ISOLDE Nuclear Reaction and Nuclear Structure Course

Fusion reaction at low energy

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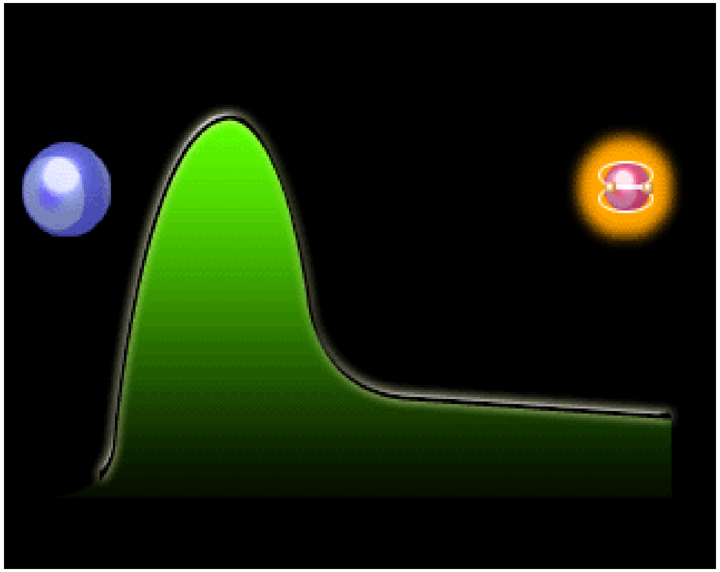
Reactions induced by halo nuclei at the Coulomb barrier

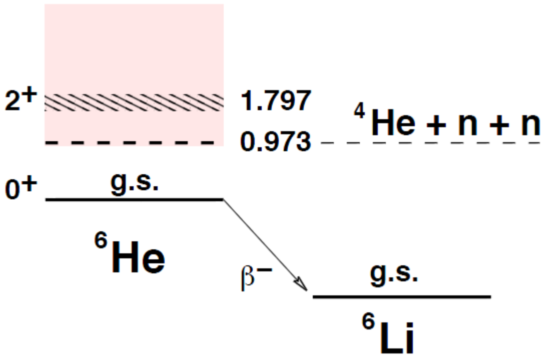


From R.Raabe K.U. Leuven

Higher total reaction cross-section than “normal” nuclei.

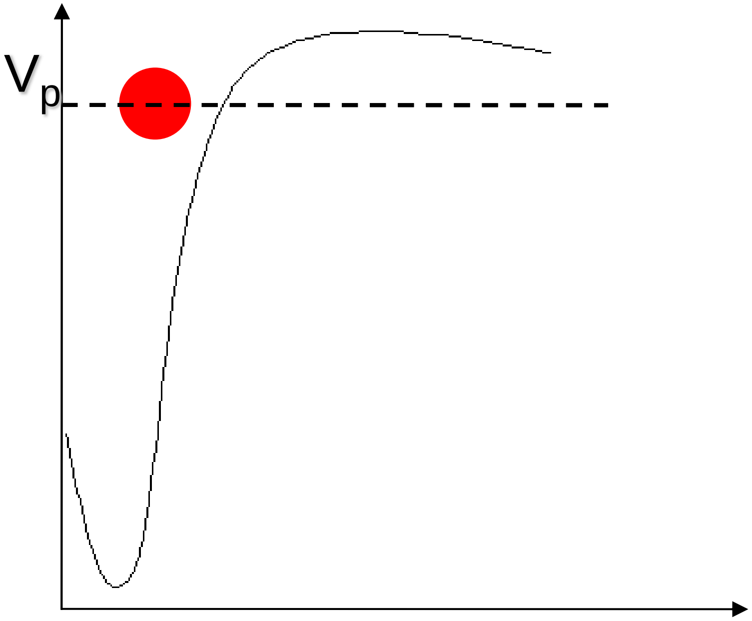
Nuclear halo

The nuclear halo is a threshold effect arising from the very weak binding energy (0.1-1 MeV) of the outer nucleon(s)



- Nuclear halo appears when the weakly bounds valence nucleon(s) are in s or p states, close to the particles emission threshold.

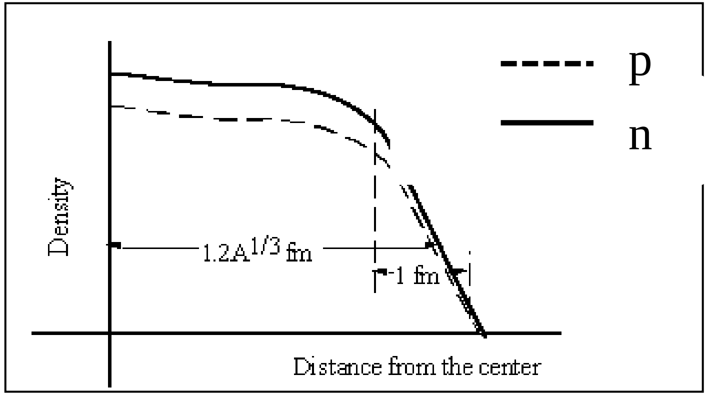
- Due to the low binding energy for these nucleon(s) tunnelling is possible. Heisenberg principles allows the valence nucleon(s) to spend a time interval $\Delta t \leq \hbar / 2\Delta E$ outside the nuclear core.

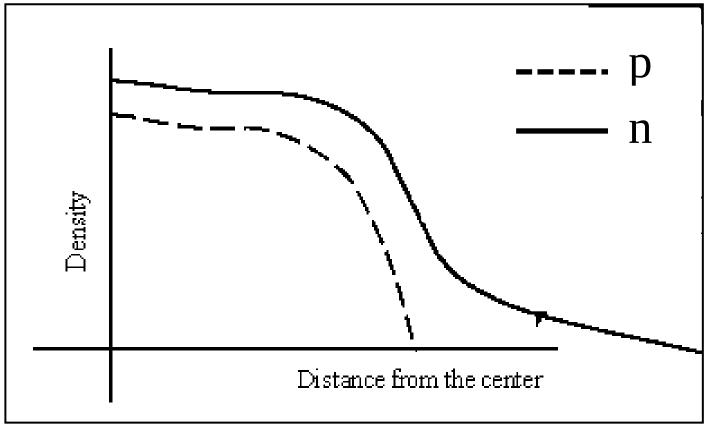


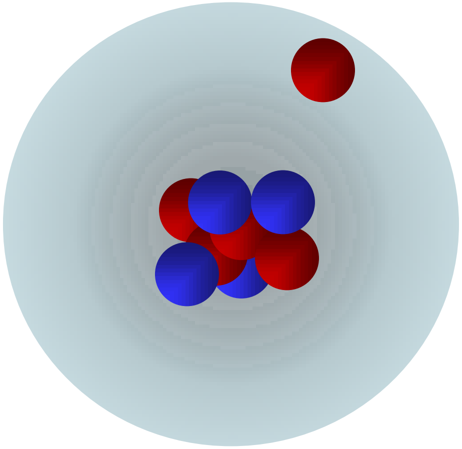
Properties of neutron halo nuclei

- The wave function presents a long tail which extends outside the potential well;
- Radius $\xcancel{=}\ r_0\, A^{1/3}$

Neutron Distribution Density







Some examples:

$^{6}\mathrm{He} \equiv {}^{4}\mathrm{He} + n + n$

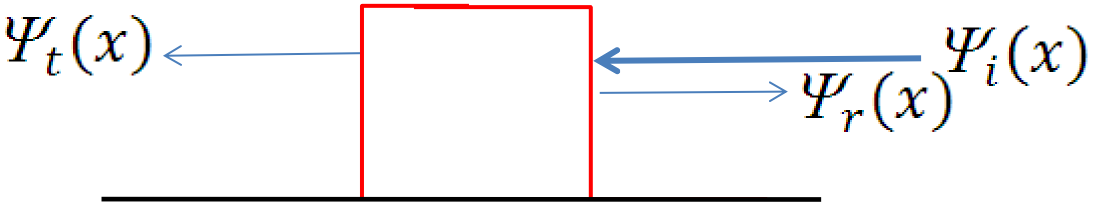
$^{11}\mathrm{Li} \equiv {}^{9}\mathrm{Li} + n + n$

$^{11}\mathrm{Be} \equiv {}^{10}\mathrm{Be} + n$

Effects of halo structure on reaction processes: the sub-barrier fusion case.

Sub-barrier fusion occurs by tunneling. Even with simple one dimensional tunneling there are challenges.

Text Book Approach:

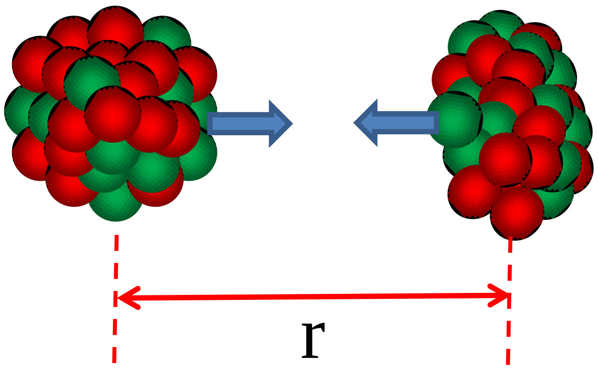


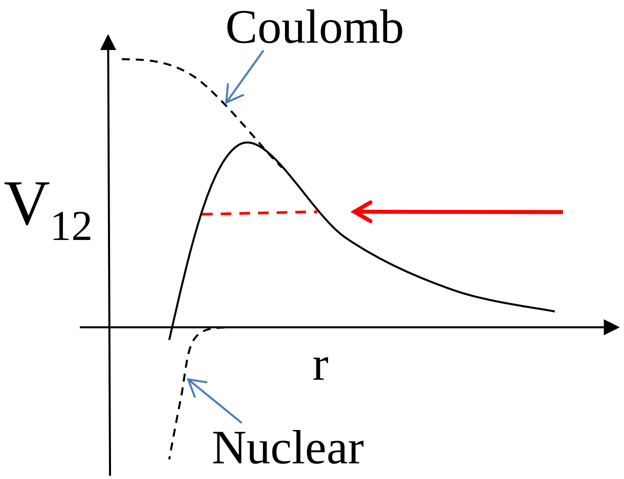
$$H\Psi = E\Psi$$

Transmission Probability T= $|\Psi_t(x)|^2/|\Psi_i(x)|^2$

T+R=1 :transmitted flux + reflected flux =1

Fusion

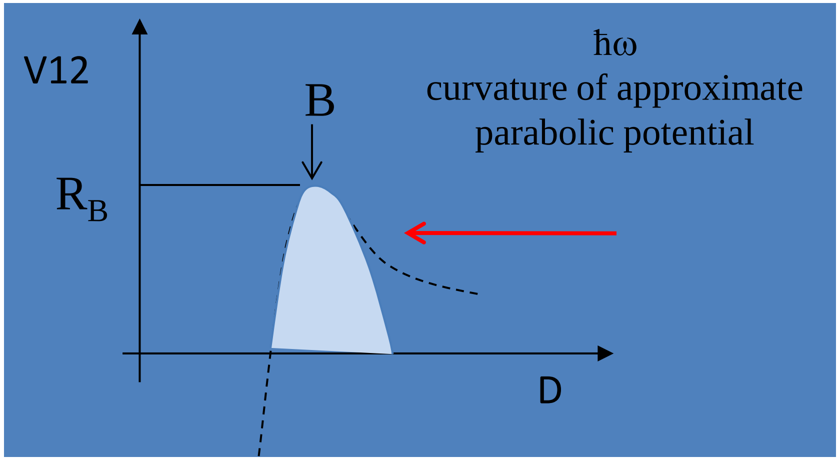


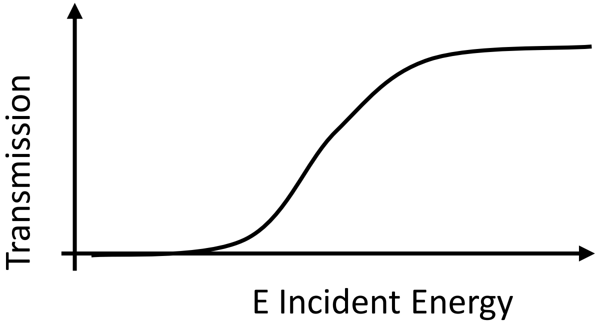


$$P_{HW} = \frac{1}{1+\exp\left[\frac{2\pi}{\hbar\omega(l,E)}\left(B+\frac{\hbar^2 l(l+1)}{\{2\mu R_B{}^2(l)\}}-E\right)\right]}$$

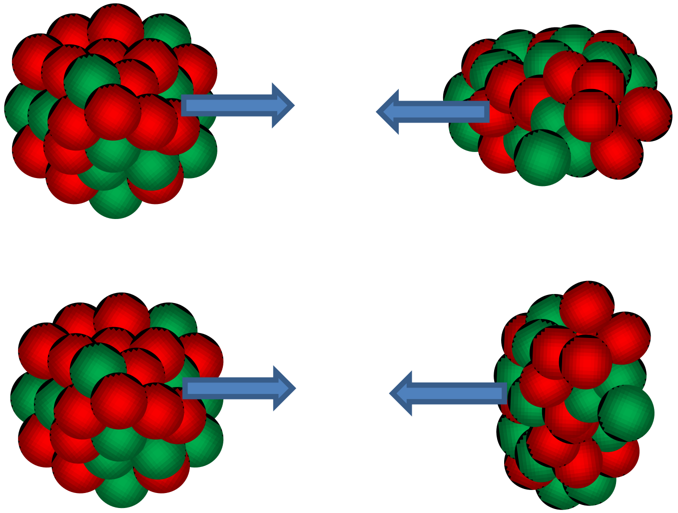
Use a one dimension parabolic potential

(Hill, Wheeler, 1953)





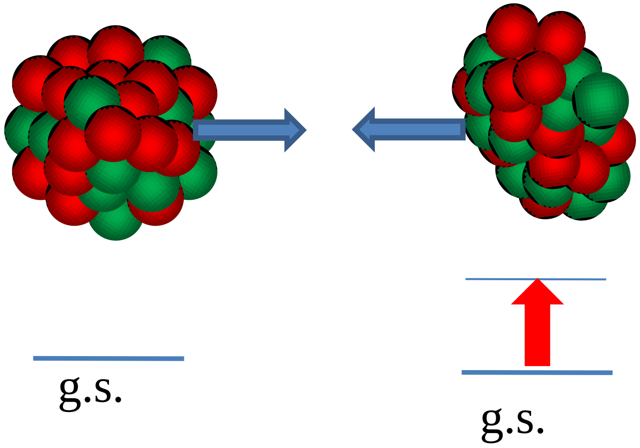
Orientation



Lower B

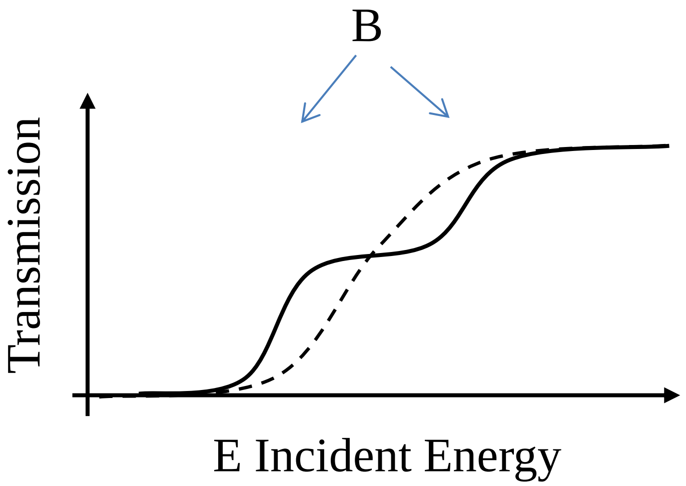
Higher B

Excitation

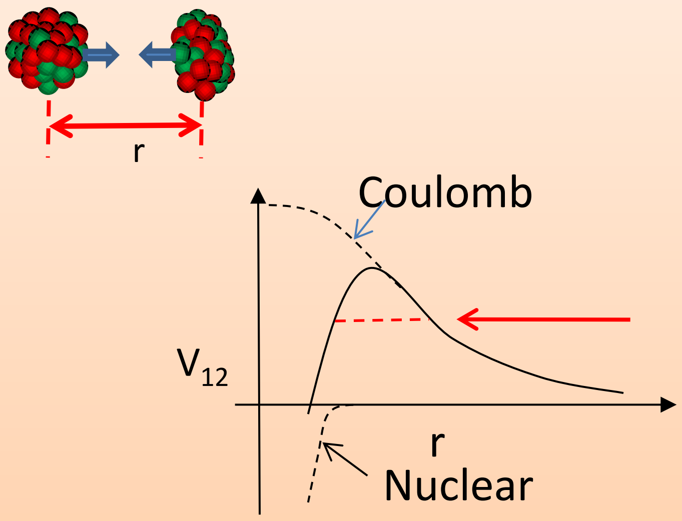


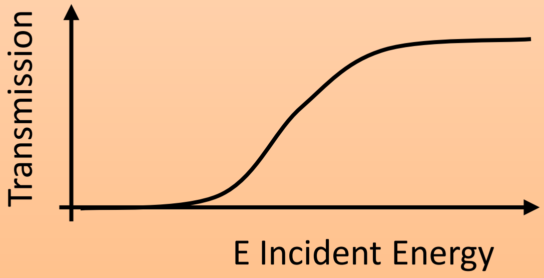
g.s.

g.s.

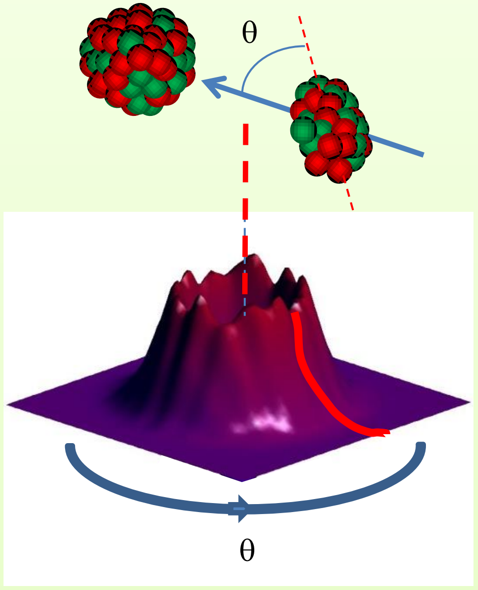


Summarising:

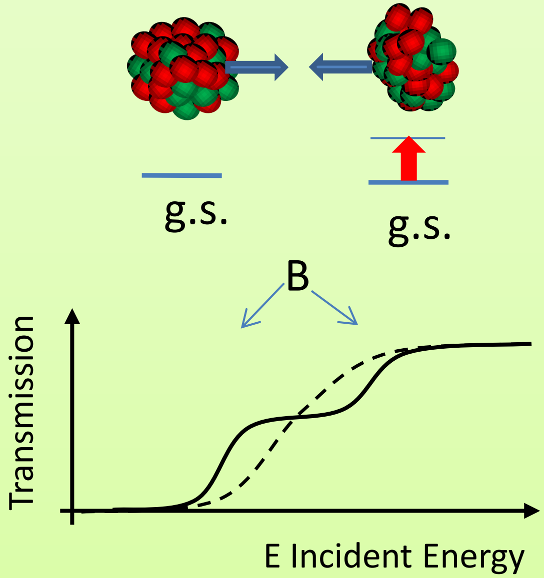




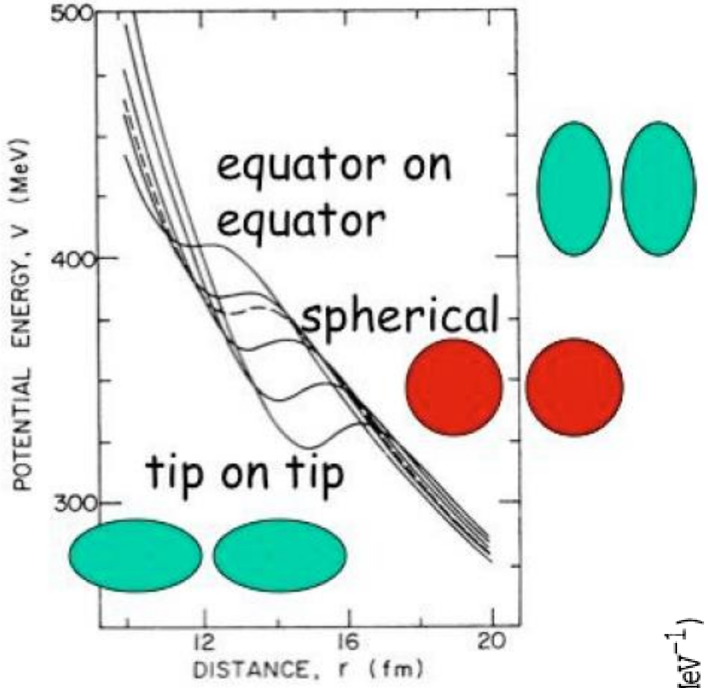
Orientation

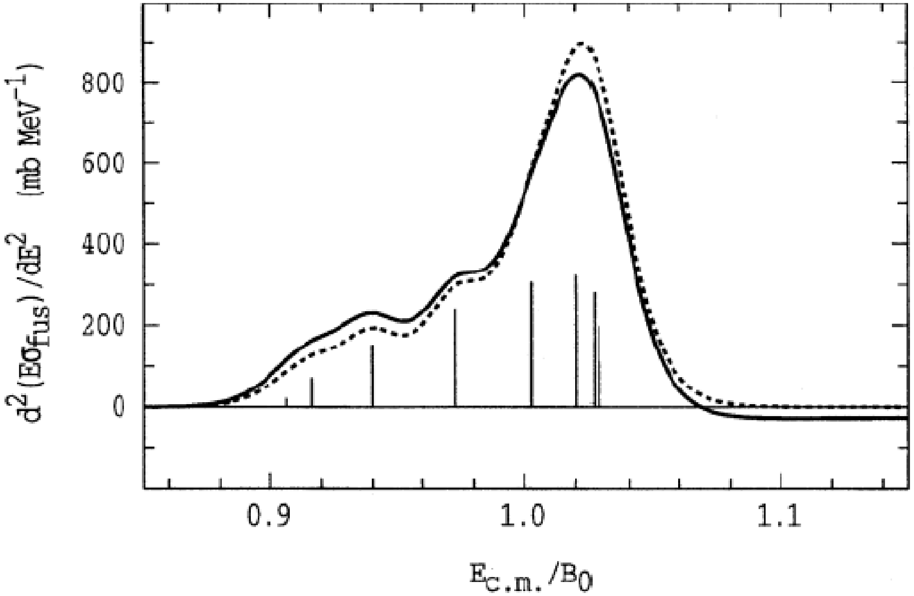


Excitation

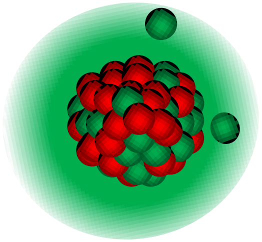


BARRIER DISTRIBUTION

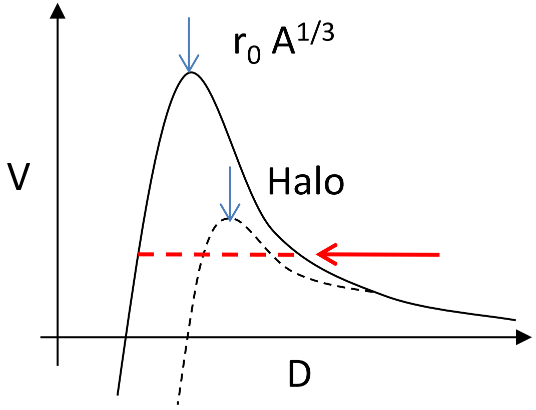




How does halo affect fusion ?
Possibilities: Static effect



Radius $\cancel{=} r_0 A^{1/3}$

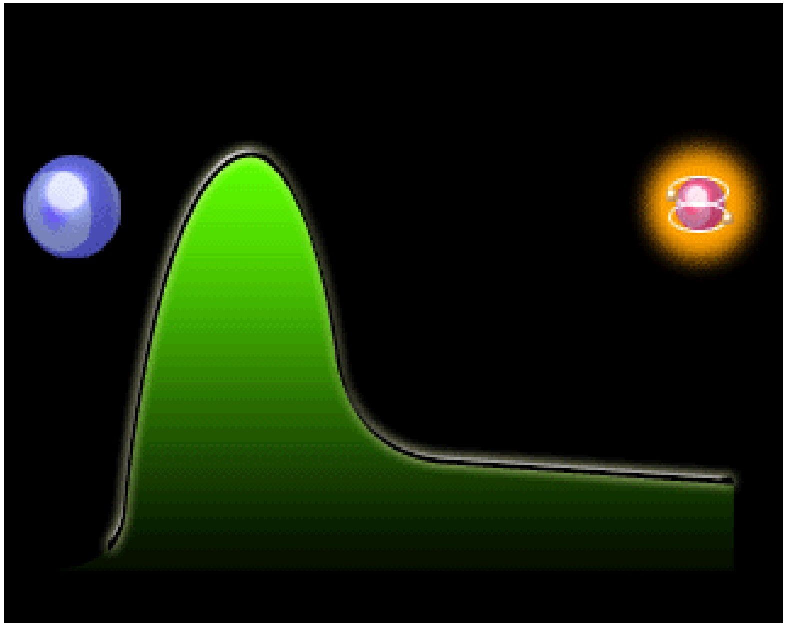


<u>Static effects</u> due to long tail in density distribution:

longer tail in ion-ion potential, lowering of Coulomb barrier, larger sub-barrier fusion probabilities, etc

Sub-barrier fusion induced by halo nuclei

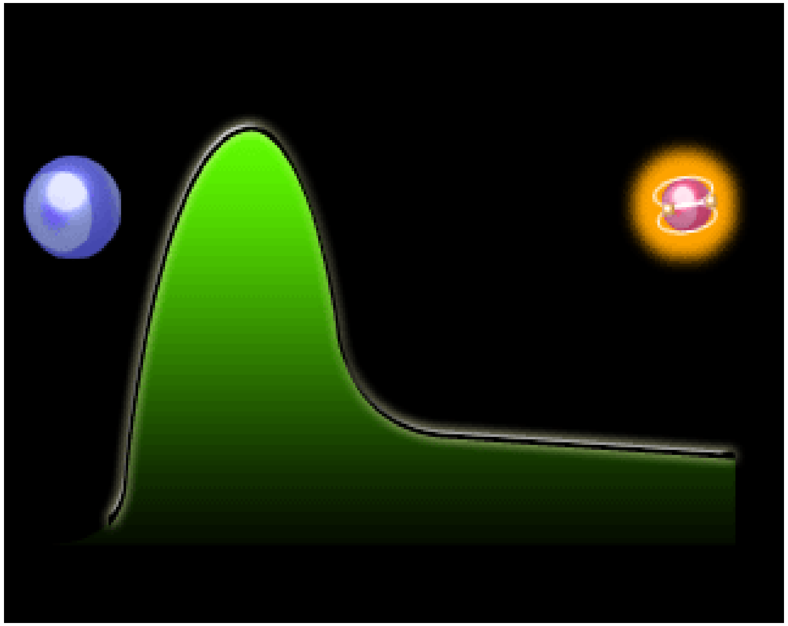
- Theory: fusion probability ***larger*** due to diffuse halo structure (static effect).



From R.Raabe K.U. Leuven

Sub-barrier fusion induced by halo nuclei

- Theory: fusion probability ***smaller*** due to competition with break-up (low binding energy).



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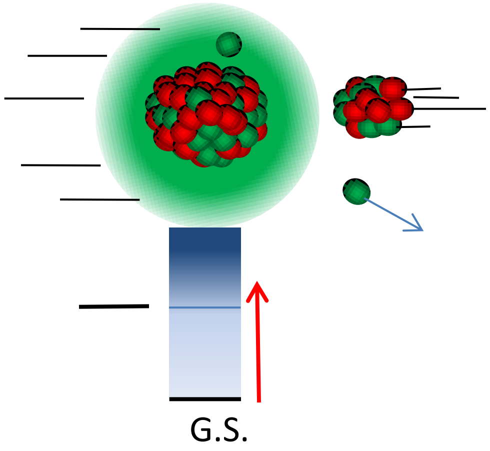
Dynamic effects

Coupling between relative motion of projectile and target and their intrinsic states.

Halo nuclei → low binding energy → g.s. close to break-up threshold → coupling with break-up important → effect on sub-barrier fusion?

Breakup



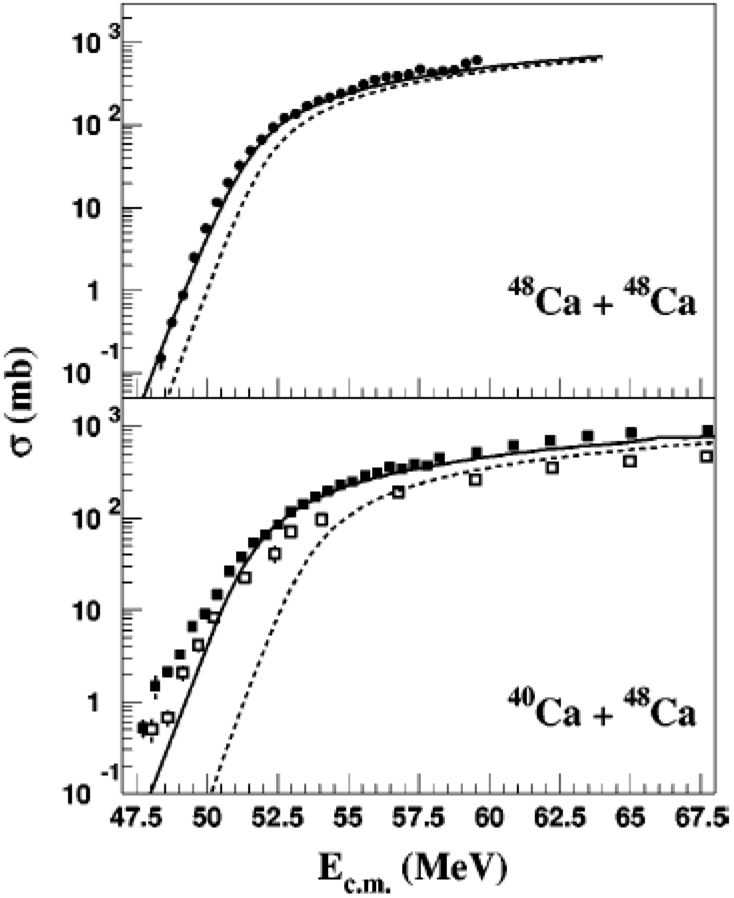
Effect?

Like any other coupling process → Increased sub barrier fusion

Decreases Flux → Decreased sub barrier fusion

Inelastic will always increase Sub- Barrier fusion

Trotta et. al (2001)



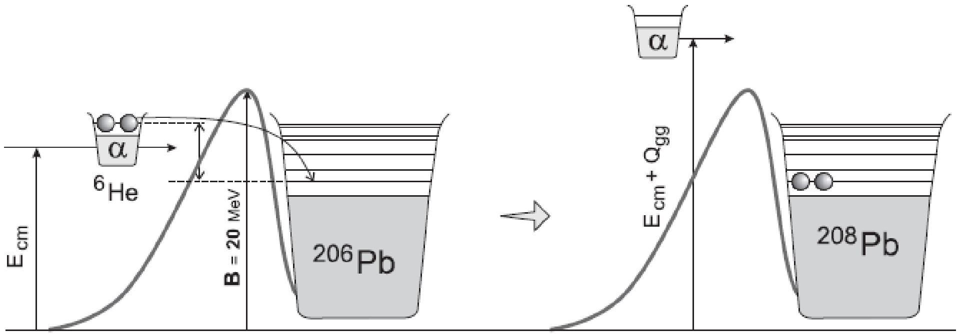
—— Coupled

······ No coupling

For stable fusing nuclei this has been a very successful approach

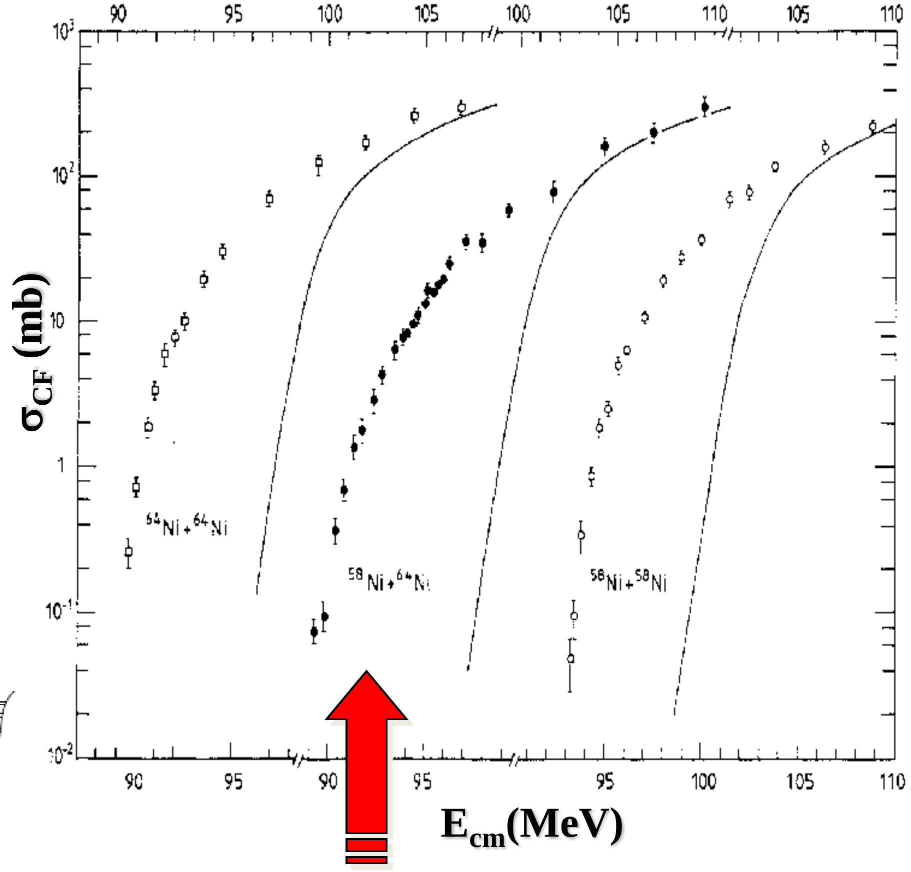
Fusion excitation function for: ^{58}Ni + ^{58,64}Ni and ^{64}Ni + ^{64}Ni

Well established that coupling of colliding nuclei relative motion to intrinsic excitations or other open reaction channels causes large enhancement of fusion cross-section at sub-barrier energies over prediction of simple penetration models.



Zagrebaev, AIP Conf. Proc. 912 (2007) 66

Zagrebaev, Phys.Rev.C 061601 (2003)

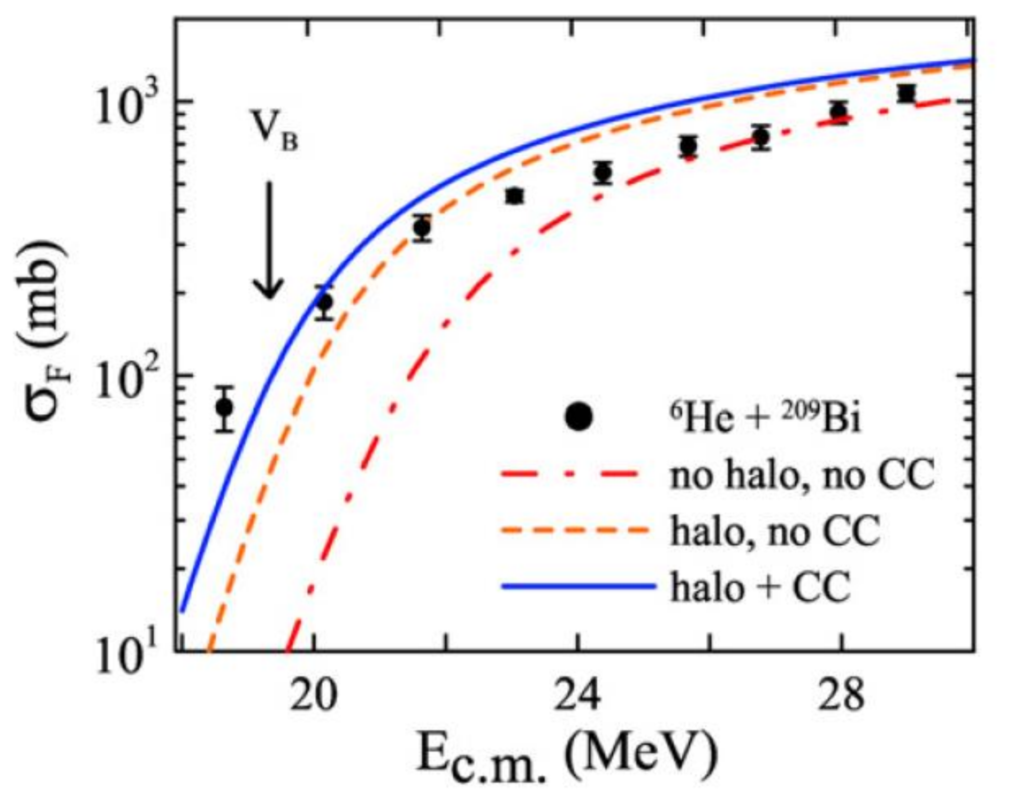


Eg: ^{58}Ni + ^{64}Ni: neutron transfer $Q_{value} > 0$

M. Beckerman et al. Phys. Rev. Lett 45 (1980) 1472 , M. Beckerman et al. Phys. Rev. C23 (1981) 1581
M. Beckerman et al. Phys. Rev. C25 (1982) 837 12

When one talks about enhancement or suppression, is that in relation to what?

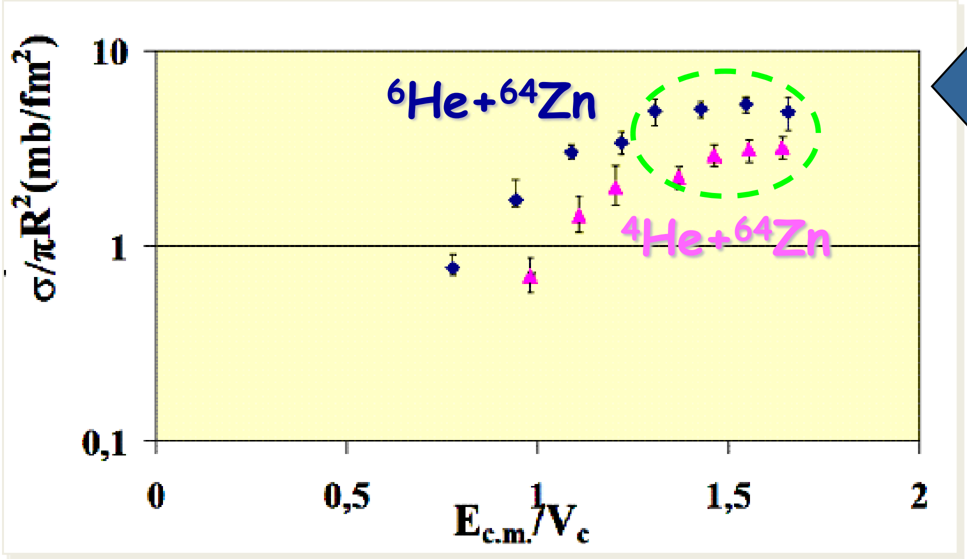
Different type of comparisons of barrier penetration:



L.F. Canto et al. Nuclear Physics A 821 (2009) 51–71

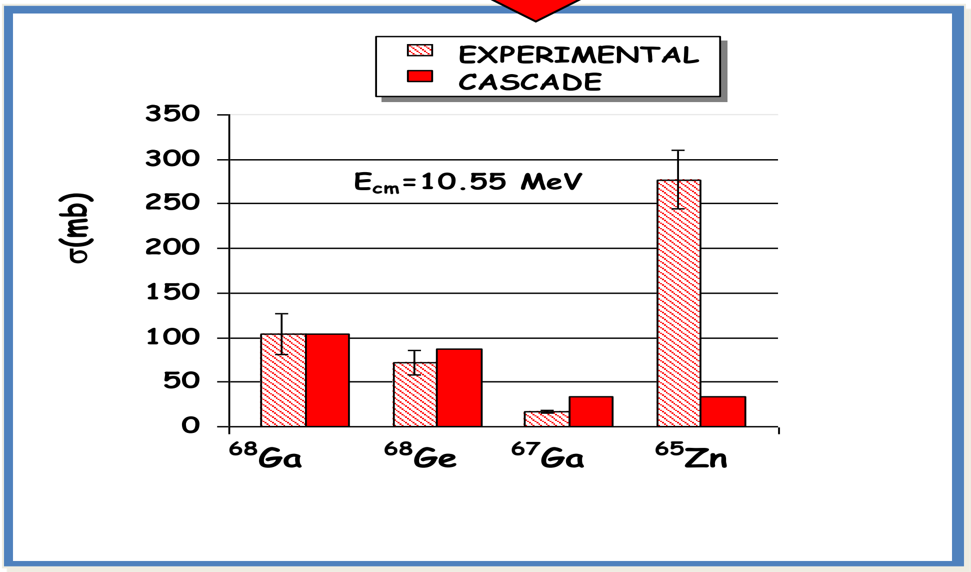
$^{4,6}He+^{64}Zn$ heavy residue excitation function

Heavy residue excitation function



A strong enhancement of the fusion cross-section seems to be present!

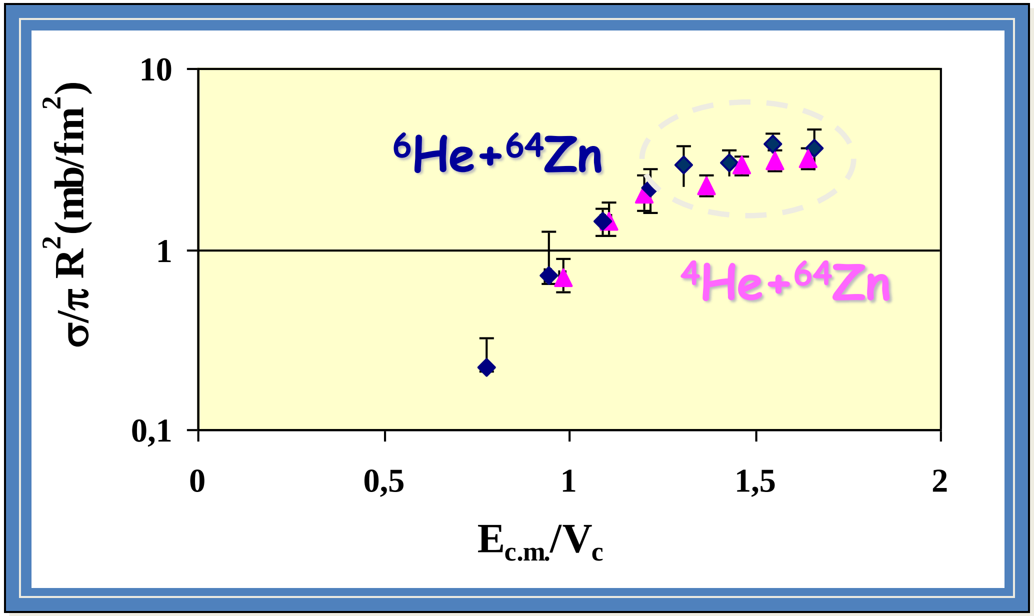
CASCADE predictions compared with experimental results



The strong enhancement comes only from one residue: ^{65}Zn.

^{65}Zn can be produced not only in fusion followed by 1α+1n evaporation but also in 1n and 2n transfer reactions.

^{4,6}He+^{64}Zn fusion excitation function

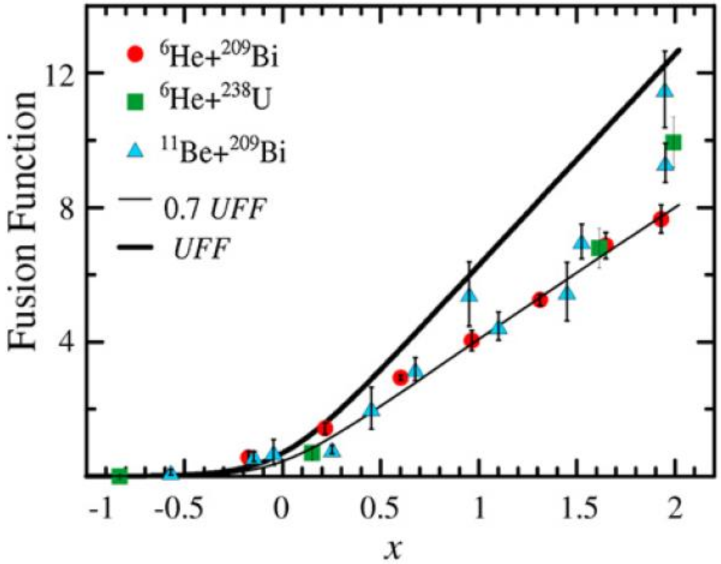


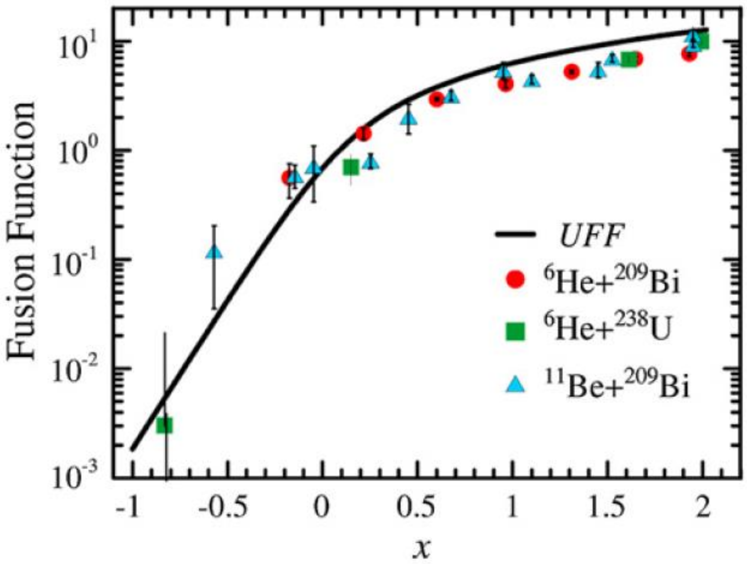
Excitation function obtained by replacing the measured ^{65}Zn contribution with the calculated value.

<u>Conclusions:</u> No evidence for fusion cross-section enhancement

A. Di Pietro et al. Phys.Rev.C 69(2004)044613

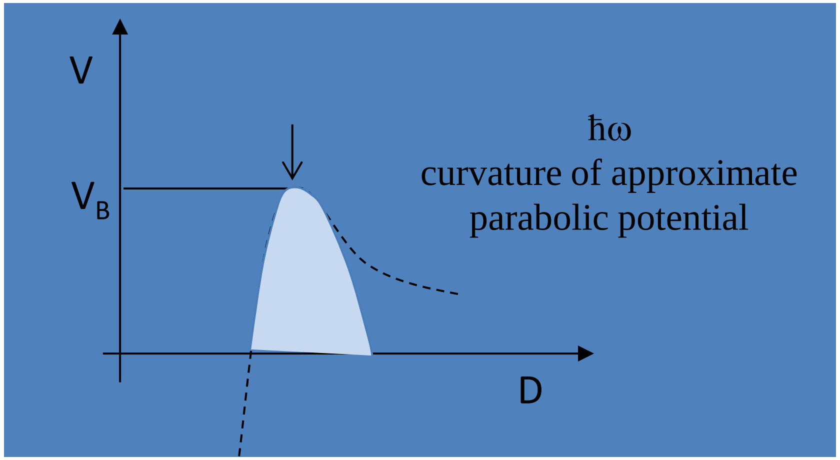
In Canto et al. NPA 821 (2009) 51 suggested a comparison independent on the system under investigation.





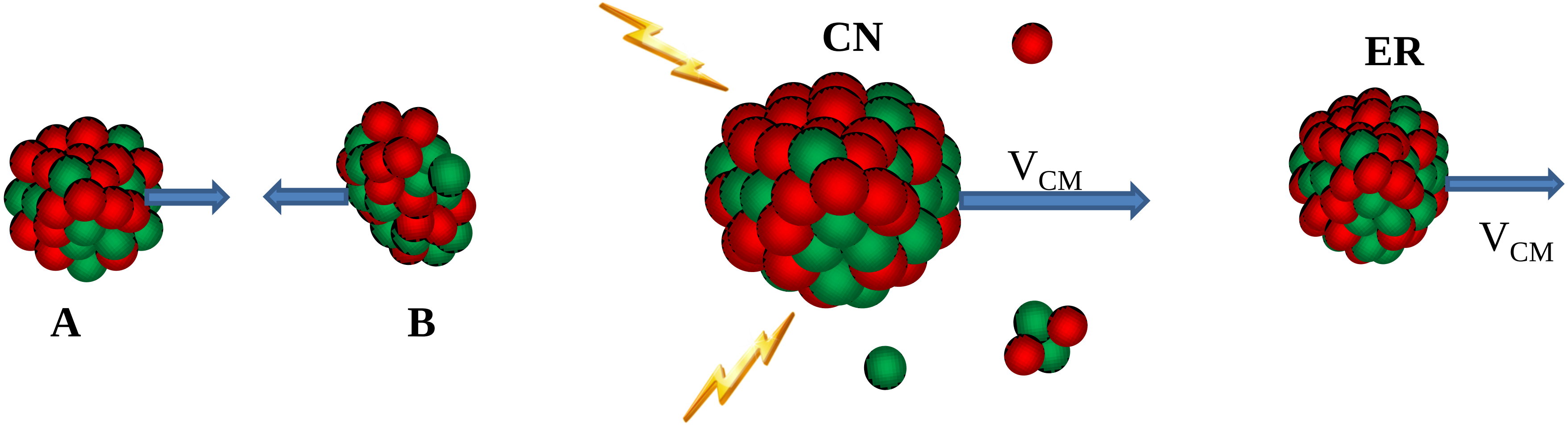
$$x = \frac{E_{c.m.} - V_B}{\hbar\omega}$$

$FF(x) = \ln[1+ \exp(2\pi x)]$



ħω
curvature of approximate
parabolic potential

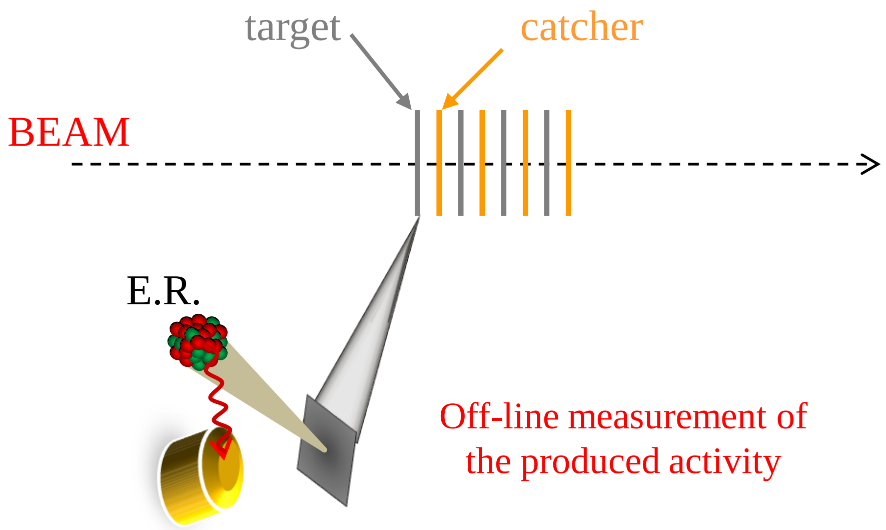
How to measure fusion cross-section?



1) Direct detection of Evaporation Residues (ER)
2) Detection of all evaporated particles (difficult to reconstruct the correct cross-section)
3) Detection of γ-rays (part of the information could be missing due to g.s. population of some ER
4) If the CN is fissile one can measure fission cross-section
5) If ER are radioactive measure of the off-line activity

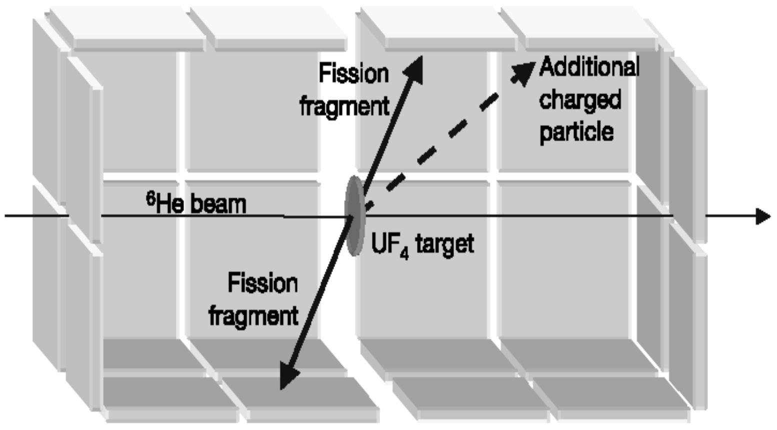
Experimental thechniques used to measure fusion with low intensity halo beams.

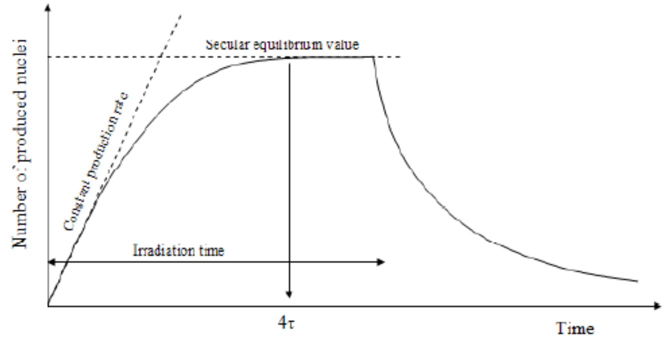
Activation experiments:
medium mass and heavy targets



Off-line measurement of the produced activity

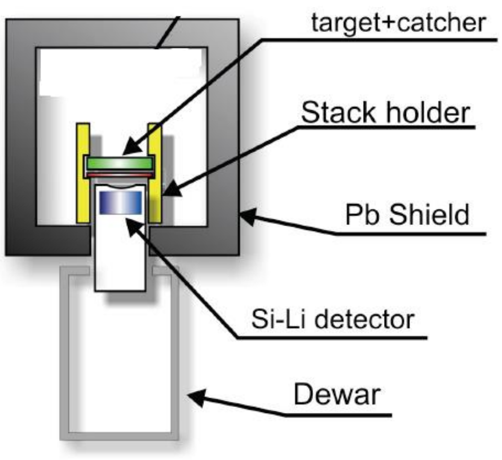
Fusion-fission:
heavy fissile targets

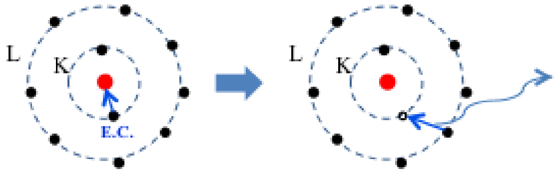


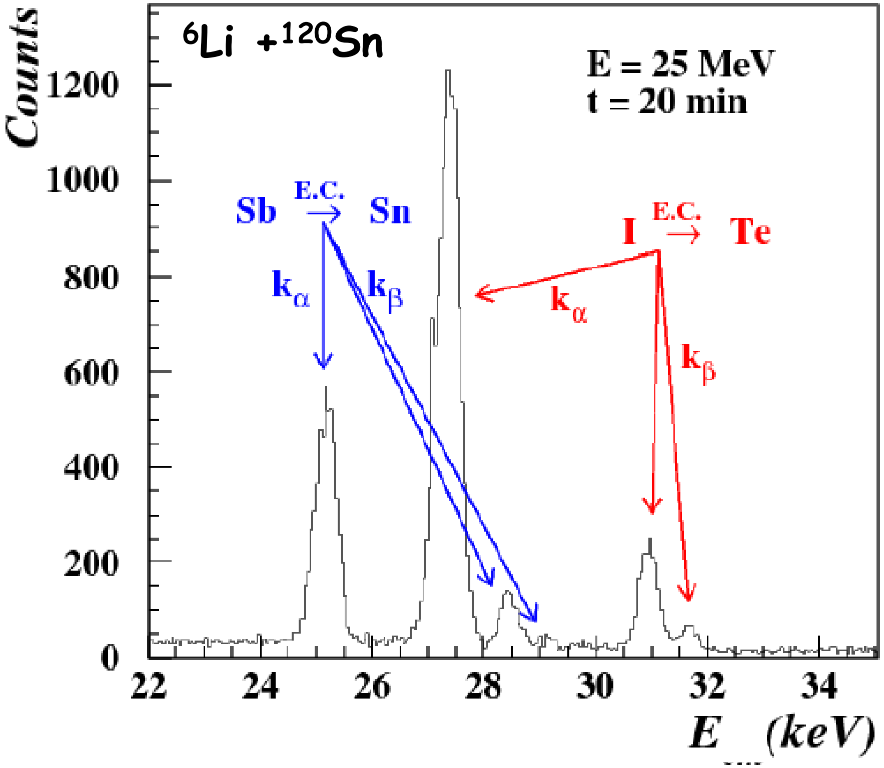


Number of produced radioactive nuclei as a function of the irradiation and decay time.

“OFF-LINE” measurement of characteristic X-rays



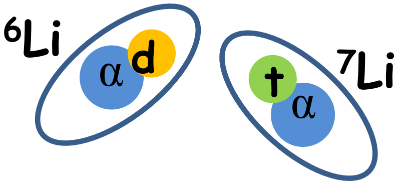




Complete fusion:

$^{6}\text{Li} + {}^{120}\text{Sn} \rightarrow {}^{126}\text{I}^{*}$

$^{7}\text{Li} + {}^{119}\text{Sn} \rightarrow {}^{126}\text{I}^{*}$



Incomplete fusion:

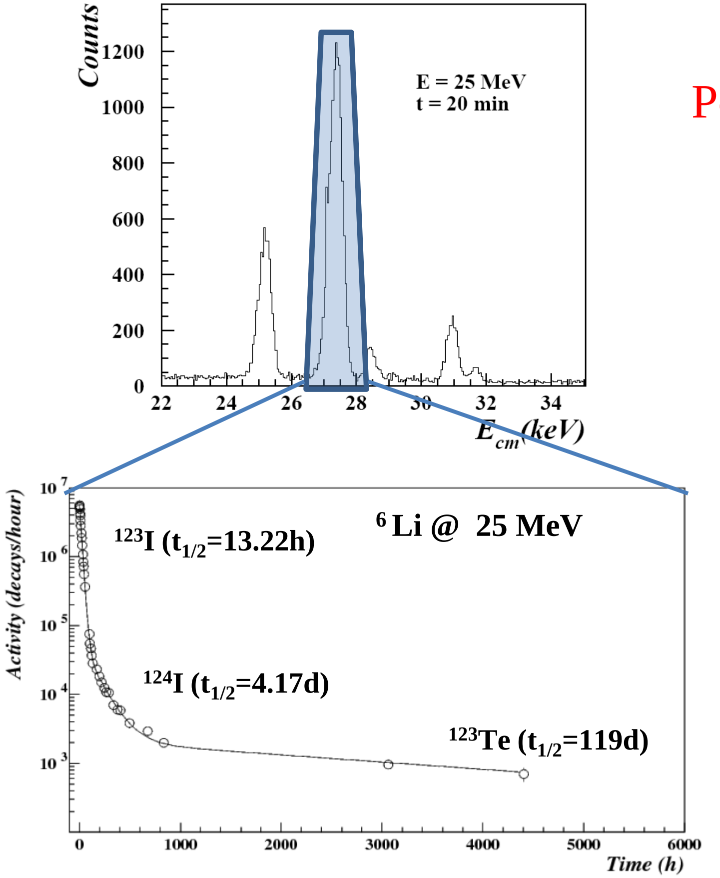
$d + {}^{120}\text{Sn} \rightarrow {}^{122}\text{Sb}^{*}$

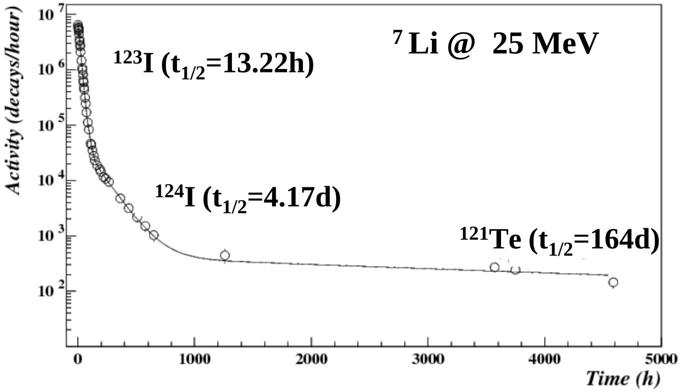
$t + {}^{119}\text{Sn} \rightarrow {}^{122}\text{Sb}^{*}$

From X-ray analysis is possible to identify in charge the evaporation residues.

Activity curve

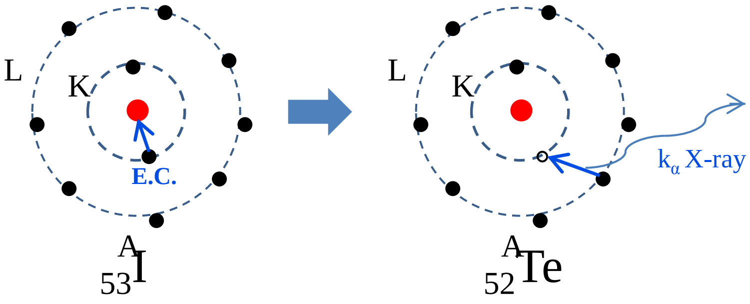
Possibility to discriminate in charge the different residues





$^{6}\mathrm{Li} + {}^{120}\mathrm{Sn} \rightarrow {}^{126}\mathrm{I}^* \xrightarrow{3n} {}^{123}\mathrm{I}$

$^{7}\mathrm{Li} + {}^{119}\mathrm{Sn} \rightarrow {}^{126}\mathrm{I}^* \xrightarrow{2n} {}^{124}\mathrm{I}$



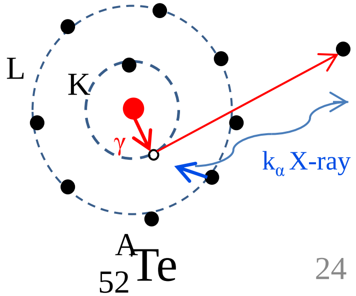
Incomplete fusion:

$\alpha + {}^{120}\mathrm{Sn} \rightarrow {}^{124}\mathrm{Te}^* \rightarrow {}^{123m}\mathrm{Te} + n$

$\alpha + {}^{119}\mathrm{Sn} \rightarrow {}^{123}\mathrm{Te}^* \rightarrow {}^{122}\mathrm{Te}$ (stable) + n

${}^{121m}\mathrm{Te} + 2n$

internal conversion

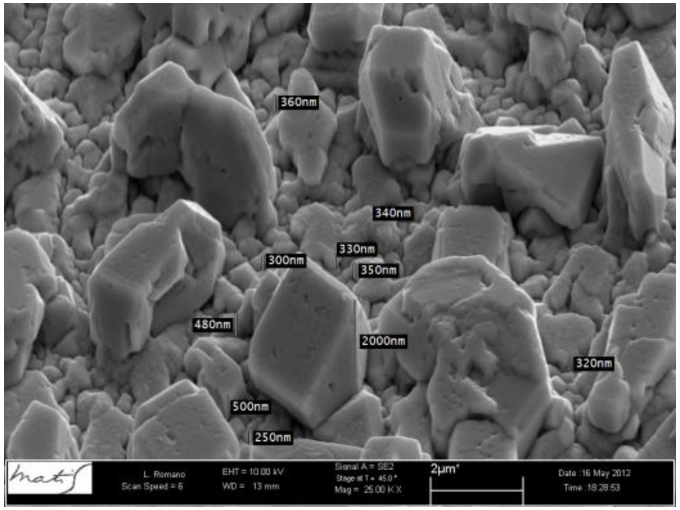


From the fit it is possible to extract $A_{0exp} \rightarrow N_o\lambda$

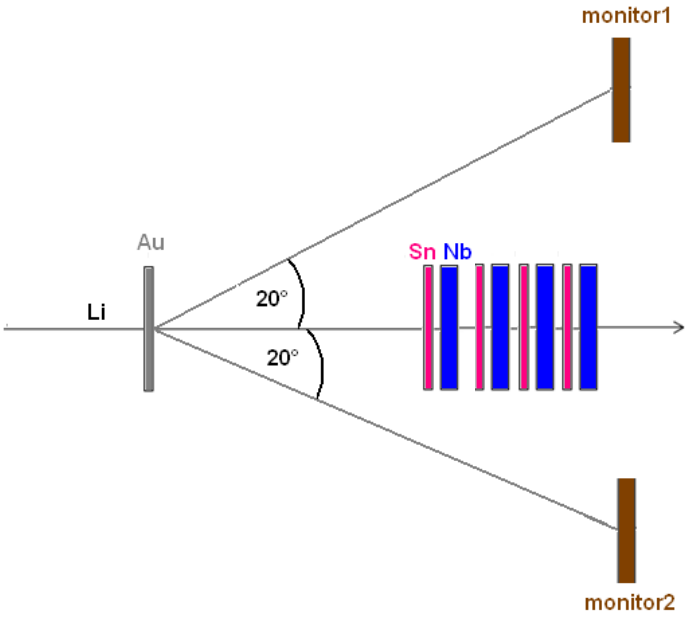
To overcome the problem of low beam intensity, large beam energy spread, thick targets and/or target stacks generally used.

What is the effect on low energy cross-section?
What about target non-uniformity?

Are the targets uniform?
SEM view of a Sn evaporated target on Nb

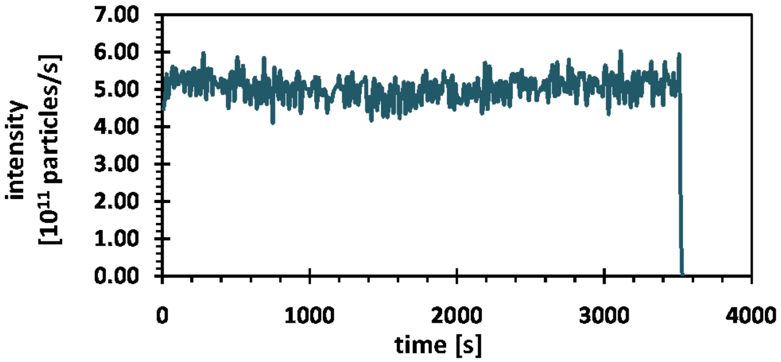


Activation technique with a stack of targets



With a stack it is possible to mesure an energy range with a single beam energy

- ✓ one needs to monitor the beam intensity as a function of time



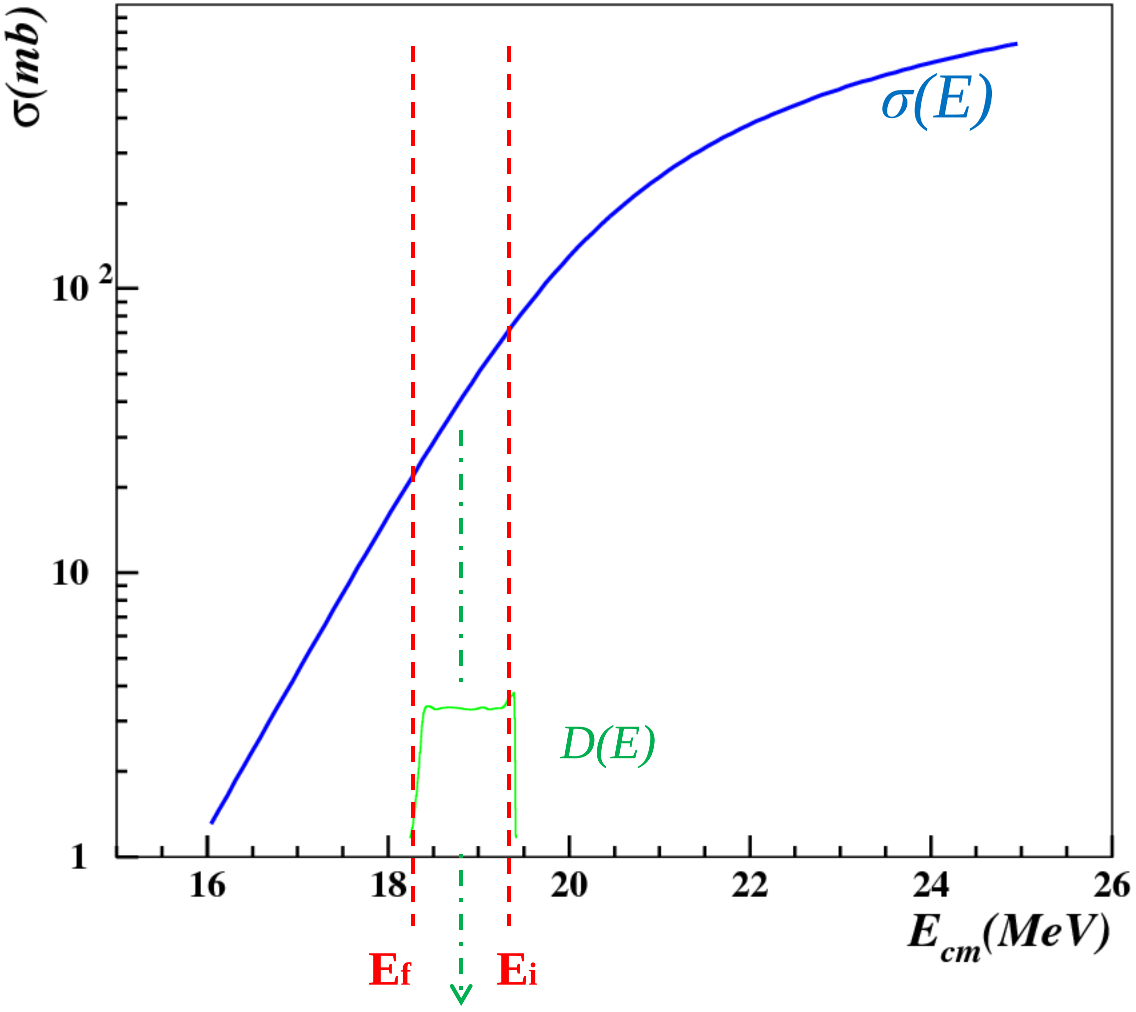
- ✓ ^{93}Nb catcher to stop ER emerging from the target

One uses activation technique when ER are too slow to be detected directly

➡ If ER are radioactive they can be identified by measuring the decay products

Activation technique with a single foil

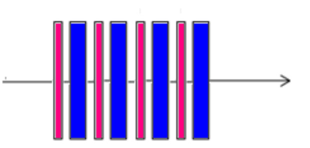
How to define the effective energy where to plot the measured cross-section



[E_i,E_f] from E_{loss} calculations.

$E = (E_i + E_f)/2$

Drawbacks of the the activation technique



For low-intensity beams
target stack used → integrated σ measured

To which effective energy E_{eff} do we have to associate the measured σ ?

a) Easy solution:

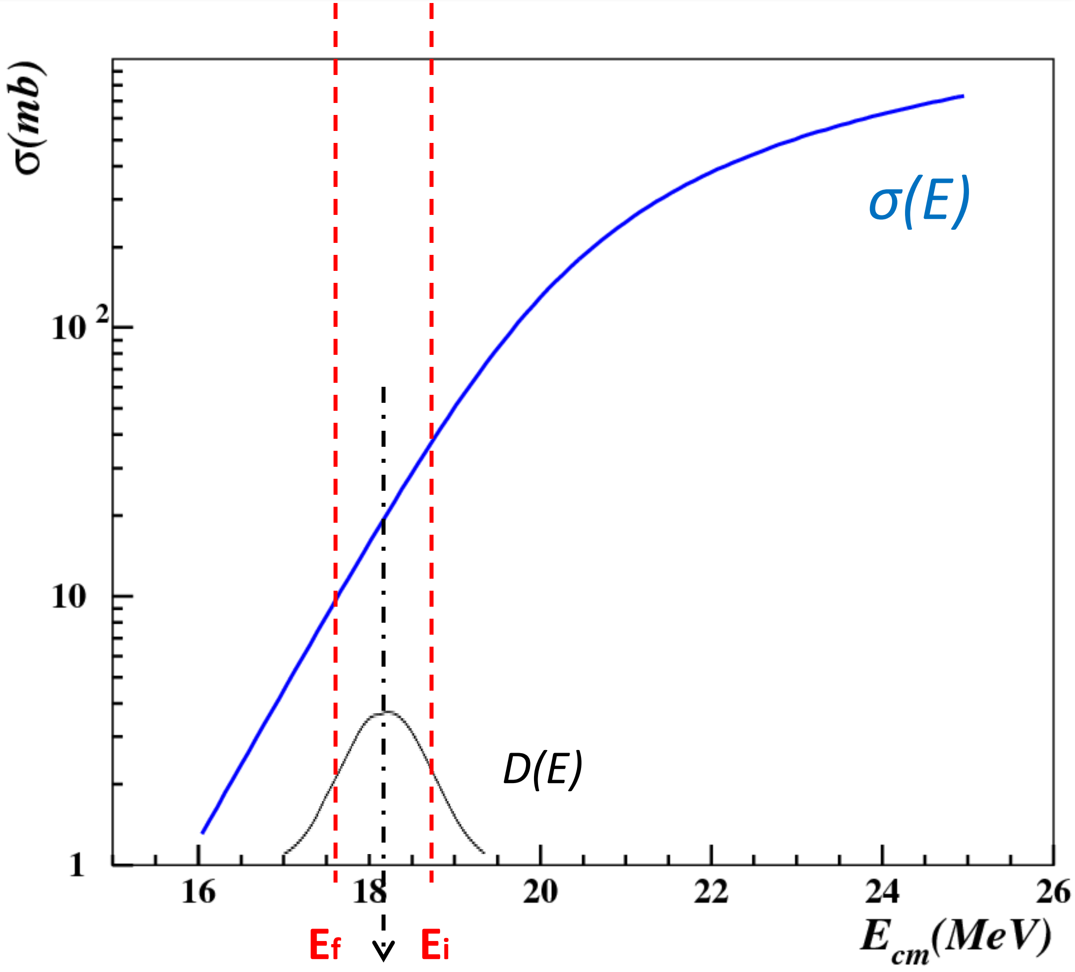
$E_{eff}=(E_i+E_f)/2$

b) A more complete formula:

$$E_{eff} = \frac{\int_{E_i}^{E_f} E \cdot \sigma(E) \cdot D(E) dE}{\int_{E_i}^{E_f} \sigma(E) \cdot D(E) dE}$$

(See e.g. R.Wolski et al.: EPJA 47,111(2011) for similar approach)

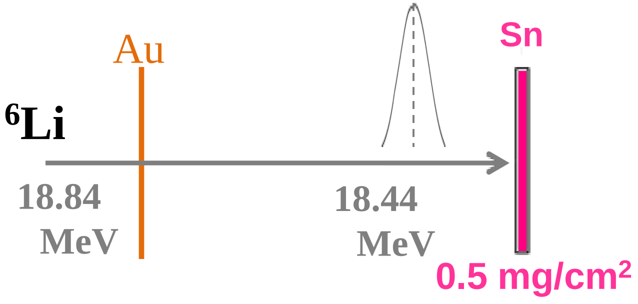
But things can be even more complicate because…

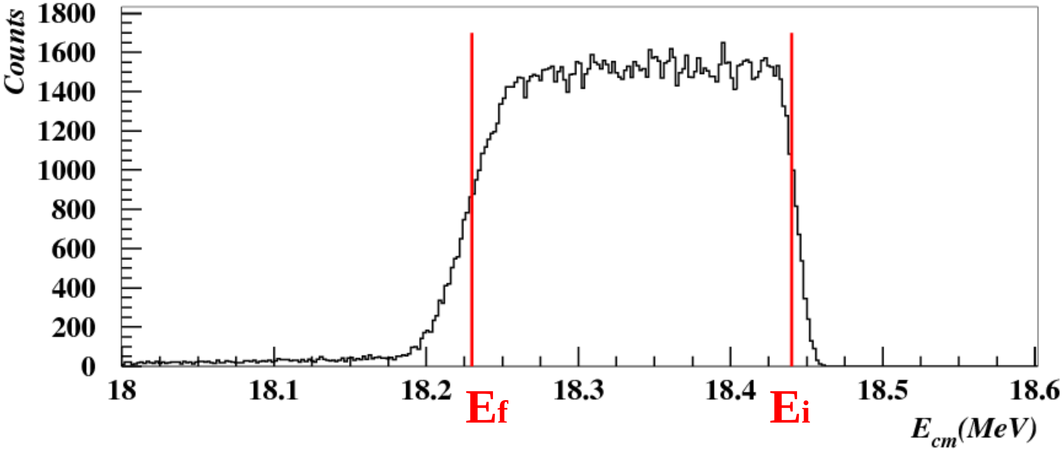


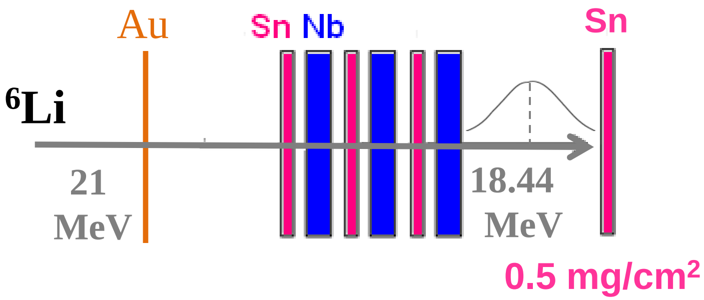
$E = (E_i + E_f)/2$

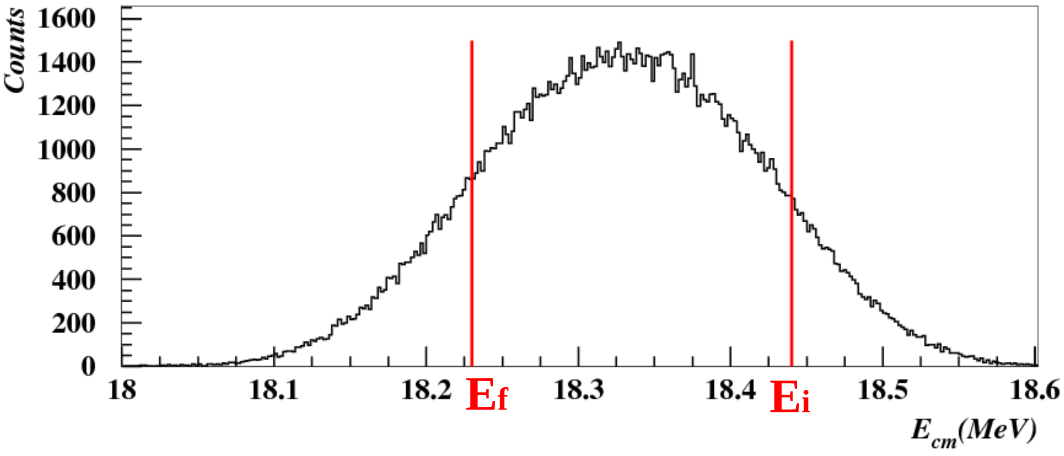
Straggling effect on energy distribution in the target

Beam energy distribution inside the target





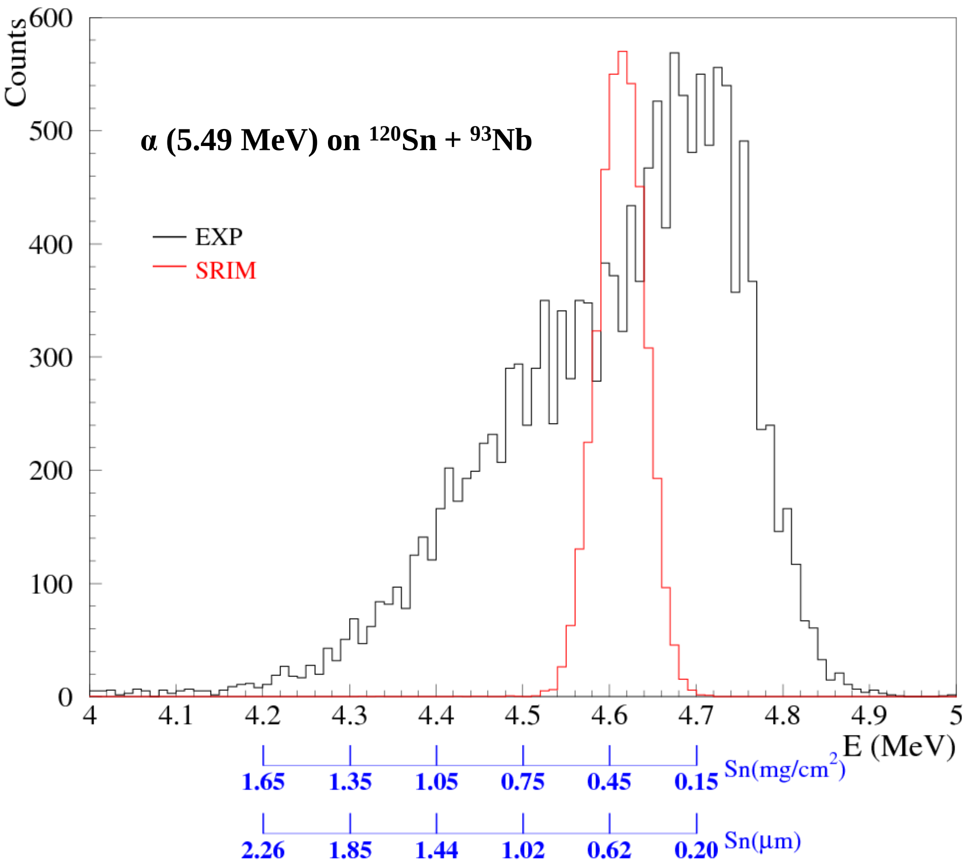




In the case of a stack the energy range is two times larger than in the single foil case.

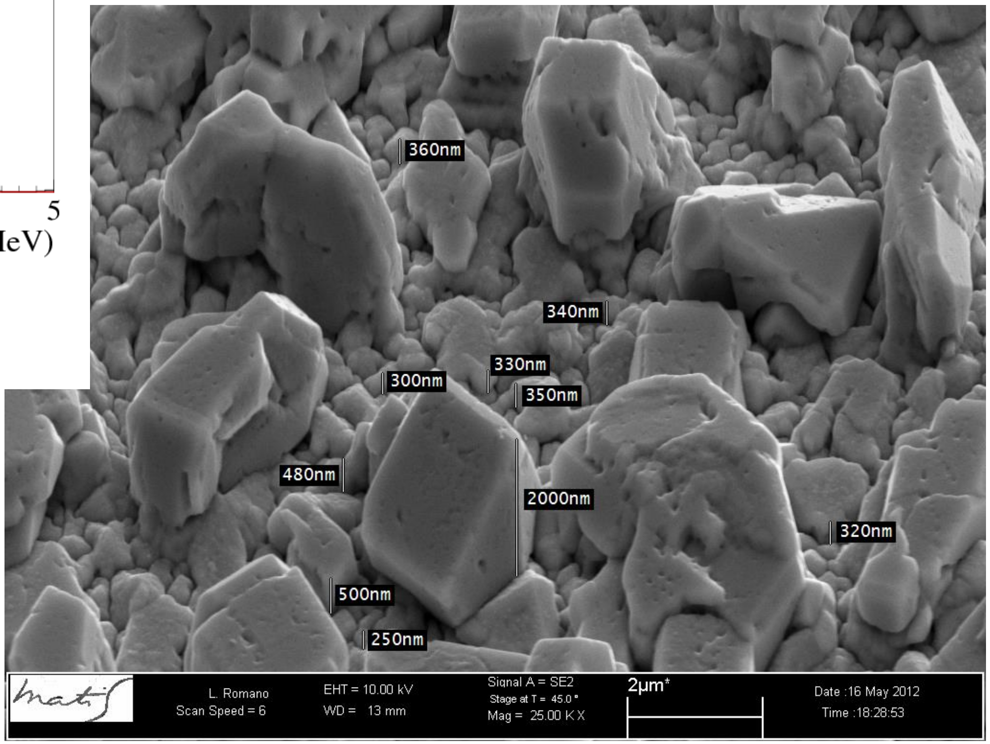
Target non-uniformity

Targets have been made by evaporating Sn on Ho o Nb

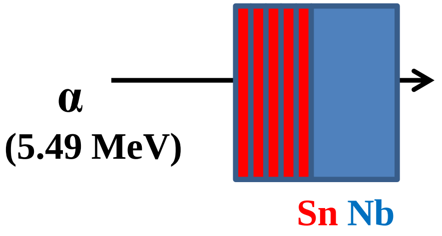


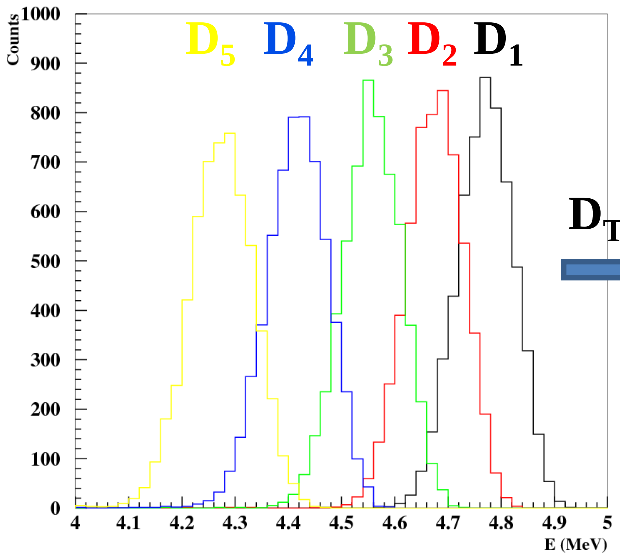
Non -uniformity Ho or Nb Δt/t ≈ 7%

SEM analysis of Sn targets



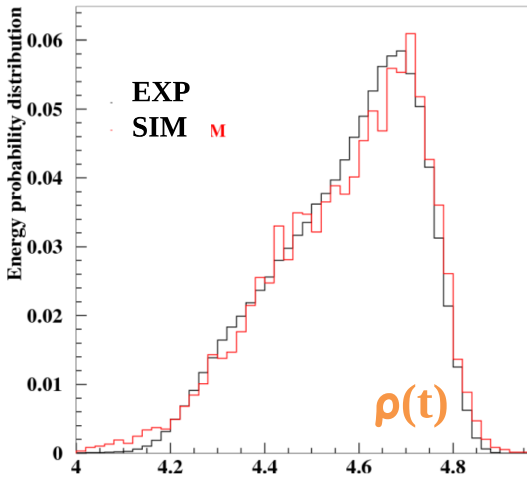
Target characterisation



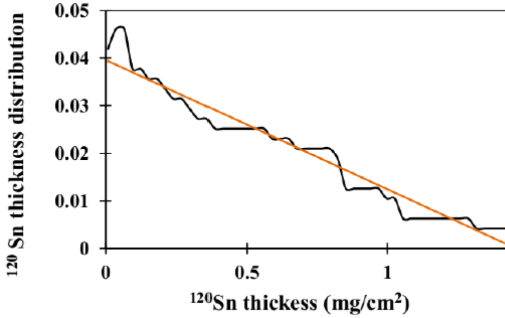


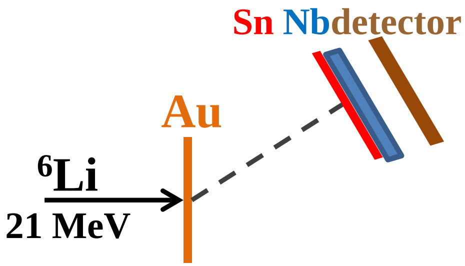
$$D_T = \sum D_i\, w_i$$

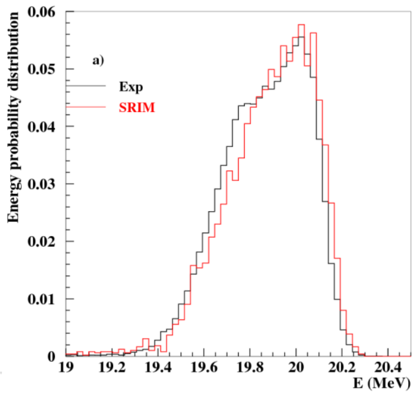
α residual energy after Sn

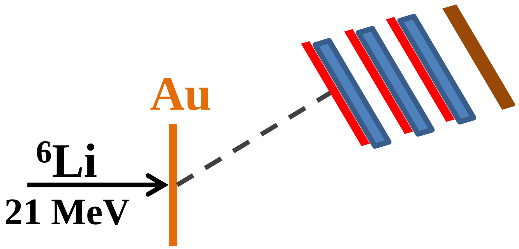


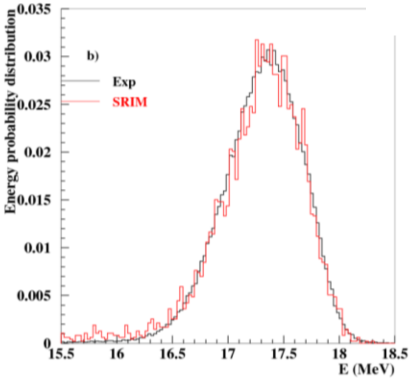
$$D_i\, w_i / D_T =$$





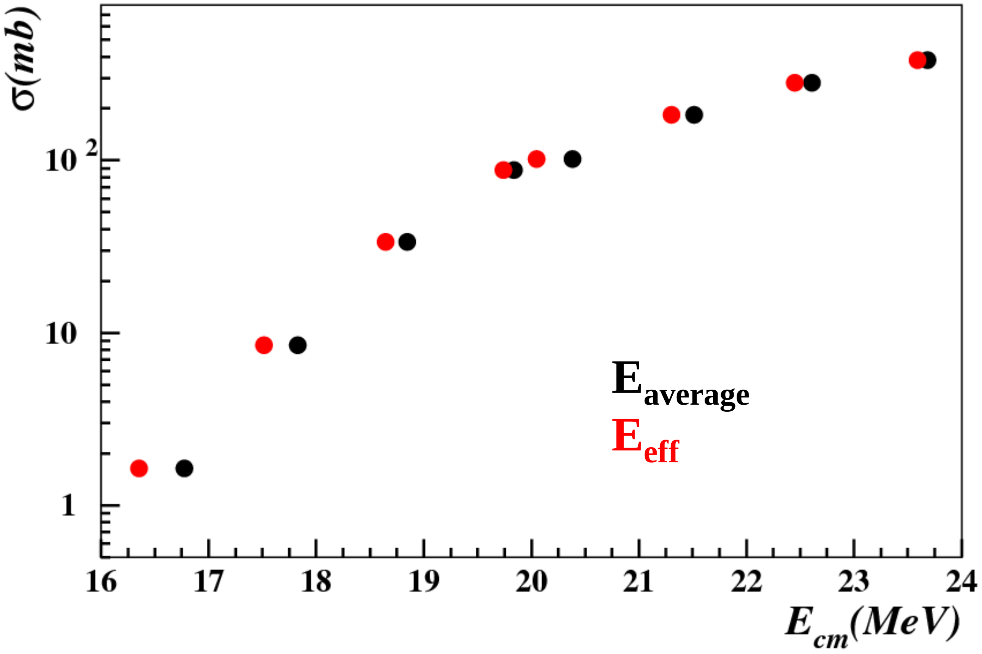






Eloss measurements with ^{241}Am α-particles allow to characterise the targets.

Effect of using a stack on the excitation function of ^{6}Li+^{120}Sn



$$\boxed{E_{eff}} = \frac{\int_{t_i}^{t_f} E(t)\cdot\sigma[E(t)]\cdot D[E(t)]\cdot\rho(t)dt}{\int_{t_i}^{t_f} \sigma[E(t)]\cdot D[E(t)]\cdot\rho(t)dt}$$

Weighted energy

✓By increasing the number of targets in the stack, increases the difference between ***average energy*** ***(E$_{average}$)*** and ***weighted average (E$_{eff}$)***.

✓ For a given number of targets in the stack the difference between ***E$_{average}$*** and ***E$_{eff}$*** increases with decreasing energy.

✓ For very thick targets even using the ***E$_{eff}$*** to plot cross-section is not correct since what is measured is not the weighted cross-section but the integrated cross-section over an energy range.

The effect of the stack is important in determining the exctation function

Summary

- With halo nuclei the σ_{rea} large and a large fraction is due to transfer and break-up processes.

- Fusion cross-section of light weakly-bound nuclei on heavy targets shows a suppression due to the competing brak-up process.

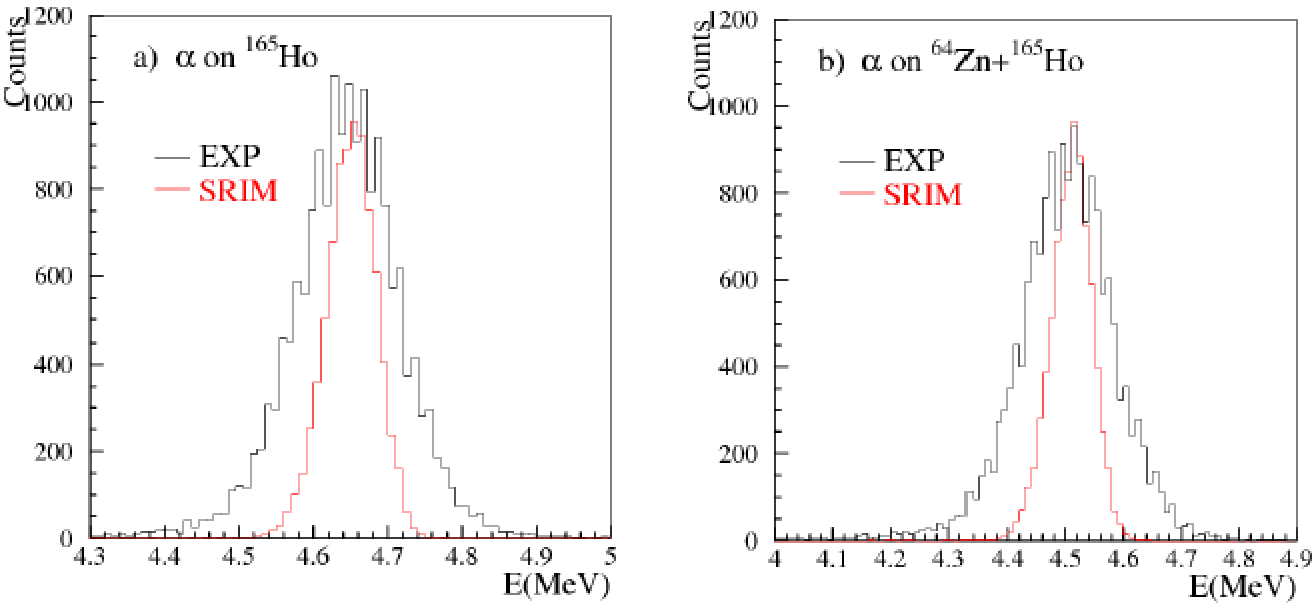
- Fusion cross-section induced by halo nuclei seem to show an enhancement due to static effects.

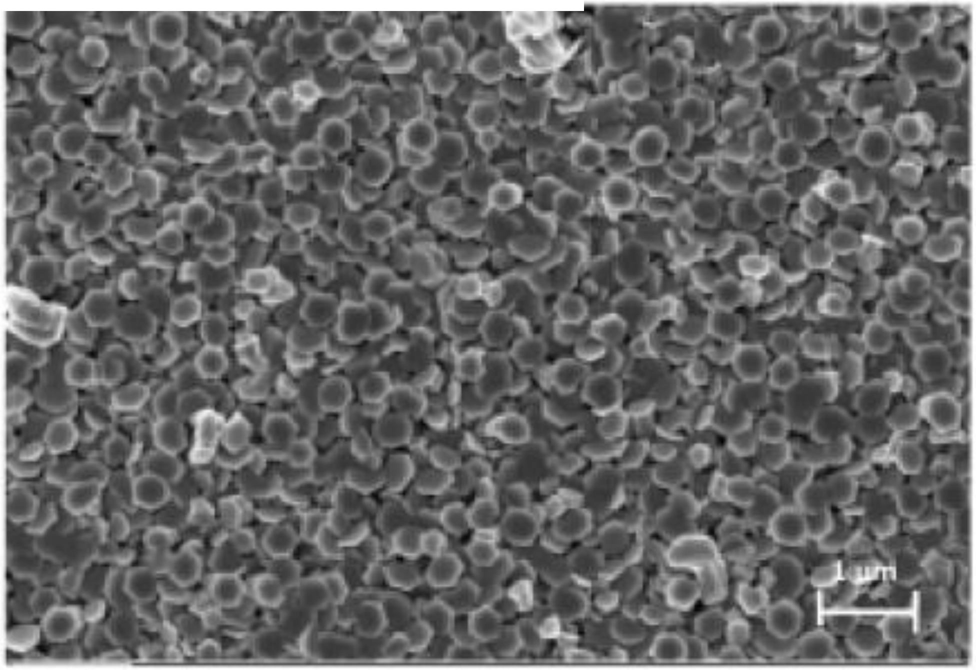
- When measuring $\sigma_{FUS}(E)$ with activation techniques and multiple thick targets, effects of straggling and target non uniformity have to be carefully considered. Related information should be reported in corresponding papers.

- New fusion data with n-halo nuclei better exploring the sub-barrier region.

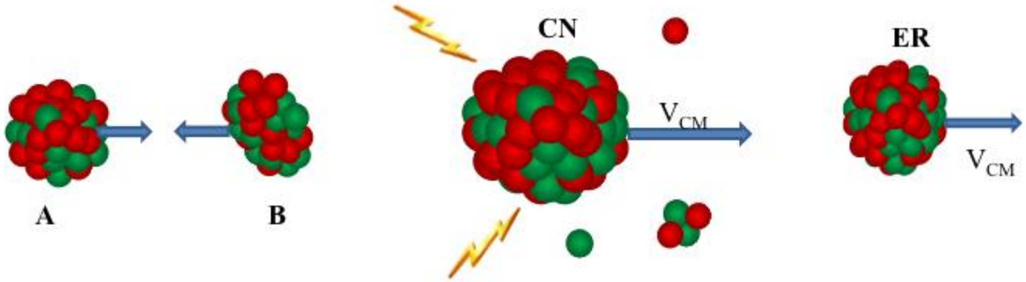
- What is the effect for p halo nuclei ? → new data needed

^{64}Zn NON-UNIFORMITY





Compound nucleus formation



$$\begin{tikzcd}
p + {}^{63}Cu \arrow[dr] & & {}^{63}Zn + n \\
& \left[{}^{64}Zn^{*}\right] \arrow[ur] \arrow[r] \arrow[dr] & {}^{62}Cu + n + p \\
\alpha + {}^{60}Ni \arrow[ur] & & {}^{62}Zn + 2n
\end{tikzcd}$$

- Each initial state can produce all three final states
- The cross section for each final state does not depend on the initial reactants.
- All reactions have the same intermediate (compound) nucleus.
- The cross section for producing each final state depends on the excitation energy in the compound nucleus.