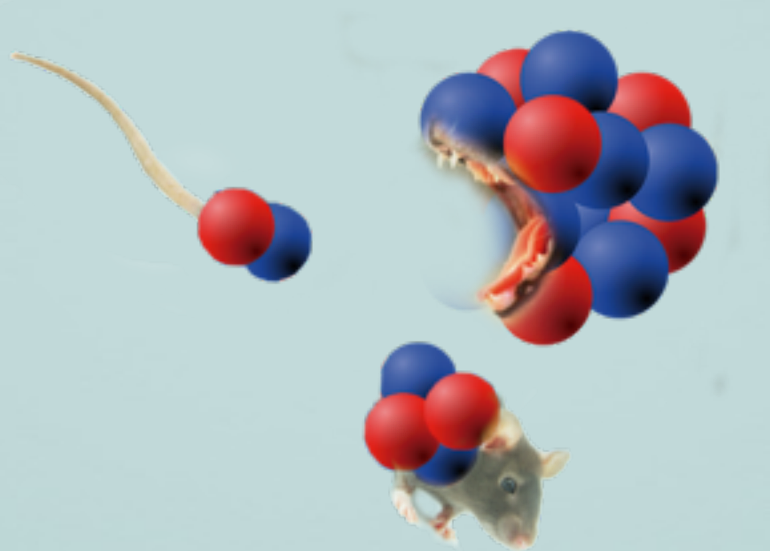
Study of Inclusive Breakup Reactions Induced by Weakly Bound Nuclei



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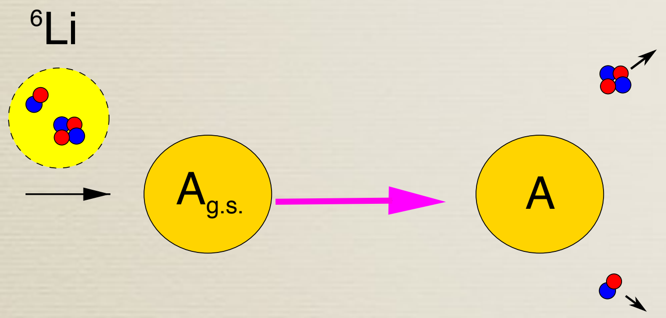
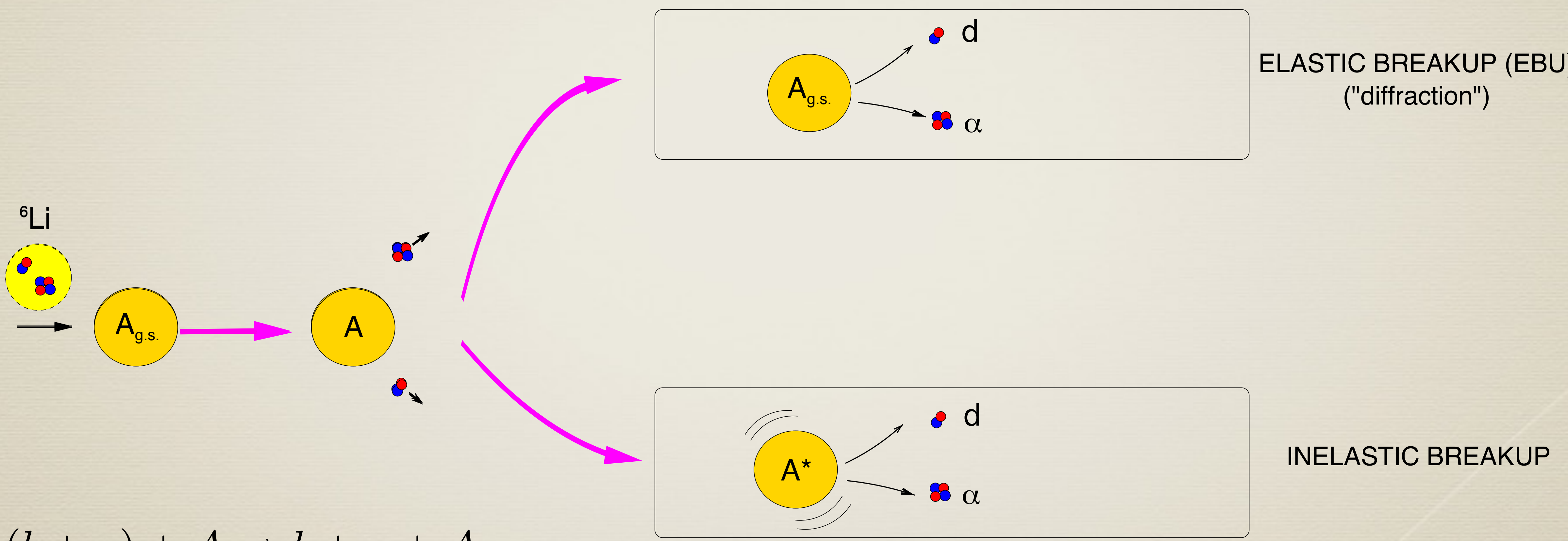


$$a(b + x) + A \rightarrow b + x + A$$

Introduction

Exclusive breakup



$$a(b+x)+A \to b+x+A$$

Introduction

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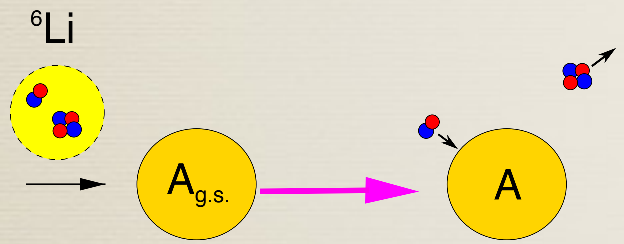

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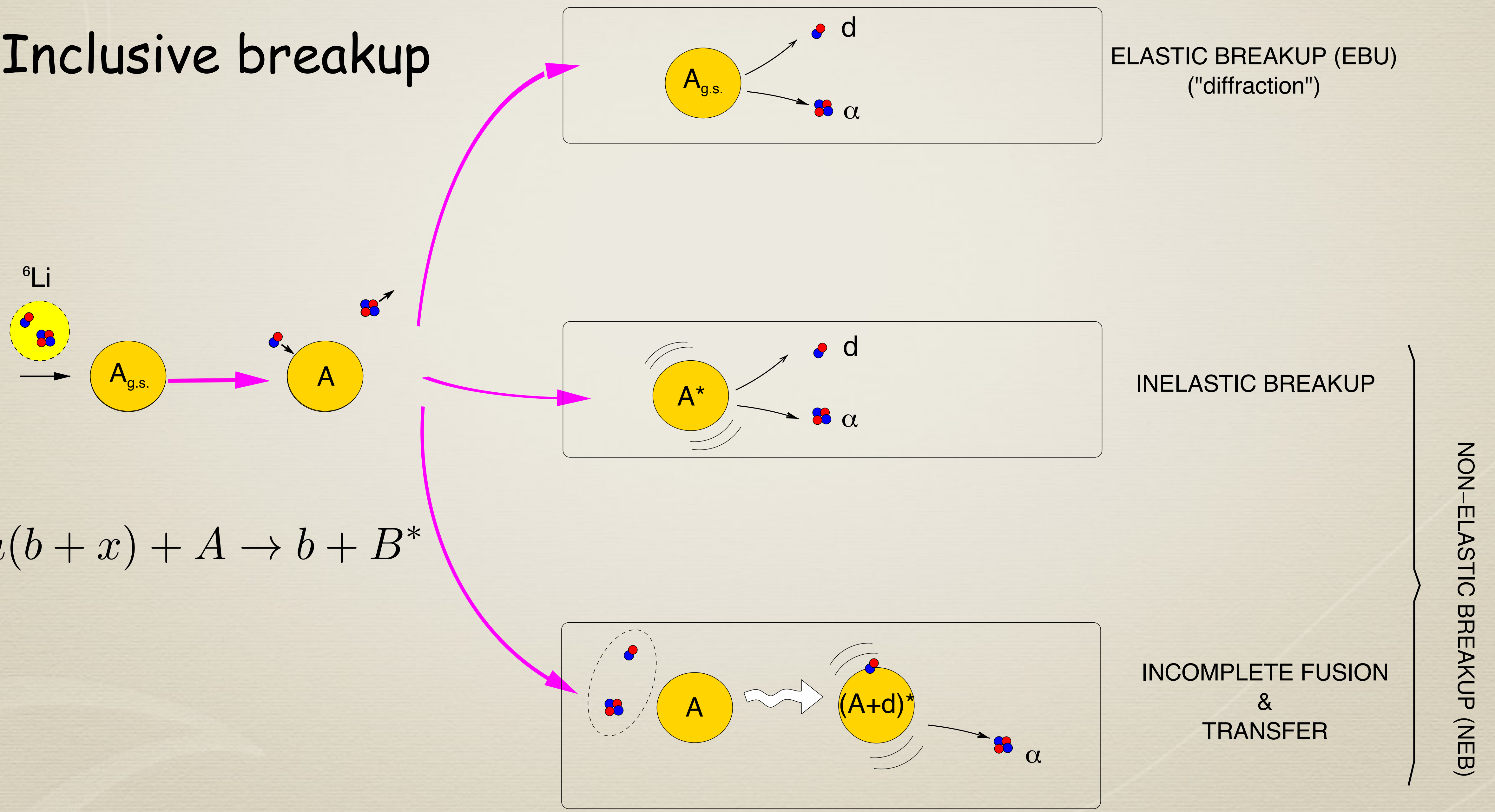

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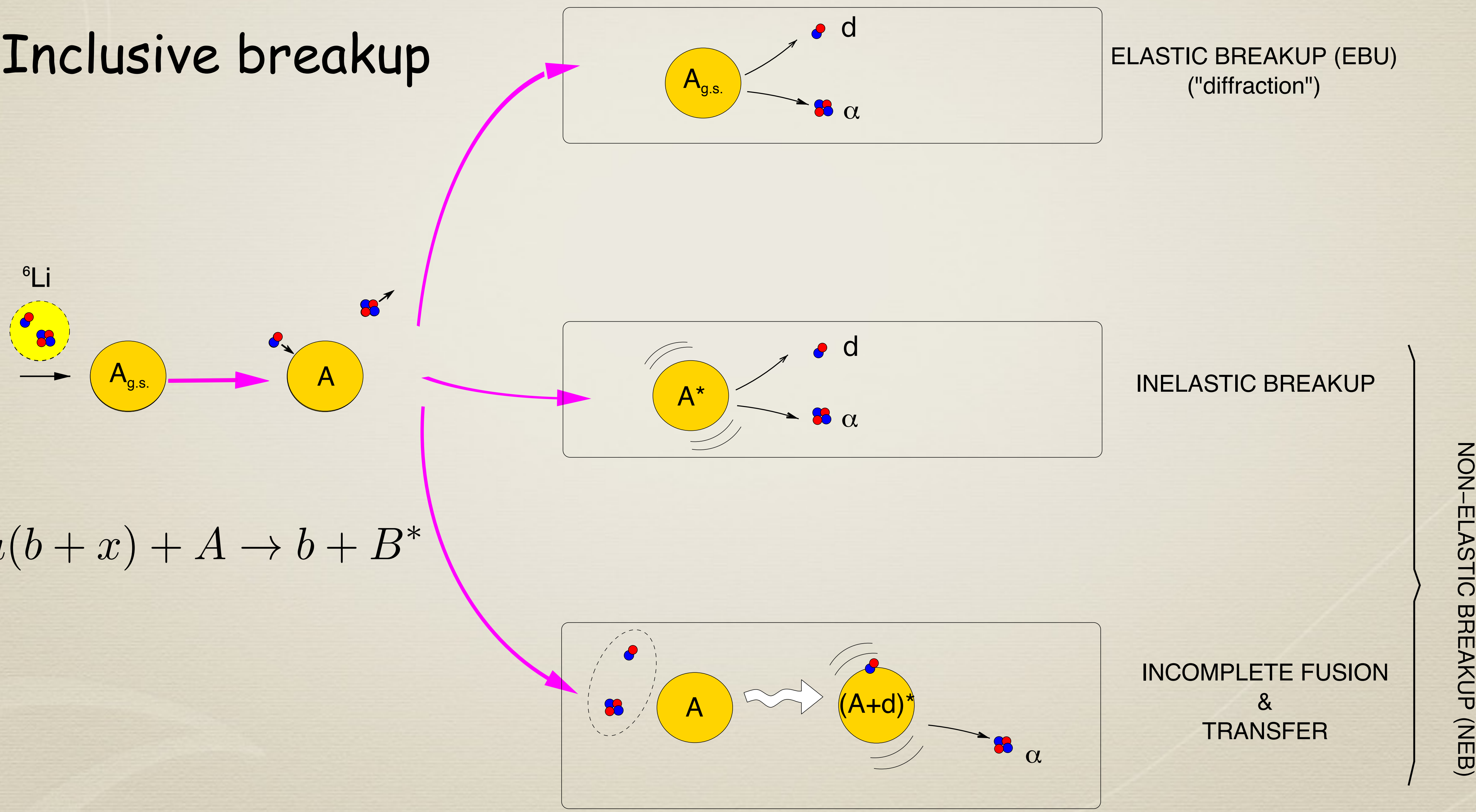
Introduction

CDCC/Faddeev 😃

Inclusive breakup



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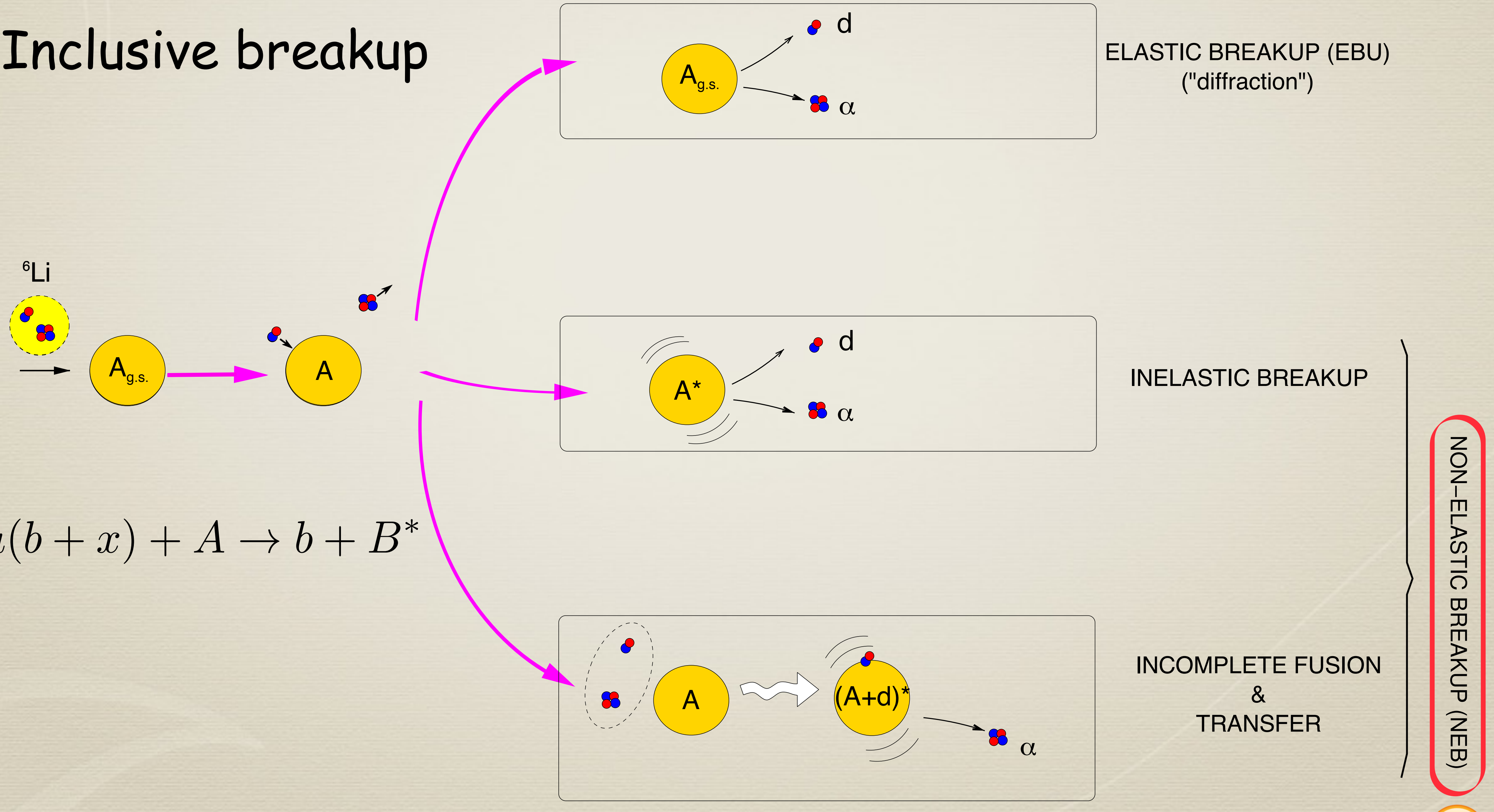

🤔

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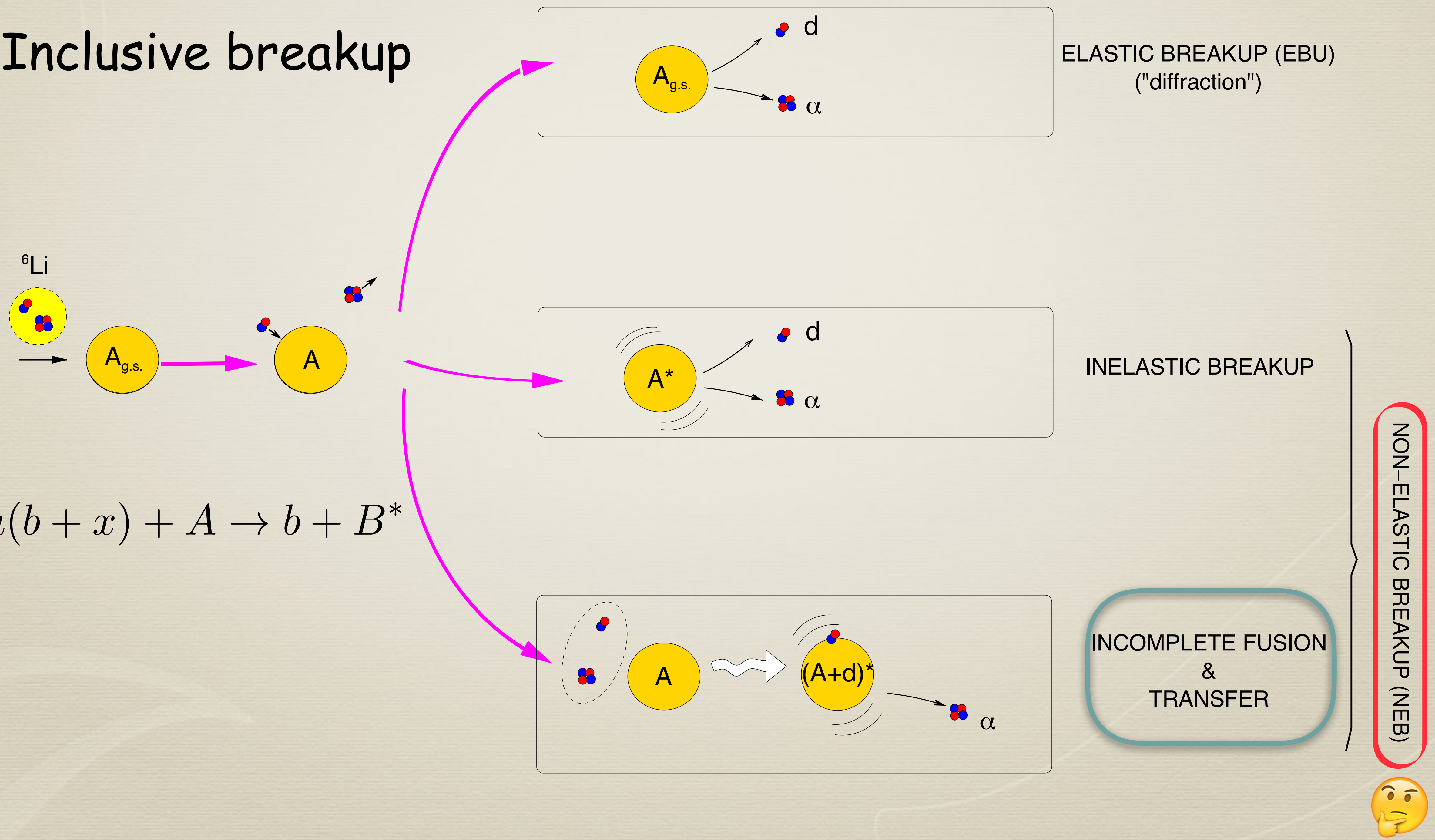

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Motivation

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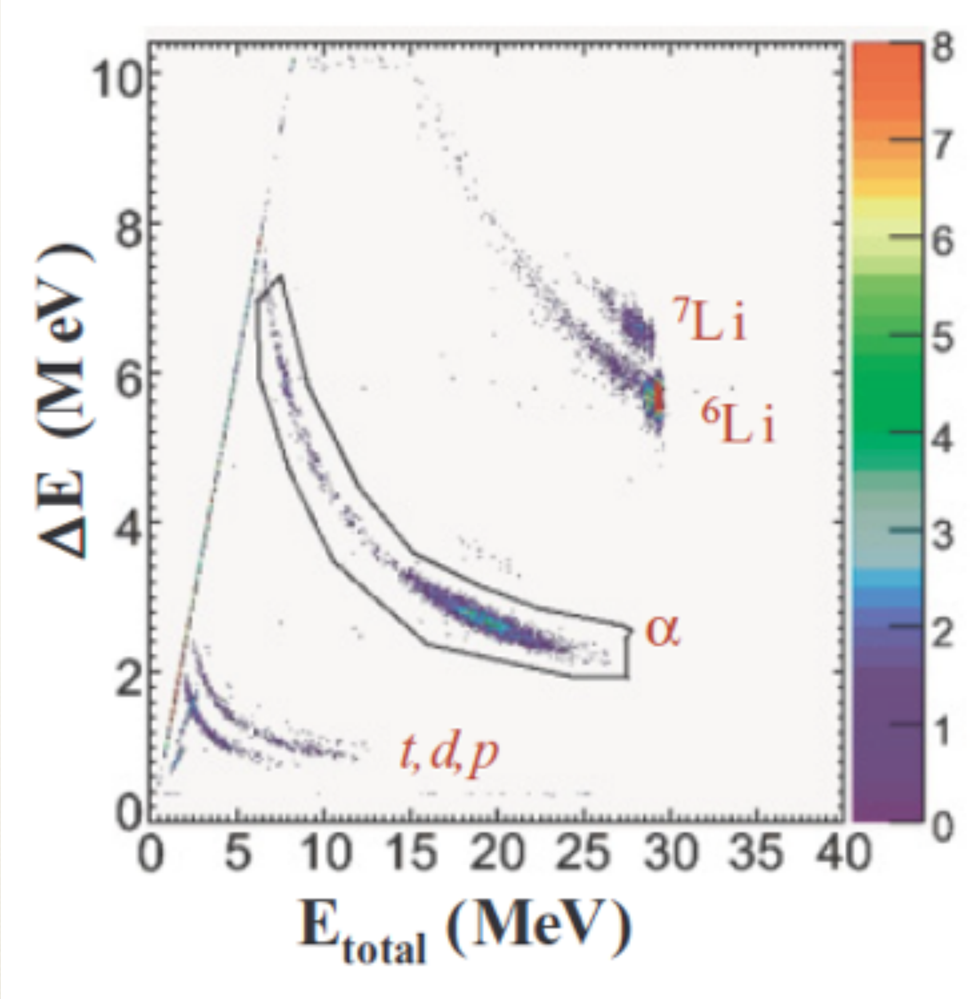
* Understanding of large inclusive alpha yields (^{6}Li,^{7}Be,^{7}Li…).



S. Santra et al, Phys. Rev. C 85, 014612 (2012).

Motivation

* Understanding of large inclusive alpha yields (^{6}Li,^{7}Be,^{7}Li…).
* Inclusive breakup reactions with halo nuclei (^{11}Be,^{6}He,^{8}B…).

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* Understanding of large
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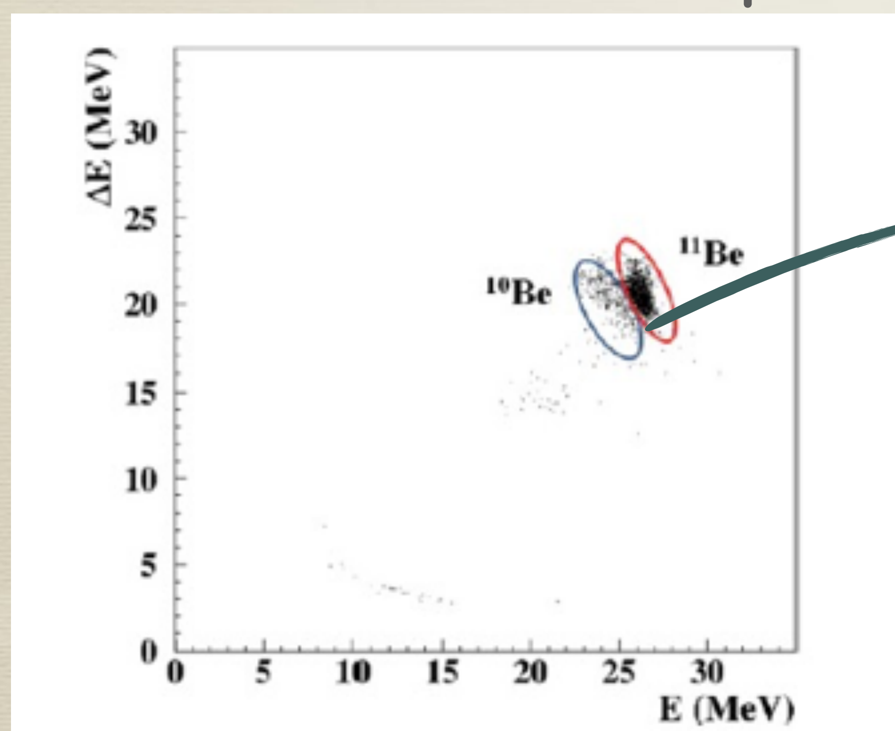


FIG. 12. (Color online) ΔE-E scatterplot for the collision ^{11}Be+^{64}Zn at $\theta = 39°$.

A. Di Pietro PRC 85, 054607 (2012)

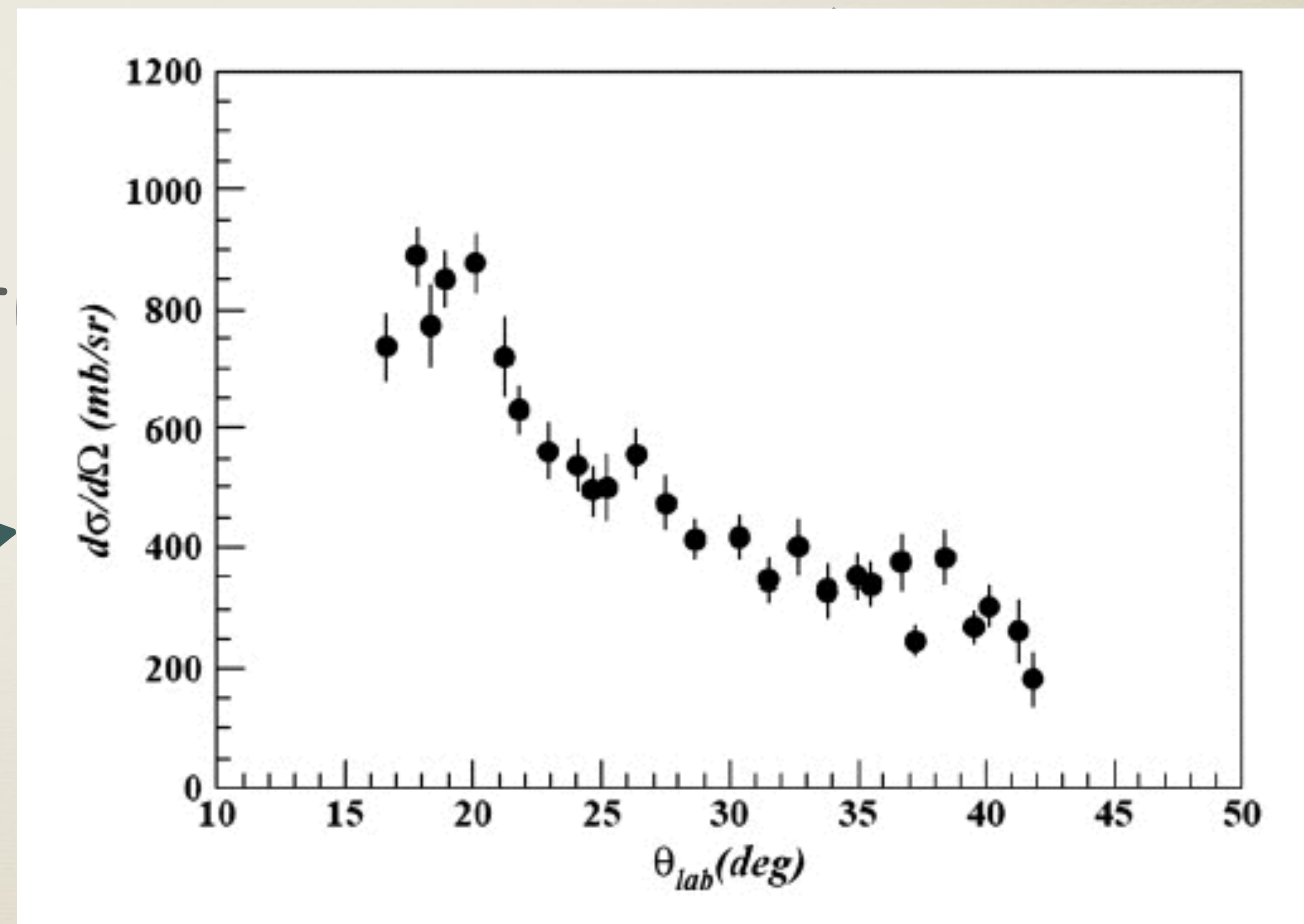
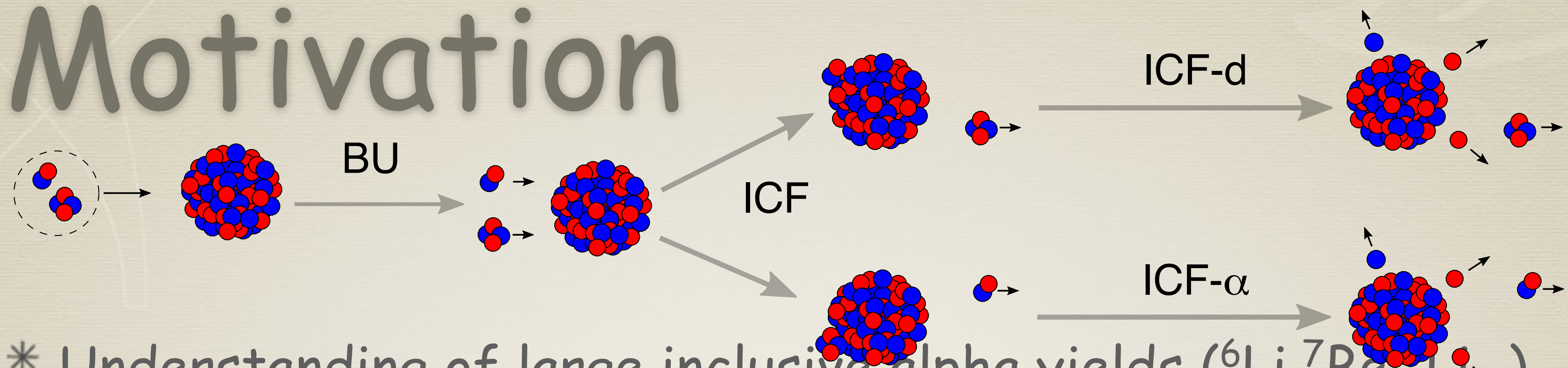


FIG. 3. AD of transfer or breakup events in ^{11}Be + ^{64}Zn obtained by selecting ^{10}Be events in the ΔE-E spectrum.

A. Di Pietro PRL 105, 022701 (2010)

Motivation



* Understanding of large inclusive alpha yields (^{6}Li,^{7}Be, Li...).

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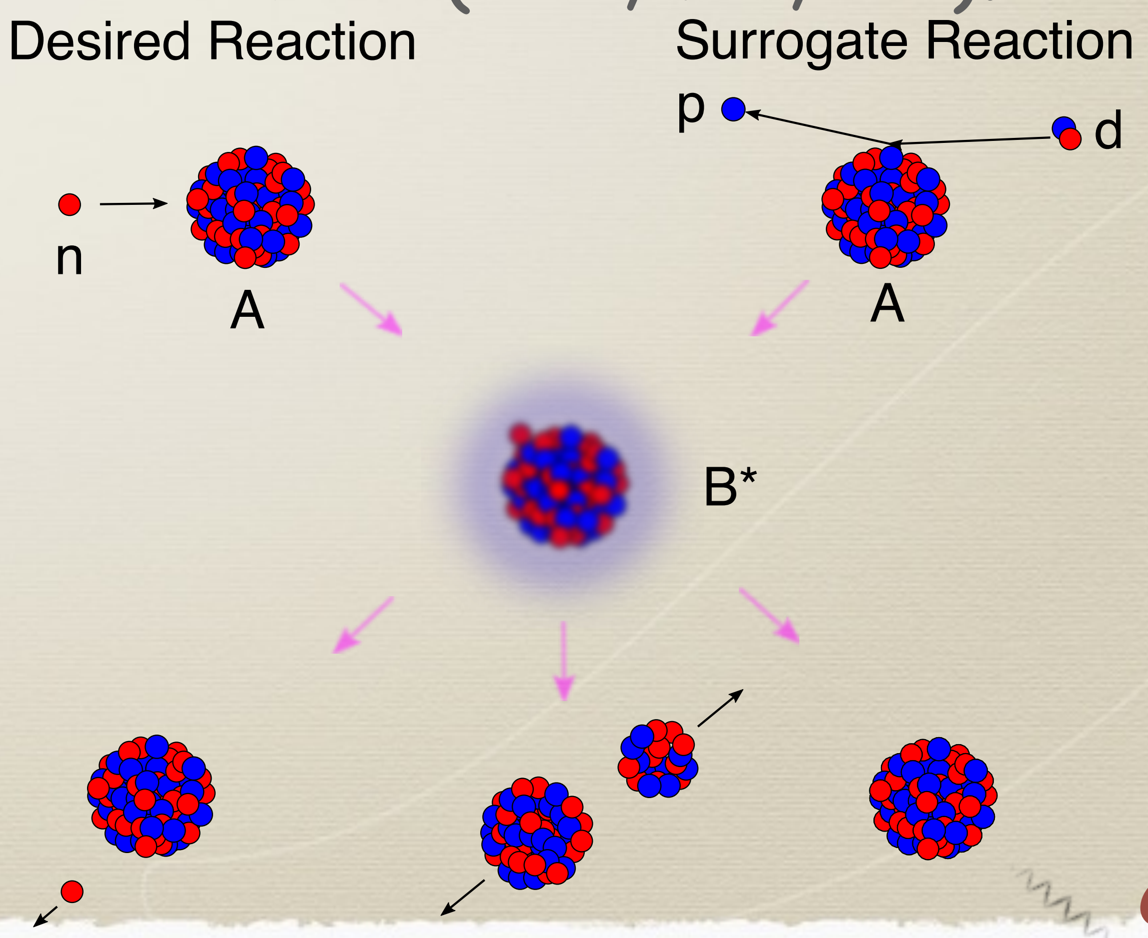

The Ichimura, Austern and Vincent Model

Theories for inclusive breakup

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- **Prior Form**
  - Kerman, McVoy(KM)
  - Udagawa, Tamura(UT)

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VS

- Post Form
  - Baur & co: surface approximation
  - Ichimura, Austern, Vincent(IAV):sum rule

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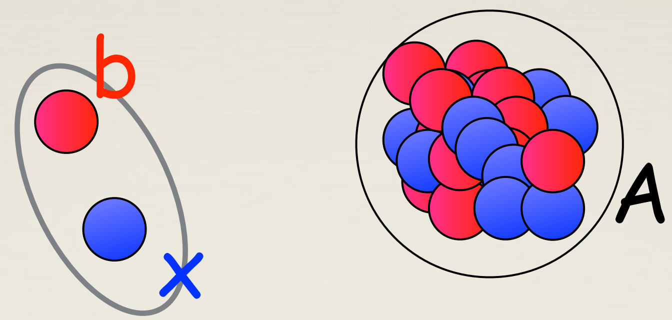

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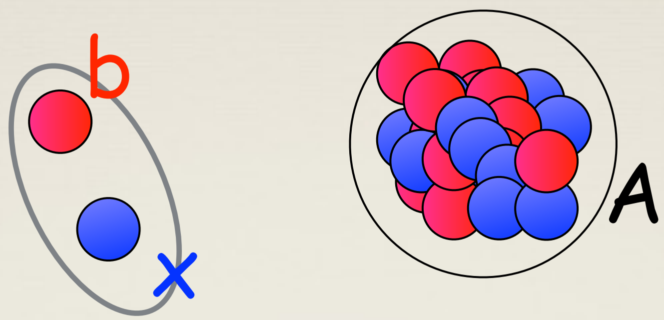

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$$\mathcal{H} = T + H_A + V_{bx} + U_{xA} + U_{bA}$$

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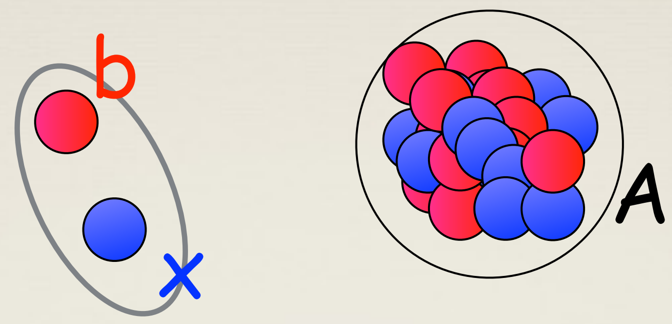

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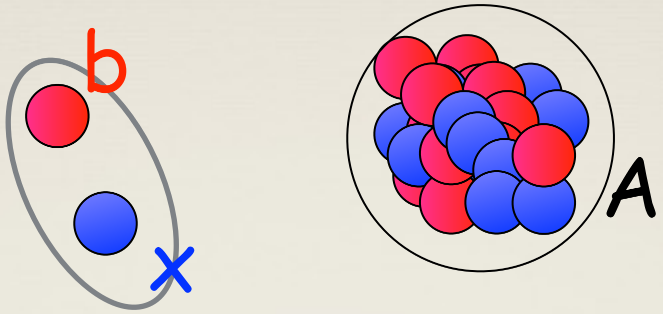

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    $b+x$

The Ichimura, Austern, Vincent Model

$(x+A)^*$

The Ichimura, Austern, Vincent Model

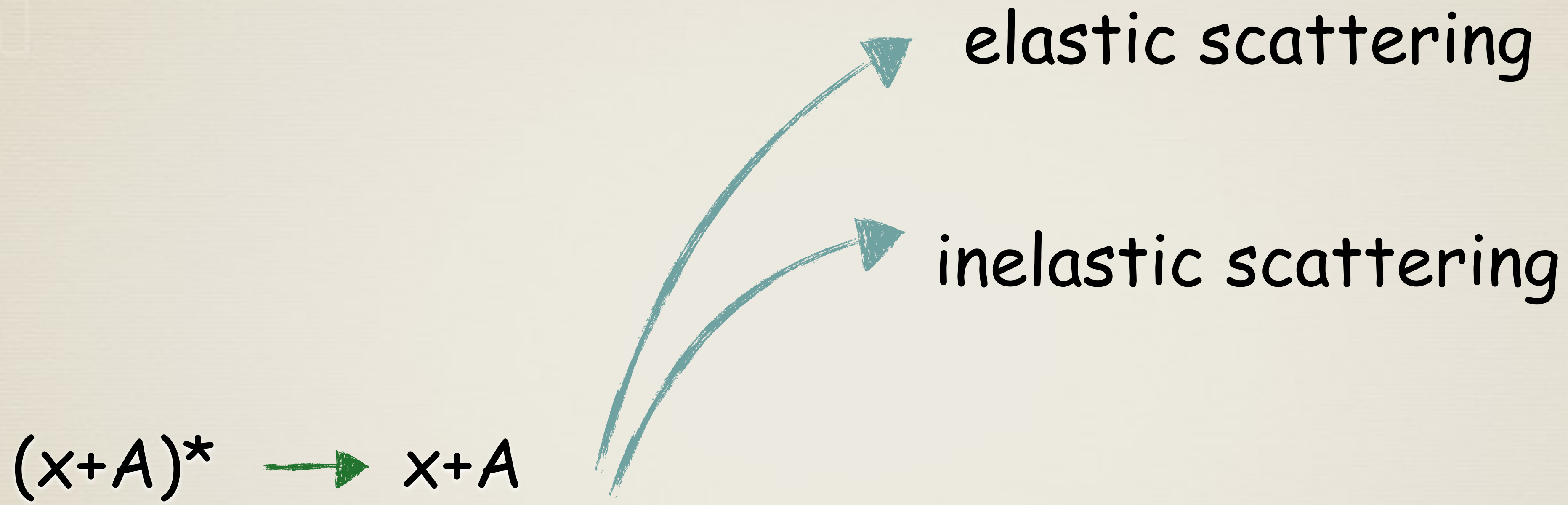
$(x+A)^* \longrightarrow x+A$

The Ichimura, Austern, Vincent Model

elastic scattering

(x+A)* → x+A

The Ichimura, Austern, Vincent Model



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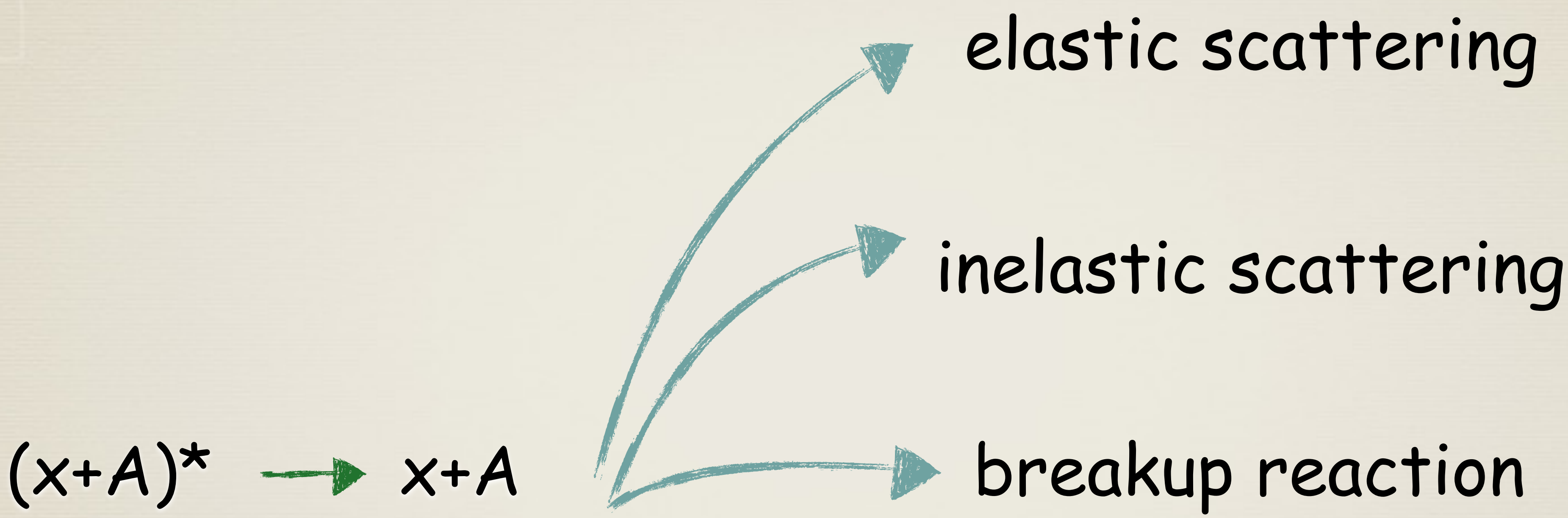

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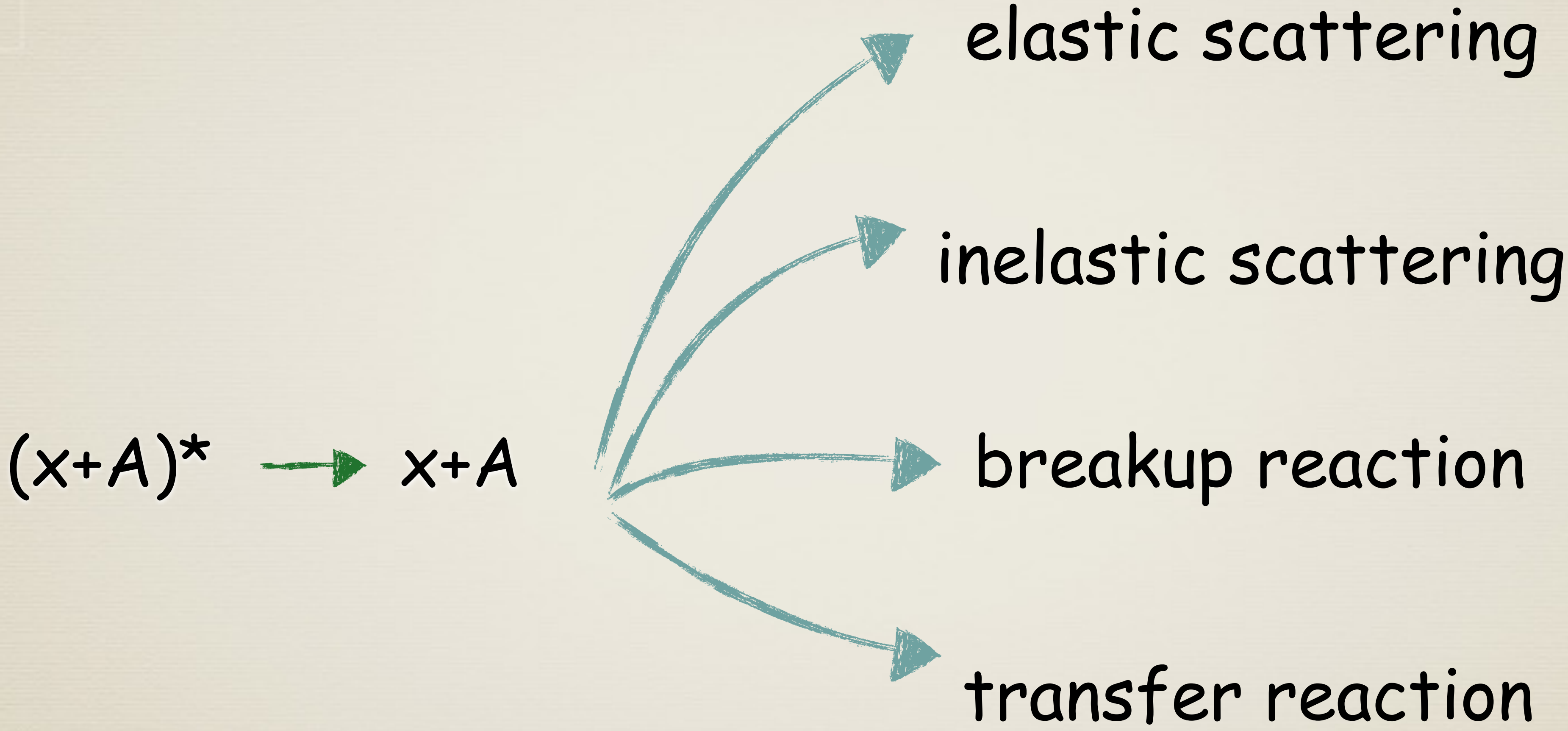

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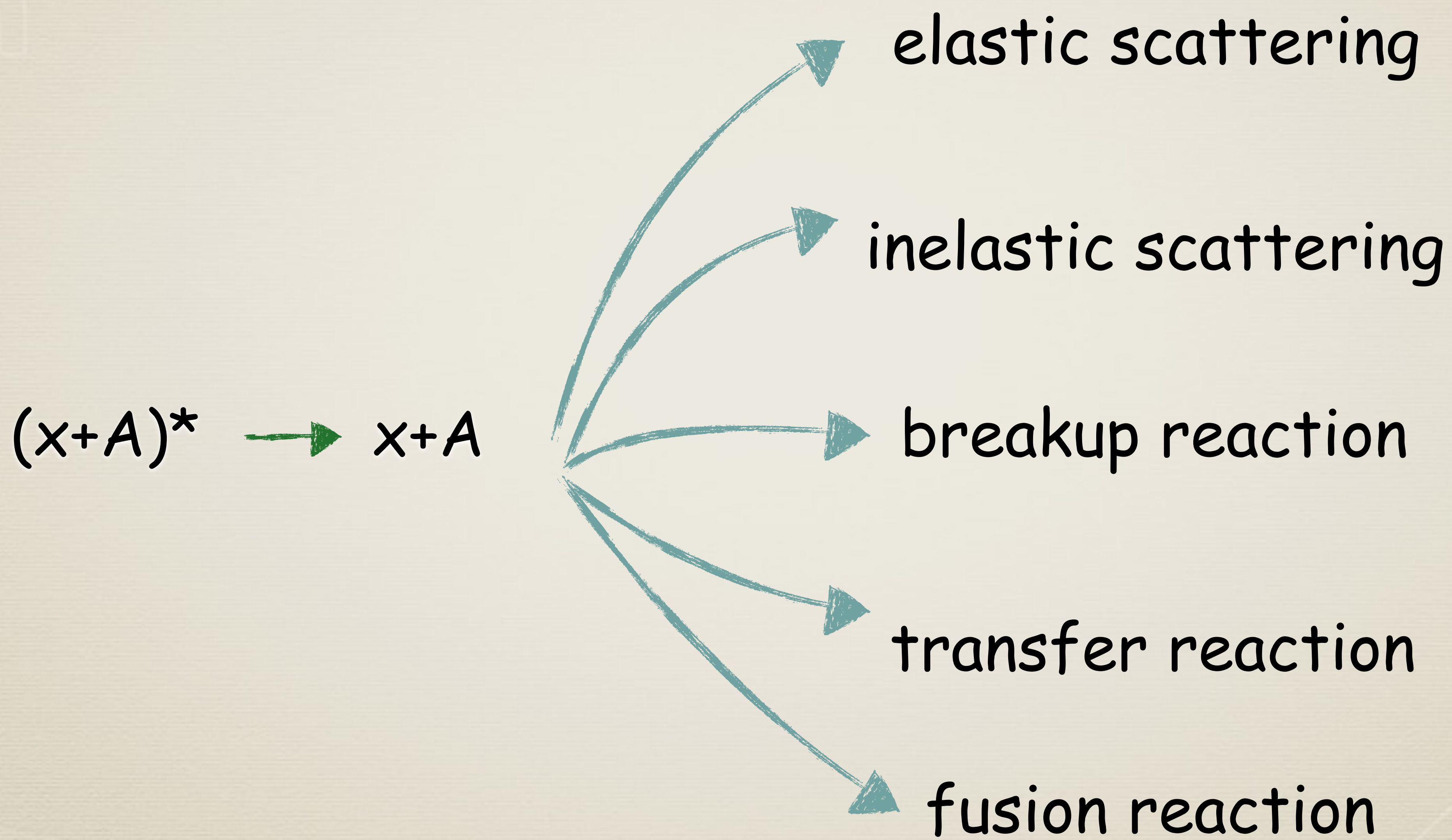

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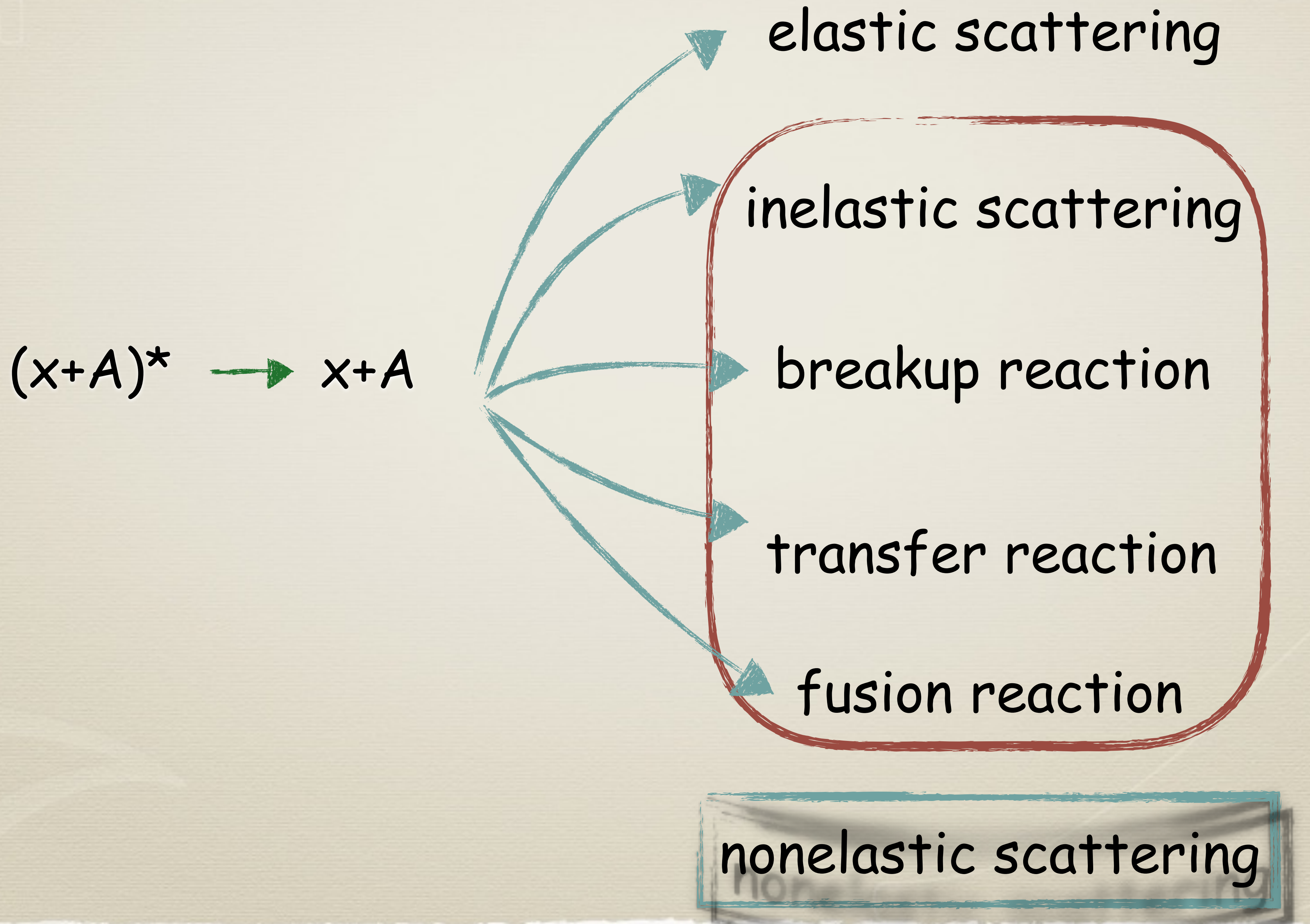

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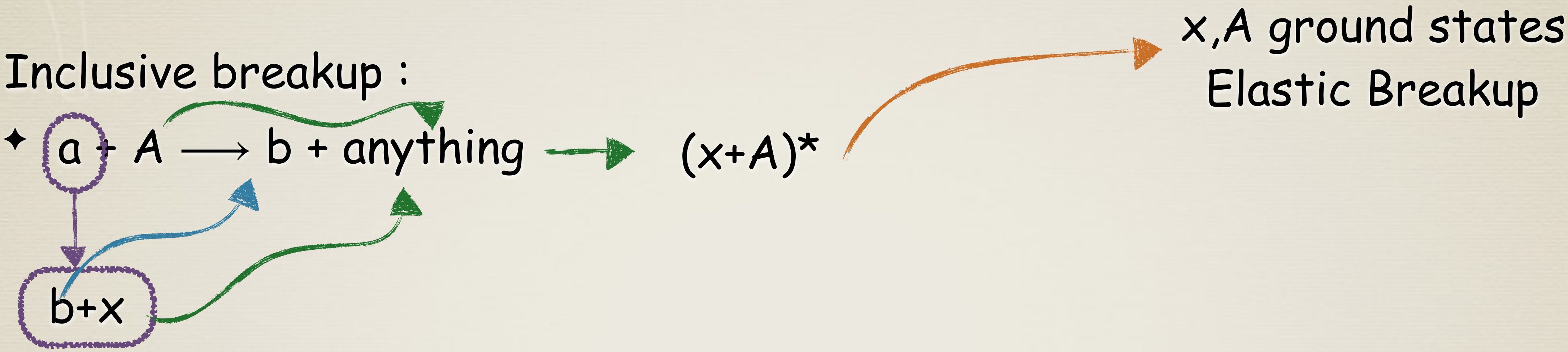

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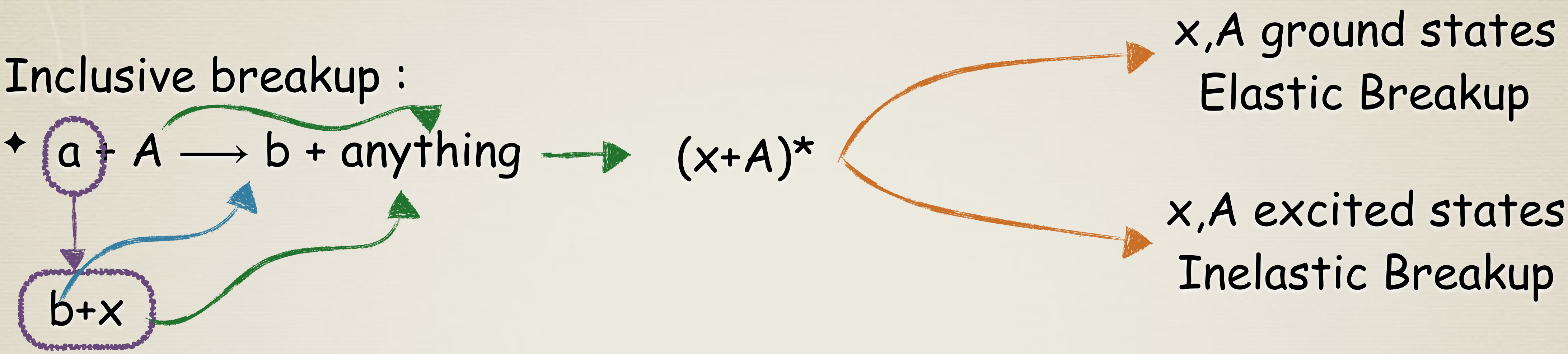

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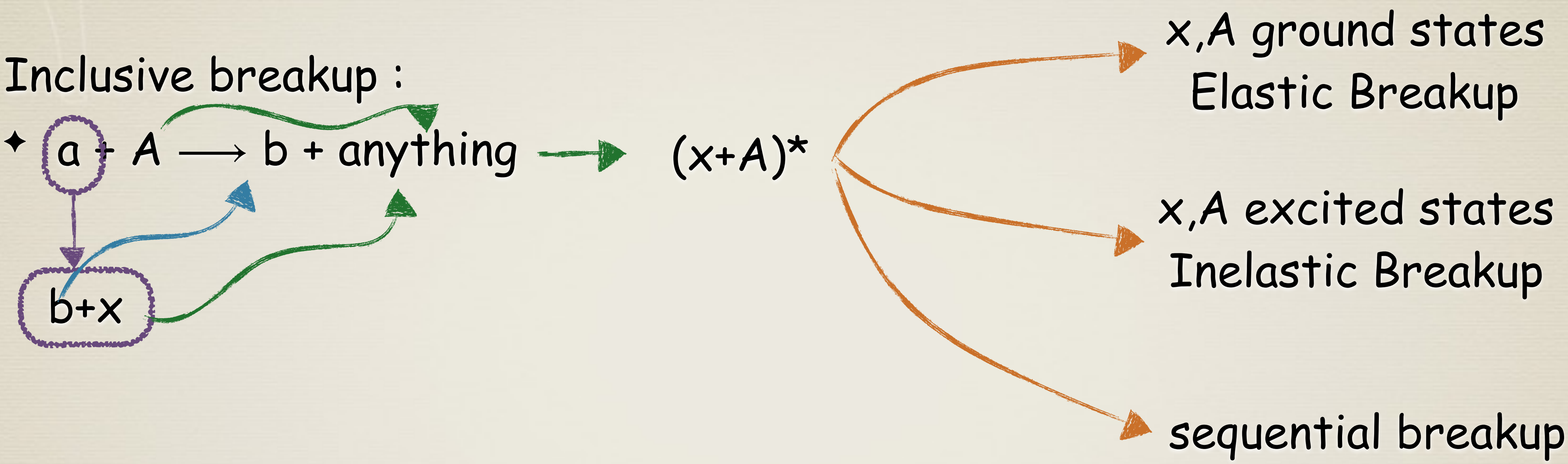

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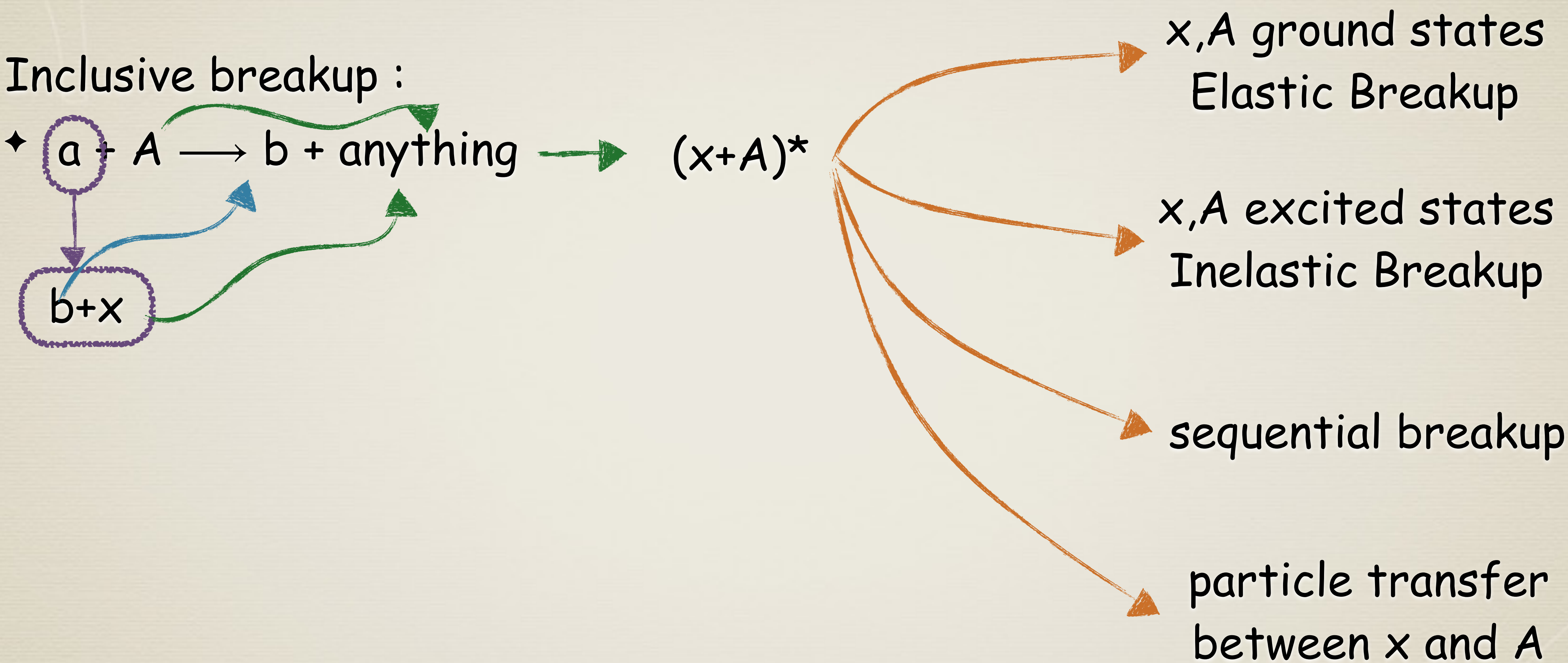

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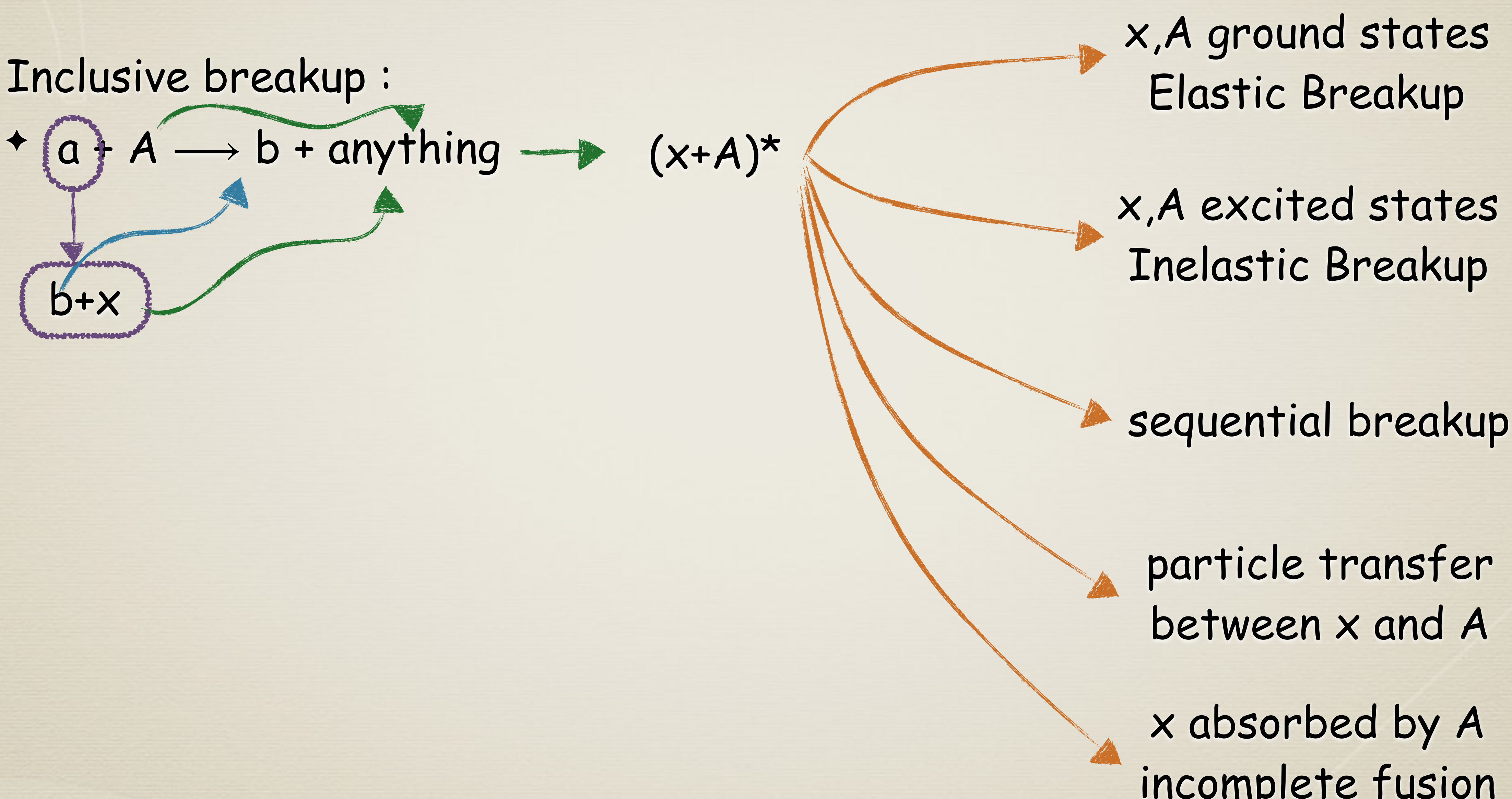

The Ichimura, Austern, Vincent Model

- Inclusive breakup :
  - a + A ⟶ b + anything ⟶ (x+A)*

b+x

x,A ground states
Elastic Breakup

x,A excited states
Inelastic Breakup

sequential breakup

particle transfer
between x and A

x absorbed by A
incomplete fusion

Nonelastic breakup

The Ichimura, Austern, Vincent Model

- Inclusive breakup :
  - $a + A \longrightarrow b + \text{anything}$ → $(x+A)^*$
  - a → b+x

- Inclusive differential cross sections :

$$\sigma_b^{TBU} = \sigma_b^{EBU} + \sigma_b^{NEB}$$

$(x+A)^*$ →

- x,A ground states
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Nonelastic breakup:
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$$\frac{d^2\sigma}{d\Omega_b dE_b} = \frac{2\pi}{\hbar v_a} \rho(E_b) \sum_c \left| \left\langle \chi_b^{(-)} \Psi_{xA}^{c,(-)} \right| V_{bx} \left| \Psi^{(+)} \right\rangle \right|^2 \delta(E - E_b - E^c)$$

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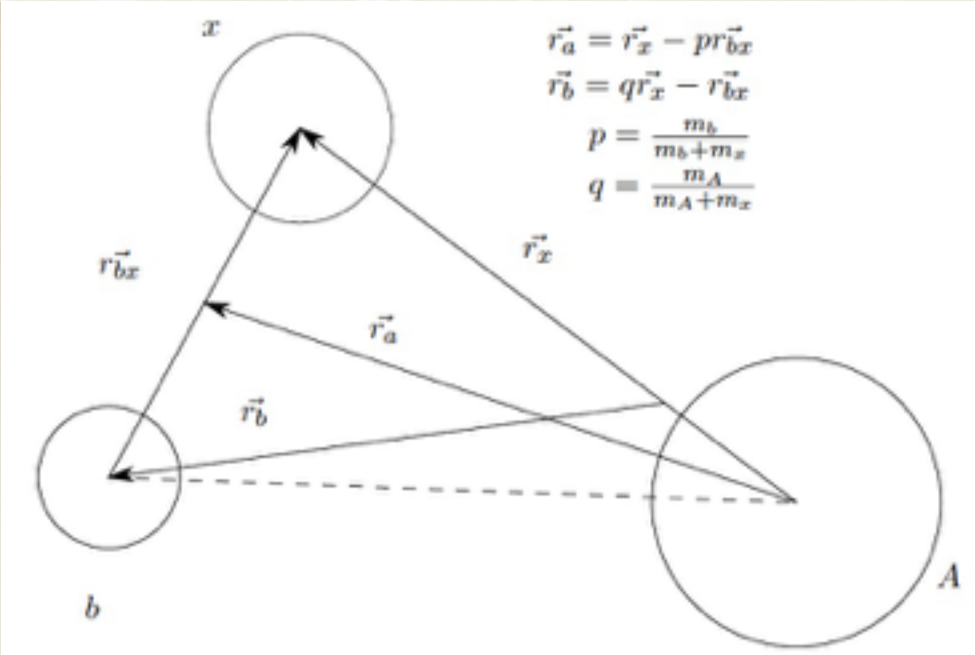
exact many body wave function

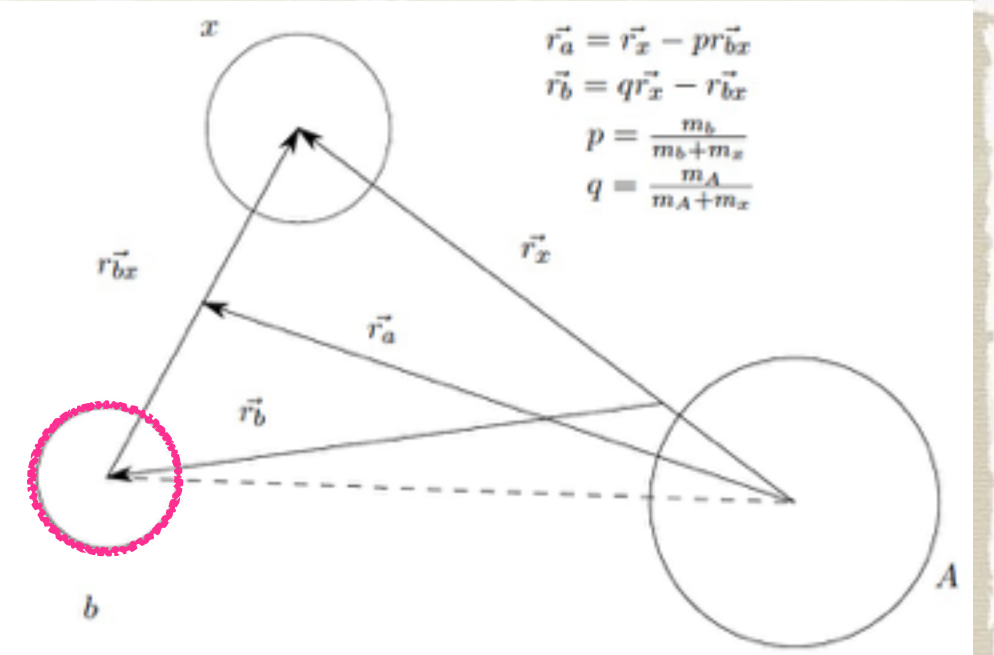
IAV Model

IAV Model



- spectator/participant model:

IAV Model



- spectator/participant model:
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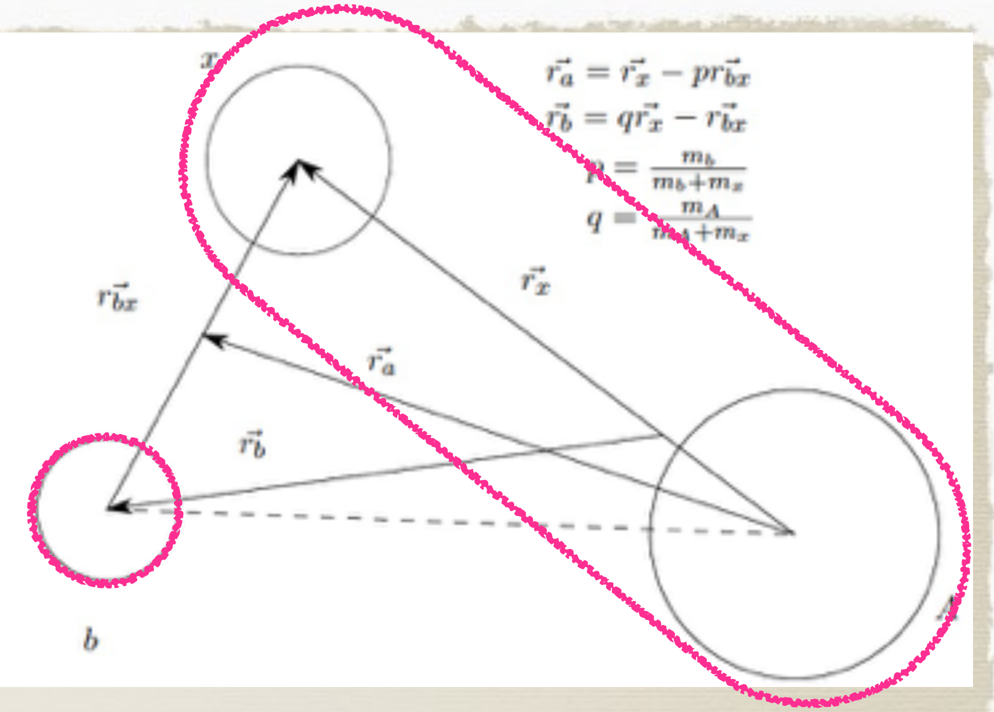
IAV Model



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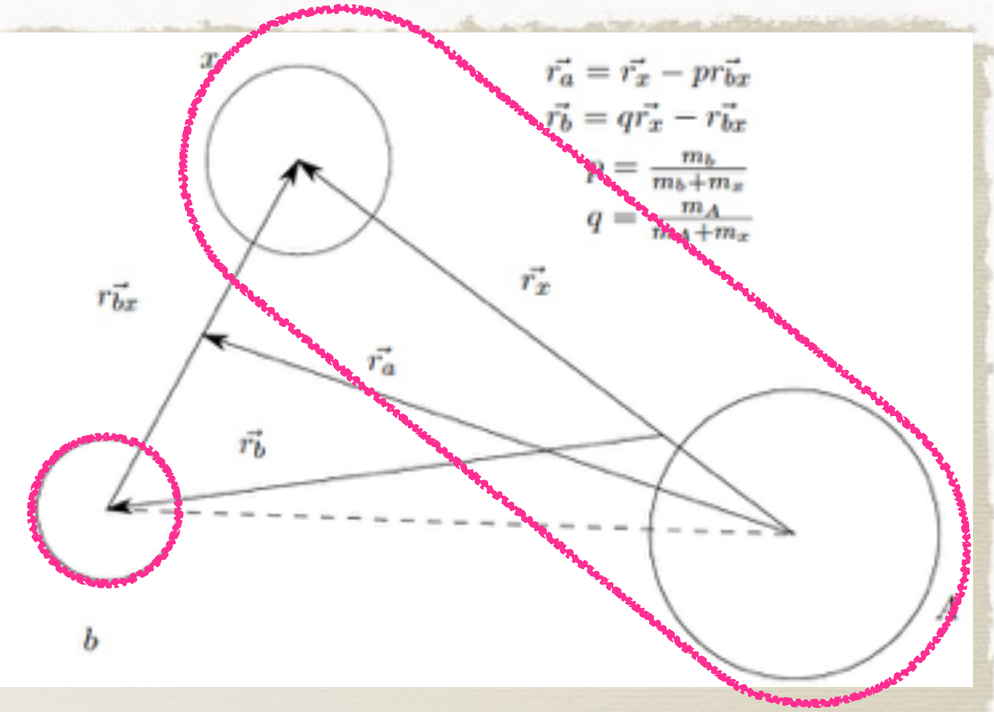

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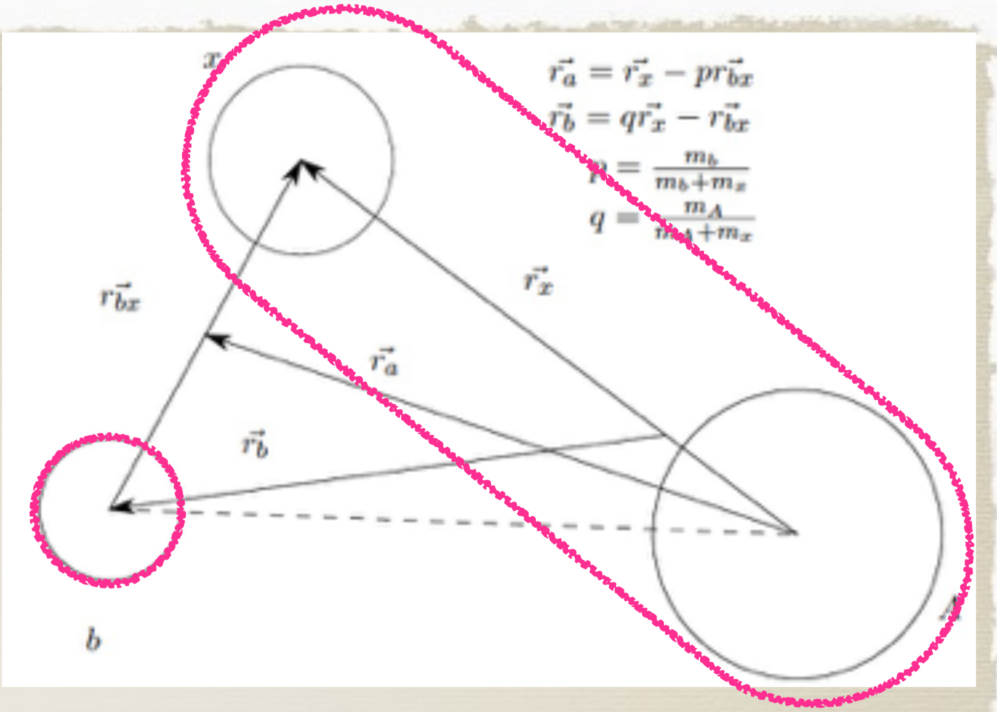

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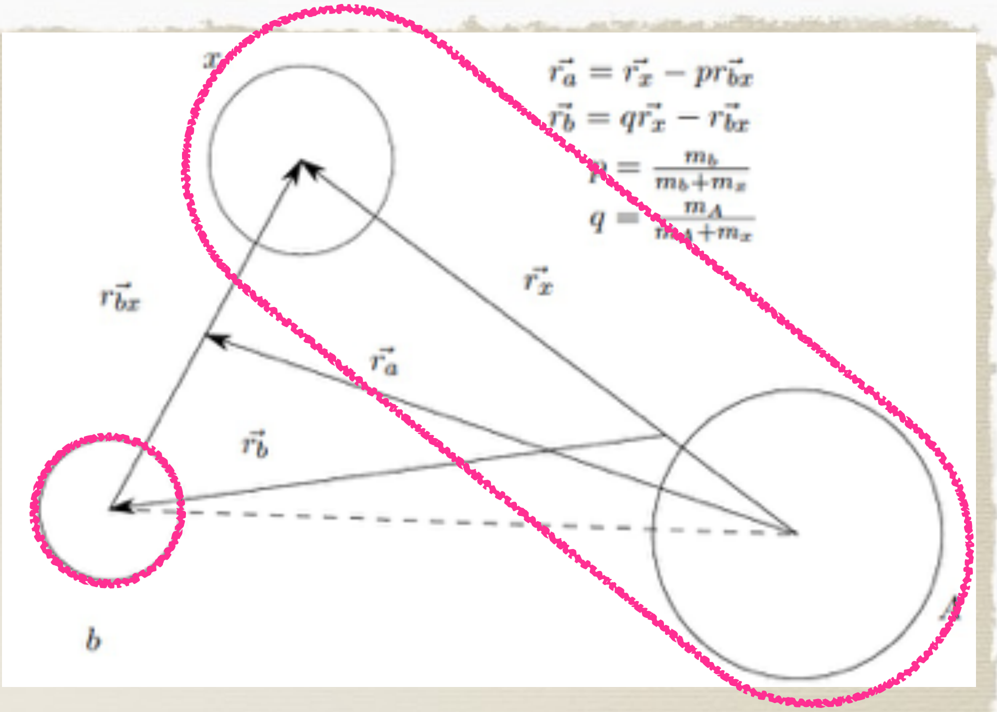

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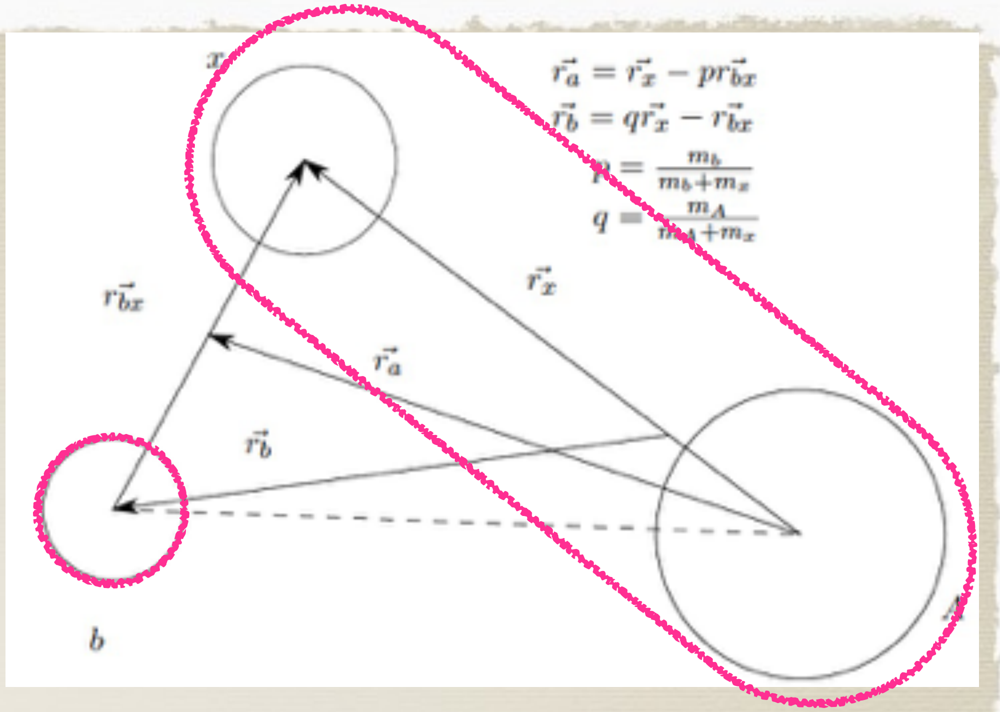

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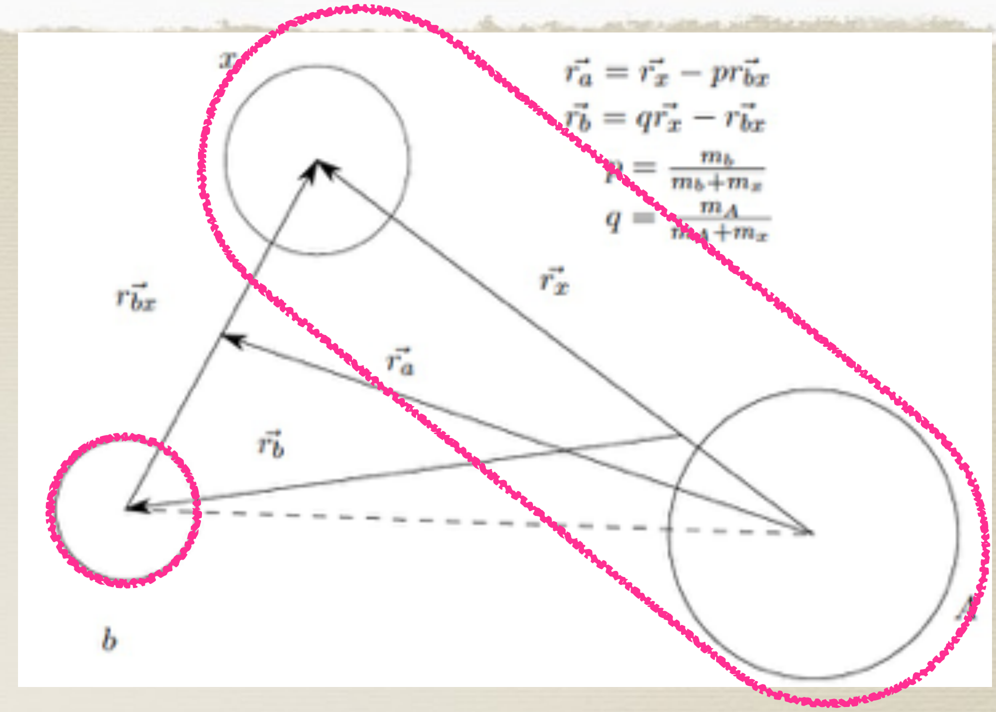

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DWBA

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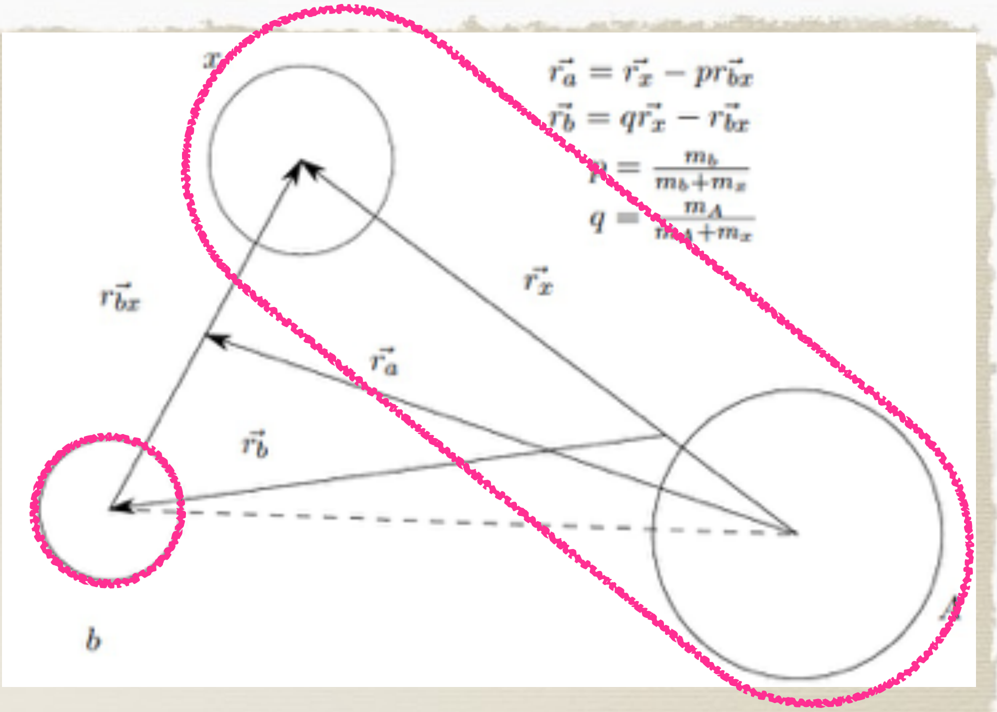

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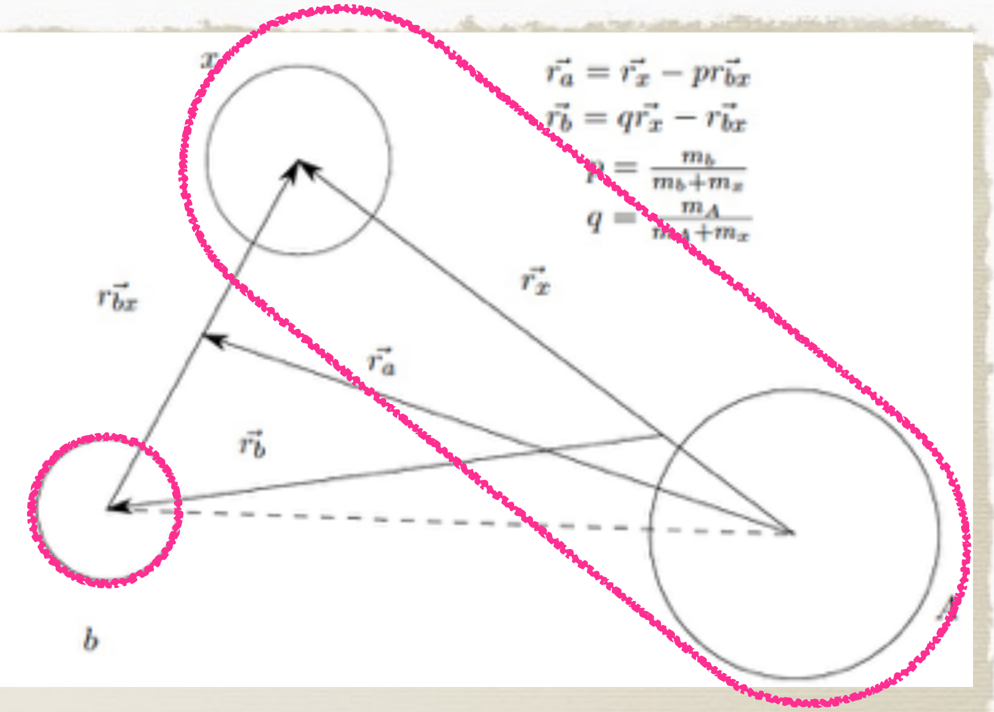
IAV Model



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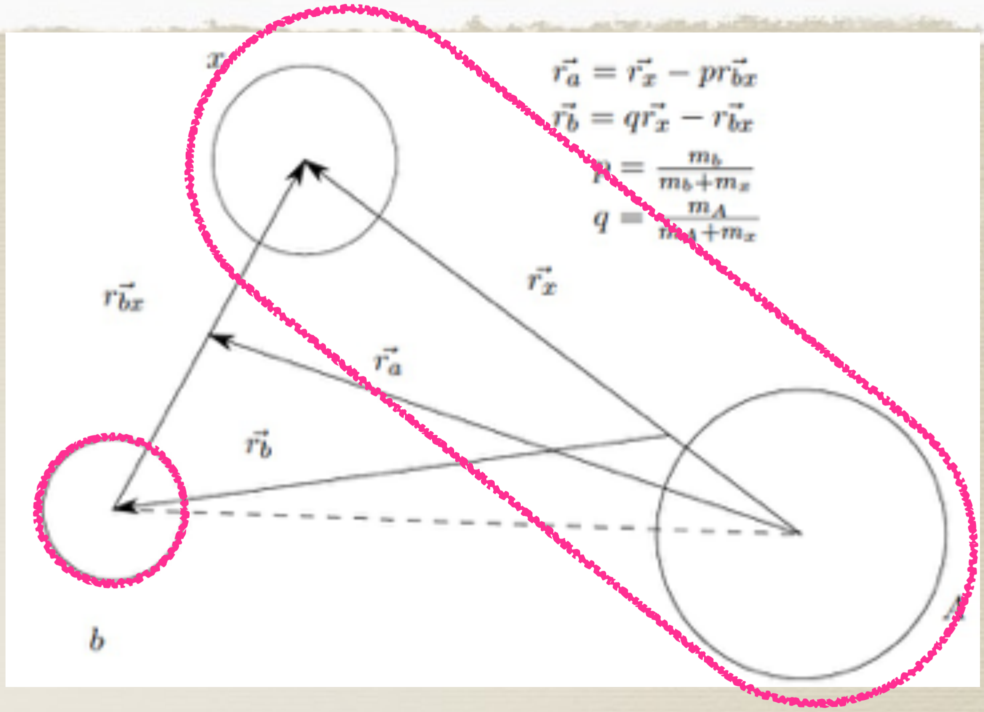

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- Nonelastic breakup (NEB): loss of flux leaving the x-A_{gs} channel

$$\frac{d^2\sigma}{dE_b d\Omega_b} = -\frac{2}{\hbar v_a}\rho_b(E_b)\langle\varphi_x^0(\vec{r}_x, \vec{k}_b)|W_x|\varphi_x^0(\vec{r}_x, \vec{k}_b)\rangle$$

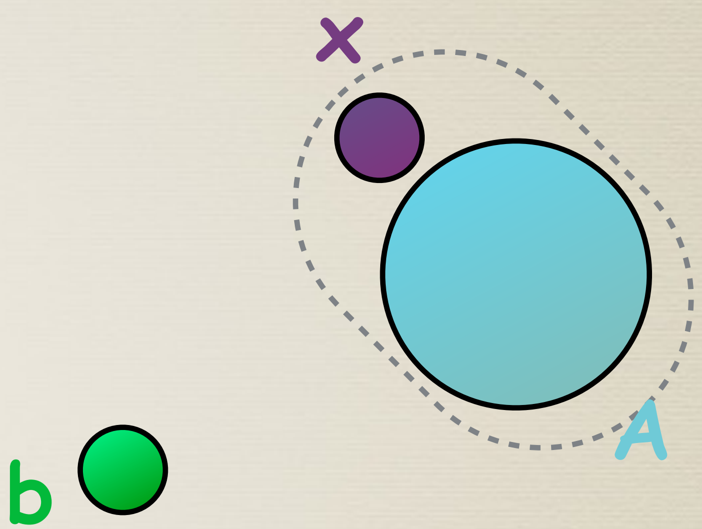
imaginary part of U_x

Analogy with two-body reaction

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E_b\mathrm{d}\Omega_b} = -\frac{2}{\hbar v_a}\rho_b(E_b)\big\langle\varphi_x^0(\vec{r}_x,\vec{k}_b)\big|W_x\big|\varphi_x^0(\vec{r}_x,\vec{k}_b)\big\rangle$$

Analogy with two-body reaction

Absorption cross section in three body reaction b + (x + A)



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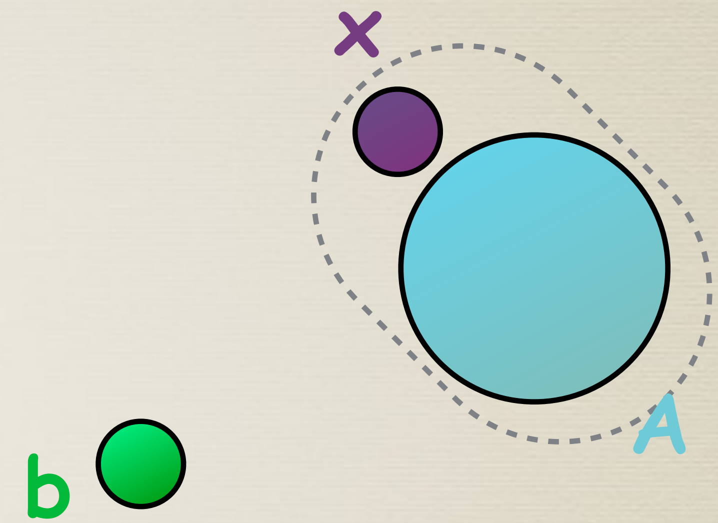

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Absorption cross section in binary reaction a+A (Optical Theorem)

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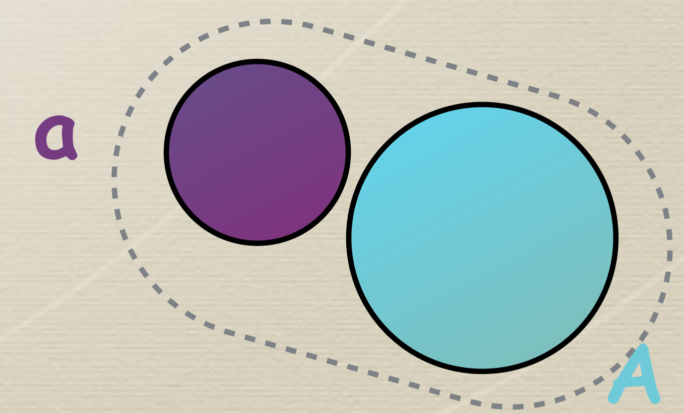

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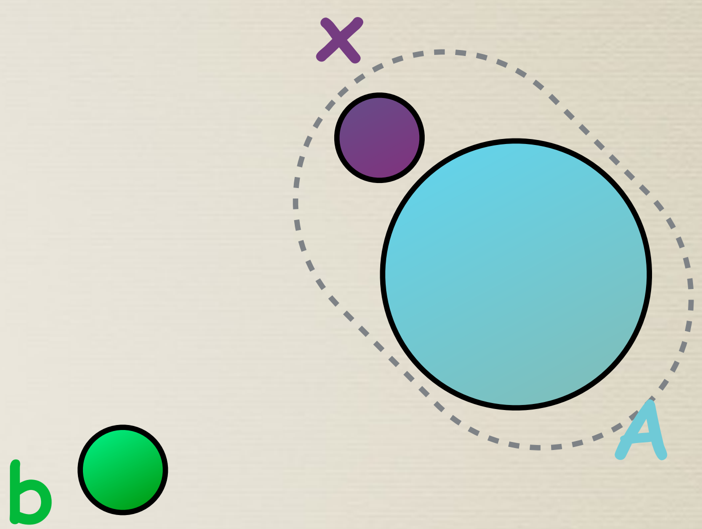

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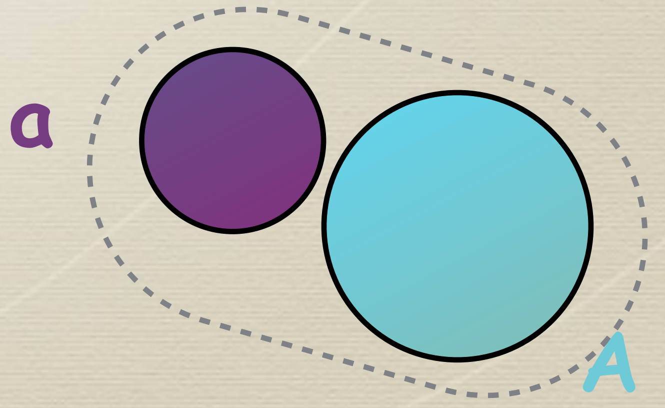


Applications

Deuteron Breakup

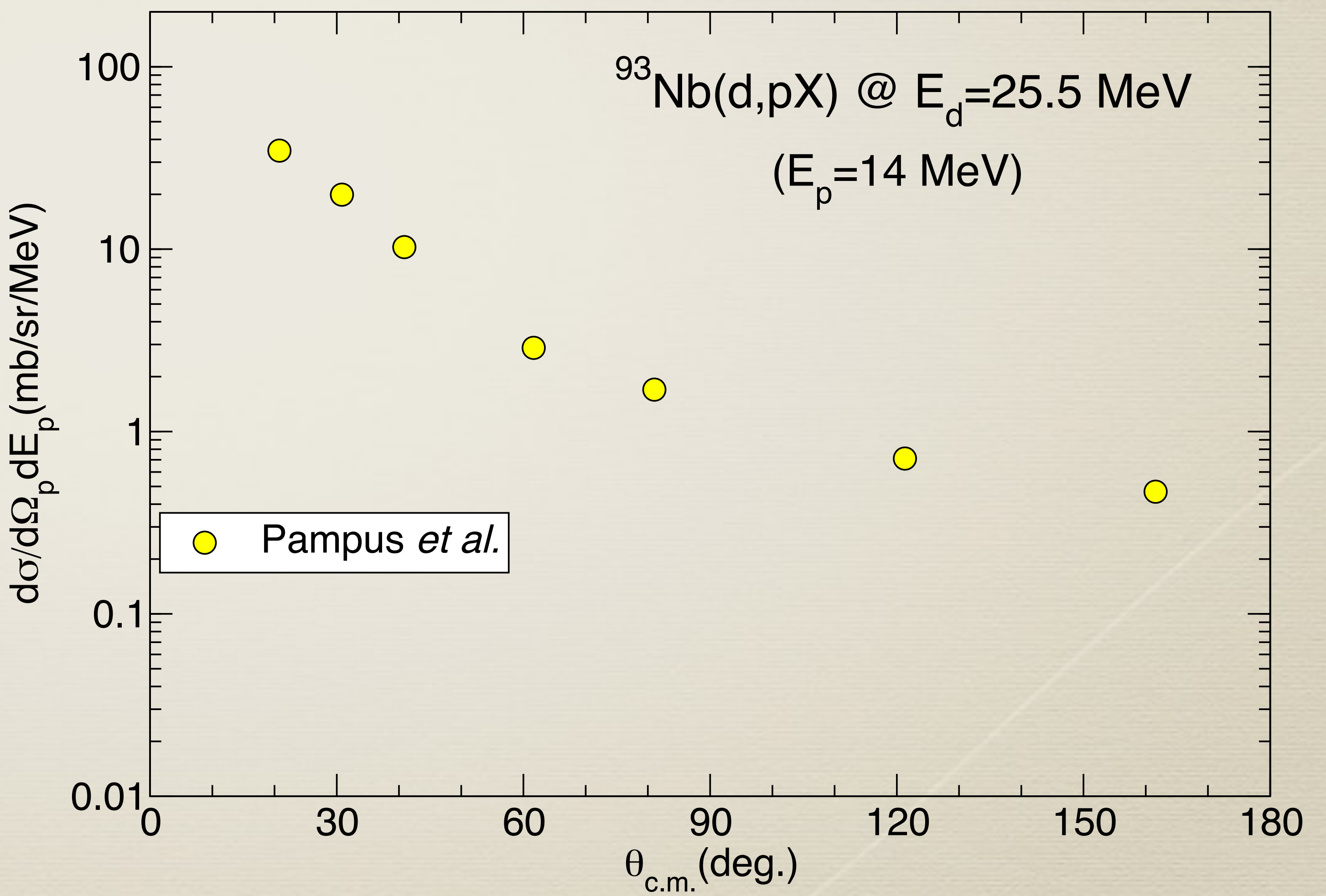
Deuteron Breakup

- d ⇒ (n + p), S_p=2.224 MeV

Deuteron Breakup

- $d \Rightarrow (n + p)$, S_p=2.224 MeV
- only proton is detected

J. Pampus et al, Nucl. Phys. A311, 141 (1978).



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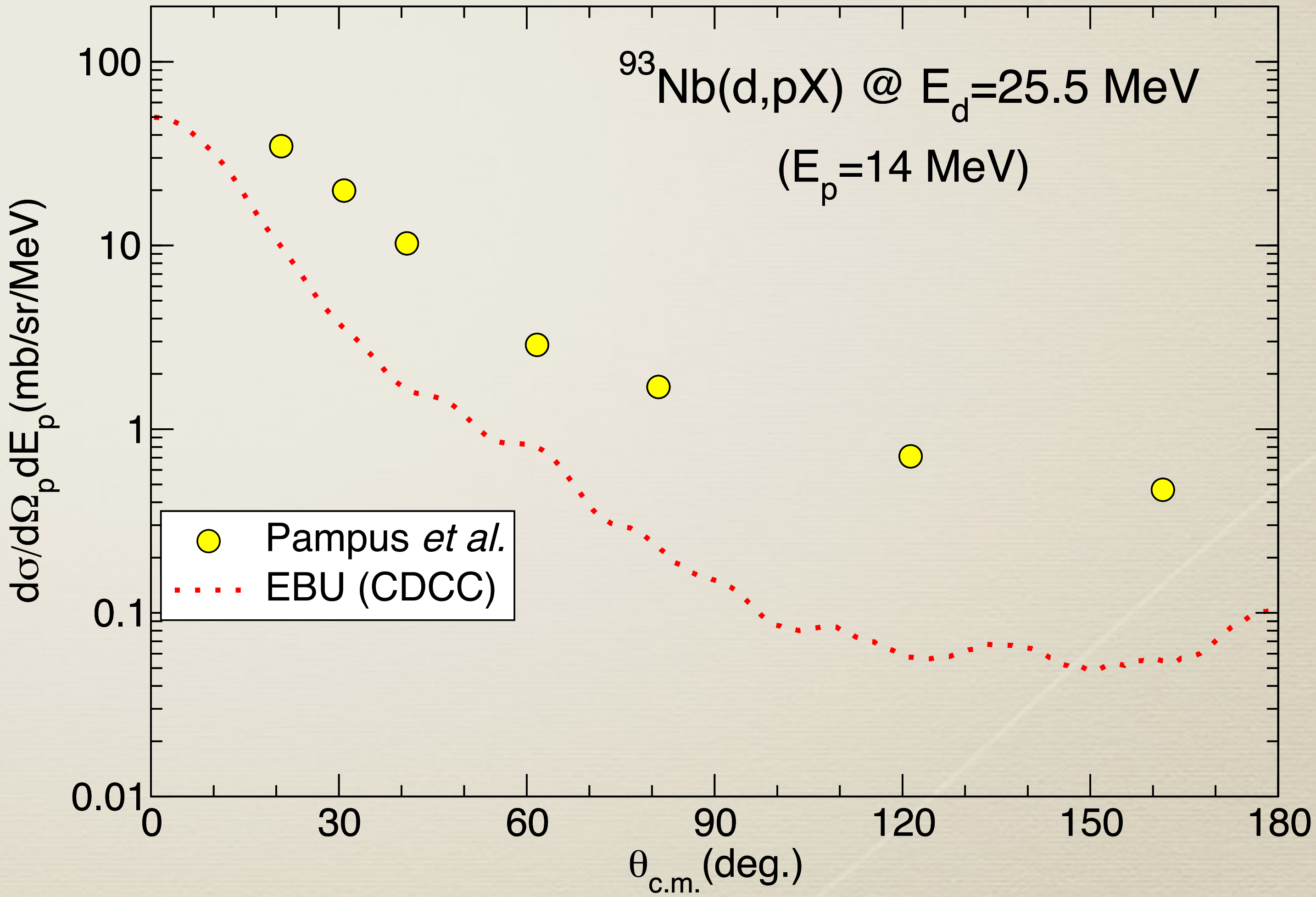

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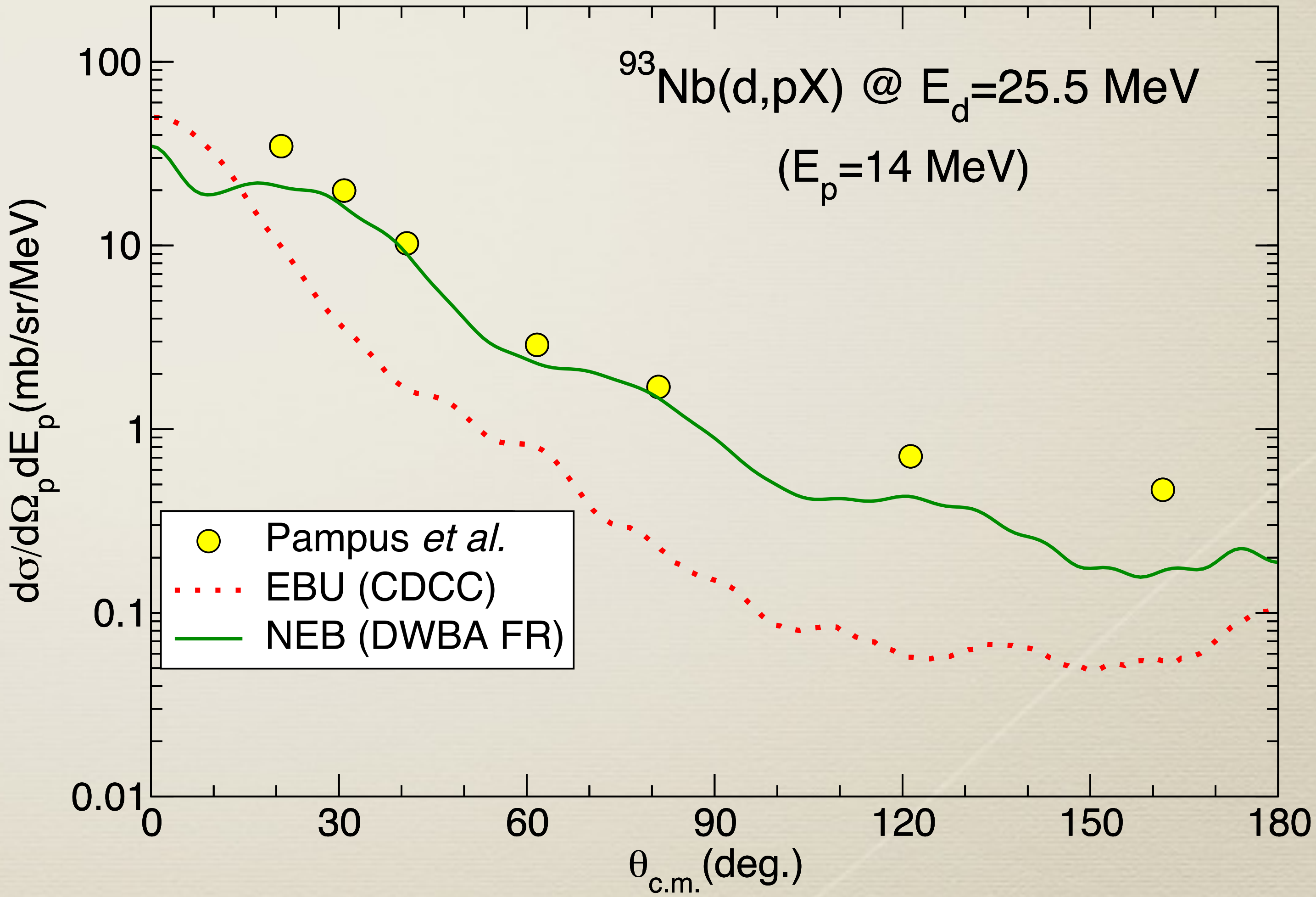

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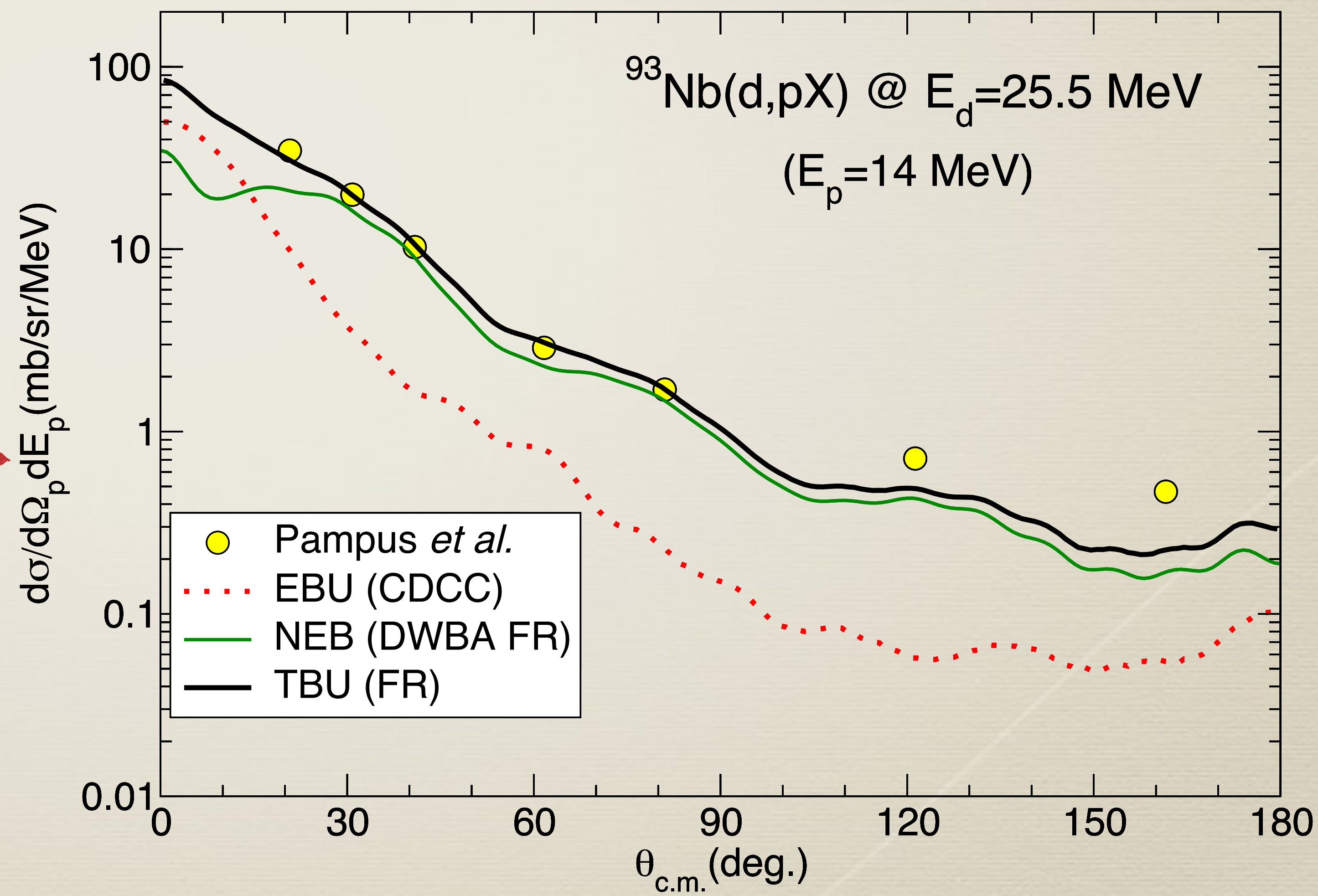

Application to ^{6}Li breakup

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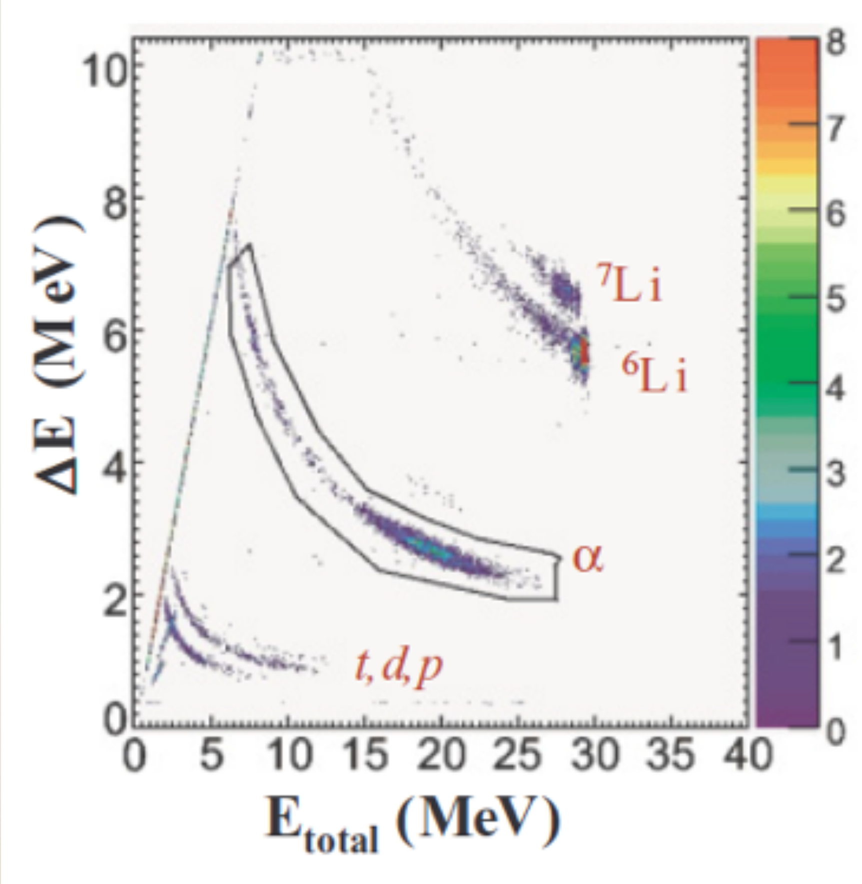

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Application to ^{6}Li breakup

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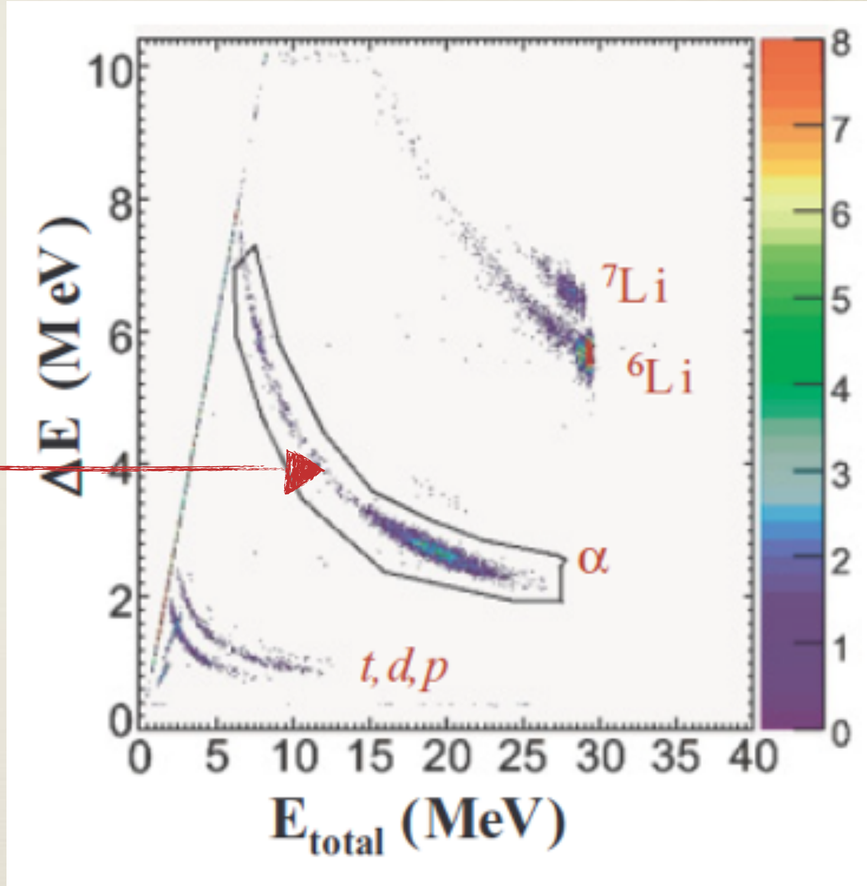
- large α yields are detected



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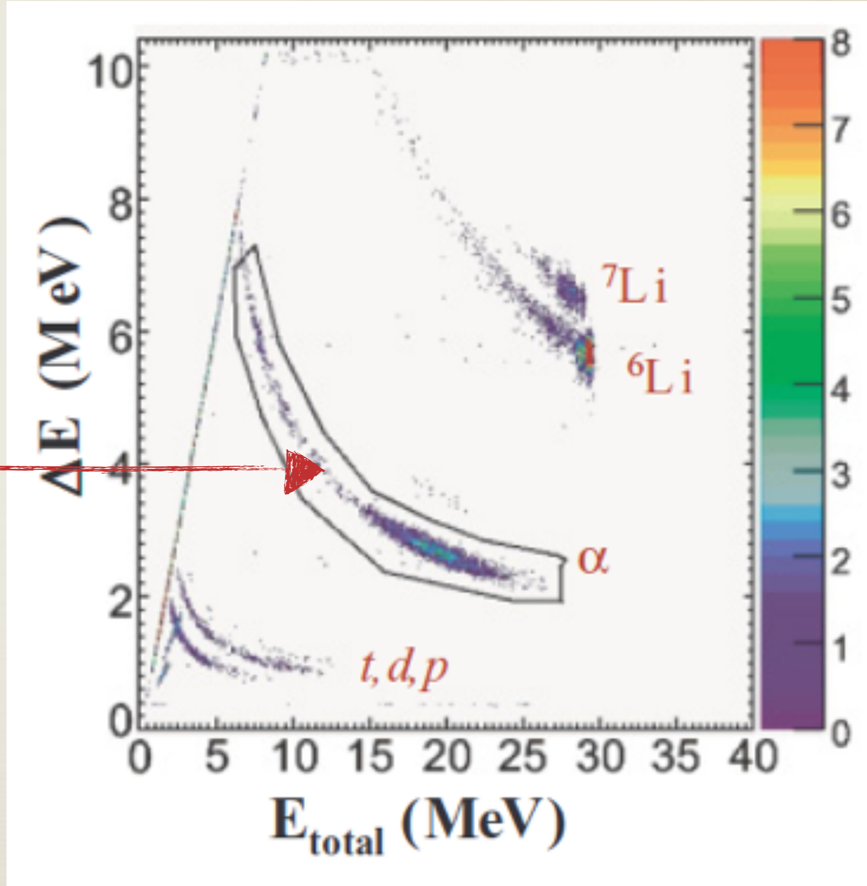
Application to ^{6}Li breakup

- ^{6}Li ⇒ (α+d), Q_α = -1.474 MeV
- large α yields are detected
- $\sigma_\alpha \gg \sigma_d$ (EBU is not dominant)



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$^{209}Bi(^{6}Li,^{6}Li)^{209}Bi$

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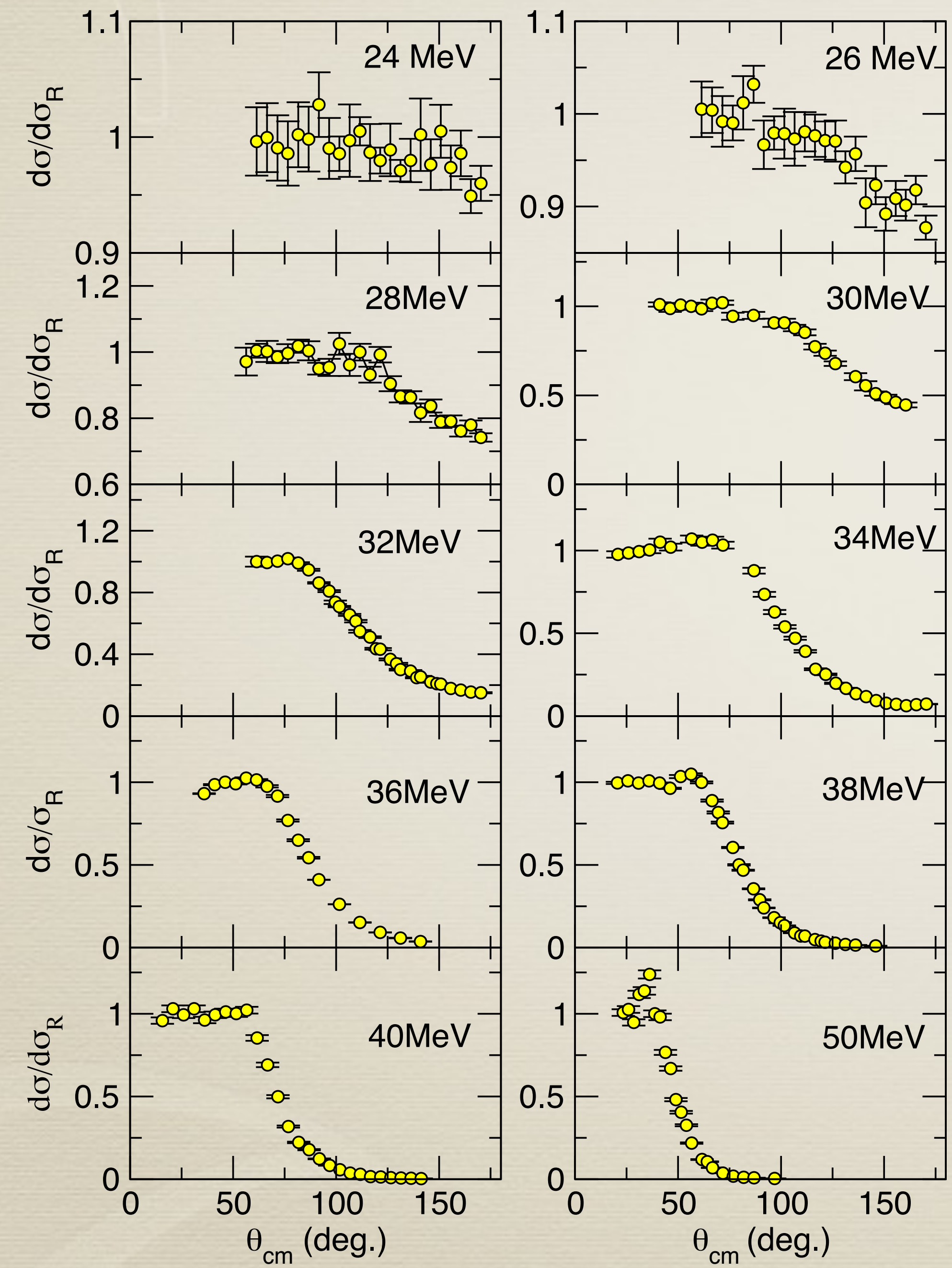
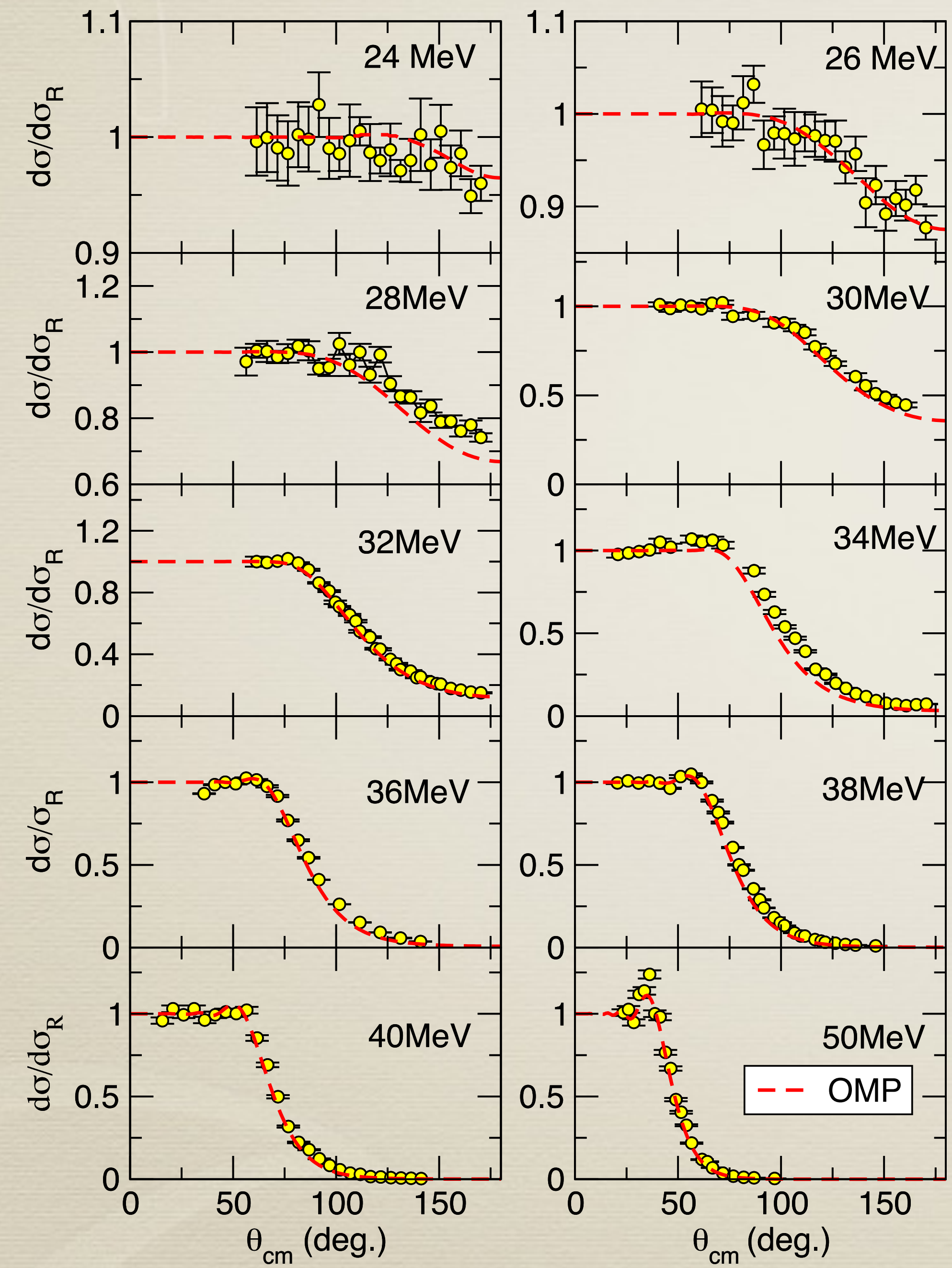


- Elastic scattering
  - data : S. Santra et al

$^{209}Bi(^{6}Li,^{6}Li)^{209}Bi$



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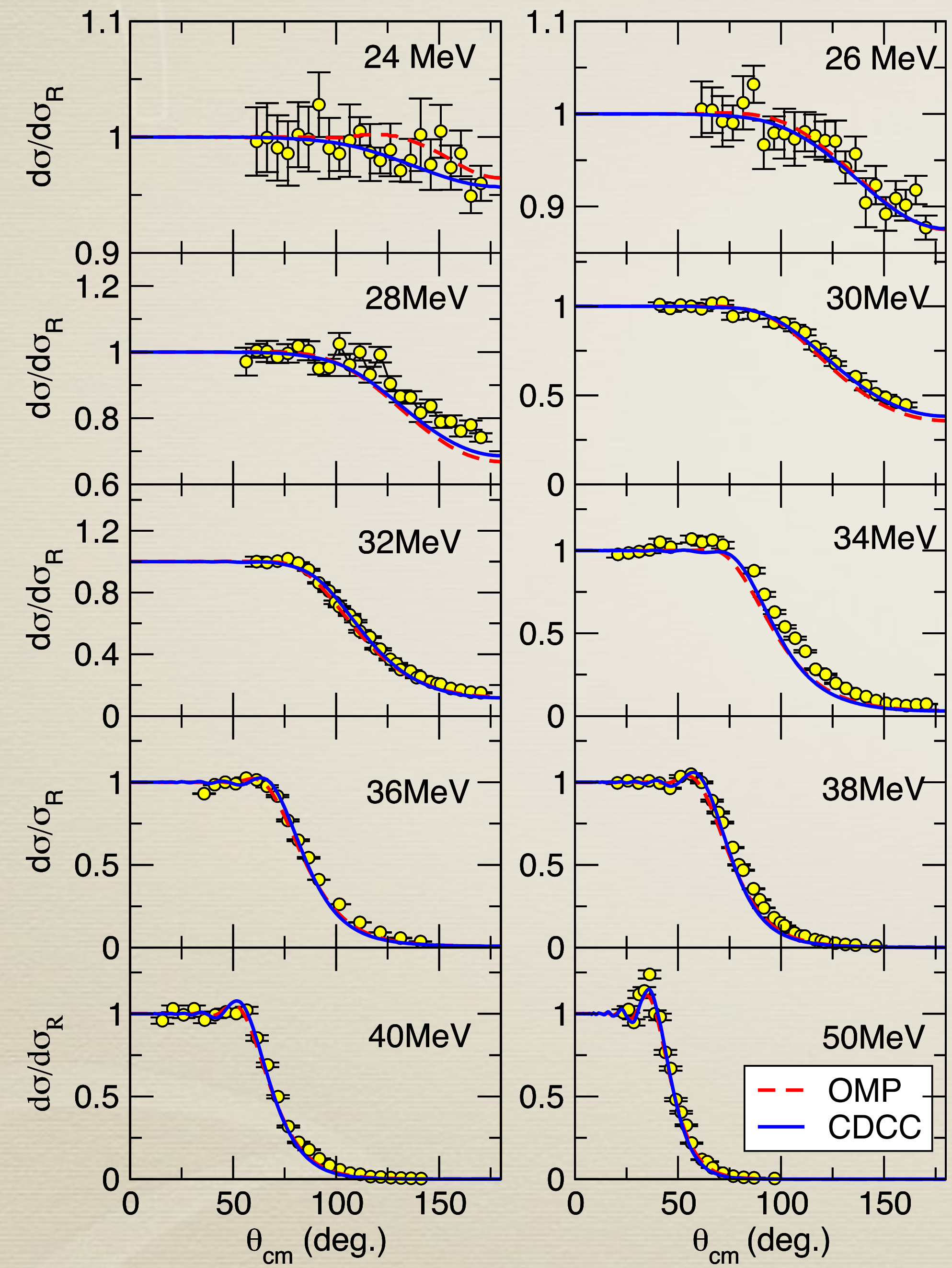

- Elastic scattering
  - data : S. Santra et al
- J. Cook potential (global $^{6,7}Li$ OMP)
- CDCC calculation
  - d/α+^{209}Bi : OMP
  - d+^{209}Bi : requires reduction of imaginary part due to the limitation of 2-body model of ^{6}Li.

$^{209}Bi(^{6}Li,\alpha X)$

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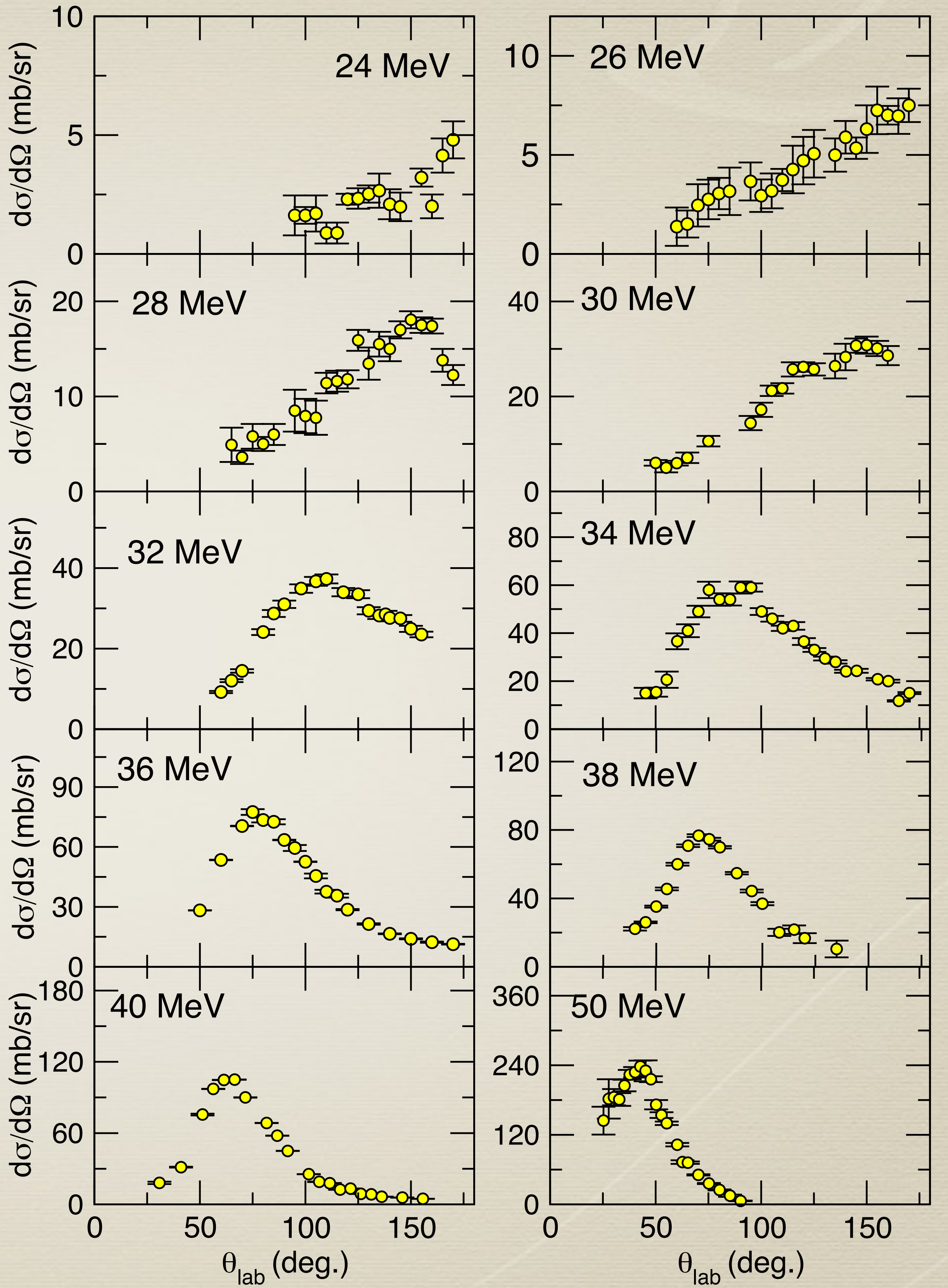
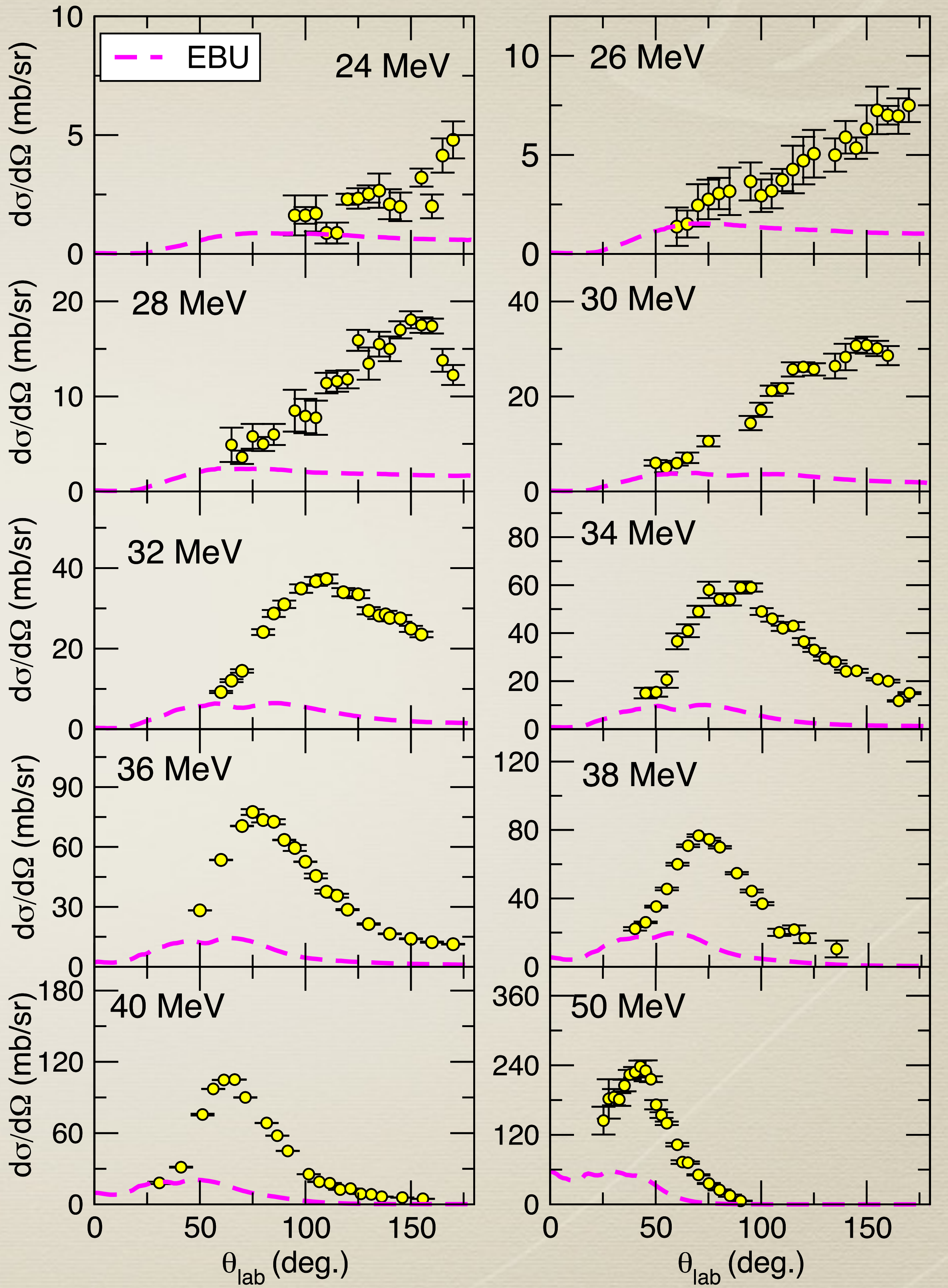
- Inclusive α
  - data: S. Santra et al



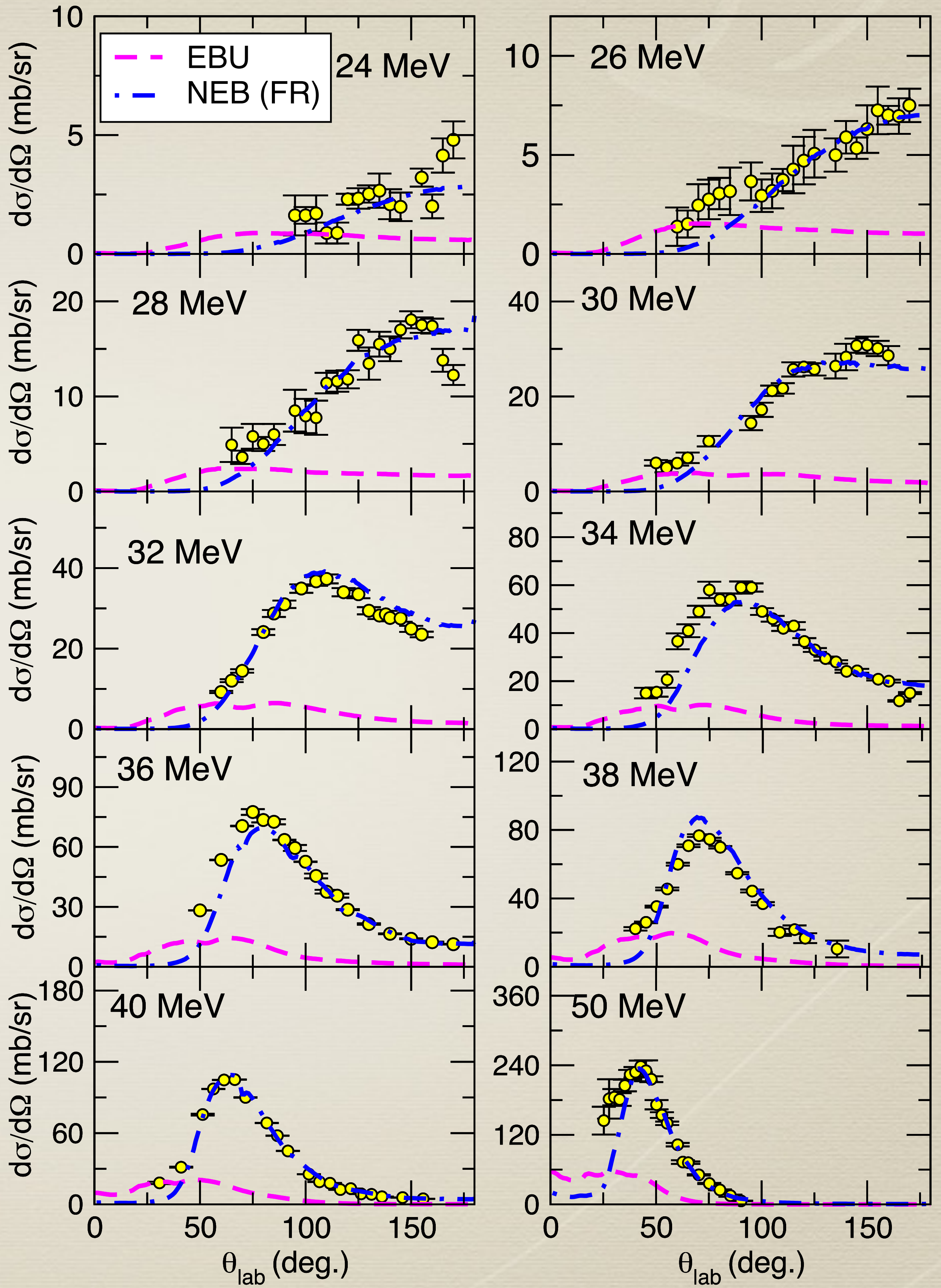
$^{209}Bi(^{6}Li,\alpha X)$

- Inclusive α
  - data: S. Santra et al
- EBU : CDCC calculation



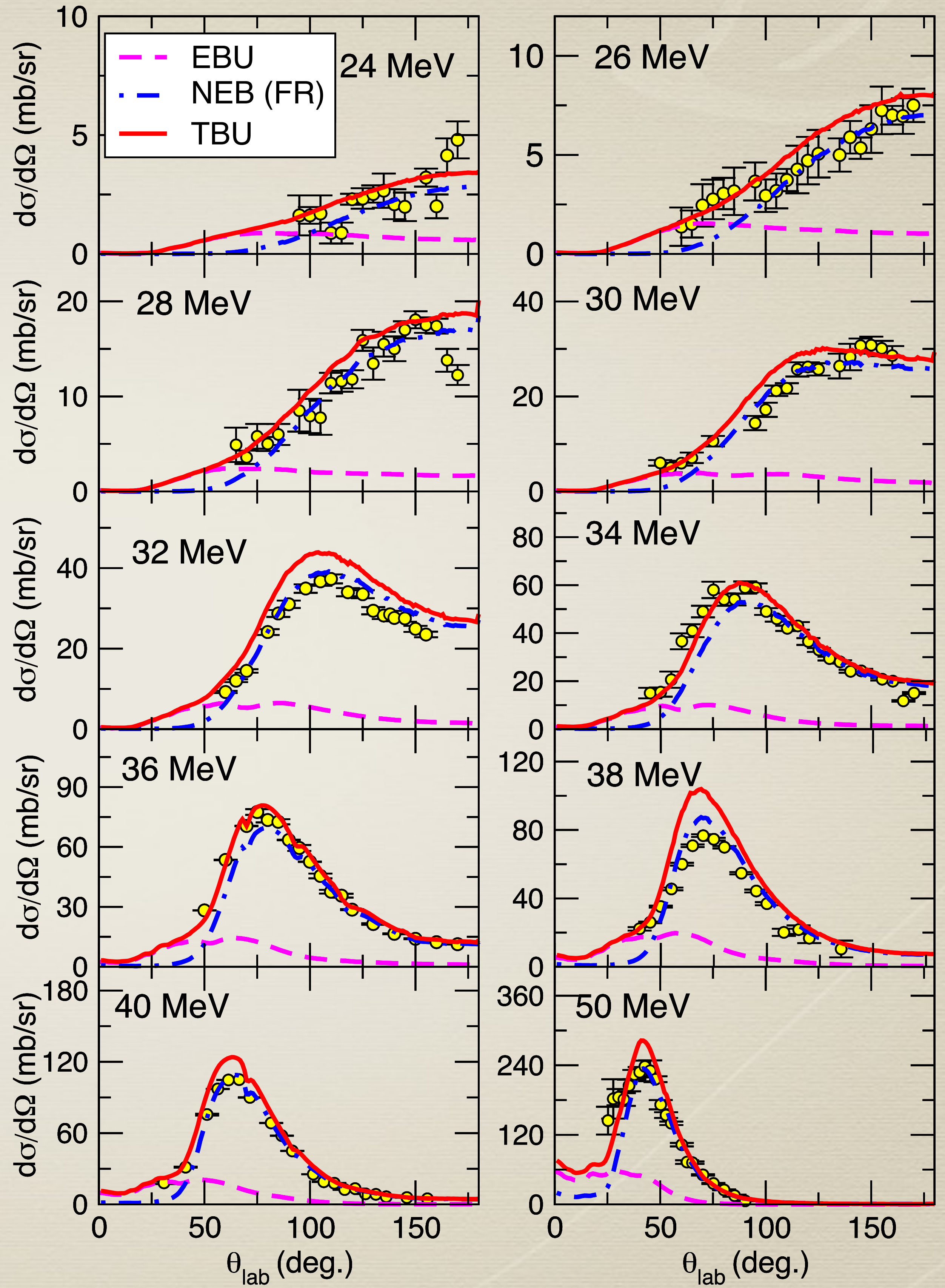
^{209}Bi(^{6}Li,αX)

- Inclusive α
  - data: S. Santra et al
- EBU : CDCC calculation
- NEB : IAV model (DWBA)
  - dominate inclusive α

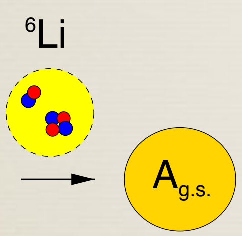


$^{209}Bi(^{6}Li,\alpha X)$

- Inclusive α
  - data: S. Santra et al
- EBU : CDCC calculation
- NEB : IAV model (DWBA)
  - dominate inclusive α
- TBU=EBU+NEB
  - overall agreement with data



Reaction cross section of $^{6}Li+^{209}Bi$



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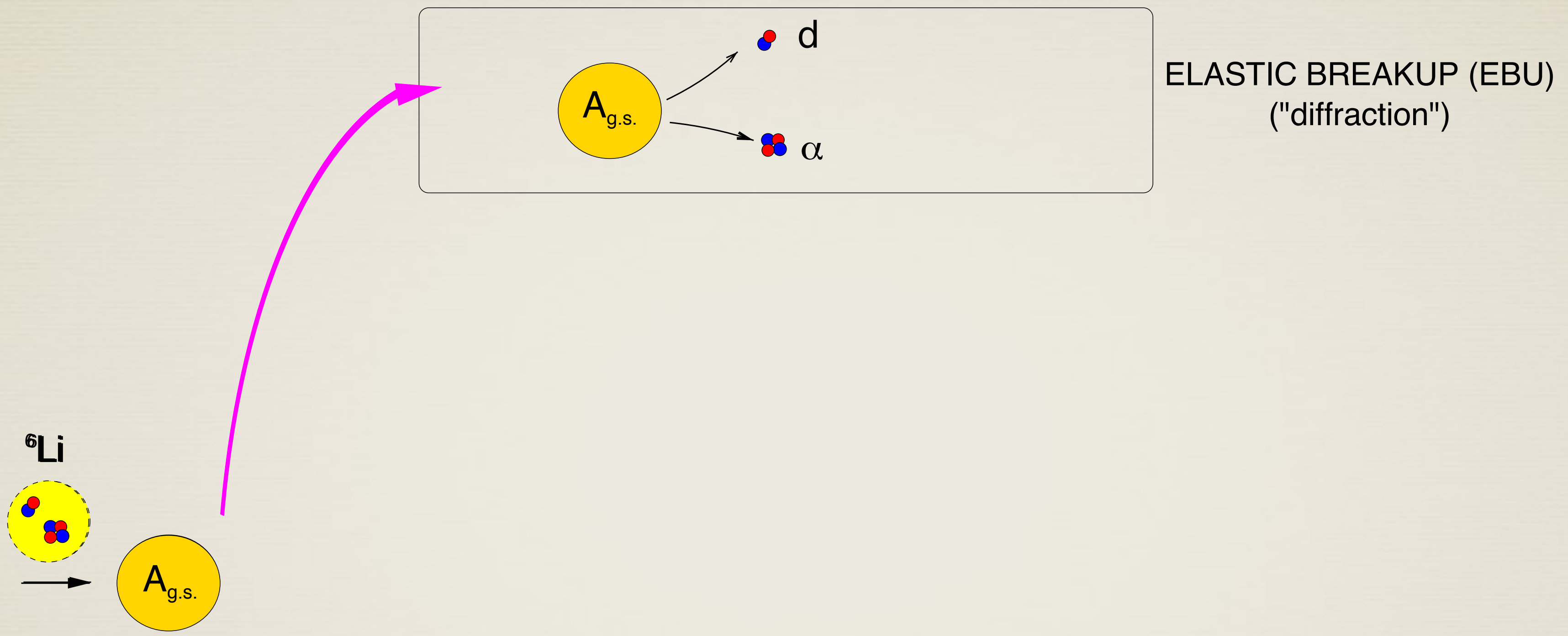

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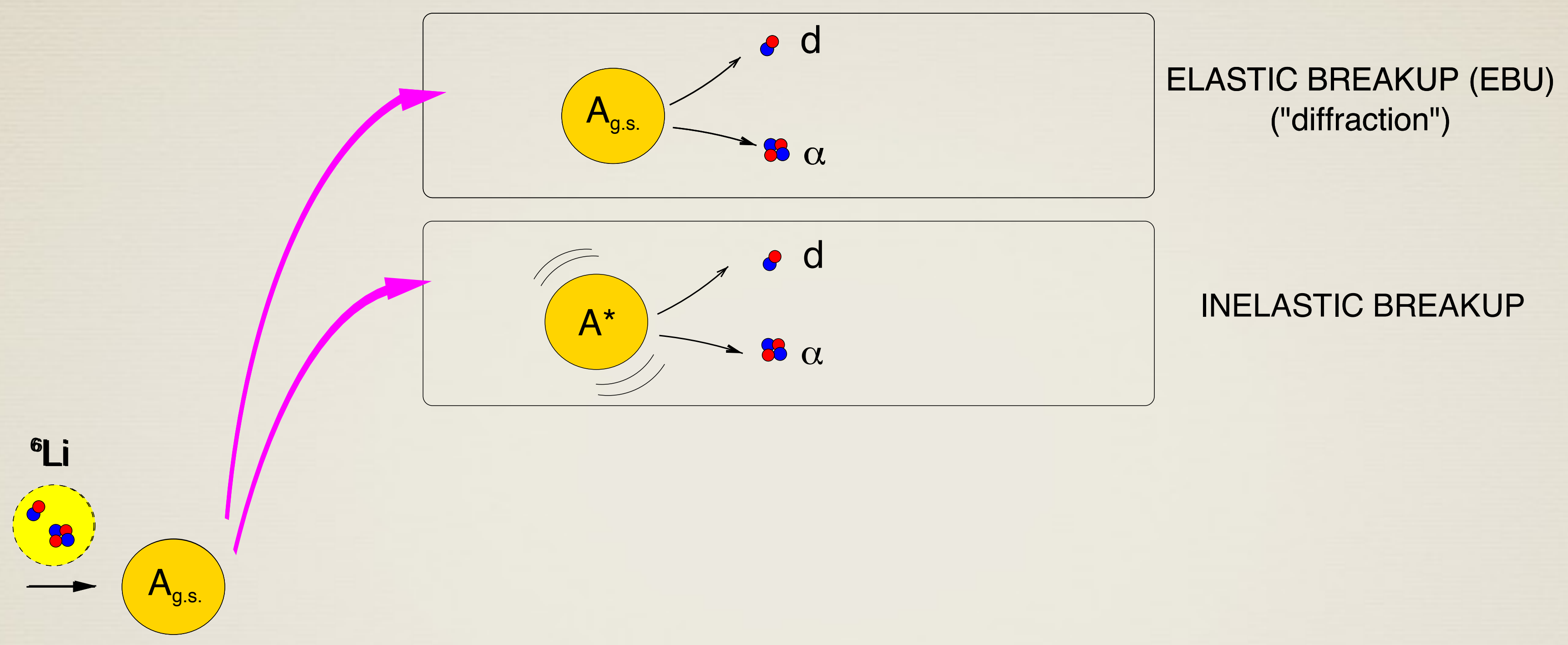

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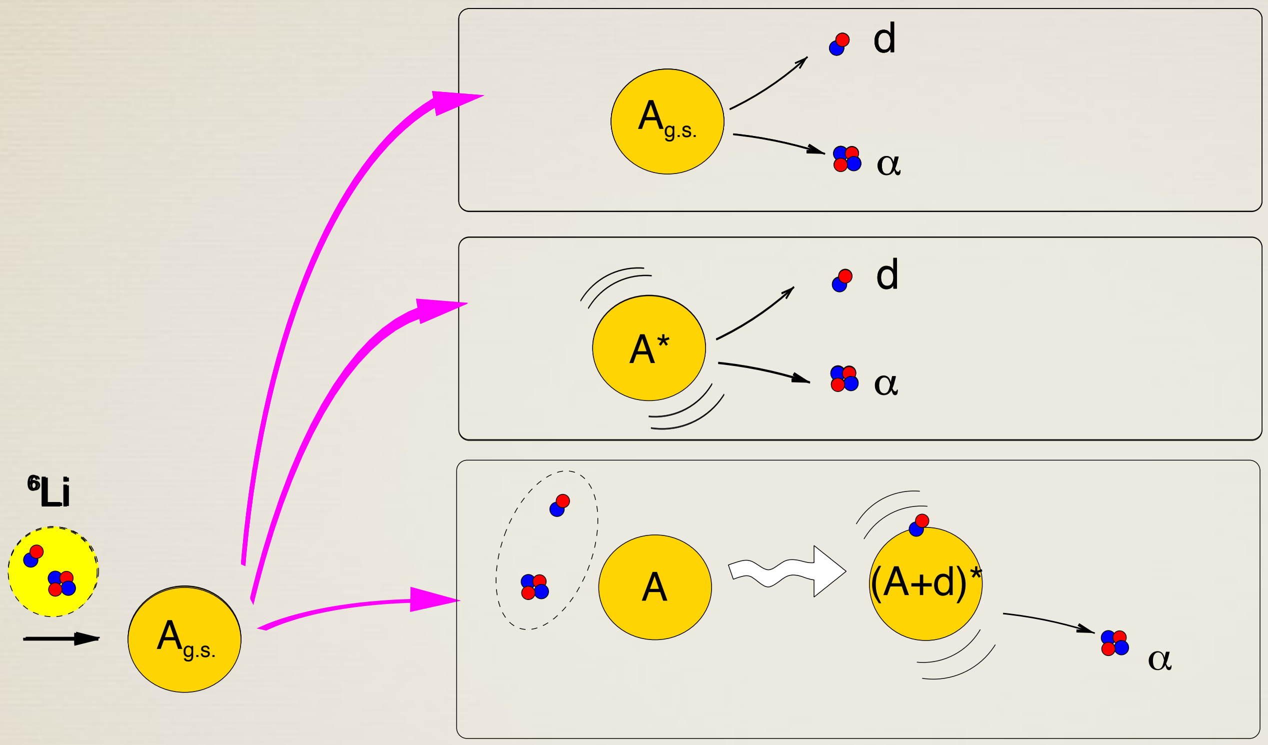
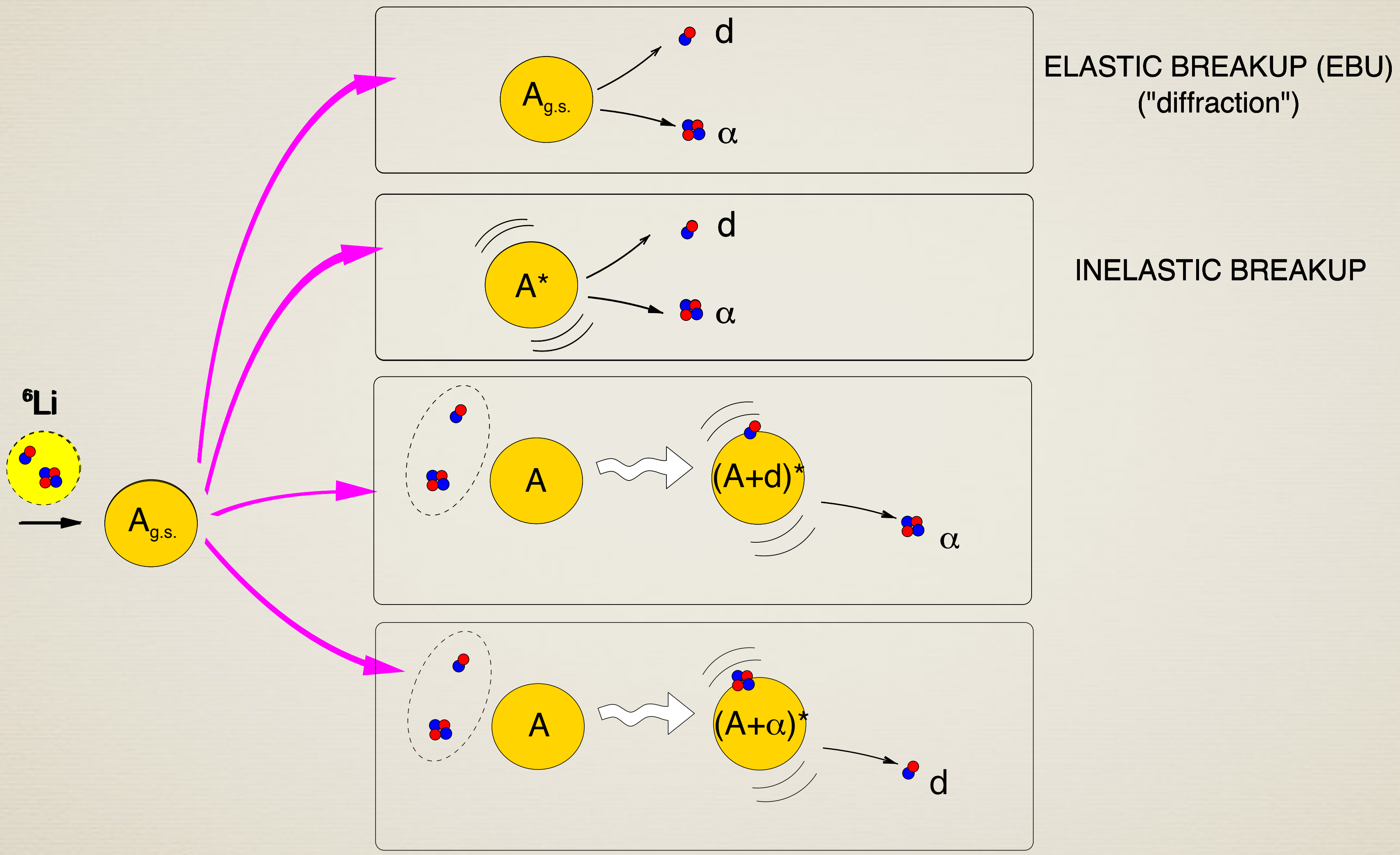


ELASTIC BREAKUP (EBU)
("diffraction")

INELASTIC BREAKUP

Reaction cross section of $^{6}Li+^{209}Bi$



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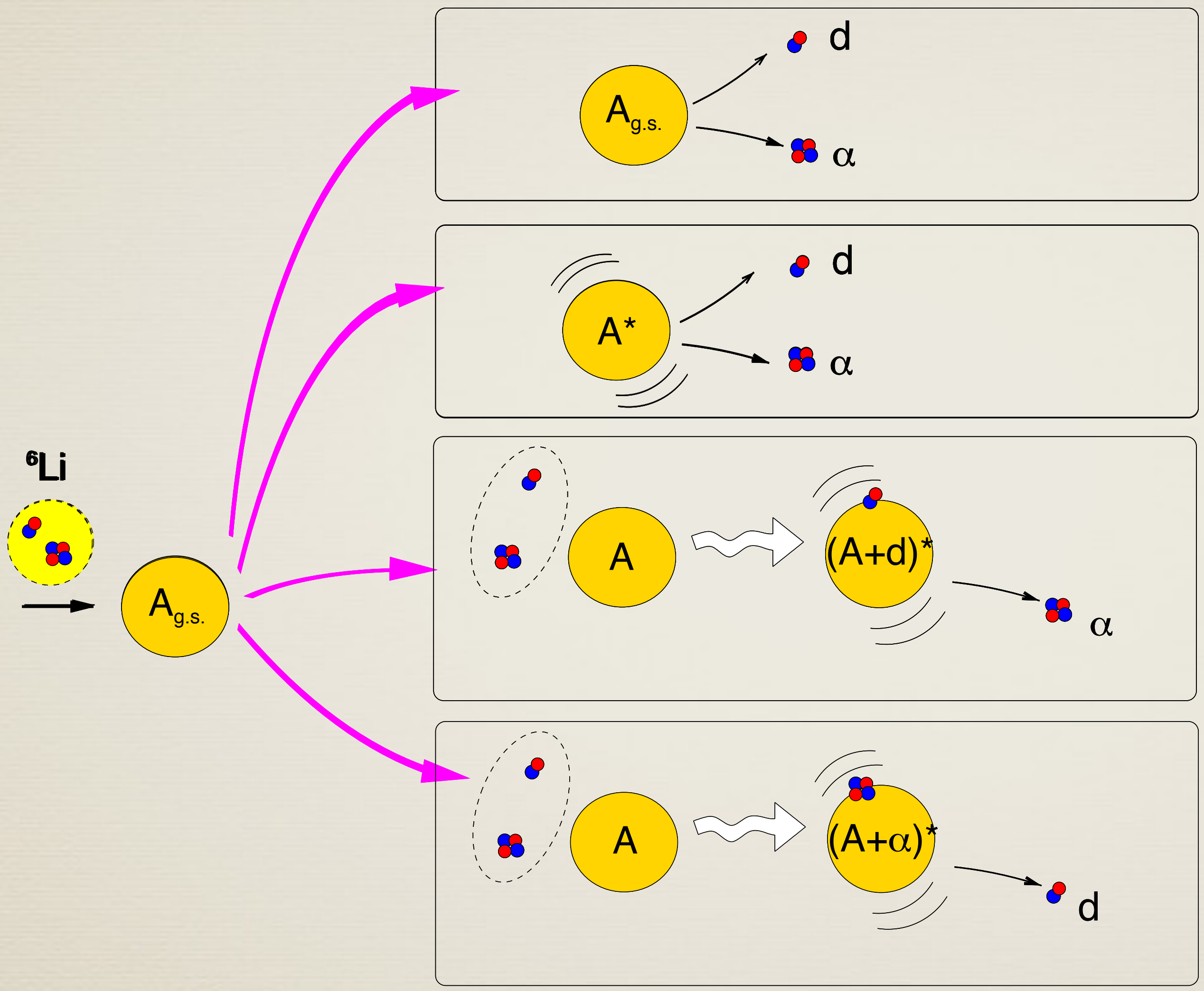

ELASTIC BREAKUP (EBU)
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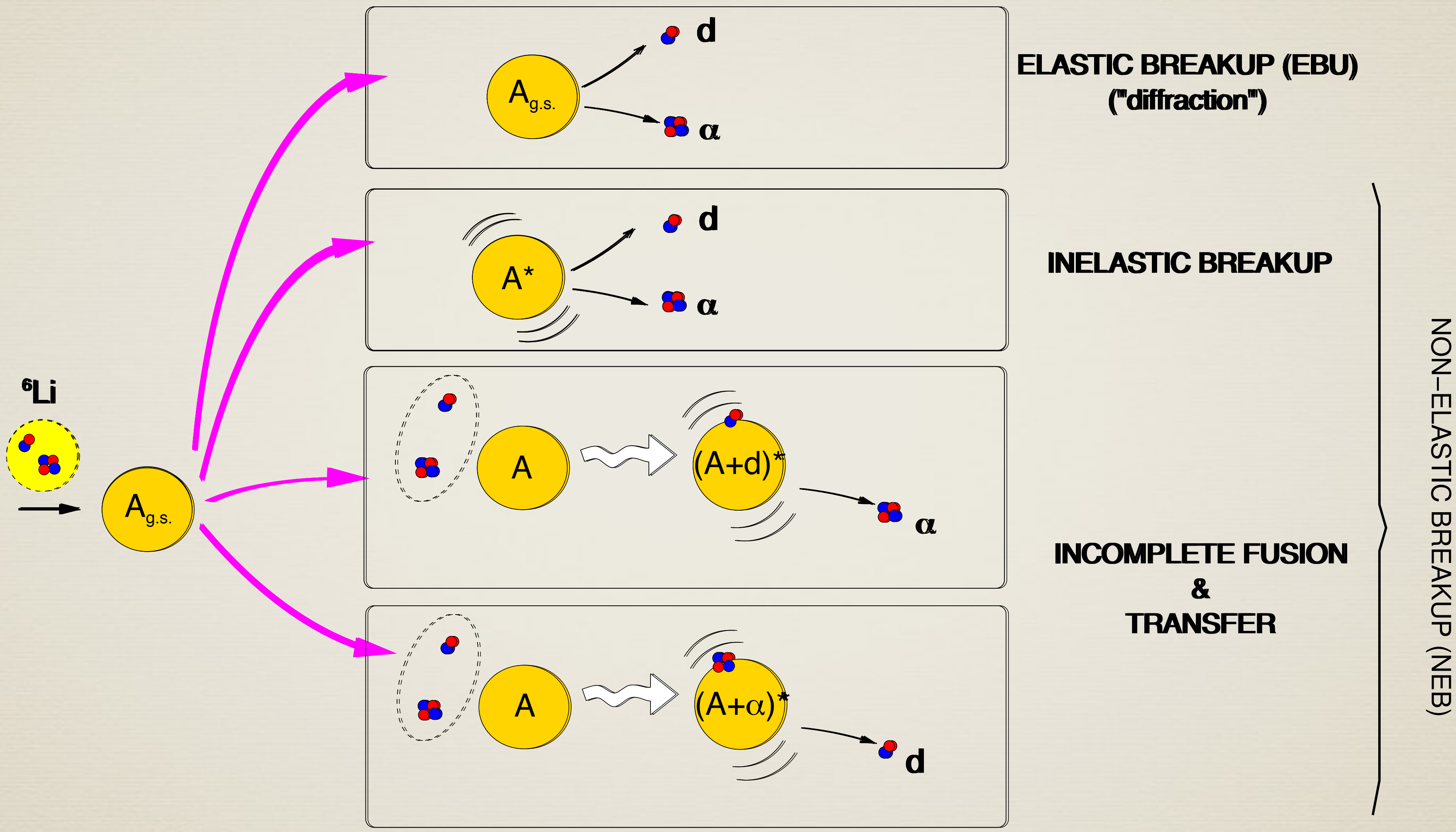
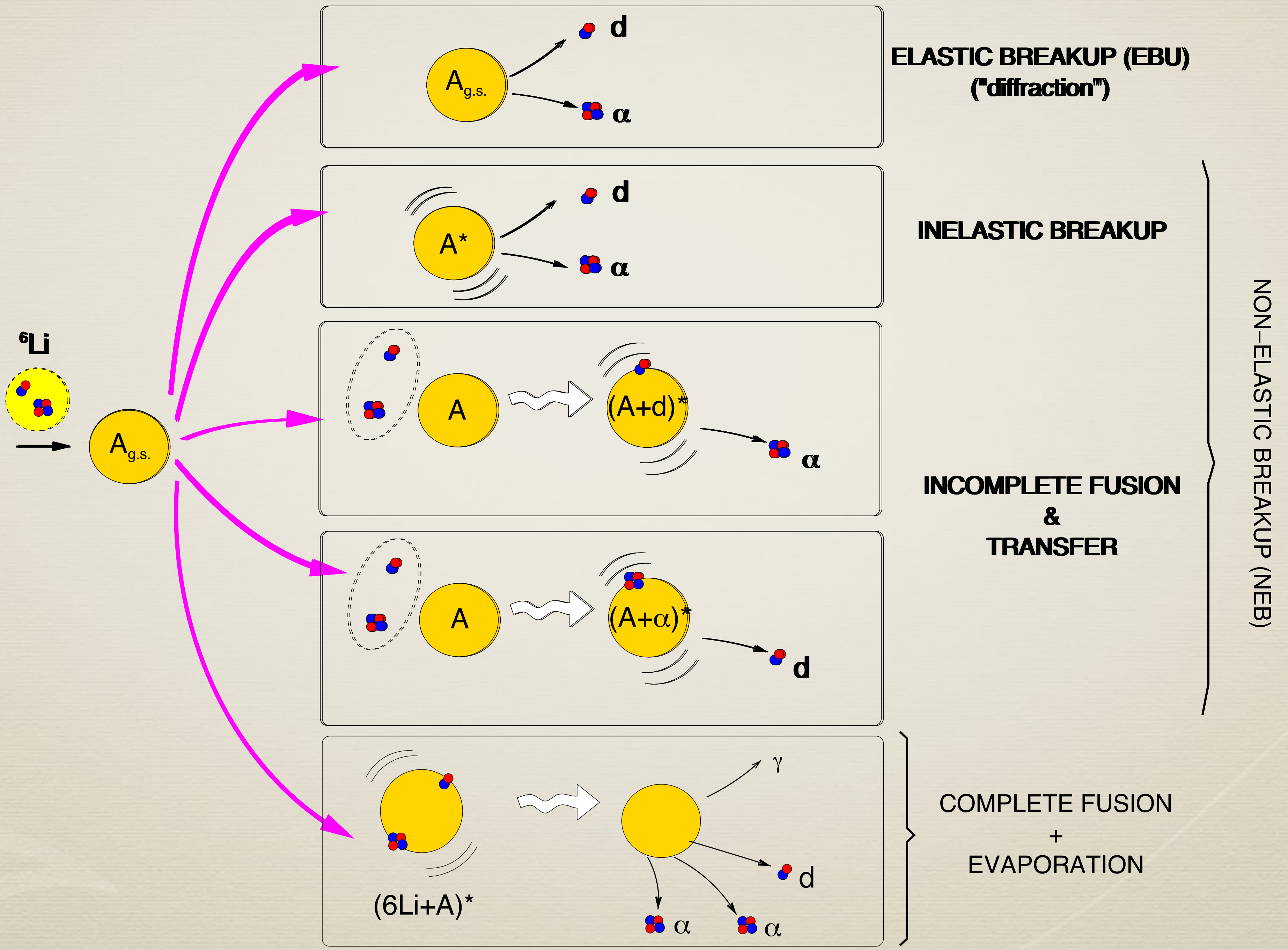
INELASTIC BREAKUP

INCOMPLETE FUSION
&
TRANSFER

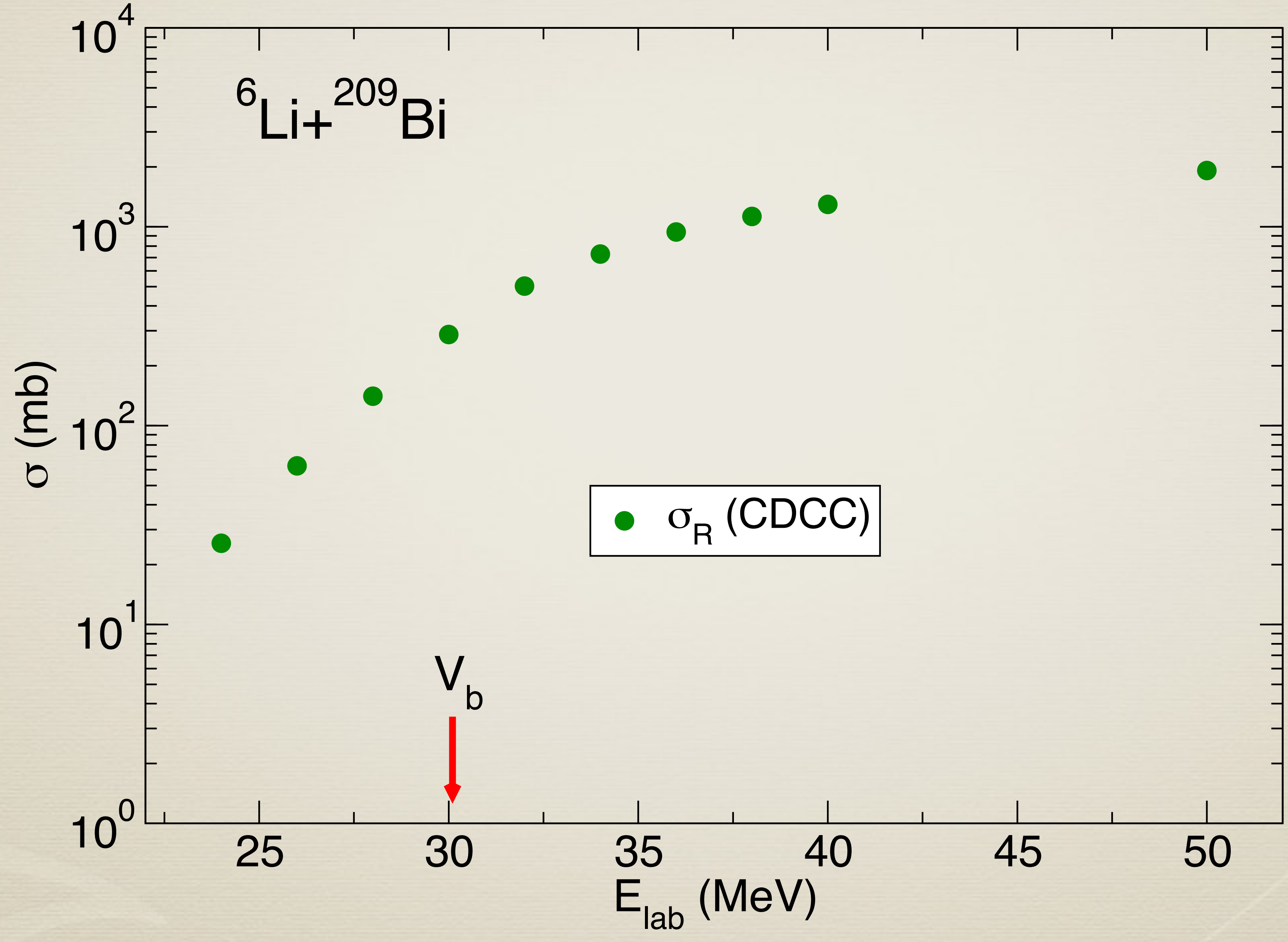
Reaction cross section of $^{6}Li+^{209}Bi$



Reaction cross section of $^{6}Li+^{209}Bi$

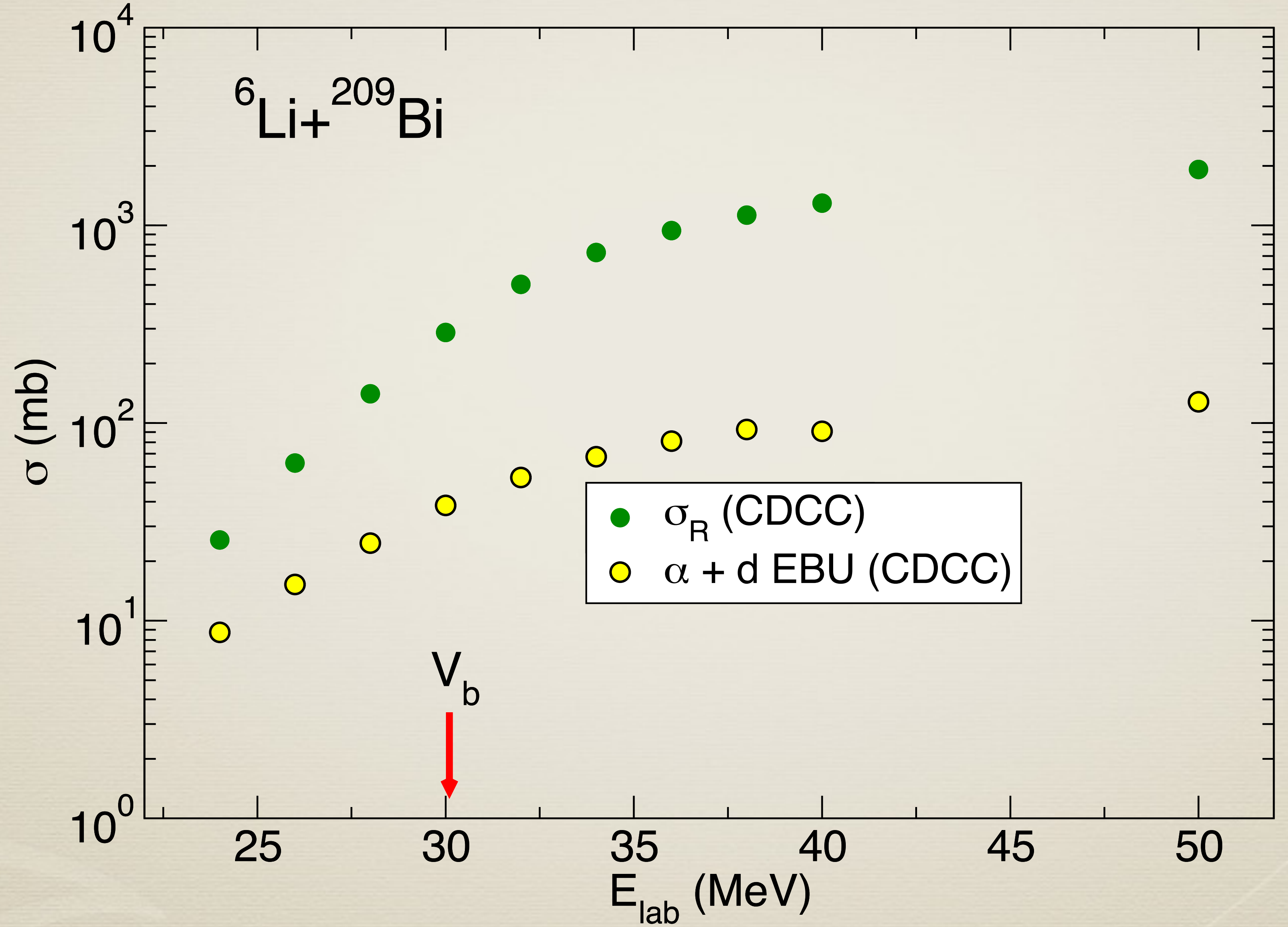


$^{6}Li+^{209}Bi$



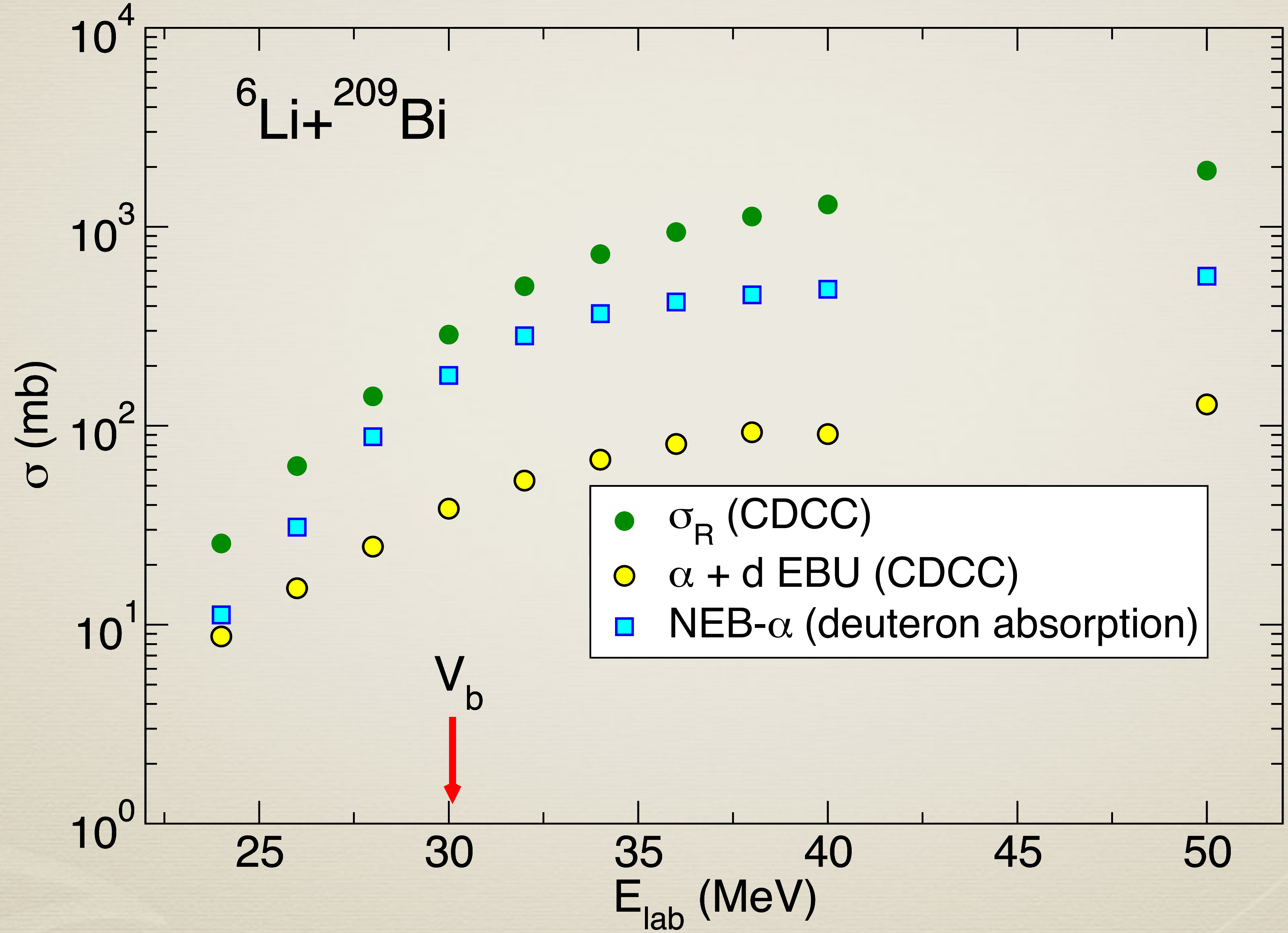
$^{6}Li+^{209}Bi$
σ_R (CDCC)
V_b
σ (mb)
E_{lab} (MeV)
10^0
10^1
10^2
10^3
10^4
25
30
35
40
45
50

$^{6}Li+^{209}Bi$



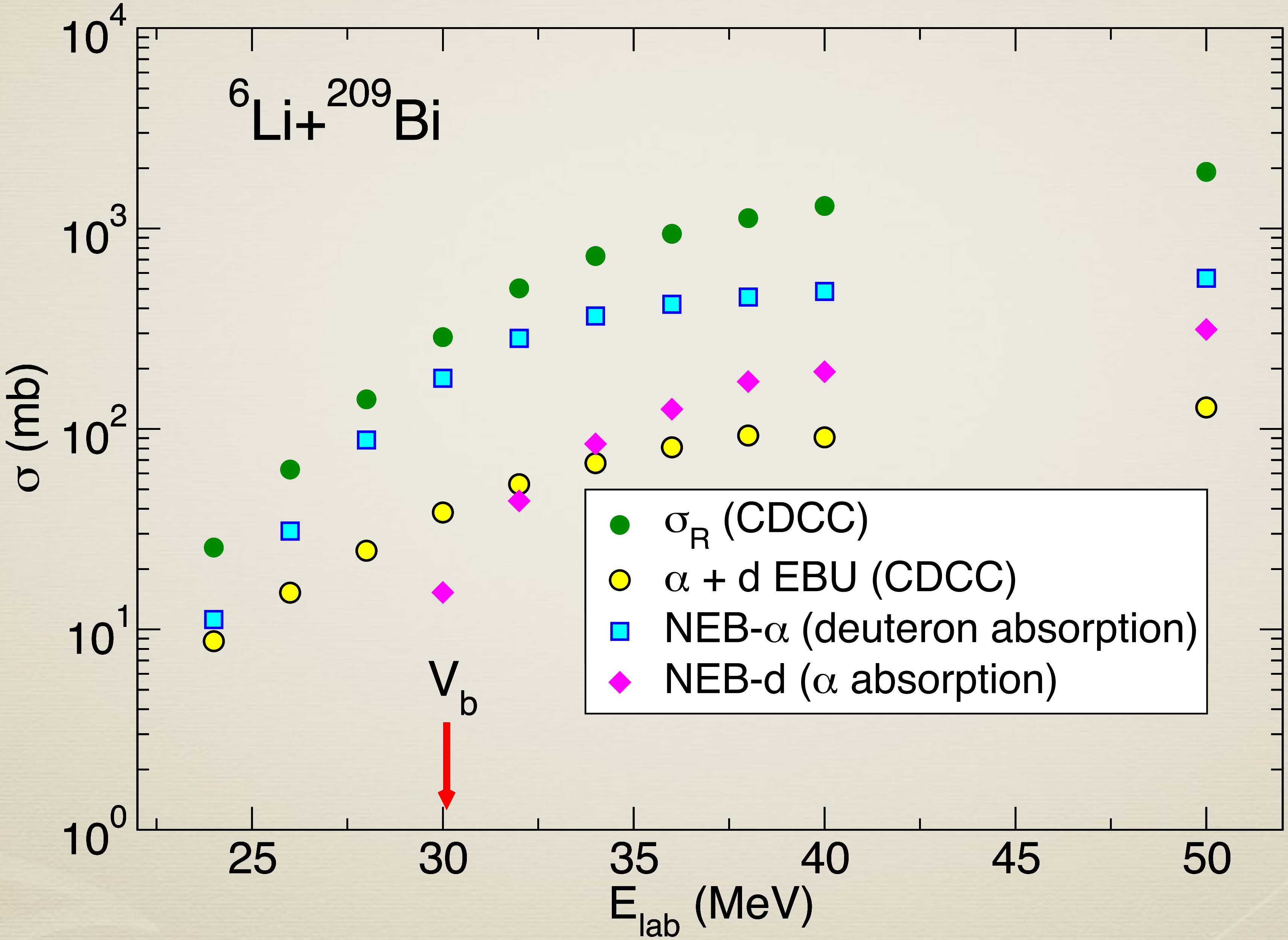
10^4
10^3
10^2
10^1
10^0
σ (mb)
6Li+209Bi
σR (CDCC)
α + d EBU (CDCC)
Vb
25
30
35
40
45
50
Elab (MeV)

$^{6}Li+^{209}Bi$



6Li+209Bi
σ (mb)
E_lab (MeV)
V_b
σ_R (CDCC)
α + d EBU (CDCC)
NEB-α (deuteron absorption)
10^0
10^1
10^2
10^3
10^4
25
30
35
40
45
50

$^{6}Li+^{209}Bi$



$^{6}Li+^{209}Bi$
σ (mb)
10^0
10^1
10^2
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25
30
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45
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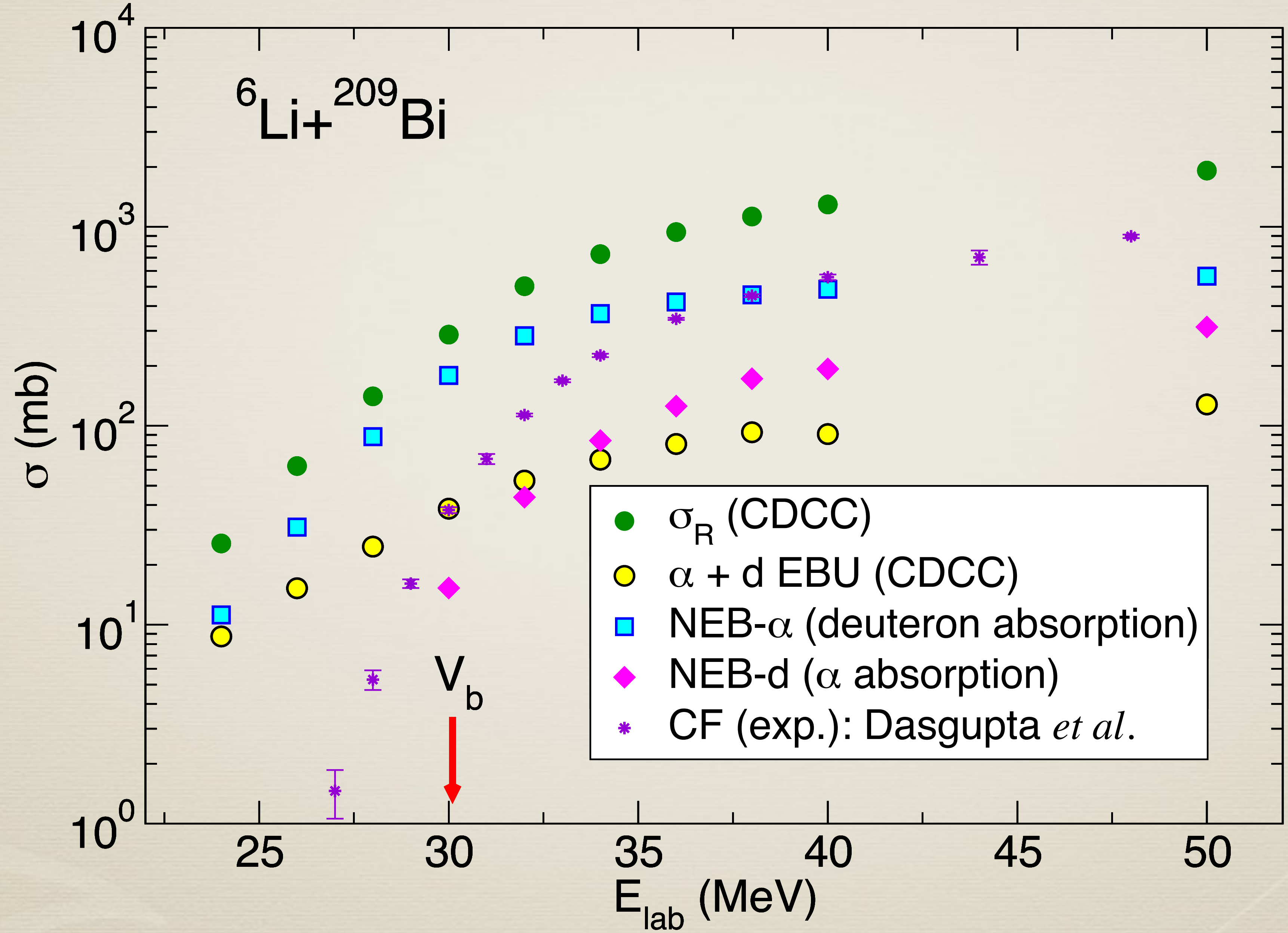
E_{lab} (MeV)
V_b
σ_R (CDCC)
α + d EBU (CDCC)
NEB-α (deuteron absorption)
NEB-d (α absorption)

$^{6}Li + ^{209}Bi$

CF: M. Dasgupta et al, Phys. Rev. C 70, 024606 (2004).



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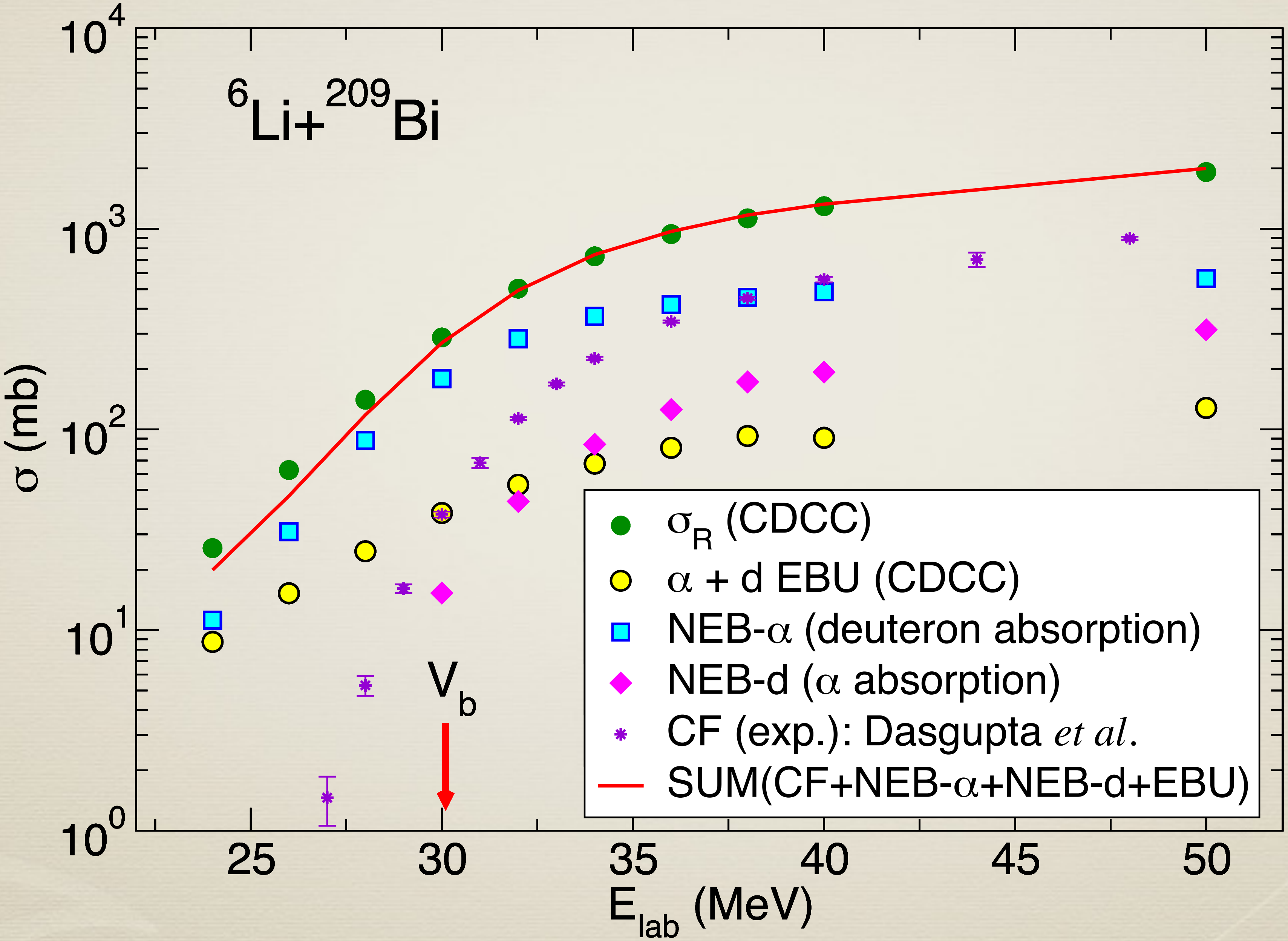
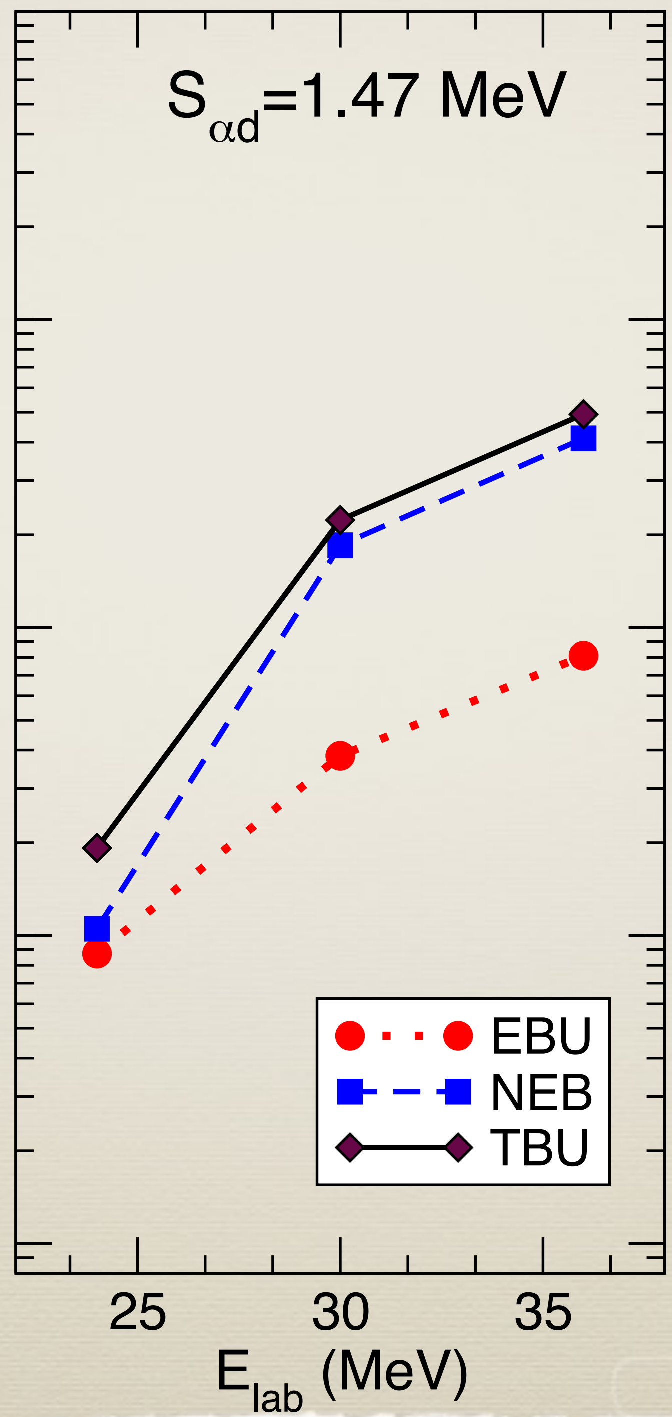


$$\sigma_R \approx \sigma_{\alpha+d}(\mathrm{EBU}) + \sigma_\alpha(\mathrm{NEB}) + \sigma_d(\mathrm{NEB}) + \sigma(\mathrm{CF})$$

Influence of the separation energy and the incident energy on the EBU and NEB



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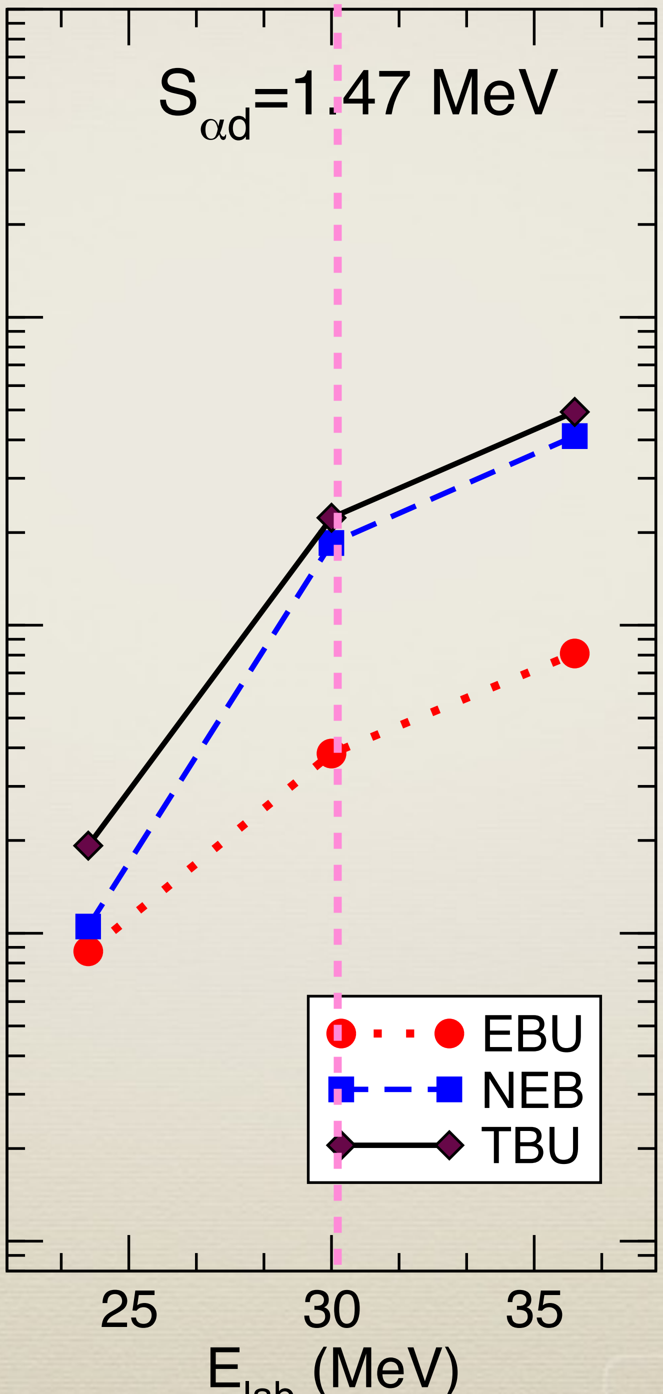

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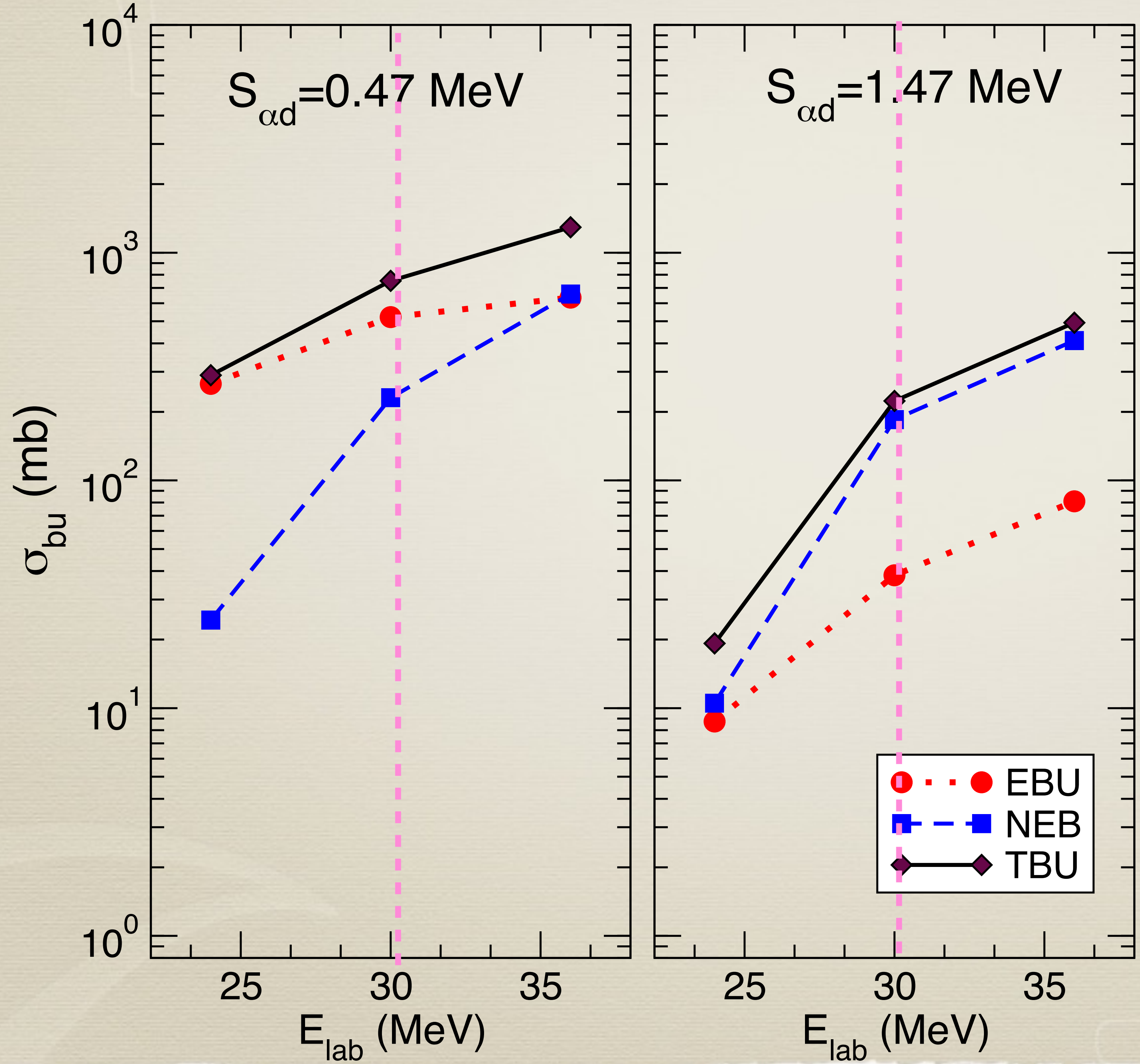

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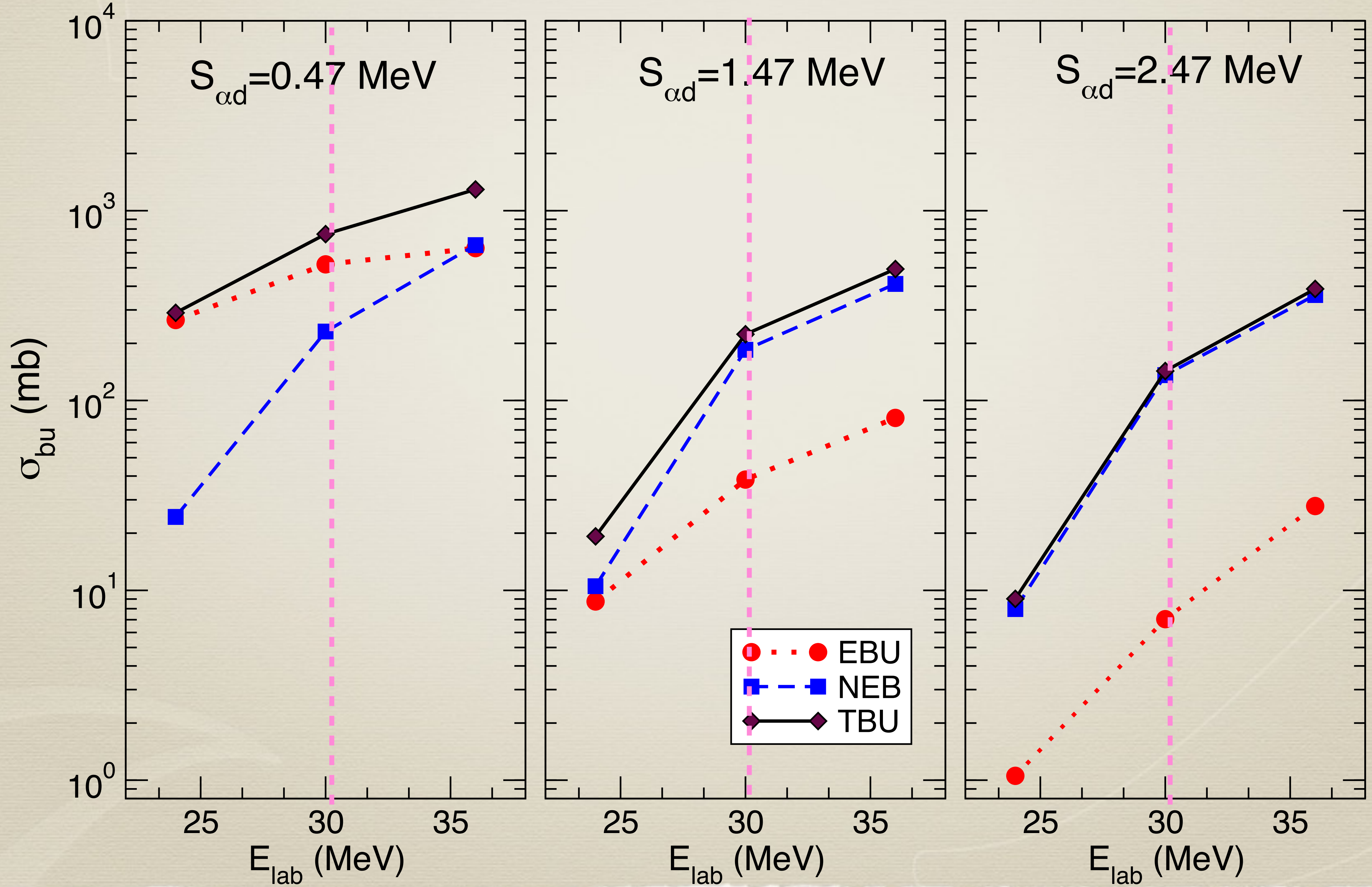
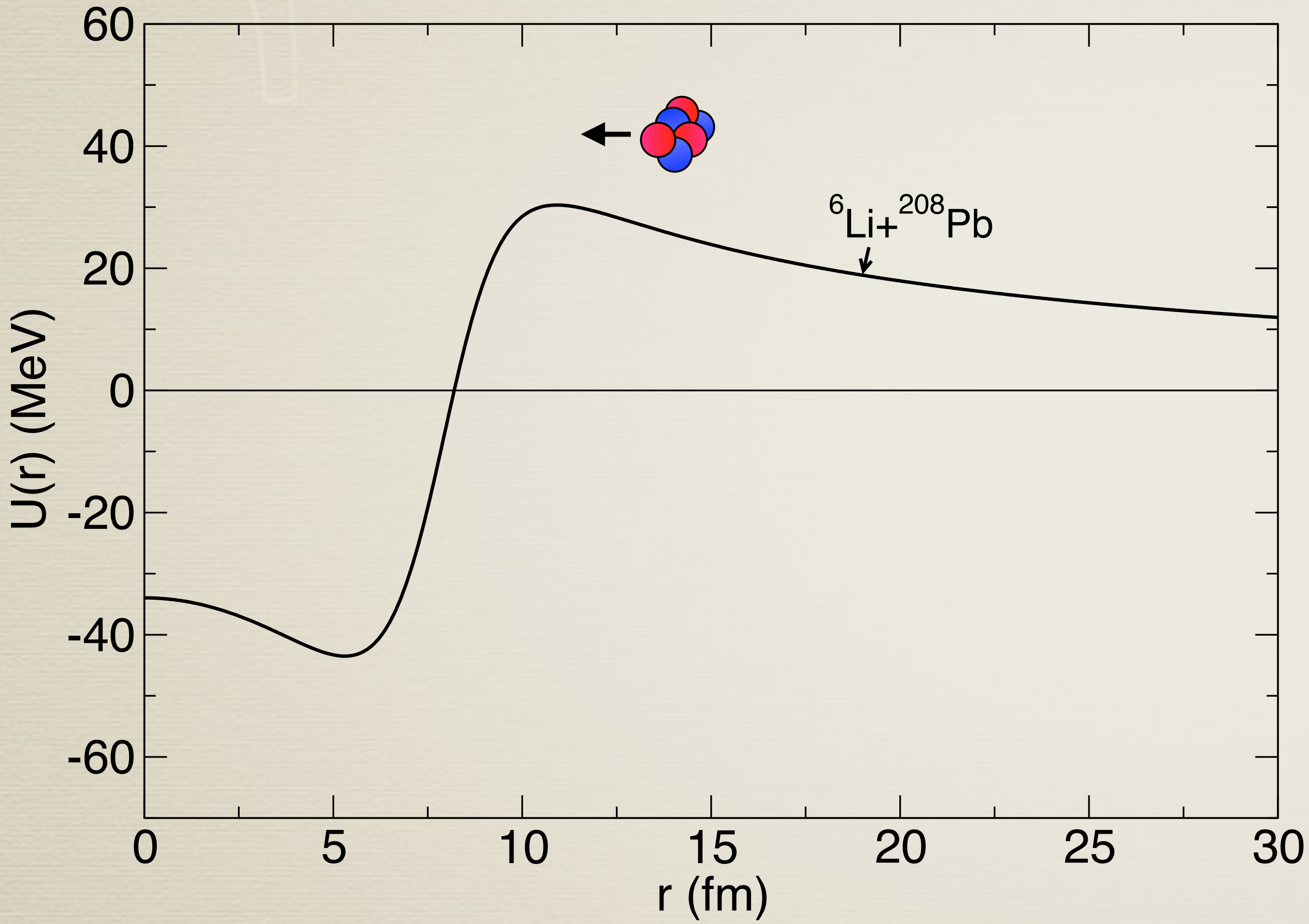


Trojan Horse type process



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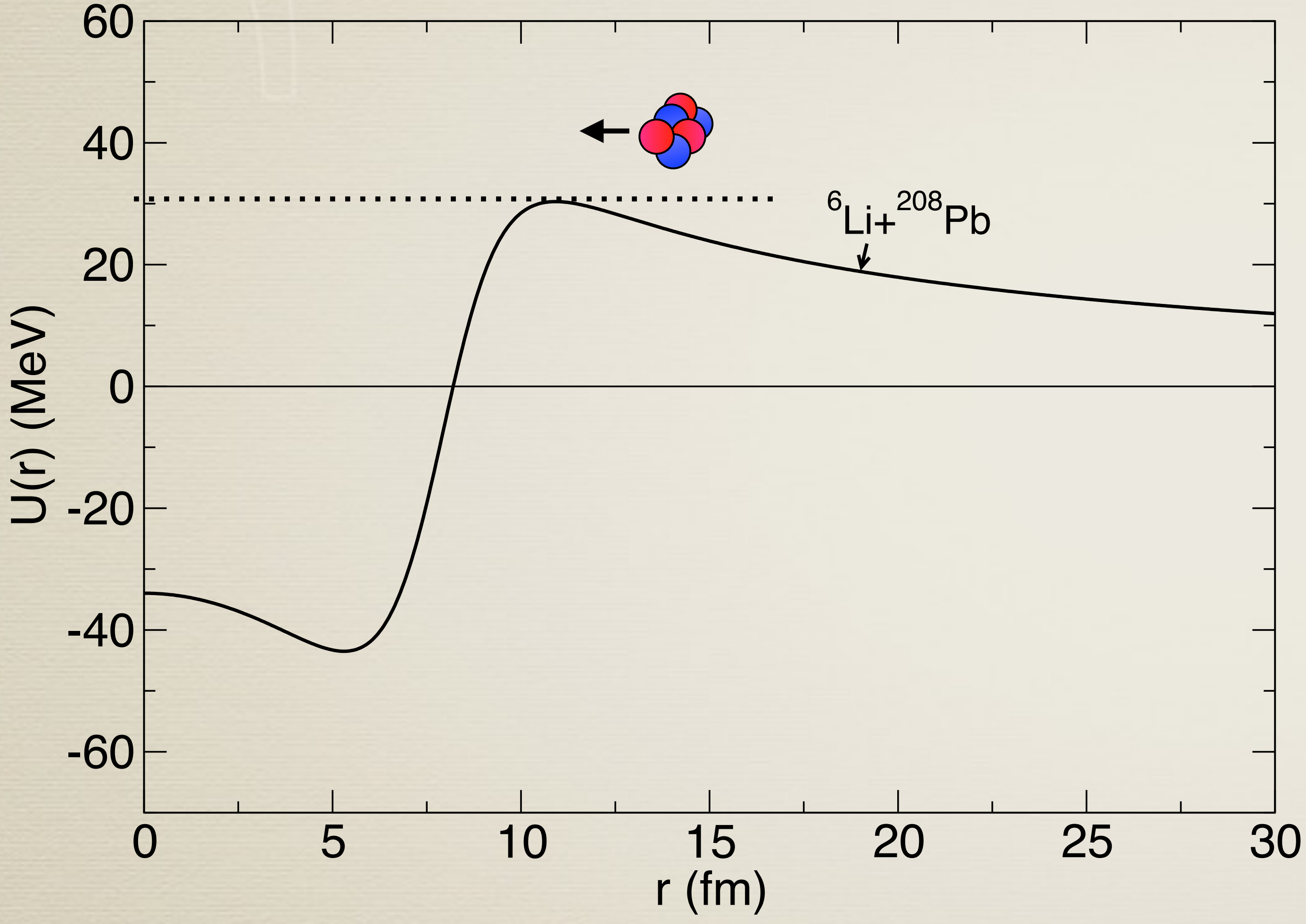

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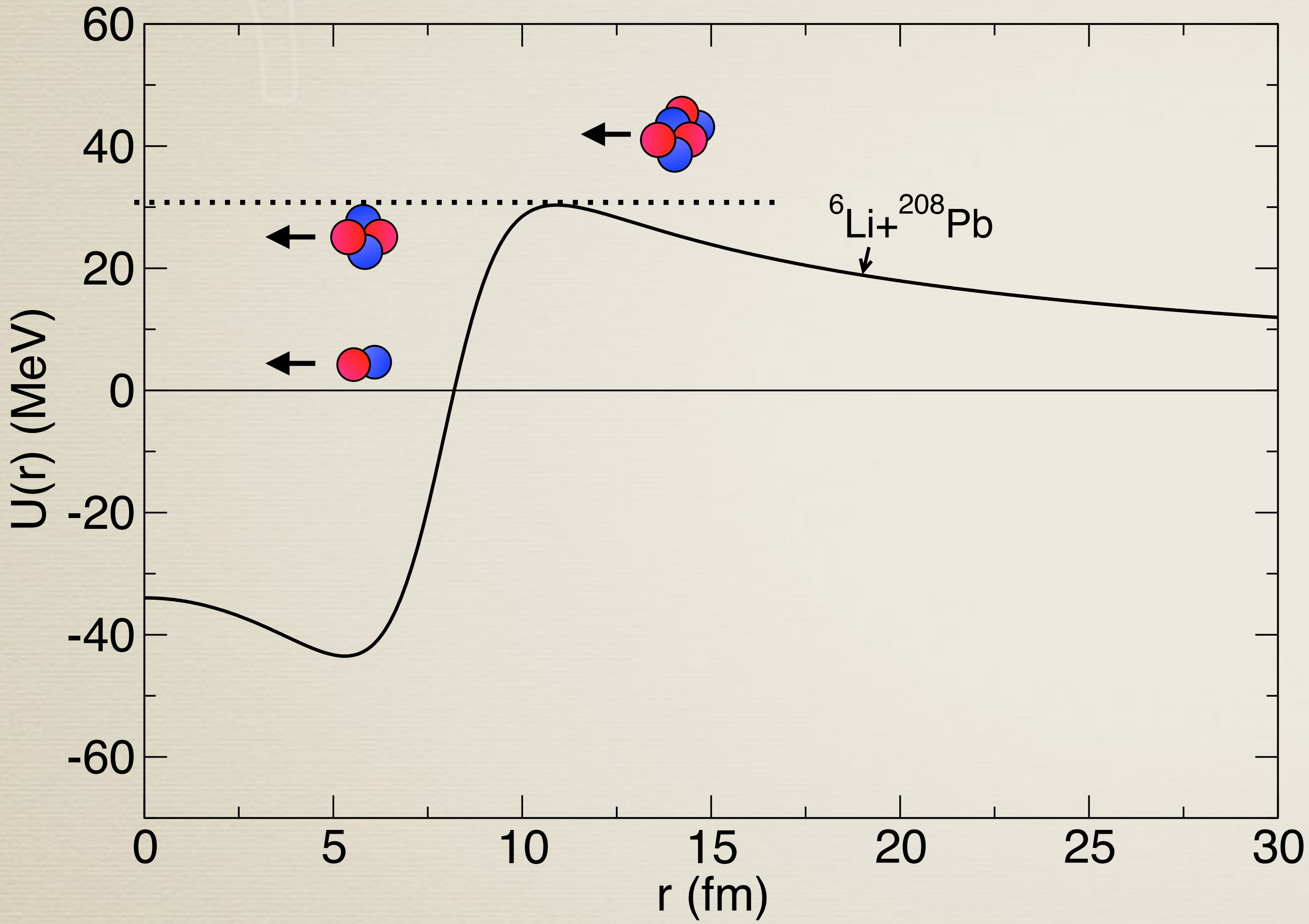

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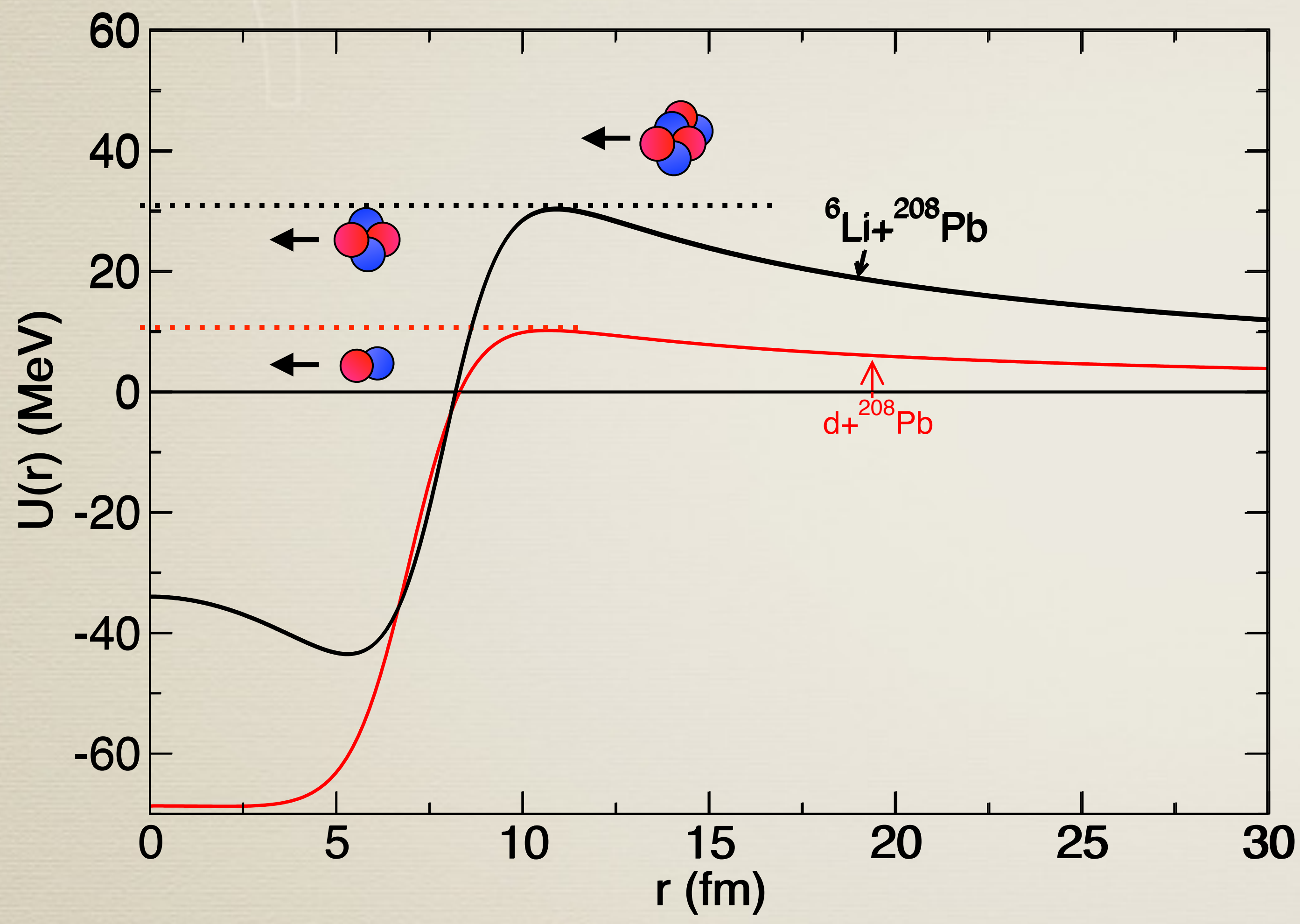

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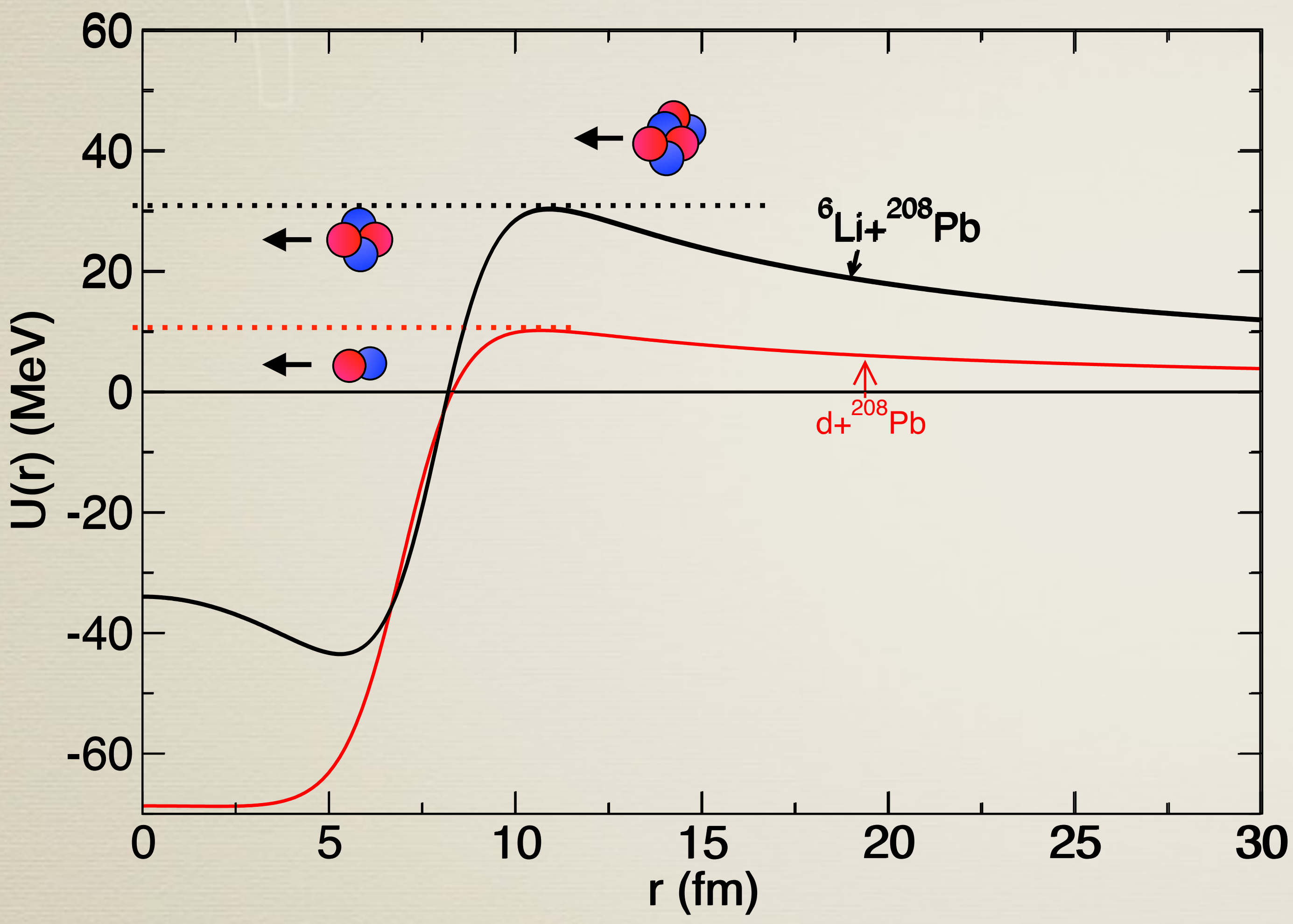

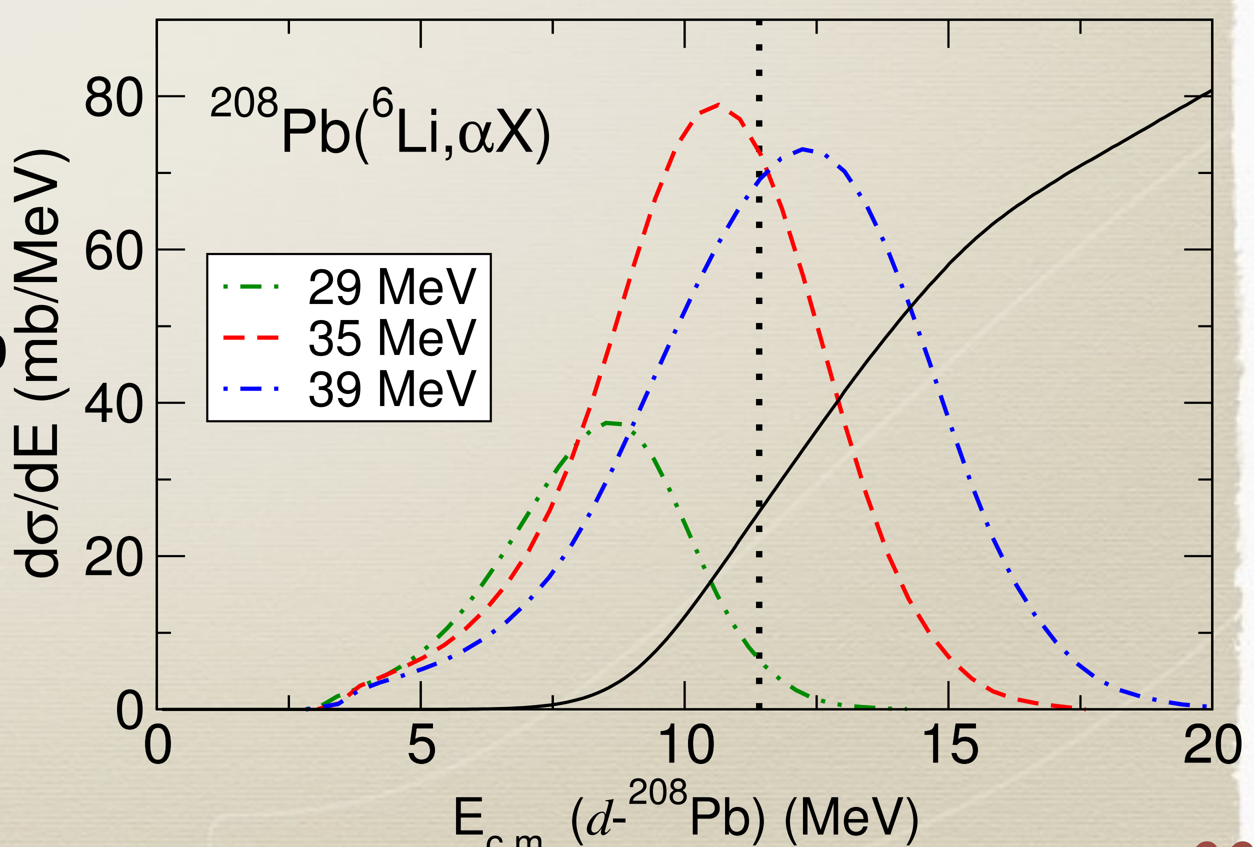

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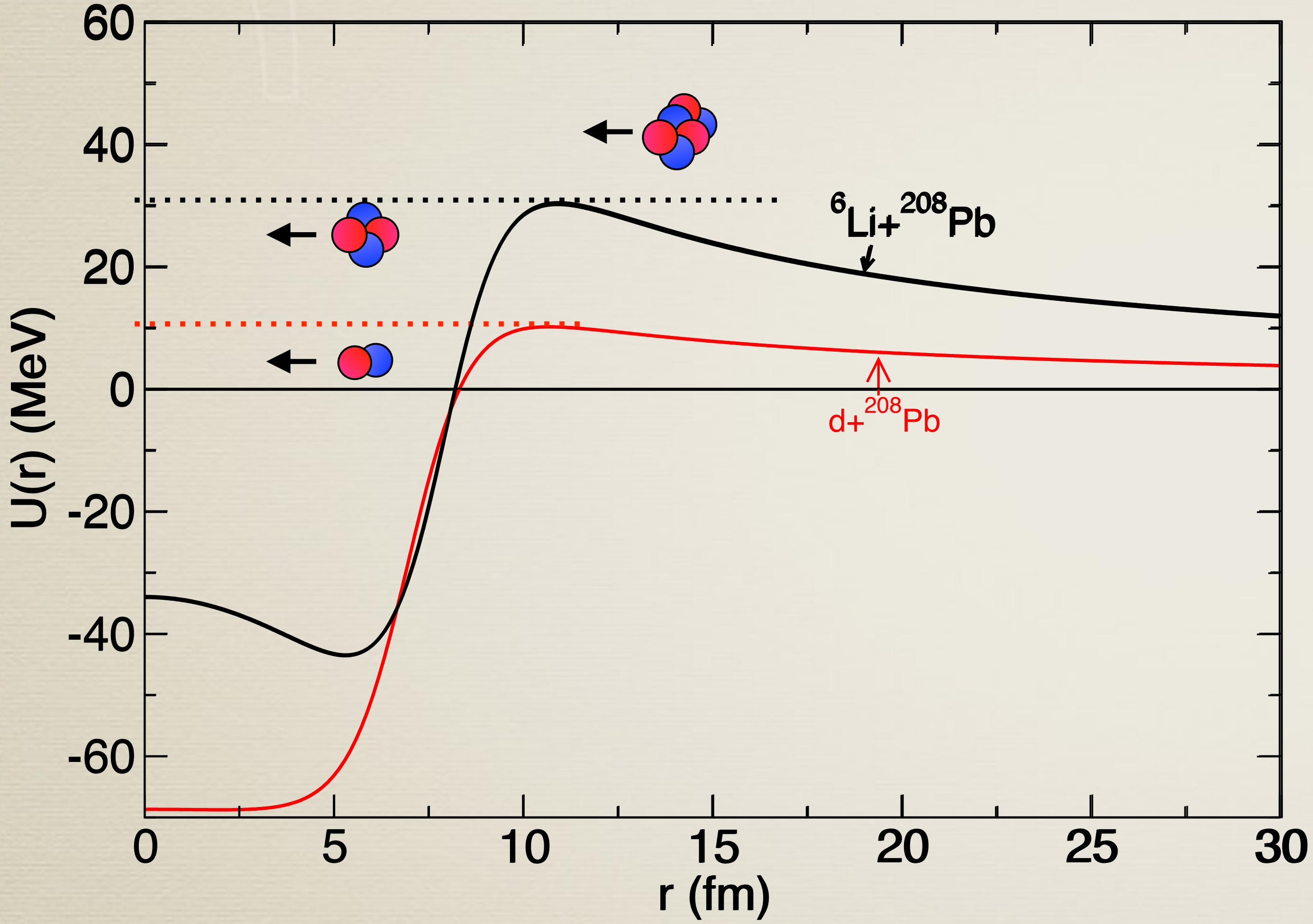

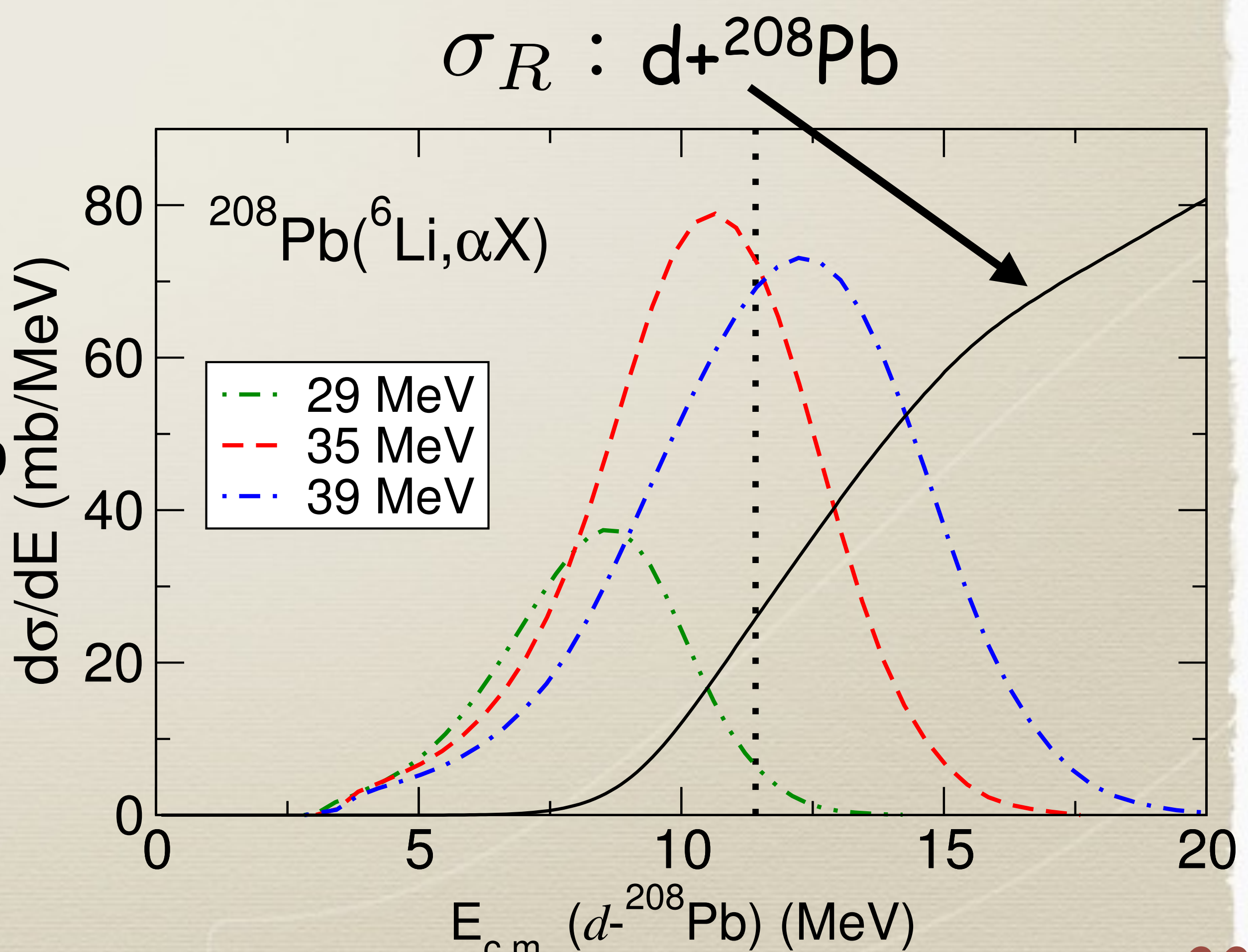

Summary and Perspectives

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Summary

* Our calculations show a overall agreement with the experimental data
* For non-halo projectile (d,^{6}Li,^{7}Li,^{7}Be), the inclusive breakup is dominated by NEB
* Relative importance between NEB and EBU depends on incident energy and projectile binding energy
* For halo nuclei (^{11}Be, ^{8}B), the EBU is found to be dominant.

Perspectives

* Extend the model beyond DWBA
  * CDCC or Faddeev description of incident channel
* Inclusion of deformation of projectile ((10Be*)11Be)
* Deep understanding of ICF and its application to surrogate reaction
* Extension to 3-body projectiles (^{9}Be->a+a+n)

Thank you for your attention!!!