Reaction dynamics with halo nuclei around the Coulomb barrier

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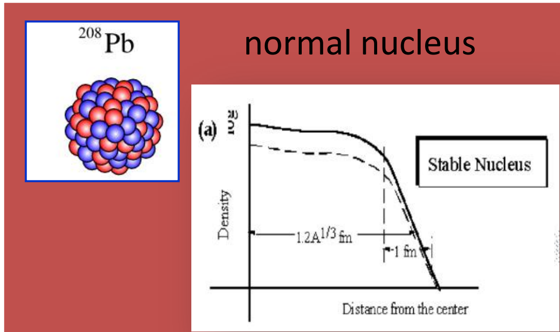
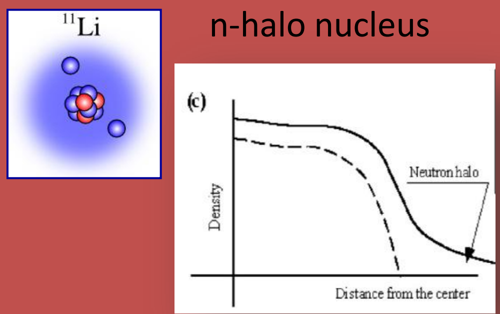
➢ Introduction .

We have tried to investigate the influence of the intrinsic structure of the colliding nuclei on the elastic scattering and reaction mechanisms in order to have a better understanding of the reaction dynamics in collision involving *exotic* systems as nuclear *halos*.





Some examples:

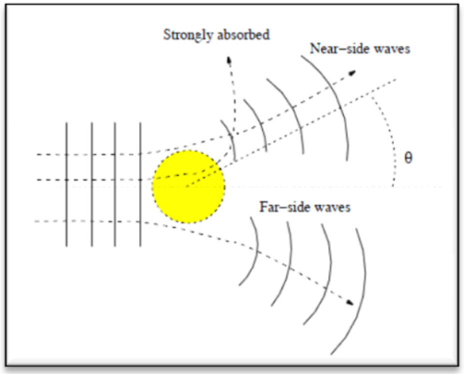
$^{6}He \equiv {}^{4}He + n + n$

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

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

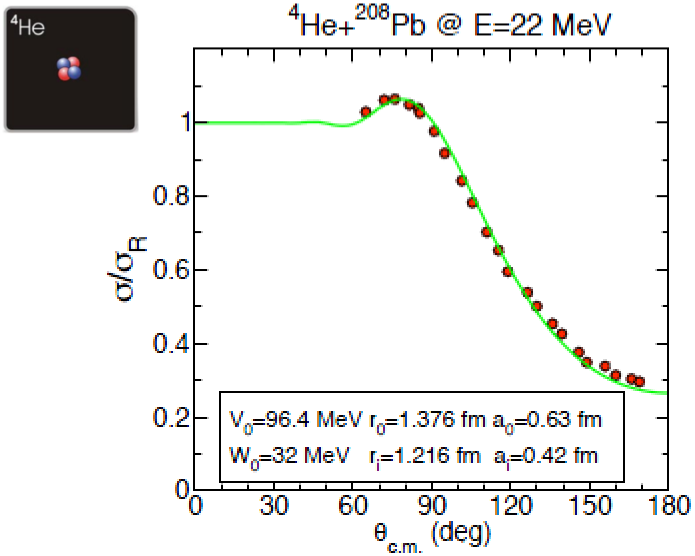
- ➢ Overview of our current understanding of reactions at energies around the barrier:
- ○ Elastic scattering;
- ○ Transfer and breakup;
- ○ Fusion;
- ○ Neutron vs proton halo.
- ➢ Summary and conclusion.

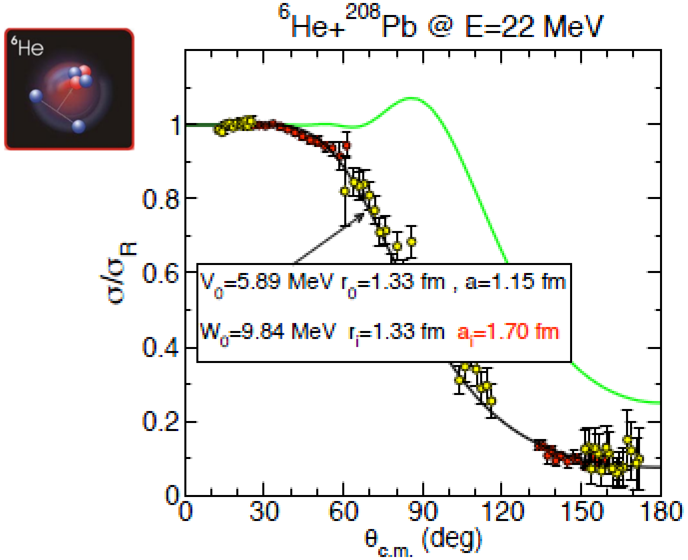
Elastic scattering: Normal versus halo nuclei



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.





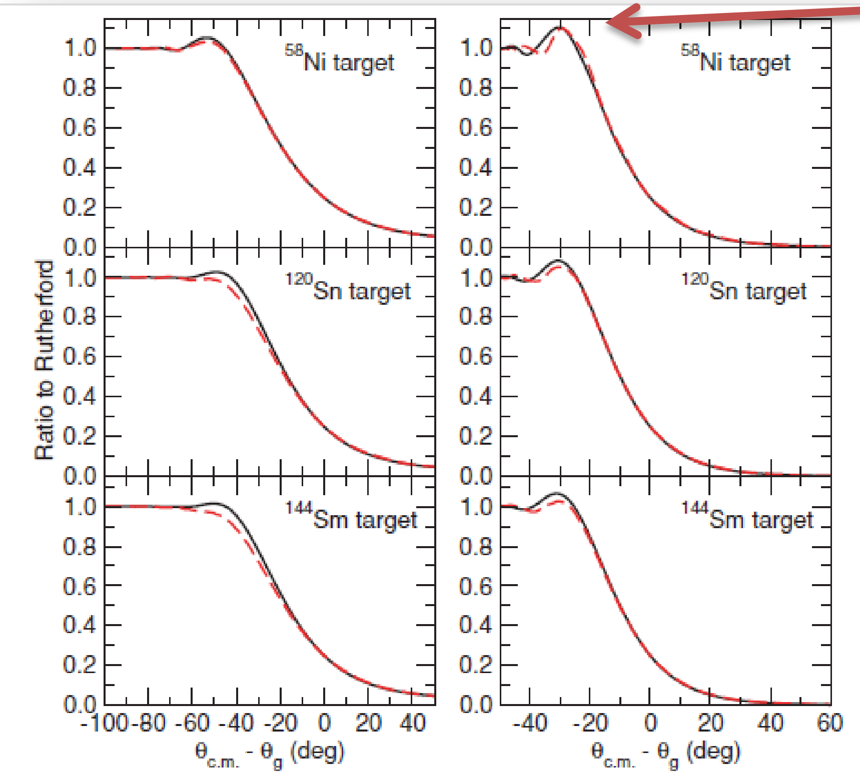
L. Acosta et al PHYS. REV. C **84, 044604 (2011)**

- ^{4}He+^{208}Pb shows typical Coulomb-nuclear interference *strong absorption*
- ^{6}He+^{208}Pb shows a reduction in the elastic cross section due to the flux going to other reaction channels (transfer, break-up or fusion?).
- ^{6}He+^{208}Pb requires a large imaginary diffuseness ! *long-range absorption*

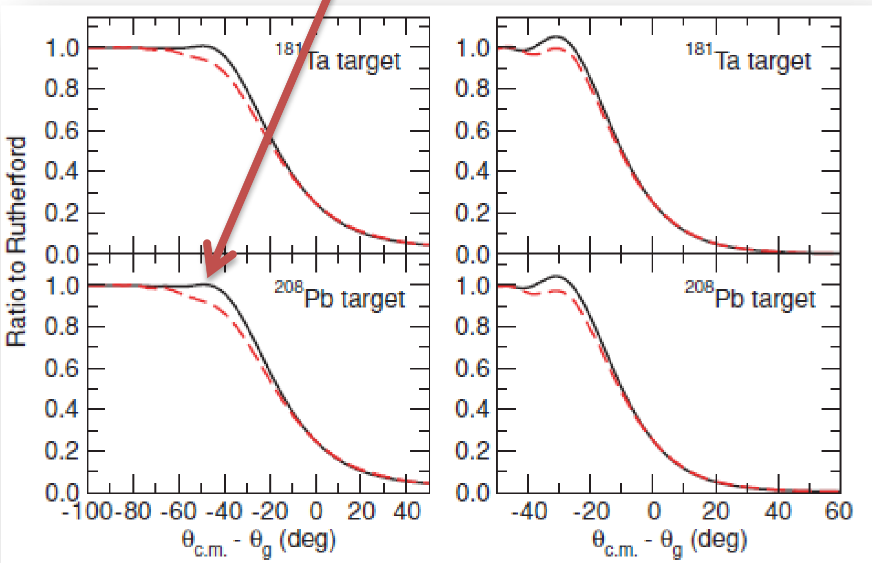
Effect of coupling to Coulomb dipole break-up as a function of the target charge for ^{6}He induced collision at energy around the barrier.

—^{6}Li+A
---^{6}He+A

No suppression on medium mass targets



Suppression on heavy targets

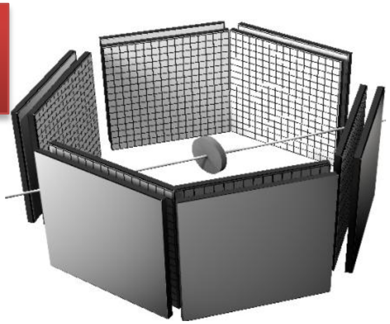


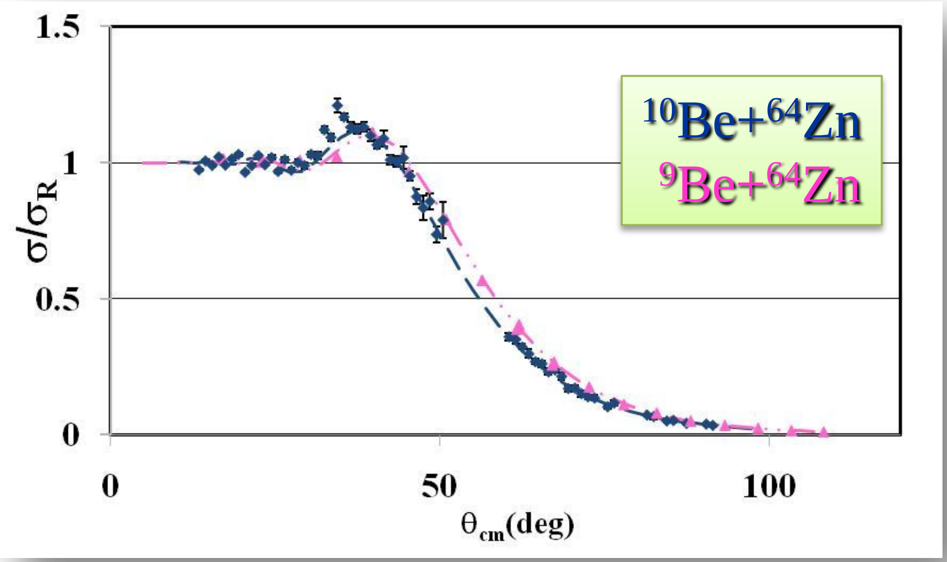
Y. Kucuk et al. PRC 79(2009)067601

Elastic scattering angular distributions @ 29MeV

^{9}Be+^{64}Zn @ INFN-LNS Catania

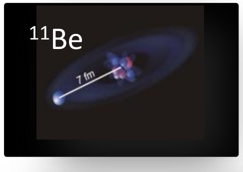
^{10,11}Be+^{64}Zn @ Rex-Isolde, CERN





A. Di Pietro et al. Phys. Rev. Lett. 105,022701(2010)

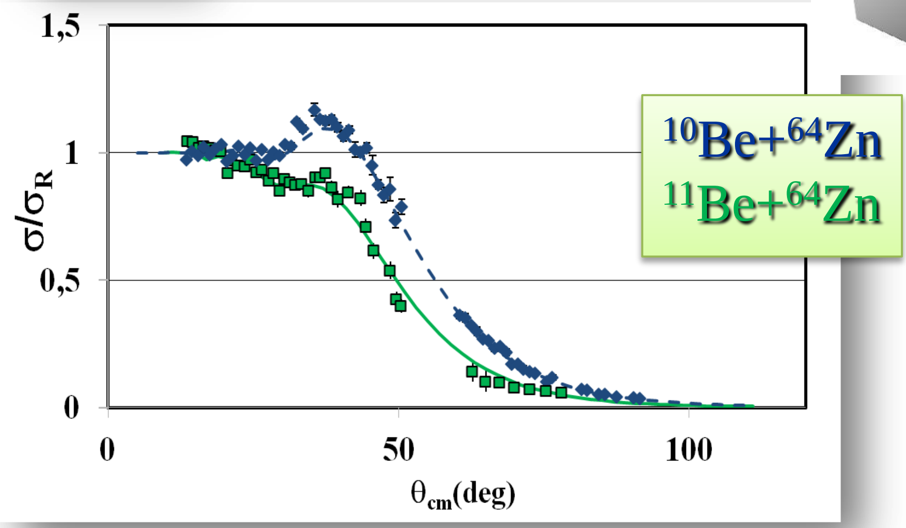
Elastic scattering angular distributions @ 29MeV



$^{10,11}Be+^{64}Zn$
@ Rex-Isolde, CERN

OM analysis adopted procedure:

- volume potential responsible for the core-target interaction obtained from the $^{10}Be+^{64}Zn$ elastic scattering fit.
- plus a complex surface DPP having the shape of a W-S derivative with a very large diffuseness.
- Very large diffuseness: ai= 3.5 fm similar to what found in A.Bonaccrso NPA 706(2002)322



Reaction cross-sections

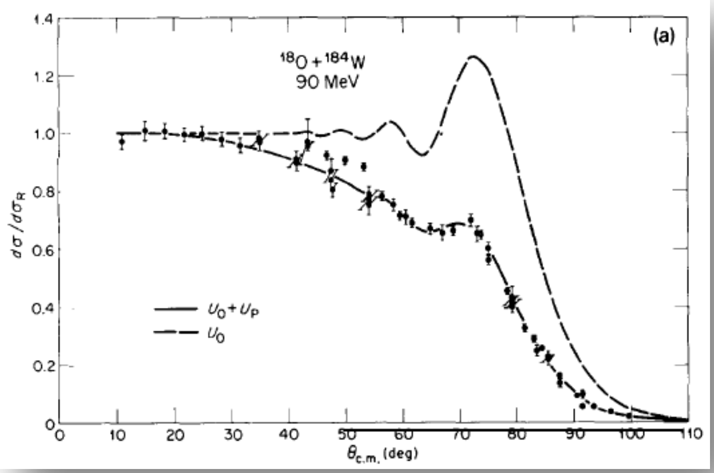
$\sigma_R\,^{9}Be \approx 1.1b$ $\sigma_R\,^{10}Be \approx 1.2b$ $\boldsymbol{\sigma_R\,^{11}Be \approx 2.7b}$

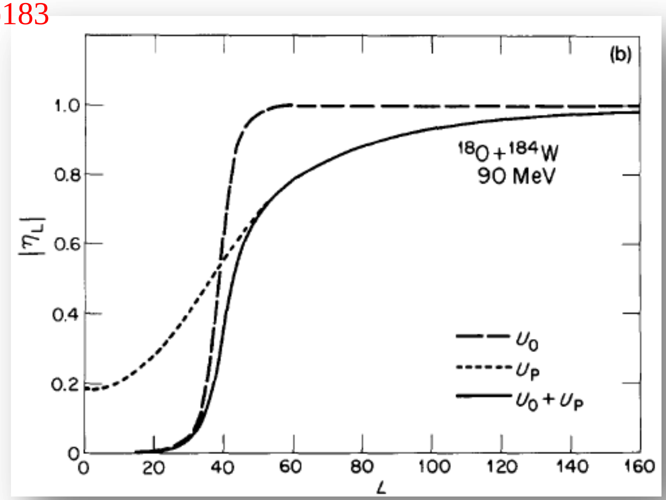
A. Di Pietro et al. Phys. Rev. Lett. 105,022701(2010)

Absorption in high partial waves causes cross-section to fall below Rutherford at forward scattering angles.

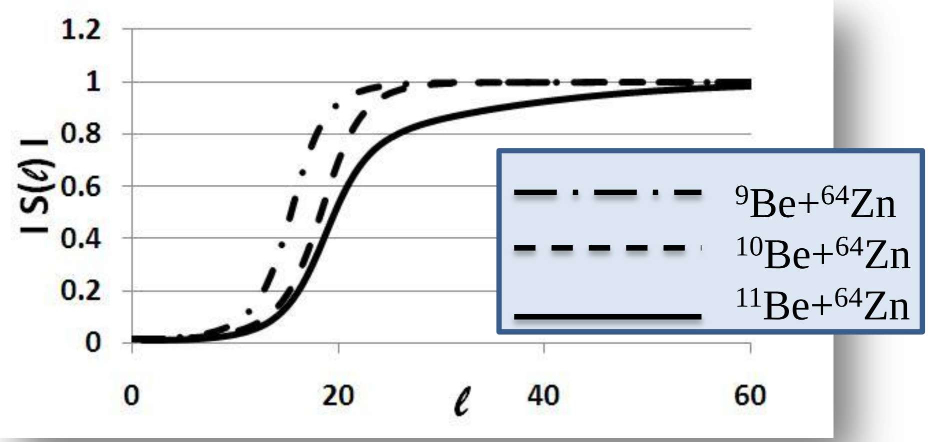
$^{18}O + ^{184}W$ @ 90MeV

W.Love et al. Nucl.Phys.A291(1977)183



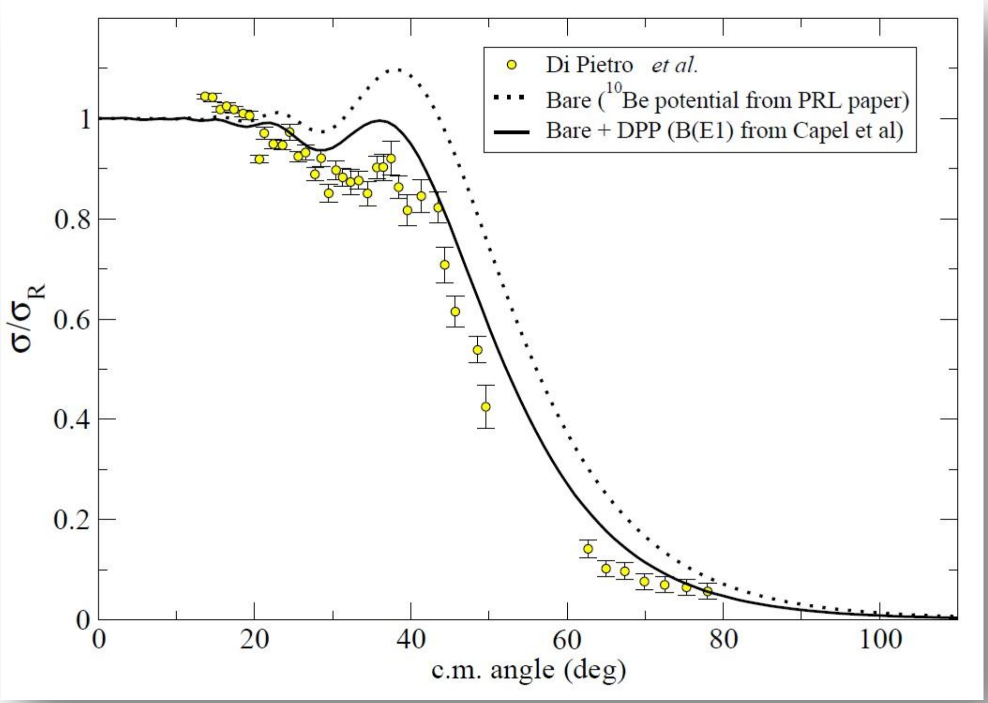


$^{9,10,11}Be + ^{64}Zn$

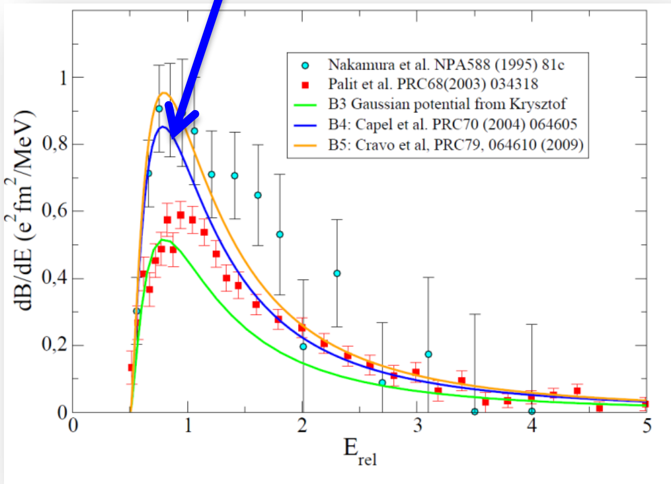


Suppression of the elastic: coupling to Coulomb or nuclear break-up?

W-S volume potential of the core + DPP due to Coulomb dipole coupling



B(E1) strenght used for DPP

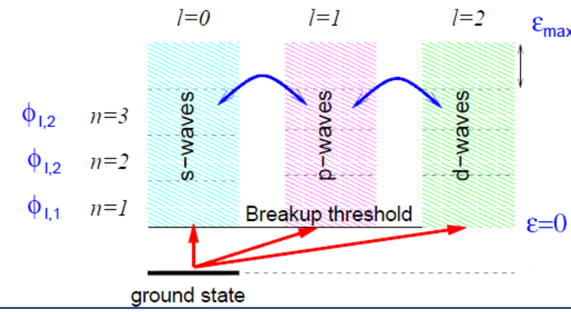


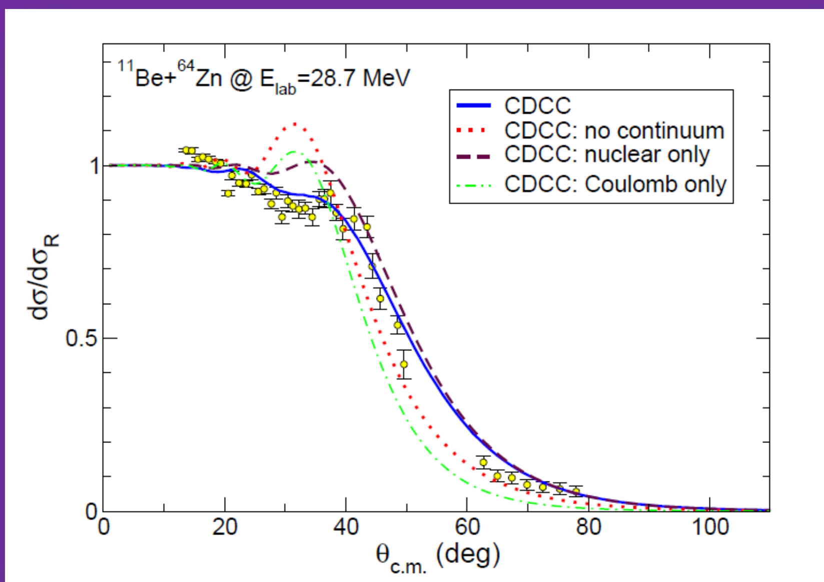
A. Di Pietro, V. Scuderi, A.M. Moro et al.
Phys. Rev. C 85, 054607 (2012)

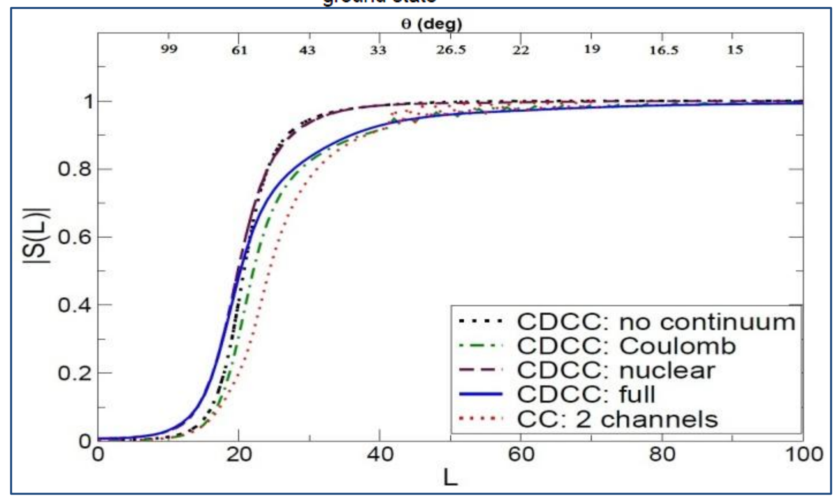
Continuum Discretized Coupled Channel Calculations (CDCC)

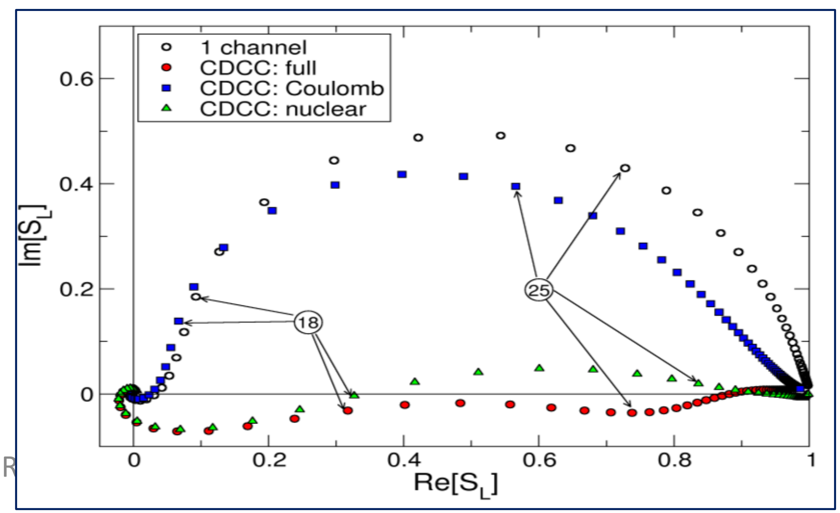
At low bombarding energy coupling between relative motion and intrinsic excitations important.

Halo nuclei → small binding energy, low break-up thresholds → coupling to break-up states (continuum) important → CDCC.









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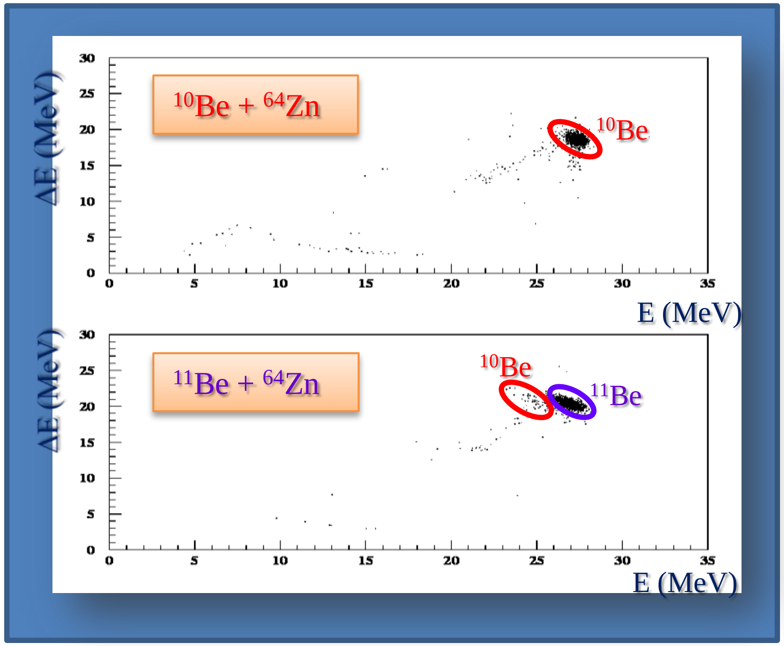
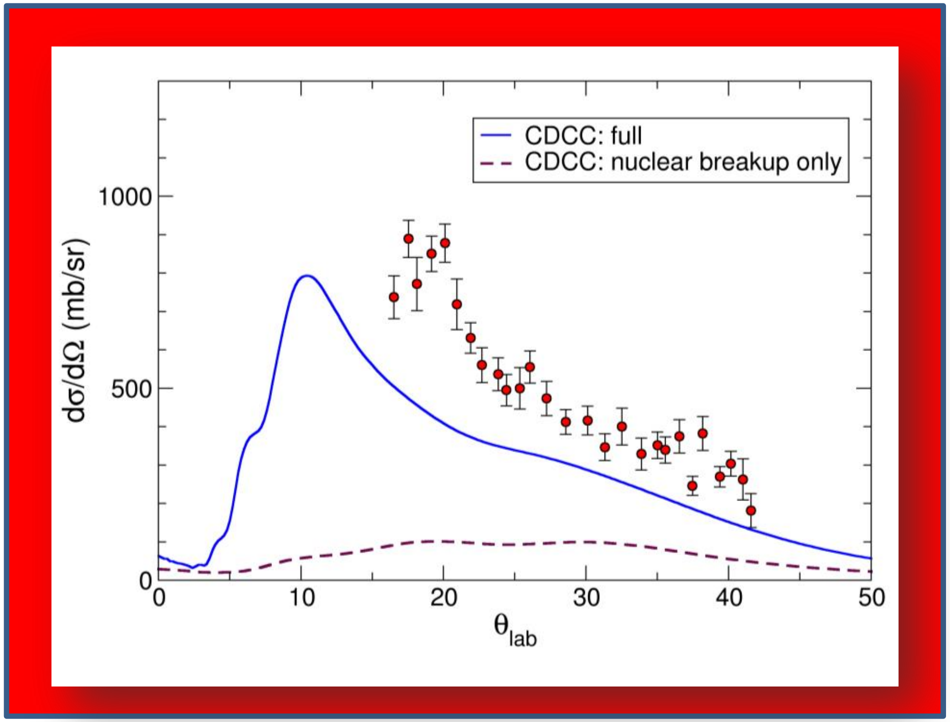
Phys. Rev. C 85, 054607 (2012)

Where is the missing elastic cross-section going?



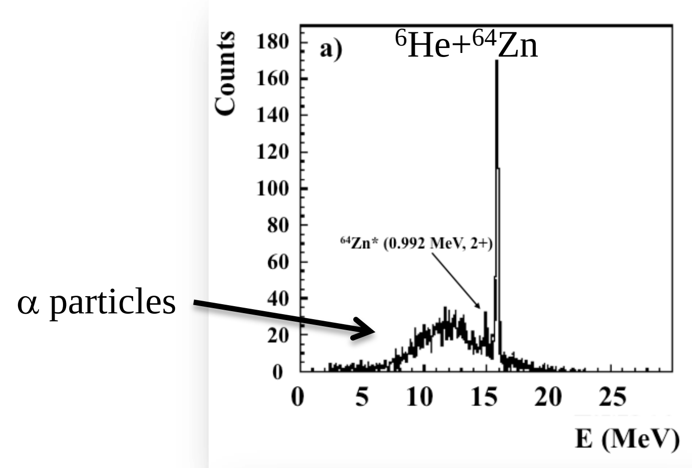
^{11}Be+^{64}Zn break-up/transf. contribution

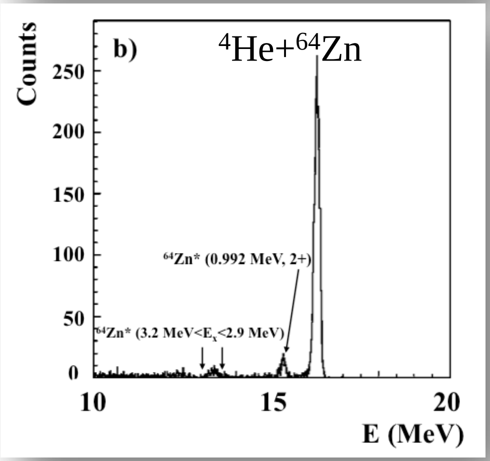


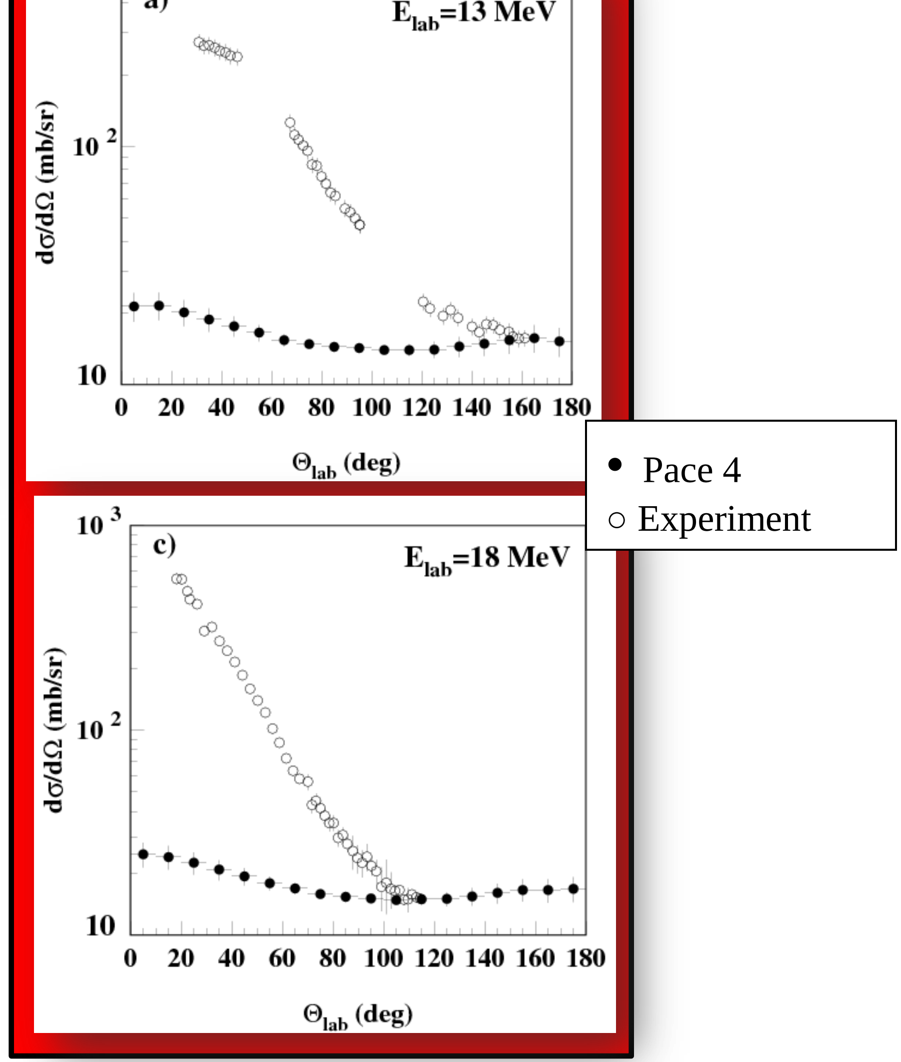
A. Di Pietro, V. Scuderi, A.M. Moro et al.
Phys. Rev. C 85, 054607 (2012)

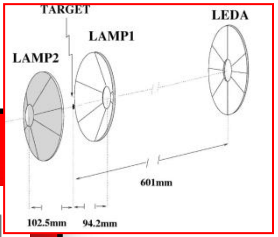
$\sigma_{BU/TRANSF} \approx 1.1b \approx 0.4\ \sigma_{reac}$

$^{4,6}He+^{64}Zn$ @ LLN: α – particle inclusive measurement transfer and break-up processes





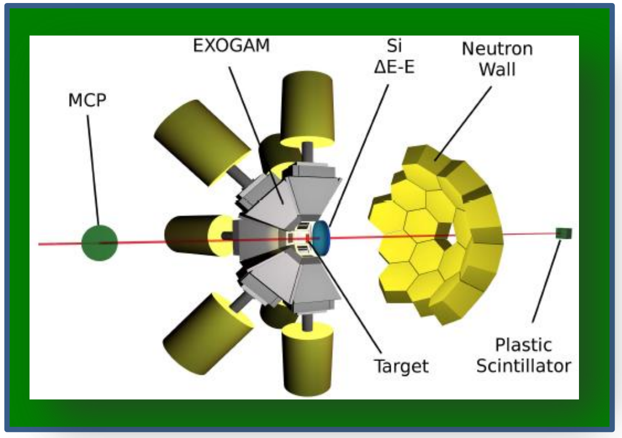


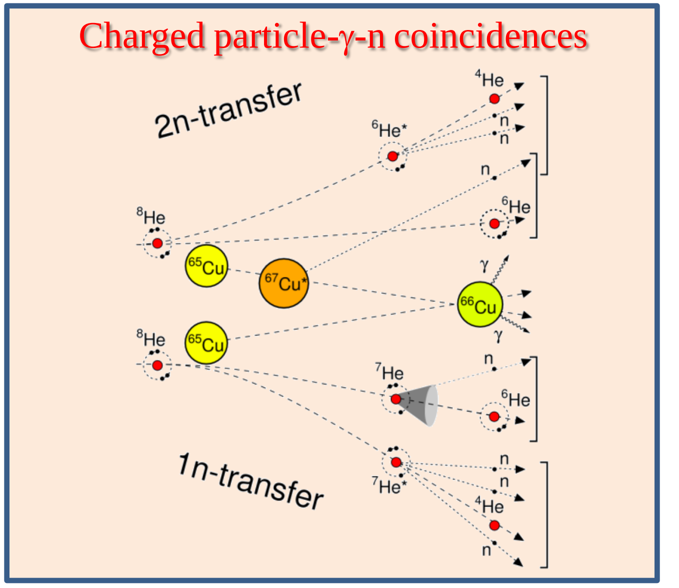


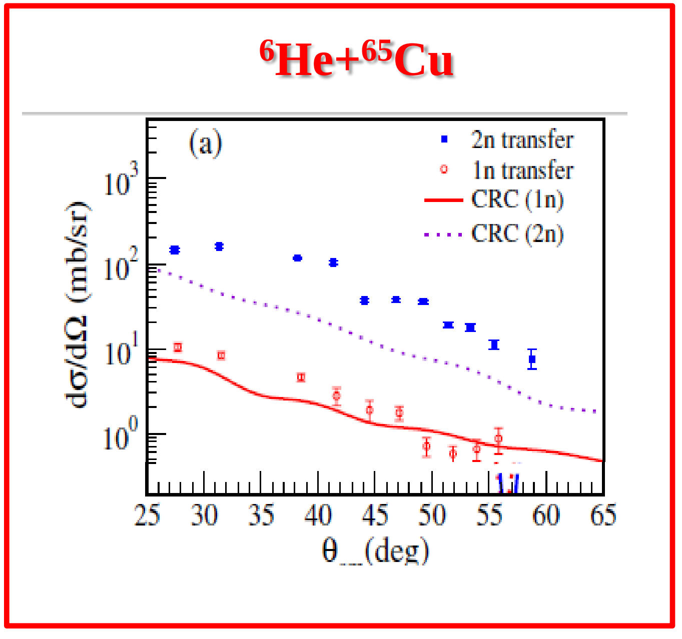
Most of the α-particle cross-section (≈ 80% of the reaction cross-section) due to transfer and break-up.

V. Scuderi et al. Phys.Rev. C 84, 064604 (2011)

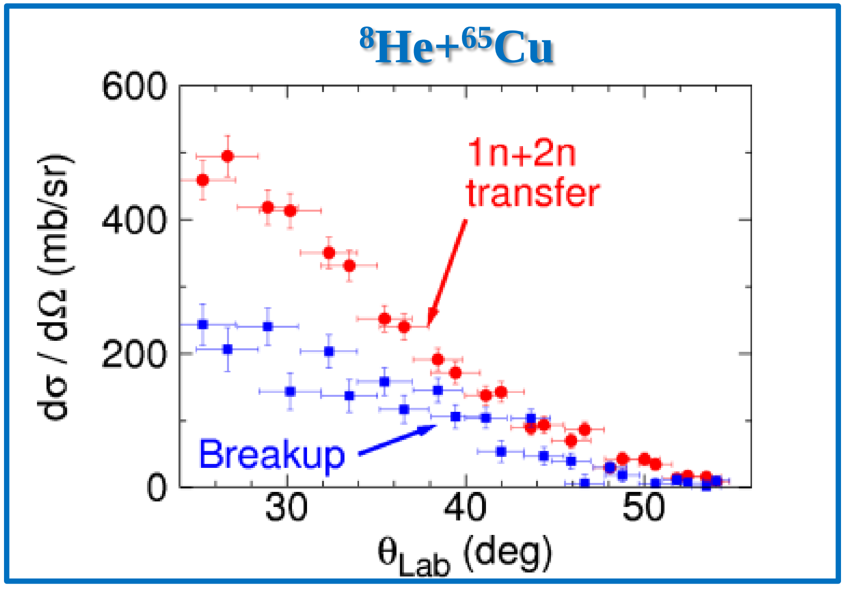
$^{6,8}He+^{65}Cu$ @ Spiral
transfer and break-up: exclusive measurement







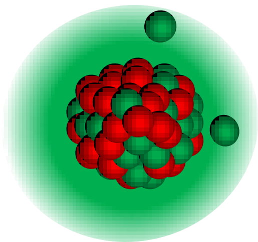
A. Chatterjee et al. PRL 101, 032701 (2008)



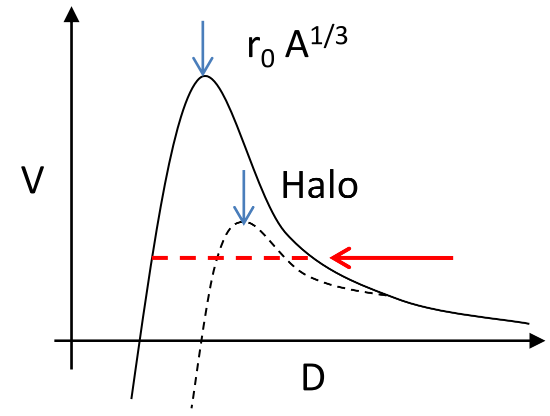
A.Navin ARIS 2011 &
A. Lemasson et al. Phys. Rev. C 82,044617 (2010)

Fusion with halo nuclei: enhancement or suppression?

How does halo affect fusion ?
Possibilities: Static effect

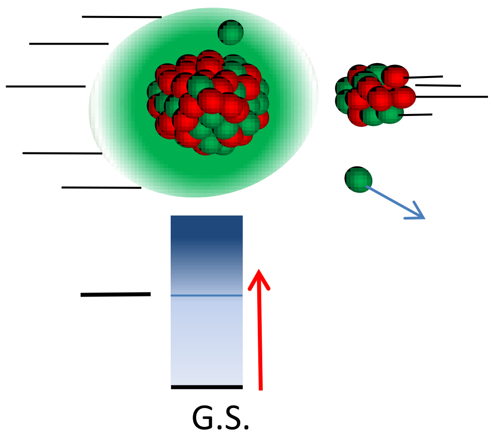


Radius ✗ $r_0 A^{1/3}$



Dynamic effect

Breakup



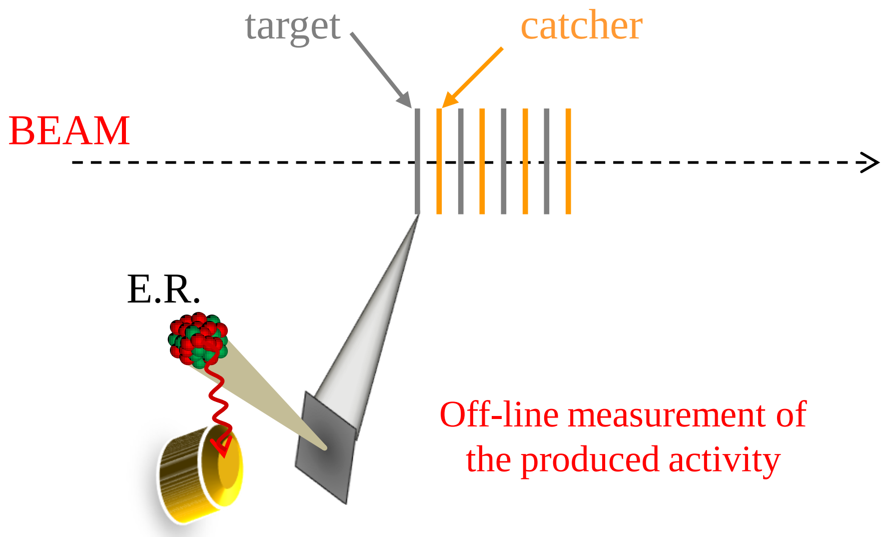
Effect?

Like any other coupling process → Increased sub barrier fusion

Decreases Flux → Decreased sub barrier fusion

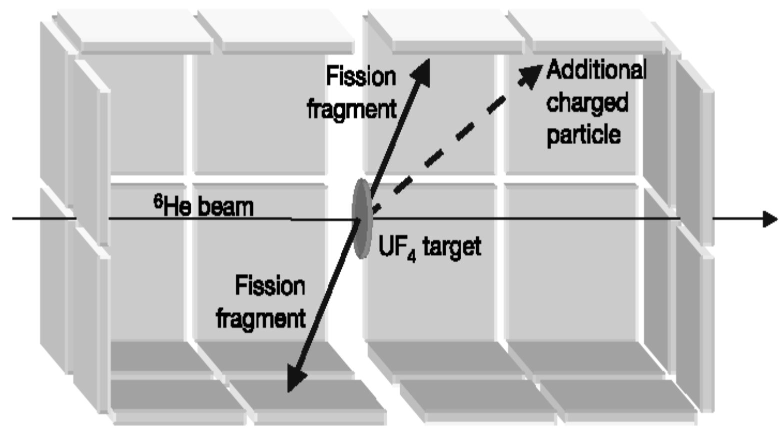
Experimental thechniques used to measure fusion with low intensity halo beams.

Activation experiments:
medium mass and heavy targets



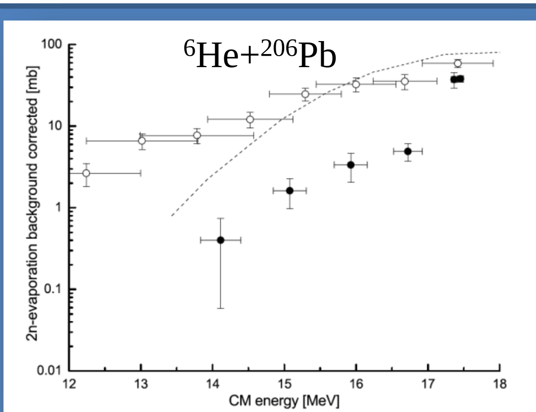
Off-line measurement of the produced activity

Fusion-fission:
heavy fissile targets



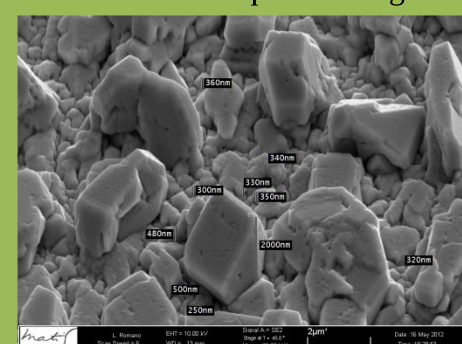
To overcome the problem of low beam intensity, large beam energy spread, thick targets and/or target stacks generally used.

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



S.M. Lukyanov et al., PLB670 (2009) 321
R.Wolski EPJA47(2011)111

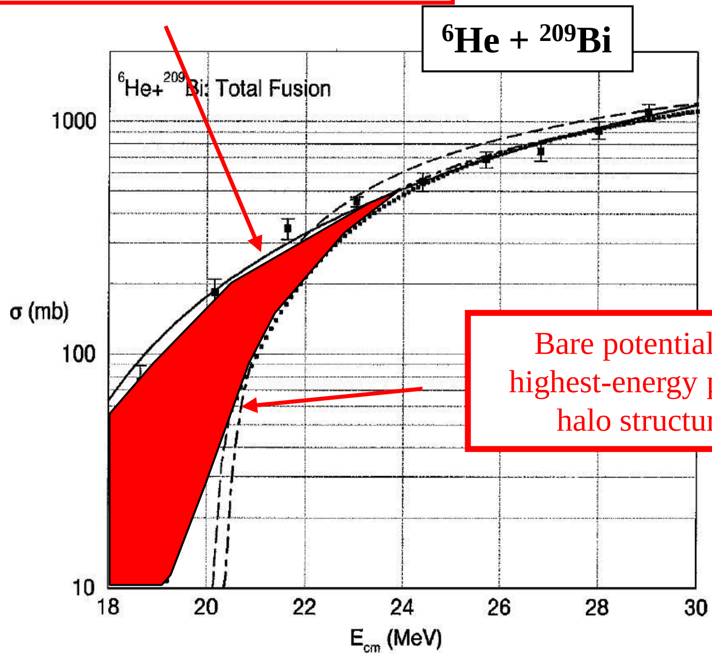
Are the targets uniform?
SEM view of a Sn evaporated target on Nb



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

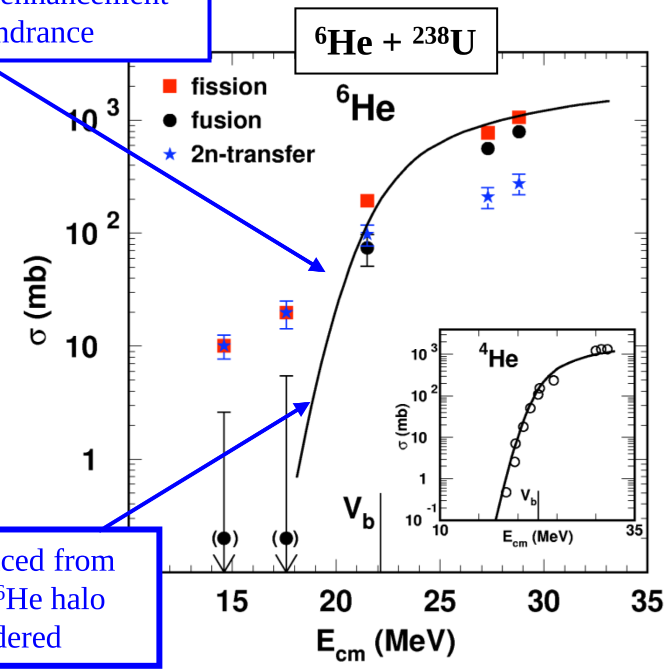
Two different type of comparisons of barrier penetration:

Sub-barrier fusion enhancement
no above barrier hindrance



Bare potential deduced from highest-energy points → no 6He halo structure considered

No sub-barrier fusion enhancement
above barrier hindrance



Bare potential deduced from double folding → ^{6}He halo structure considered

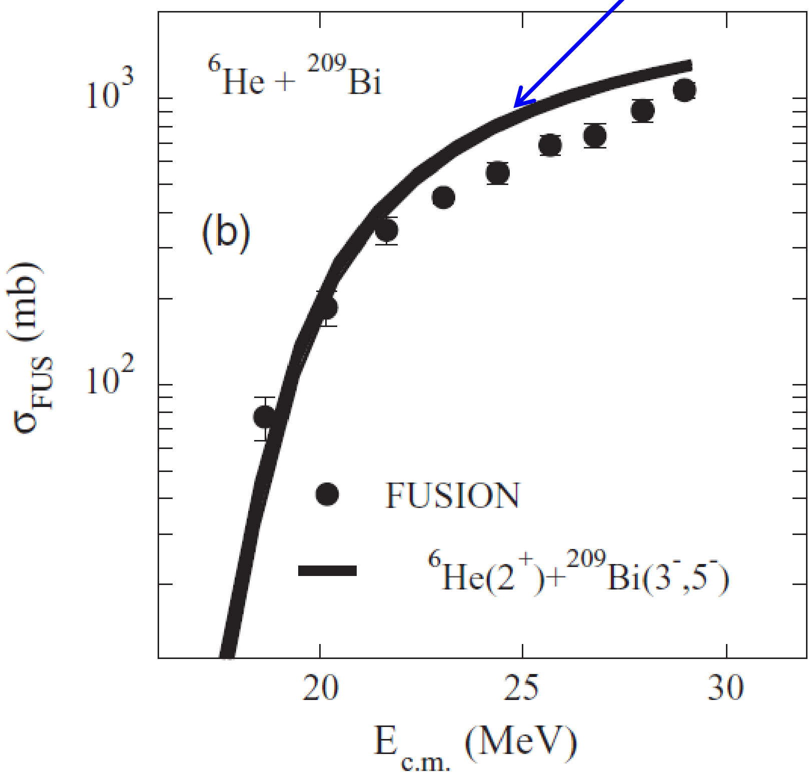
J.J.Kolata et al. PRL 81 (1998) 4580

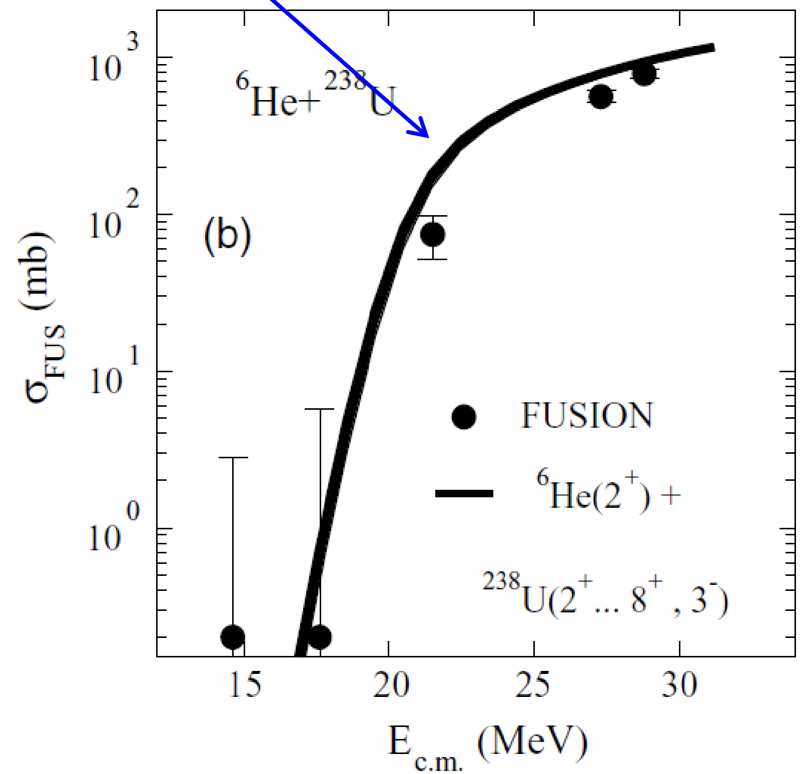
R. Raabe et al. Nature 431 (2004) 823

Different conclusion drawn on sub-barrier fusion enhancement for the two systems!

Same data, different type of comparison, different conclusion?

^{6}He halo structure considered in Double Folding potential.
No sub-barrier fusion enhancement
above barrier hindrance



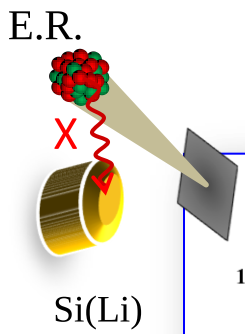


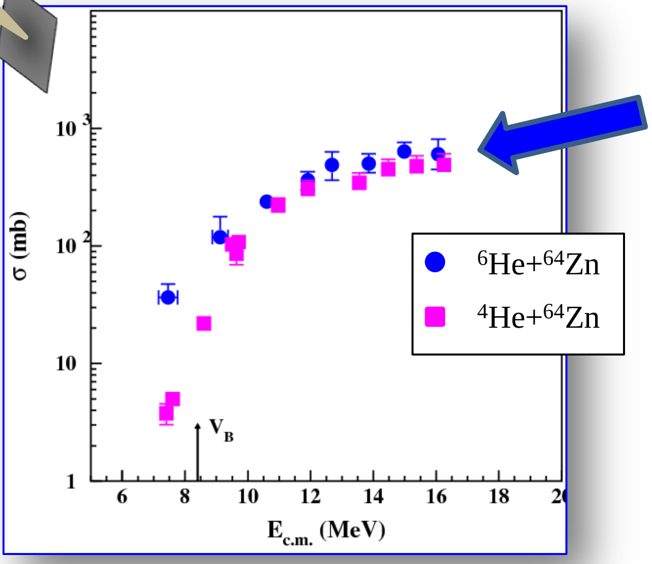
Different conclusion than
J.J.Kolata et al. PRL 81 (1998) 4580

Same conclusion as
R. Raabe et al. Nature 431 (2004) 823

E.Crema et al. PRC 75, 037601(2007)

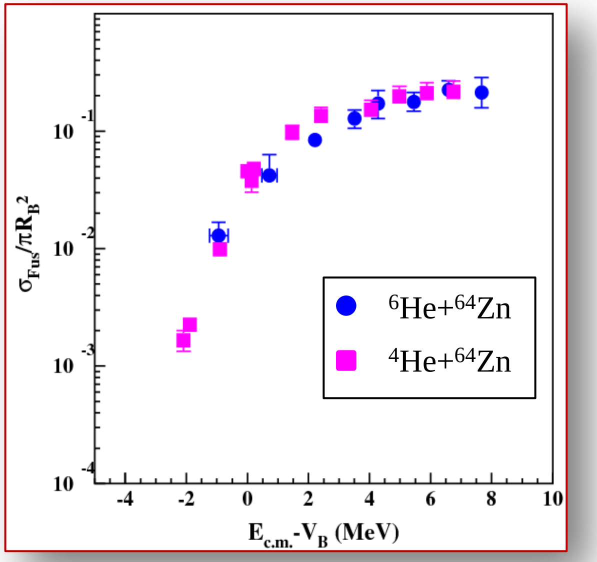
$^{4,6}He+^{64}Zn$ @ LLN: Fusion excitation function





Activation technique used.
Off-line measurement of X-rays.

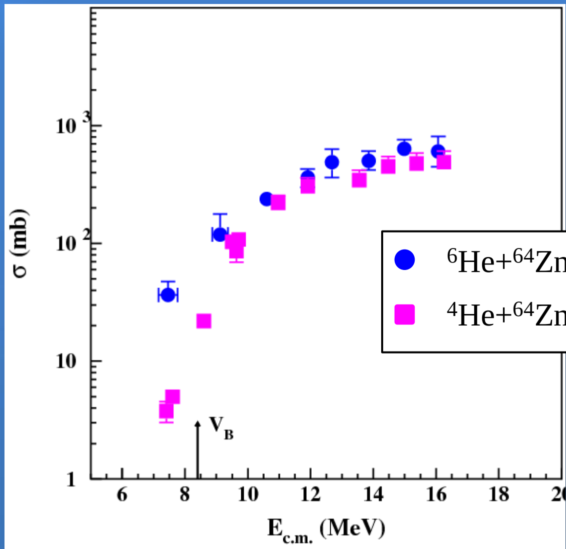
Enhancement of σ_{FUS} for ^6He with respect to σ_{FUS} for ^4He

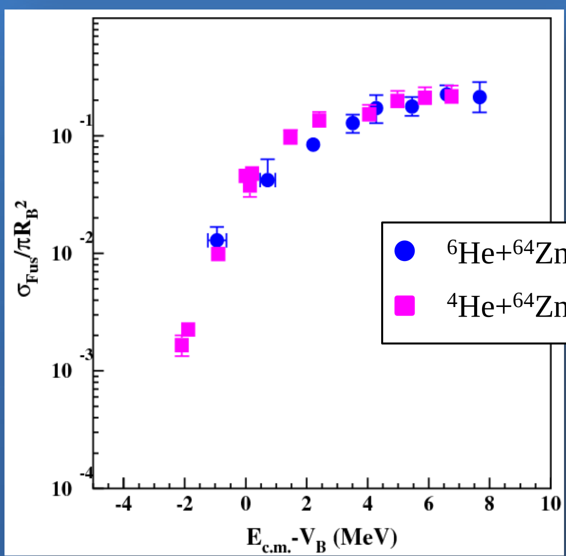


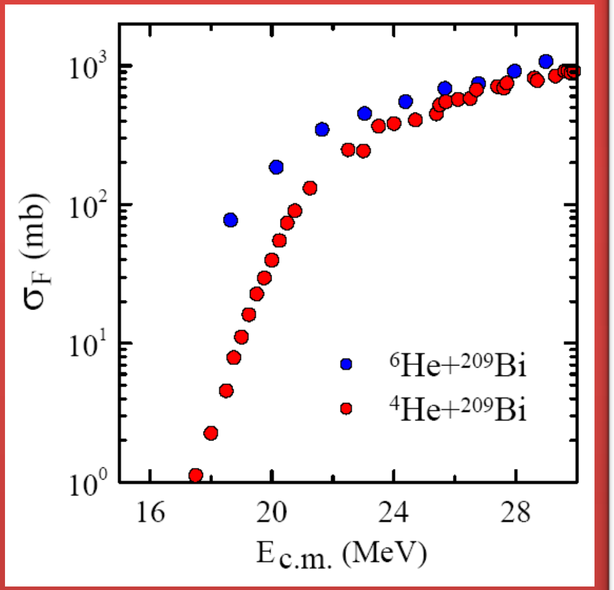
V_B and R_B from double folding Sao Paulo potential.
From this comparison it seems that the observed enhancement is due to static effects.

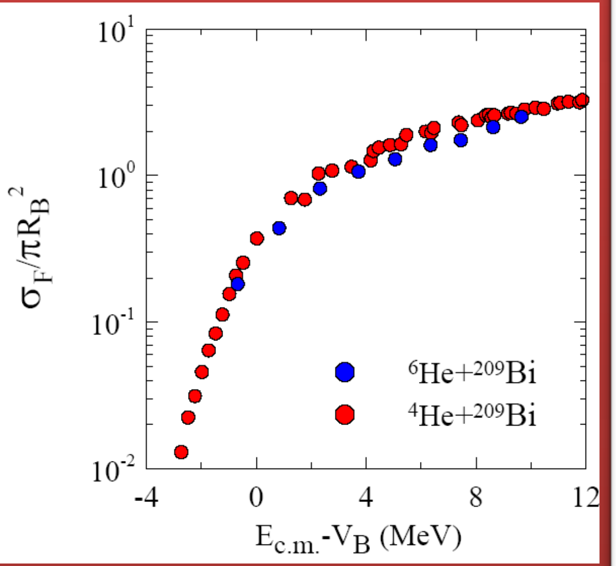
V.Scuderi et al. PRC 84, 064604(2011)

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





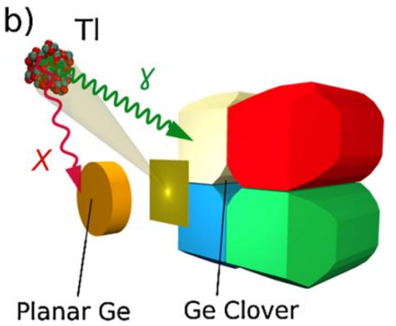




L.F. Canto et al.
NP A 821 (2009) 51

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

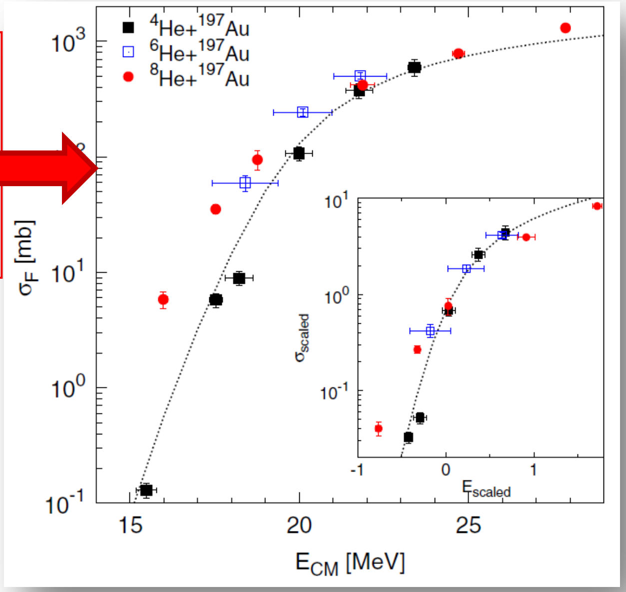
$^{4,6}He+^{197}Au$ @ DUBNA and $^{8}He+^{197}Au$ @ GANIL



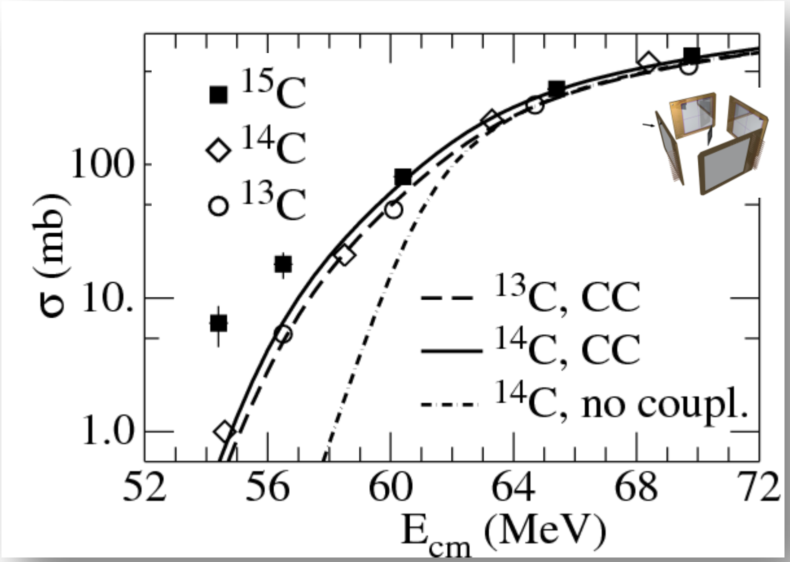
Activation techniques used.
Off-line γ and γ-X coincidences measured.

Enhancement of σ_{FUS} for $^{6,8}He$ with respect to σ_{FUS} for ^{4}He.

A.Lemasson et al, PRL 103,232701,(2009)
Yu.E.Penionzhkevich et al, EPJ A31,185,(2007)



$^{13,14,15}C+^{232}Th$



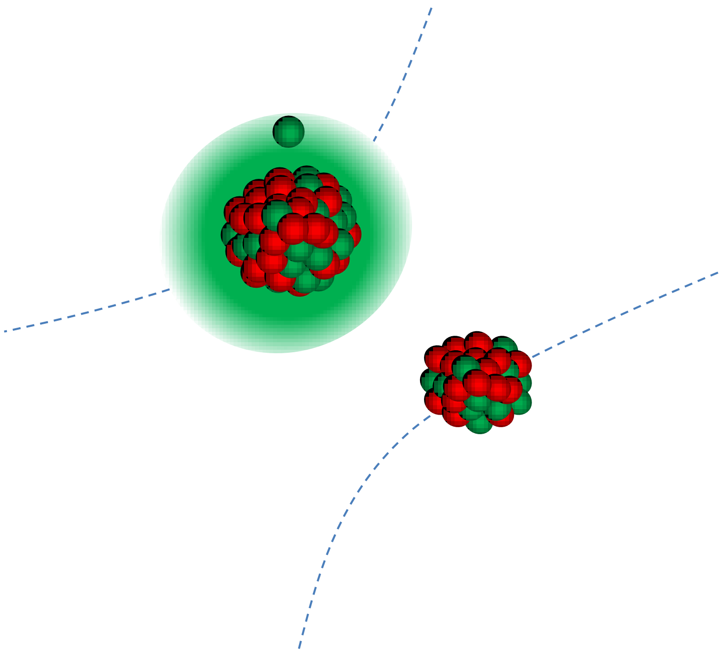
Alcorta et al. PRL 106, 172701 (2011)

Fusion-fission cross-section
Enhancement of σ_{FUS} for ^{15}C with respect to σ_{FUS} for ^{14}C or CC calculations where the ^{15}C structure is not considered

p-halo vs n-halo

p-halo at Coulomb barrier not well studied due to luck of available beams.

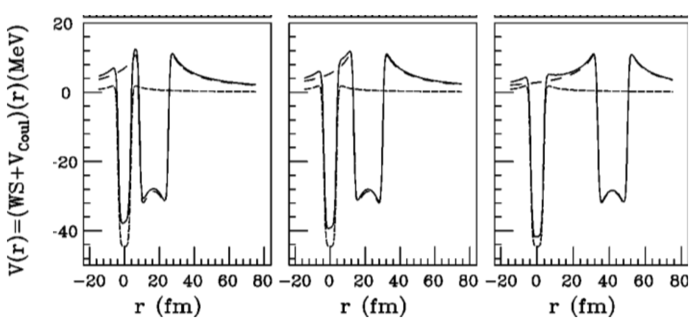
Differences with n-halo: dynamical polarization effect→ reduction of break-up probability.



For p-halo systems nuclear break-up accounts for ≈ 0.5 total break-up cross section.
Coulomb coupling is not the dominat contribution to break-up.

The effect of p-target potential in addition to the core-target one create an effective barrier which makes the p-halo more bound.

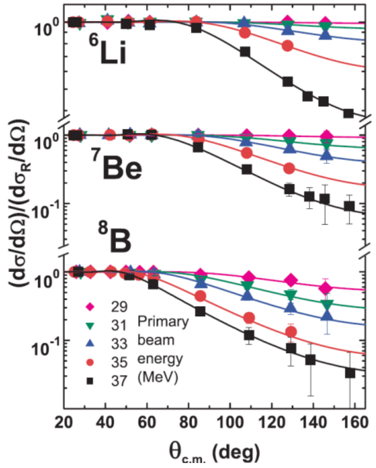
$^{17}F+^{208}Pb$ potentials at different distances from the centers.



A. Bonaccorso et al. PRC 69, 024615 (2004)

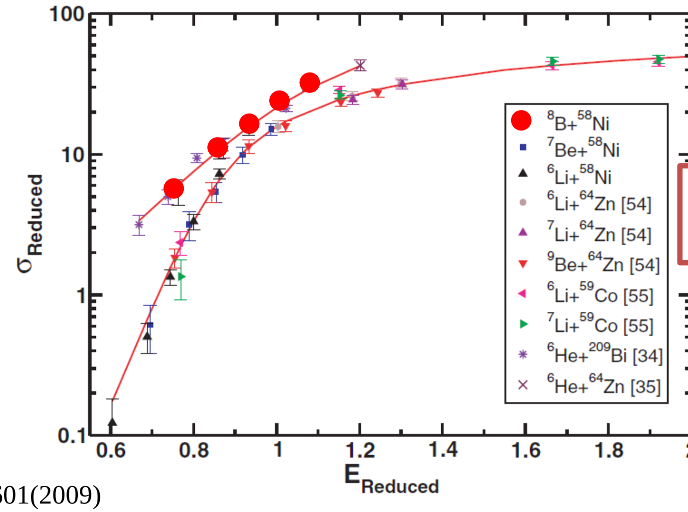
p-transfer small due to Coulomb barrier
N.Keeley et l. Prog.Part.Nucl.Phys. 63,396(2009)

Elastic scattering angular distribution on ^{58}Ni



^{8}B+^{58}Ni

Total reaction cross-section

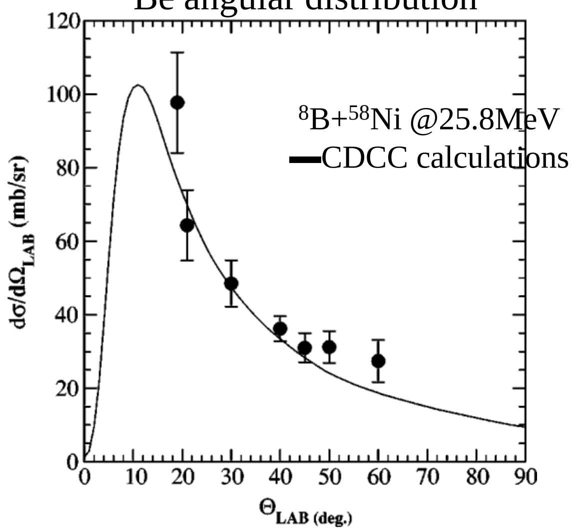


Agreement with n-halo results

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

Break-up

^{7}Be angular distribution



Coulomb-nuclear interference at large distances important

J.J.Kolata et al. PRC63(2001)024616

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-section e.g. $\sigma_{rea}(^{11}Be) > 2\ \sigma_{rea}(^{9,10}Be)$.

✓Large cross-section for transfer and breakup events. Exclusive measurements have shown that in n-halo induced reactions the n-transfer larger than break-up.

✓Fusion induced by 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. However very few data exist at low energy.

Collaboration

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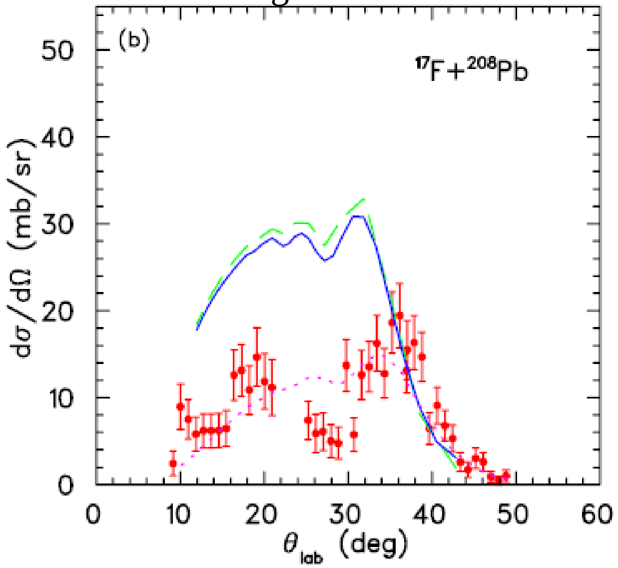
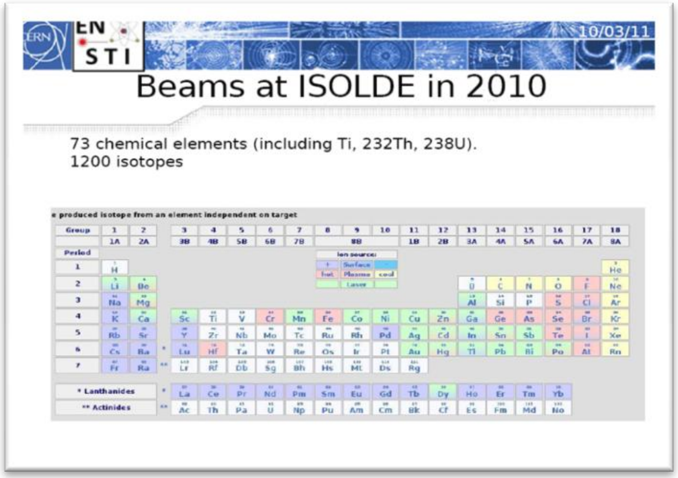
^{16}O angular distribution



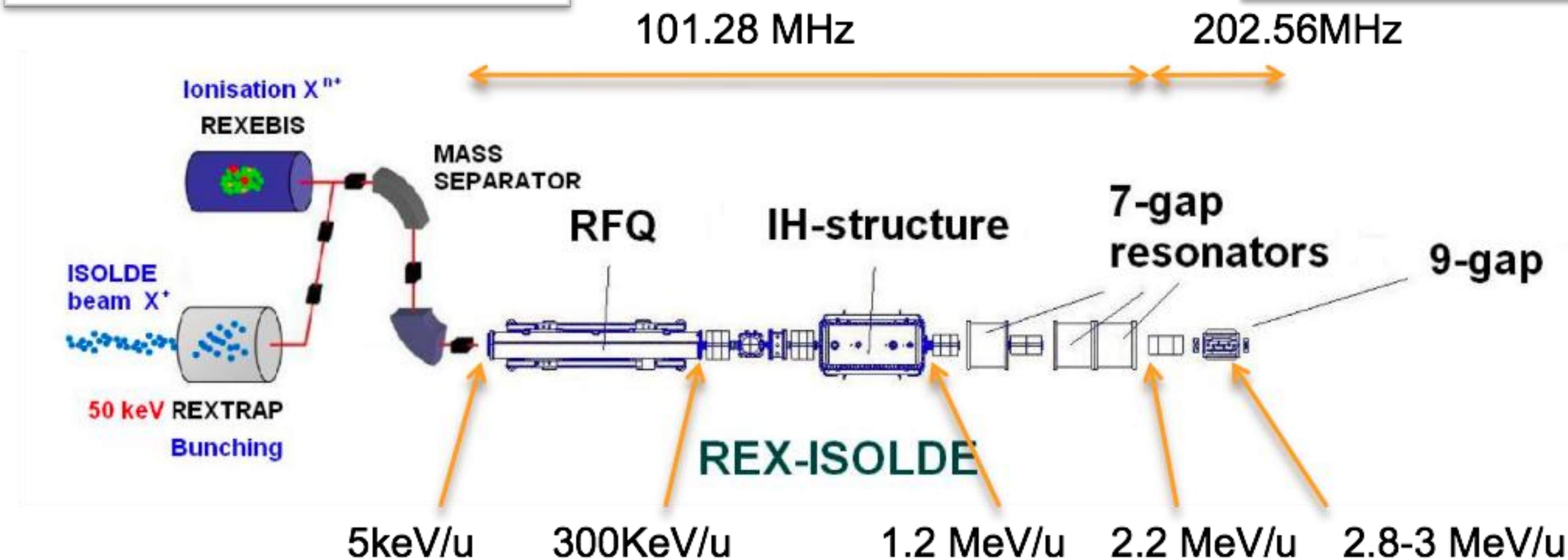
J.F.Liang et al. PLB681(2009)22

$^{10,11}Be + ^{64}Zn$ @ REX-ISOLDE



REX-ISOLDE post accelerator
all elements can be post-accelerated to 3 MeV/u.
HI-Isolde→upgrade to 10MeV/u.

- **$I(^{10}Be) \approx 10^6$ pps**
- **$I(^{11}Be) \approx 10^4$ pps**



Fusion: low energy RIBs - tunneling through the barrier