Reactions involving weakly bound stable projectiles

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Weakly bound stable projectiles are interesting, why?

Low breakup threshold

Stable ions

$^{6}Li \rightarrow \alpha + d$, $S_{\alpha d} = 1.48$ MeV,

$^{7}Li \rightarrow \alpha + t$, $S_{\alpha d} = 2.47$ MeV,

$^{9}Be \rightarrow \alpha + \alpha + n$, $S_{\alpha n} = 1.57$ MeV,

Unstable ions

$^{6}He \rightarrow \alpha + 2n$, $S_{\alpha 2n} = 0.97$ MeV,

- Study simulates reactions involving RIBs
- Synthesis of superheavy element by fusion of nuclei near neutron drip line
- Extrapolation to low energy capture cross section → Astrophysical interest

Advantage→Stable and large intensity

Channels to be looked at

1. Elastic scattering – Optical potential and its energy dependence→ threshold anomaly

2. Alpha production – Origin of large inclusive alpha cross section

3. Complete fusion – Suppression/enhancement compared to calculation and ones with tightly bound projectiles

1. Elastic scattering

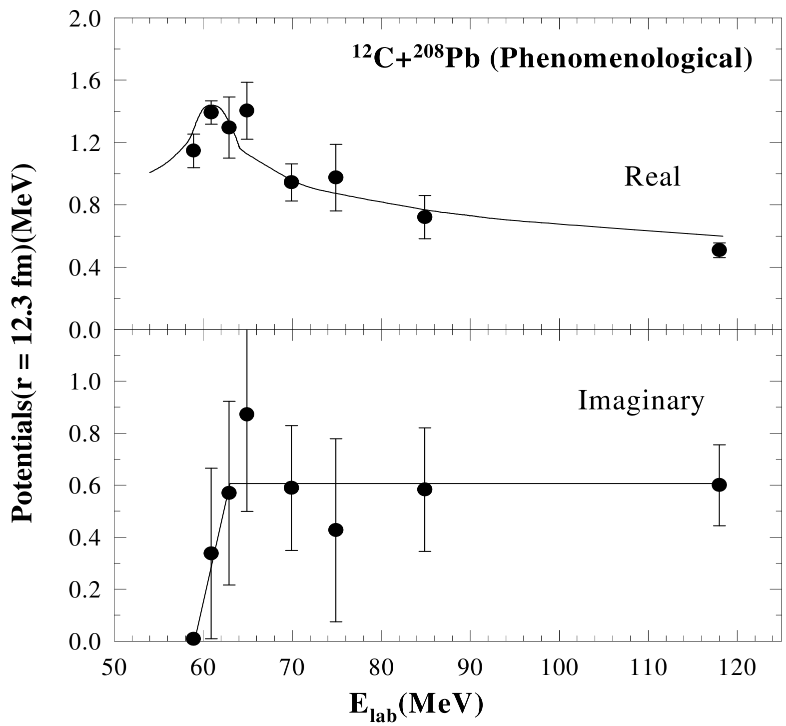
Elastic scattering

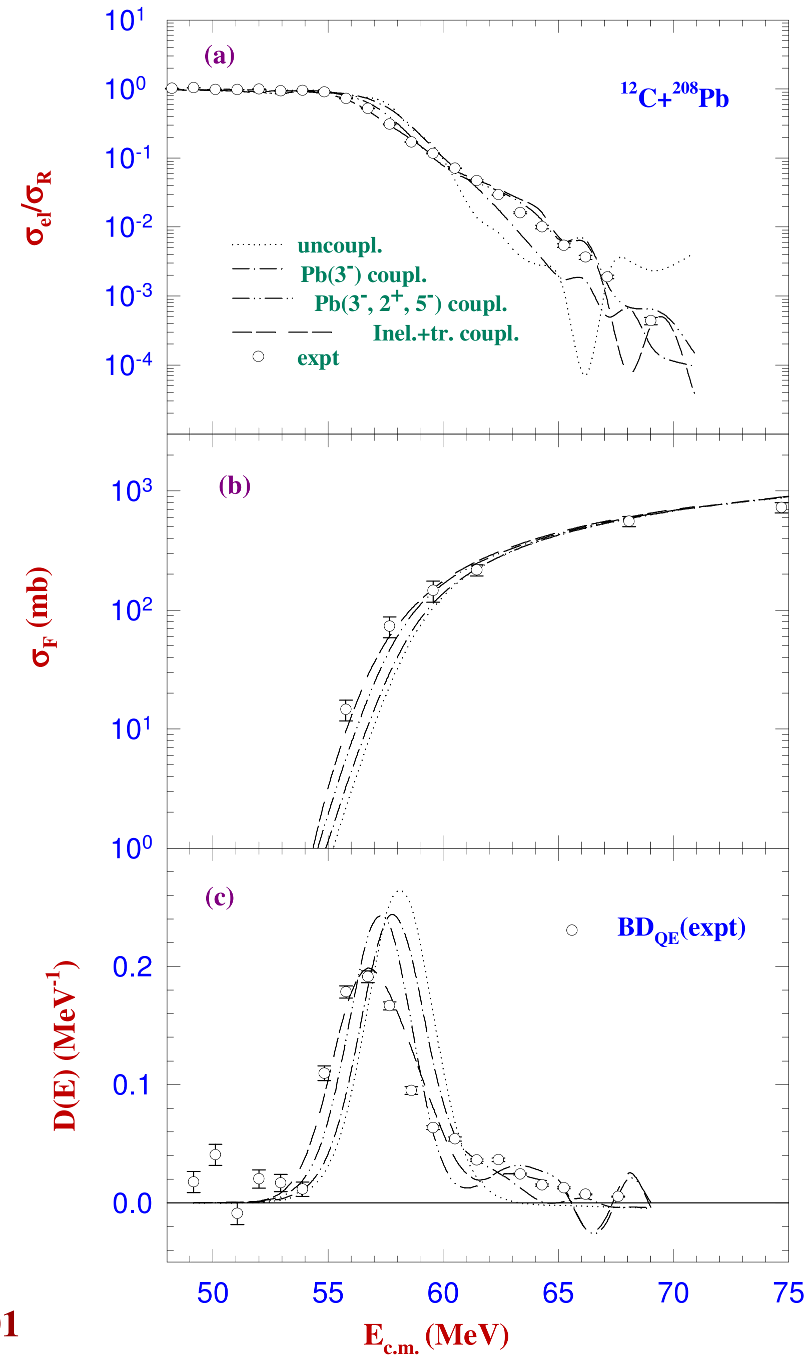
Tightly bound stable & heavy projectiles

→ "Threshold anomaly"

→ Subbarrier fusion enhancement

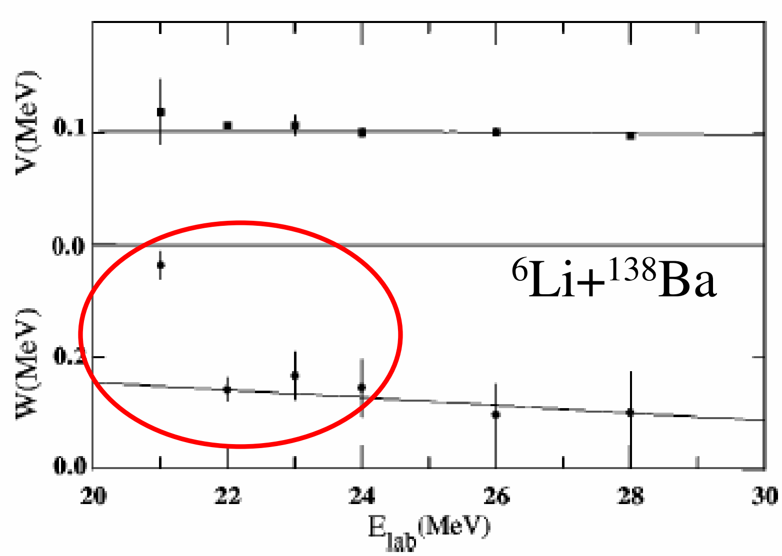
→ COUPLING

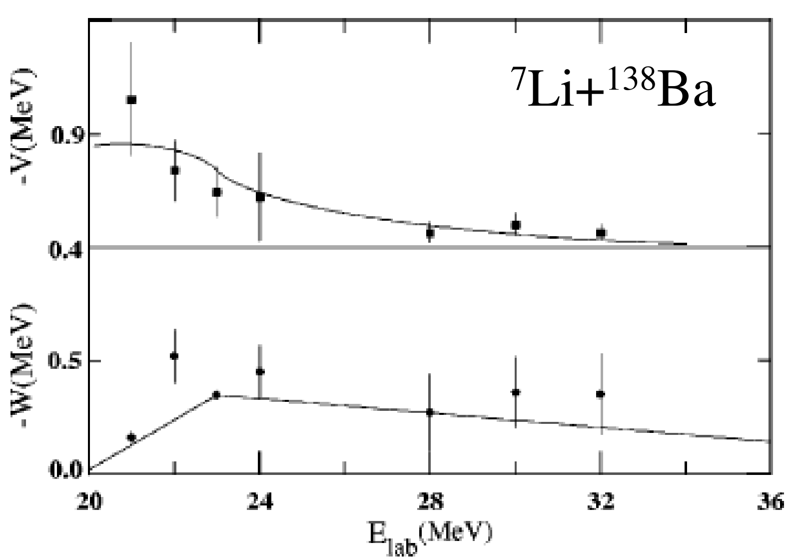




S. Santra et al.,
PRC 64, 024602 (2001

Elastic scattering with weakly bound projectiles





Optical model analysis:

→ No threshold anomaly (TA) in systems involving ^{6}Li and ^{9}Be ($e.g.$, ^{6}Li+^{138}Ba, ^{208}Pb, ^{59}Co, ^{9}Be+ ^{209}Bi, etc.)

→ Exists for ^{7}Li (higher breakup threshold and bound excited state)

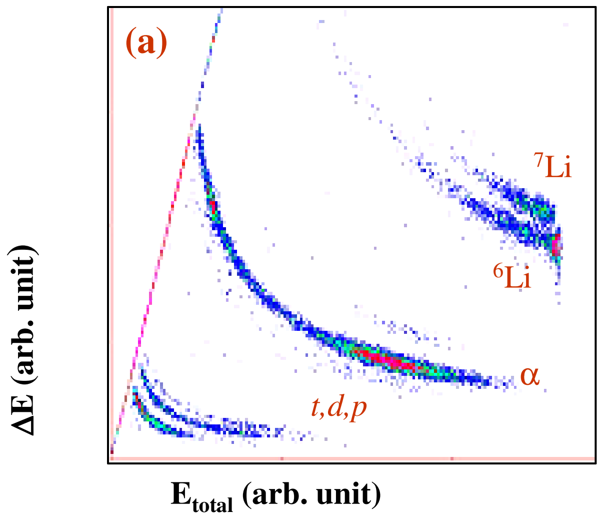
Controversy:

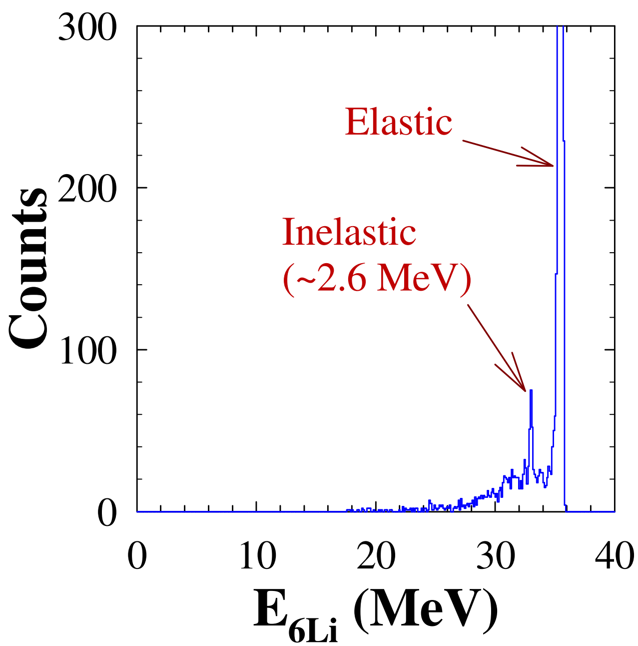
→ ^{9}Be+ ^{208}Pb, TA exists [Woolliscroft et al.]

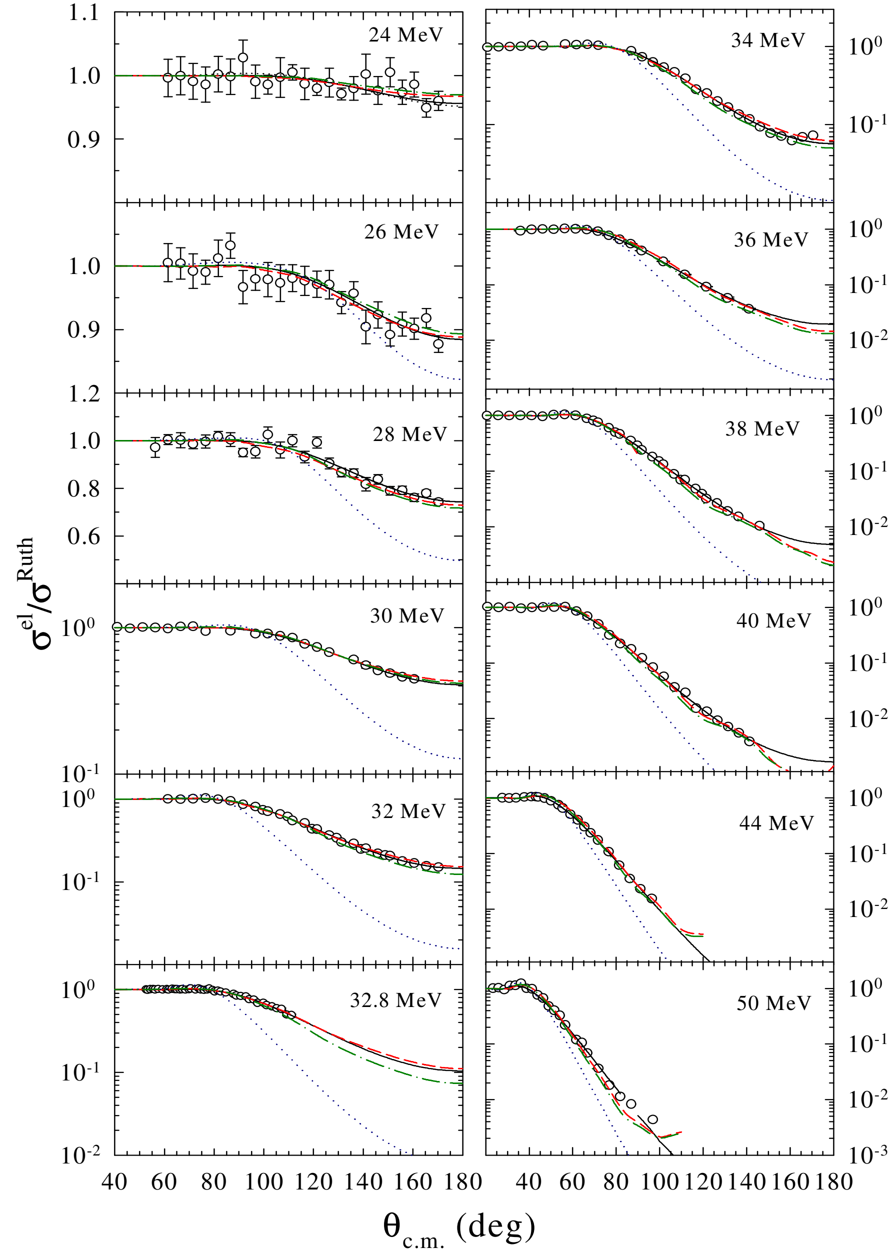
→ ^{9}Be+ ^{209}Bi, TA doesn't exist [Signorini et al.]

→ Needs further studies, a simultaneous description

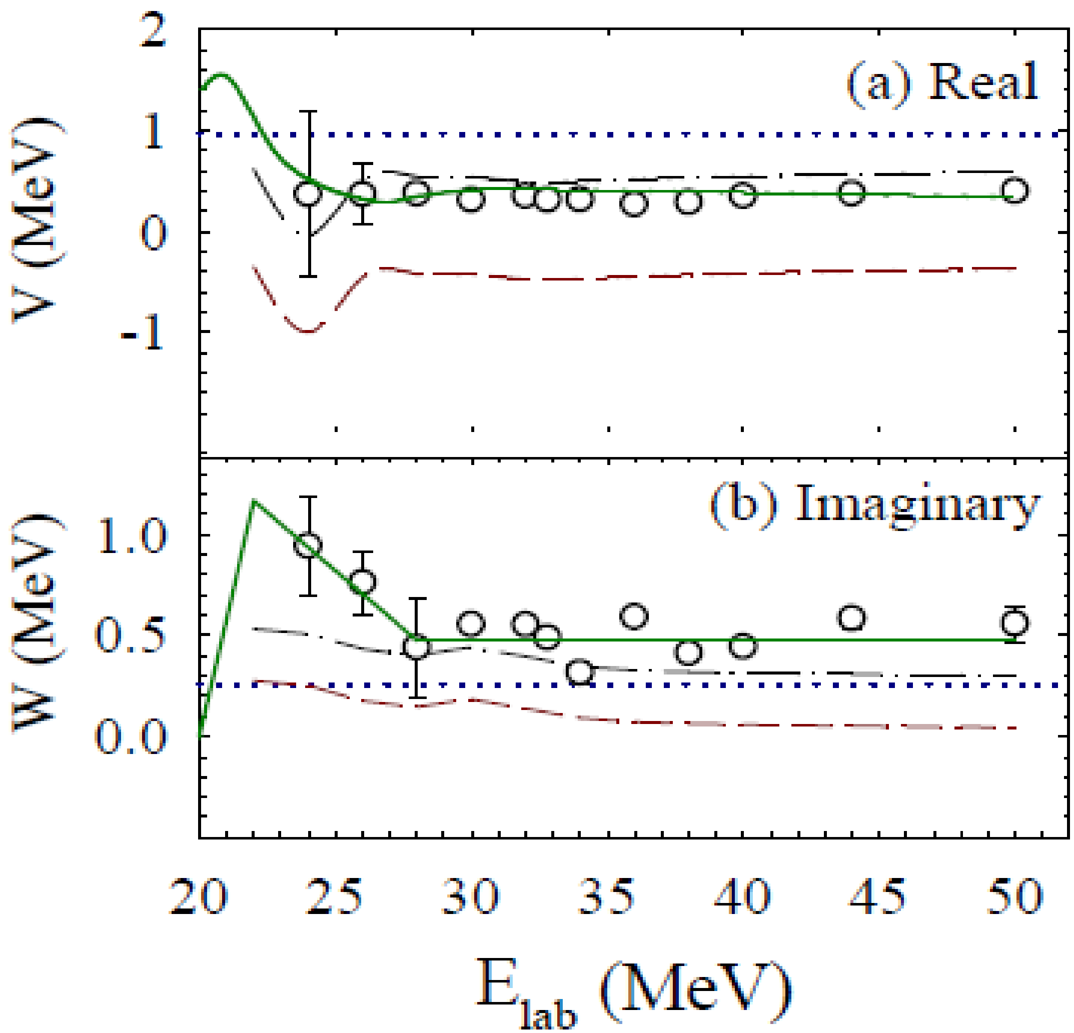
Elastic Scattering in $^{6}Li+^{209}Bi$







Energy dependence of OM potential in $^{6}Li + ^{209}Bi$

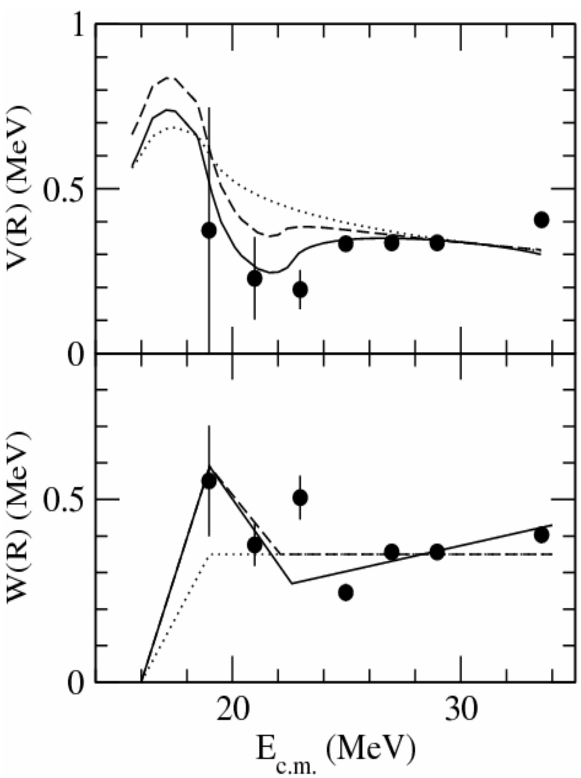


Bare potential : dotted line
Polarization: dashed line
Bare+polarize: dash-dotted line
Dispersion: solid line

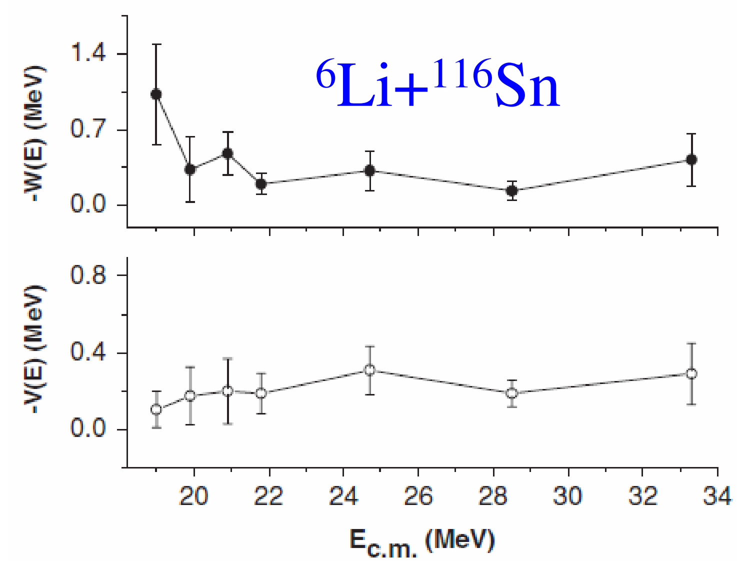
- No threshold anomaly
- Imaginary potential is non zero even at $E<<V_B$

Breakup threshold anomaly in $^{9}Be+^{89}Y$ and $^{6,7}Li+^{116}Sn$

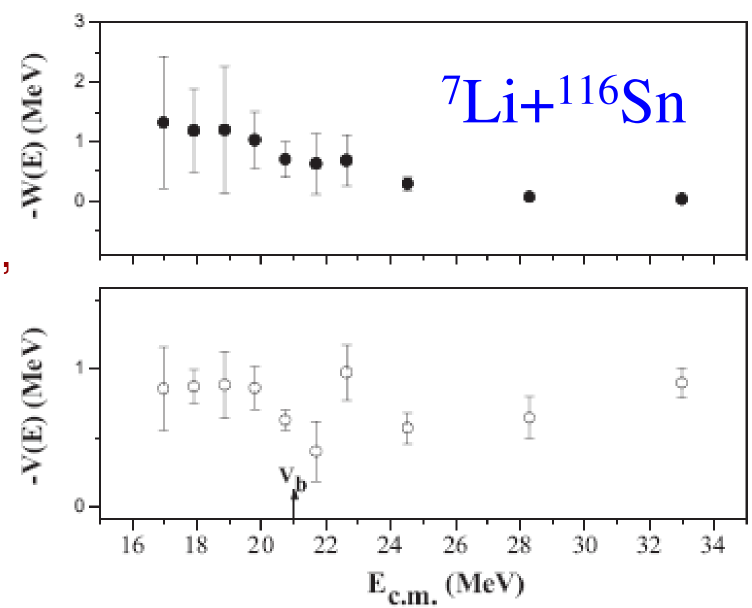
$^{9}Be+^{89}Y$



C. S. Palshetkar et al., Fusion11



Deshmukh et al., PRC 83, 051601 (2011)



Deshmukh et al., EPJA 47, 118 (2011)

Simultaneous description of elastic inelastic, transfer and breakup channels

To understand the energy dependence of OM potential

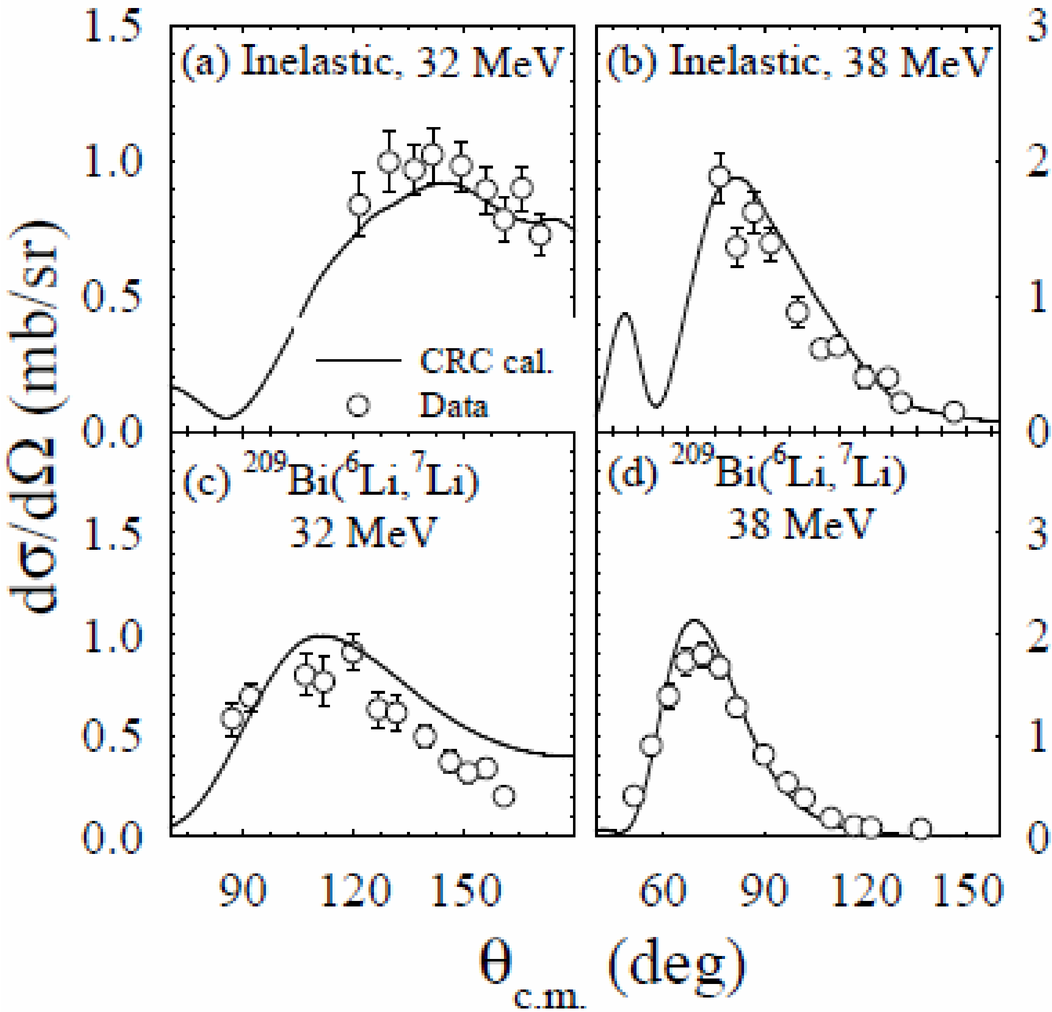
→ Coupled-channels calculations

→ Need non-arbitrary potentials and coupling parameters

→ Should explain simultaneously the elastic, inelastic, transfer and breakup channels

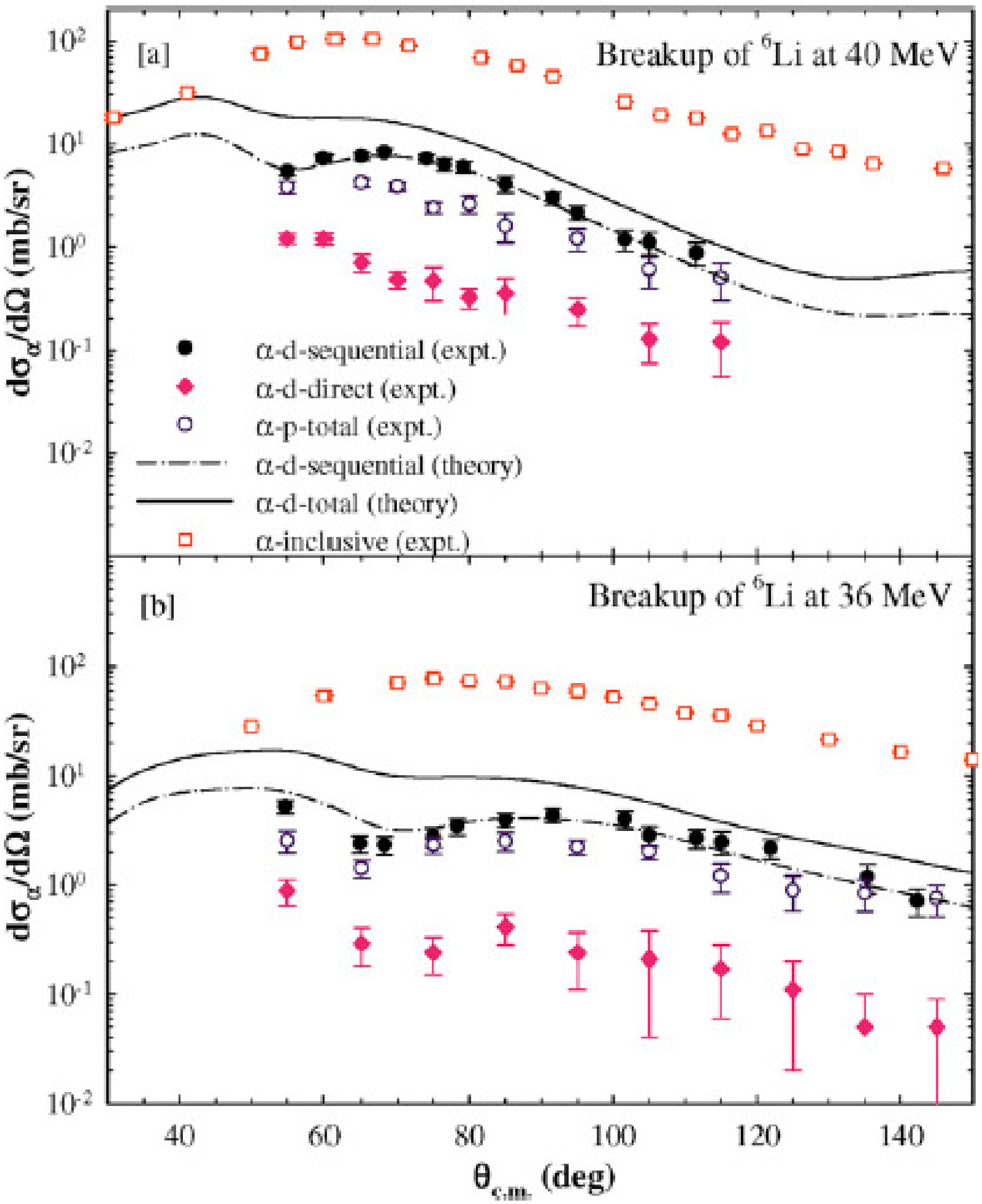
→ Need data for these channels

Description of inelastic and transfer data



→ Measured data explained by same coupled-channels calculations→ potentials are not arbitrary

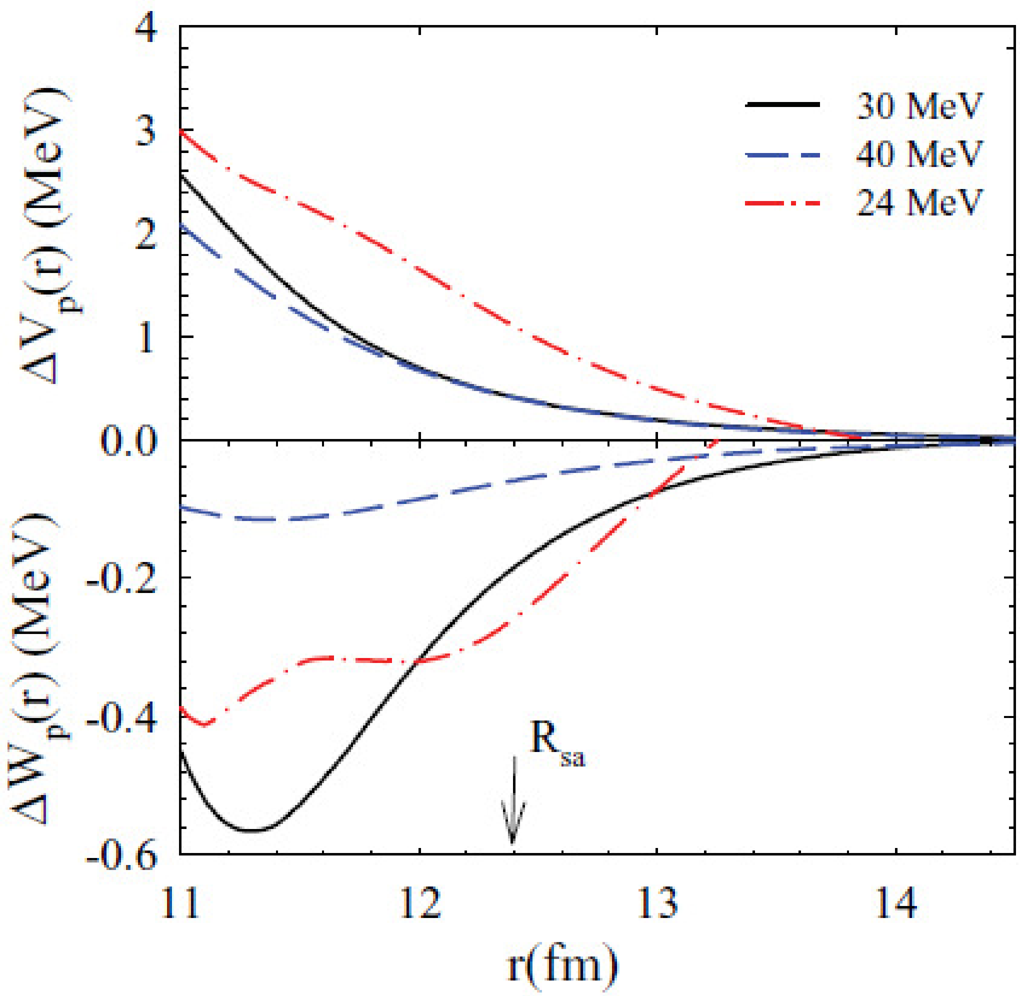
Exclusive breakup measurements



- Exclusive meaurements for α+d, and α+p cross sections
- Potentials used in coupled-channels calculations explains α+d breakup

S. Santra et al., PLB 677, 139 (2009)

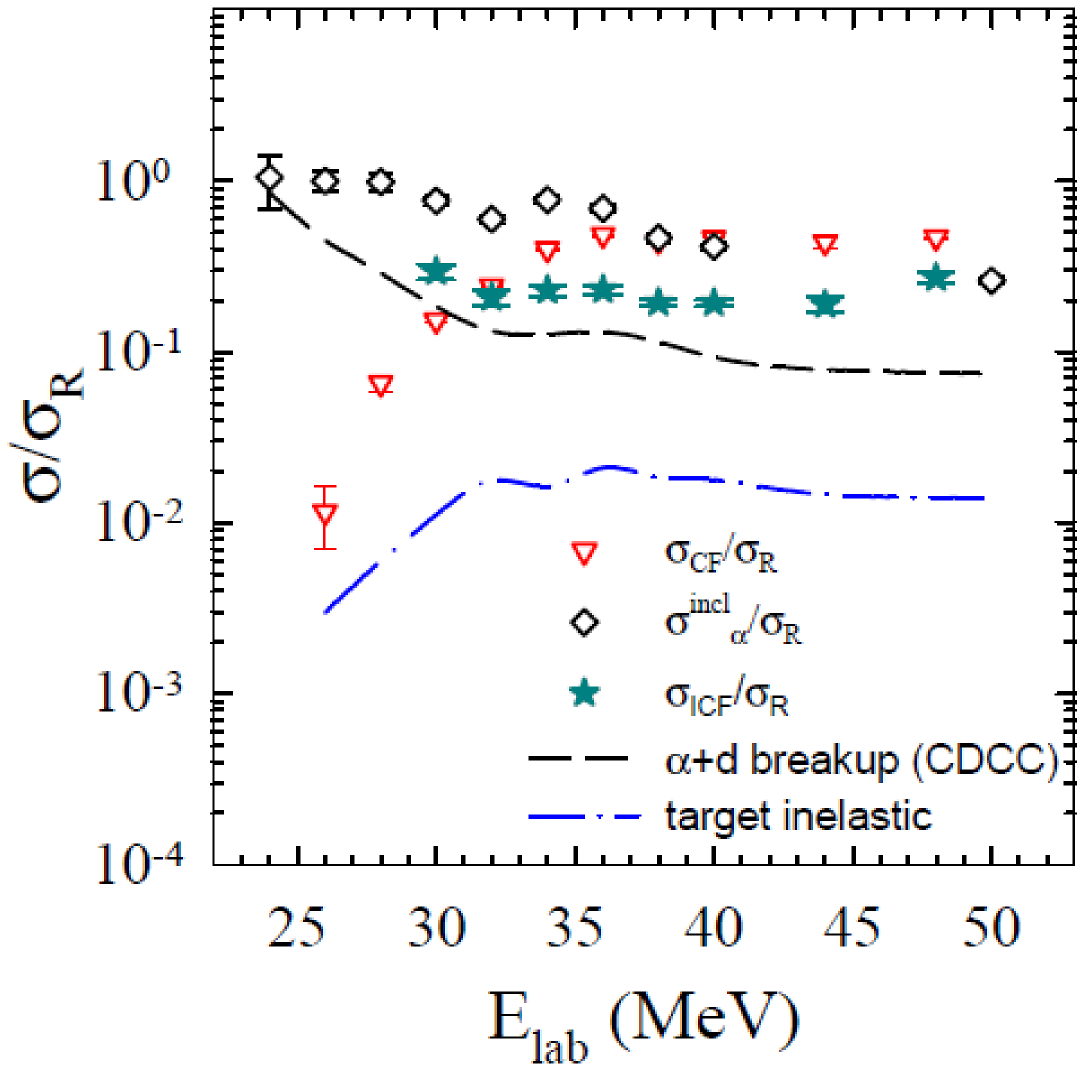
Dynamic polarization potential generated due to breakup coupling



$V_{eff}=V_{bare}+\Delta V_P$

- Real dynamic polarization potential is +ve (repulsive) → no TA
- Imaginary dynamic polarization potential is -ve (attractive) → nonzero W

Reaction probabilities vs beam energy



- Breakup, ICF and incl-alpha increases as energy decreases
- Behaviour opposite to CF, inelastic and transfer
- Breakup at sub-barrier energies → nonzero imaginary potential

S. Santra et al., PRC 83, 034616 (2011)

Papers on ^{6}Li+^{209}Bi

Physics Letters B 677 (2009) 139–144

Contents lists available at ScienceDirect

1 → Physics Letters B

www.elsevier.com/locate/physletb

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PHYSICS LETTERS B

Resonant breakup of ^{6}Li by ^{209}Bi

S. Santra *, V.V. Parkar, K. Ramachandran, U.K. Pal, A. Shrivastava, B.J. Roy, B.K. Nayak, A. Chatterjee, R.K. Choudhury, S. Kailas

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2 → PHYSICAL REVIEW C **83**, 034616 (2011)

Reaction mechanisms involving weakly bound ^{6}Li and ^{209}Bi at energies near the Coulomb barrier

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Summary 1

- Threshold anomaly was not observed for $^{6}Li+^{209}Bi$ (so also for $^{6}Li+^{90}Zr,^{116}Sn$ and $^{9}Be+^{89}Y$) in contrast to the observation by Woolliscroft et al for $^{9}Be+^{208}Pb$.

- Coupled-channels calculations that describe simultaneously the elastic, inelastic, transfer and breakup channels explain the observed energy dependence of the optical potential

- Breakup contribution to reaction increases as energy decreases (in contrast to CF, inelastic, transfer) → nonzero imaginary potential below the barrier

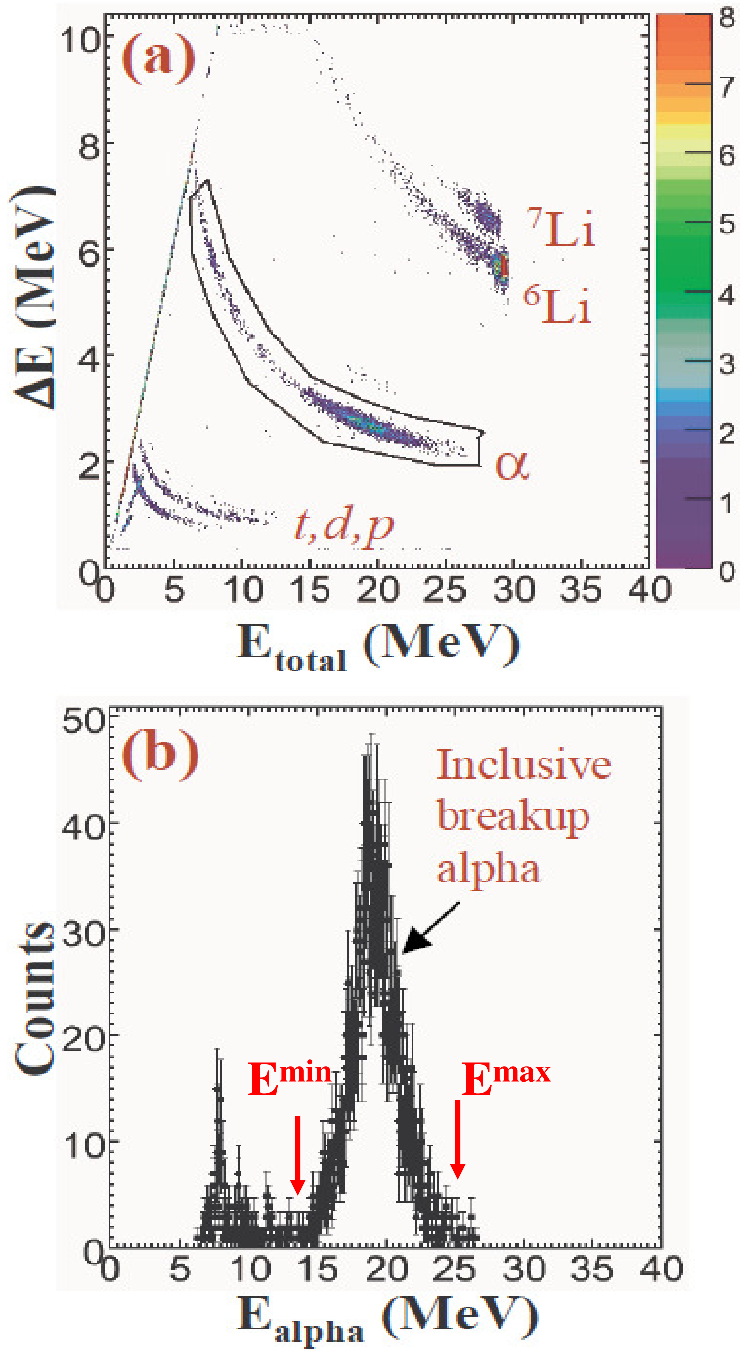
2. Alpha production

Motivation

1. Measurements involving the projectiles ($^{6,7}Li$, ^{6}He, ^{9}Be) with α+x cluster structure show significantly large cross sections for α-particles produced by breakup and transfer reactions

2. Exclusive measurements of α-particles and details calculations are essential to delineate different processes leading to such a large inclusive cross section

Measurements

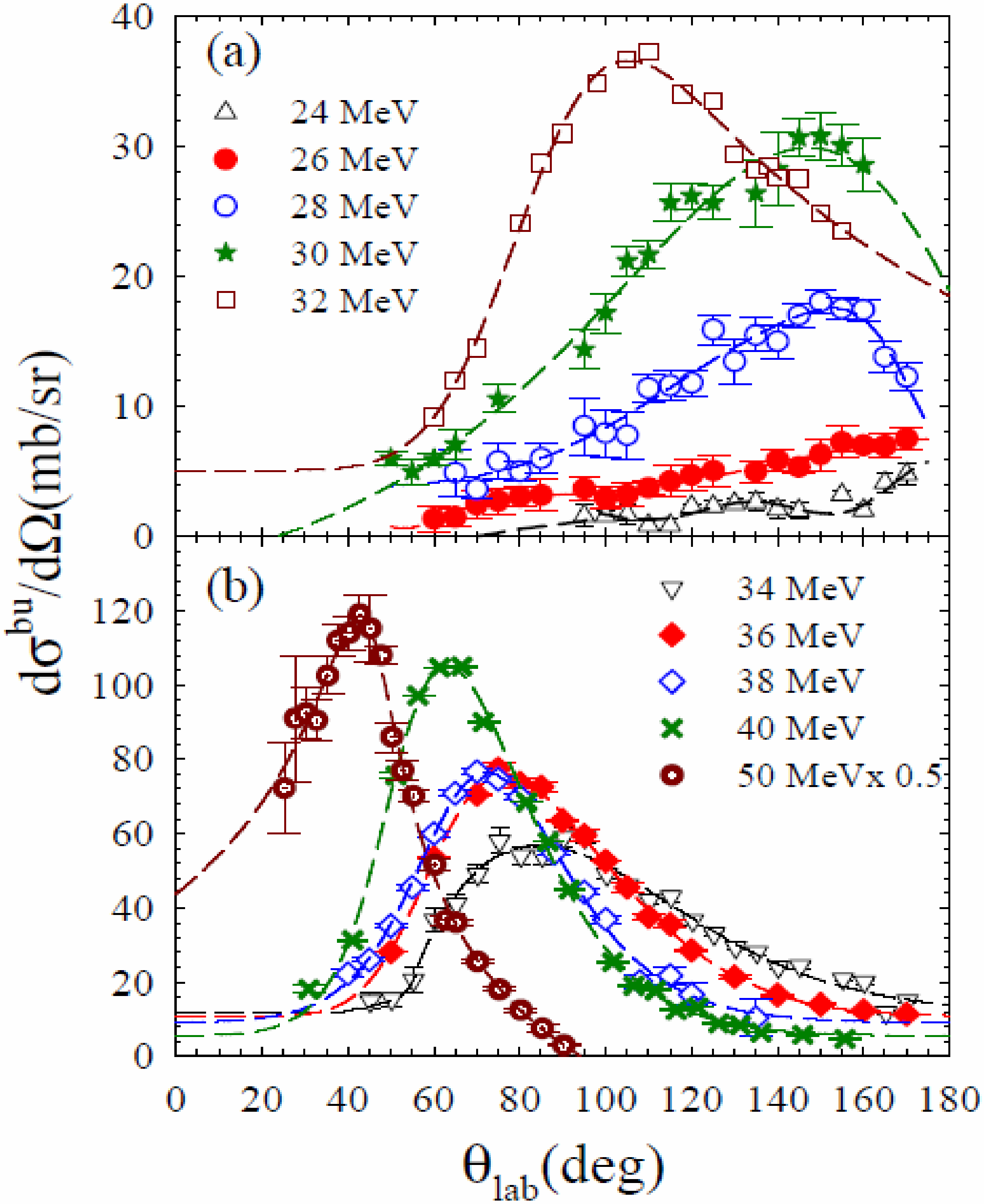


Inclusive breakup alpha →

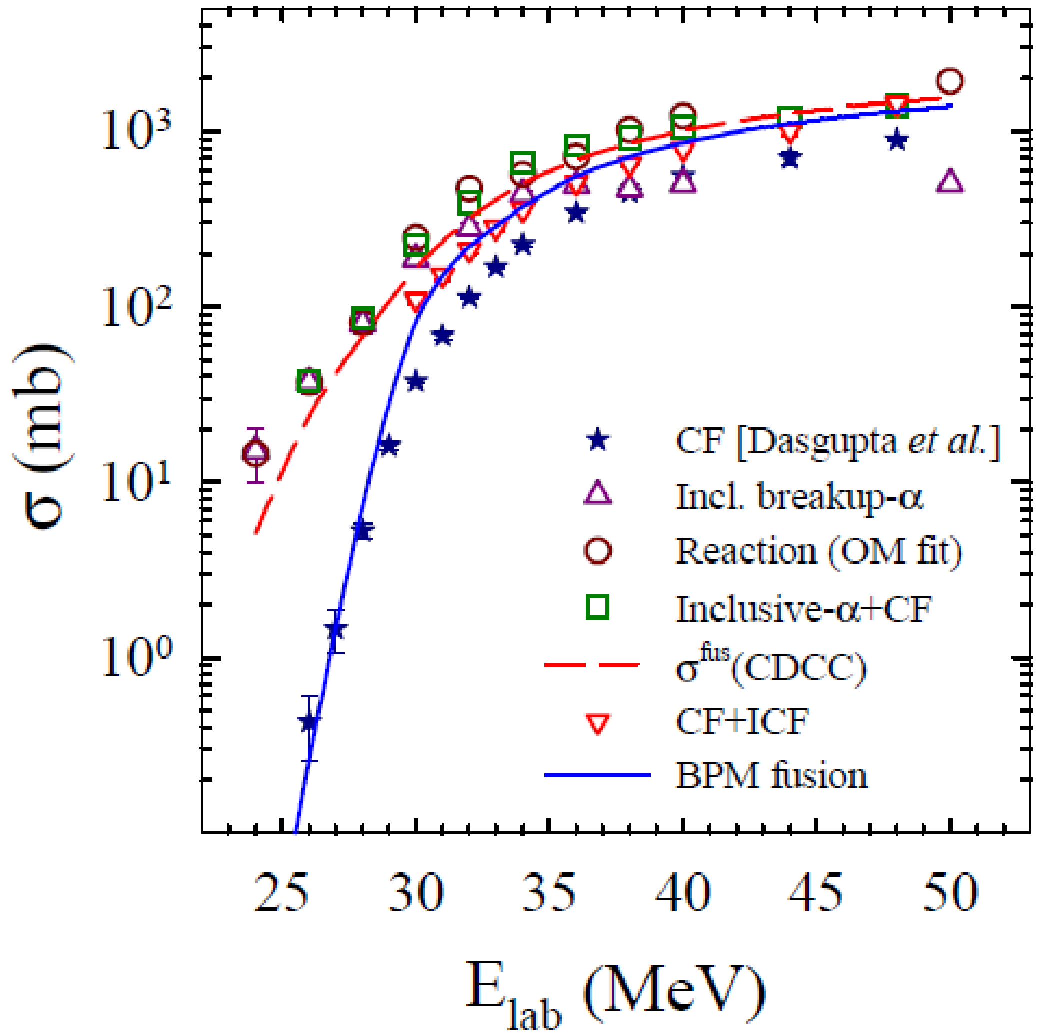
$$E^{\alpha}_{min,max} = E\frac{m_\alpha}{M_{Li}}\left(1+\frac{\epsilon m_d}{E m_\alpha} \pm 2\sqrt{\frac{\epsilon}{E}\frac{m_d}{m_\alpha}}\right)$$

$E_\alpha^{max} - E_\alpha^{min} \approx 9$ MeV

Inclusive alpha angular distribution



Inclusive breakup, fusion and reaction



- Inclusive breakup is a major reaction channel
- At E≤Vb it exhausts σ^R
- σ^{CF}+ σ^{incl} exhausts all of σ^R at any energy
- BPM fusion equals TF at E>Vb
- CDCC fusion = σ^{TF} + σ^{inel} + σ^{tr}

Alpha production mechanisms

1. Non-capture breakup of $^{6}Li \rightarrow \alpha + d$ *(exclusive measurement & CDCC calculation)*

2. $\alpha + d$ breakup followed by d-capture (part of ICF) (*derive from measured ICF by Wong model*)

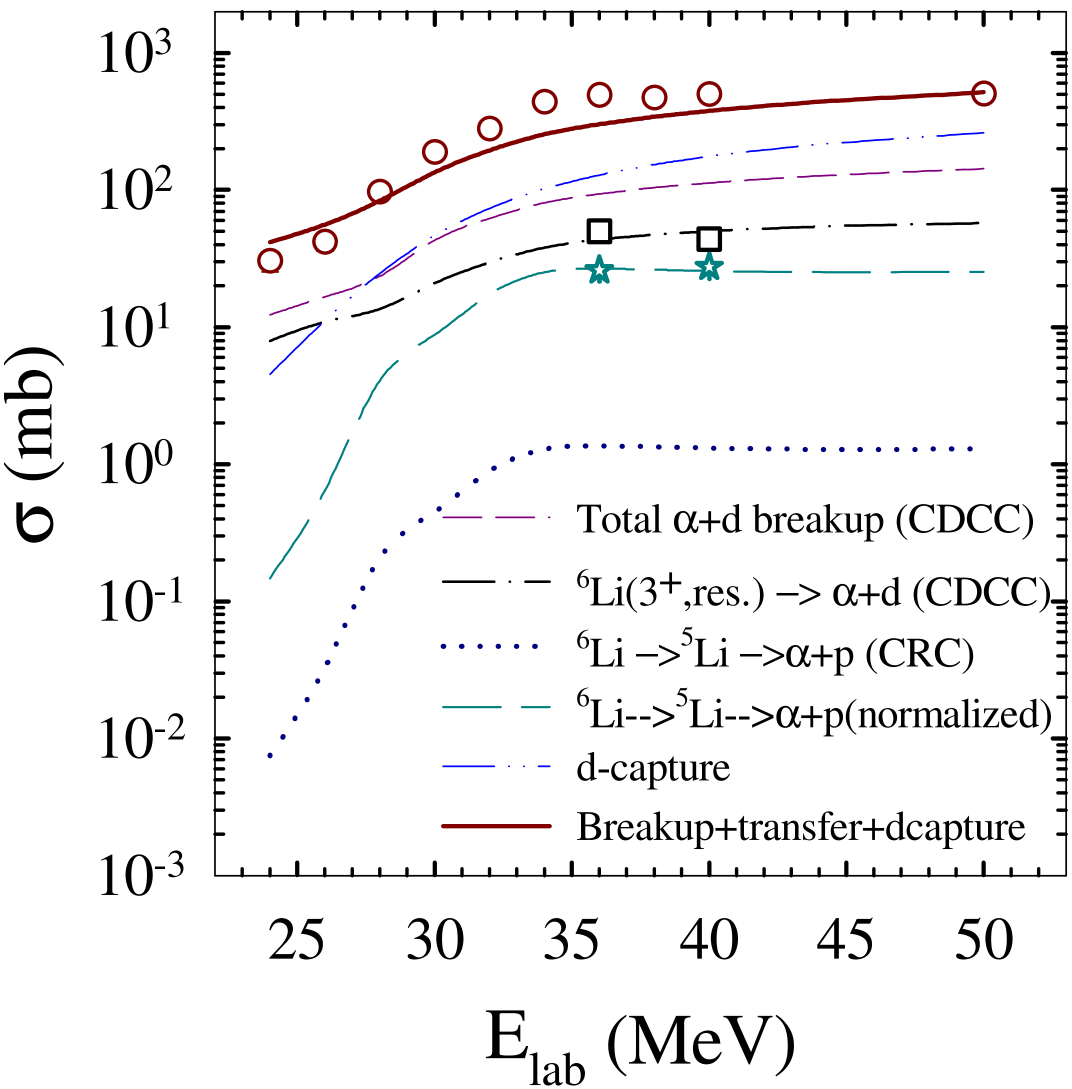
3. Neutron stripping followed by breakup ($^{6}Li \rightarrow {}^{5}Li \rightarrow \alpha + p$) (*exclusive measurement & CRC calculation*)

4. Proton stripping followed by breakup ($^{6}Li \rightarrow {}^{5}He \rightarrow \alpha + n$) (*CRC calculation*)

5. Neutron pickup followed by breakup ($^{6}Li \rightarrow {}^{7}Li \rightarrow \alpha + t$) (*exclusive measurement & CRC calculation*)

6. Deuteron stripping ($^{6}Li, \alpha$) (*CRC calculation*)

Alpha production mechanisms



- ✓ ICF has maximum contribution, followed by exclusive breakup channels of α+*d* and α+*p*
- ✓ ^{7}Li→α+t, ^{5}He→α+n, and deuteron stripping(via low excitation) are negligible

Summary 2

- Inclusive breakup alpha cross sections for $^{6}Li+^{209}Bi$ reaction was found to be a major fraction of the total reaction
- It exhausts almost all of the reaction cross section at sub-barrier energies
- Existence of large breakup probability in this region allows the imaginary part of the optical potential to remain non-zero
- ICF (d-capture) followed by exclusive α+d and α+p breakup seem to be the main source of such a large alpha production cross section

S. Santra et al., Submitted to PRC

3. Fusion with weakly bound projectiles

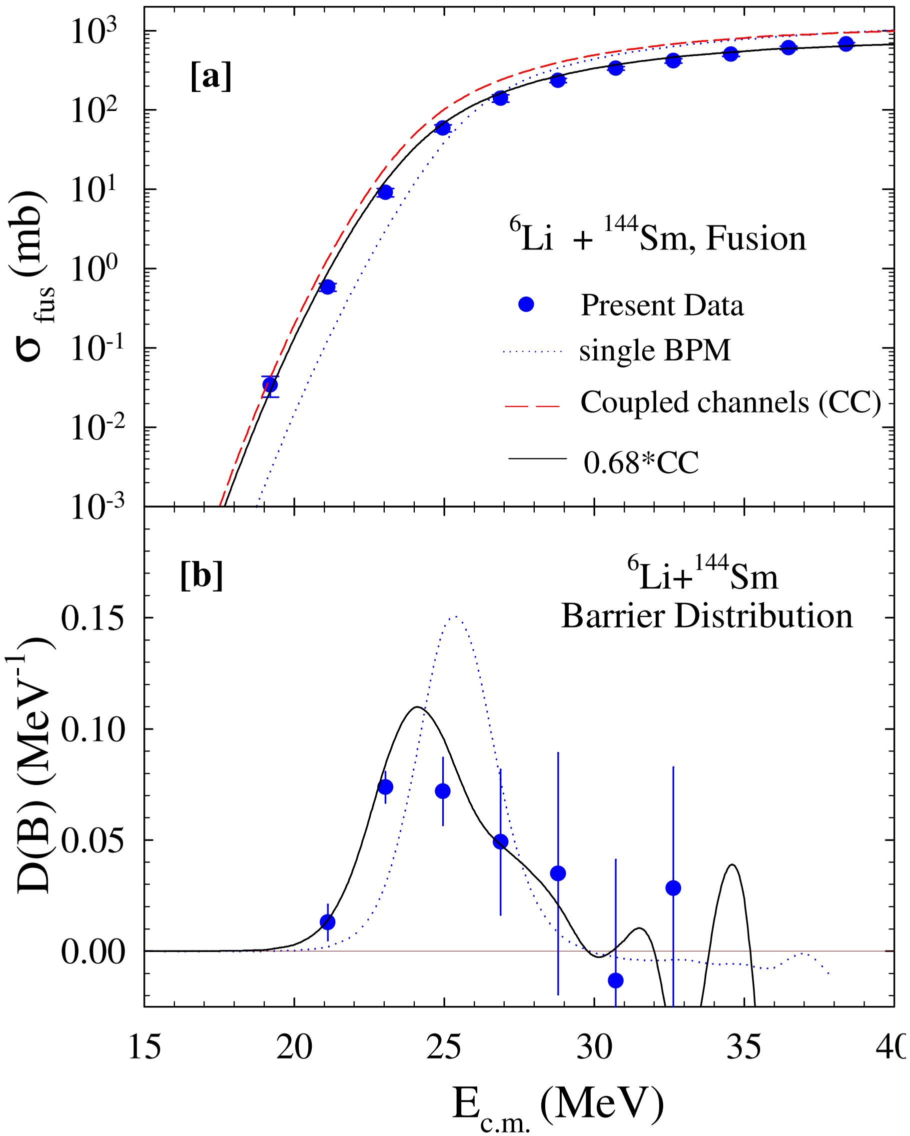
Motivation

Fusion in presence of breakup channel

→enhance fusion due to coupling /

→suppress fusion due to loss of flux

Complete fusion in $^{6}Li+^{144}Sm$



CC Calculations:

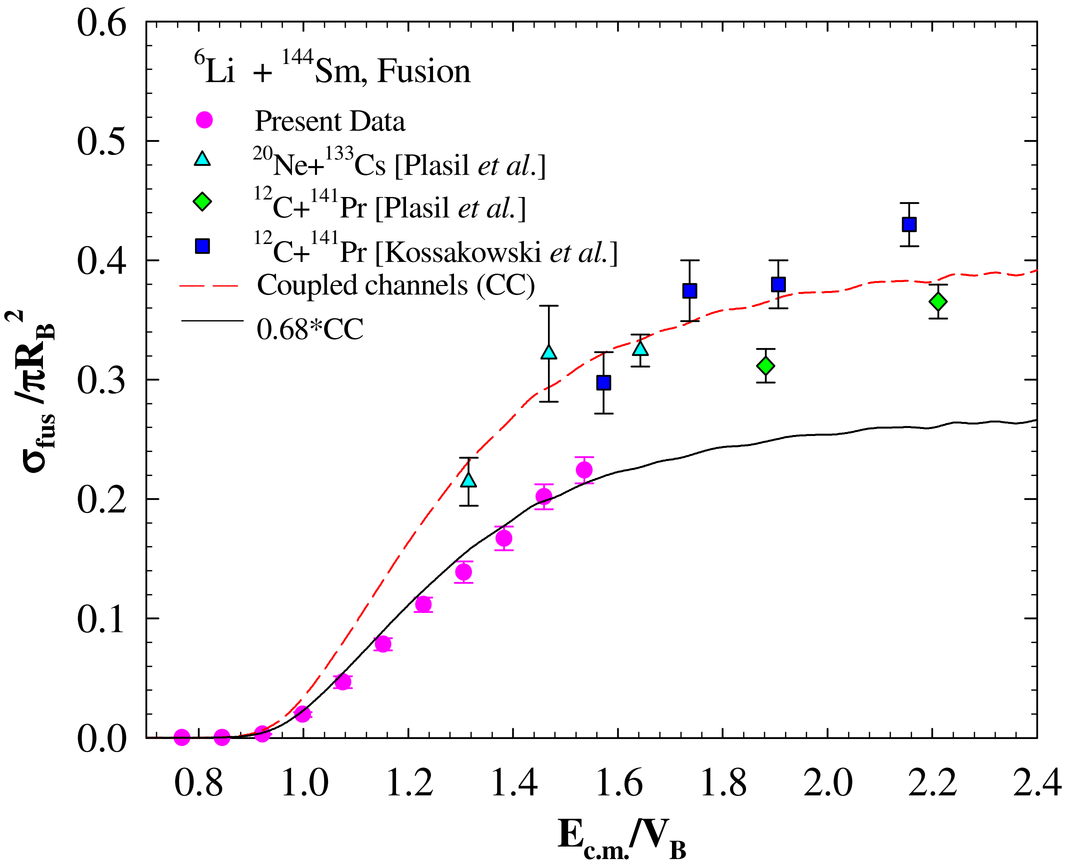
→Potential chosen to reproduce the average experimental barrier distribution

→Target inelastic (3^{-}, 1.81 MeV) as vibrational state

→^{6}Li (3^{+}, 2.18 MeV) is coupled. Reorientation coupling included.

→Overall suppression in CF ~ 32%

Comparison with tightly bound projectiles



CC Calculations:

→CF for ^{6}Li+^{144}Sm is suppressed by about same order (32%) compared to other two systems

Conclusion→ overall suppression in CF ~ 32%

Systematics of CF supression

Projectile	Breakup threshold (MeV)	Target	Suppression factor
6Li	$S_{\alpha d}$=1.48	209Bi	36%
		208Pb	34%
		144Sm	32%
		152Sm	28%
9Be	$S_{\alpha\alpha n}$=1.57	208Pb	32%
		144Sm	10%
		124Sn	20%
		89Y	20%
7Li	$S_{\alpha t}$=2.45	209Bi	26%
		165Ho	18%
		159Tb	26%
		152Sm	20%
		144Sm	20%

Suppression fraction
→increases as projectile breakup threshold deceases
→increases with target charge

Paper on ^{6}Li+^{144}Sm

RAPID COMM

PHYSICAL REVIEW C **79**, 051601(R) (2009)

Suppression of complete fusion in the ^{6}Li + ^{144}Sm reaction

P. K. Rath,[1] S. Santra,[2,*] N. L. Singh,[1] R. Tripathi,[3] V. V. Parkar,[2] B. K. Nayak,[2] K. Mahata,[2] R. Palit,[4] Suresh Kumar,[4] S. Mukherjee,[1] S. Appannababu,[1] and R. K. Choudhury[2]

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Complete fusion excitation function for the ^{6}Li + ^{144}Sm reaction has been measured at near barrier energies by the activation technique. Coupled-channel calculations show an enhancement in fusion cross section at energies below the barrier compared to the one-dimensional barrier penetration model calculation, but they overpredict it in the entire energy range compared to the experimental data. Reduced fusion cross sections for the present system at energies normalized to the Coulomb barrier were also found to be systematically lower than those with strongly bound projectiles forming a similar compound nucleus. These two observations conclusively show that the complete fusion cross section, at above barrier energies, is suppressed by $\sim$32% in the ^{6}Li + ^{144}Sm reaction

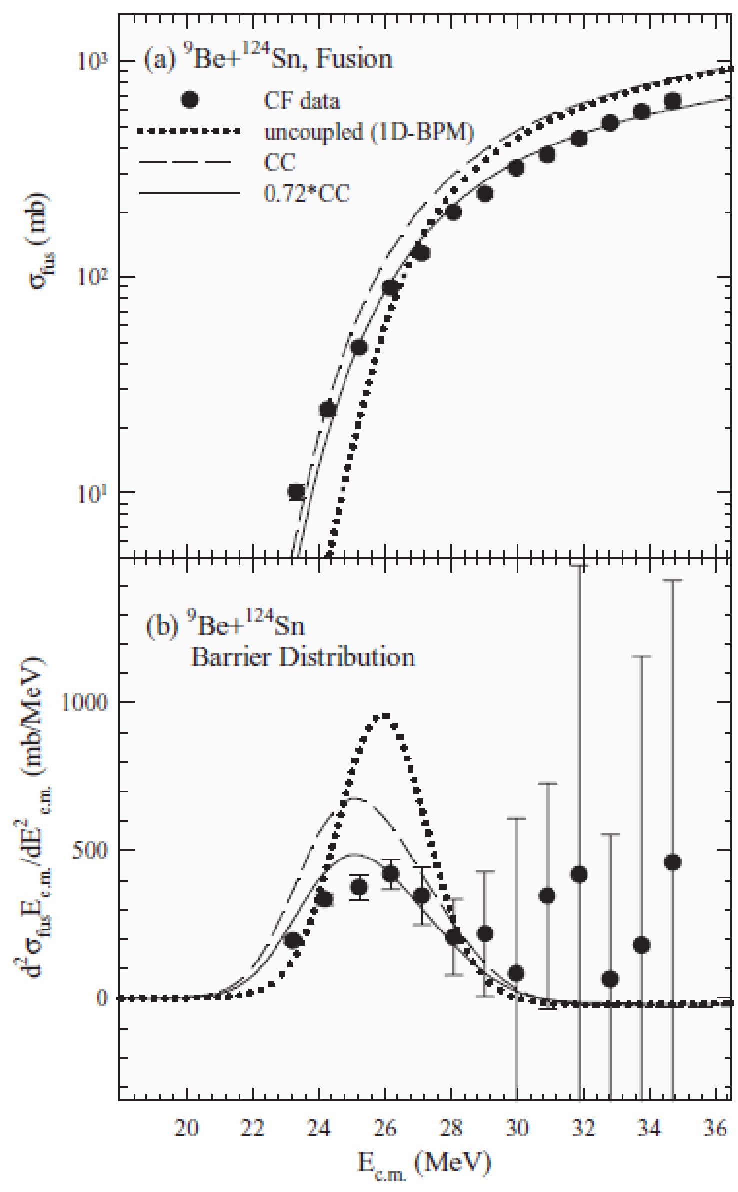
Fusion of ^{9}Be with ^{124}Sn

Suppression factor:

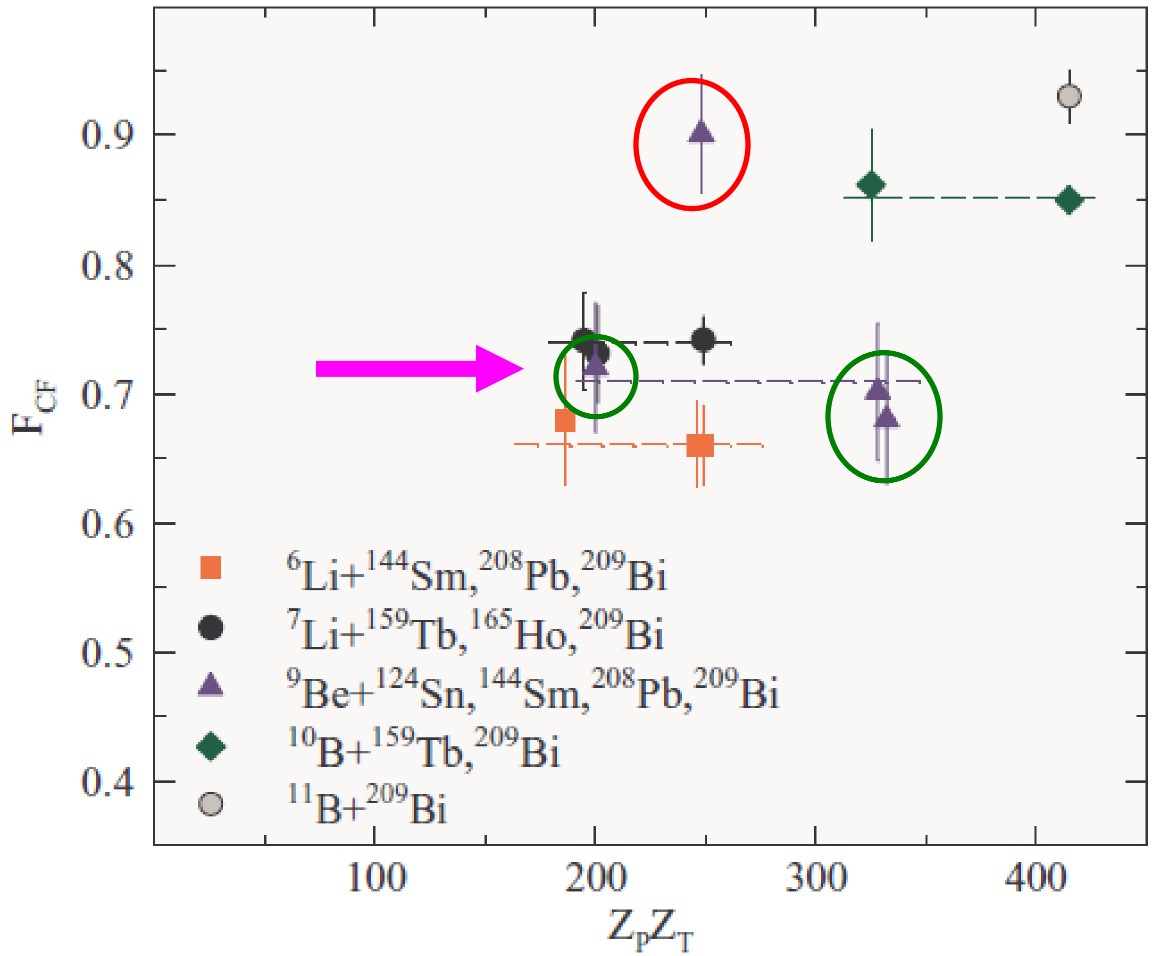
→ $^{9}Be+^{208}Pb$ ~32%

→ $^{9}Be+^{144}Sm$ ~10%

→ for $^{9}Be+^{124}Sn,^{89}Y$ should be < 10%



Systematics of complete fusion fraction



→FCF for $^{9}Be+^{144}Sm$ << $^{9}Be+^{208}Pb,^{209}Bi$

→FCF for $^{9}Be+^{124}Sn$ found to be much larger than $^{9}Be+^{144}Sm$

Paper on ^{9}Be+^{124}Sn

→ PHYSICAL REVIEW C **82**, 054601 (2010)

Fusion cross sections for the ^{9}Be+^{124}Sn reaction at energies near the Coulomb barrier

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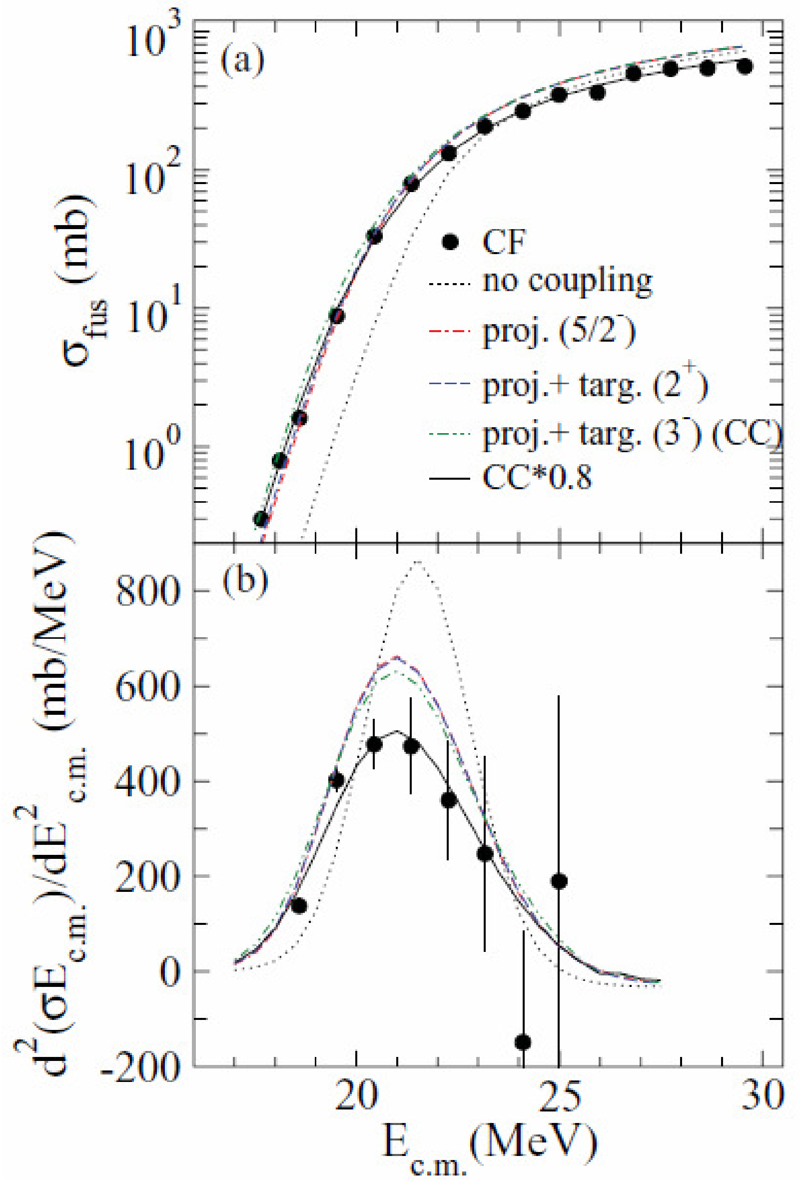
The complete and incomplete fusion cross sections for ^{9}Be+^{124}Sn reaction have been deduced using the online γ-ray measurement technique. Complete fusion at energies above the Coulomb barrier was found to be suppressed by $\sim$28% compared to the coupled-channels calculations and is in agreement with the systematics of L. R. Gasques *et al.* [Phys. Rev. C **79**, 034605 (2009)]. Study of the projectile dependence for fusion on a ^{124}Sn target shows that, for ^{9}Be nuclei, the enhancement at below-barrier energies is substantial compared to that of tightly bound nuclei.

Fusion of weakly bound ^{9}Be with ^{89}Y



CC Calculations:

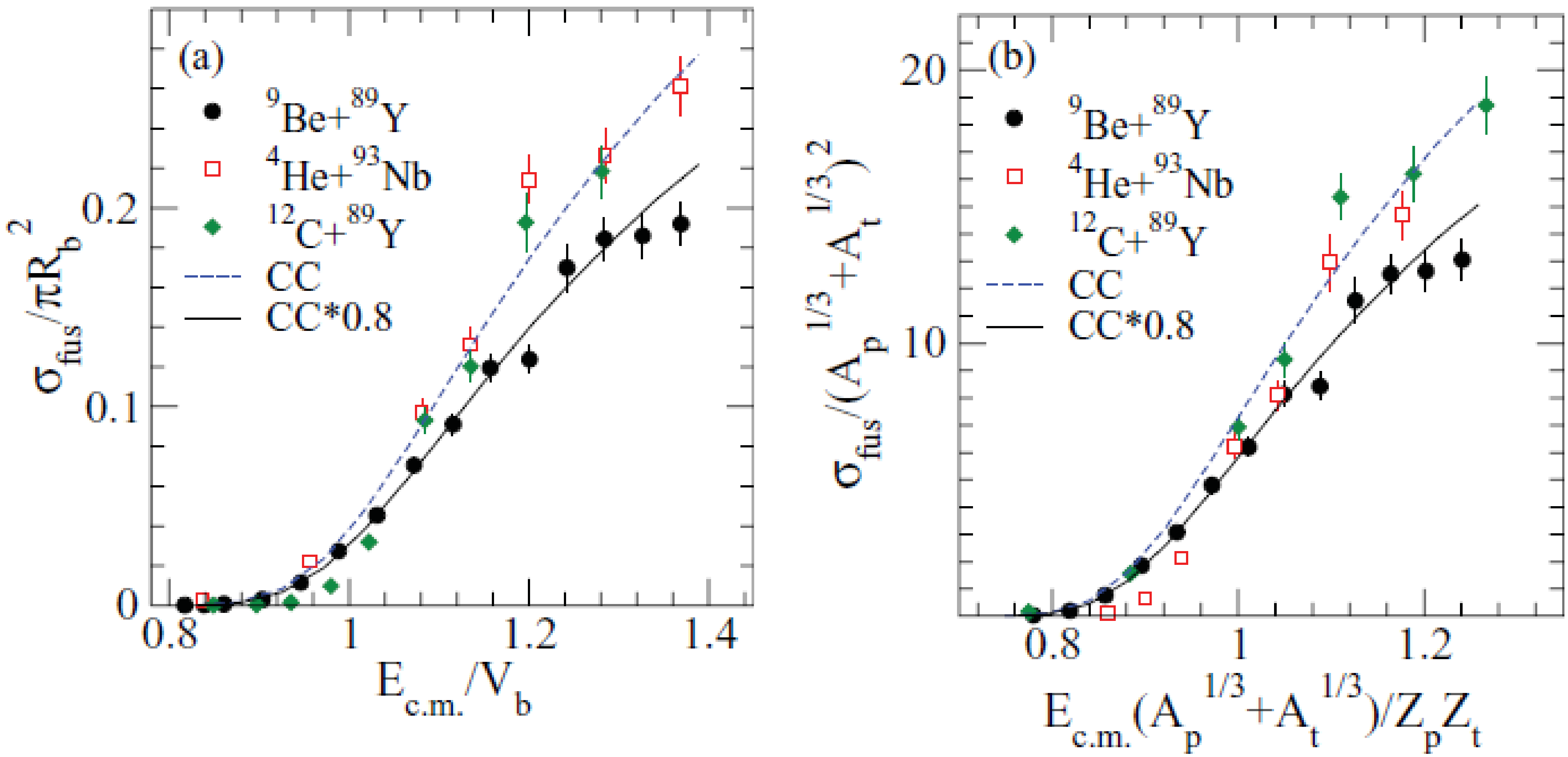
→Potential chosen to reproduce the average experimental barrier distribution

→Target inelastic (3^-, 2.742 MeV, β_3=0.208) as vibrational state

→^{9}Be: ($3/2^-$, 0.0 MeV, b=1.3) and ($5/2^-$, 2.429 MeV, b=0.72) are coupled.

→Overall suppression in CF ~ 20%

Fusion of weakly bound ^{9}Be with ^{89}Y



→CF measured for ^{4}He+^{93}Nb, ^{12}C+^{89}Y and compared with ^{9}Be+^{89}Y

→CF suppression factor ~20%

Paper on $^{9}Be+^{89}Y$

PHYSICAL REVIEW C **82**, 044608 (2010)

Fusion of the weakly bound projectile ^{9}Be with ^{89}Y

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(Received 20 August 2010; published 19 October 2010)

The excitation function for the complete fusion of $^{9}\mathrm{Be}+{}^{89}\mathrm{Y}$ has been measured at near-barrier energies, and the barrier distribution has been extracted from the fusion data. Coupled-channels calculations have been carried out to understand the effect of coupling of both the projectile and target excitations on the above quantities. The complete fusion cross sections, especially at above-barrier energies, have been found to be suppressed by $(20 \pm 5)\%$ compared to the ones predicted by the coupled-channels calculations that do not include the couplings to the projectile continuum, indicating the loss of flux from the entrance channel before fusion. This conclusion is also supported by a considerable incomplete fusion cross section observed for this system. Fusion measurements for two more systems have been carried out, namely, for $^{4}\mathrm{He}+{}^{93}\mathrm{Nb}$ and $^{12}\mathrm{C}+{}^{89}\mathrm{Y}$, which involve tightly bound projectiles and form compound nuclei nearby to that formed in $^{9}\mathrm{Be}+{}^{89}\mathrm{Y}$ fusion. Comparison of the fusion data obtained for all three systems further confirms the suppression of complete fusion in the $^{9}\mathrm{Be}+{}^{89}\mathrm{Y}$ system. Systematics of the suppression factor observed for ^{9}Be induced fusion in different mass targets is discussed.

DOI: 10.1103/PhysRevC.82.044608 PACS number(s): 25.70.Jj, 25.70.Gh

Fusion of ^{6}Li with ^{152}Sm: Role of target deformation vs projectile breakup

CF for $^{6}Li+^{144}Sm$ suppressed by ~32%

^{144}Sm → Spherical

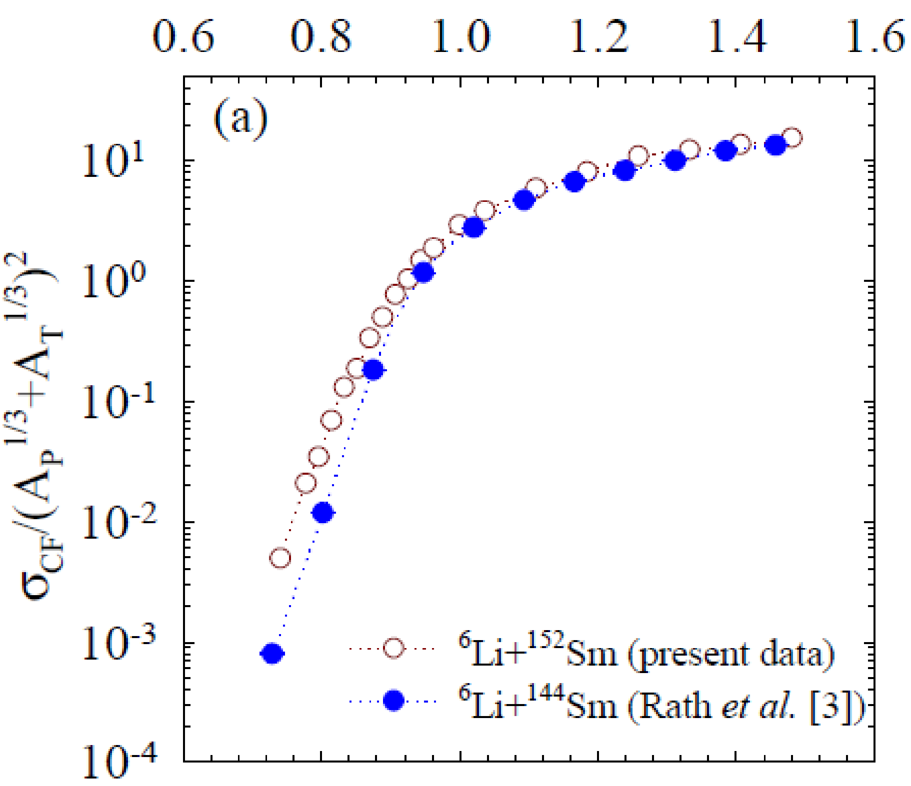
^{152}Sm → g.s. deformed; $\beta=0.26$

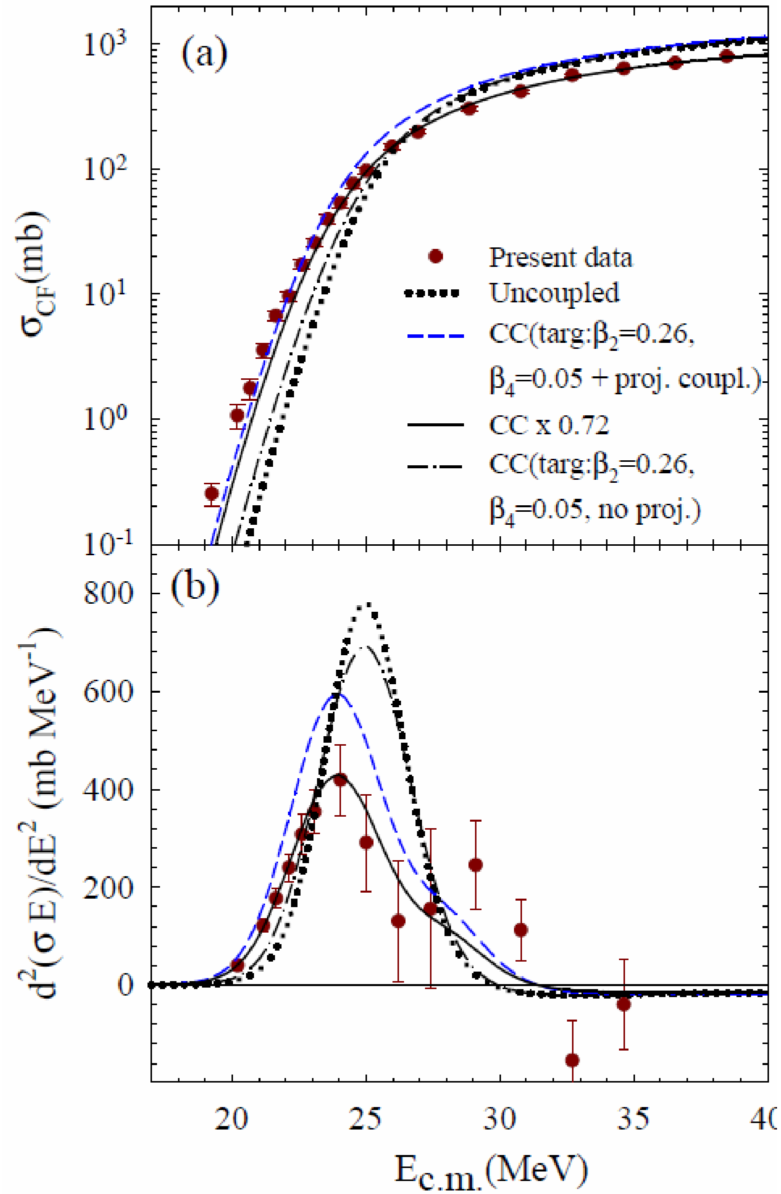
CF for $^{6}Li+^{152}Sm$:

Dominance of breakup or deformation?

P.K. Rath, S. Santra et al.,
In press, Nucl. Phys. A (2011)

Fusion of ^{6}Li with ^{152}Sm: Role of target deformation vs projectile breakup





Suppression (~28%) at E>Vb → breakup

Enhancement at E<Vb → target deformation

→Effect of breakup and deformation coexist

Summary 3

- CF for $^{6,7}Li+^{144,152}Sm$, $^{9}Be+^{124}Sn$,^{89}Y at E>Vb are suppressed compared to CC calculations (w/o projectile breakup) as well as those involving tightly bound projectiles.

- Suppression factor $^{9}Be+^{124}Sn$ and $^{9}Be+^{89}Y$ are much higher in contrast to $^{9}Be+^{144}Sm$
- At E<Vb, the effect is not clear. Competition between enhancement due to coupling versus suppression due to flux loss.

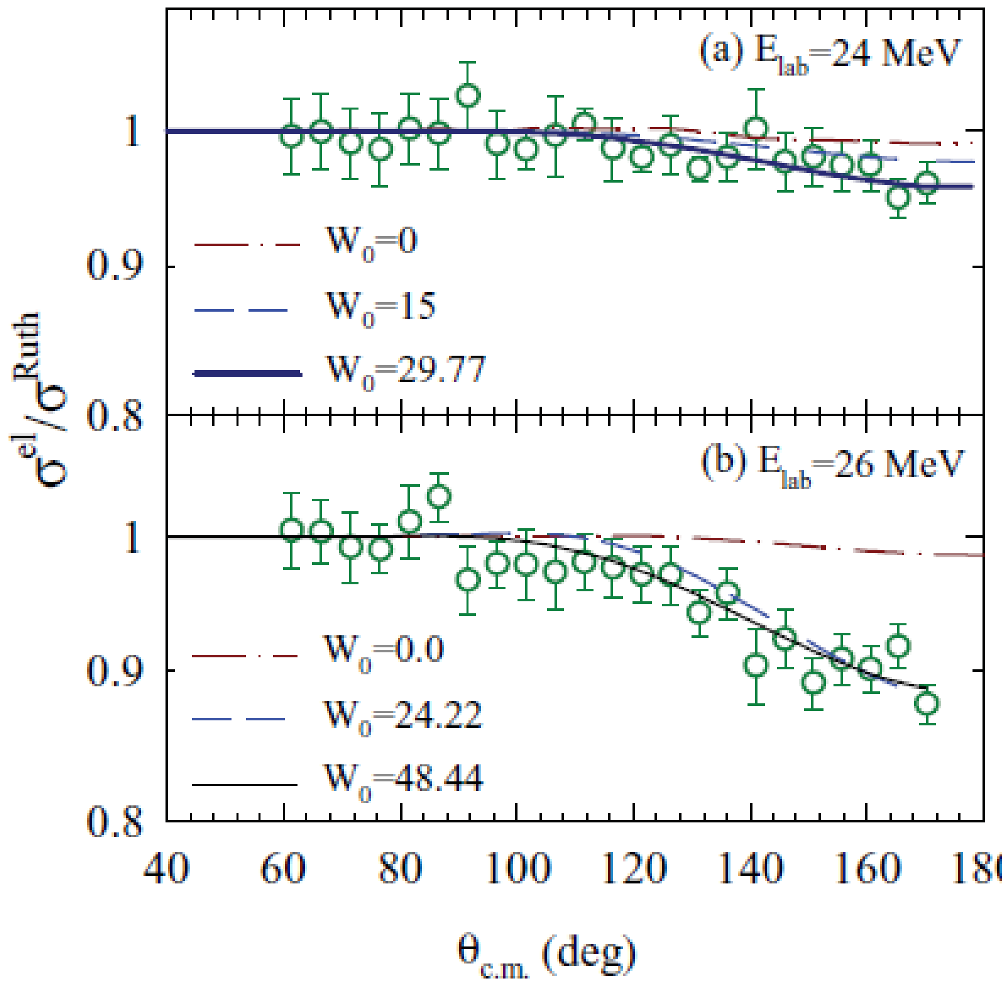
- Observation of a large ICF for the above reactions is an indication of projectile breakup which leads to loss of flux from the entrance channel thereby reducing CF.

- Systematics shows the CF suppression increases with target Z and with the decrease of breakup threshold

- For $^{6}Li+^{152}Sm$, CF enhancement at below barrier → mainly due to the target deformation → Effect of breakup and deformation coexist in $^{6}Li+^{152}Sm$ reaction.

Thanks for your attention

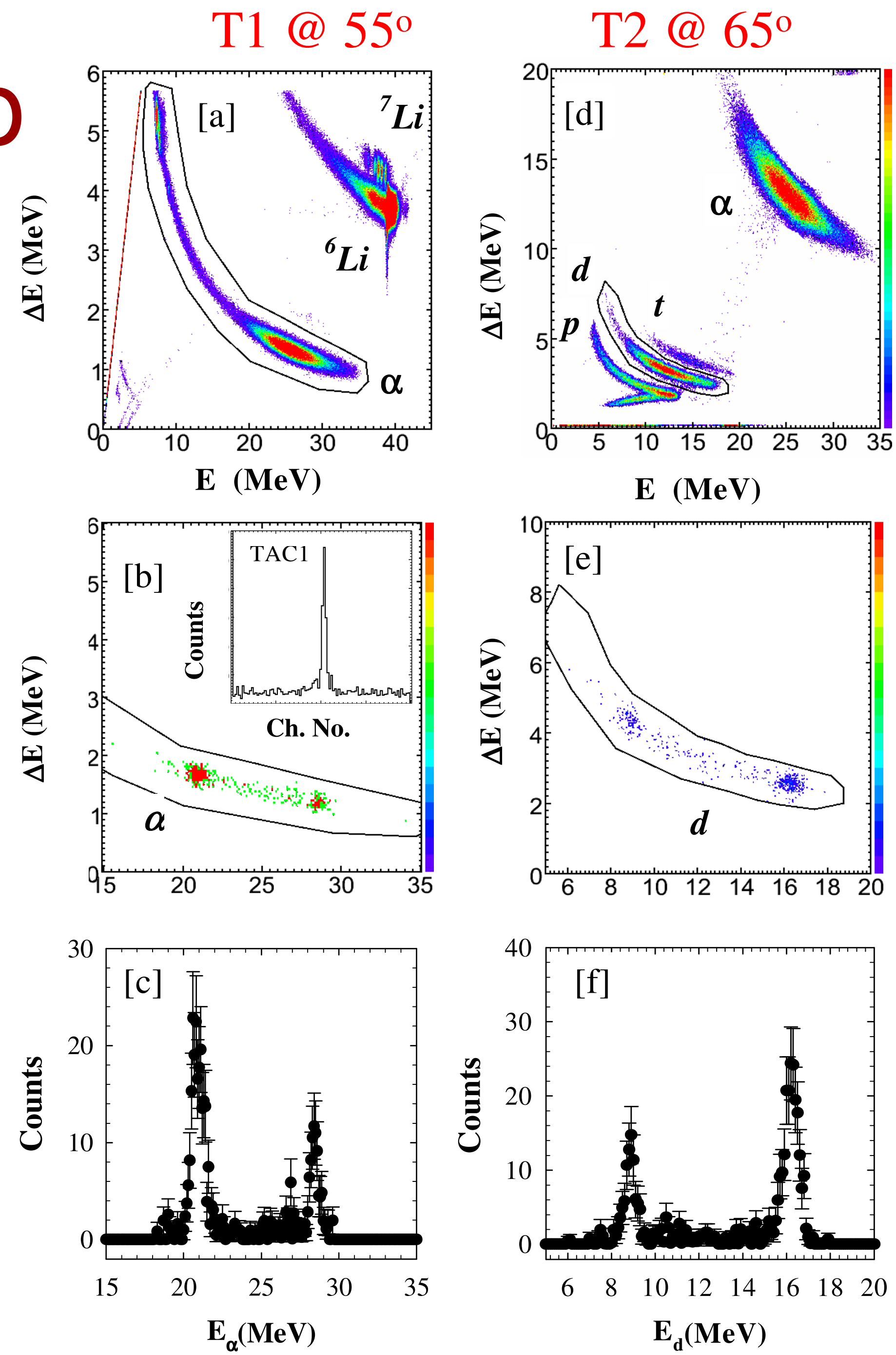
Sensitivity of imaginary potential



→Nonzero value of "W" is must to fit the measured elastic data

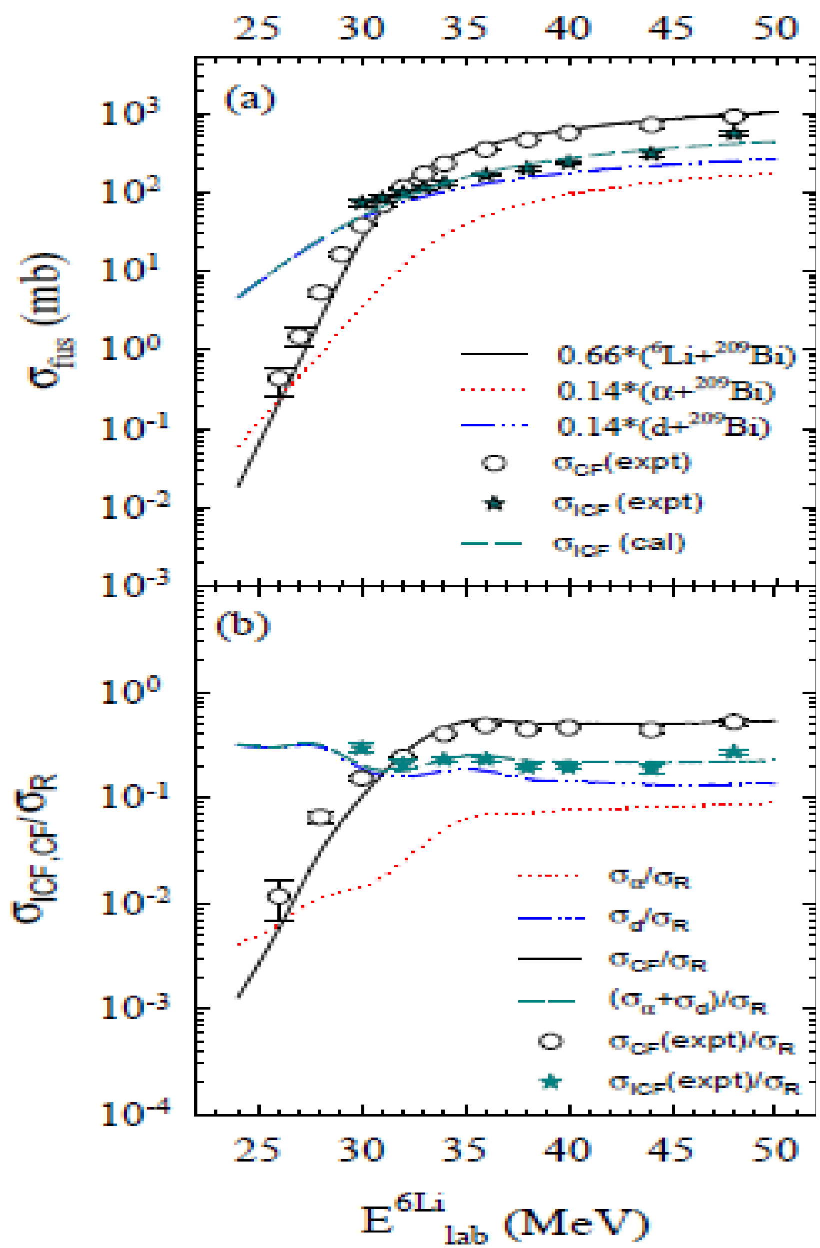
→Reaction (breakup channel) is still open at deep sub-barrier energies

Exclusive breakup measurements



Typical two dimensional spectra with and without coincidence conditions.

Alpha contribution from ICF



- Wong model calculations → ratio of α-capture and d-capture at 2/3rd and 1/3rd of beam energies respectively
- Alpha contribution from ICF, i.e., d-capture cross section derived from total ICF.