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Fusion, breakup and scattering of light unstable nuclei

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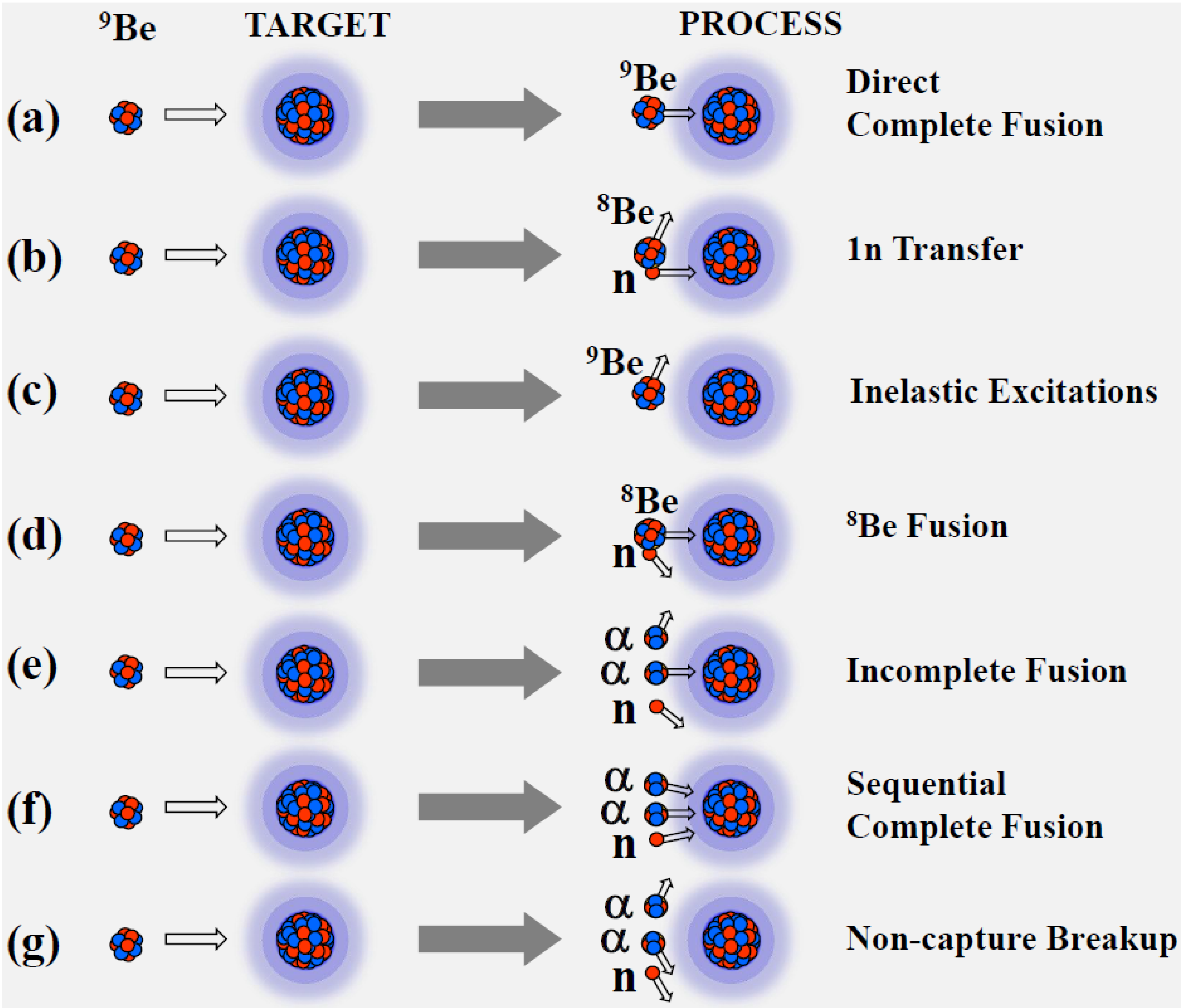
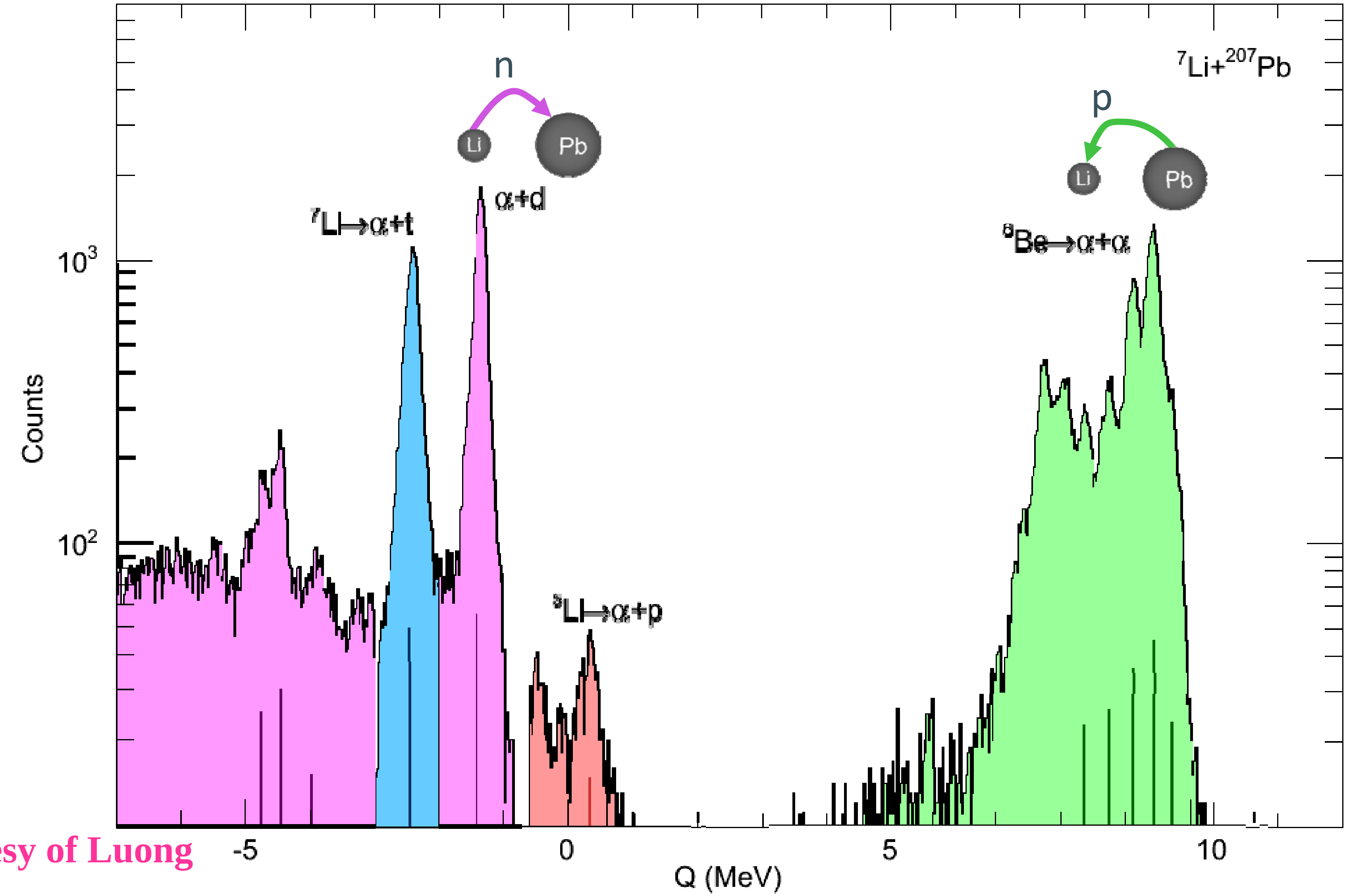
Reactions with weakly bound nuclei – example with ^{9}Be



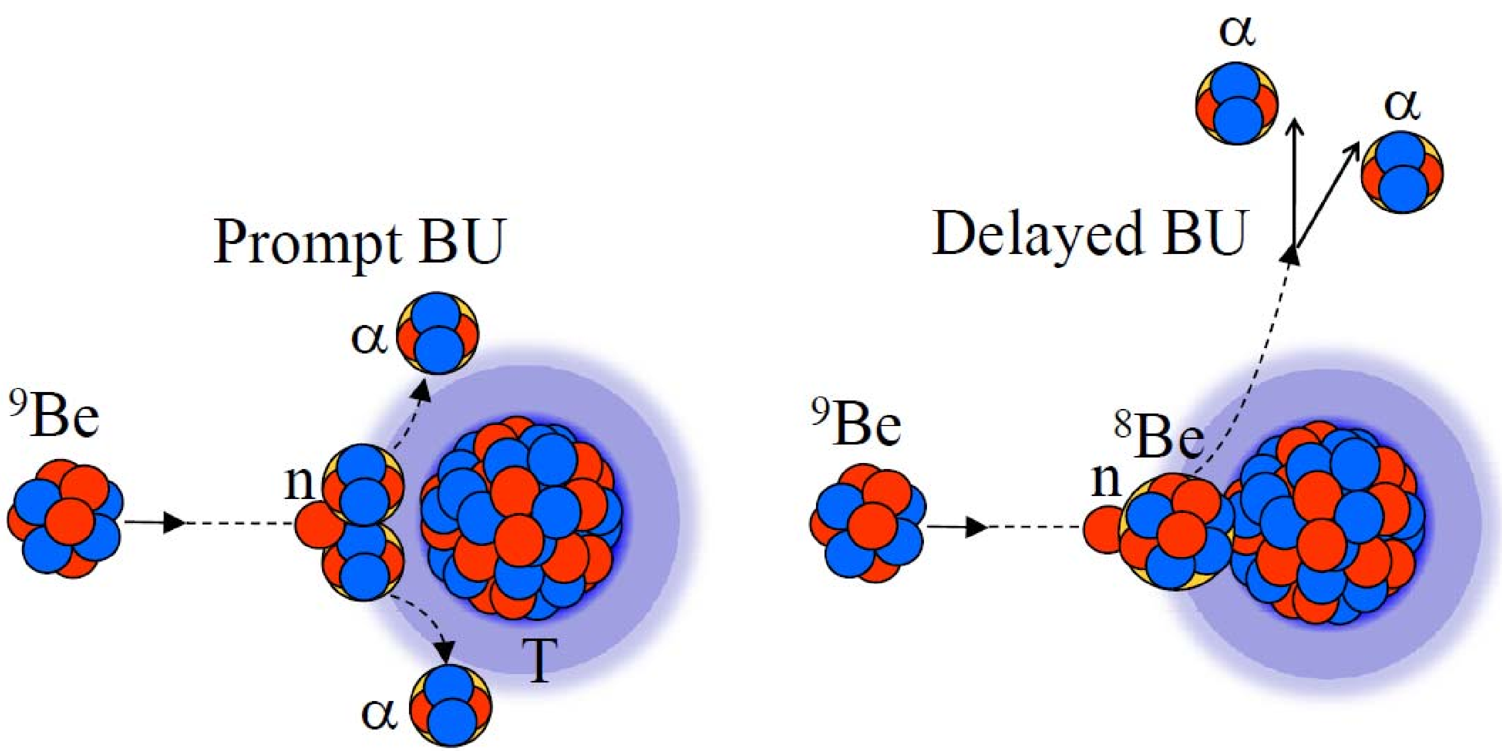
However, nature is even more complicated than that simple picture: Breakup following transfer

RESULTS



Courtesy of Luong

Breakup time scale

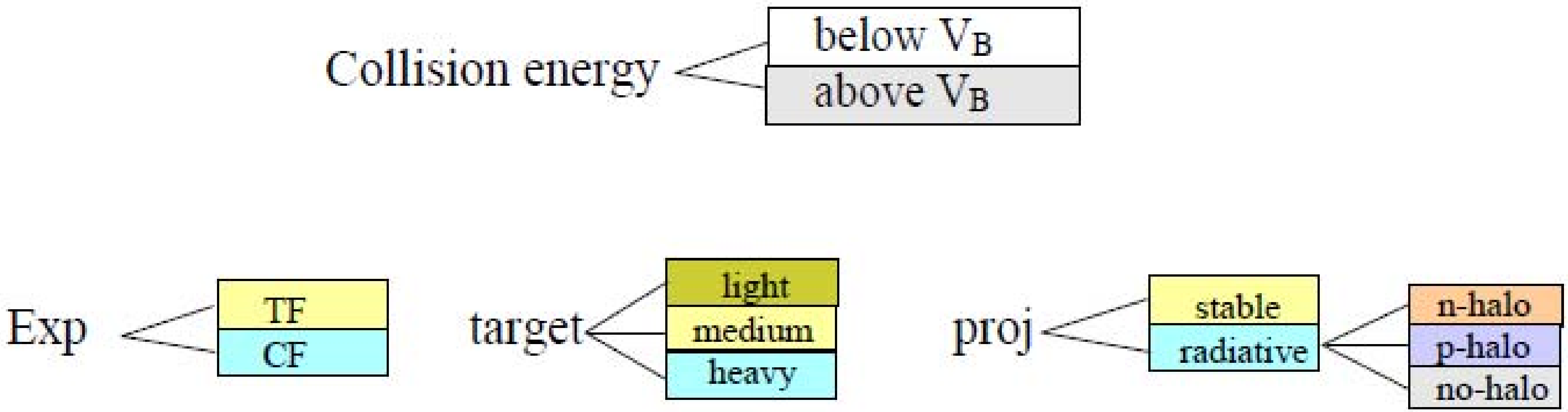


Only prompt breakup may affect fusion

Questions that we investigate and try to answer

- -Does the BU channel enhance or suppress the fusion cross section? Is the effect on σ_{CF} or $\sigma_{TF= CF + ICF}$?
- -What are the effects on different energy regimes and on different target mass regions?
- What is the relative importance between nuclear and Coulomb breakups? Do they interfer ?
- How large is the σ_{NCBU} compared with σ_{CF} ? How does it depend on the energy region and target mass?

Different answers, depending on several things



Very important question

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

Frequently used procedures to answer “Enhancement or suppression in relation to what?

a) Comparison of data with theoretical predictions.

b) Comparison of data for weakly and tightly bound systems.

Effects to be considered

- **Static effects:** longer tail of the optical potential arising from the weakly bound nucleons.

- **Dynamical effects:** strong coupling between the elastic channel and the continuum states representing the break-up channel.

1. Experiment vs. theory

$\Delta\sigma_F \equiv \sigma_F^{exp} - \sigma_F^{theo} \Rightarrow$ 'ingredients' missing in the theory

Theoretical possibilities:

a) Single channel - standard densities

$\Delta\sigma_F$ arises from all static and dynamic effects

b) Single channel - realistic densities

$\Delta\sigma_F$ arises from couplings to all channels

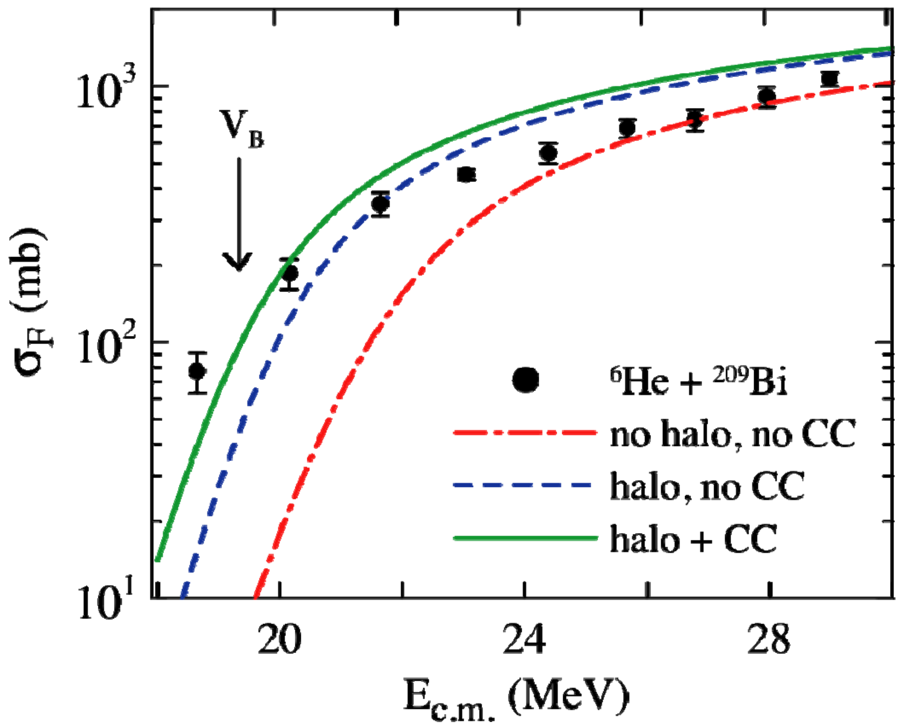
c) CC calculation with all relevant bound channels

$\Delta\sigma_F$ arises from continuum couplings

d) CDCC

no deviation expected

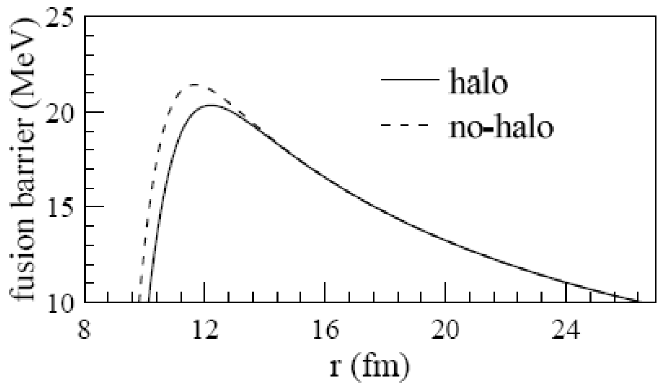
Example: $^{6}He + ^{209}Bi$



Single channel - no halo

Single channel – with halo

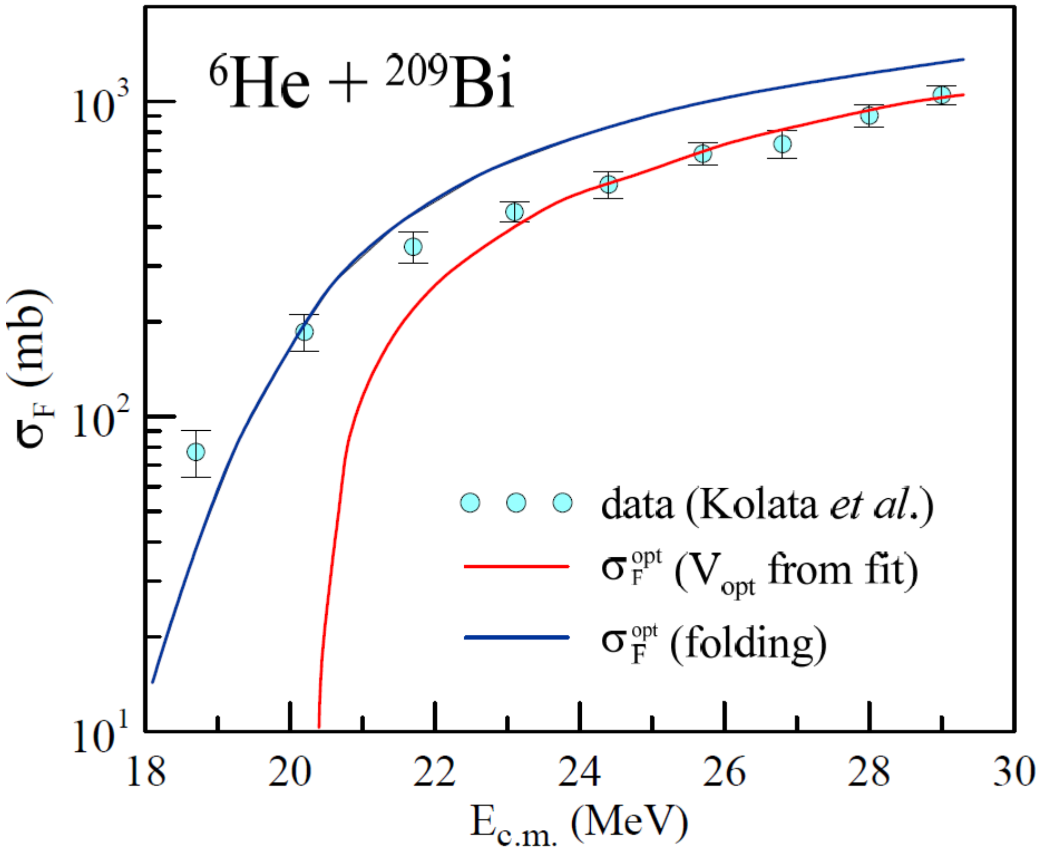
CC with bound channels
(schematic calculation)



Shortcomings of the procedure:

- Choice of interaction plays fundamental role
- Does not allow comparisons of different systems
- Difficult to include continuum – no separate CF and ICF

Example of Model Dependent Conclusions

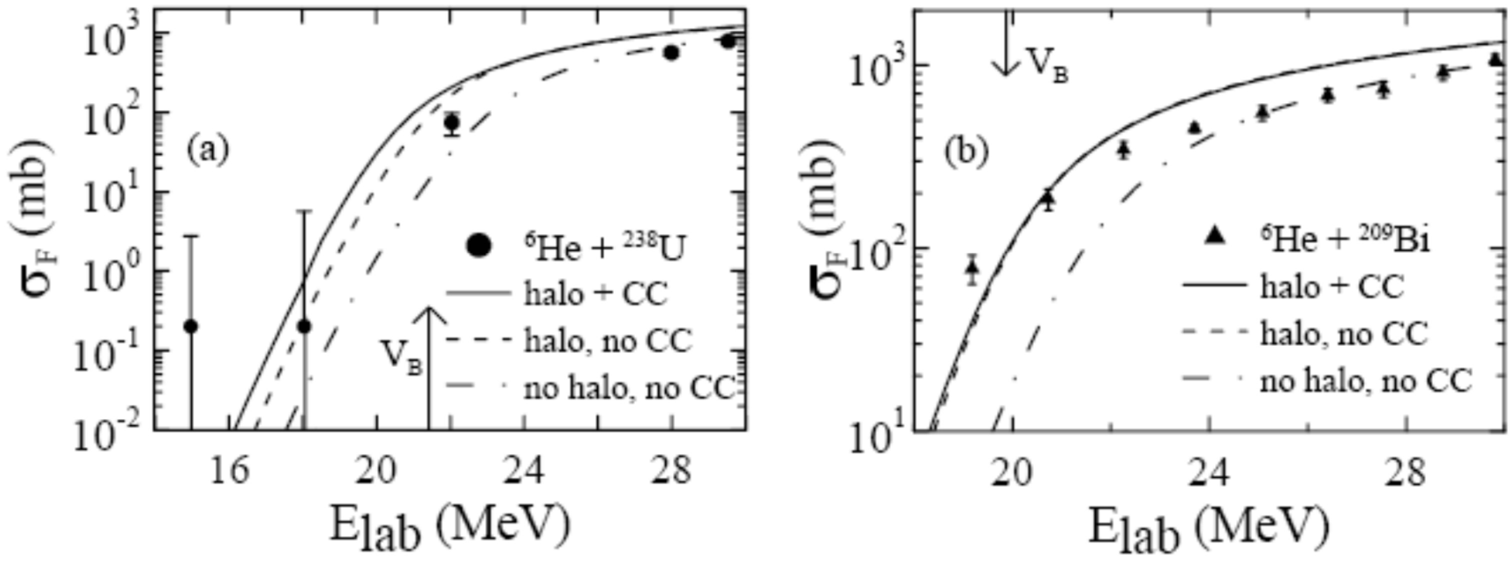


Kolata et al., PRL 81, 4580 (1998)

Gomes et al., PLB 695, 320 (2011)

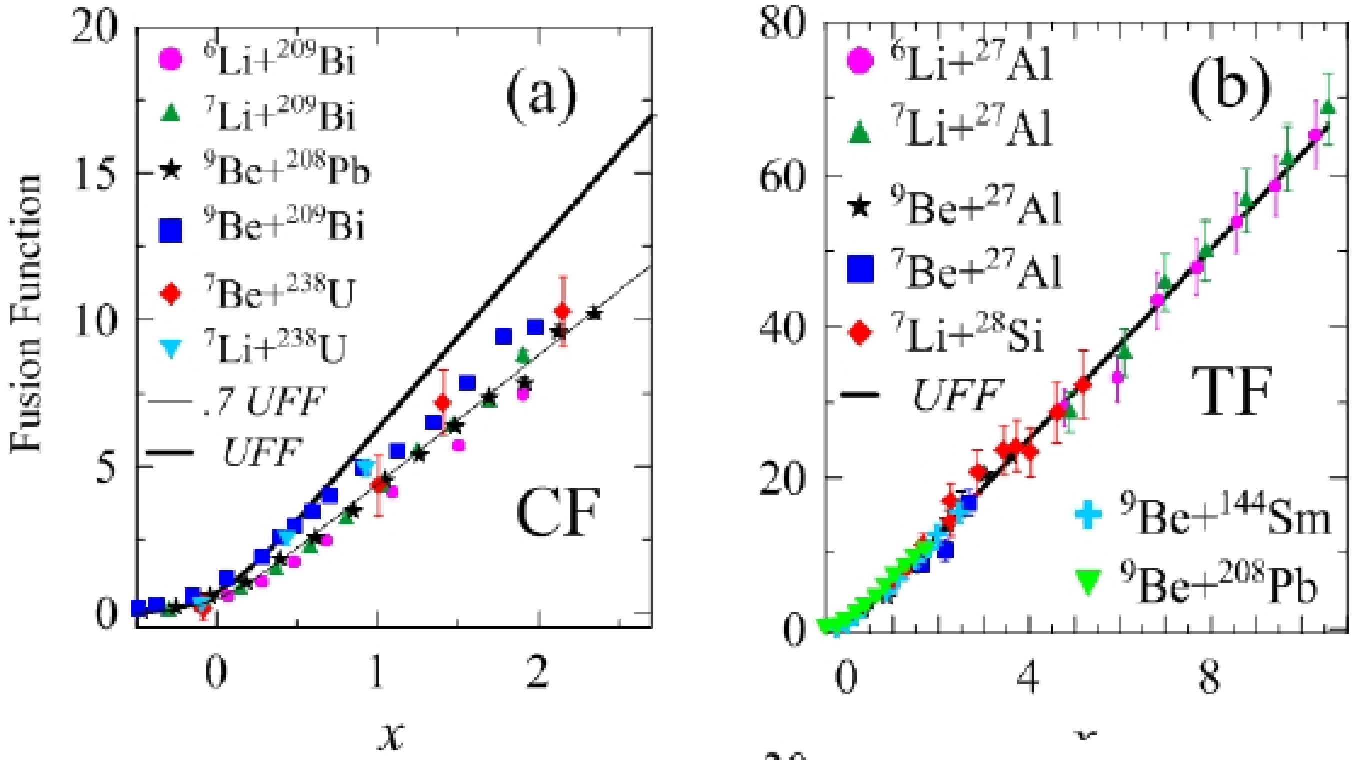
Old controversy between Kolata`s and Raabe`s data (6He + 209Bi and 238U)

Important: Bare Potential deduced from double-folding procedure



Gomes et al., PLB 695, 320 (2011)

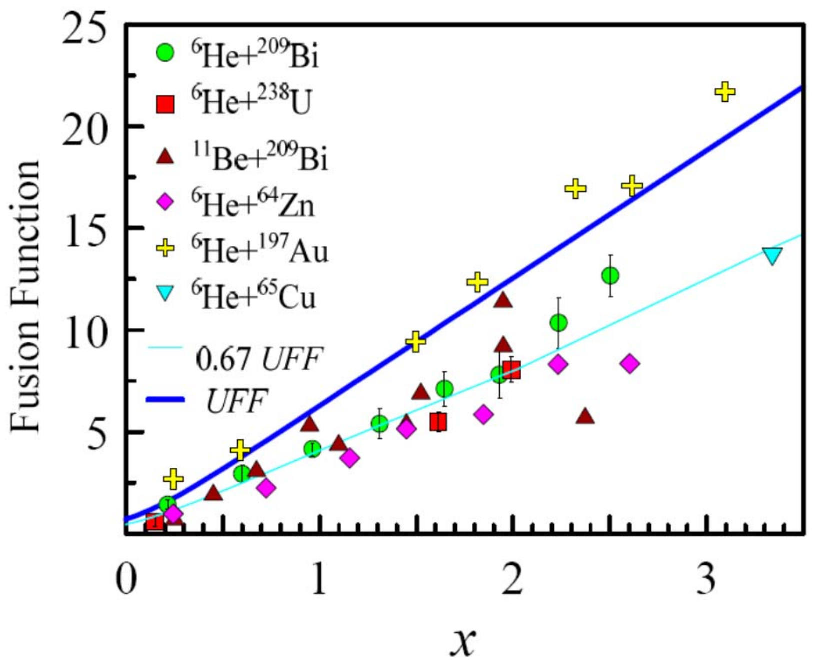
Systematics reached from the investigation of he role of BU dynamical effects on the complete and total fusion of stable weakly bound heavy systems

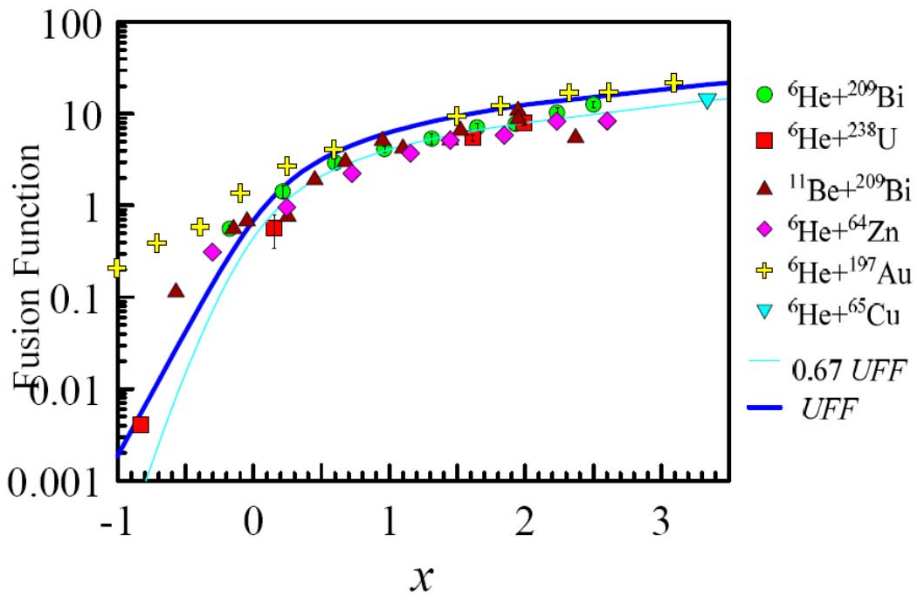


We did not include any resonance of the projectiles in CCC.

Suppression above the barrier- enhancement below the barrier

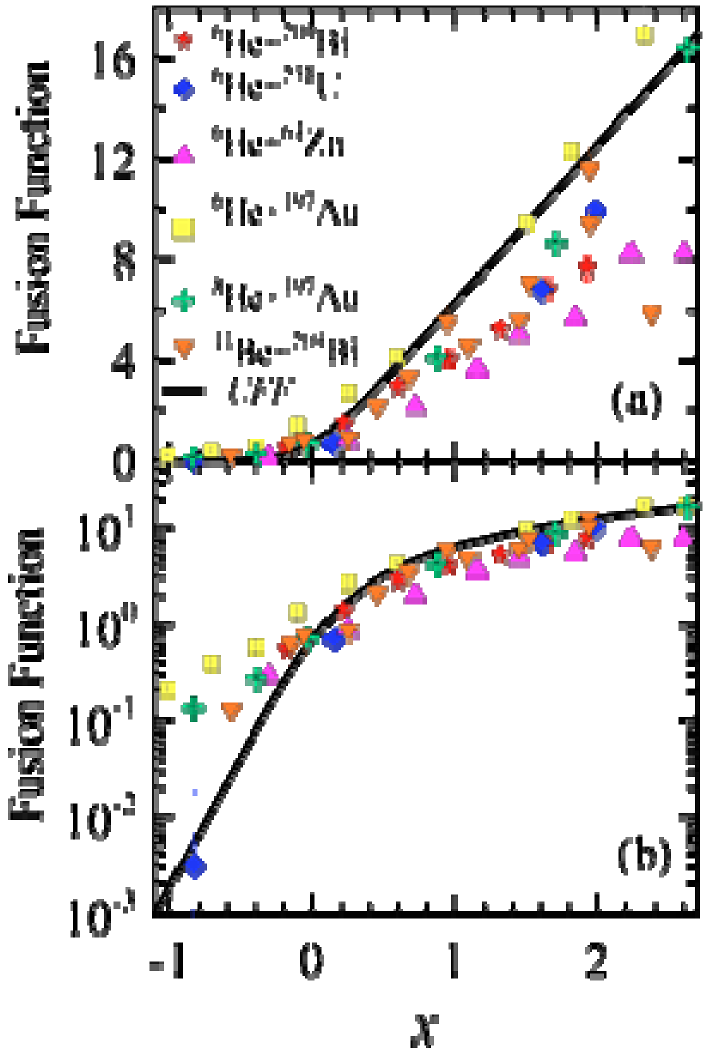
Systematics reached from investigation of the role of BU dynamical effects on fusion of neutron halo ^{6}He, ^{11}Be weakly bound systems



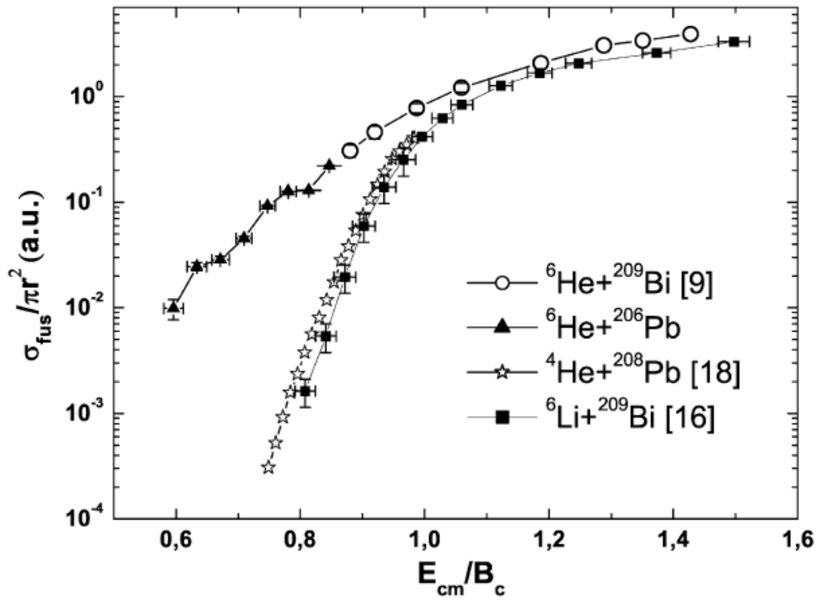


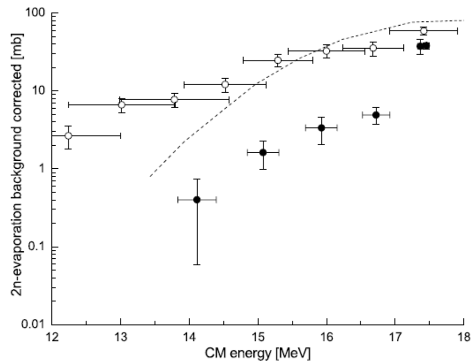
Suppression above the barrier- enhancement below the barrier

Fusion of neutron halo $^{6,8}He$, ^{11}Be weakly bound systems



Controversy on 6He + 206Pb fusion

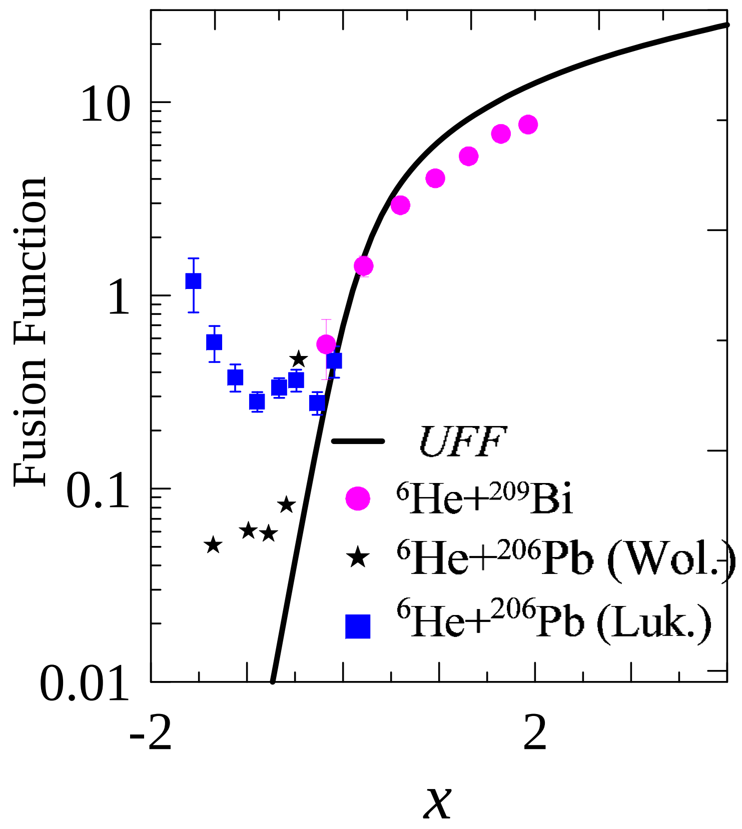




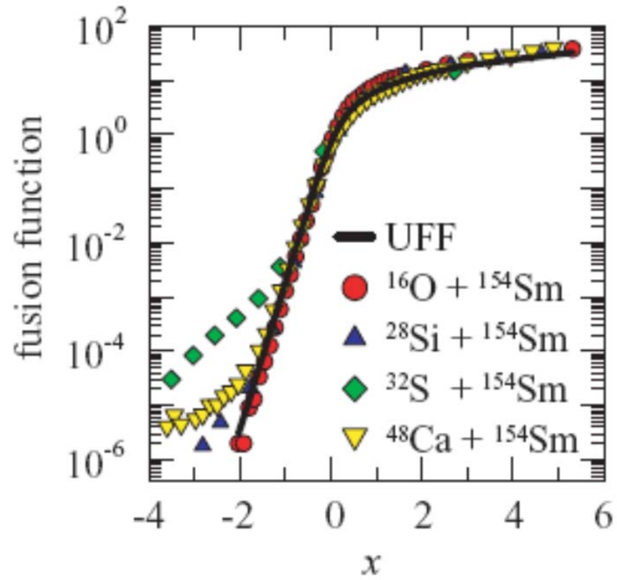
Lukyanov PLB 670, 321 (2009)

Wolski- EPJA 47, 111 (2011)

How are the fusion functions?



Transfer effect on sub-barrier fusion fucntion



Shorto PRC 81, 044601 (2010)

Conclusion from the systematics (several systems): CF enhancement at sub-barrier energies and suppression above the barrier, when compared with what it should be without any dynamical effect due to breakup and transfer channels.

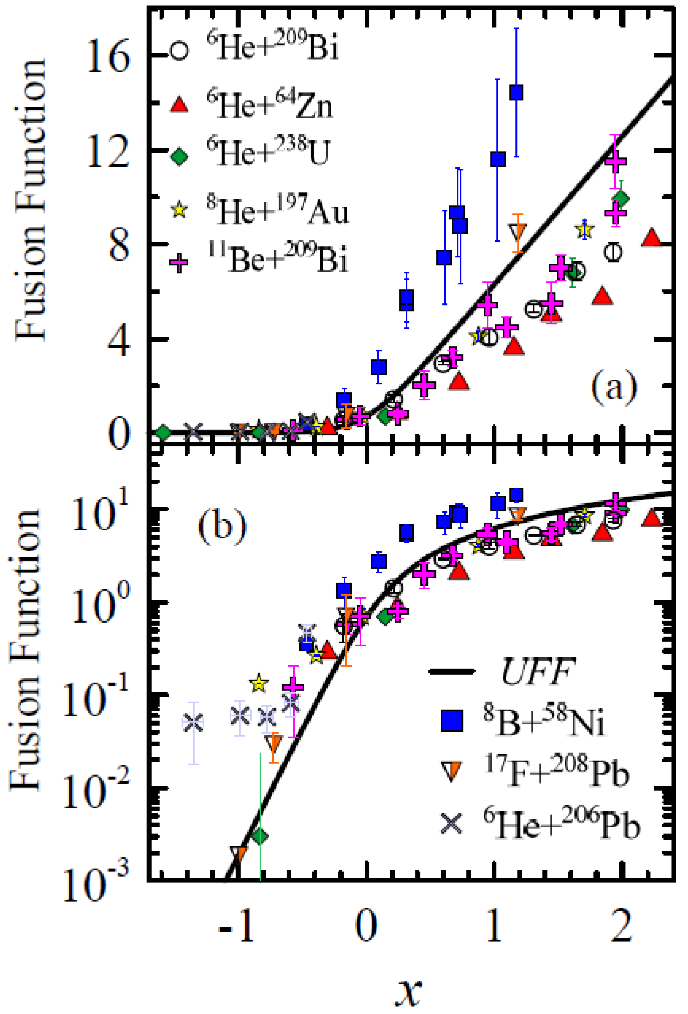
What about proton-halo systems?

Up to recently, there was only one system measured

- **Fusion of proton-halo $^{8}B + {}^{58}Ni$**

Aguilera PRL 107, 092701 (2011)

Fusion of proton-halo $^{8}B + ^{58}Ni$



New dynamic effect for proton-halo fusion?

Or

Something wrong with the data?

Rangel et al., EPJA 49, 57 (2013)

Some details of Aguilera's derivation of fusion cross section

Fusion cross section was obtained by measuring proton multiplicities.

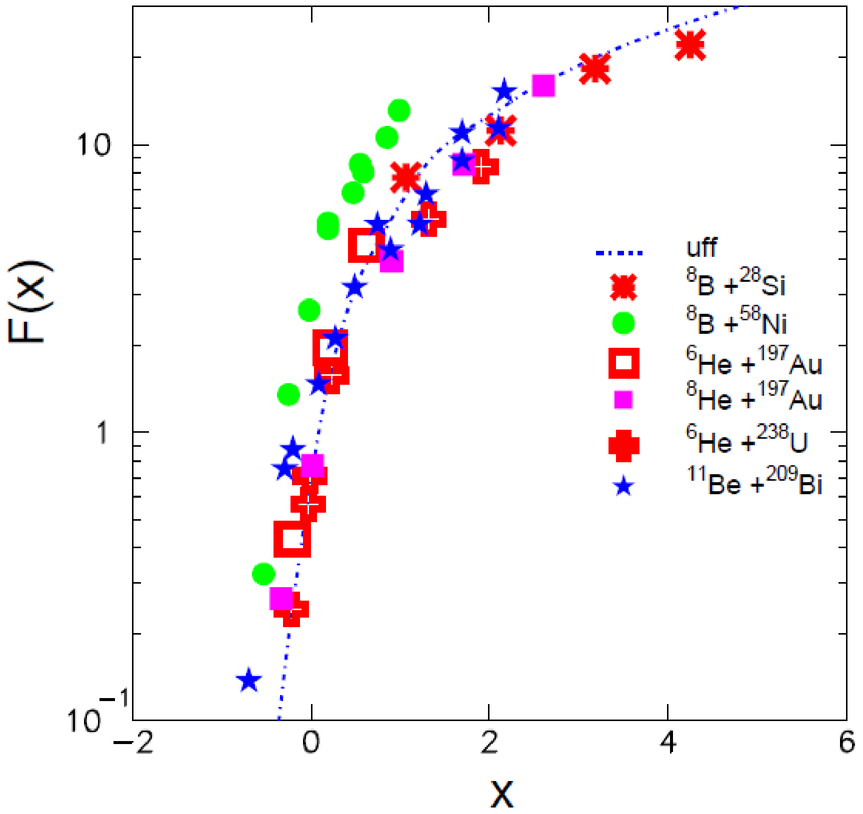
It was assumed that all protons detected at backward angles come from fusion evaporation, and no protons from breakup reach the detectors, based on CDCC calculations by Tostevin-Nunes-Thompson.

However, see what happens for ^{6,7}Li at sub-barrier energies (measurements at ANU (Canberra). They measured NCBU by detecting charged fragments at backward angles.

Other recent result: Fusion of $^{8}B + ^{28}Si$

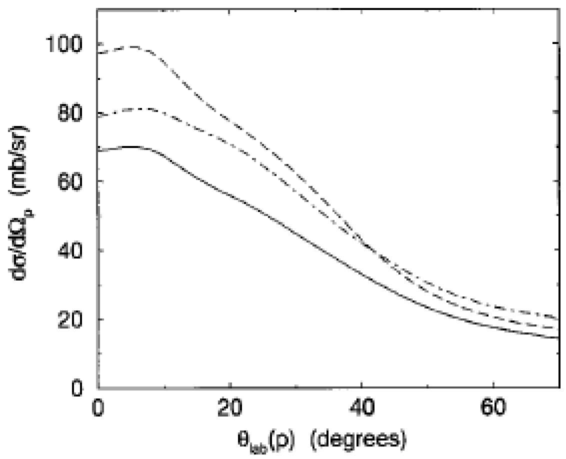
Pakou et al. PRC 87, 014619 (2013)

Measurements at Legnaro. Fusion cross sections derived from alpha measurements (there is no alpha from BU)



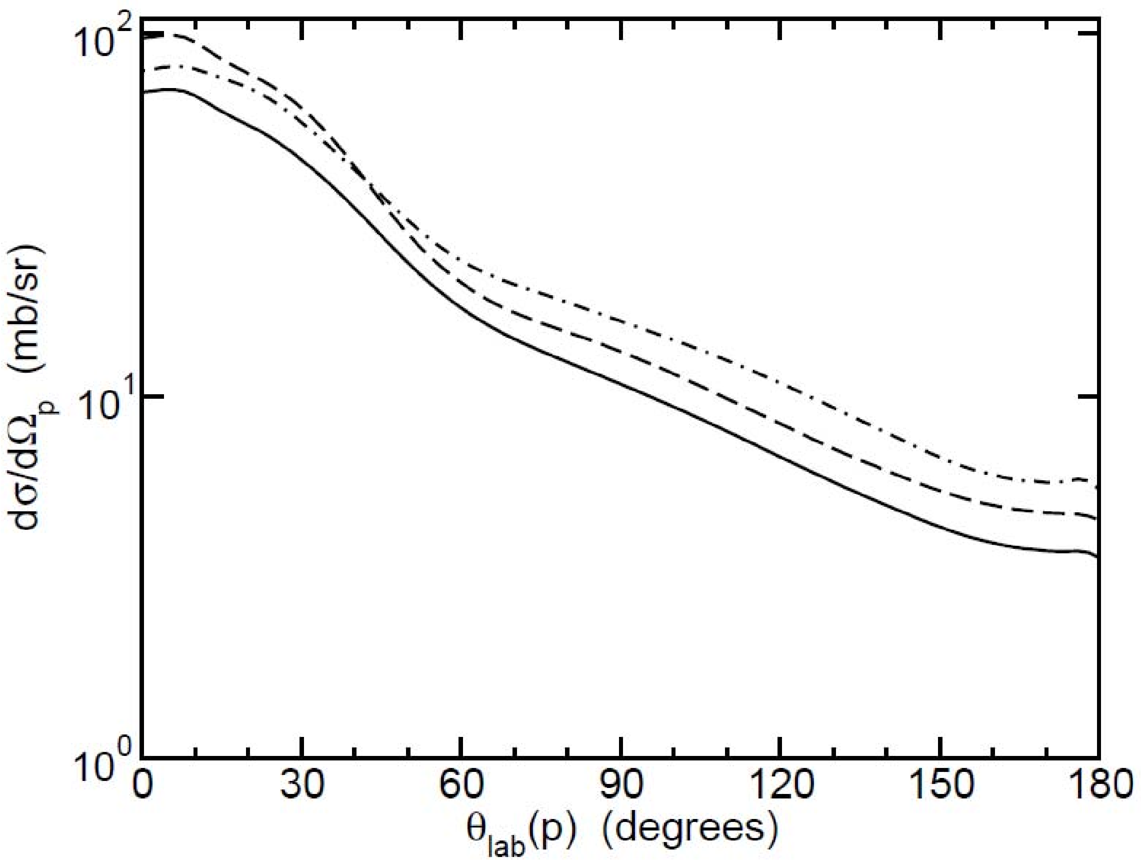
Normal behavior, within our systematic!!!

Calculations by Tostevin, Nunes and Thompson used by Aguilera to say that no breakup protons reach the detectors placed at backward angles (PRC 63, 024617 (2001))



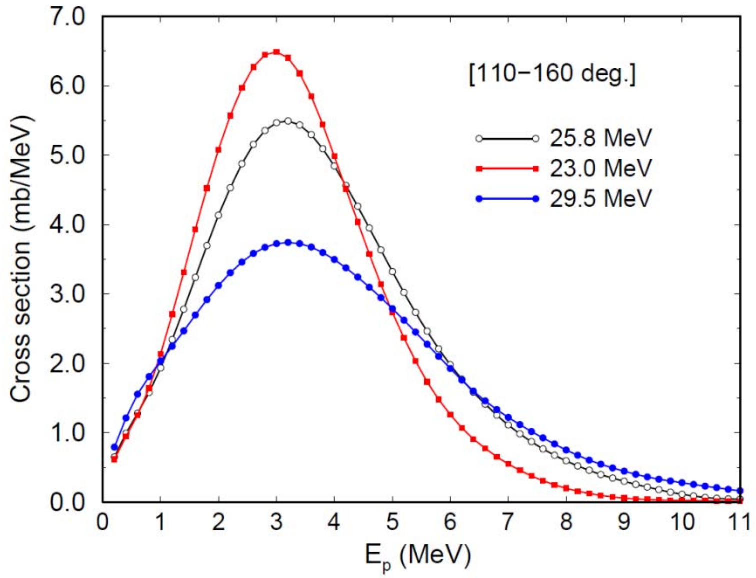
Does it go to zero at backward angles?

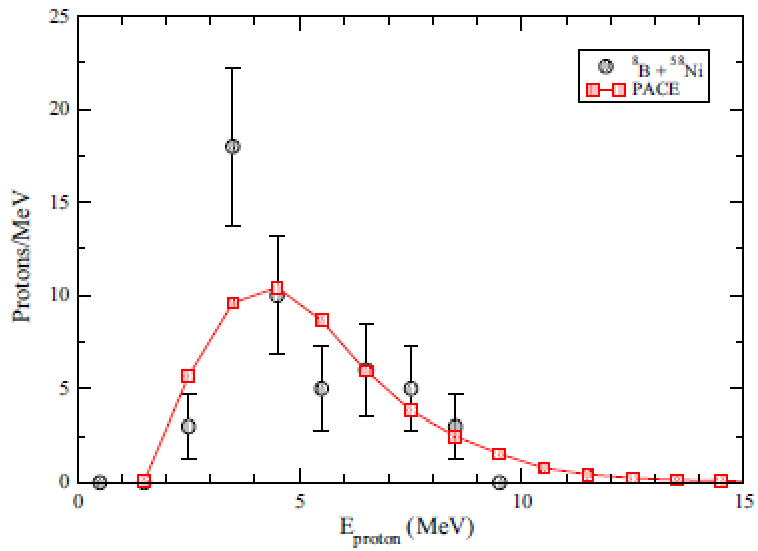
Tostevin extended the calculations up to 180 degrees (for us)



It does not vanish at large angles!!!!

Furthermore, see the proton spectra and Tostevin calculations





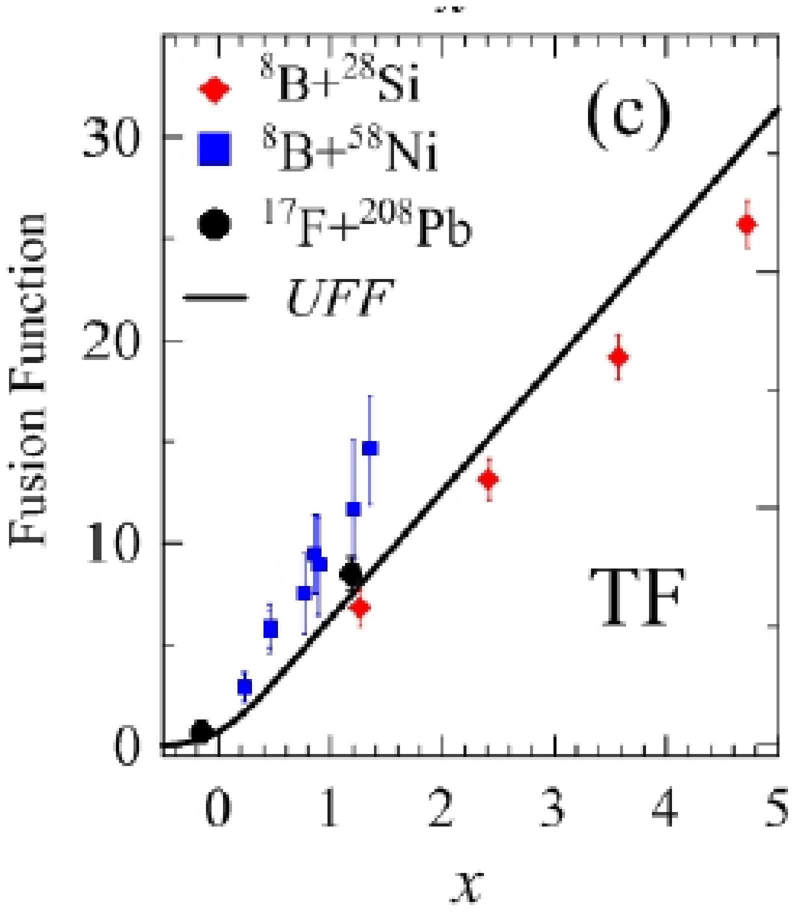
Prediction for BU protons at E_{lab} = 25.8 MeV (Tostevin)

Experimental "evaporation" protons at E_{lab} = 22.4 MeV (Aguilera)

Rangel et al., EPJA 49, 57 (2013)

How can one separate experimentally protons from fusion and breakup?

We believe that there is nothing special with fusion of proton-halo nuclei

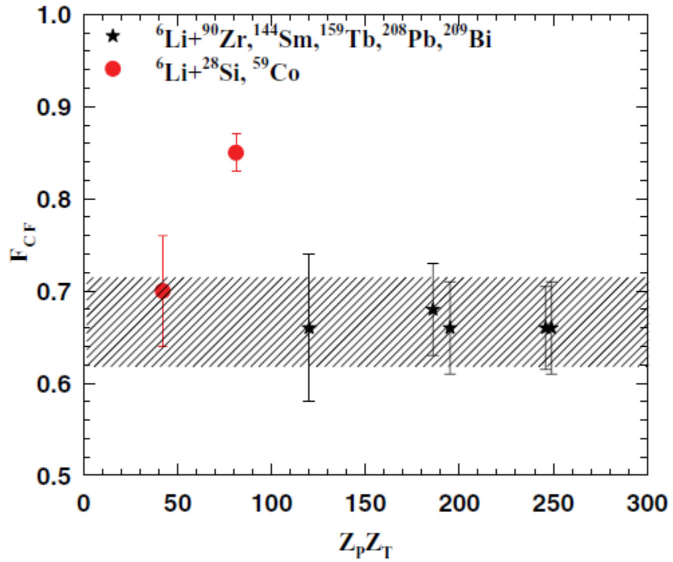


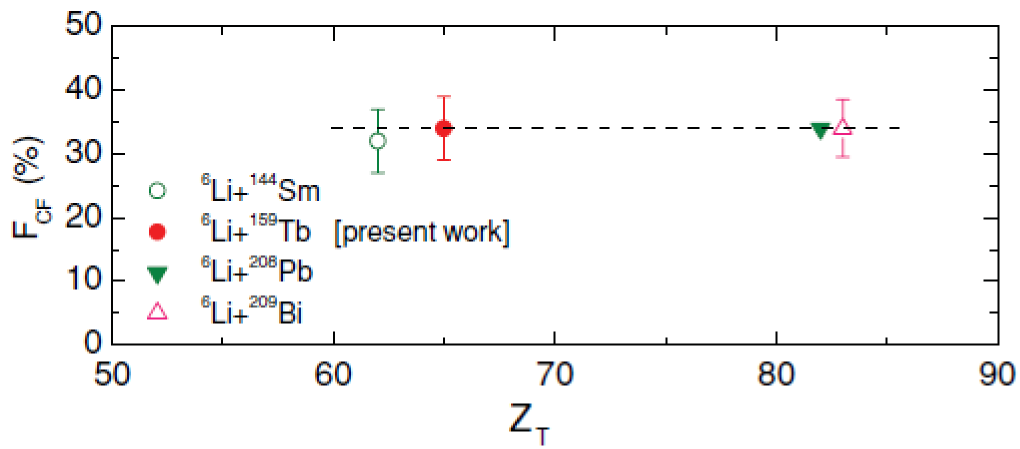
So, the next question is:

How does the BU vary with target mass (or charge)? Coulomb and nuclear breakups: Is there interference between them?

One believes that the BU depends on the target mass (charge).

Effect of the ^{6}Li BU on CF cross sections





Kumawat – PRC 86, 024607 (2012)

Pradhan – PRC 83, 064606 (2011)

The BU effect on fusion does not seem to depend on the target charge!!!!

Interference between Coulomb and nuclear breakups

E_{lab}	σ^{BU}_{Nuc}	σ^{BU}_{Cou}	σ^{BU}_{tot}	$(\sigma^{BU}_{tot} - \sigma^{BU}_{Nuc}) / \sigma^{BU}_{Cou}$
^{6}Li + ^{59}Co				
11.0	0.84	1.44	1.11	0.19
13.0	4.33	5.31	5.68	0.25
14.0	8.72	9.27	11.56	0.31
^{6}Li + ^{144}Sm				
22.0	11.3	22.1	18.8	0.34
25.0	30.0	41.6	48.0	0.43
27.0	43.6	57.3	69.6	0.45
^{6}Li + ^{208}Pb				
27.0	8.8	34.9	29.3	0.58
29.0	22.8	46.8	37.2	0.31
33.0	38.7	66.8	82.5	0.66

TABLE I. Integrated breakup cross section for the systems discussed in the text, for three collision energies. The energies are given in MeV and the cross sections in mb.

If there were were no interference, the last column should be unity.

What is the relative importance between breakup and fusion cross sections?

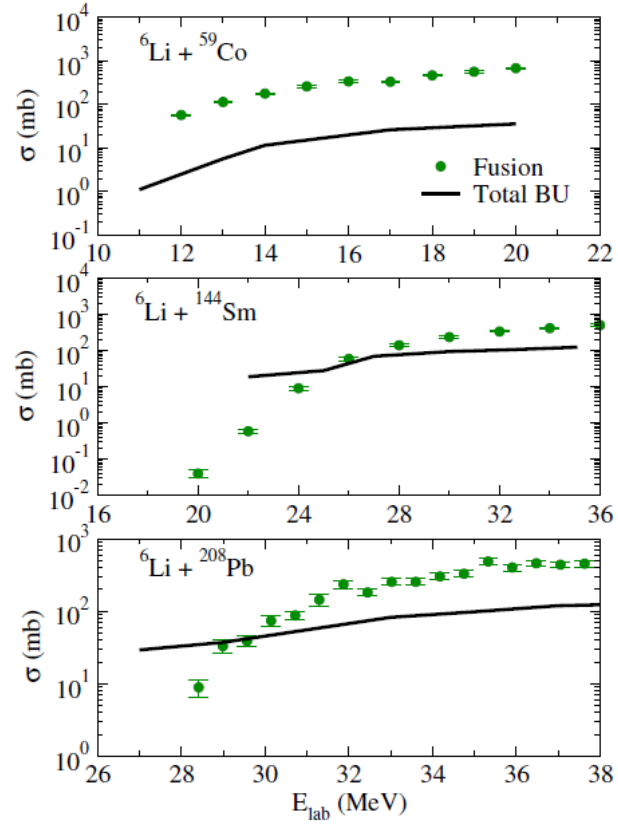
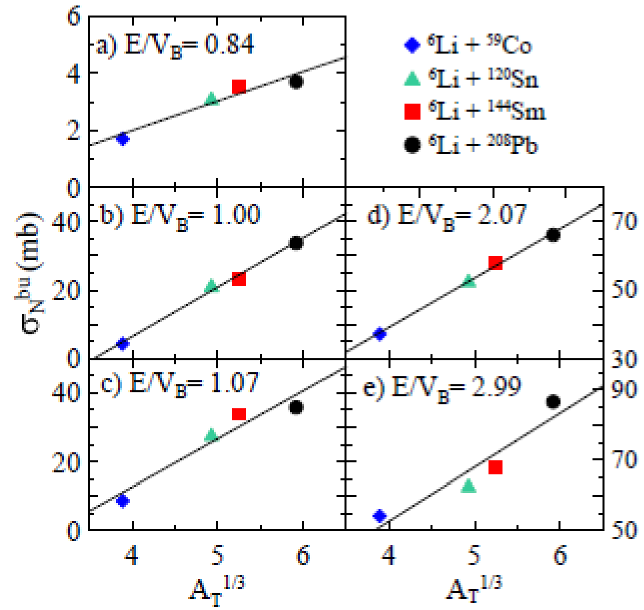
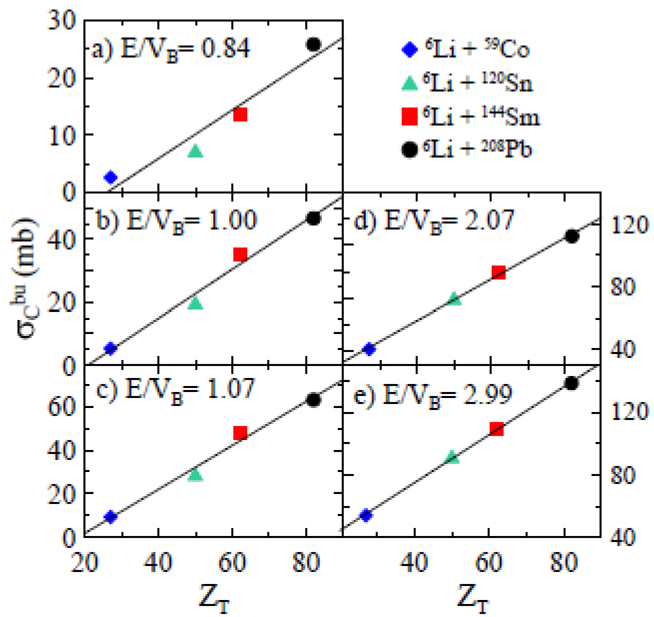


FIG. 7. (Color online) Comparison of fusion cross section with the breakup cross section for the three studied systems.

Otomar – PRC 87, 014615 (2013)

How does the BU vary with target mass (or charge)? Coulomb and nuclear breakups?





The nuclear BU increases linearly with A_T $^{1/3}$ for the same $E_{c.m.}/V_B$

The Coulomb BU increases linearly with Z_T for the same $E_{c.m.}/V_B$.

Hussein – PRC 88, 047601 (2013)

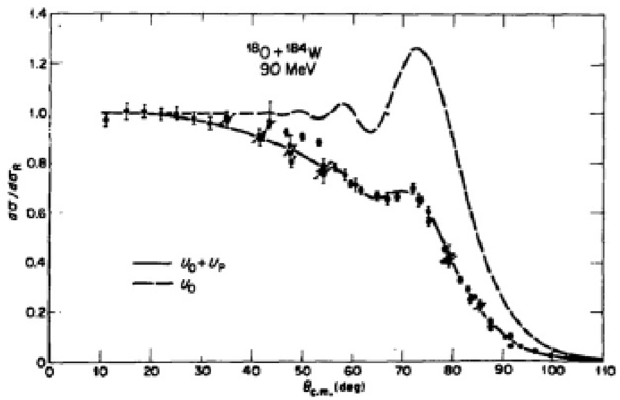
Conclusions

- **The relative importance between nuclear and Coulomb breakups is not so simple as it is usually thought.**
- **When one calculates BU cross sections with CDCC, one does not distinguish prompt and delayed BU. Most of the BU seems to be delayed and only the prompt BU affects fusion.**

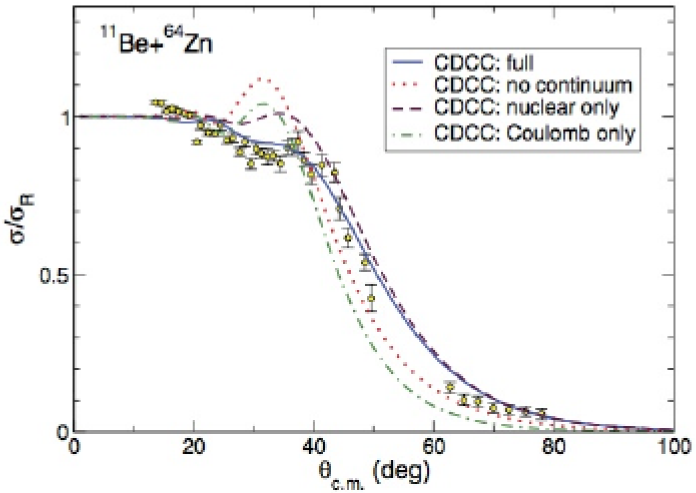
Thank you!!

Damping of the Fresnel diffraction bump (Coulomb rainbow)

If there is another long range potential (apart from the Coulomb dipole), there is a damping of the Fresnel diffraction:
-For highly deformed targets: Coulomb quadrupole)
-- For halo nulcei: extended nuclear form factor – coupling interaction has long range)

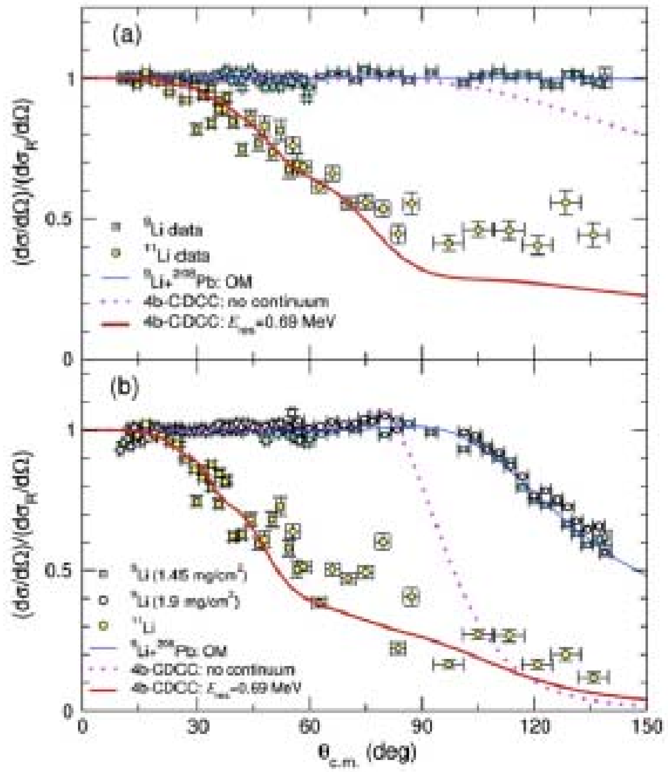


Love – NPA 291, (1977), 183

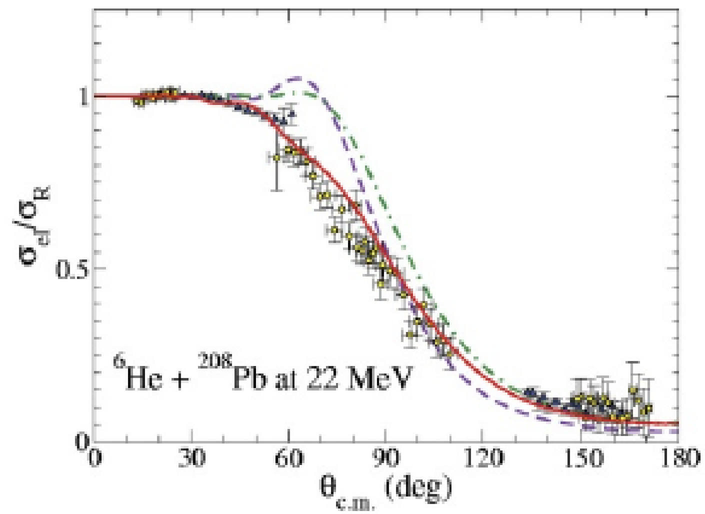


Di Pietro – PRC 85, 054607 (2012)

Other examples of the damping of Fresnel diffraction bump for halo nuclei



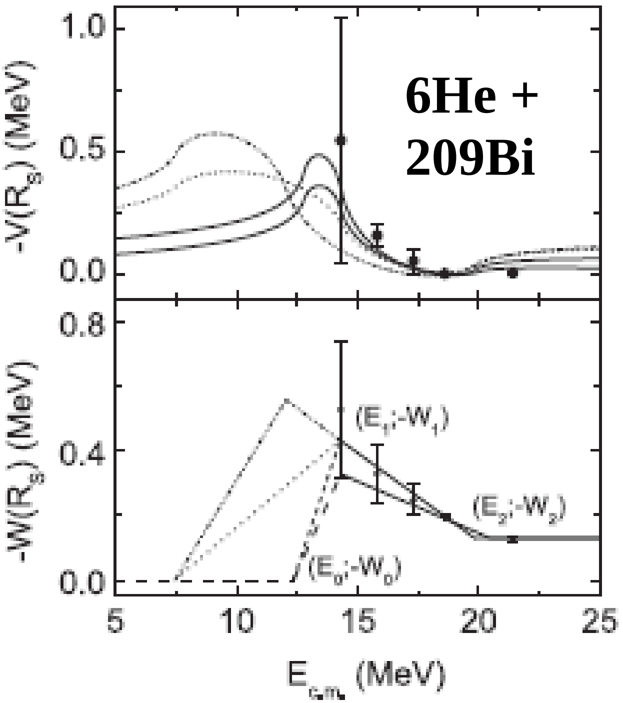
Cubero- PRL 109, 262701 (2012)



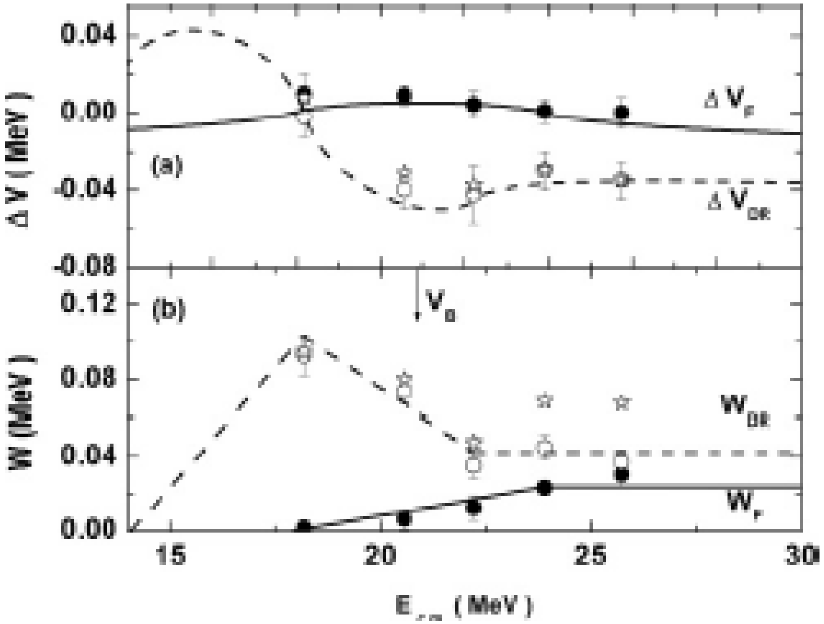
Acosta – PRC 84, 044604 (2011)

Breakup threshold anomaly in the scattering of halo nuclei

(evidence of repulsive BU polarization potential)



8B + 58Ni



Garcia – PRC 76, 067603 (2007)

Gomez-Camacho, PRC 84, 034615 (2011)