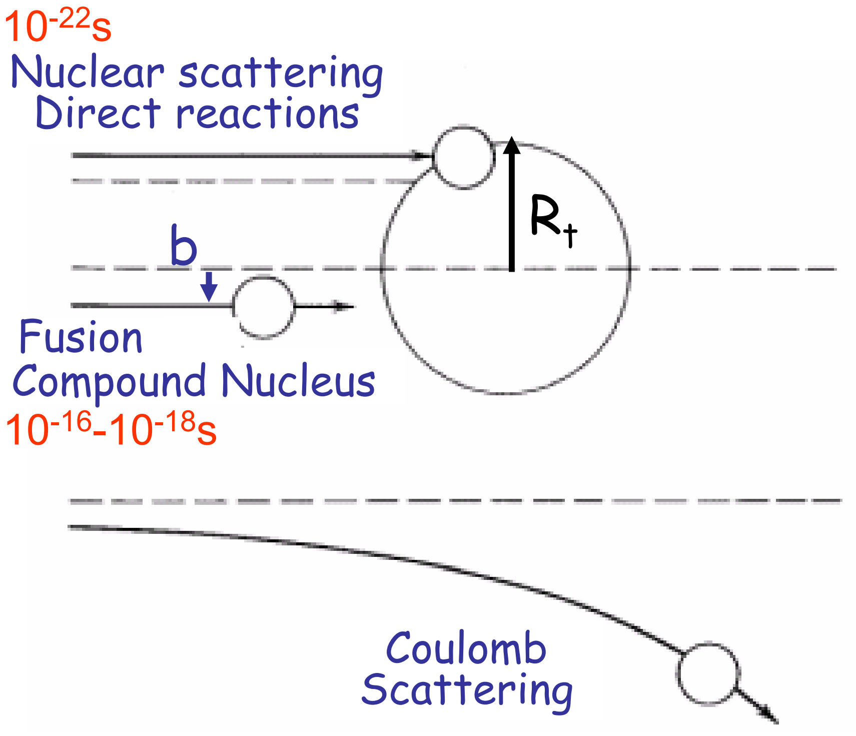
Nuclei at high spins and Finite Temperature

1. Heavy Ions Fusion reactions
2. Compound nucleus decay
3. Level Density
4. Angular Momentum Degree of Freedom
5. Temperature Degree of Freedom
6. Experimental Setups: γ-ray and particles detection

Heavy Ion Fusion Reactions

(A>4 up to ^{238}U)



Study of

- **equation of state**
  (relationship among pressure, density and temperature in nuclear matter→ neutron stars…)
- **nuclear structure**

at finite Temperature

The **compound nucleus** formed by heavy ions fusion reactions has
Density, Temperature and Angular Momentum
Not reachible with light ions

Heavy Ion Reactions

$$l\hbar = \mu v b = p b = \hbar k b$$

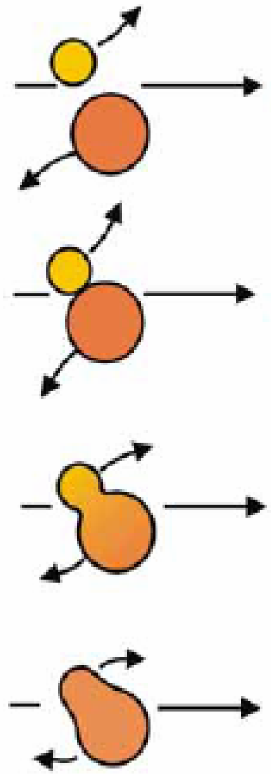
$$\sigma_i = \frac{\pi}{k^2} \sum_{l=l_i}^{l=l_i+1} (2l+1) T_l$$

elastic scattering and **Coulomb excitation**

inelastic scattering and onset of nucleon exchange

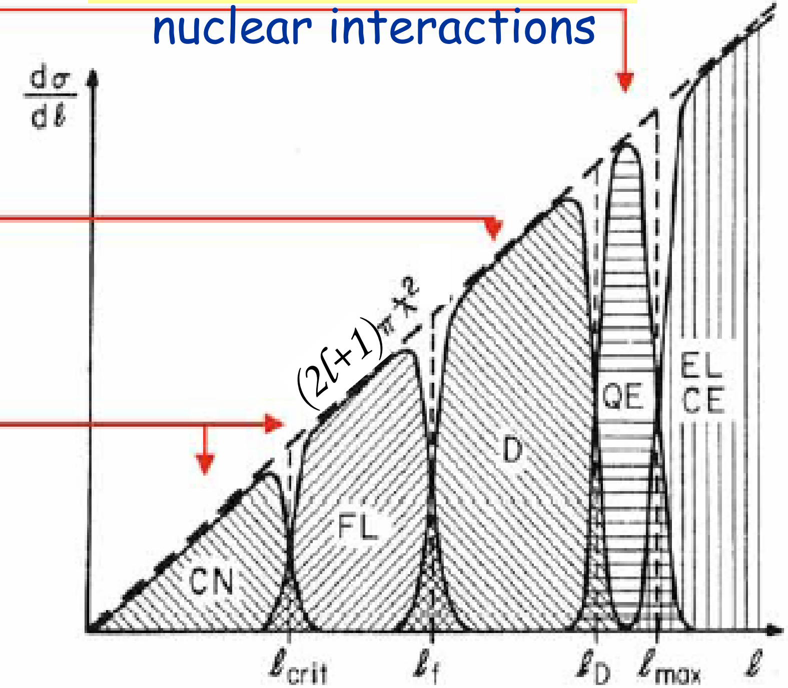
deep-inelastic or dumped reactions - substantial kinetic energy damping and mass exchange

fusion-fission and **fusion-evaporation** reactions



$$\hbar l_{max} = \hbar k b_{max} = \hbar k (R_p + R_t)$$

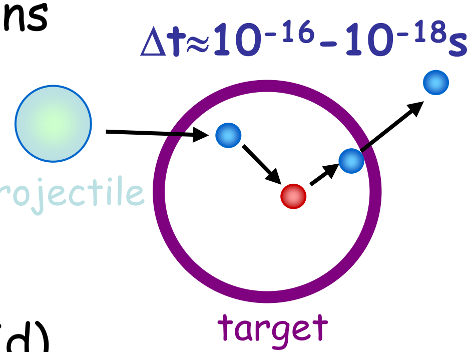
nuclear interactions



Compound Nucleus Reactions

If b < R_{target}

1. scattering of incident nucleons with target nucleons
2. target nucleons collide with each others
3. ripartition of incident energy among nucleons of combined system (projectile + target)

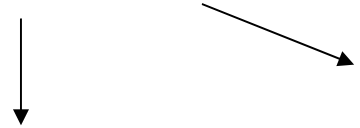


evaporation: **statistical probability** that a nucleon gains enough energy to escape

(analogous: evaporation of molecule from warm liquid)

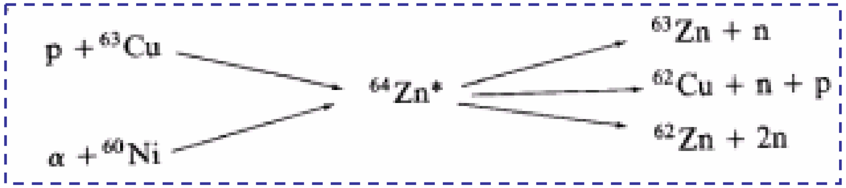
The intermediate state is called **compound nucleus state**

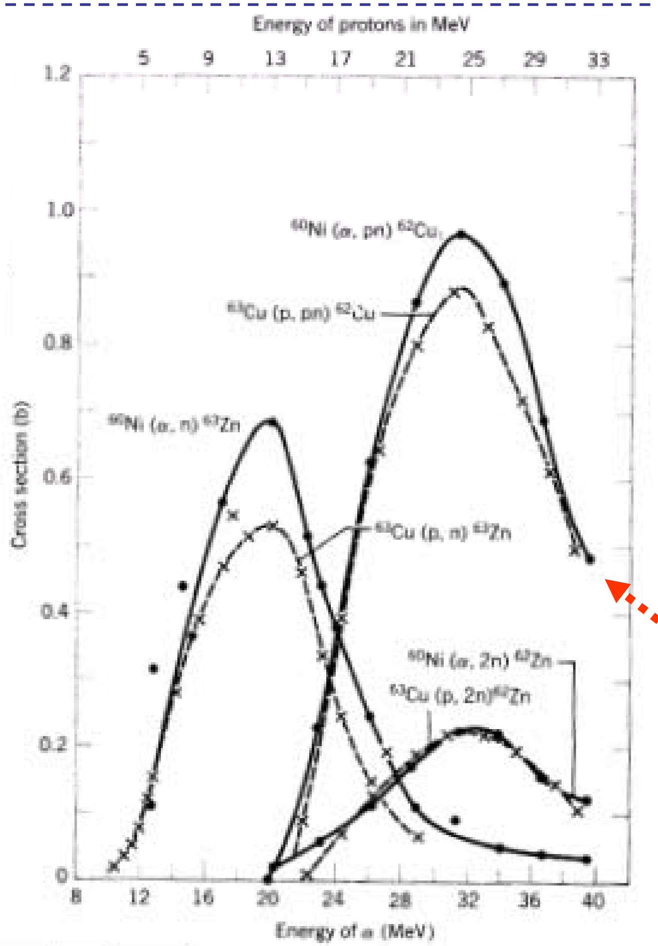
$$A+X \rightarrow C^{*} \rightarrow Y+b$$



The reaction is a **two step process**
1. formation
2. decay

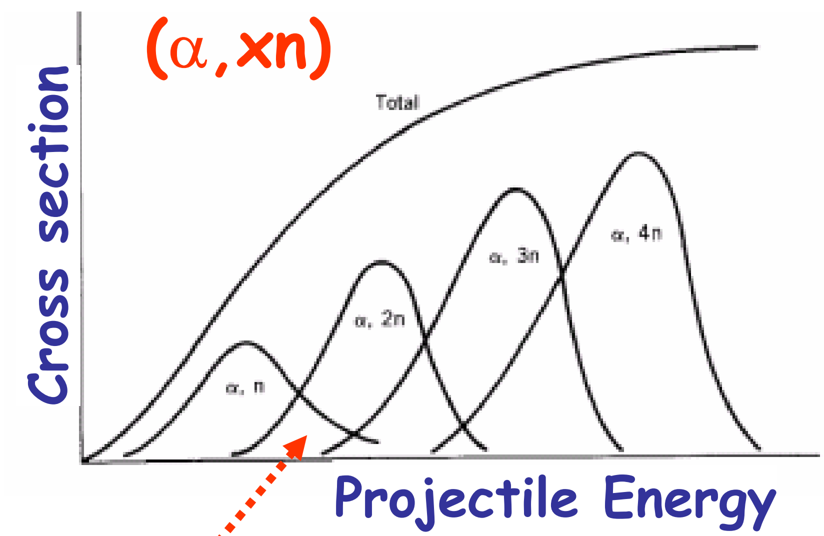
Decay probability to a given final state is **indipendent** of **formation** of compound nucleus





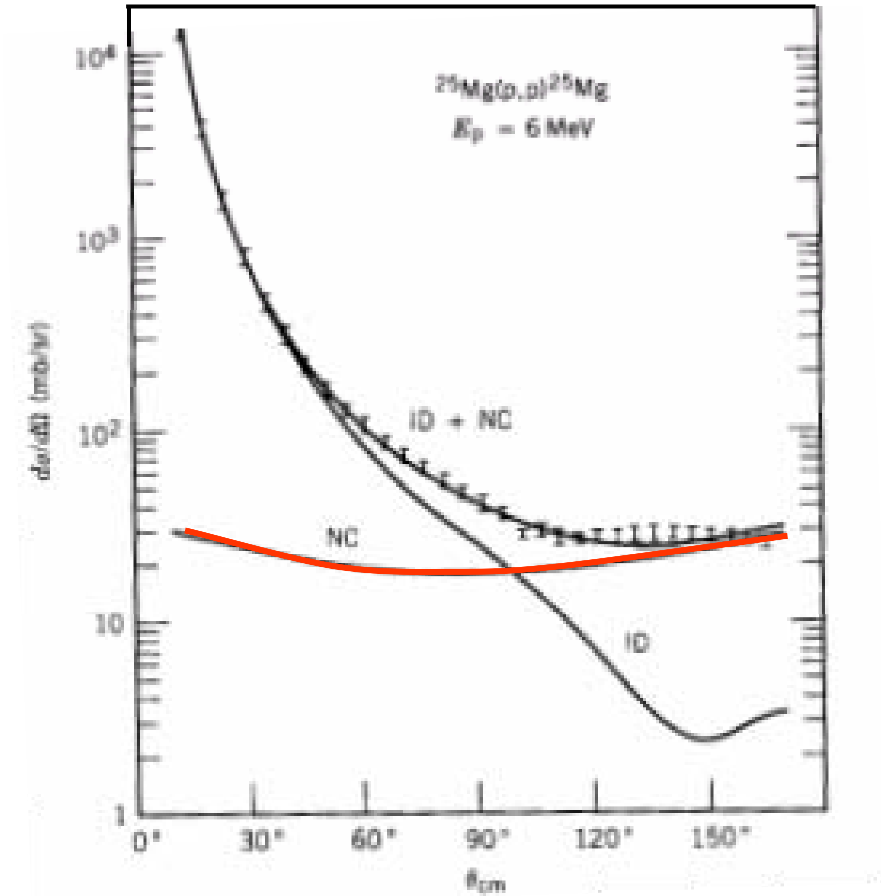
Evaporation:

Giving **more energy to CN** **more particles** are evaporated

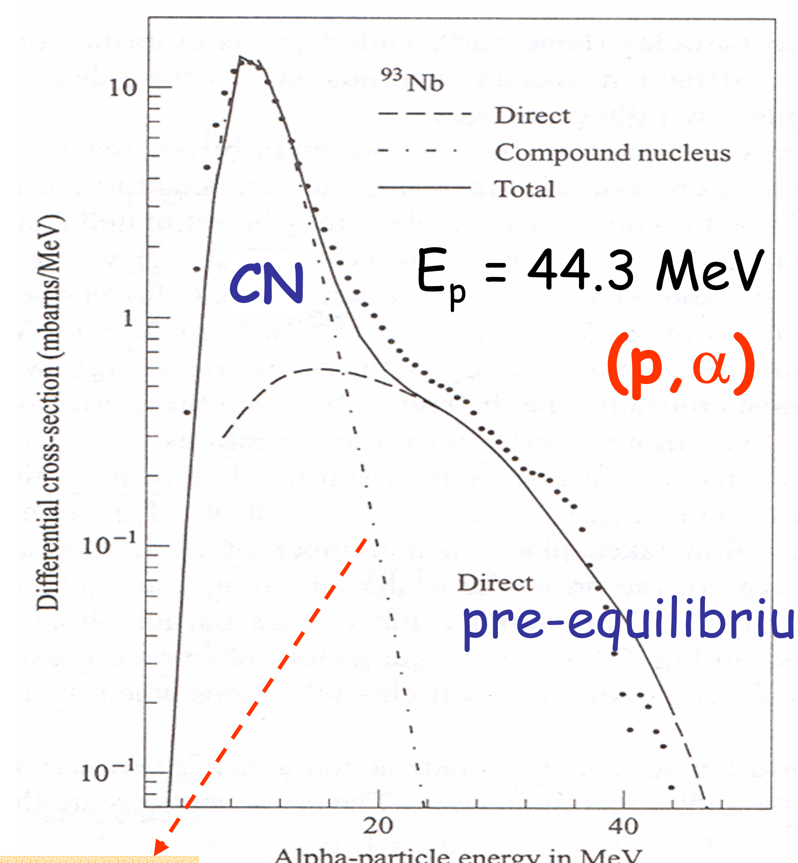


Gaussian shapes

Isotropic angular distribution



Maxwellian distribution
of emitted particles:
CN decay is a **statistical process**
from an **equilibrated** system

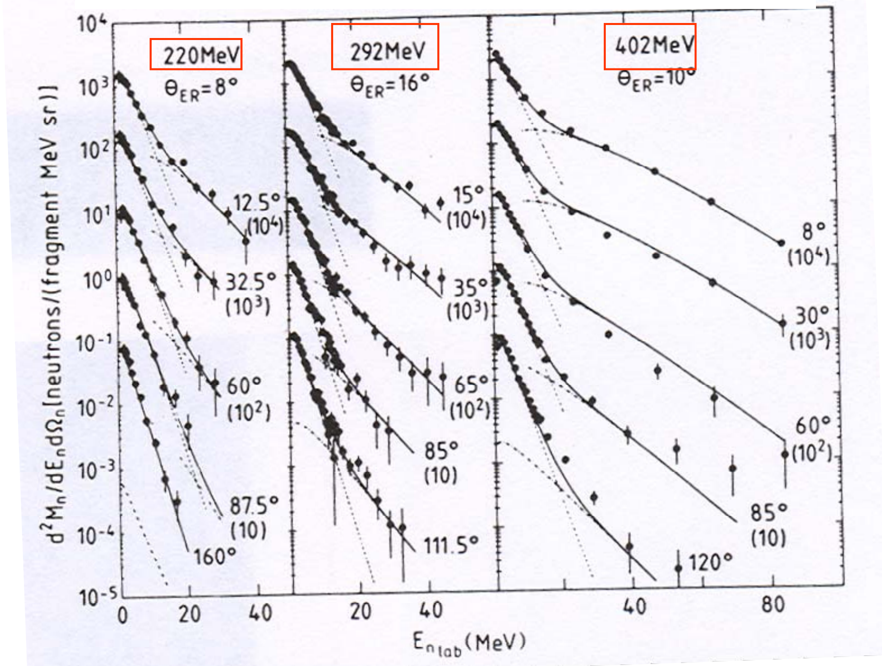


$$N_M(E) = \frac{2E^{1/2}}{\pi^{1/2} T_M^{3/2}} . \exp\left(-\frac{E}{T_M}\right)$$

Maxwellian Distribution
at given temperature T

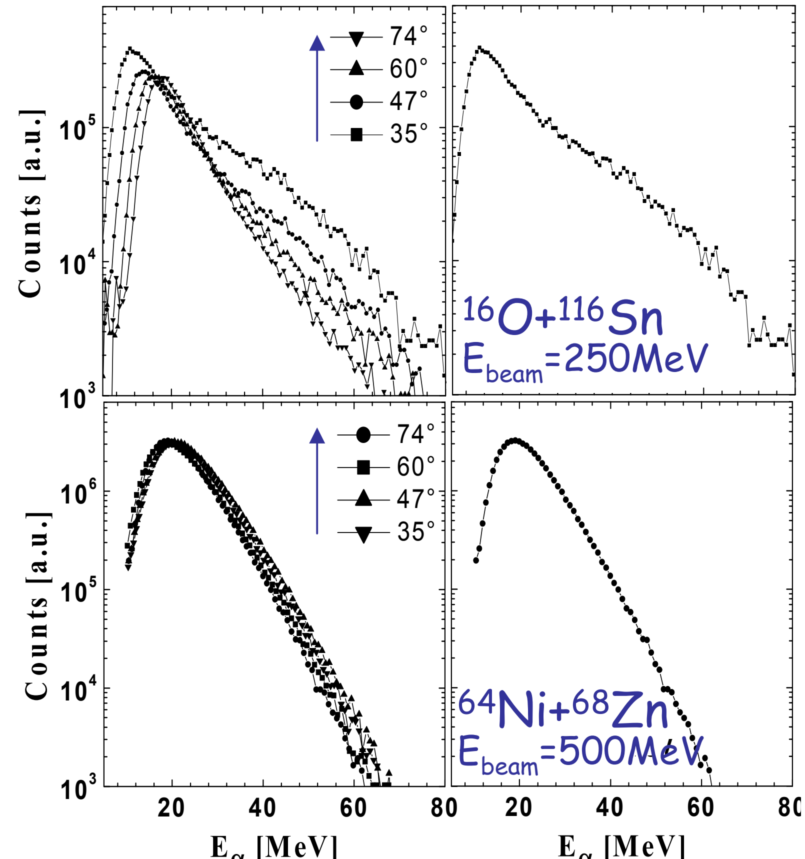
The **energy distribution** of the **emitted particles** is used as an indicator of **equilibrated** compound nucleus formation

$^{20}Ne + ^{165}Ho \rightarrow ^{184}Ir + n$



Increasing incident energy
Pre-equilibrium component increases

$^{132}Ce^*$ at $E^*=200MeV$



The compound nucleus model works well at **low energies** (≤ 10 MeV/u) and for **medium-heavy nuclei**

Heavy Ion reactions populate nuclear states at high spins

Effective potential acting between the two ions

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

Nuclear (Wood-Saxon)

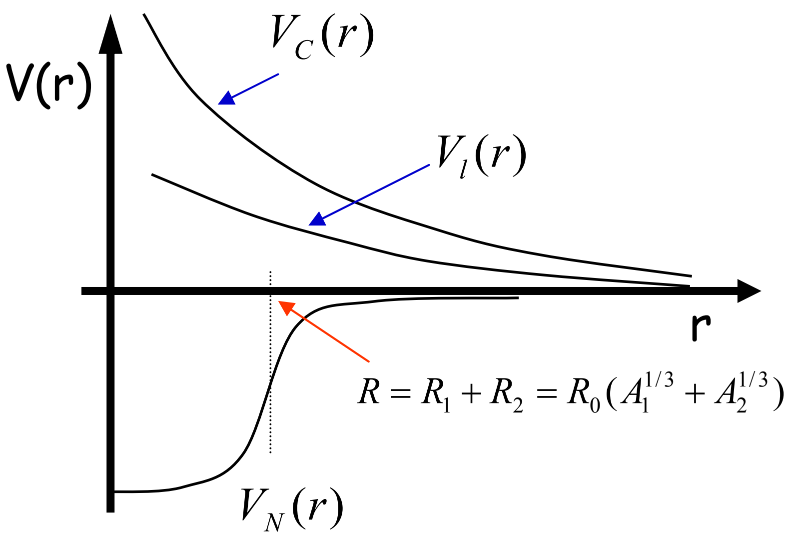
$$V_N(r) = \frac{-V_0}{1+\exp\left(\frac{r-R}{a}\right)}$$

Coulomb

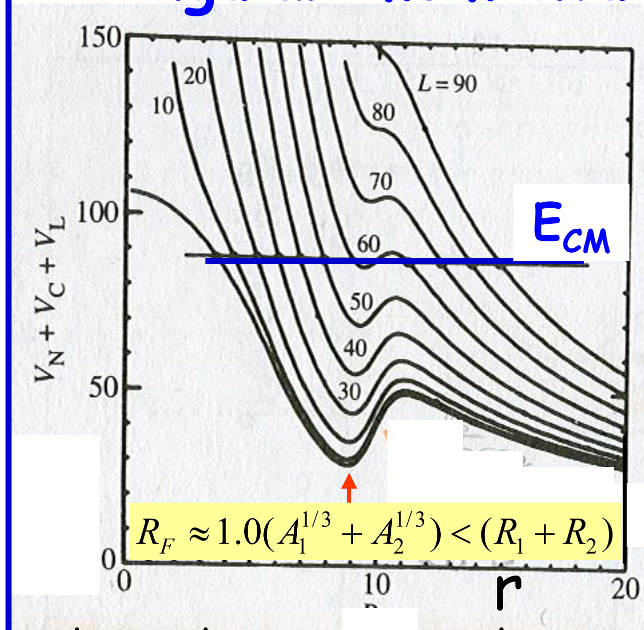
$$V_C(r) = \frac{Z_1 Z_2 e^2}{r}$$

Centrifugal

$$V_l(r) = \frac{\hbar^2 l(l+1)}{2\mu r^2}$$



Angular momentum limit



$^{16}O + ^{120}Sn$

E_{CM} incident energy in CM

the pocket occurs at the same distance R_F

$$E_{cm} \geq E_{cb} + \frac{\hbar^2 l(l+1)}{2\mu R_{cb}^2}$$

$$l_{\max} = R_{cb}[2\mu(E_{cm} - E_{cb})]^{1/2}$$

$$R_{cb} = 1.36(A_1^{1/3} + A_2^{1/3}) + 0.5\,fm$$

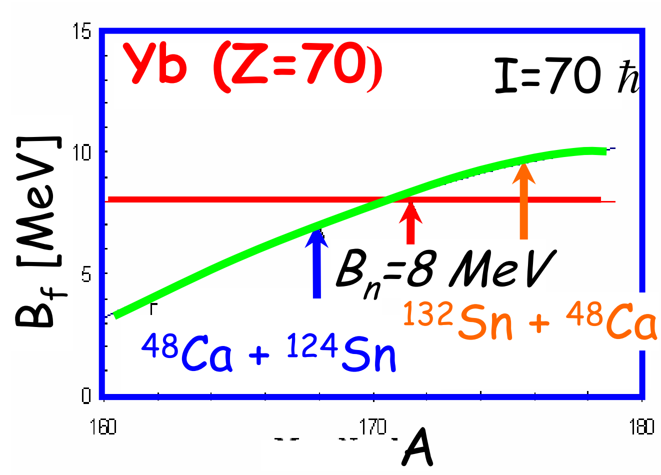
$$E_{cb}(MeV) = \frac{Z_1 Z_2 e^2}{R_{cb}} = \frac{1.44 Z_1 Z_2}{R_{cb}(fm)}$$

$l_{max} \approx 70\hbar$ for $A \approx 160$

Angular momentum limits
(from liquid drop calculations)

Radioactive Beams
(Neutron Rich)

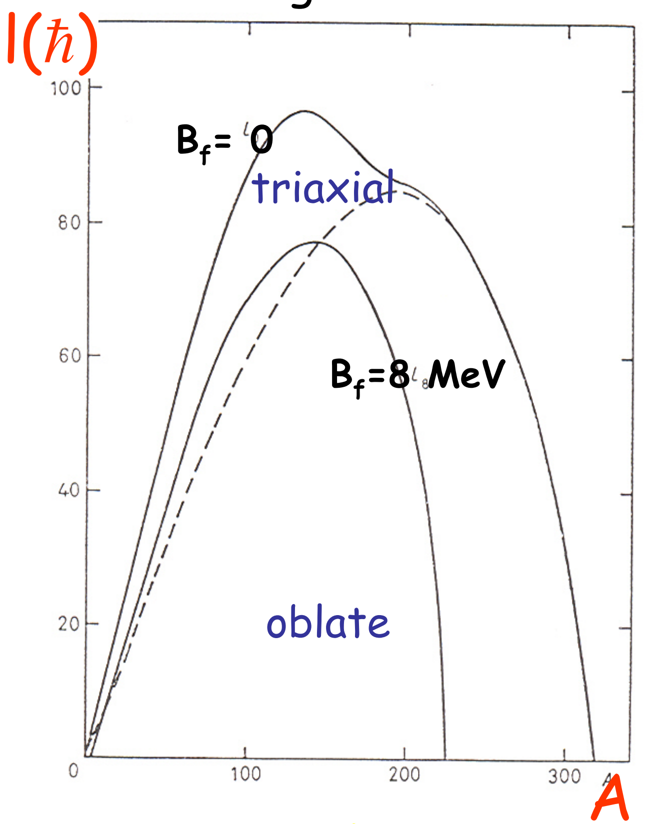
population of **larger** angular momenta:
fission barrier increases with neutron number



$$B_f = \frac{2\delta_s^2}{5} a_s A^{2/3} \left(1 - \frac{a_c}{2a_s}\frac{Z^2}{A}\right)$$

Stable Beams

fission limits
maximum angular momentum



≈ 10^{21} rotations/sec