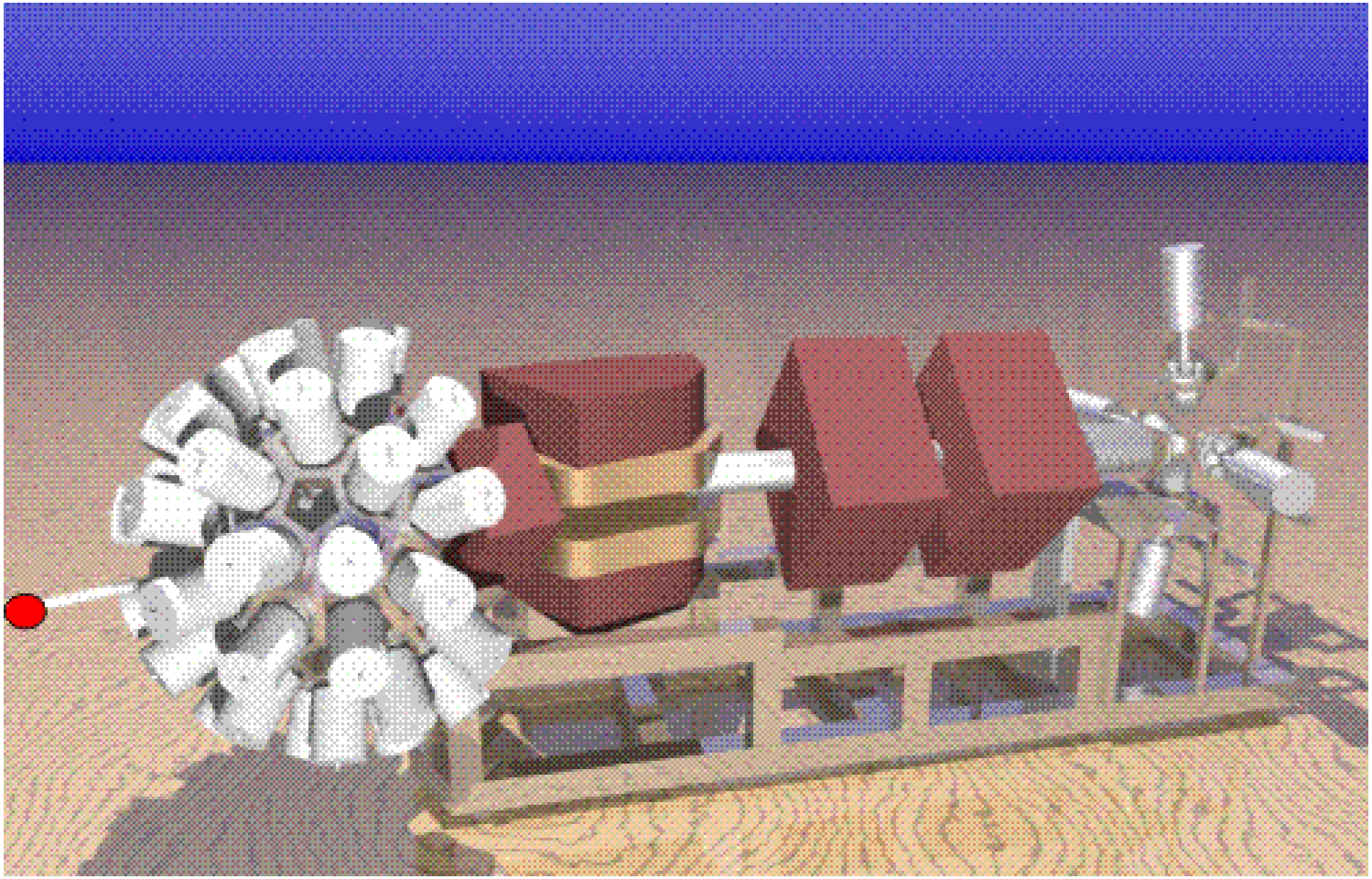
The JUROGAM array + RITU + GREAT spectrometer




Total γ-singles
Counts
6×10^7
4×10^7
2×10^7
0


Recoil-γ
176Pt gsb
Counts
8×10^5
6×10^5
4×10^5
2×10^5
0

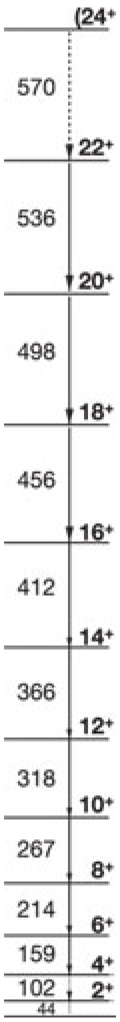

176Hg α-Recoil-γ
Counts
250
200
150
100
50
0
401
455
501
530
551
613
756

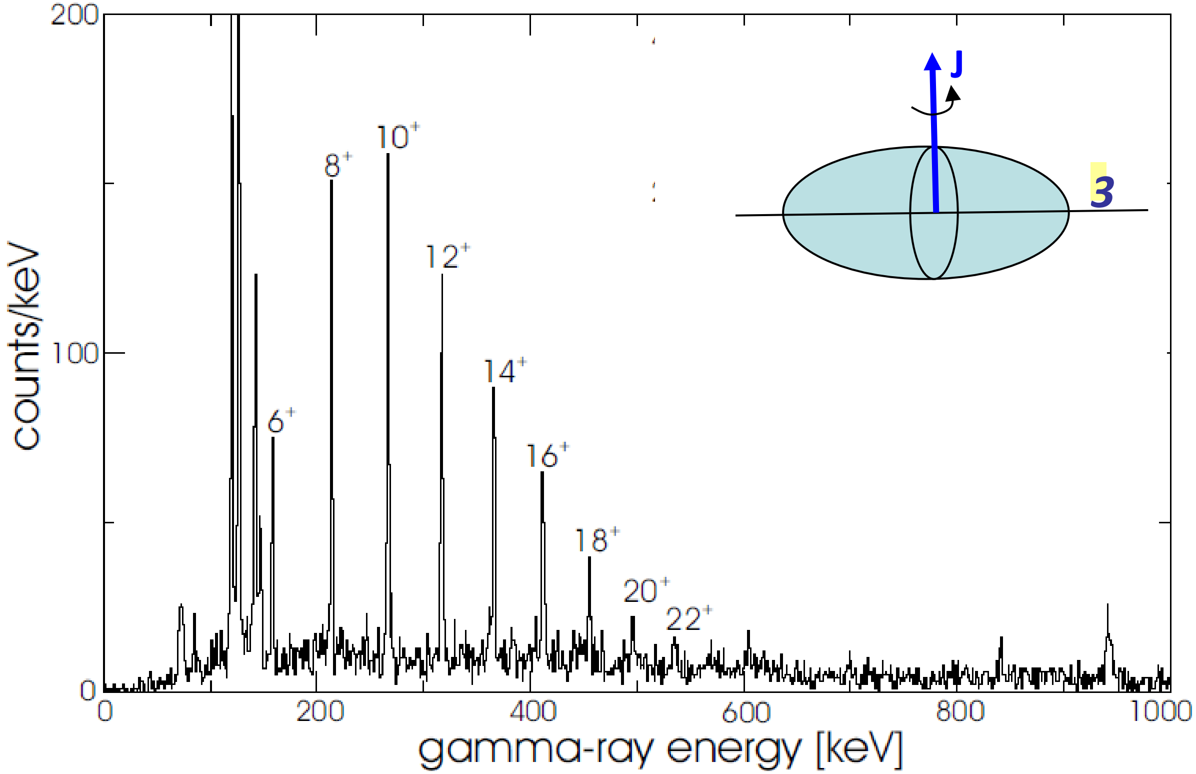


The rotational spectrum of ^{254}No

rotational energy: $$E_J = \frac{\hbar^2}{2\Im} \cdot J \cdot (J+1)$$

gamma – energy: $$E_J - E_{J-2} = \frac{\hbar^2}{2\Im} \cdot (4 \cdot J - 2)$$





S. Eeckhaudt et al., Eur. Phys. J. A 26, 227 (2005)

Chemistry of superheavy elements

Group→ / ↓Period	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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
5	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
6	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
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	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	
				**	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	

- Are the new elements in the same period?
- Does e.g. **Lv** show the same chemical properties as **O**, **S**, **Se**, **Te** and Po?