Reazioni indotte da nuclei leggeri debolmente legati

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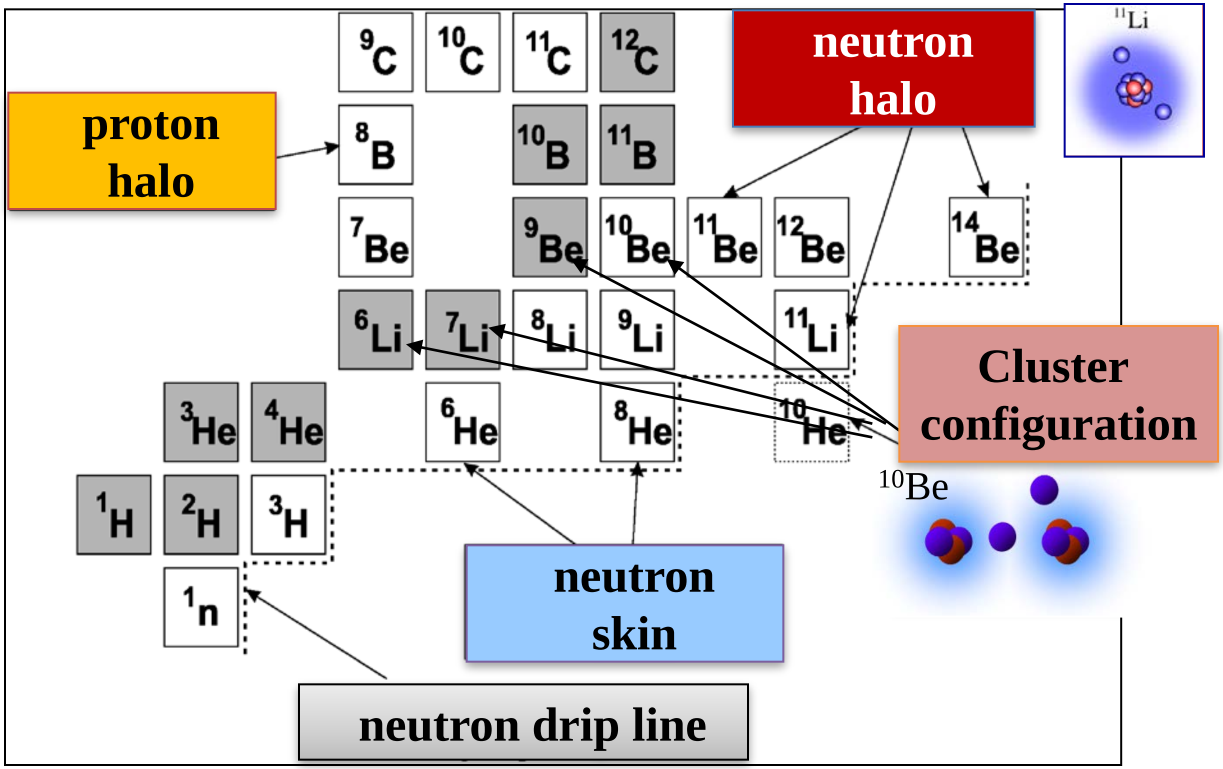
Light Nuclei



proton halo

neutron halo

Cluster configuration

neutron skin

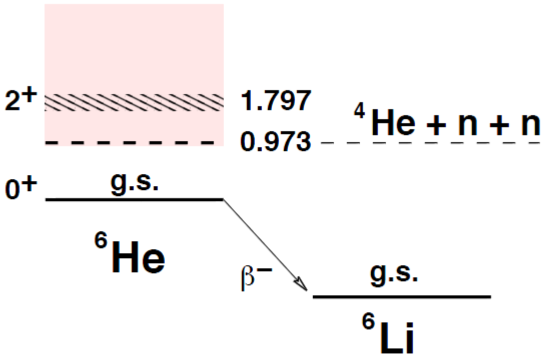
neutron drip line

Quantum mechanics plays a role in creating peculiar structures in ground states of light nuclei namely: nuclear clusters, nuclear skins and/or nuclear halos.

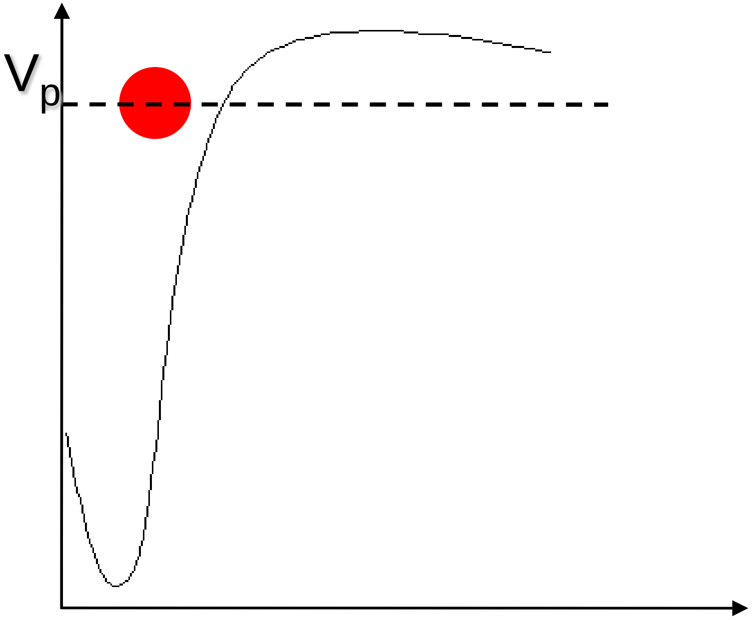
We have investigated the effects of such structures in different reaction mechanisms:

- **Elastic scattering**
- **Direct reactions**
- **Fusion**

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)



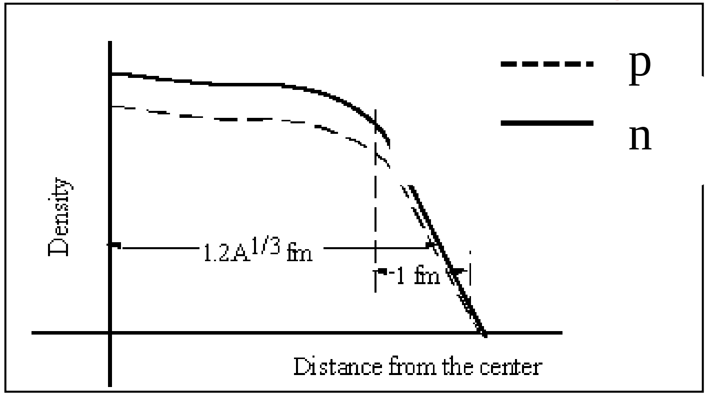
- Nuclear halo appears when the weakly bounds valence nucleon(s) are in s or p states, close to the particles emission threshold.

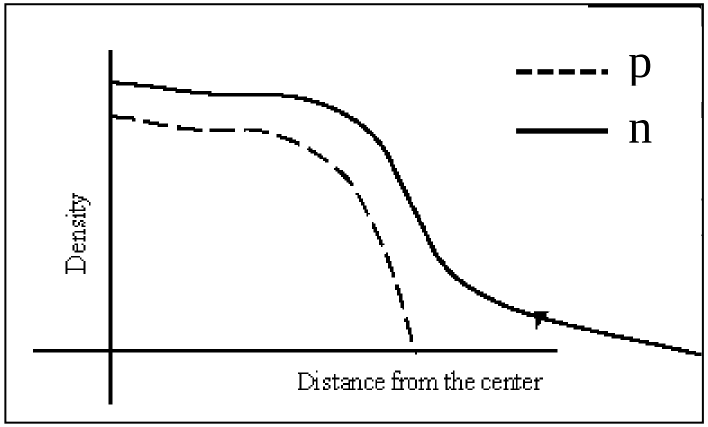
- Due to the low binding energy for these nucleon(s) tunnelling is possible. Heisemberg principles allows the valence nucleon(s) to spend a time interval $\Delta t \leq \hbar/2\Delta E$ outside the nuclear core.

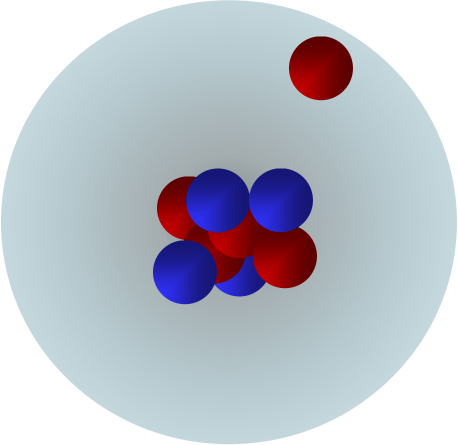
Properties of neutron halo nuclei

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

Neutron Distribution Density







Some examples:

$^{6}\mathrm{He} \equiv {}^{4}\mathrm{He} + n + n$
$^{11}\mathrm{Li} \equiv {}^{9}\mathrm{Li} + n + n$
$^{11}\mathrm{Be} \equiv {}^{10}\mathrm{Be} + n$

Collisions induced by light weakly bound or halo nuclei

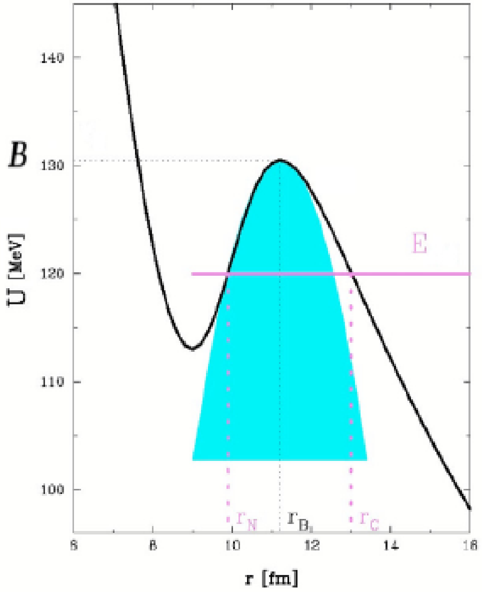
Characteristics of the projectiles:

Low break-up thresholds, diffuse tails
Continuum lies close to ground state → coupling to continuum expected to be important in all channels (elastic scattering and reactions)
⇓

- Direct mechanisms (e.g. break-up, transfer) could be favored
- What do we expect for fusion reactions ?

a)Static effects:
diffuse tail affects the shape of potential

b) Dynamic effects:
Coupling not only to resonant states but also to continuum



For such type of studies, light stable weakly bound beam as well as radioactive beams are used.

Elastic scattering and direct processes

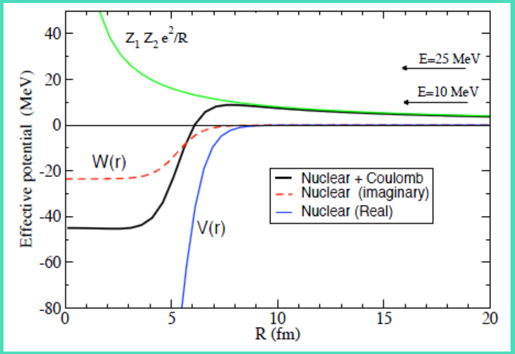
Some ‘tools’ for data interpretation

Optical model

Elastic scattering A.D. can be reproduced using O.M. with potentials: U(r)= Vc(R)+V(r)+iW(r)

Hamiltonian: H = T(r)+ U(r)

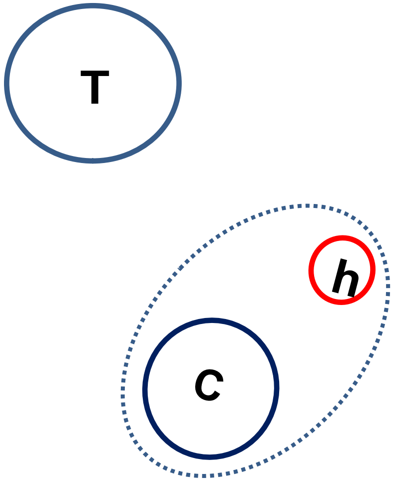
The inclusion of a DPP ΔV(r) potential to simulate coupling effects.

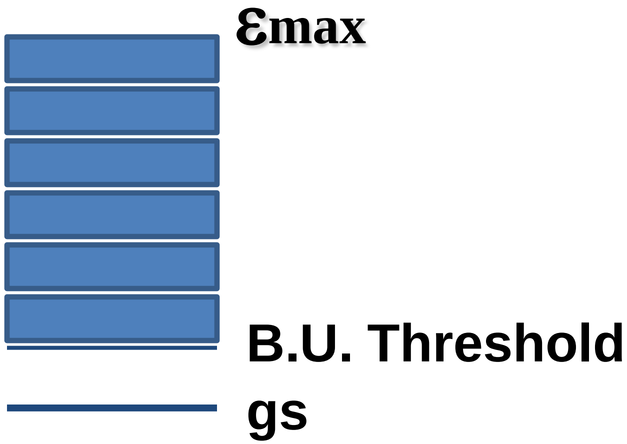


CDCC

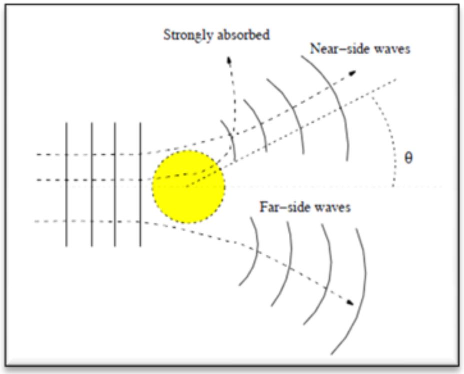
Hamiltonian: H= h+T(r)+U(r) h= intrinsic Hamiltonian

Coupling to continuum treated discretizing it into a finite number of bins from the BU threshold to a certain ε_{max}.





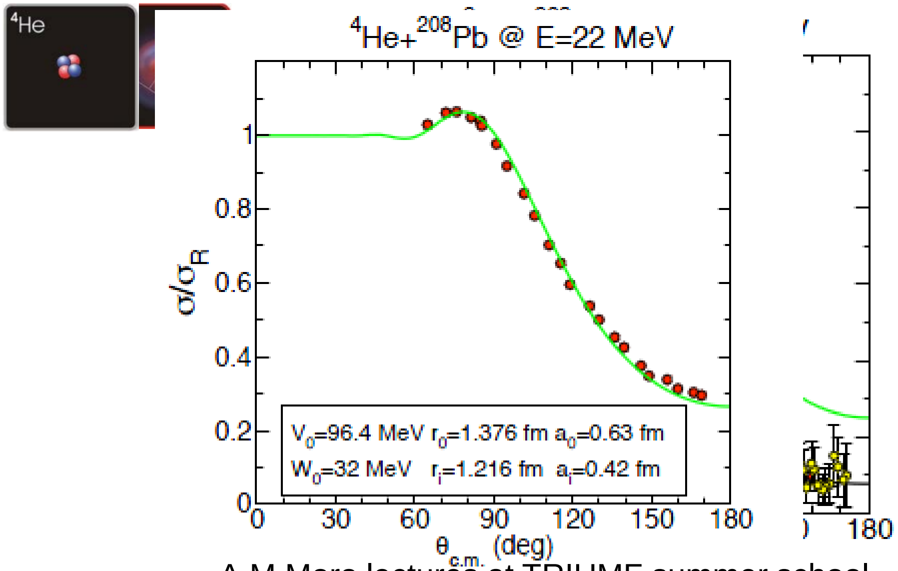
Elastic scattering: Normal versus halo nuclei



How does the halo structure affect the elastic scattering?

Low energy and heavy targets

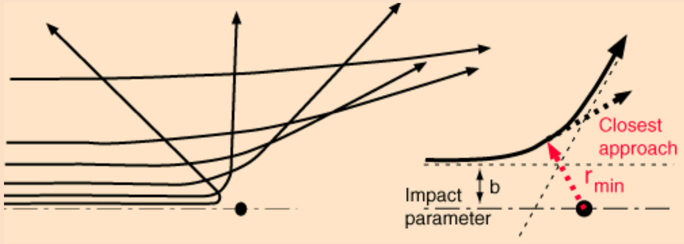
- Coulomb strong ($\eta >> 1$)
- ’Illuminated’ region → interference pattern.
- ’Shadow’ region → strong absorption.



A.M.Moro lectures at TRIUMF summer school

Scattering angle $\theta_{c.m.}$ related to distance of closest approach.

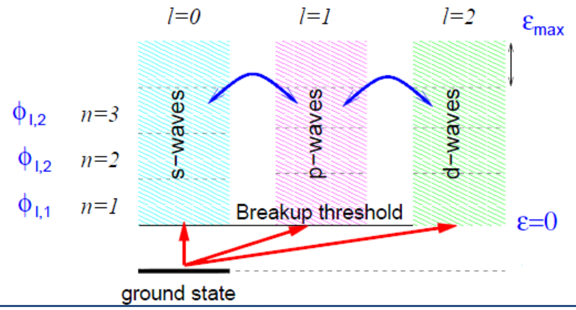
$$d(\theta) = \frac{2b}{\cot\left(\frac{\theta}{2}\right)}$$

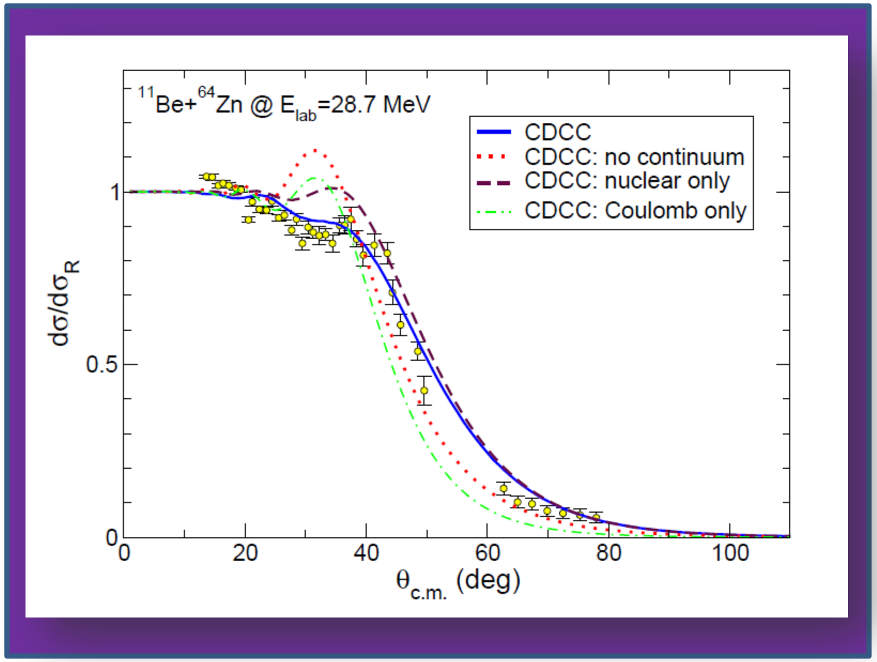


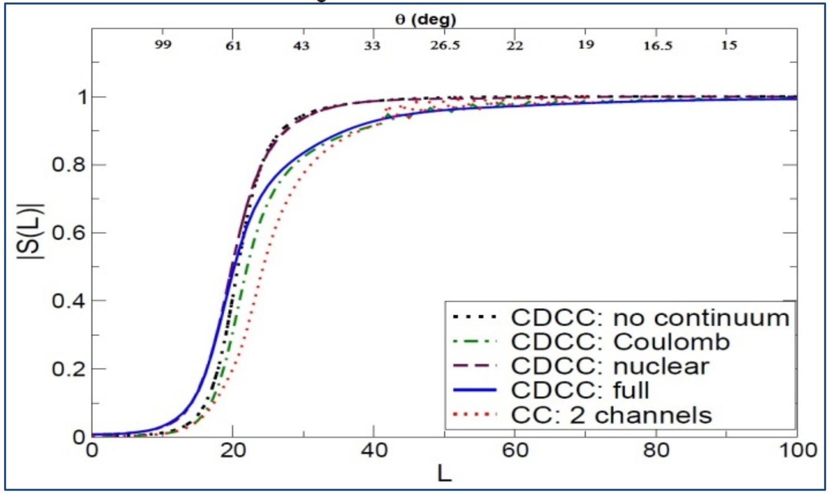
- ^{6}He+^{208}Pb requires a large imaginary diffuseness ! *long-range absorption*

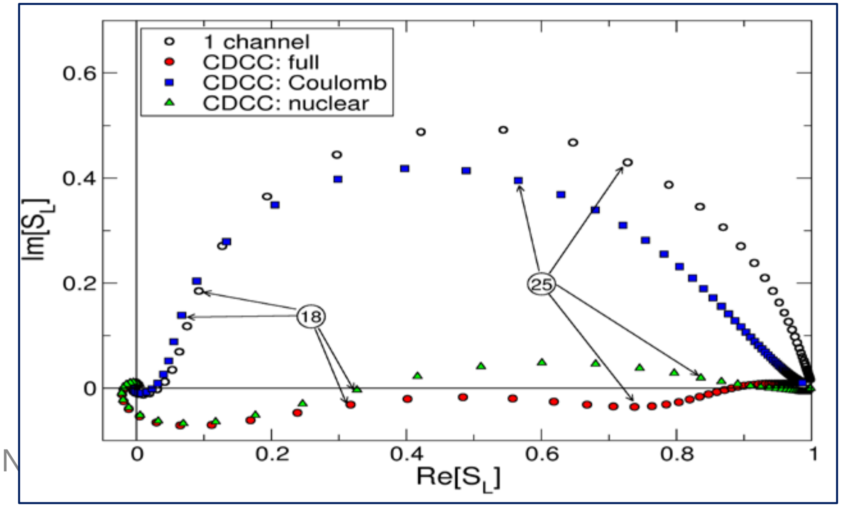
Elastic scattering angular distribution ^{11}Be+^{64}Zn @ 29 MeV

At low bombarding energy coupling between relative motion and intrinsic excitations important.
Halo nuclei → small binding energy, low break-up thresholds → coupling to break-up states (continuum) important → CDCC.



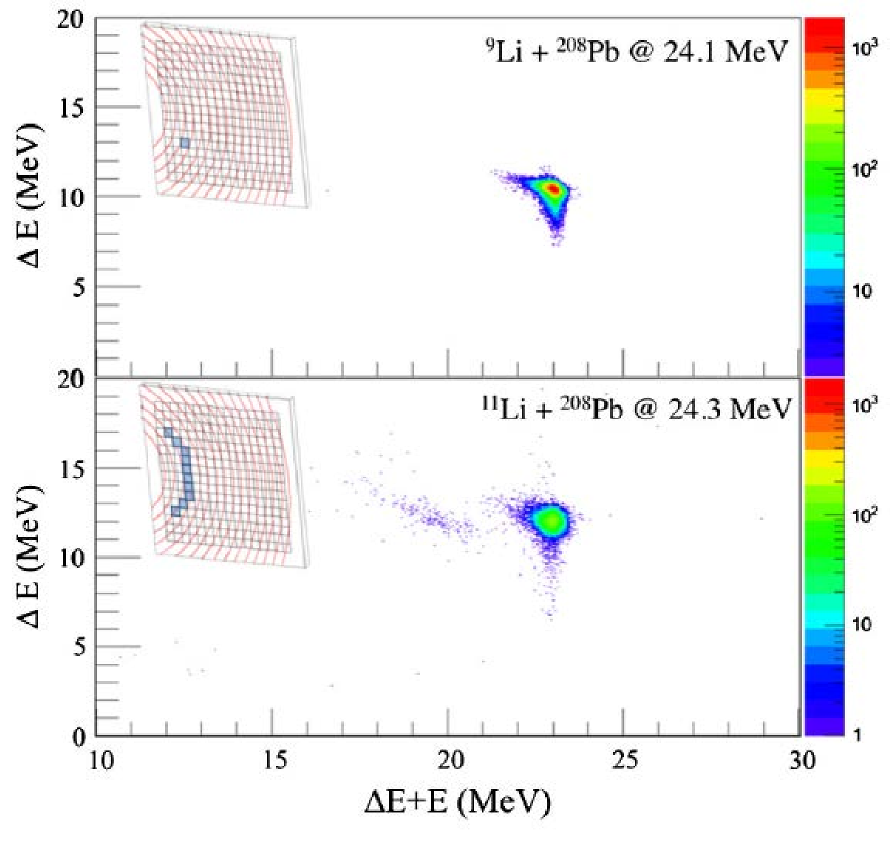


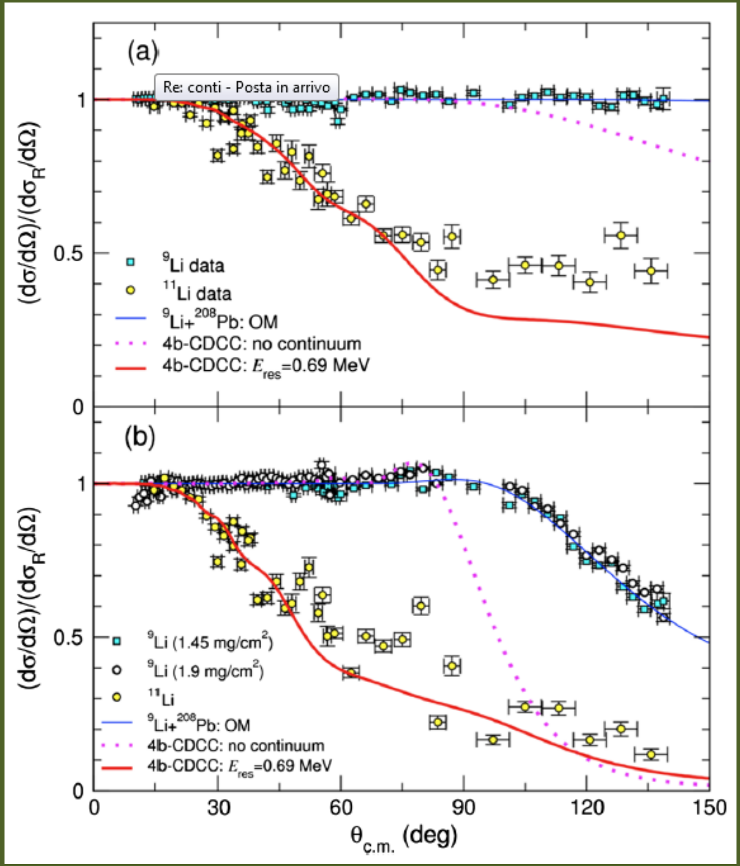




A. Di Pietro et al. Phys. Rev. Lett. 105,022701(2010)
A. Di Pietro, V. Scuderi, A.M. Moro et al.
Phys. Rev. C 85, 054607 (2012)

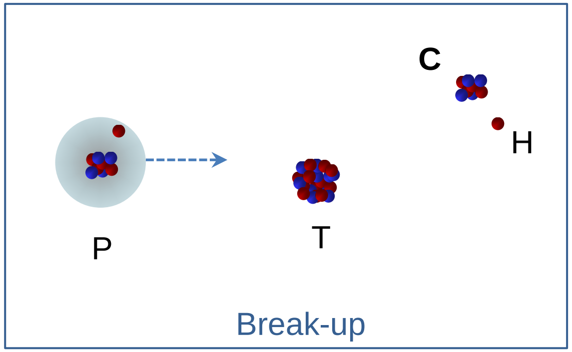
^{9,11}Li+^{208}Pb @ TRIUMF
Elastic scattering angular distribution

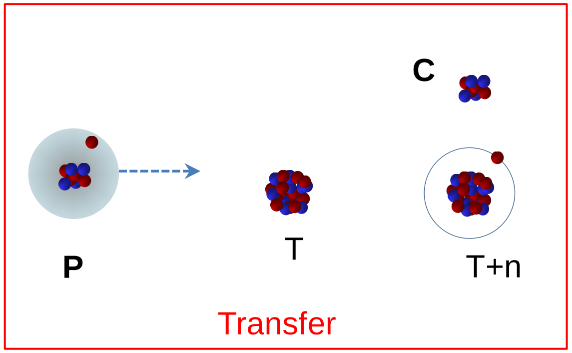




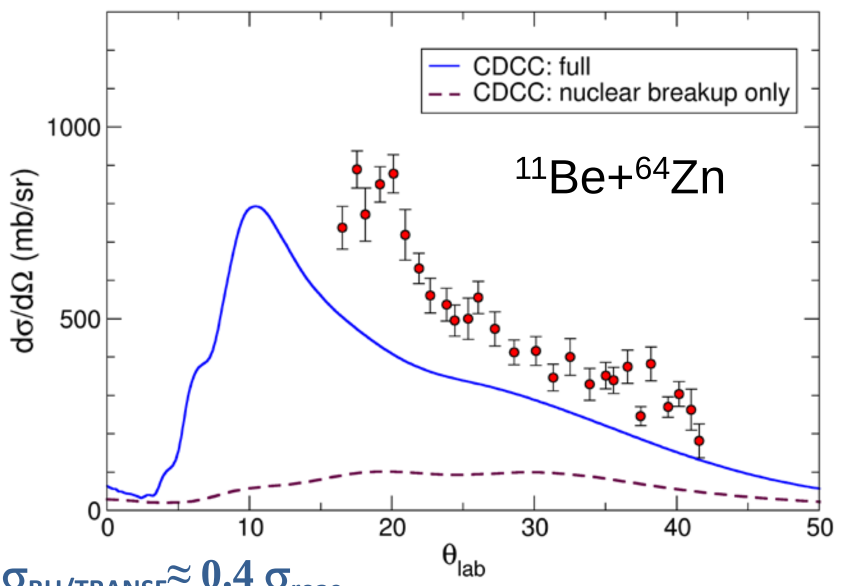
M.Cubero et al.,PRL 109, 262701 (2012)

Where is the missing elastic cross-section going?



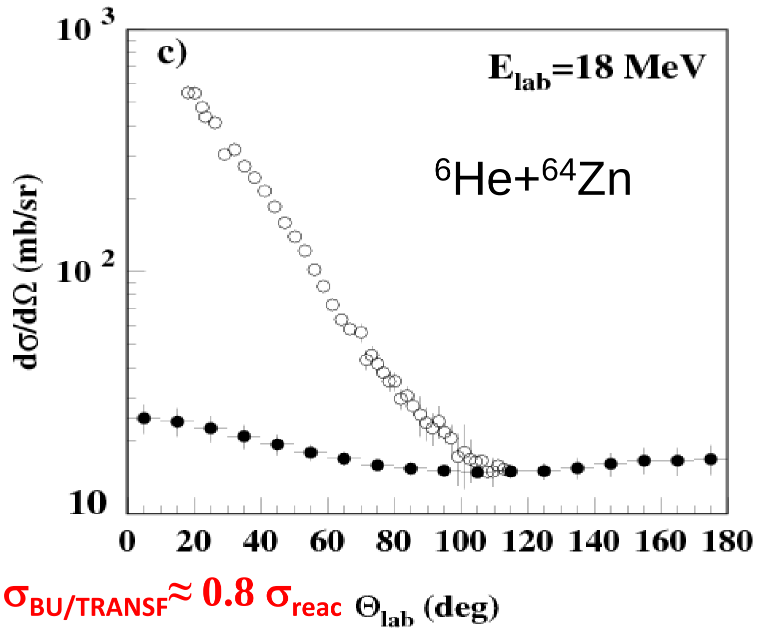


^{10}Be angular distribution



$\sigma_{BU/TRANSF} \approx 0.4\ \sigma_{reac}$

^{4}He angular distribution

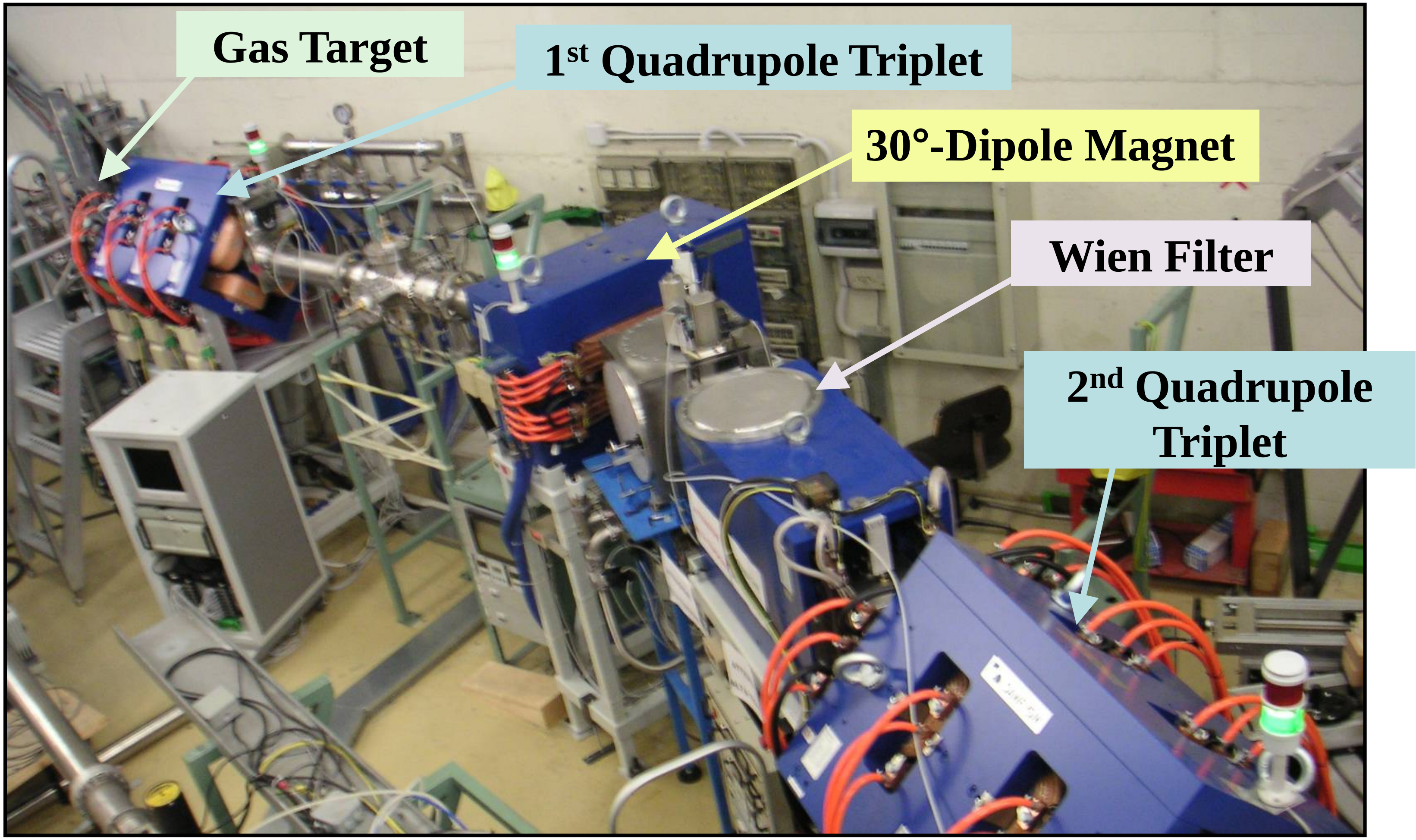


$\sigma_{BU/TRANSF} \approx 0.8\ \sigma_{reac}$

A. Di Pietro, V. Scuderi, A.M. Moro et al.
Phys. Rev. C 85, 054607 (2012)

V.Scuderi et al.
PRC 84, 064604(2011)

The EXOTIC Facility at LNL



The Project EXOTIC @LNL

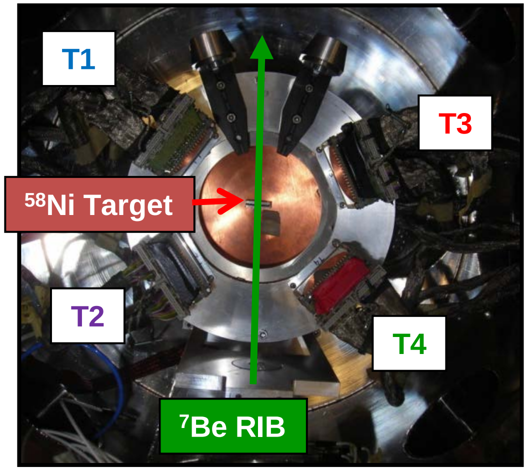
The production mechanism employs **inverse kinematics reactions** with heavy projectiles impinging on **gas targets** (**p**,**d**,**^{3}He**).

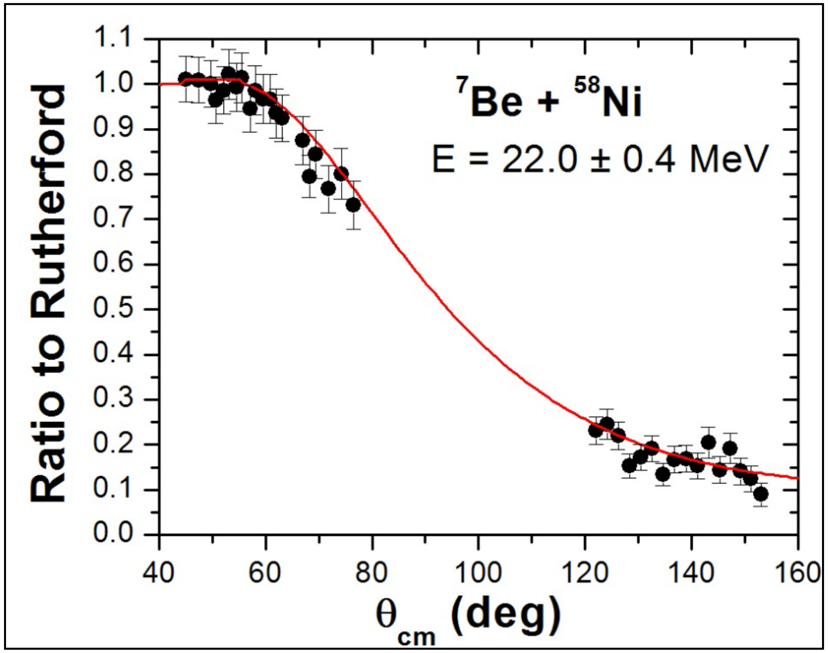
The **commissioning** of the facility was performed in 2004 (F. Farinon et al., NIM B 266, 4097 (2008))

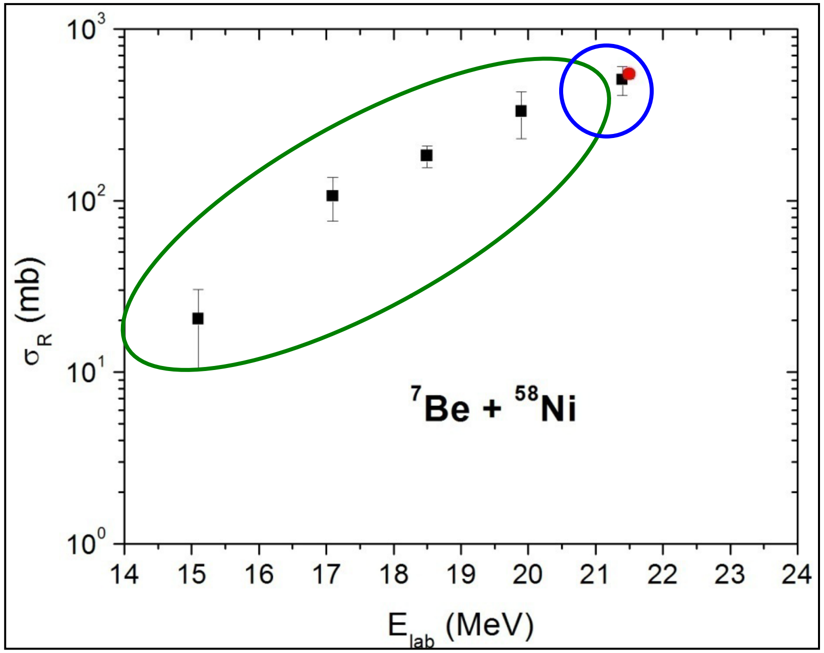
So far have been produced **5** different **RIBs**:

- **^{17}F** E = 3–5 MeV/u Purity: **93-96 %** Intensity: **10^{5} pps**
- **^{8}B** E = 3–5 MeV/u Purity: **30-43 %** Intensity: **10^{3} pps**
- **^{7}Be** E = 2.5–6 MeV/u Purity: **99 %** Intensity: **$3*10^{5}$ pps**
- **^{15}O** E = 1.3 MeV/u Purity: **97-98 %** Intensity: **$4*10^{4}$ pps**
- **^{8}Li** E = 2–2.5 MeV/u Purity: **99 %** Intensity: **$2*10^{5}$ pps**

^{7}Be + ^{58}Ni Reaction Cross Sections @ EXOTIC







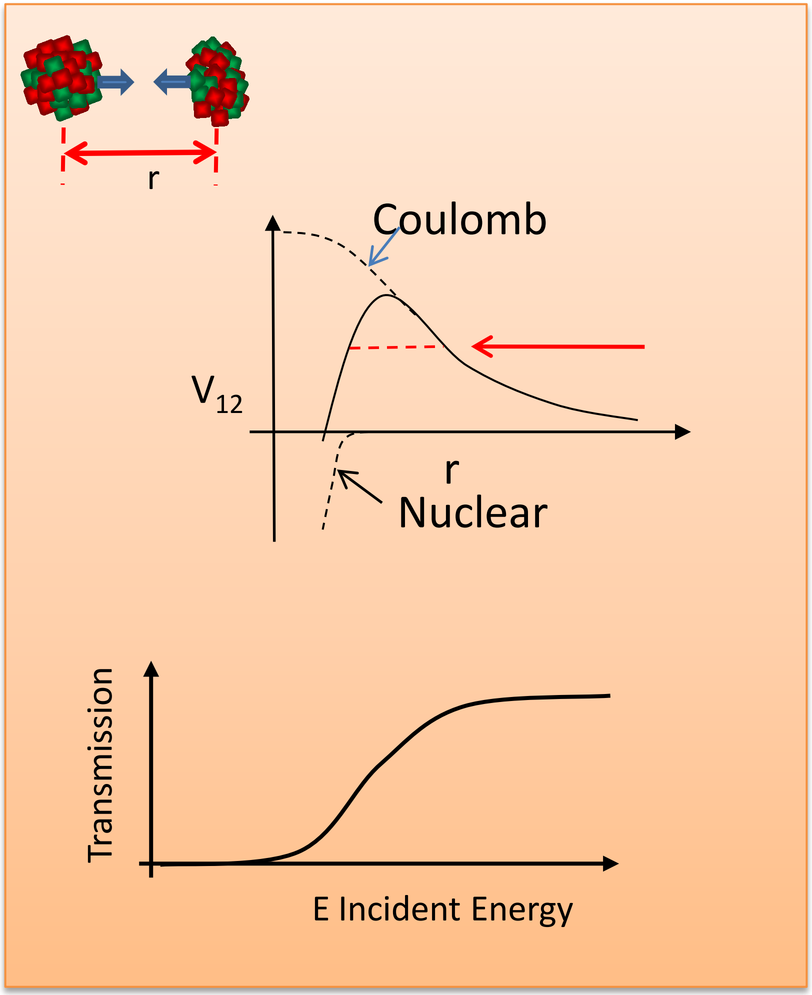
Quasi-elastic scattering differential cross section compared with **CDCC** calculations.

The **total reaction cross section** (546 mb) is in **fairly good agreement** with the trend individuated by the data at lower energies.

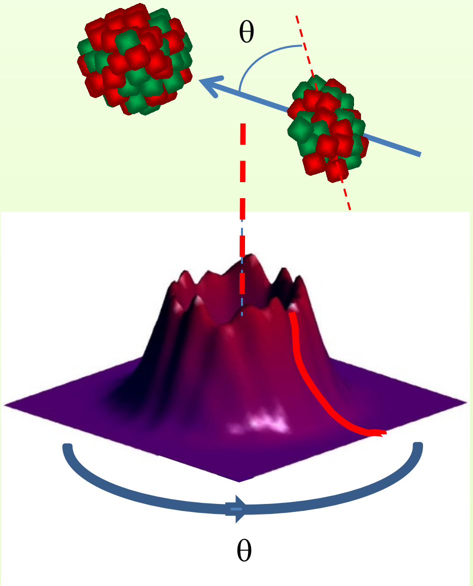
E.F. Aguilera et al., PRC 79, 021601 (2009)

Fusion with halo nuclei: enhancement or suppression?

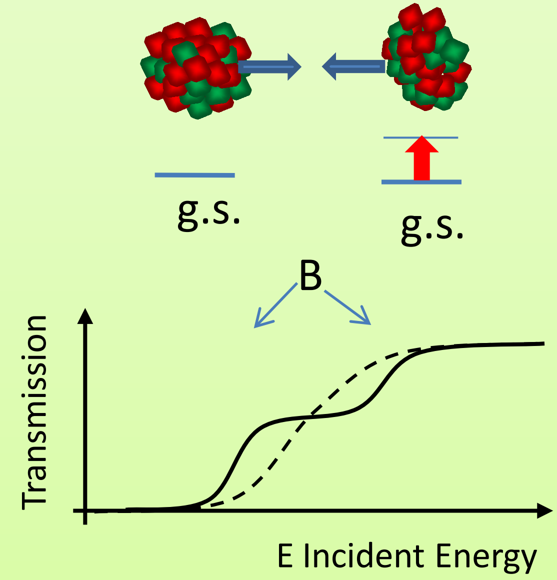
Fusion: low energy RIBs - tunneling through the barrier



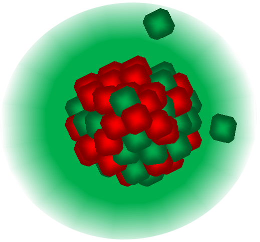
Orientation



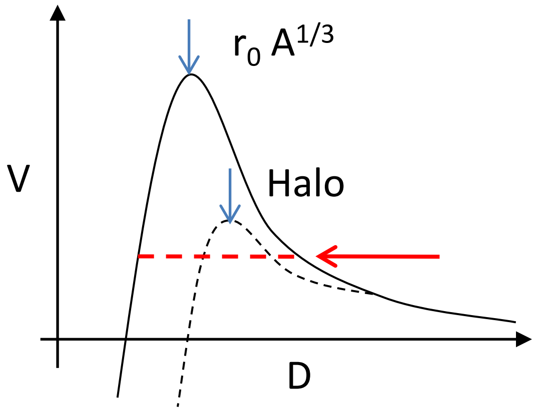
Excitation



How does halo affect fusion ?
Possibilities: Static effect

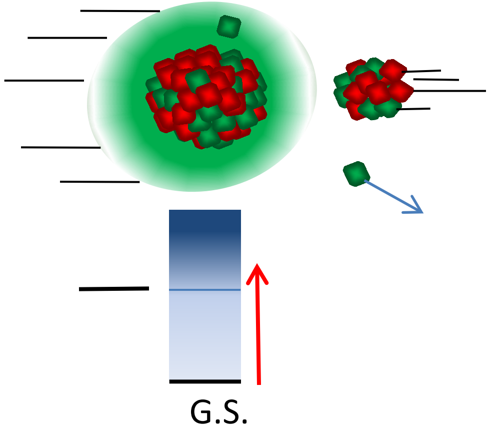


Radius ≠ $r_0 A^{1/3}$



Dynamic effect

Breakup



Effect?

Like any other coupling process

Increased sub barrier fusion

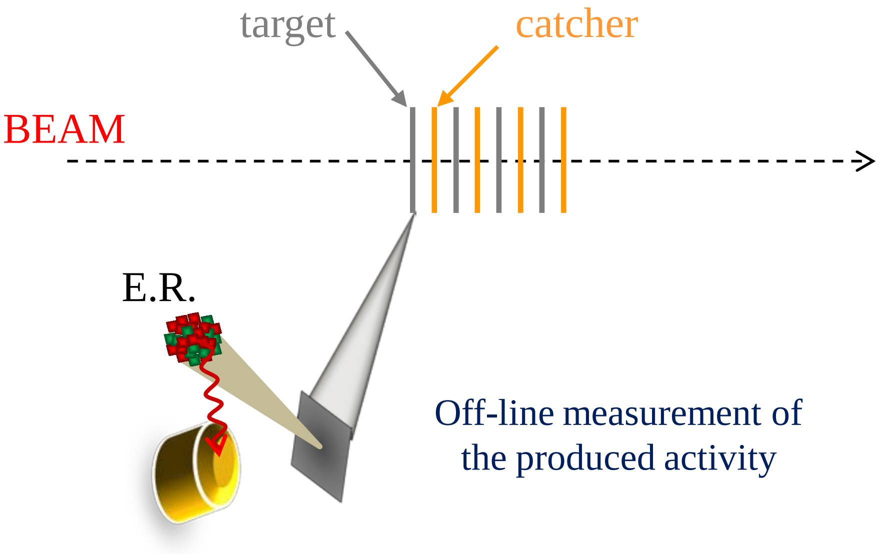
Decreases Flux

Decreased sub barrier fusion

Experimental thechniques used to measure fusion at low energies.

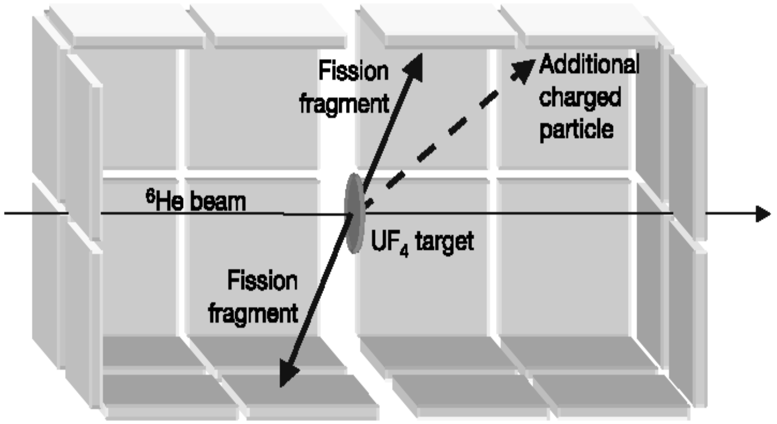
Problem: light beams on heavy targets at low Ec.m. very low kinetic energy of evaporation residues.

Activation experiments:
medium mass and heavy targets



Off-line measurement of the produced activity

Fusion-fission:
heavy fissile targets

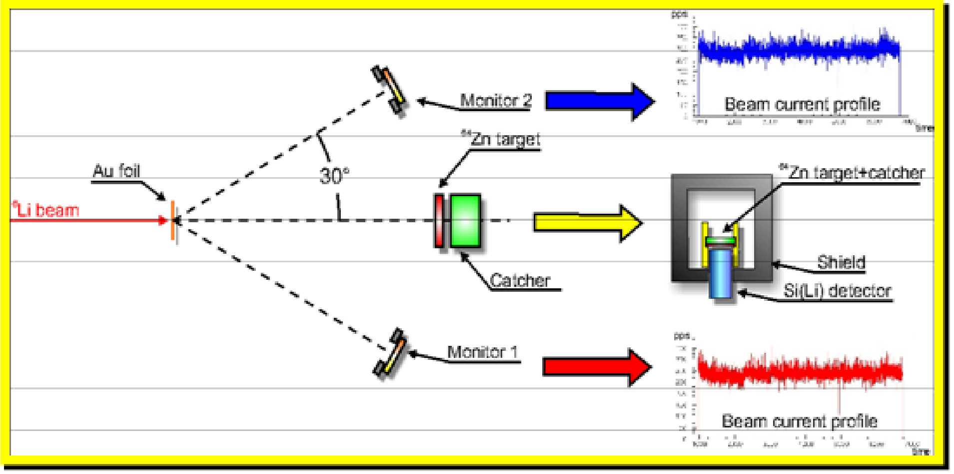


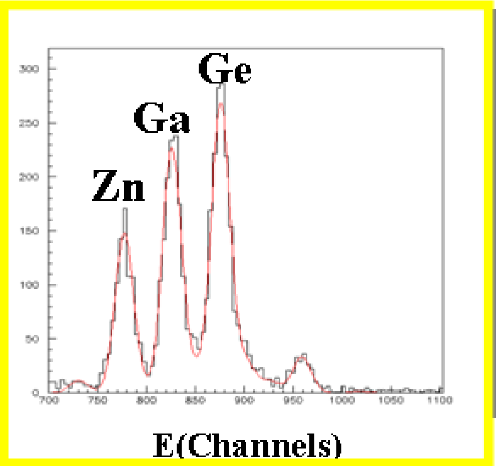
The activation technique we are using to measure $\sigma_{FUS}(E)$

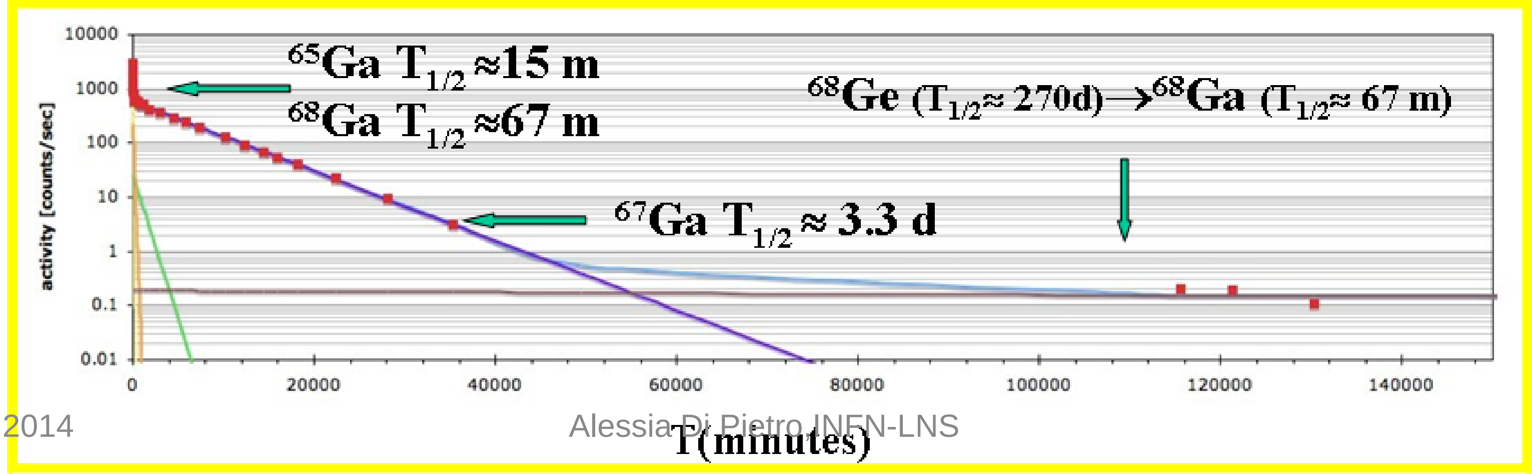
Off line detection of atomic X rays following EC decay of the ER.

- High intrinsic detection efficiency for X rays + very low background ⇒ suitable for experiments with RIBs
- Z and A ER identification

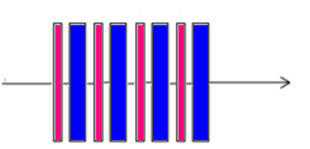
Example: The ^{6}Li+^{64}Zn collision @ LNS







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:

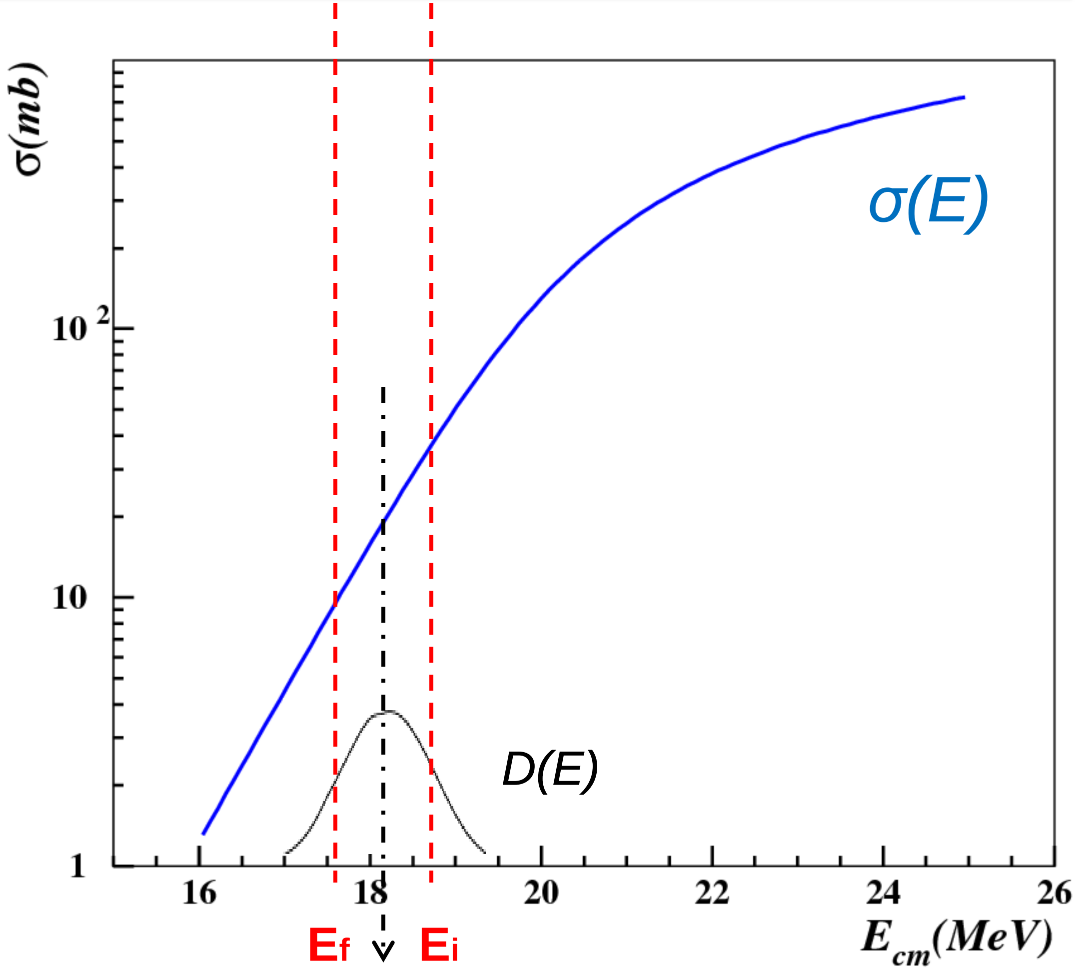
$$E_{eff}=(E_i+E_f)/2$$

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)

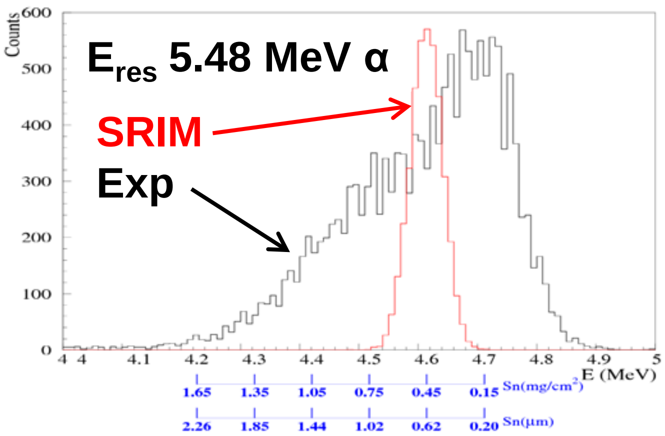
But things can be even more complicate because…

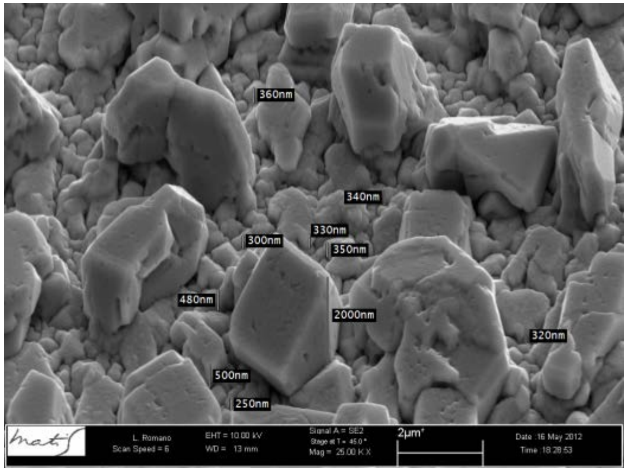


$E = (E_i + E_f)/2$

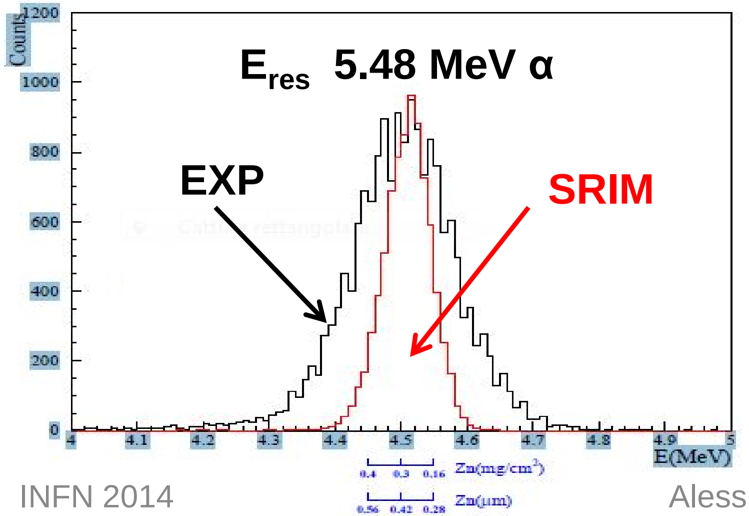
Good looking targets can be not really uniform….

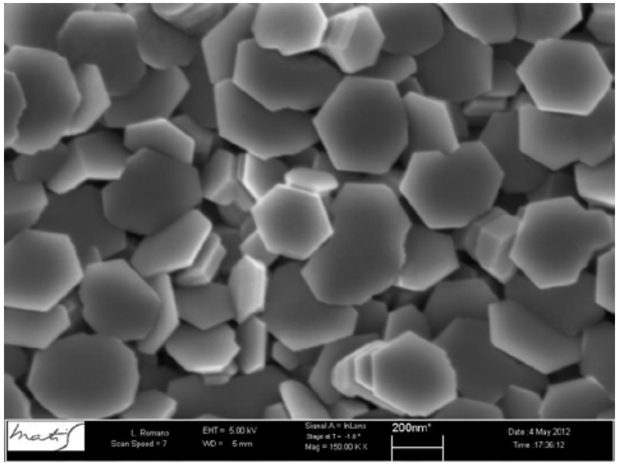
^{120}Sn target ~ 0.7 µm average thickness, size of grains up to 2 µm !





^{64}Zn target ~ 0.4 µm average thickness, exagonal grains 0.2 µm



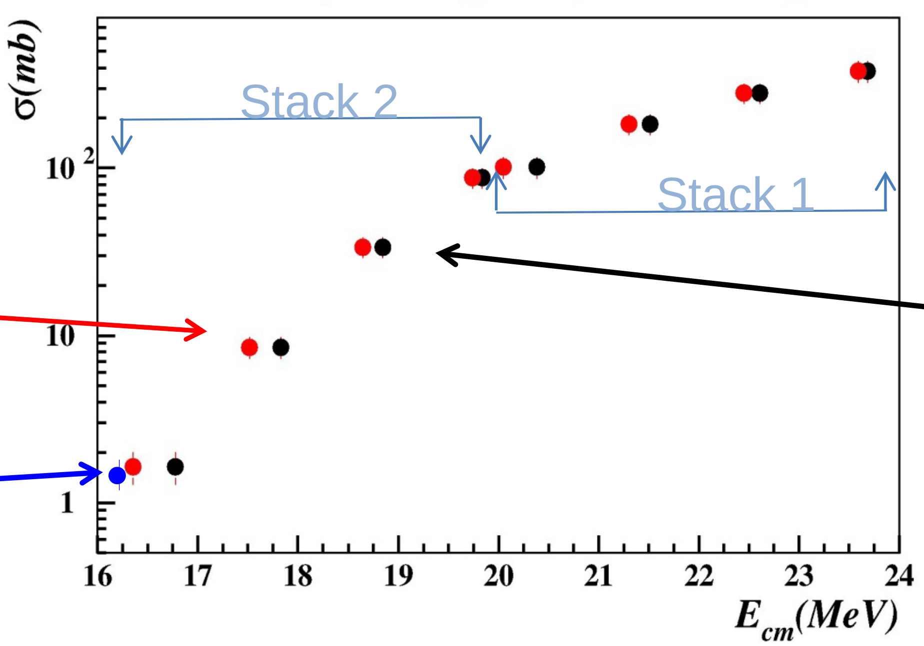


Drawbacks of the the activation technique: effects on $\sigma_{FUS}(E)$

Example: ^{6}Li+^{120}Sn . Two runs each irradiating
a stack of 4 targets (0.5 mg/cm^2) each followed by a Nb catcher (2mg /cm^2)

E_{eff}
weighted average
taking all effects
into account.

Measured with a
single thin target



E_{eff}
average energy
at target center
$E_{eff}=(E_i+E_f)/2$

M. Fisichella et al.
in preparation

- The larger is the number of crossed targets
the larger is the difference between the two E_{eff}.

- For a fixed number of crossed targets
the lower is the energy the bigger is the difference between the two E_{eff}.

Beam energy distribution and target non uniformity have to be taken properly into account when irradiating multiple stack of targets.
Related information should be reported in the corresponding papers.

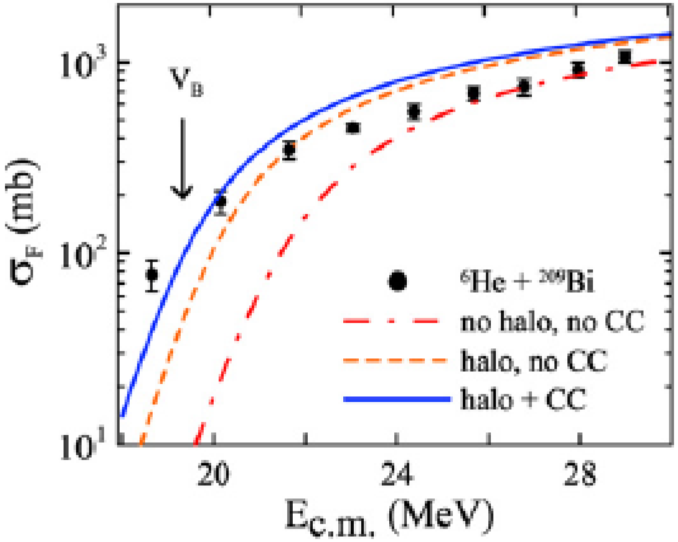
Fusion with n-halo nuclei

EXAMPLE

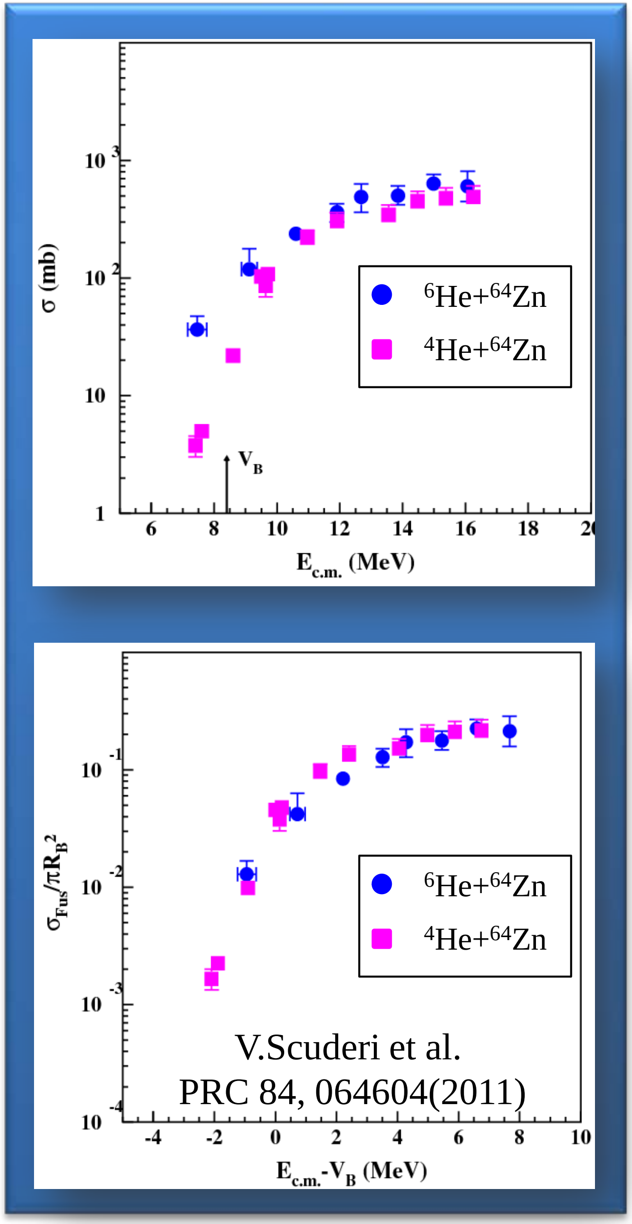
$^{6}He + ^{209}Bi$ @Notre Dame

Data:
J.J. Kolata et al PRL 81,4580,(1998)
Figures:
L.F.Canto et al NPA 821, 51, (2009)

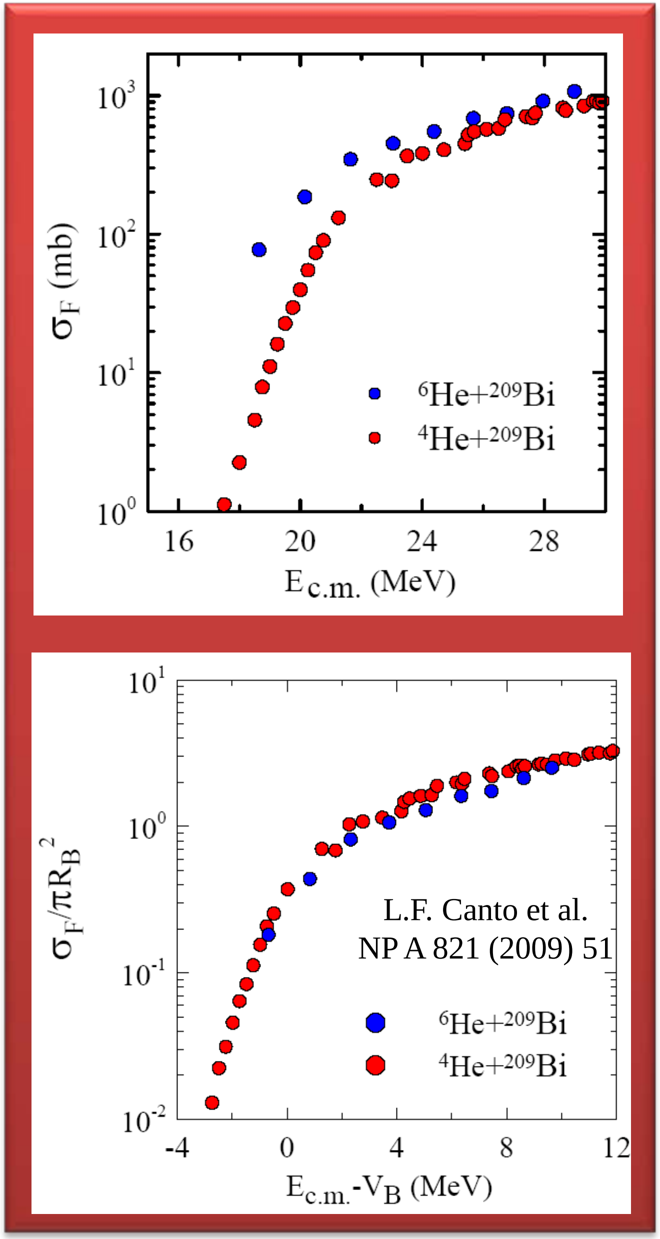
Comparison with calculations



^{4,6}He+^{64}Zn and ^{4,6}He+^{209}Bi



V.Scuderi et al.
PRC 84, 064604(2011)



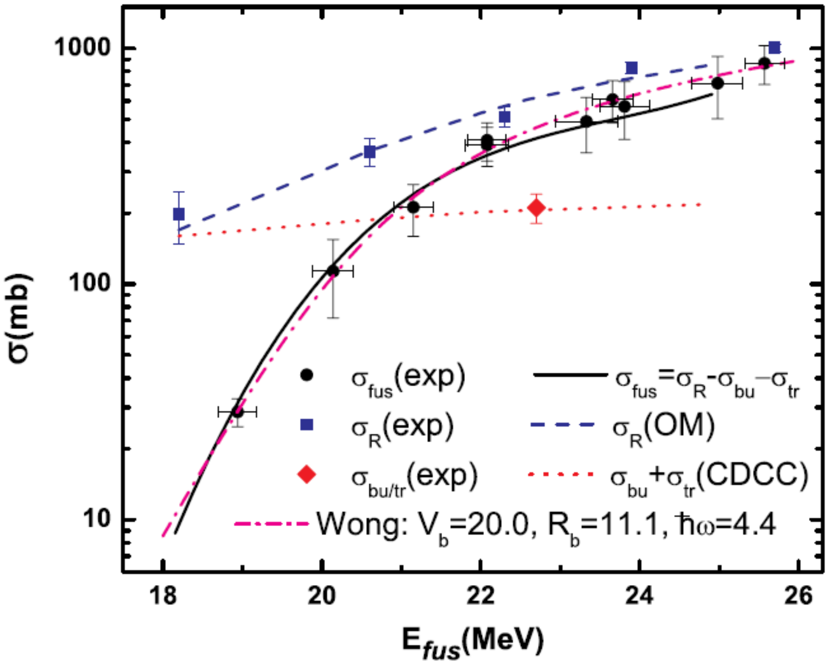
L.F. Canto et al.
NP A 821 (2009) 51

Same result but…^{6}He data stop at the barrier!

Fusion reaction with p-halo nuclei

^{8}B+^{58}Ni

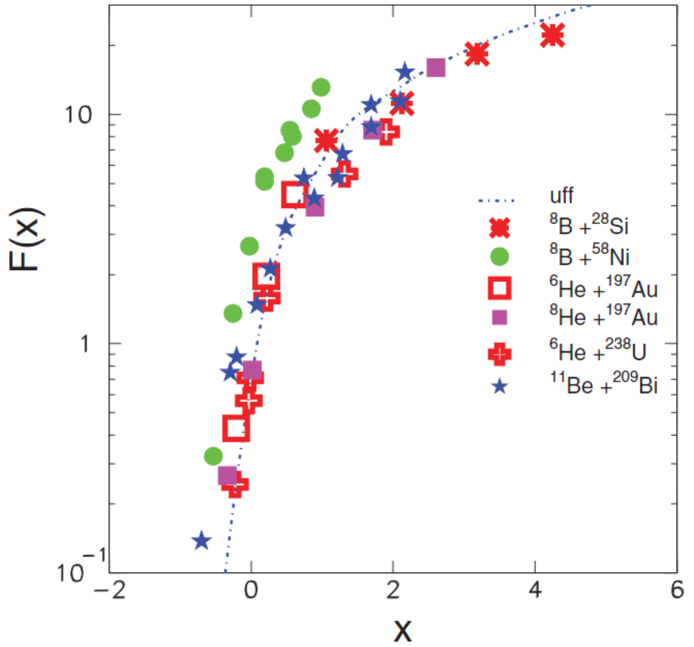
E. F. Aguilera PRL 107, 092701 (2011)



Enhancement of fusion cross-section

^{8}B+^{28}Si @ Exotic

A.PAKOU et al. PRC 87, 014619 (2013)



No-enhancement of fusion cross-section

$$F(x) = \frac{2E_{\mathrm{c.m.}}}{\hbar\omega R_B^2}\sigma_F, \qquad x = \frac{E_{\mathrm{c.m.}} - V_B}{\hbar\omega}$$

Fusion of weakly bound nuclei with no halo structure

What has been observed for fusion of weakly bound nuclei with no halo structure such as the stable ^{6}Li ($S_\alpha \sim 1.5$ MeV), ^{7}Li ($S_\alpha \sim 2.5$ MeV), ^{9}Be ($S_p \sim 1.7$ MeV) ?

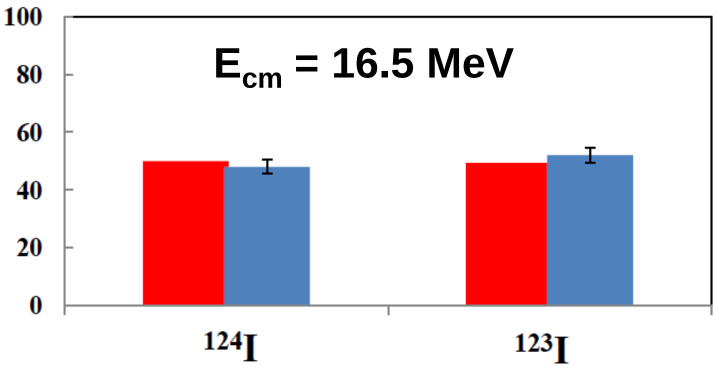
- Breakup and coupling to continuum expected to be still important.

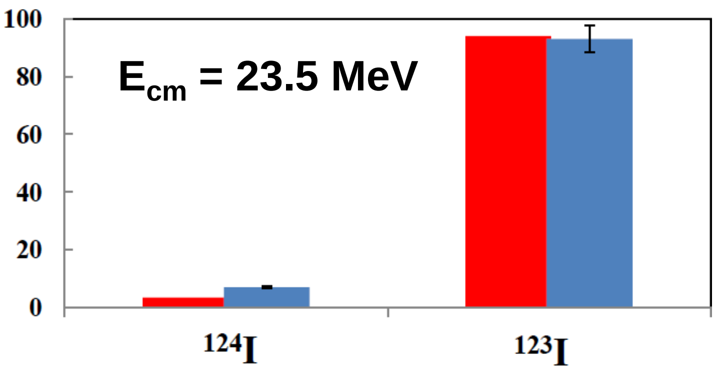
- Stable beams → better data quality

The ^{6,7}Li+^{120,119}Sn collision @ LNS

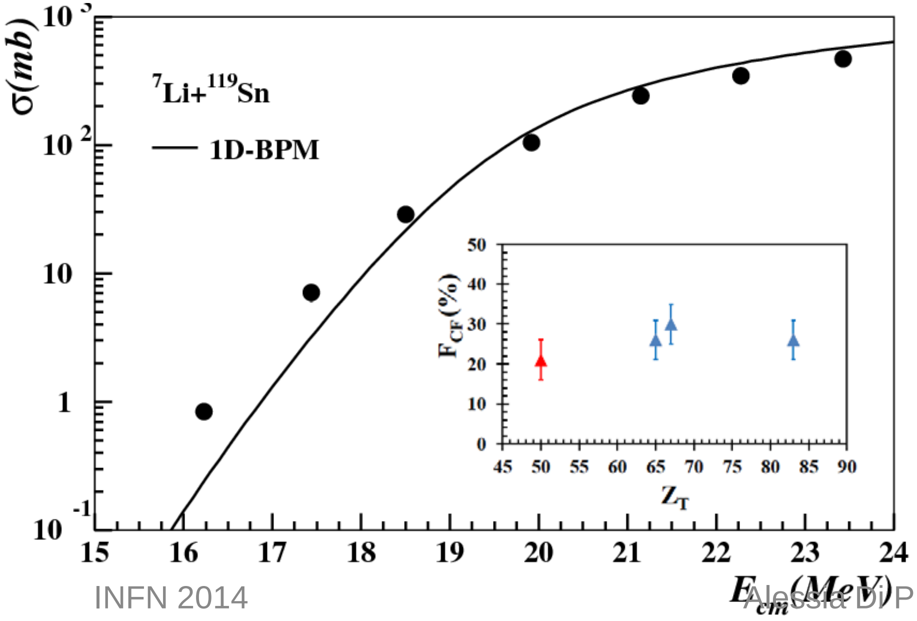
ER relative yield for CF well reproduced by statistical model.

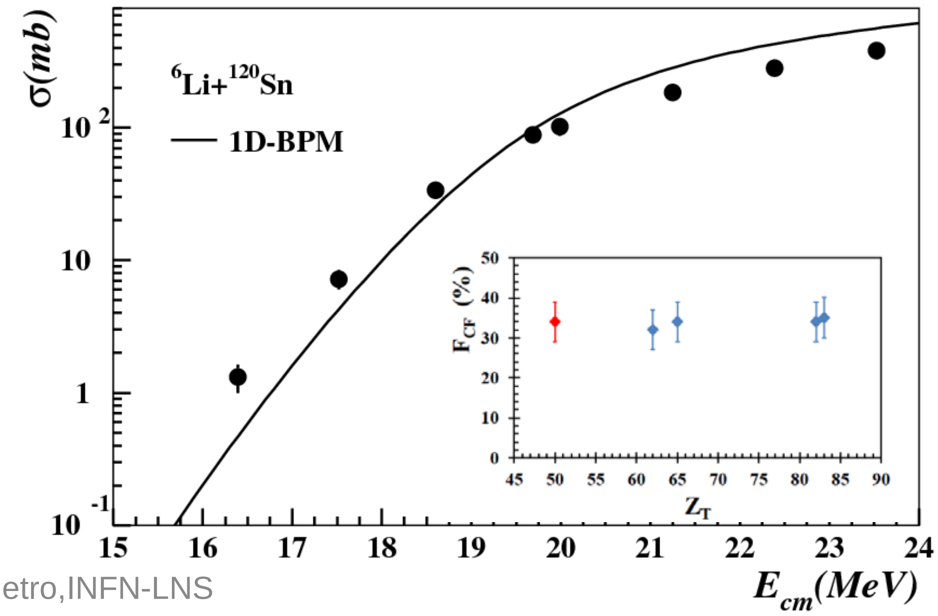
Example: ^{6}Li+^{120}Sn CASCADE DATA



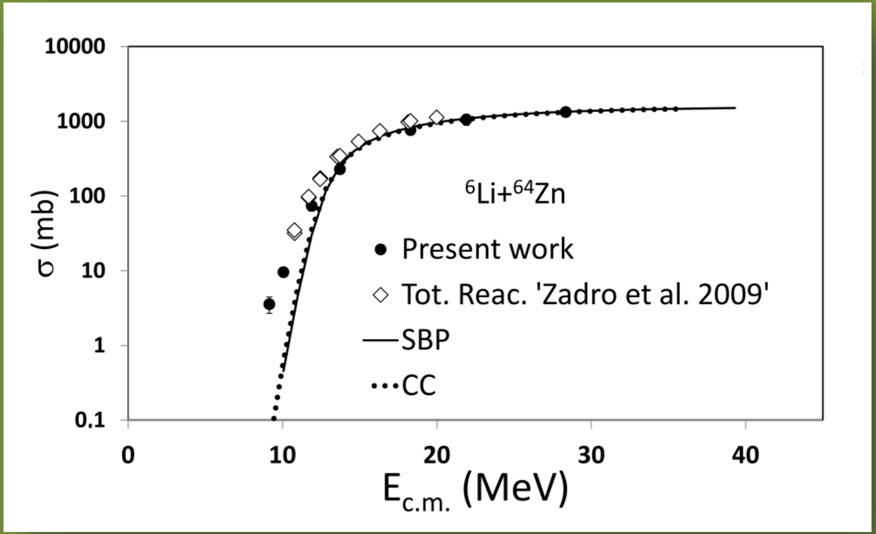


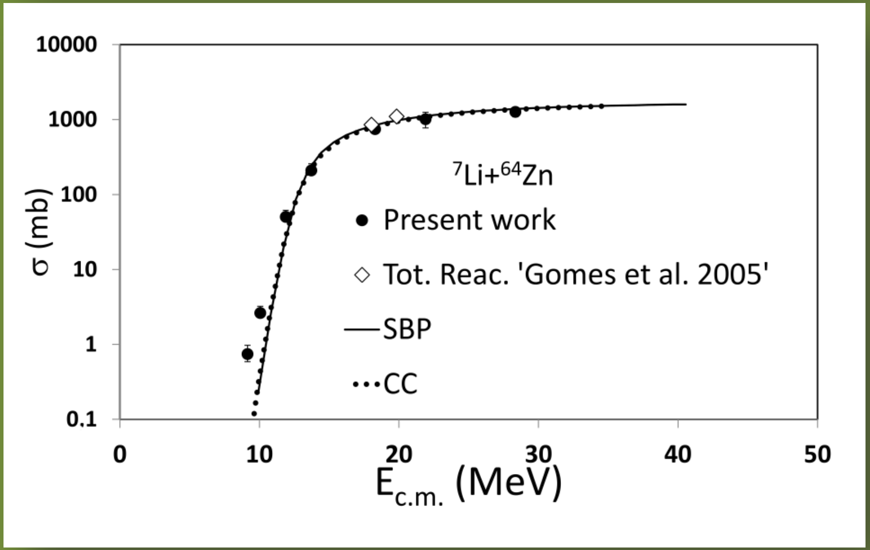
Measured σ_{FUS}(E) show the usual suppression above barrier with respect to SPB or CC



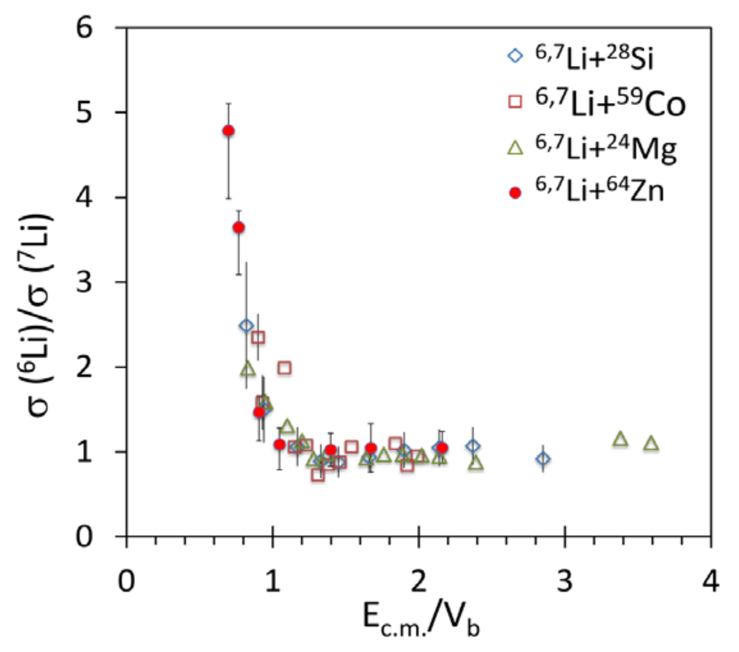


^{6,7}Li+^{64}Zn Heavy Residue excitation function





Ratio of H.R. cross-section



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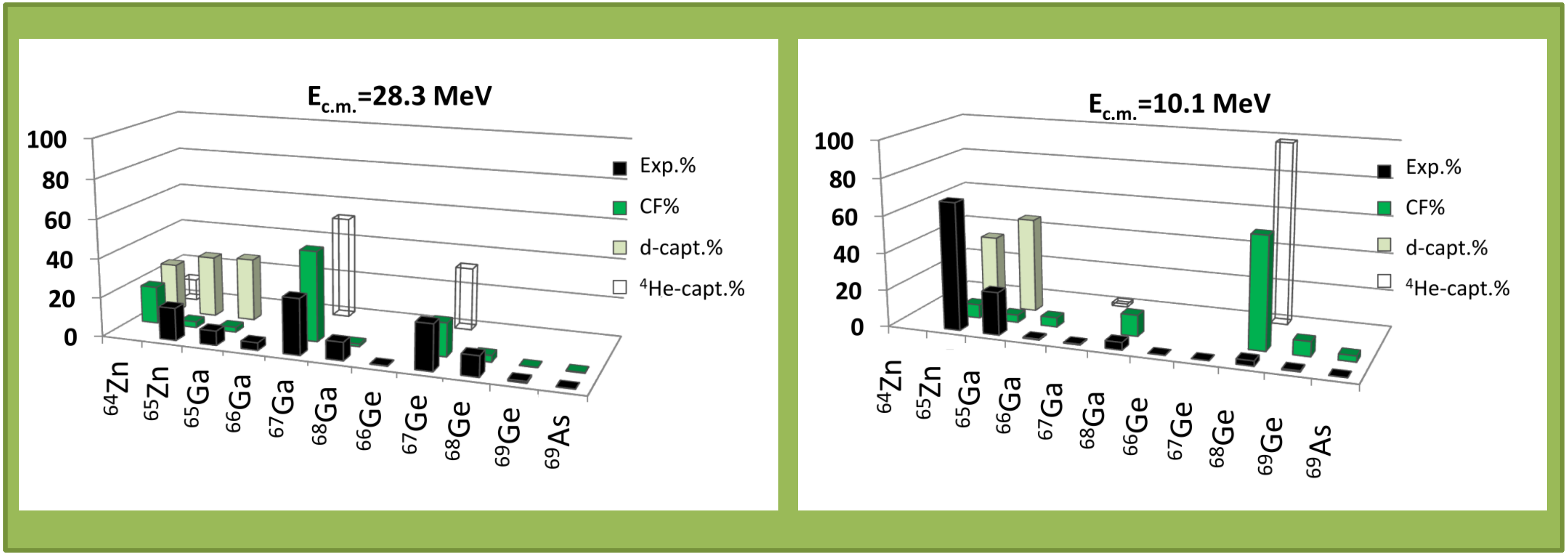
Heavy Residue relative yields ($\sigma_{H.R.}/\sigma_{tot}$)



Is d or α capture from ^{6}Li important ?

- ICF $E^* \sim (E_{cm} - S_{\alpha})x(m_{clu}/m_{proj}) + Q_{(Clu+64Zn)}$
- Cluster transfer $E^* \sim Q_{gg} - Q_{opt}$

■ Experiment
🟩 Complete Fusion calculations
▨ d-capture calculations
☐ α-capture calculations

1n or 1p transfer leading to ^{65}Zn and ^{65}Ga can also contribute

Above barrier CF dominates
Below the barrier different processes dominate

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Summary and conclusions

Reaction studies with halo beams have shown many peculiarities due to the low binding and extended wave function :

✓Damping of elastic cross-section at large impact parameters due to the coupling to the continuum. Both Coulomb and nuclear coupling contribute to the effect.

✓Large total reaction cross-sections.

✓Large cross-section for transfer and breakup events.

✓Fusion induced by n-halo nuclei seems indeed to be enhanced below the barrier but mainly due to static effects owing to the larger radius of these nuclei. Need for precise data at lower energies to investigate possible dynamic effects.

✓The reaction dynamics for p-halo nuclei is expected to be different due to the presence of Coulomb interaction also with the halo. Discrepancy have been observed from the only two existing fusion measurement. Again need for more and better quality data.