A Perspective on Understanding Fusion of Exotic Nuclei

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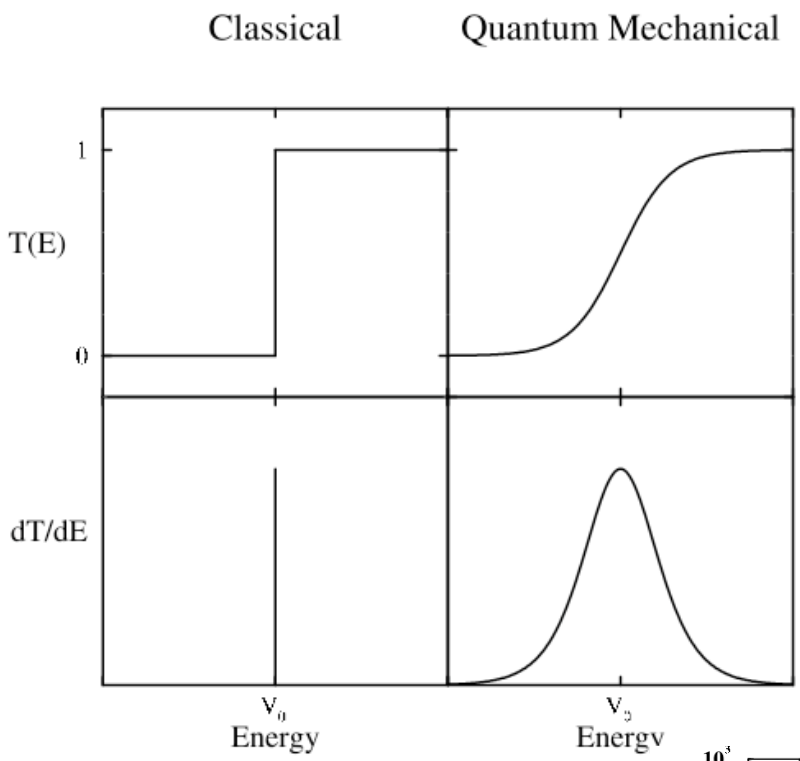
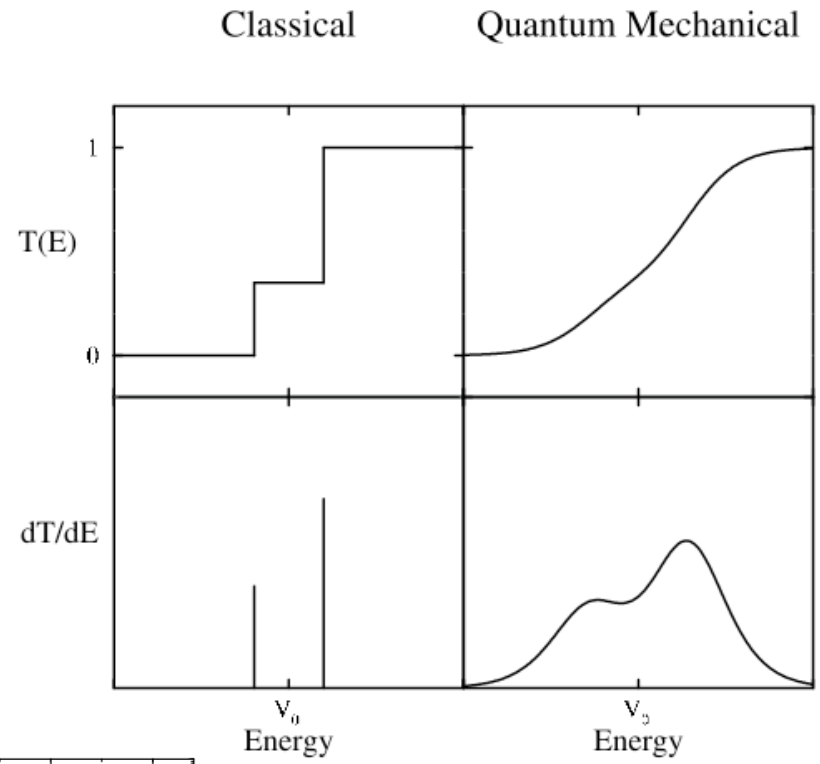
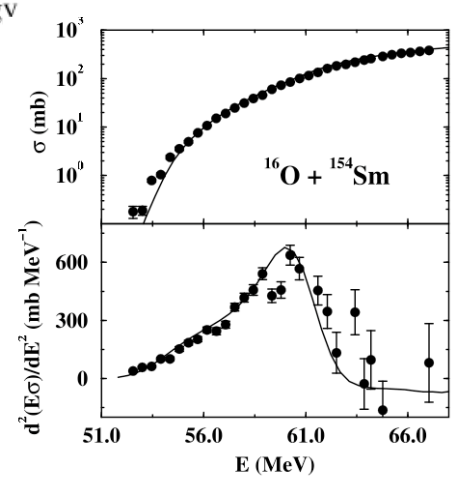
Classical versus Quantum Tunneling



One-dimensional



Multi-dimensional

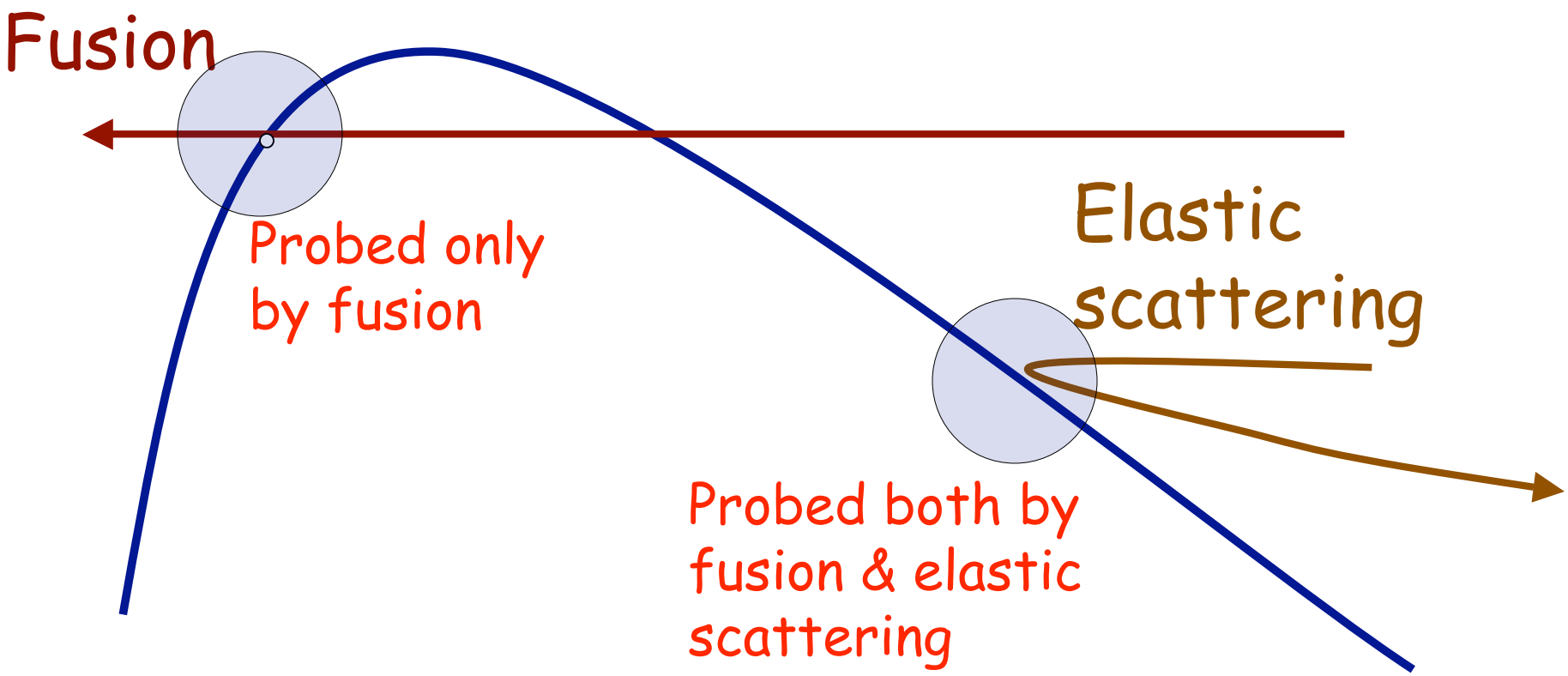


Rowley, Satchler, and Stelson, 1997

Towards the Fusion of Exotic Nuclei, Key Issues

- Do we understand the effects of barrier penetration and transfer processes?
- Do weakly-bound systems with a positive Q-value exhibit a reduction of σ_{fusion}?
- How do we separate complete and incomplete fusion?
- What is the origin of the "fusion hindrance" recently observed in several systems?

An outstanding question: Why is the diffuseness for both fusion and quasi-elastic scattering equal to 1.5 to 2 times the diffuseness for elastic scattering?



Fusion of unstable nuclei

- Coupling to a resonance state

  Balantekin and Takigawa

- Molecular Bond Formation ($^{9}Li + ^{11}Li$)

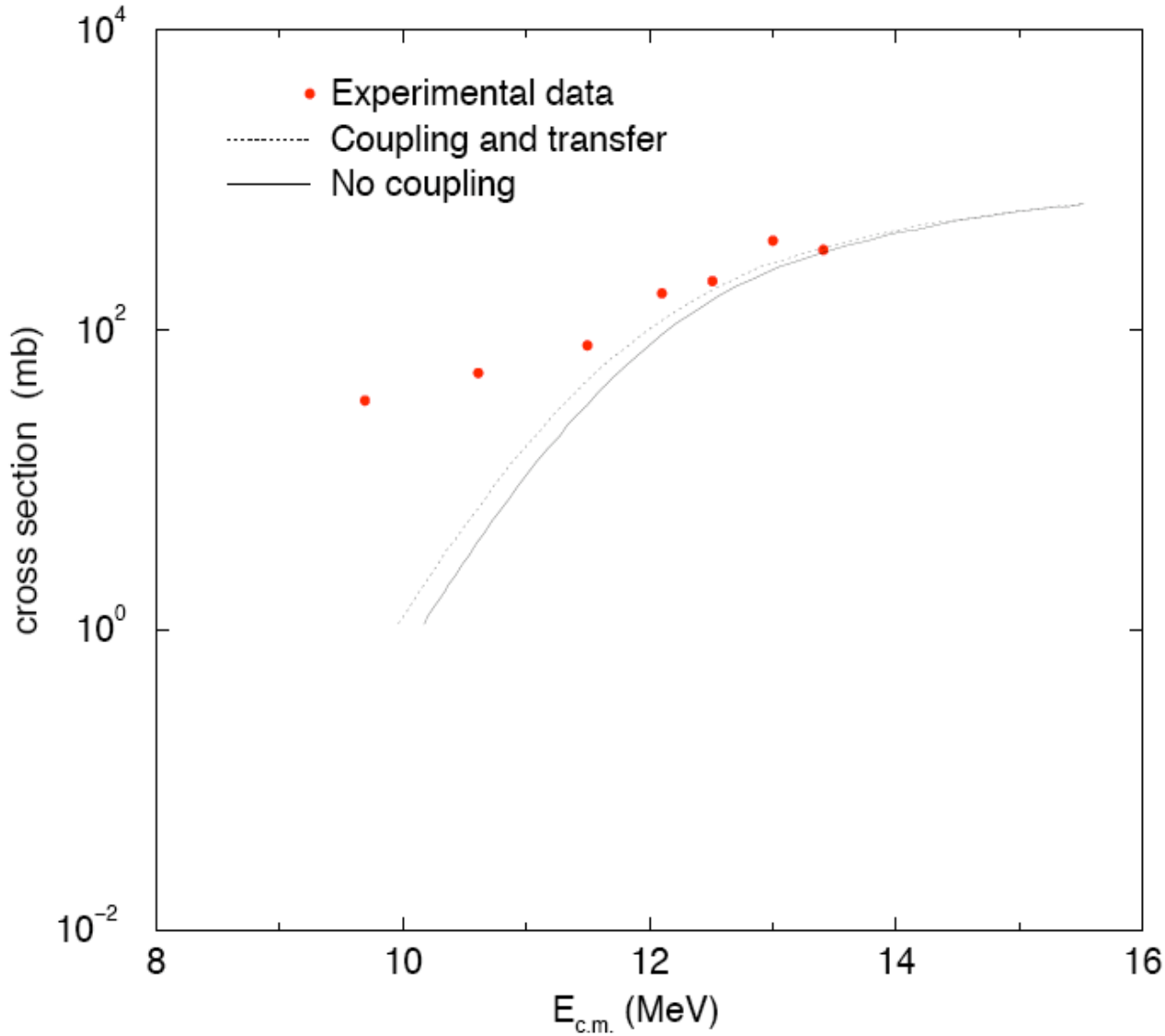
  Balantekin and Bertulani

Fusion of asymmetric systems (low $V_{nuclear}/V_{coulomb}$ in the tail of the potential) is well understood. Can we use this knowledge to probe neutron rich nuclei?

Subbarrier Fusion of ^{9}Li with ^{70}Zn

Data: Loveland, *et al.* PRC **74**, 064609 (2006) measured using ISAC facility at TRIUMF

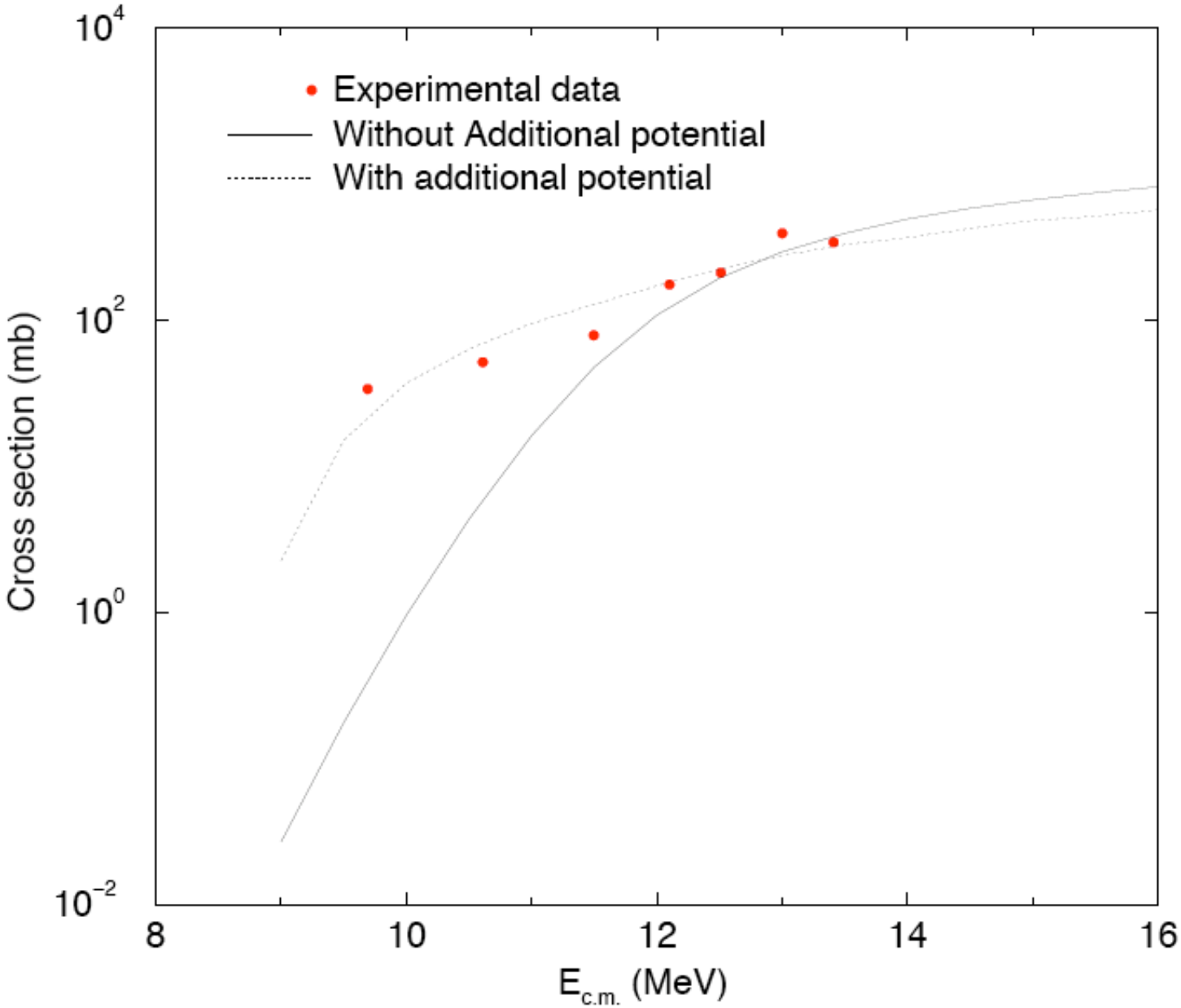
Calculation: Kocak and Balantekin using CCFULL



Could ^{9}Li be capturing two neutrons from ^{70}Zn prior to tunneling since ^{11}Li is also stable?

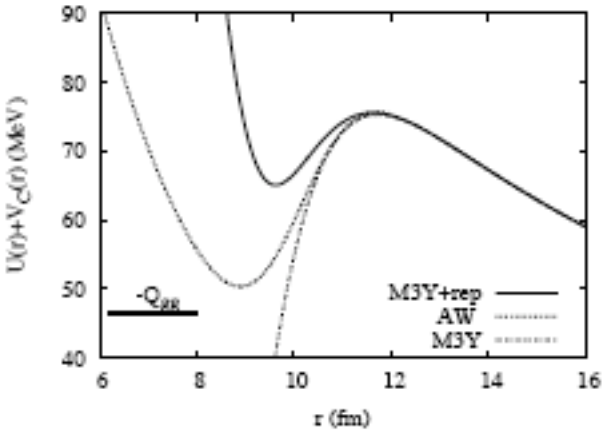
Add a small potential to describe this two-neutron transfer:

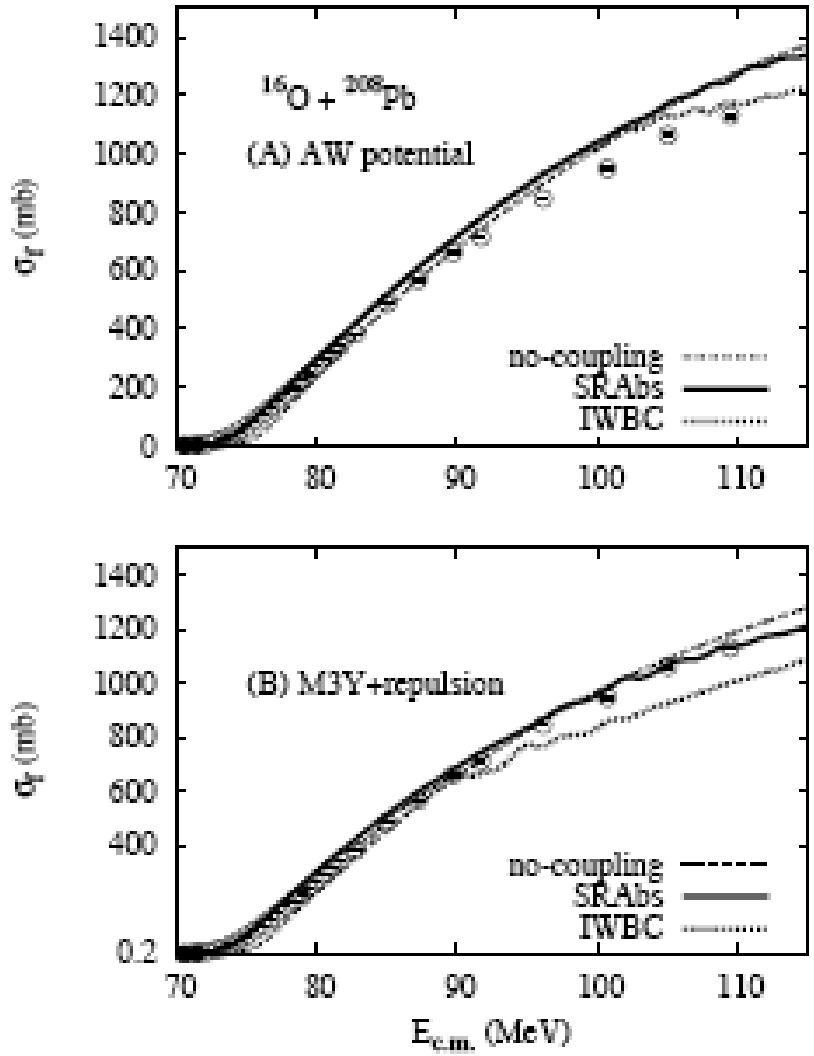
$$V_{2n} = V_d \frac{d}{dr}\left(\frac{1}{1+e^{\frac{r-R}{a}}}\right)$$


Experimental data
Without Additional potential
With additional potential
Cross section (mb)
10^4
10^2
10^0
10^{-2}
8
10
12
14
16
$E_{c.m.}$ (MeV)

Fusion of ^{16}O with ^{208}Pb

- Recently remeasured with good accuracy well below the barrier by DasGupta, *et al.*, PRL **99**, 192701 (2007).
- Akyuz-Winther potential overestimates the data well above the barrier. Esbensen and Misicu were able to fit it with M3Y+repulsive core yielding a very shallow pocket in the potential. (Note that at higher energies & angular momenta rotating-frame approximation would fail).





Esbensen & Misicu, arXiv:0711.3189

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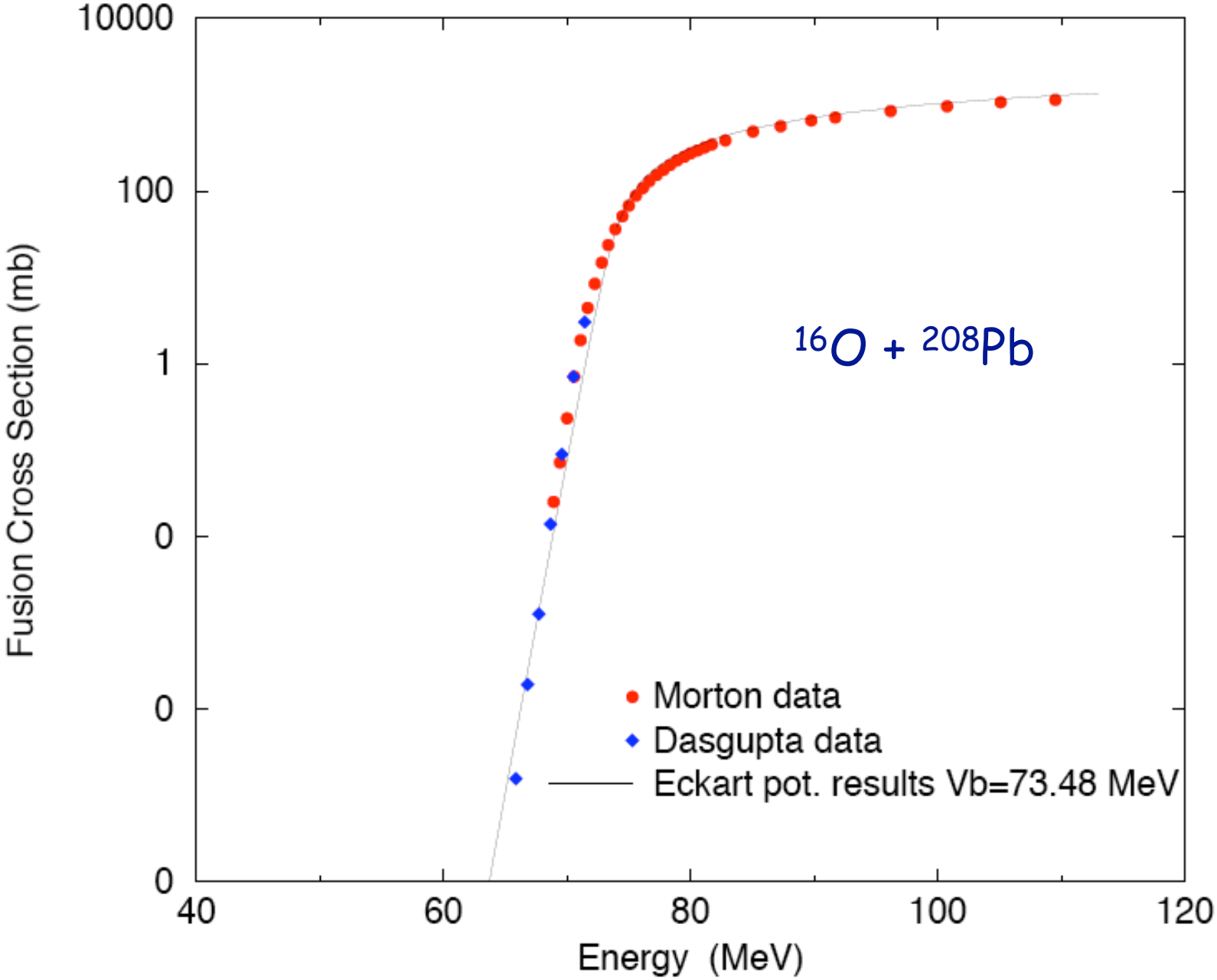
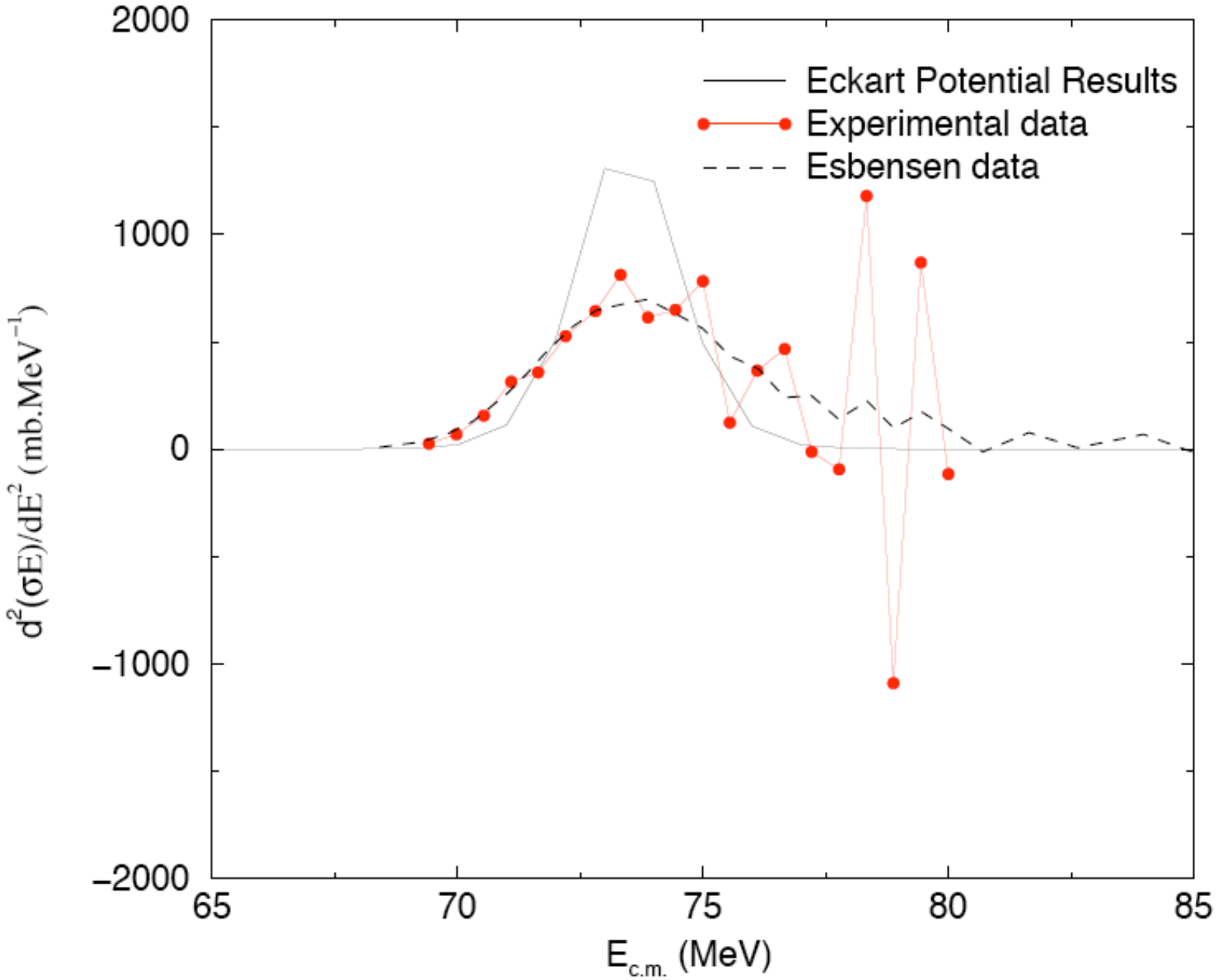
- One can illustrate that any shallow potential would fit the data by using a generalization of Wong's formula (Wong's formula uses a parabolic barrier continuing down to very low energies, we expand it to the case of an Eckart barrier which truncates).
- Both approaches fail to produce the barrier distribution; hence shallow potential is only part of the answer.


10000
100
1
0
0
0
40
60
80
100
120
Fusion Cross Section (mb)
Energy (MeV)
$^{16}O + ^{208}Pb$
Morton data
Dasgupta data
Eckart pot. results Vb=73.48 MeV


Eckart Potential Results
Experimental data
Esbensen data
2000
1000
0
−1000
−2000
65
70
75
80
85
$d^2(\sigma E)/dE^2$ (mb.MeV^{-1})
$E_{c.m.}$ (MeV)

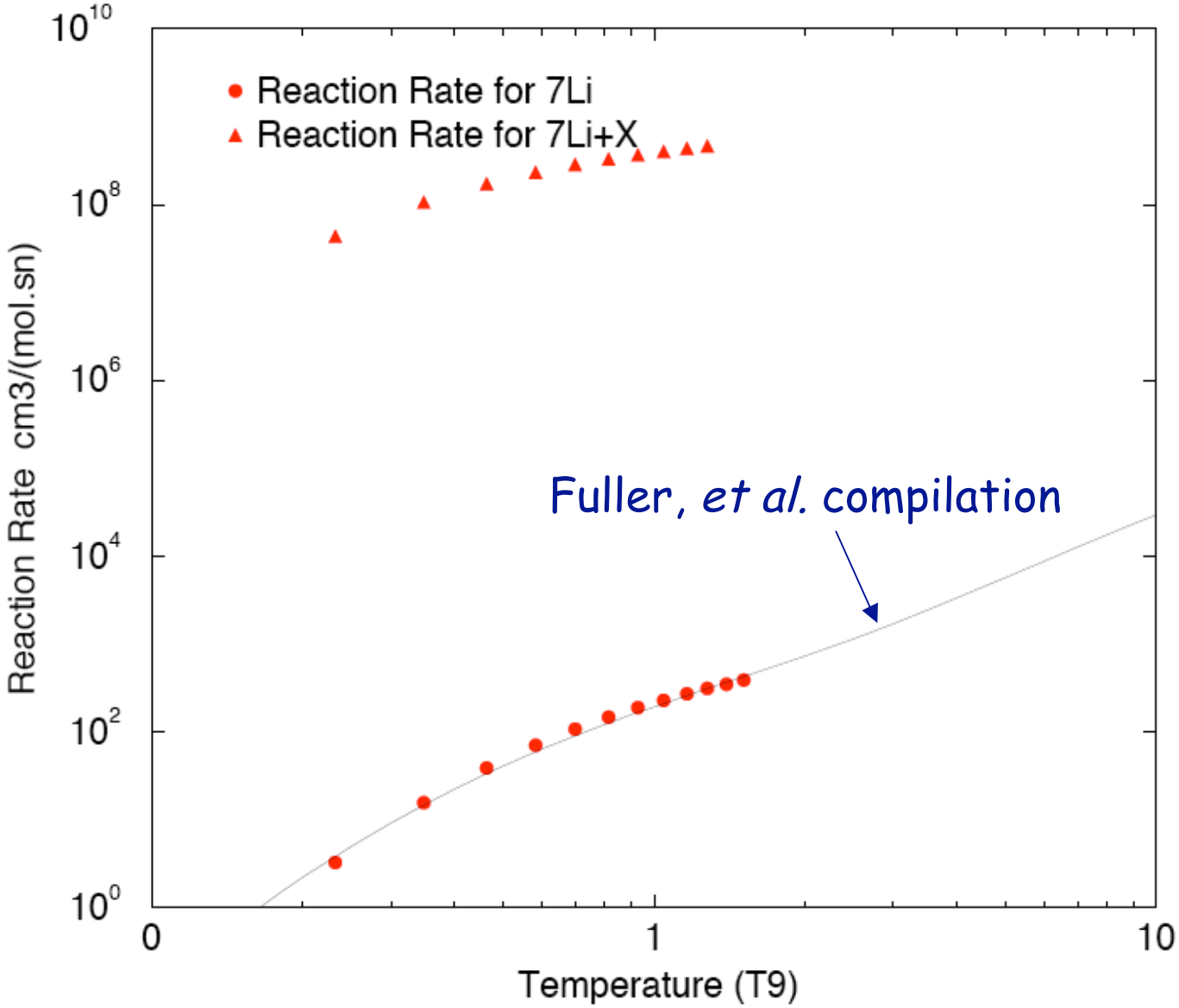
Is there a problem with the big-bang nucleosynthesis?

- WMAP observations of D and ^{4}He are in good agreement with BBN predictions but nuclear physics predicts a higher ^{7}Li abundance (by a factor of 2 or 3) than what is observed. What can we do to reduce the abundance of ^{7}Li and ^{7}Be while keeping ^{6}Li within observational limits?

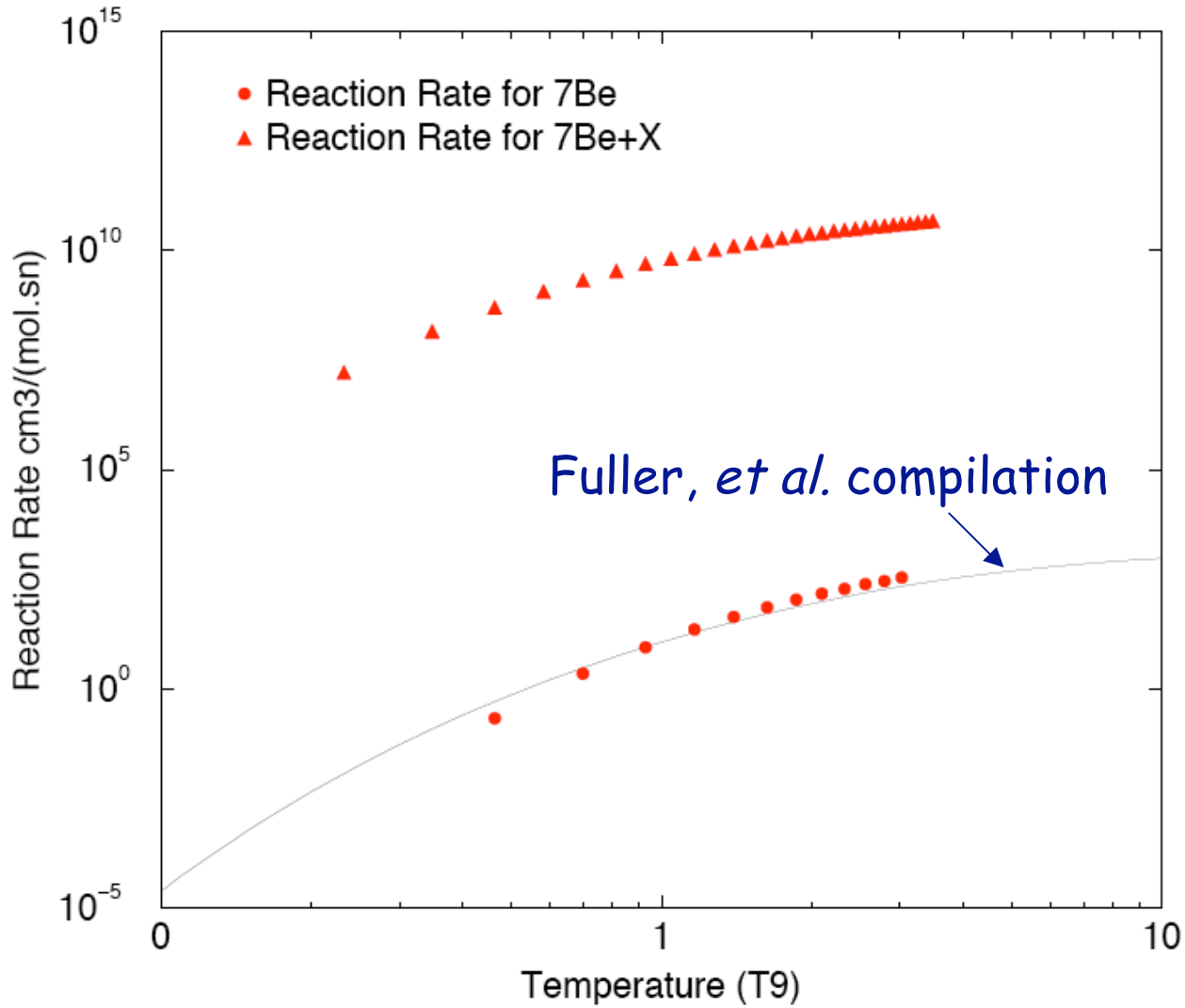
- Pospelov proposed that a metastable negatively-charged particle X^- (appearing for example in supersymmetric extensions of the Standard Model) can fix this problem. This is achieved by the formation of $^7BeX^-$ compound nuclei which is then destroyed as the additional proton and neutron capture channels open up.

- However, we find that such a particle also increases the formation rate of both ^{7}Li and ^{7}Be.

Reaction rates for $^{3}H + ^{4}He \rightarrow ^{7}Li$ vs. $^{3}H + ^{4}HeX^{-} \rightarrow ^{7}LiX^{--}$



Reaction rates for $^{3}He + ^{4}He \rightarrow ^{7}Be$ vs. $^{3}He + ^{4}HeX^{-} \rightarrow ^{7}BeX^{--}$



Concluding questions

- For asymmetric systems the barrier is well-outside the region where nuclei touch. Multidimensional barrier penetration is conceptually well-defined. Do we really understand the fusion of such nuclei? What is the large diffuseness telling us?

- What happens when nuclei fuse at energies well-below the barrier? What physics does the very shallow potentials needed to fit the data mimick?

- Do we understand how we should theoretically formulate the fusion of unstable nuclei? What can we learn by studying fusion of nuclei off the line of stability?

- We need data for the fusion of exotic nuclei, both below and above the Coulomb barrier. Such data would open a new chapter in the study of multidimensional quantum tunneling.