INSTITUTO DE FÍSICA
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Breakup of weakly bound nuclei and its influence on fusion

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Forum Brasil-JINR – Dubna , June, 2015

For a comprehensive review of this subject up to 2006: Phys. Rep. 424 (2006), 1-111

An update will come out later in 2015 or 2016

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Physics Reports 424 (2006) 1 – 111

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Fusion and breakup of weakly bound nuclei☆

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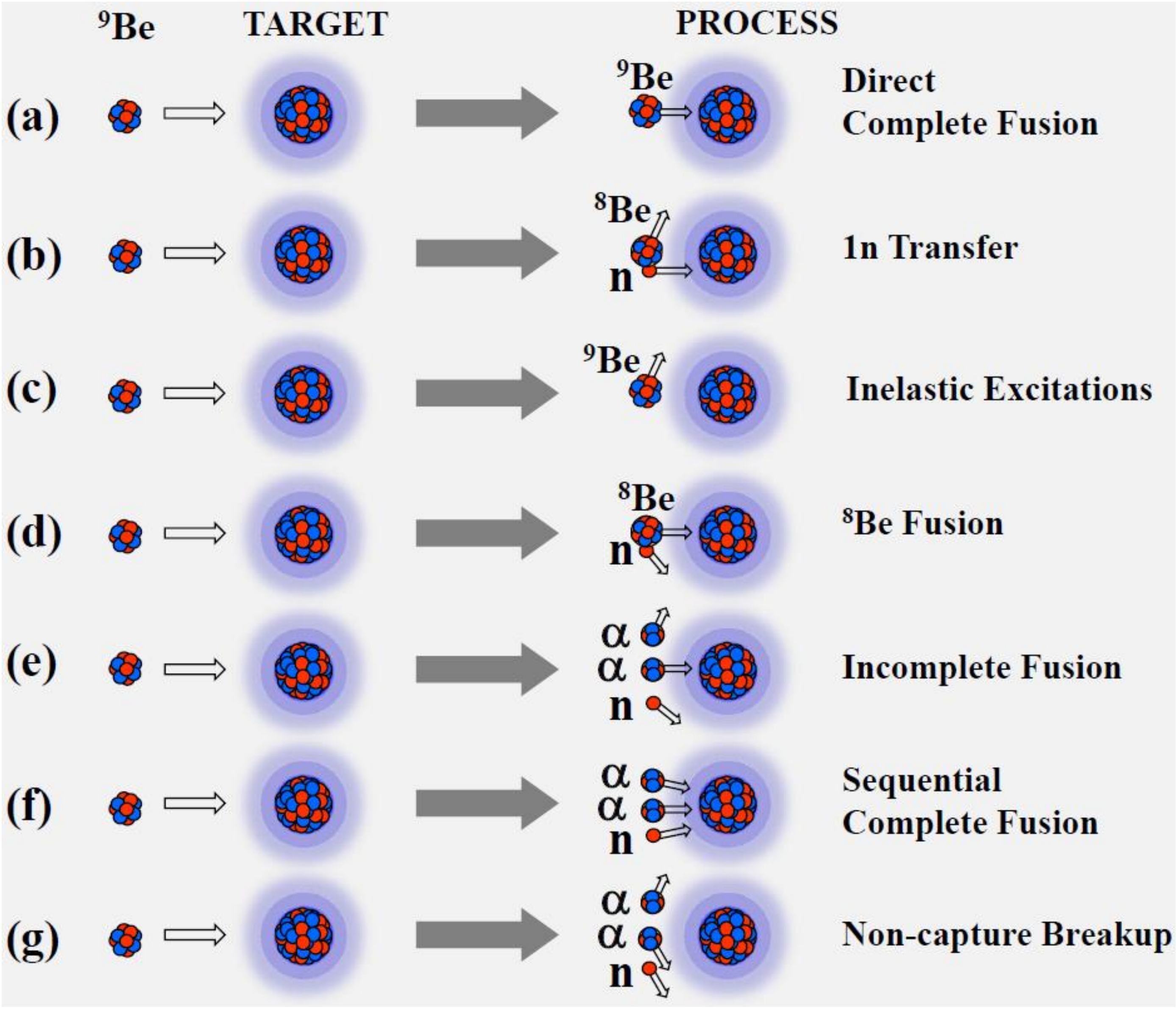
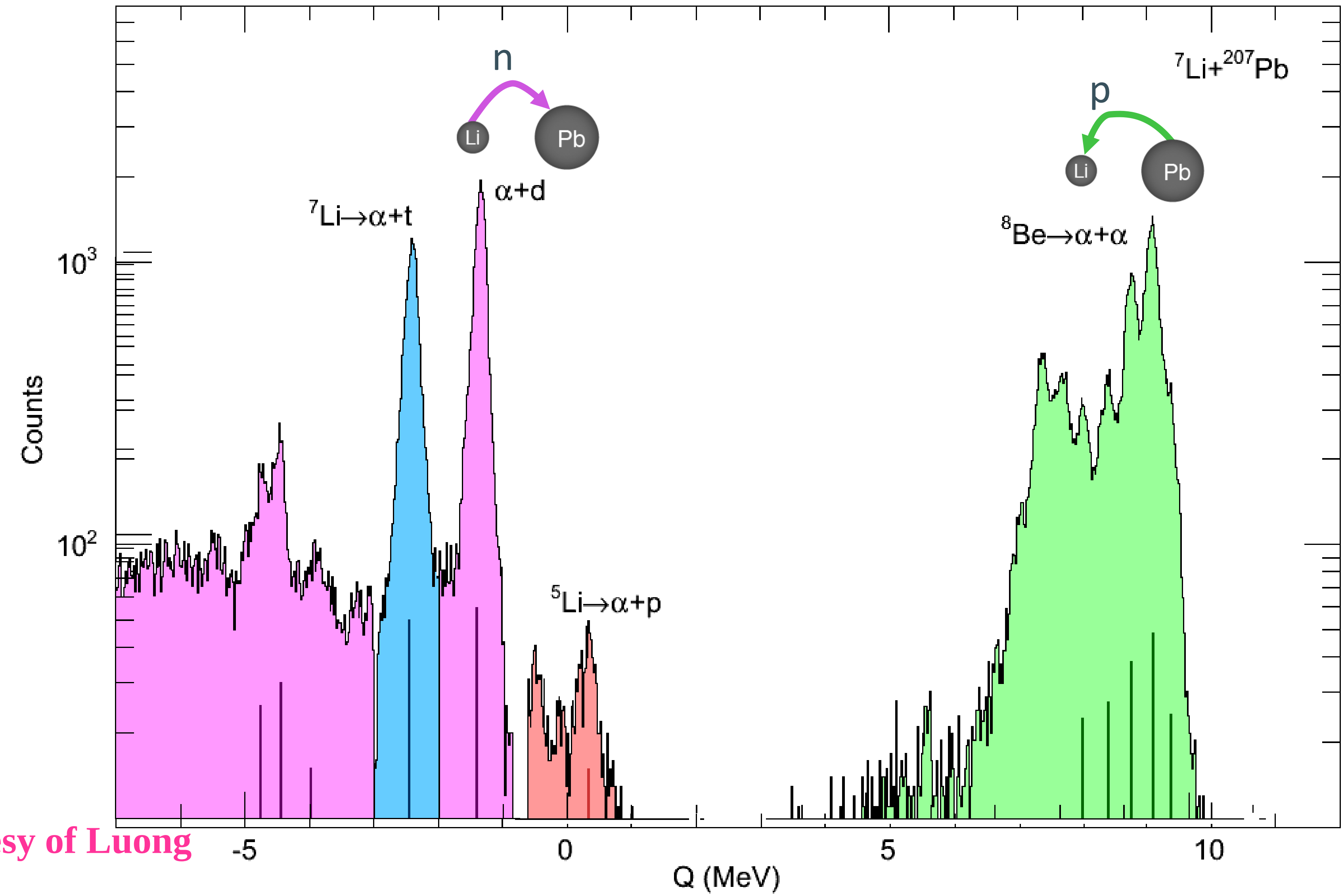
editor: G.E. Brown

Reactions with weakly bound nuclei – example with ^9Be



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

RESULTS



Courtesy of Luong

Questions that we investigate and try to answer

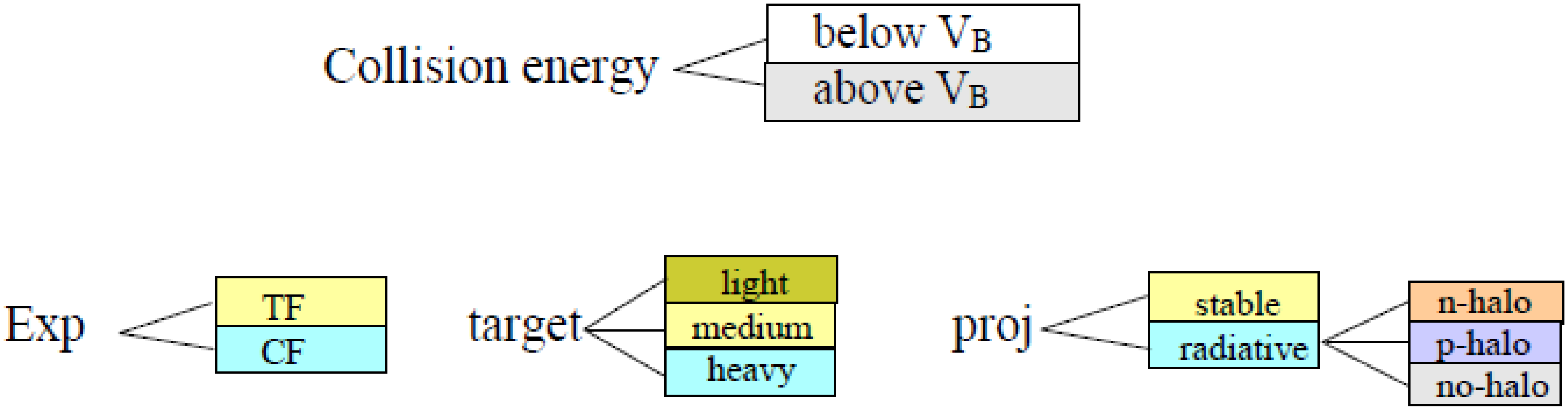
-Does the BU channel enhance or suppress the fusion cross section? Is the effect on σ_{CF} or $\sigma_{TF= CF + ICF}$?

-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



NCBU - Recent results at ANU

- D. H. Luong, M. Dasgupta, D.J. Hinde et al.

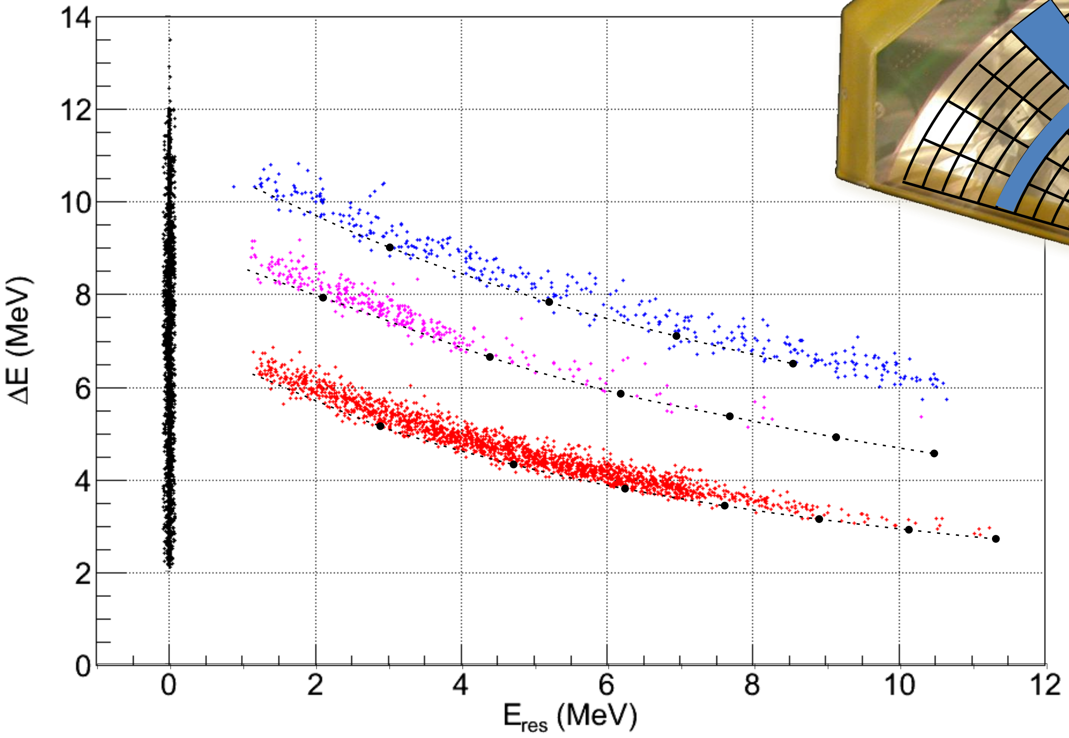
  Physics Letters B 695 (2011) 105

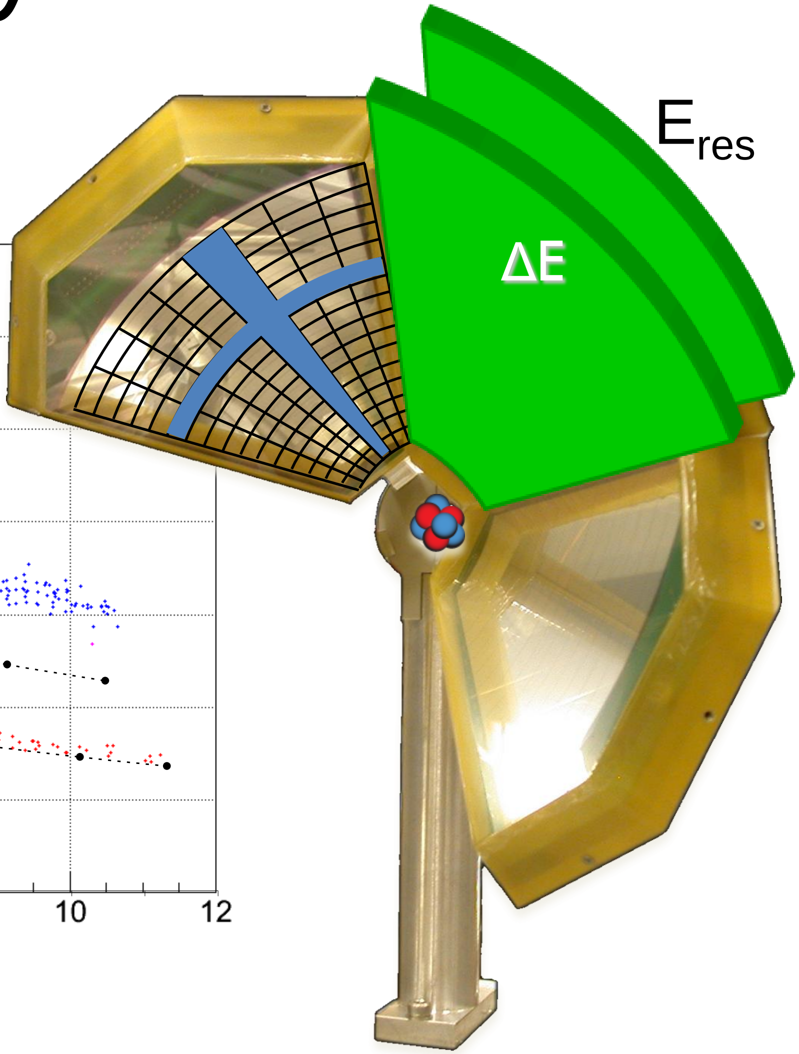
  PRC 88 (2013) 034609

Sub-barrier breakup dominated by transfer

Slides by Luong and Dasgupta

Detector system





Breakup mechanism: Q-values

after

before

$$Q = E_1 + E_2 + E_{recoil} - E_{lab}$$

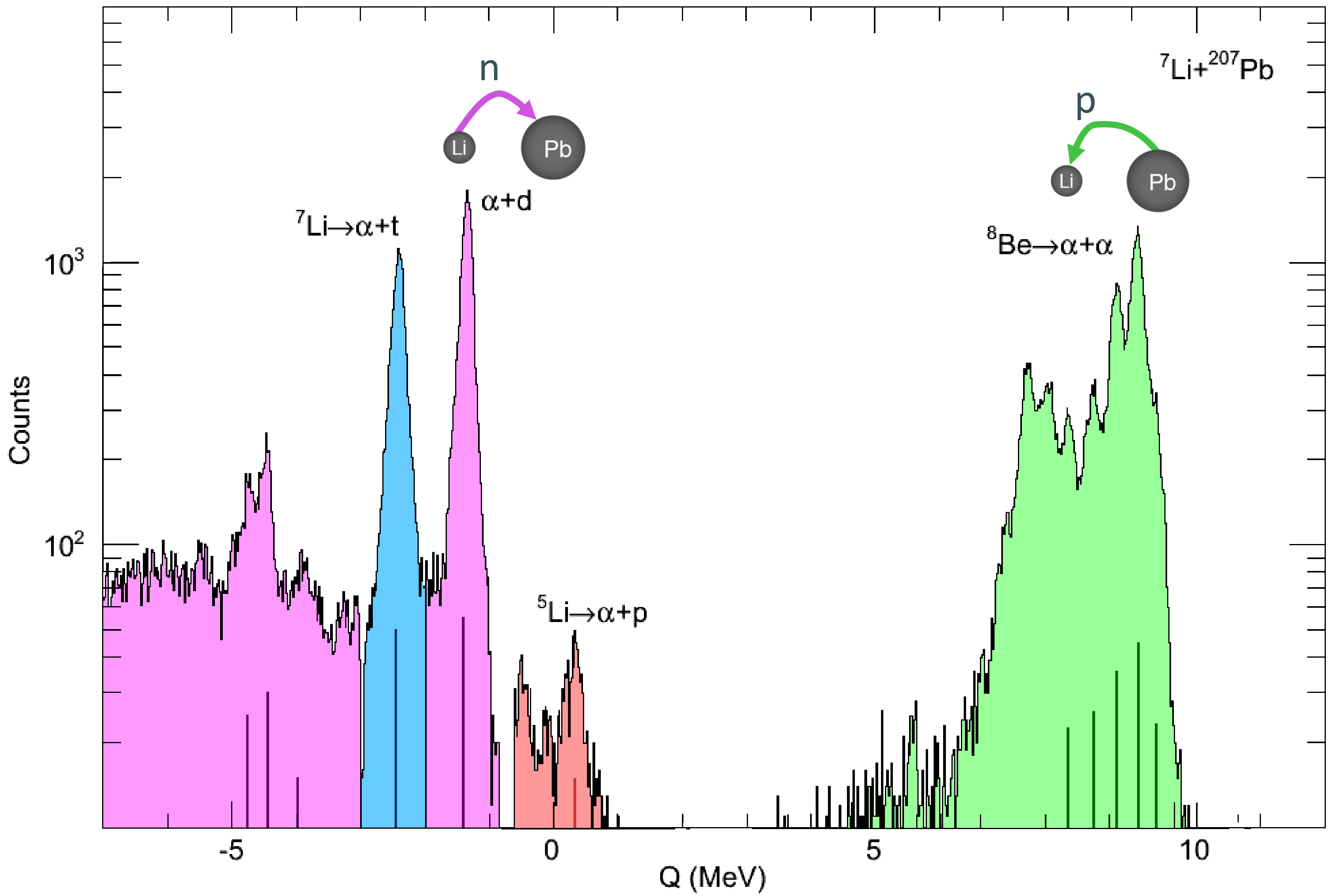
measured

measured

calculated by *p* conservation

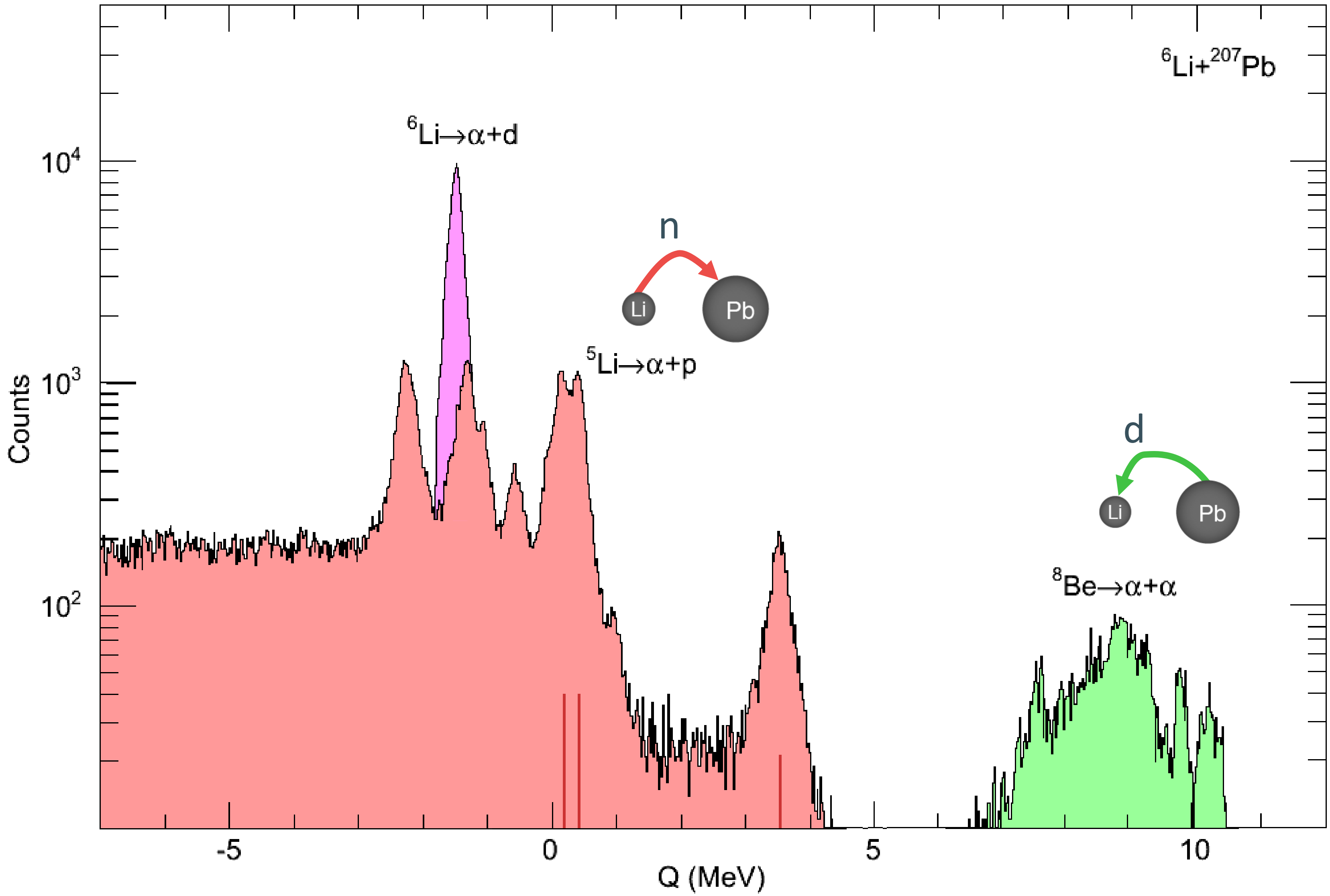
known

Breakup mechanism: Q-values

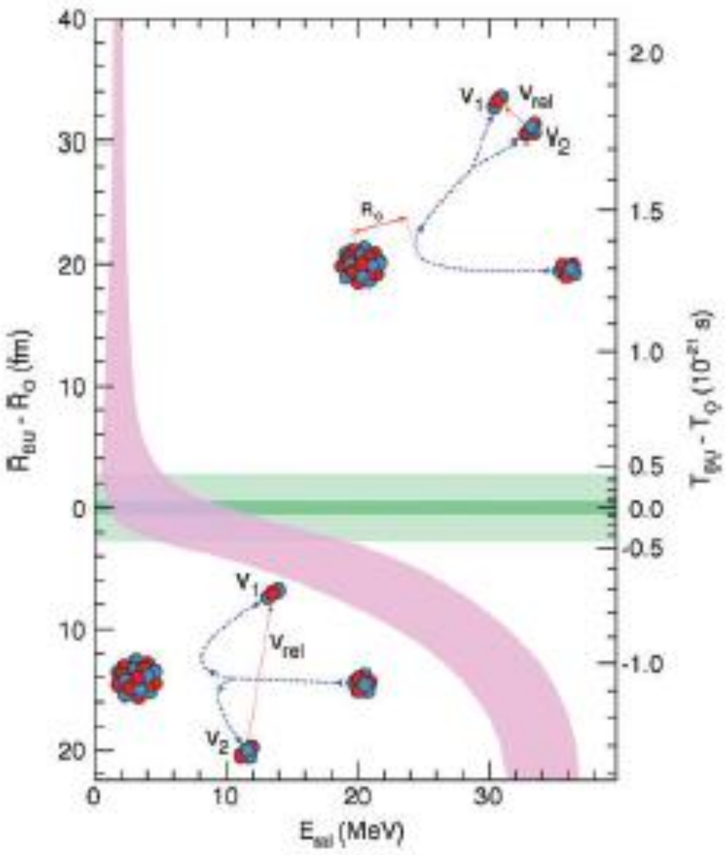


Breakup mechanism: Q-values

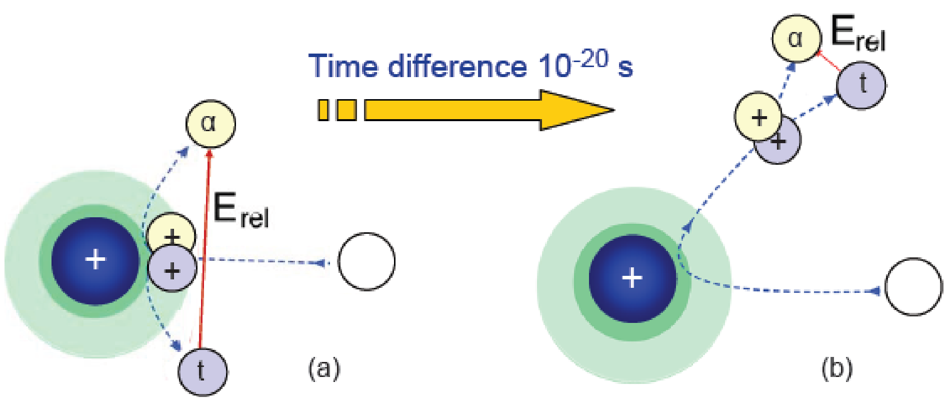
RESULTS



Breakup time scale: Relative energy



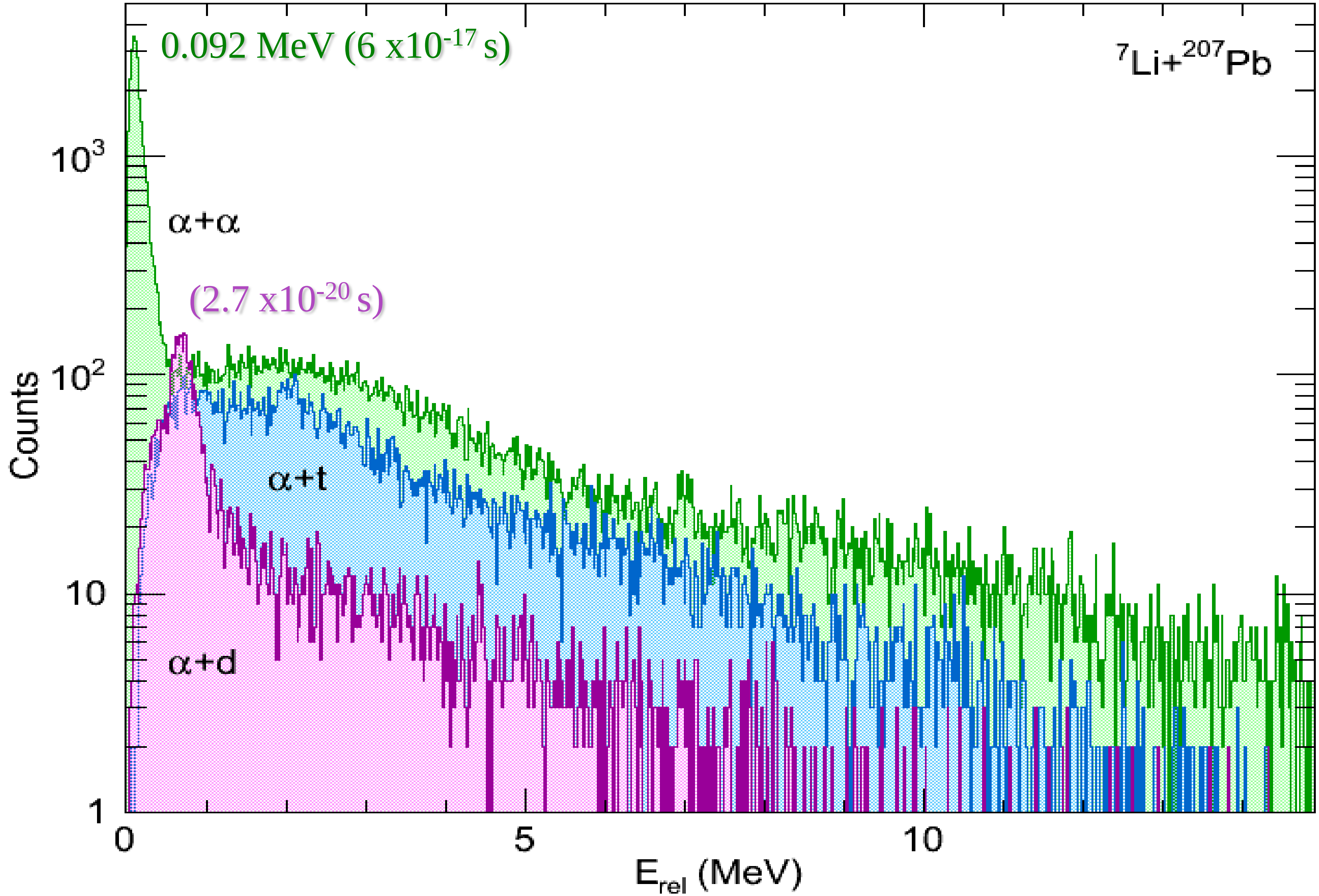
$$E_{rel} = \frac{m_2 E_1 + m_1 E_2 - 2\sqrt{m_1 E_1 m_2 E_2} \cos\theta_{12}}{m_1 + m_2}.$$



Only prompt breakup may affect fusion

^{7}Li breakup timescale

RESULTS



Fusion

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

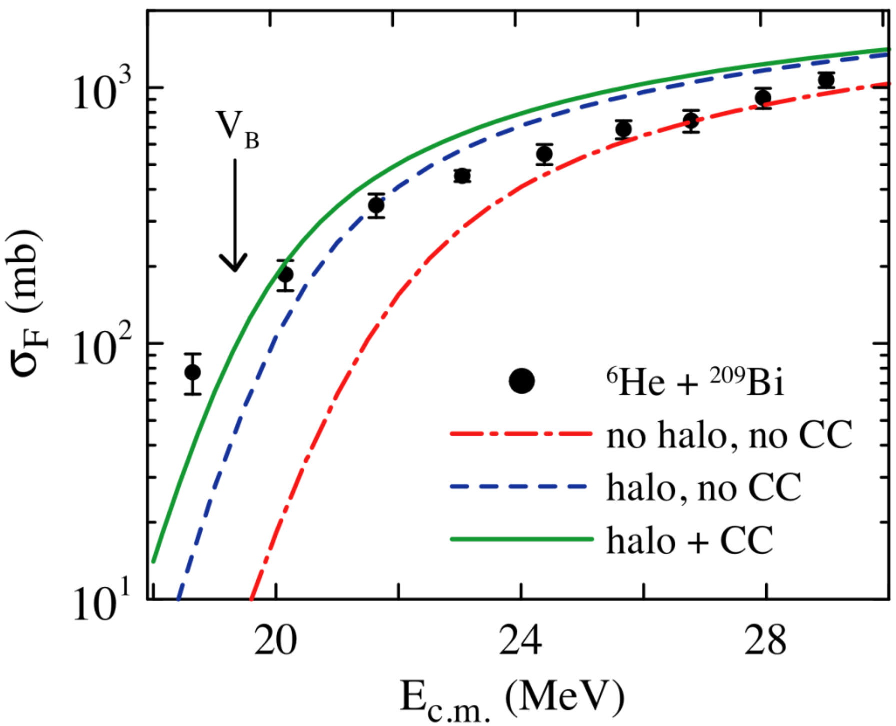
c) CC calculation with all relevant bound channels

$\Delta\sigma_F$ arises from continuum couplings

d) CDCC

no deviation expected

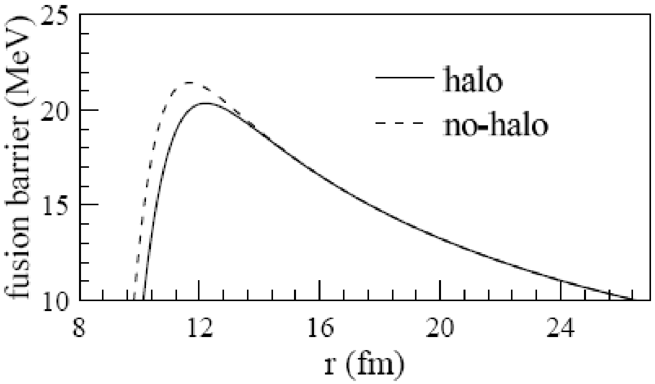
Example: $^{6}He + ^{209}Bi$



Single channel - no halo

Single channel – with halo

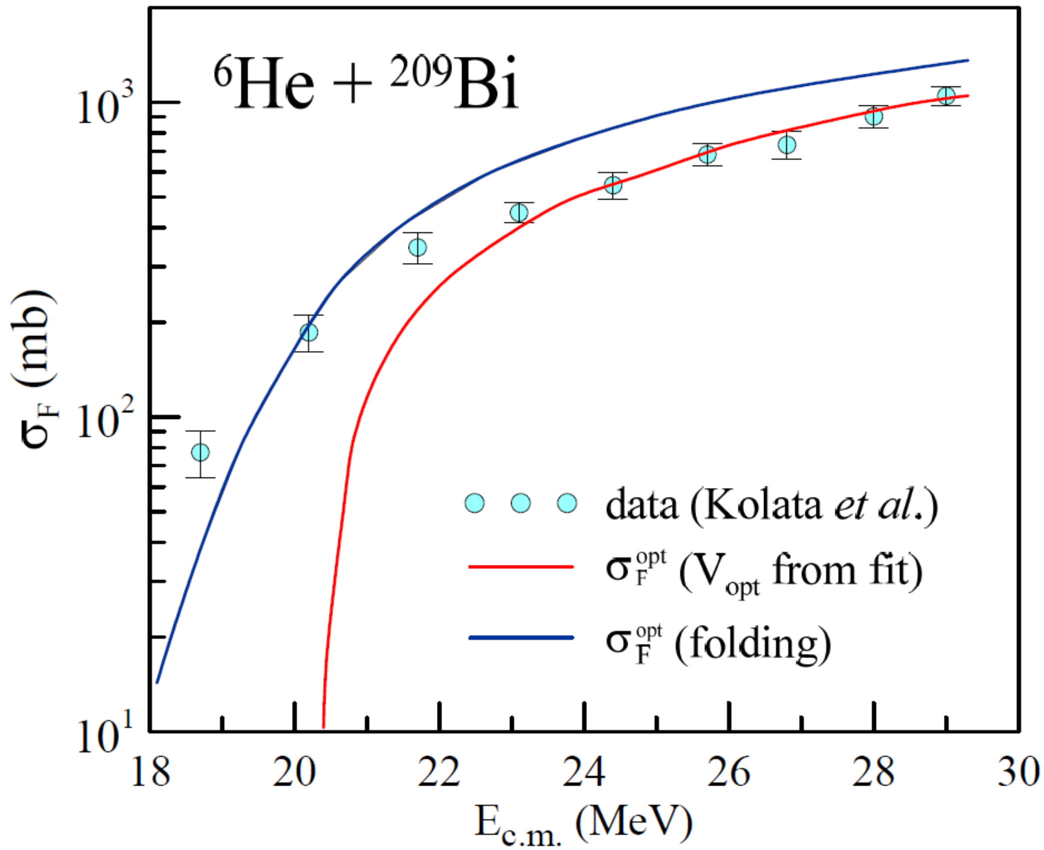
CC with bound channels
(schematic calculation)



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

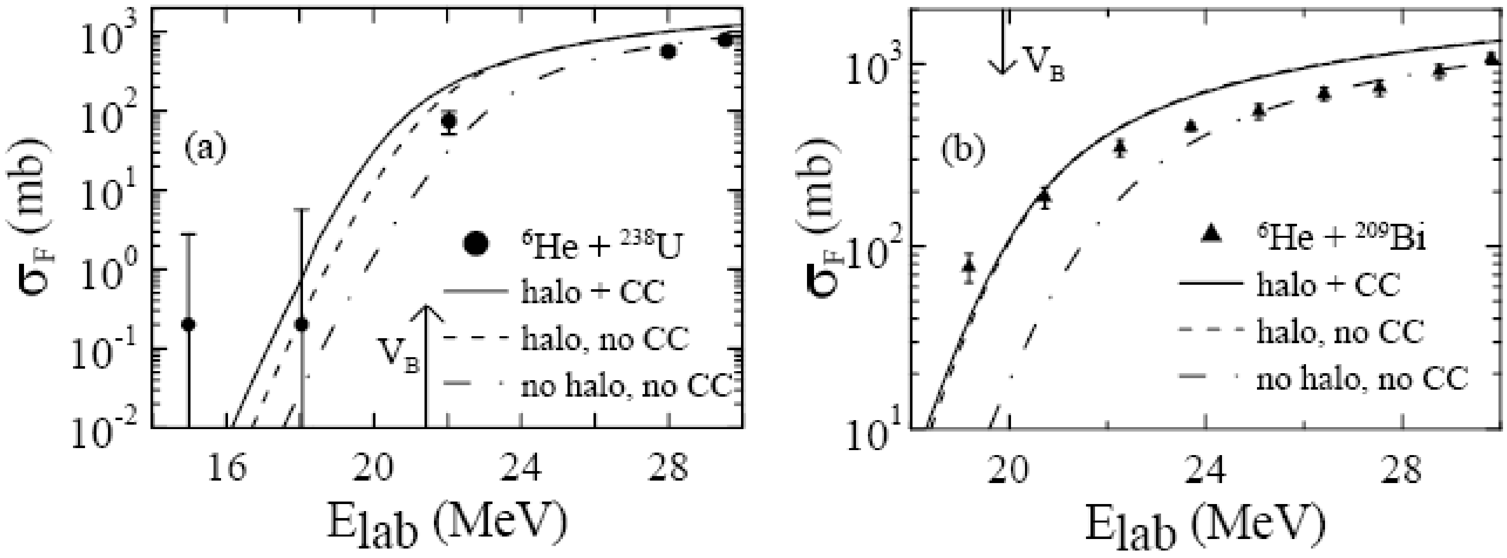


Kolata et al., PRL 81, 4580 (1998)

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)

2. Compare with σ_F of a similar tightly bound system

(example: $^{6}He + ^{238}U$ vs. $^{4}He + ^{238}U$)

Differences due to static effects:

1. Gross dependence on size and charge:

   Z_P, Z_T, A_P, A_T – affects V_B and R_B

   $V_B : Z_P Z_T e^2 / R_B$; $\sigma_{geo} : \pi R_B^2$, $R_B \propto A_P^{1/3} + A_T^{1/3}$)

2. Different barrier parameters due to diffuse densities

   (lower and thicker barriers)

Differences due to dynamic effects:

3. Couplings to bound channels

(larger σ_F at $E < V_B$)

4. Continuum couplings (breakup)

To investigate 4, it is necessary

to eliminate effects 1, 2 and 3 !

Fusion data reduction required !

Fusion functions *F*(*x*)
(our reduction method)

$$E \rightarrow x = \frac{E - V_B}{\hbar\omega} \quad \text{and} \quad \sigma_F^{\exp} \rightarrow F_{\exp}(x) = \frac{2E}{\hbar\omega R_B^2}\,\sigma_F^{\exp}$$

Inspired in Wong's approximation

$$\sigma_F^{W} = R_B^2 \frac{\hbar\omega}{2E} \ln\left[1 + \exp\left(\frac{2\pi(E - V_B)}{\hbar\omega}\right)\right]$$

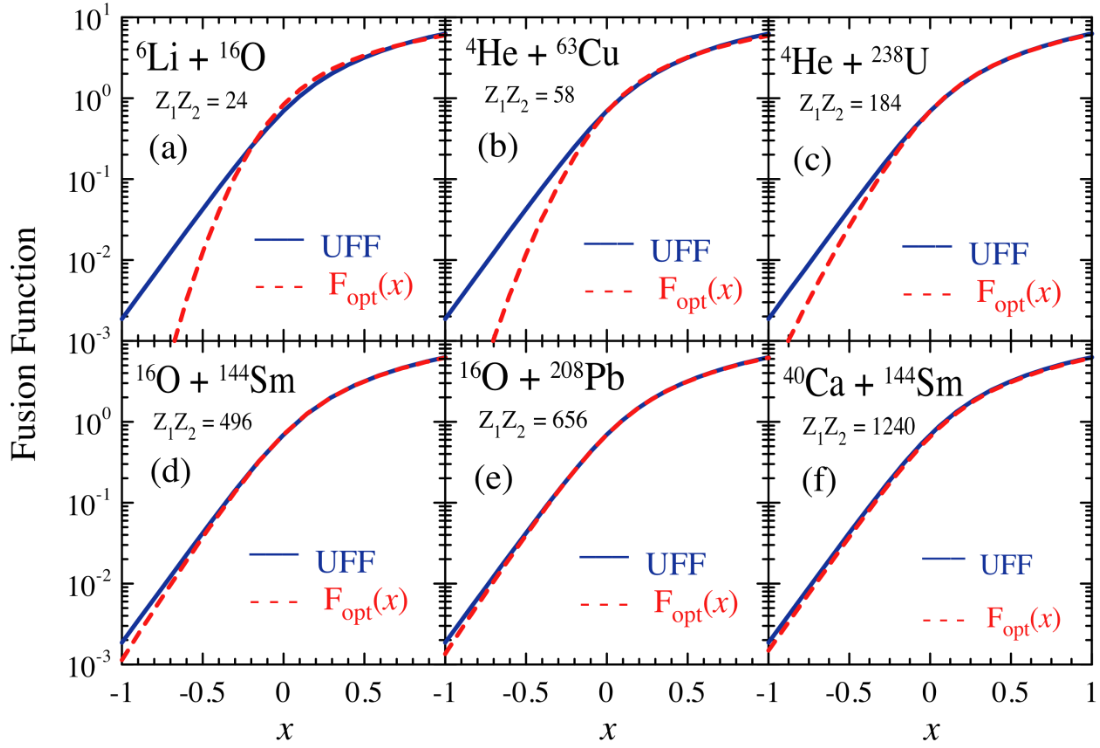
$$\text{If} \quad \sigma_{\rm F}^{\exp} = \sigma_{\rm F}^{\rm W} \quad \Rightarrow \quad F(x) = F_0(x) = \ln\left[1 + \exp(2\pi x)\right]$$

$F_0(x)$ = Universal Fusion Function (UFF)

system independent !

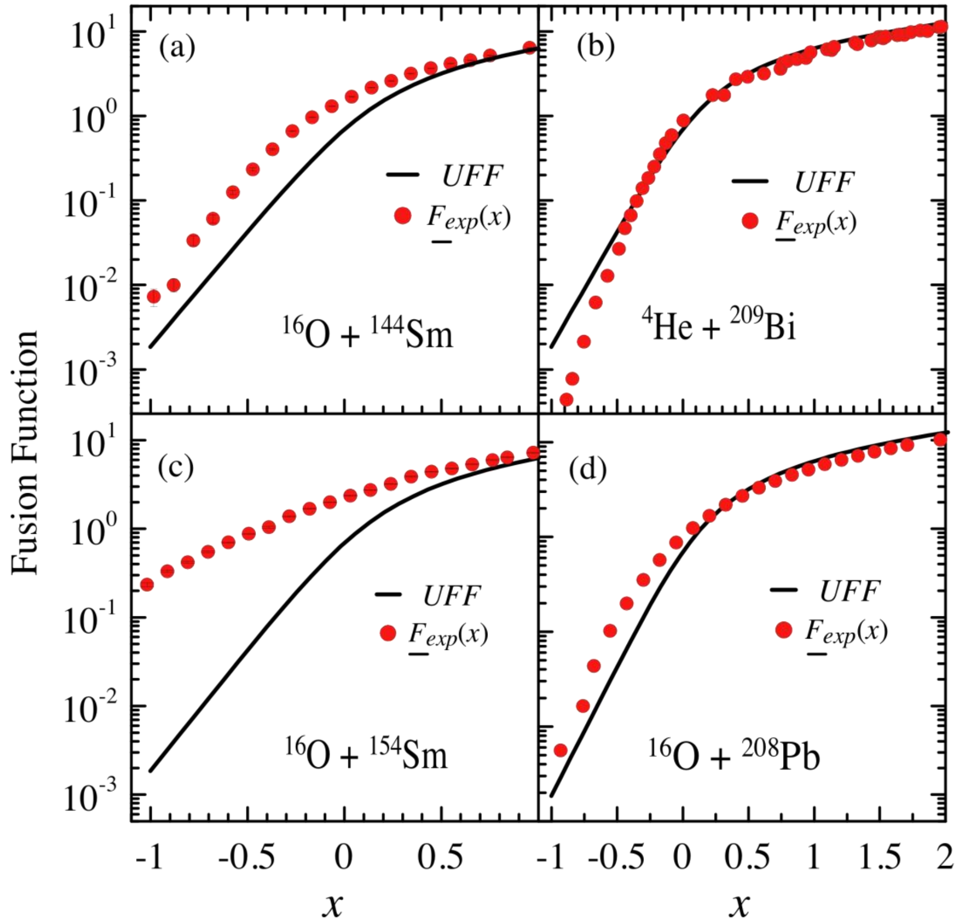
Shortcomings:

a) Wong approximation may not work



- O.K. for light systems only above V_B
- O.K. for heavy systems ($Z_P Z_T > 500$), even below V_B

b) Channel coupling channel effects



(a) CC: 2^+,3^- (T); 3^- (P)

(a) Wong is bad

(a) CC Rot. band (T); 3^- (P)

(a) CC 3^-,5^- (T)

Direct use of the reduction method

Compare $F_{exp}(x)$ with UFF for x values where $\sigma_F^{opt} = \sigma_F^{W}$

Deviations are due to couplings with bound channels and breakup

Refining the method

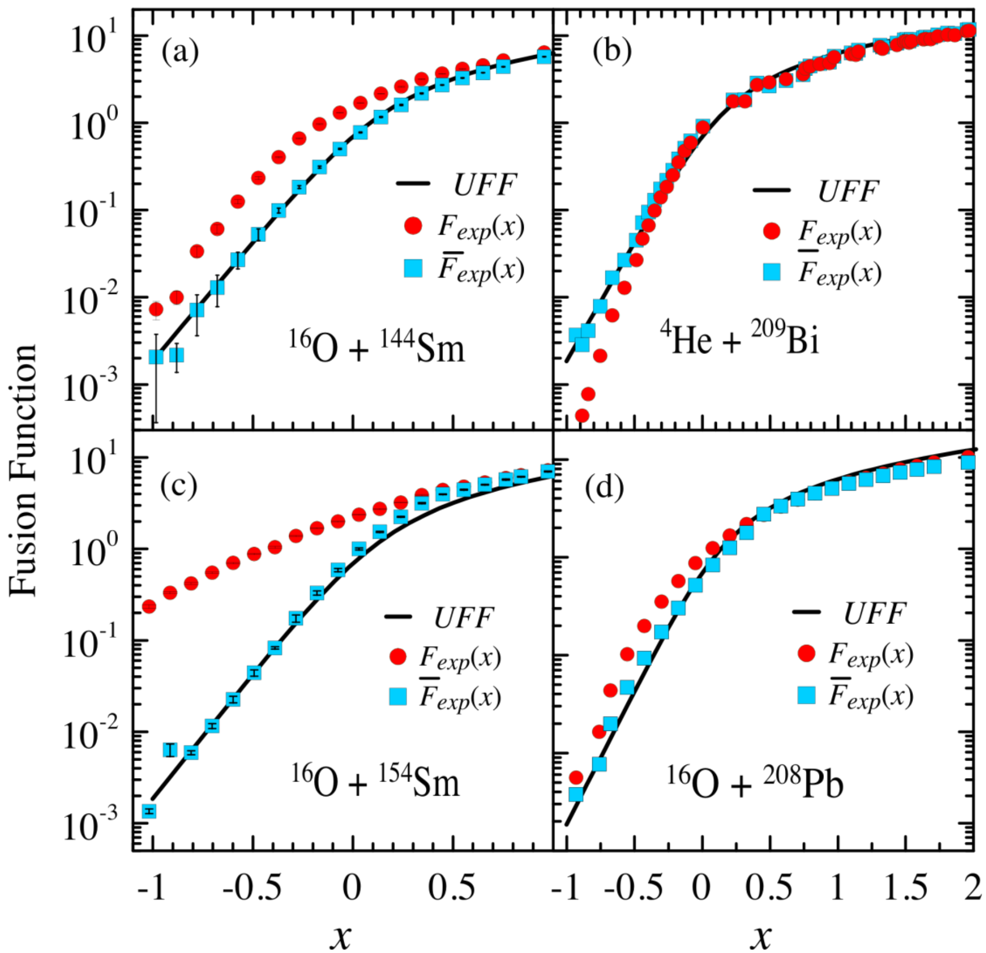
Eliminate influence of couplings with bound channels

Renormalized fusion function

$$F_{exp}(x) \rightarrow \bar{F}_{exp}(x) = \frac{F_{exp}(x)}{R(x)}, \quad \text{with} \quad R(x) = \frac{\sigma_F^{CC}}{\sigma_F^{W}} = \frac{\sigma_F^{CC}}{\sigma_F^{opt}}$$

If CC calculation describes data $\rightarrow \bar{F}_{exp} = \text{UFF}$

Illustration:



If CC calculations are accurate:

for tightly bound systems $\overline{F}_{exp}(x)$ = UFF

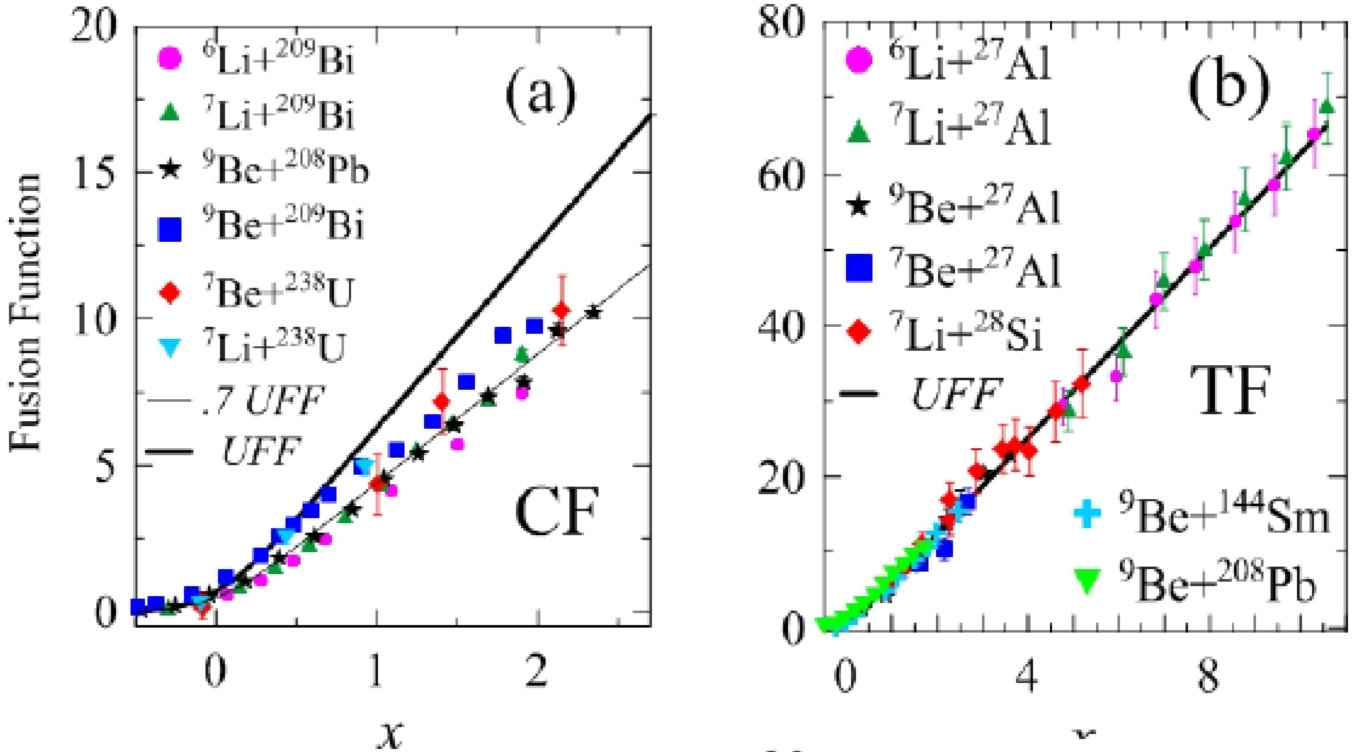
for weakly bound systems difference is due to breakup

Applications with weakly bound systems

1. **Canto, Gomes, Lubian, Chamon, Crema, J.Phys. G36 (2009) 015109; NPA 821(2009)51**

2. **Gomes, , Lubian, Canto, PRC 79 (2009) 027606**

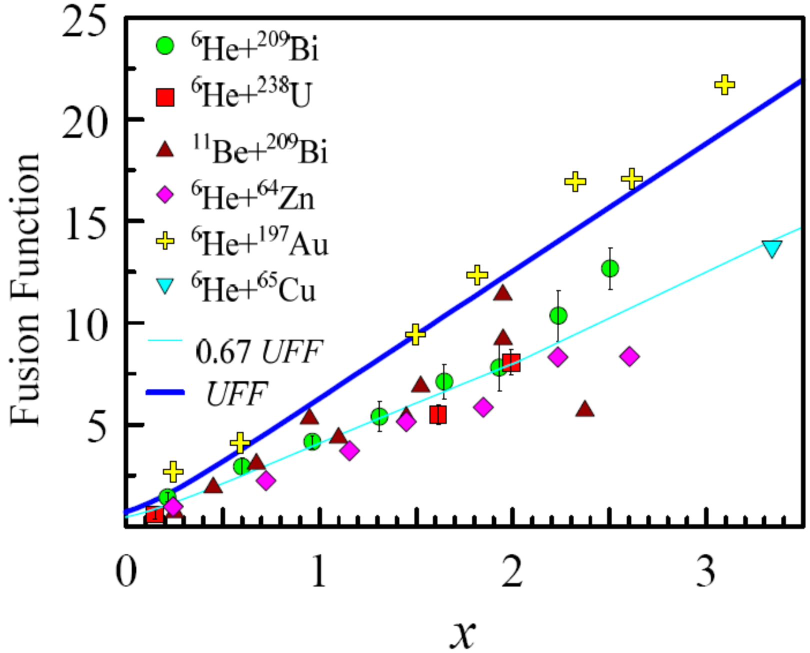
Systematics reached from the investigation of he role of BU dynamical effects on the complete and total fusion of stable weakly bound heavy systems

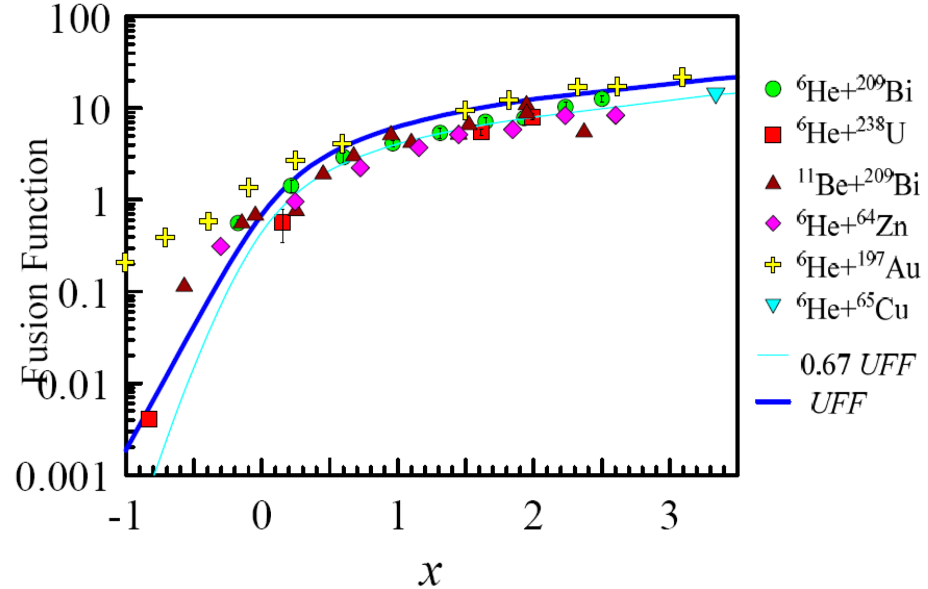


We did not include any resonance of the projectiles in CCC.

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

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.

Do all the systems follow the systematics?

Almost all of the tens of systems follow the systematics.

For those which do not follow, either

a) There is something very special with those systems.

b) There is something wrong with the data.

c) Wrong CC calculations.

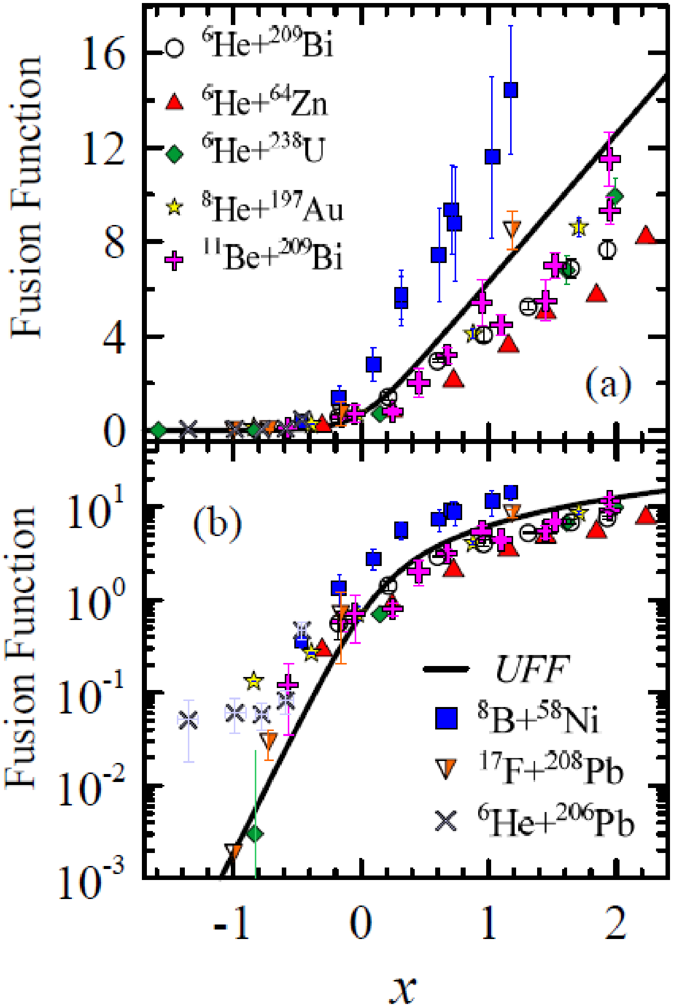
What about proton-halo systems?

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

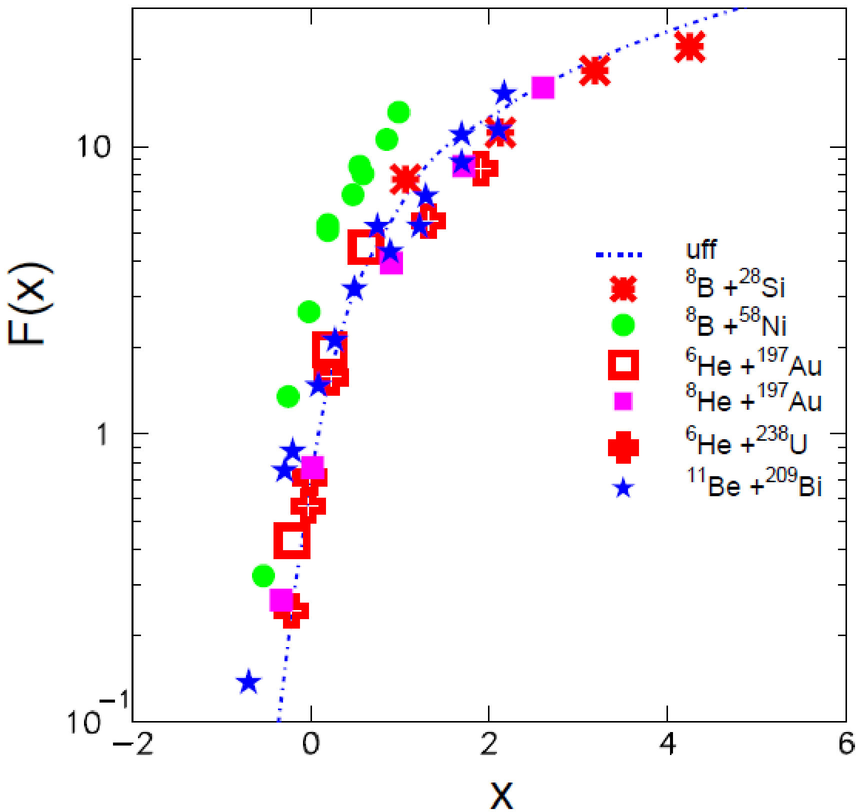
Something wrong with the data?

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

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

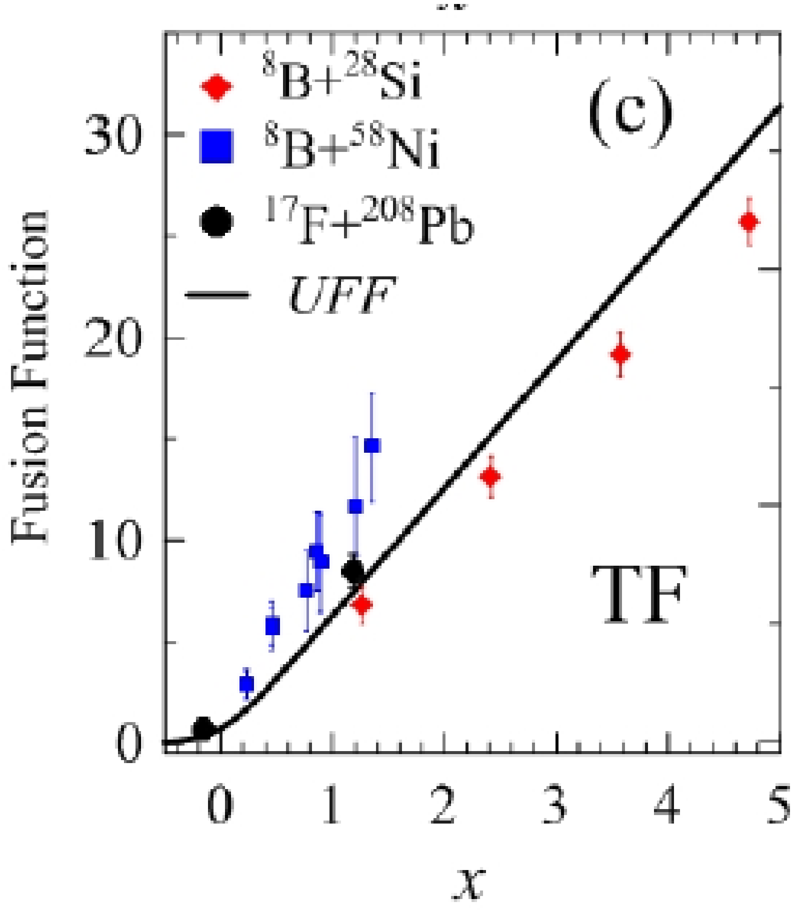
Pakou et al. PRC 87, 014619 (2013)

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



Normal behavior, within our systematic!!!

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



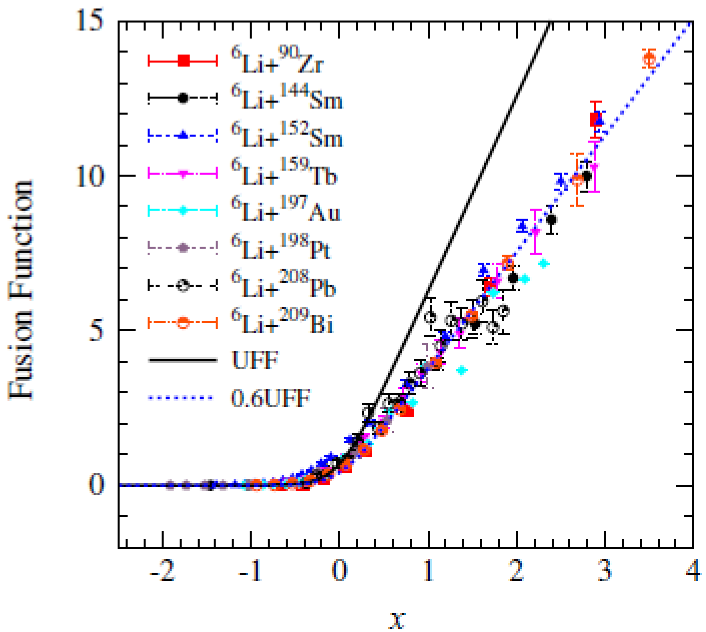
We believe it is very important to measure fusion of 8B with other (or the same) targets.

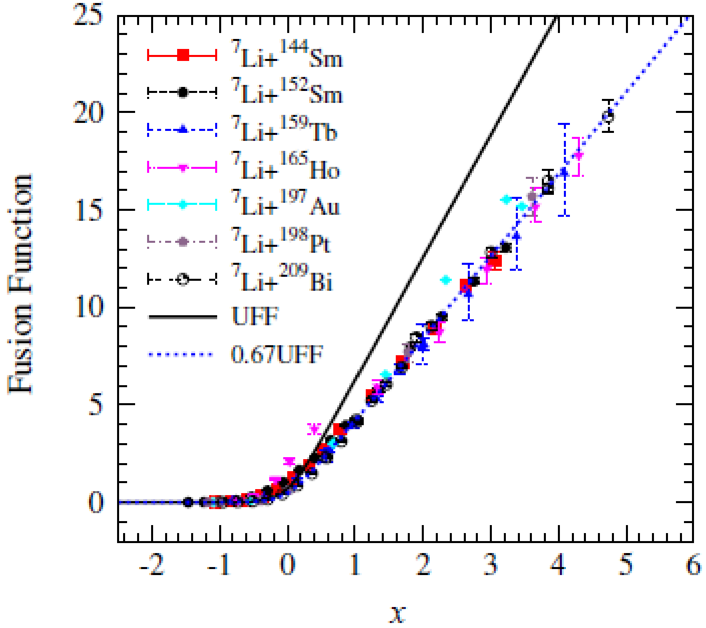
So, the next question is:

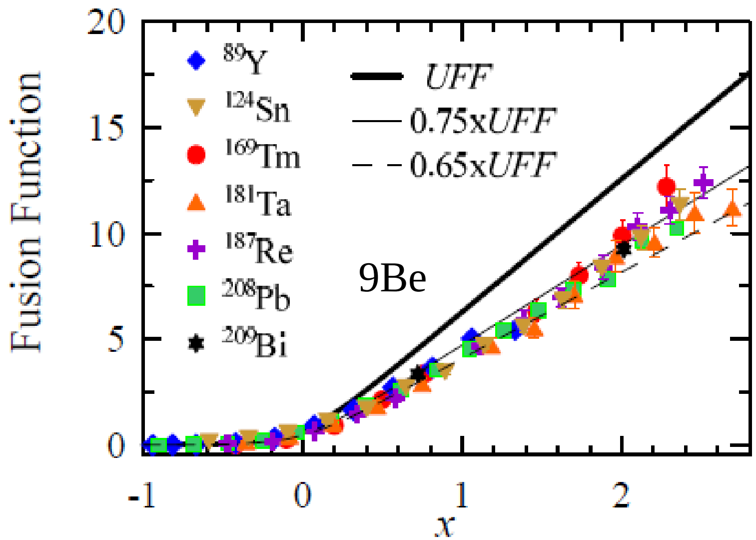
How does the BU vary with target mass (or charge)? Coulomb and nuclear breakups: Is there interference between them?

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

CF Suppression for stable weakly bound nuclei on different targets



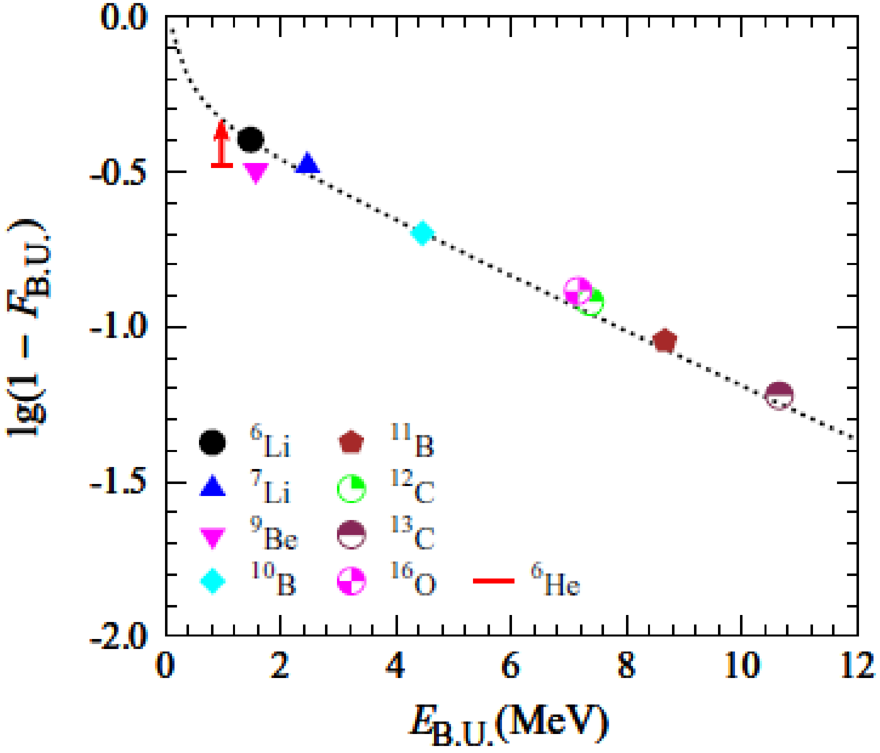




The BU effect on fusion does not seem to depend on the target charge!!!!

Wang et al. – PRC 90, 034612 (2014)

CF suppression factor as a function of the BU threshold energy



$$\lg(1 - F_{\mathrm{B.U.}}) = -0.33\exp(-0.29/E_{\mathrm{B.U.}}) - 0.087E_{\mathrm{B.U.}}$$

Wang – PRC 90, 034612 (2014)

Calculations of NCBU by means of CDCC:

D. R. Otomar, P.R.S. Gomes, J. Lubian, L.F. Canto, M. S. Hussein
PRC 87, 014615 (2013)

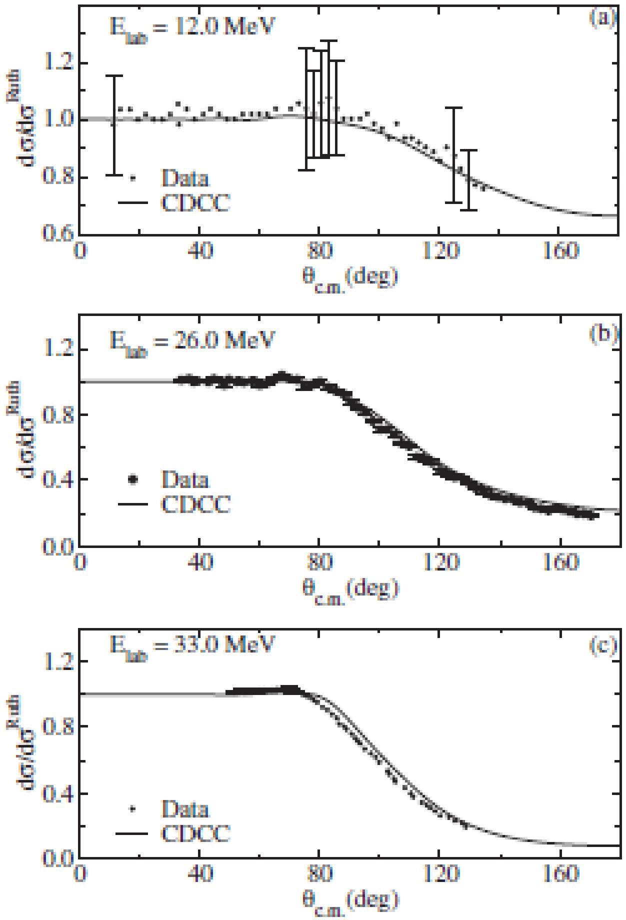
M.S. Hussein, P.R.S. Gomes, J. Lubian, D.R. Otomar, L. F. Canto
PRC 88, 047601 (2013)

Our first theoretical step was to perform reliable CDCC calculations.

What do we mean by reliable? No free parameters, only predictions. The predictions have to agree with some data.

Which data are available? Elastic scattering angular distributions.

Examples of calculations for elastic scattering

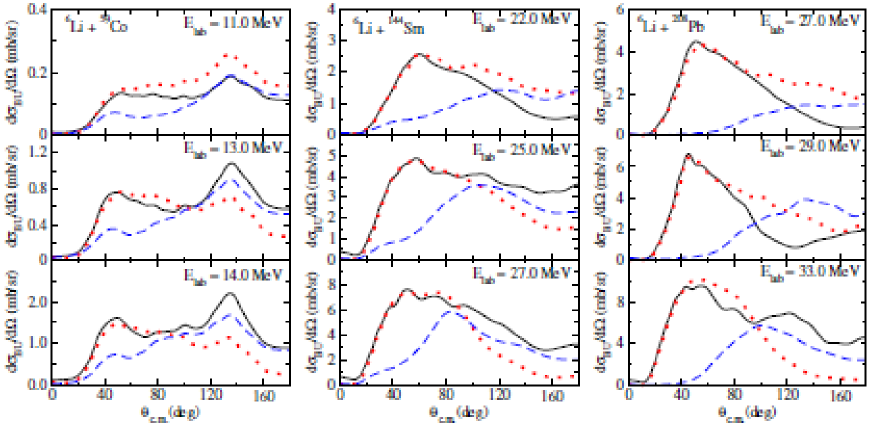


^{6}Li + ^{59}Co

^{6}Li + ^{144}Sm

^{6}Li + ^{208}Pb

Relative importance between Coulomb and nuclear breakups



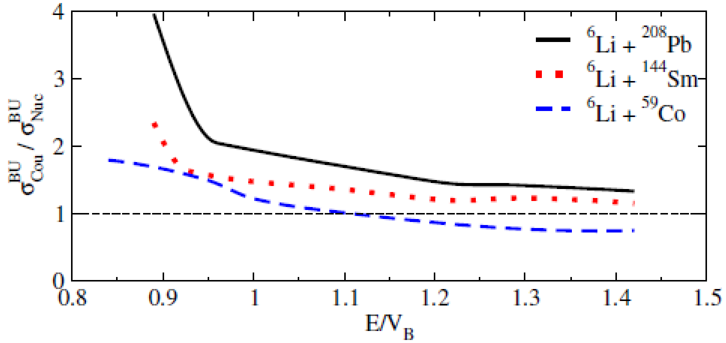


FIG. 4. (Color online) Coulomb to nuclear ratio of integrated breakup cross section for the three systems under investigation.

Total BU – black
Coulomb BU – red
Nuclear BU - blue

For higher energies and light targets, nuclear BU may predominate

Small angles (large distances) – Coulomb BU always predominates
For larger angles, nuclear BU may predominate – crossing angle.

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?

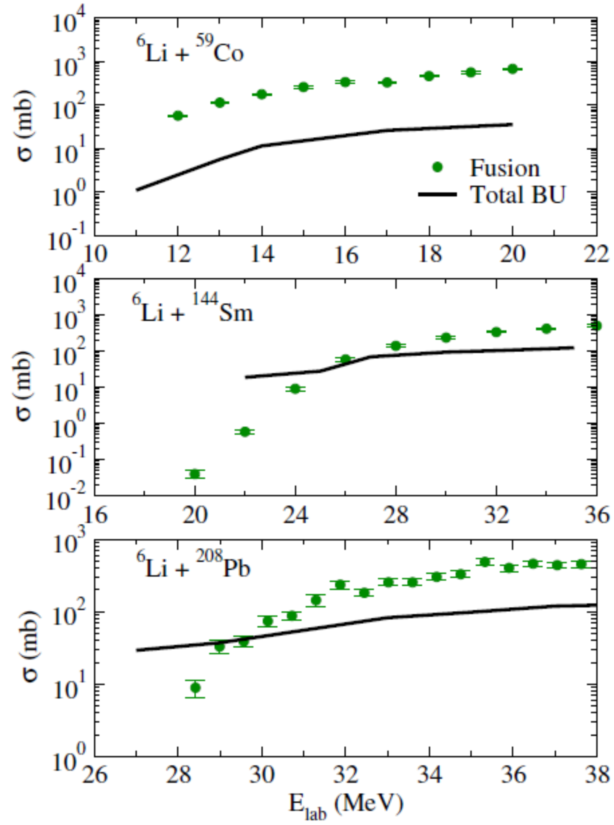
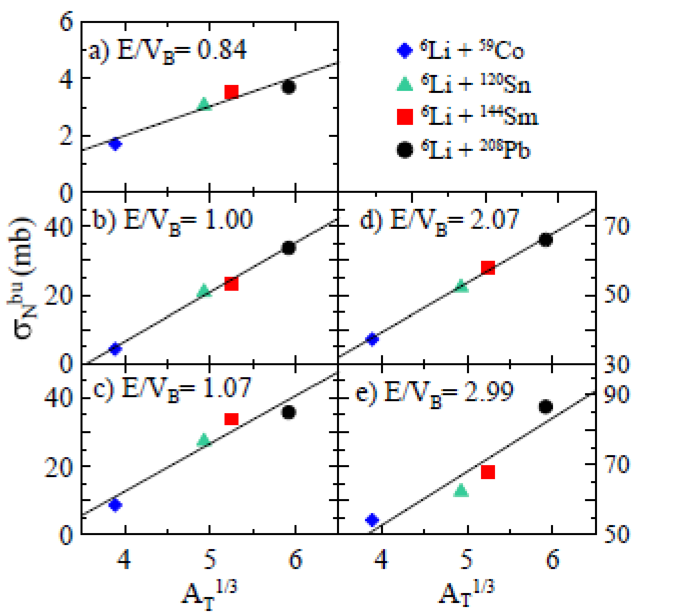
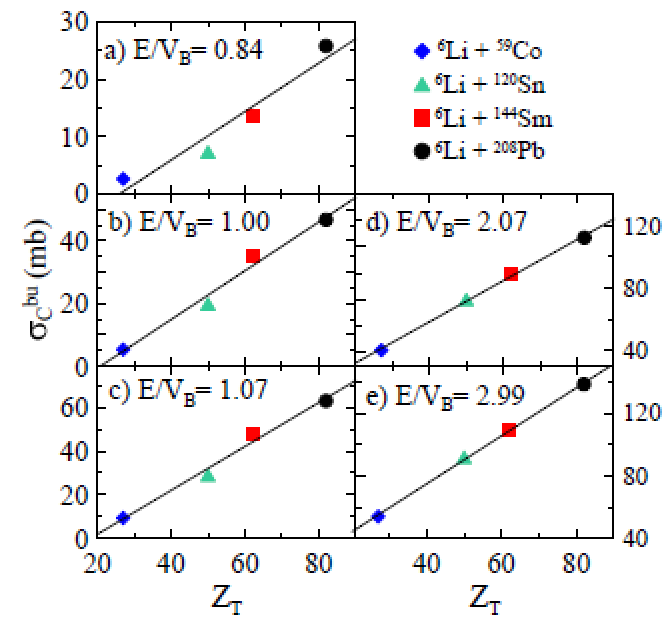


FIG. 7. (Color online) Comparison of fusion cross section with the breakup cross section for the three studied systems.

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 $E_{c.m.}/V_B$

Conclusions from direct BU calculations

- Both, the nuclear and Coulomb BU components increase with target mass and charge.
- The relative importance between nuclear and Coulomb breakups is not so simple as it is usually thought.
- There is a strong destructive interference between nuclear and Coulomb breakup.

Otomar et al – PRC 87, 014615 (2013)

It seems that we have a contradiction!!!

Possible explanation for the contradiction

- **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.**

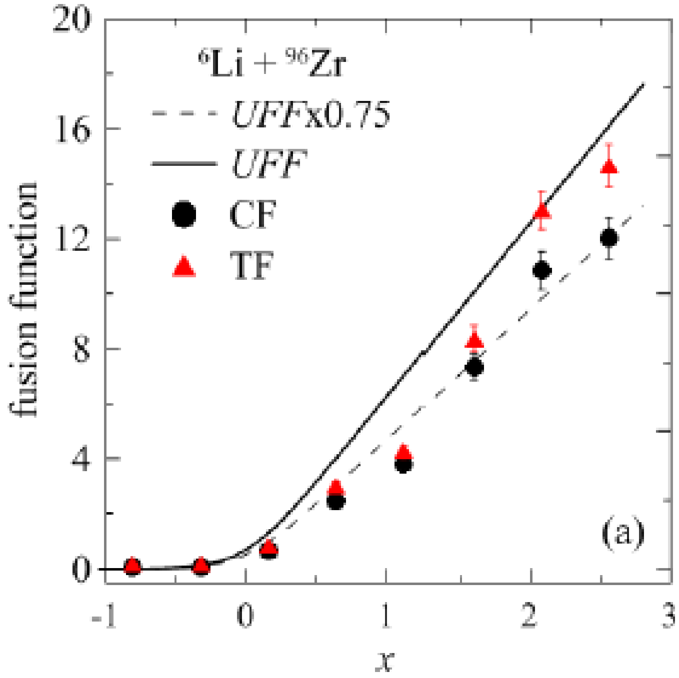
Possible explanation for the contradiction

- **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.**

Or....

Very recent results for 6Li + 96Zr

S.P. Hu et al. – PRC (2015)



Only 25% suppression

One needs to measure CF for light systems
How?

Thank you