Description of transfer reactions with coupled-channels Born approximation

Tokuro Fukui

Nuclear Data Center, Japan Atomic Energy Agency

in collaboration with
Y. Kanada-En'yo, Y. Kikuchi, T. Matsumoto,
K. Ogata, T. Suhara, Y. Taniguchi, and M. Yahiro

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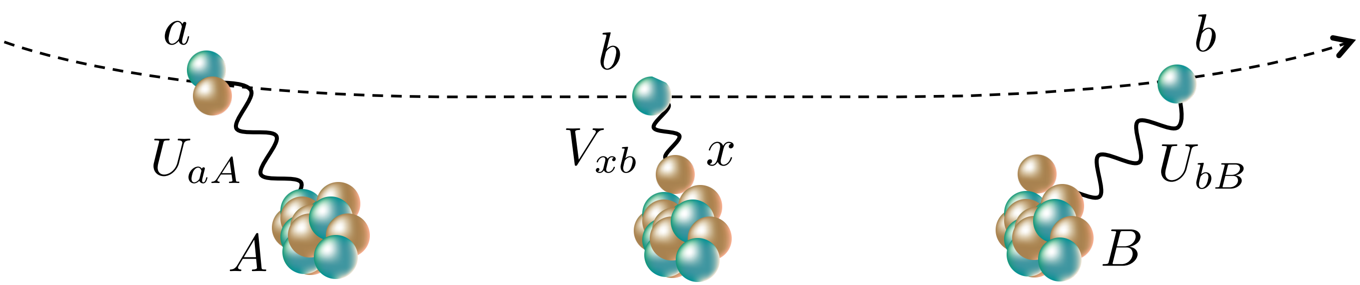
Description of transfer reactions (conventional approach)

✓ The transition matrix for the $A(a, b)B$ reaction within the **distorted-wave Born approximation (DWBA)**.

$$T_{\mathrm{DWBA}} = \left\langle \Psi_\beta^{(-)} \middle| V_{xb} \middle| \Psi_\alpha^{(+)} \right\rangle$$



✓ **The optical potential** U_{aA} (U_{bB}) for the $a + A$ ($b + B$) **2-body system** generates the distorted wave.

✓ **One-step transition** induced by the residual interaction V_{xb} (V_{xA}) for the post (prior) form is assumed.

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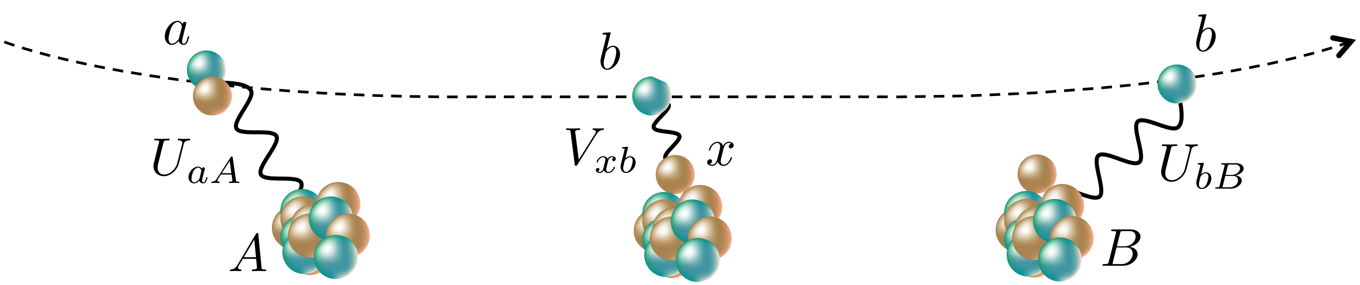

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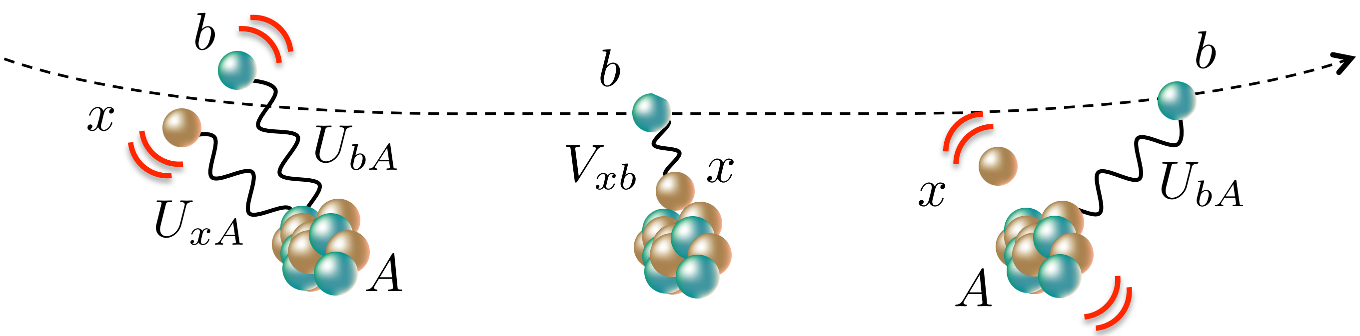
Can DWBA describe the reaction even if a or B is **loosely bound system**?

Beyond DWBA

M. Kamimura *et al.*, Prog. Theor. Phys. Suppl. No. 89, 1 (1986).
N. Austern *et al.*, Phys. Rep. **154**, 125 (1987) .
M. Yahiro *et al.*, Prog. Theor. Exp. Phys. **2012**, 01A209 (2012).

- ✓ **Coupled-channels Born approximation (CCBA)** with **the continuum-discretized coupled-channels (CDCC)** method.

$$T_{\mathrm{CCBA}} = \left\langle \Psi^{(-)}_{\beta(\mathrm{CDCC})} \middle| V_{xb} \middle| \Psi^{(+)}_{\alpha(\mathrm{CDCC})} \right\rangle$$



- ✓ **The optical potential** U_{xA} (U_{bA}) for the subsystem $x + A$ ($b + A$) generates the distorted wave based on the **3-body model**.

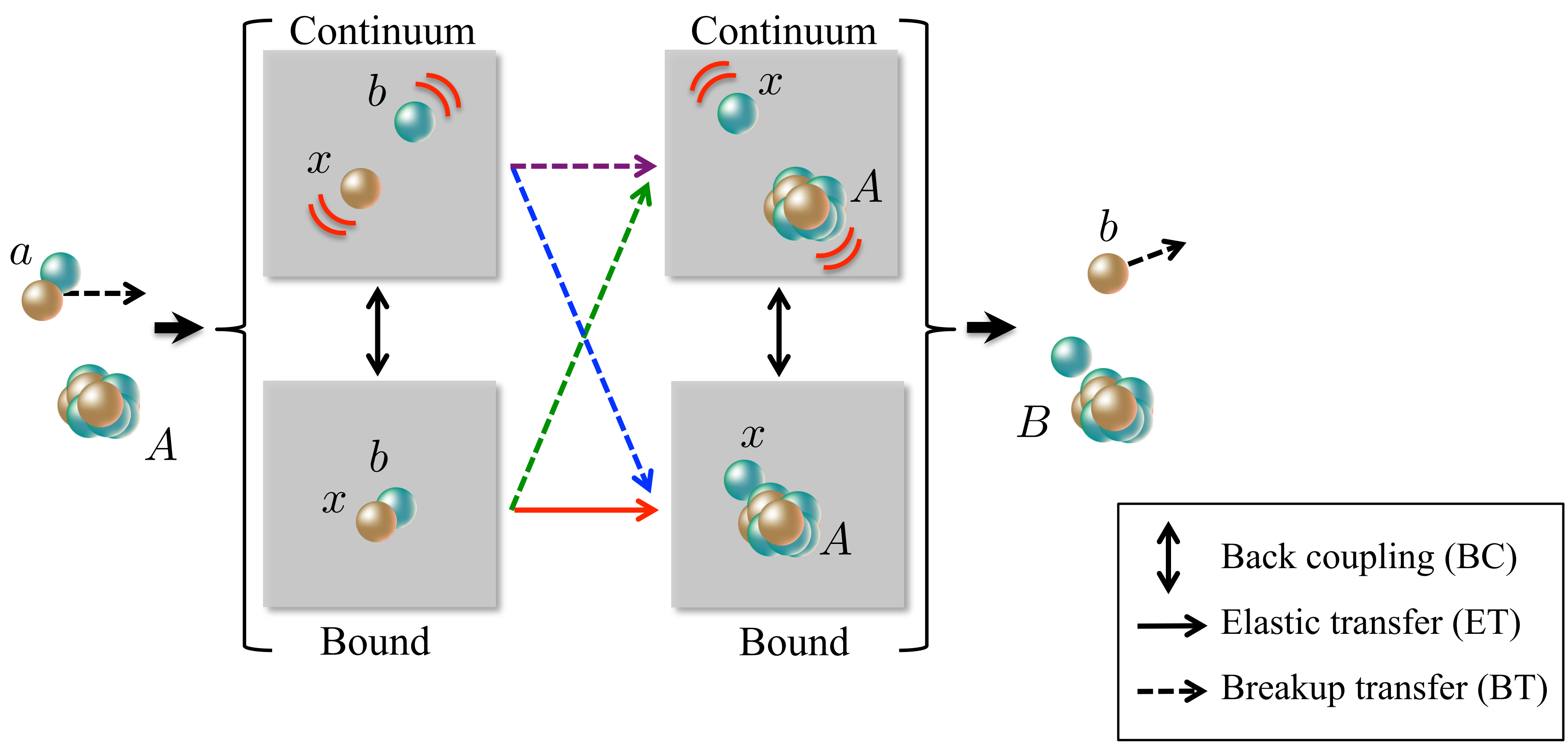
- ✓ **The CDCC wave functions both in the initial and final channels**.
  → **Remnant term** is canceled out exactly.
  → **Rearrangement component** is involved implicitly.

A. M. Moro *et al.*, Phys. Rev. C **80**, 064606 (2009).

Breakup process

✓ Decomposition of the transition matrix

$$T_{\mathrm{CCBA}} = T_{\beta(\mathrm{el}),\alpha(\mathrm{el})} + T_{\beta(\mathrm{el}),\alpha(\mathrm{br})} + T_{\beta(\mathrm{br}),\alpha(\mathrm{el})} + T_{\beta(\mathrm{br}),\alpha(\mathrm{br})}$$

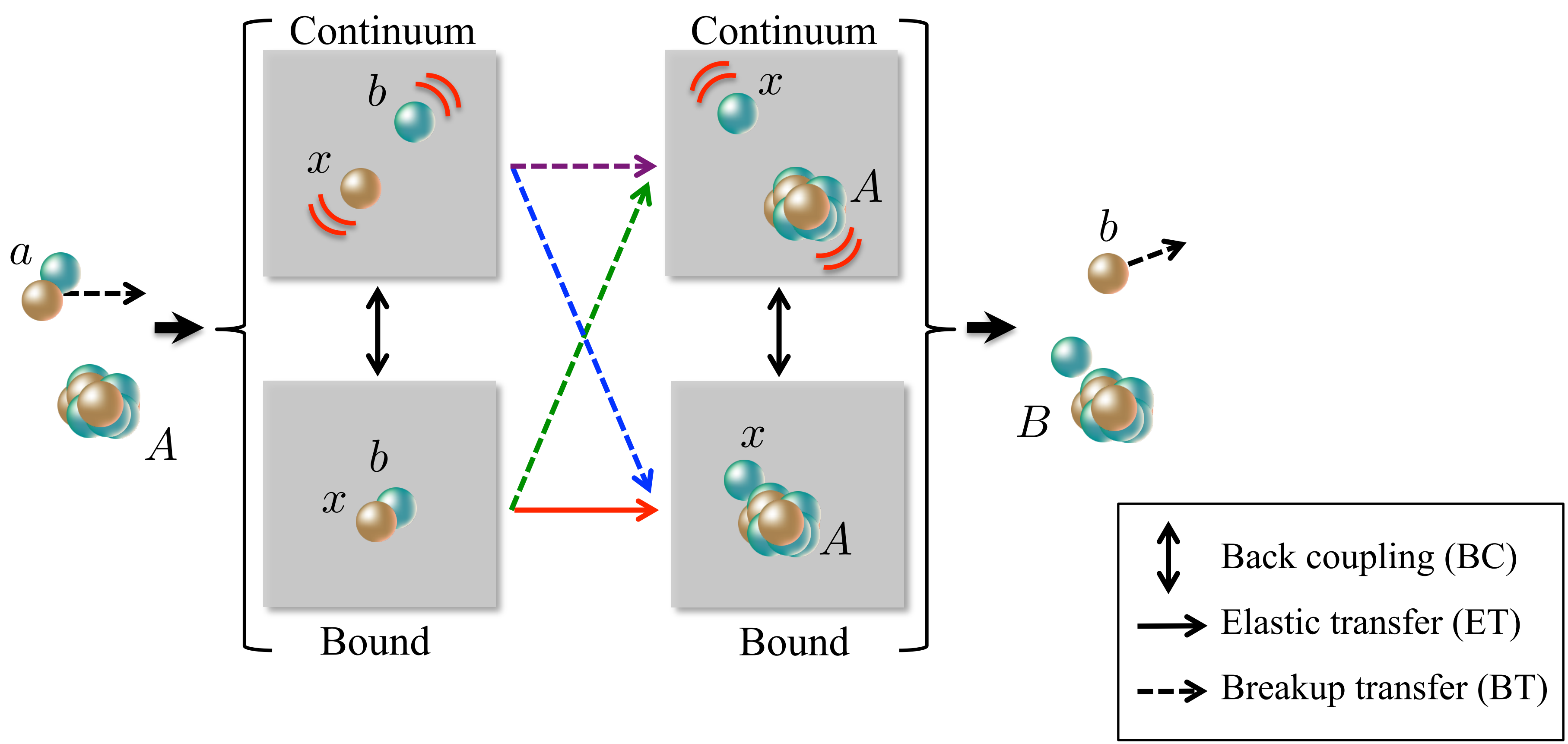


Breakup process

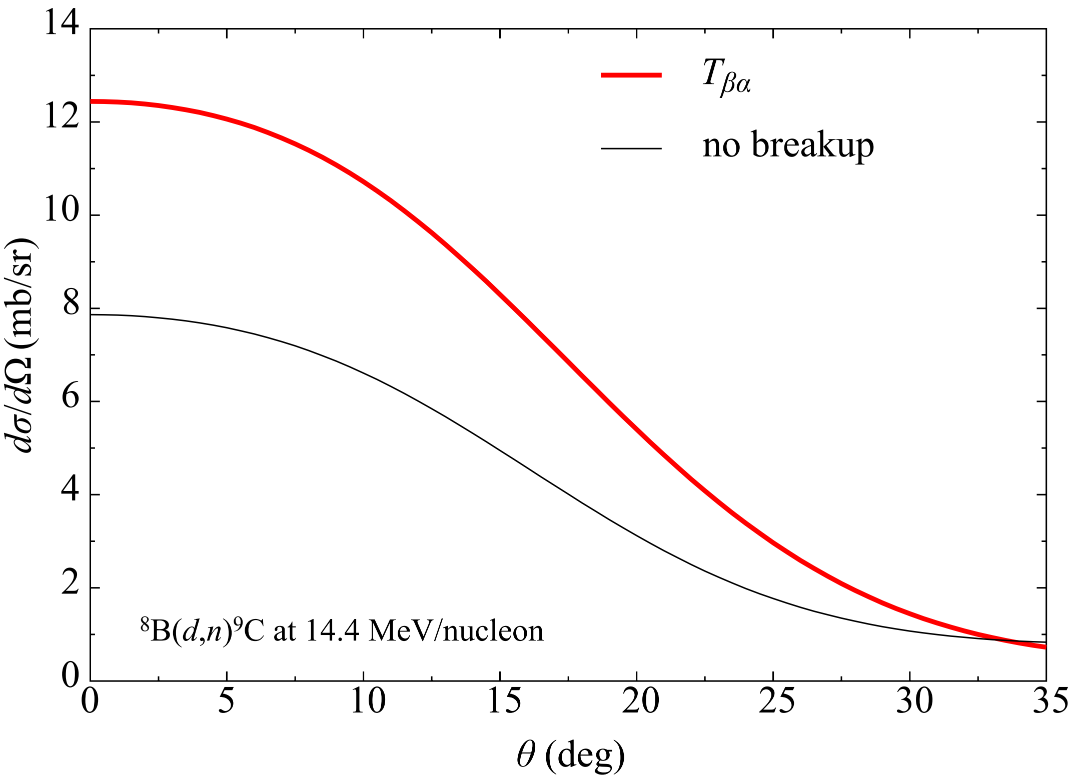
✓ BC is implicitly taken into account in DWBA as "absorption".
✓ BT is never involved in DWBA.

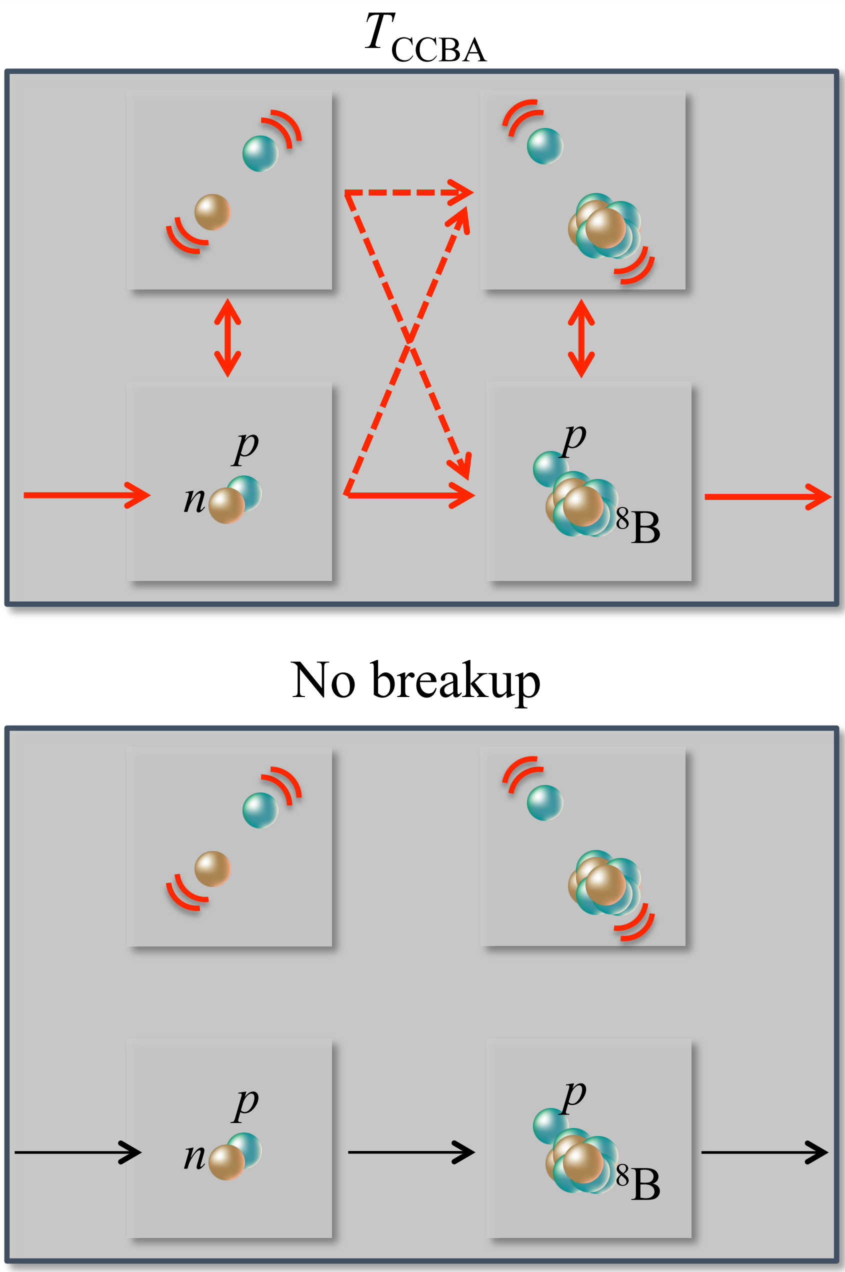
✓ Decomposition of the transition matrix

$$T_{\mathrm{CCBA}} = T_{\beta(\mathrm{el}),\alpha(\mathrm{el})} + T_{\beta(\mathrm{el}),\alpha(\mathrm{br})} + T_{\beta(\mathrm{br}),\alpha(\mathrm{el})} + T_{\beta(\mathrm{br}),\alpha(\mathrm{br})}$$



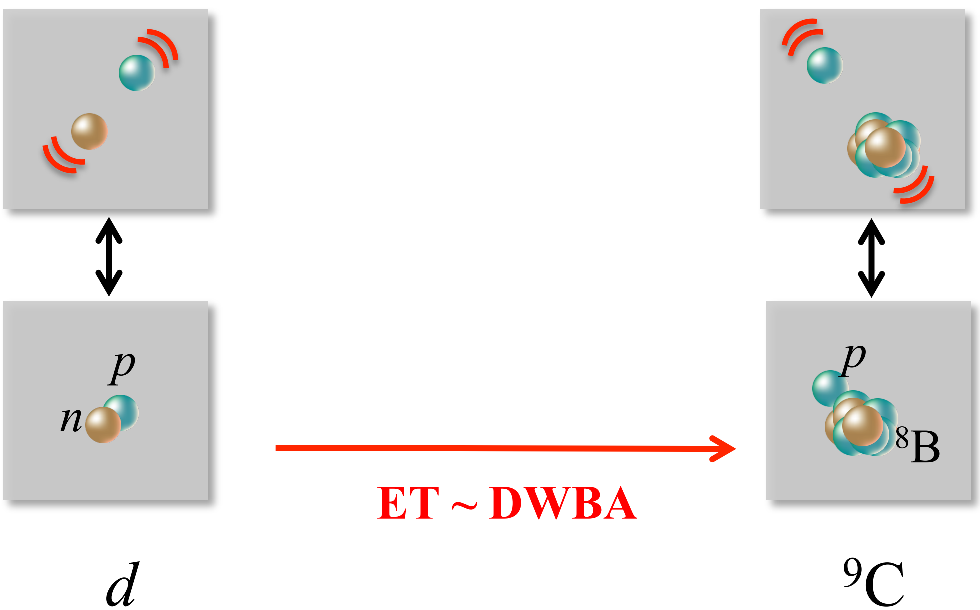
Breakup effect on ^{8}B(d, n)^{9}C

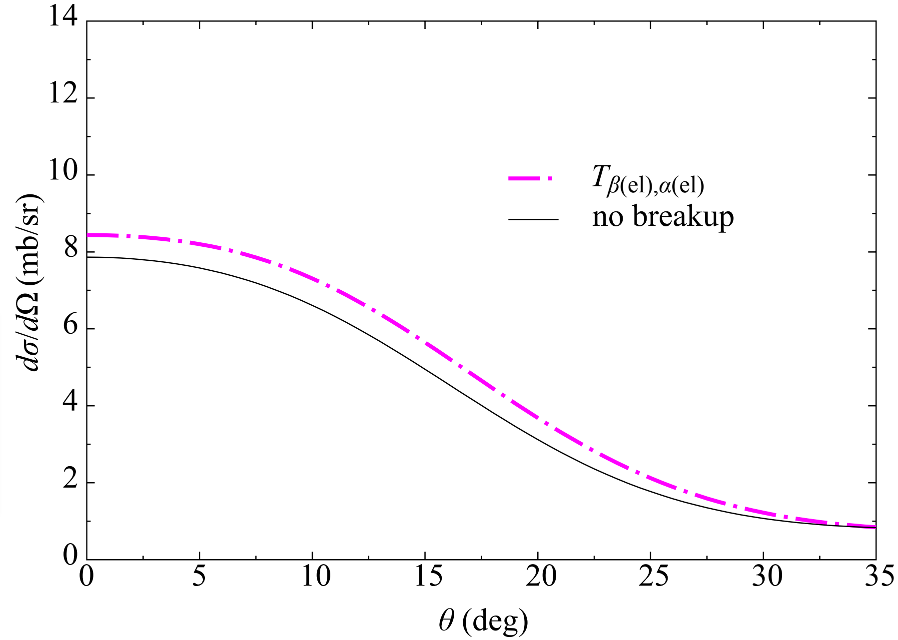




- ✓ The ^{8}B(d, n)^{9}C reaction is paid attention with astrophysical interest.
- ✓ Significant breakup effect (**58%**) can be seen at the forward angles of the angular distribution of the cross section.

Breakup effects of each path



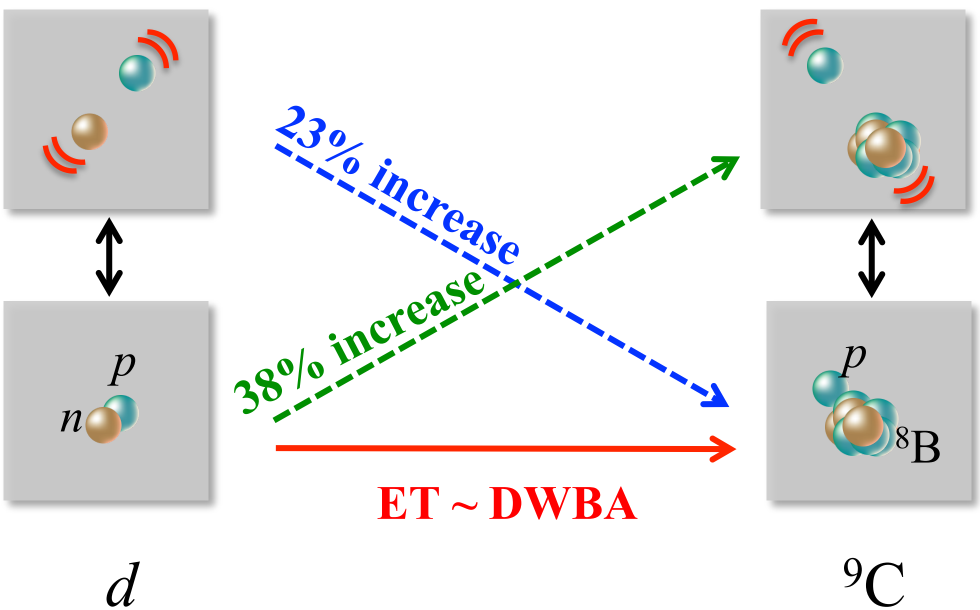


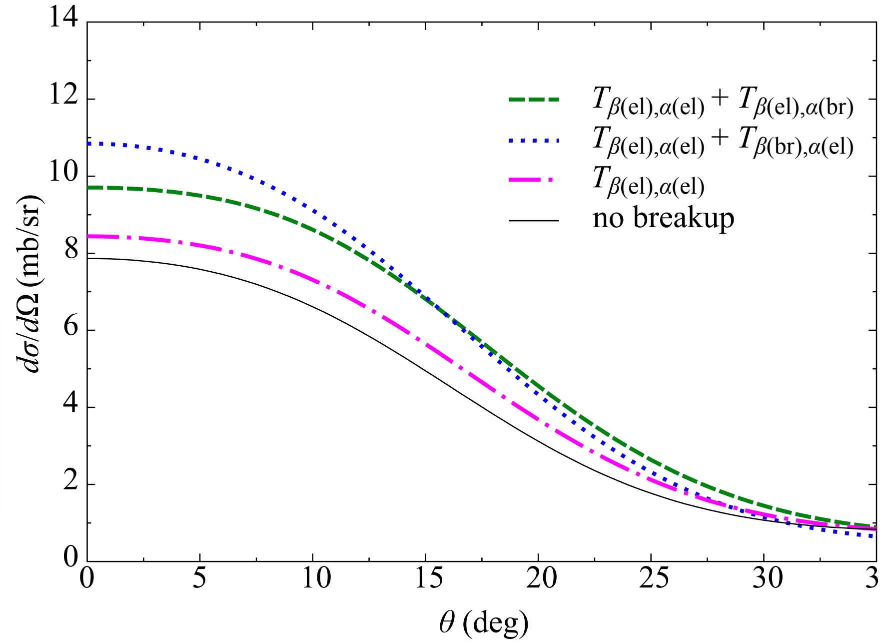
✓ The BC is weak and the ET result can be regarded as that of DWBA.

Result 1

T. Fukui *et al.*, Phys. Rev. C **91**, 014604 (2015).

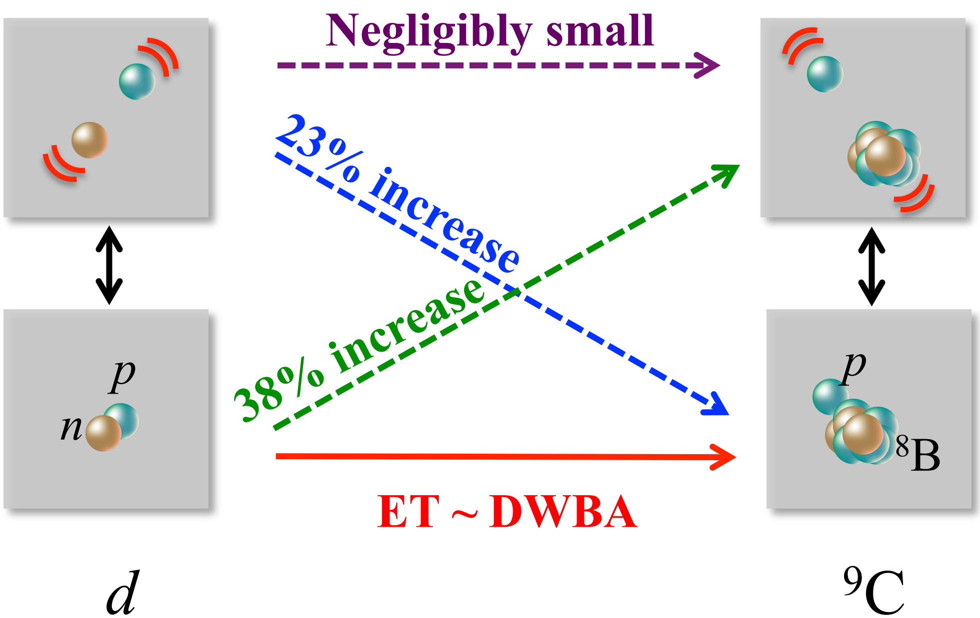
Breakup effects of each path

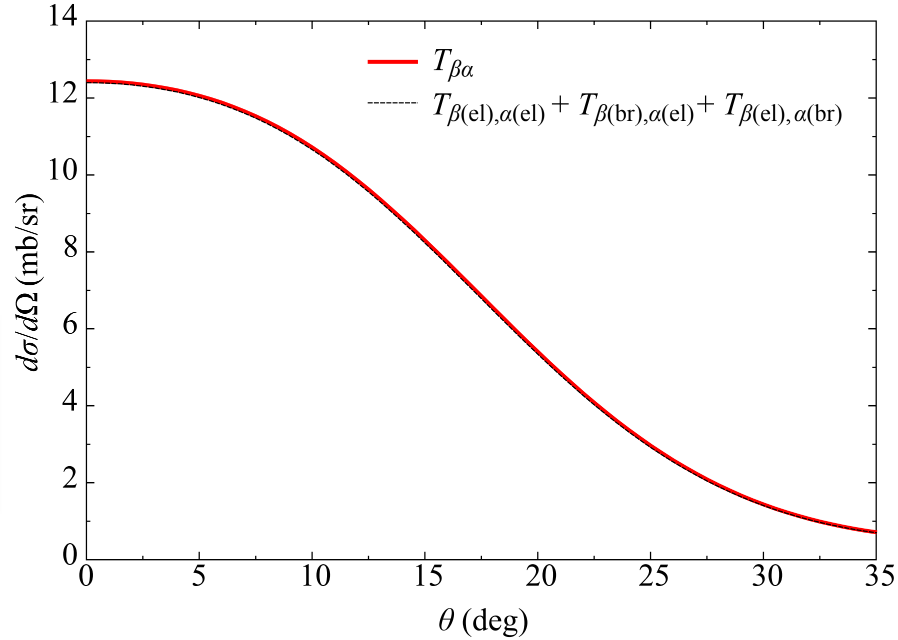




- ✓ The BC is weak and the ET result can be regarded as that of DWBA.
- ✓ Strong interferences between the ET and the BT in each channel enhance the cross section. → **Never involved in DWBA**.

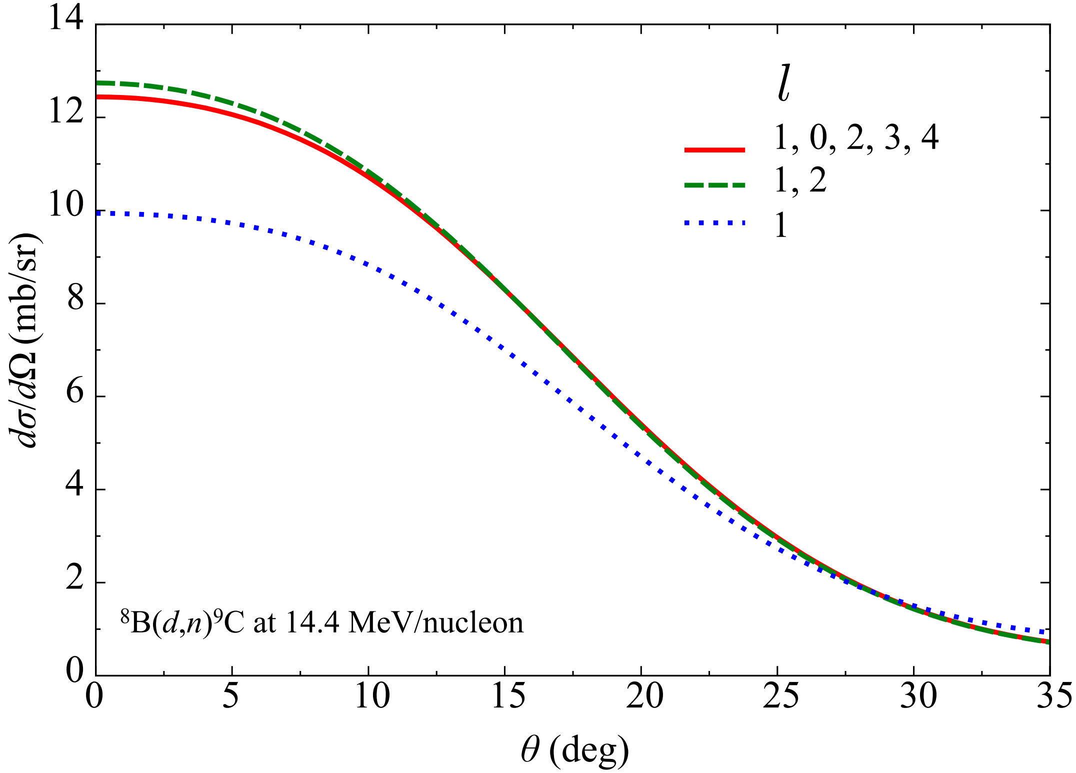
Breakup effects of each path

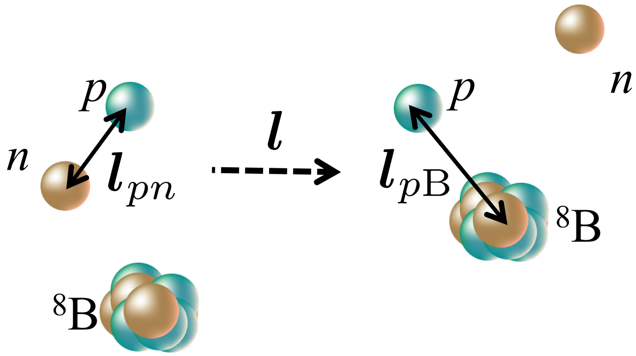




- ✓ The BC is weak and the ET result can be regarded as that of DWBA.
- ✓ Strong interferences between the ET and the BT in each channel enhance the cross section. → **Never involved in DWBA**.
- ✓ The BT among continuum states is negligible.

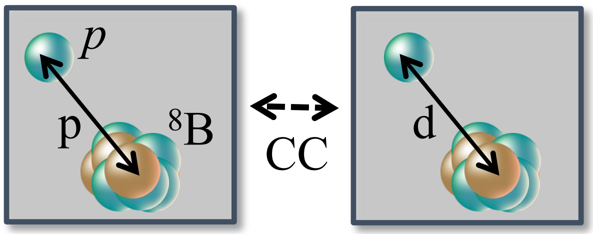
Dynamical change of transferred angular momentum *l*





$$l = l_{pB} \quad (l_{pn} = 0)$$

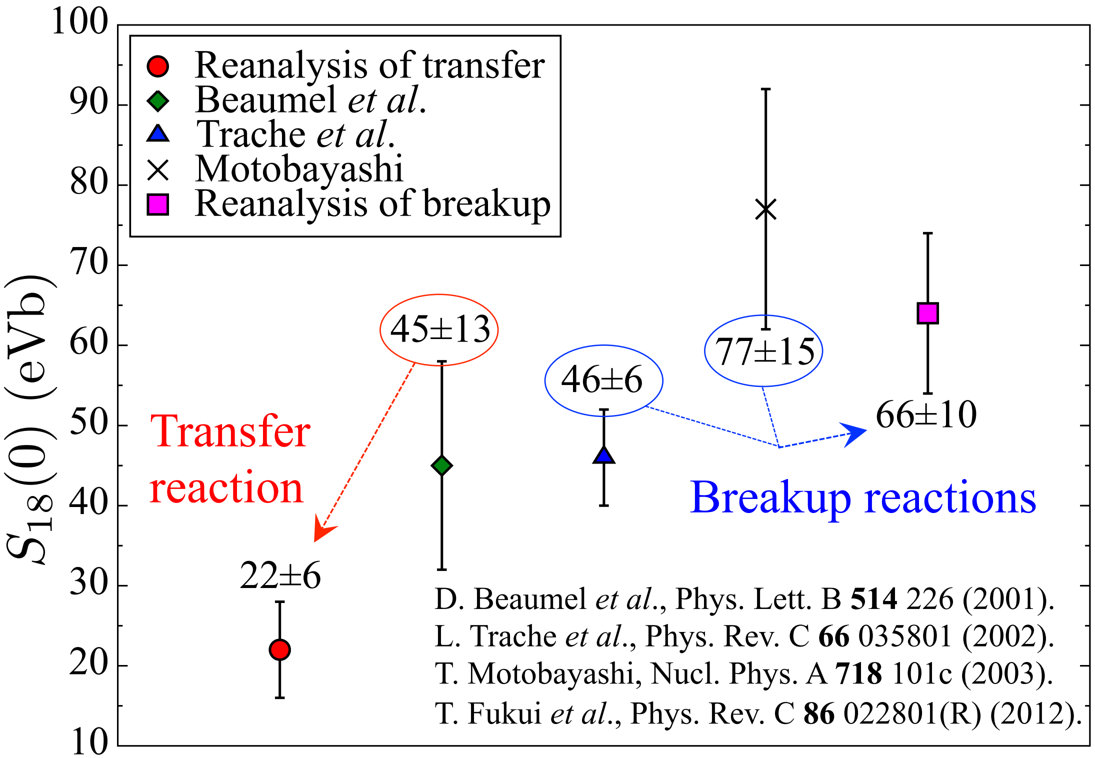
DWBA: *l* = 1 (unique)
CCBA: *l* can dynamically change

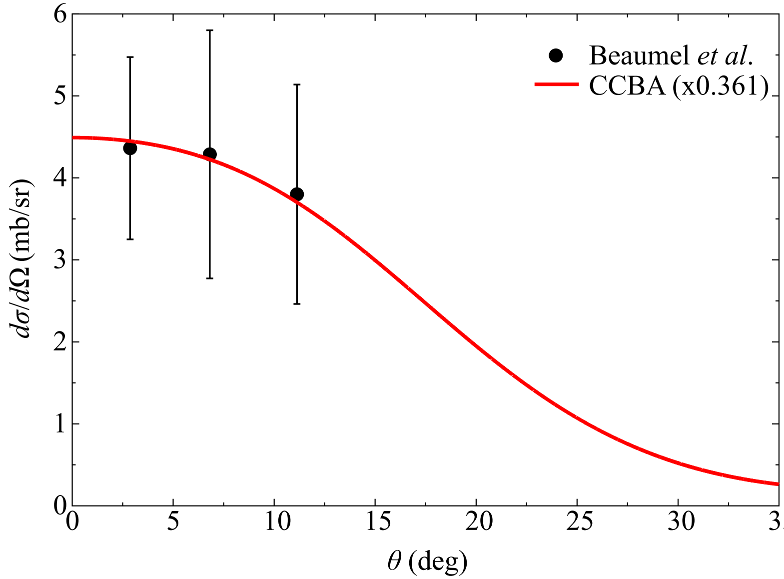


✓ A **25%** increase due to CC with the d-wave of ^{9}C is confirmed.

Breakup effect on S_{18} of ^{8}B(p, γ)^{9}C

$$S_{18}(\varepsilon_{p\mathrm{B}}) = \sigma_{p\gamma}(\varepsilon_{p\mathrm{B}})\varepsilon_{p\mathrm{B}} \exp[2\pi\eta]$$





What we can say is that the breakup effect enhances the transfer cross section.

Future work

(1) Inclusion of the 3-body configuration in ^{9}C ($p + p +$ ^{7}Be).
(2) The CCBA analysis of the mirror reaction ^{8}Li(d, p)^{9}Li.

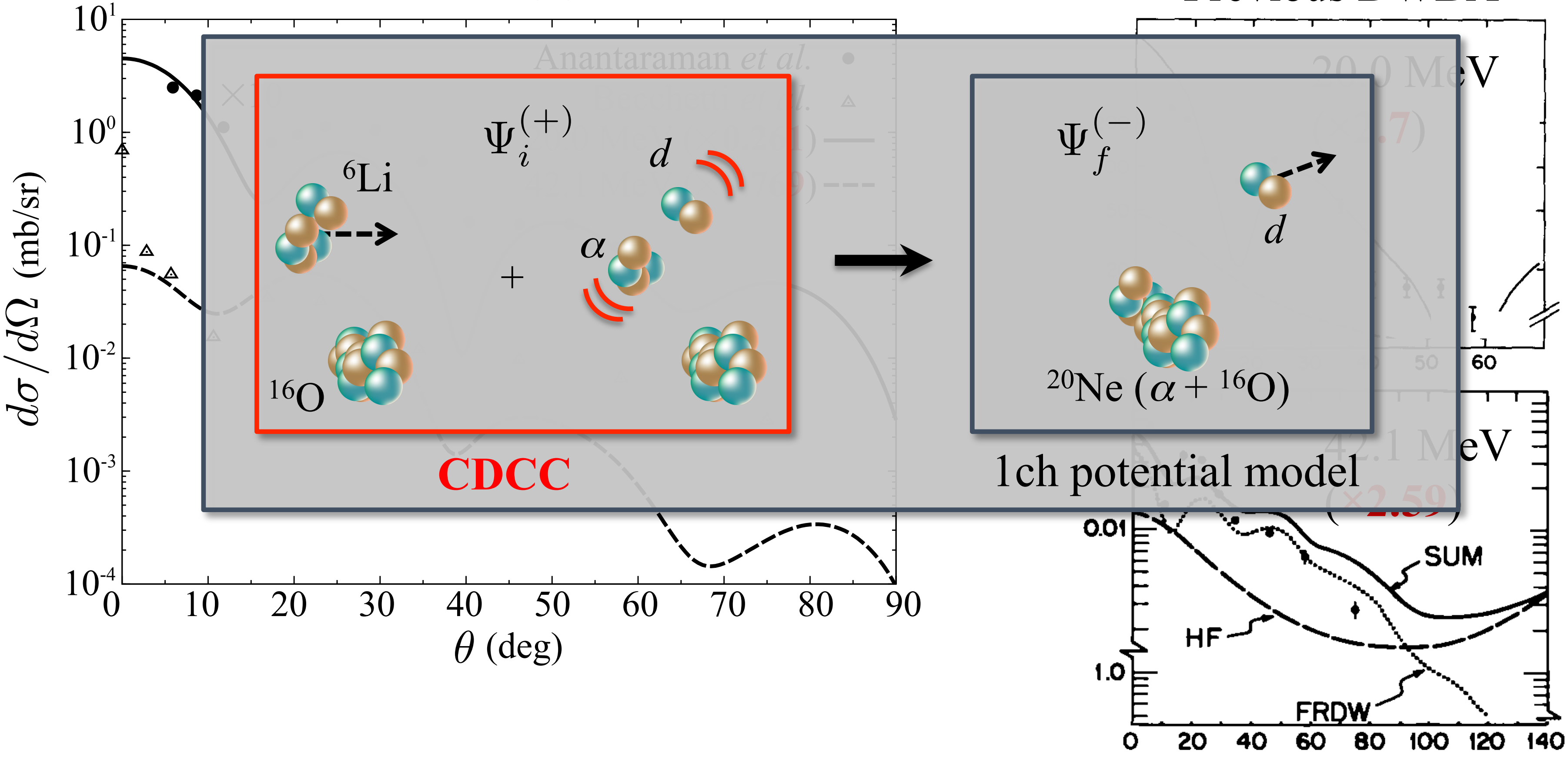
[12] B. Guo *et al.*, Nucl. Phys. **A761**, 162 (2005).

Result 2 T. Fukui *et al.*, Phys. Rev. C **93**, 034606 (2016).

^{16}O(^{6}Li, *d*)^{20}Ne(g.s.) to search surface manifestation of cluster

Present CCBA

Previous DWBA



N. Anantaraman *et al.,* Nucl. Phys. **A313**, 445 (1979).
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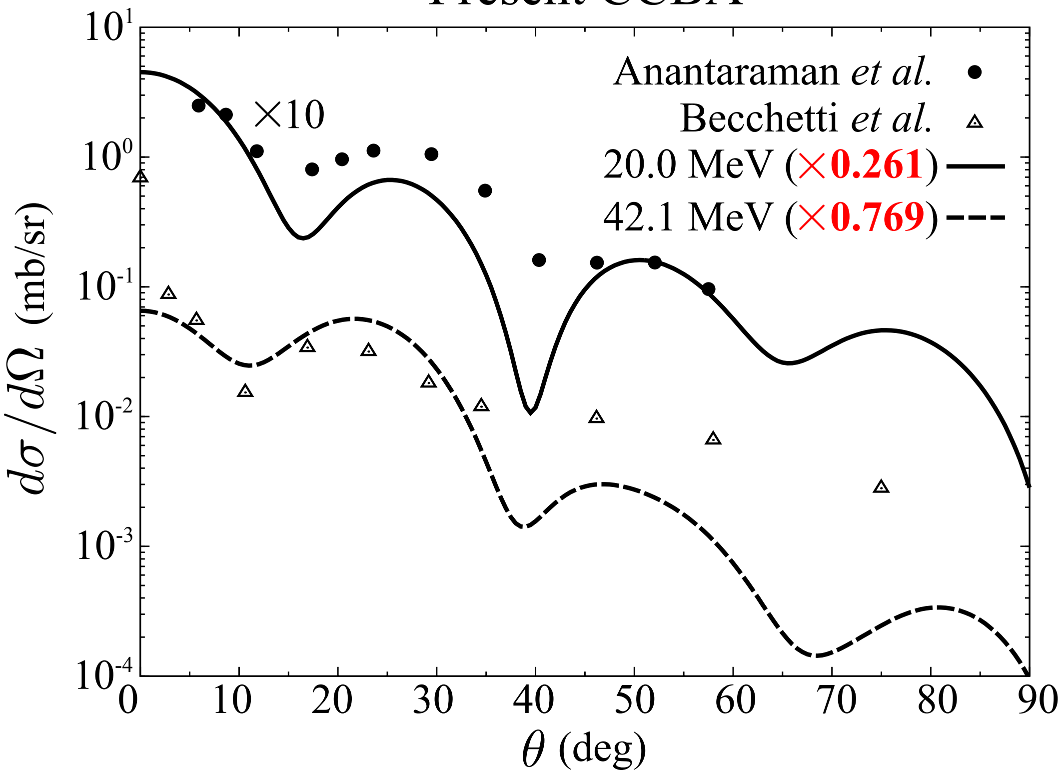
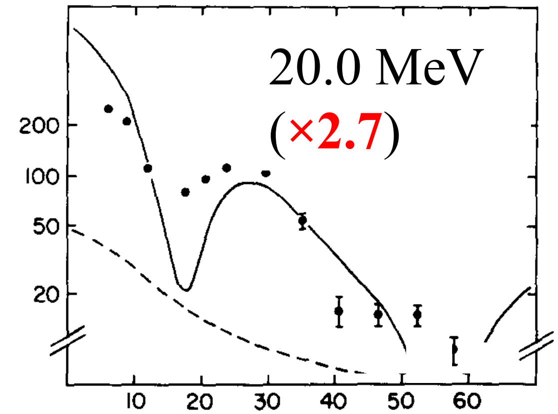
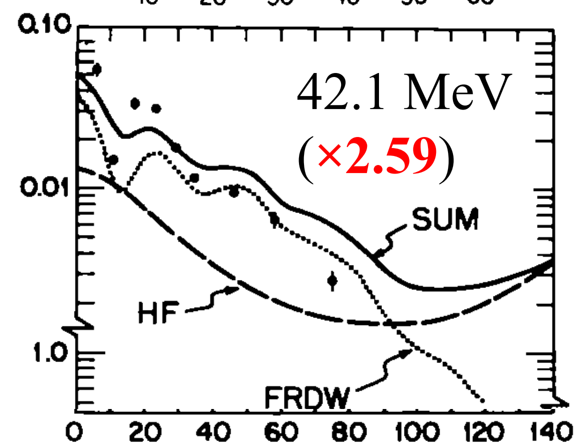


Previous DWBA





Improvement

(1) Diffraction pattern of the 1st and 2nd peaks

(2) Reasonable values of the normalization factors

→ Governed by reliabilities of both **the α-^{16}O WF** and **OMP**

N. Anantaraman *et al.*, Nucl. Phys. **A313**, 445 (1979).
F. D. Becchetti *et al.*, Nucl. Phys. **A303**, 313 (1978).

Result 2

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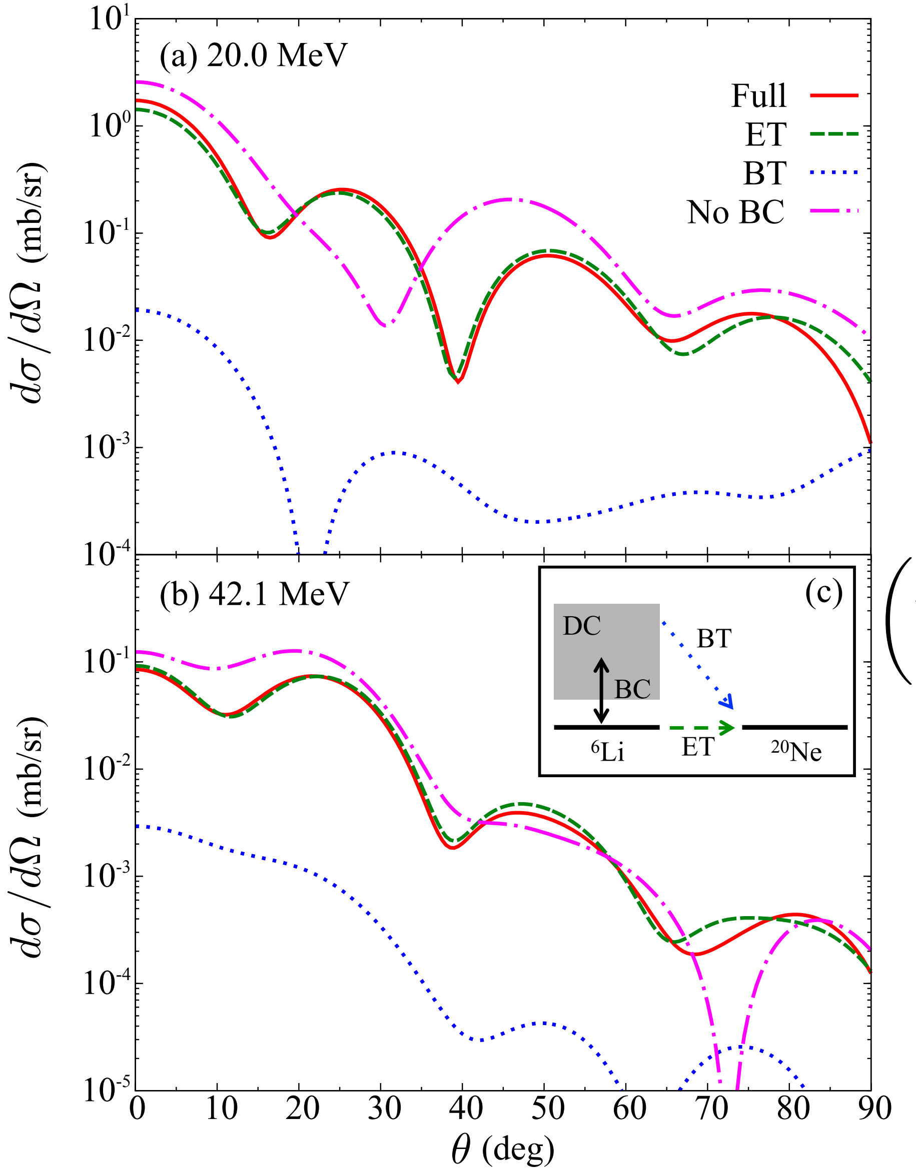
Breakup effects of ^{6}Li



✓ Decomposition of the CDCC distorted wave into **elastic** and **breakup** channels.

$$\chi_{\rm CDCC}(\boldsymbol{r}_i) = \underline{\chi_0(\boldsymbol{r}_i)} + \underline{\chi_c(\boldsymbol{r}_i)}$$

✓ **Full** ~ **Elastic transfer (ET)** ≠ **No back coupling (BC)**

→ **Breakup transfer (BT)** is negligible. **Only the BC** (CC due to off-diagonal potentials) is essential.

$$\begin{pmatrix} K_i + U_{00} - E_0 & U_{0c} \\ U_{c0} & K_i + U_{cc} - E_c \end{pmatrix} \begin{pmatrix} \chi_0 \\ \chi_c \end{pmatrix} = 0$$

→ DWBA can provide reasonable results, if an appropriate ^{6}Li-OMP, in which BC is implicitly taken into account as its imaginary part, is given.

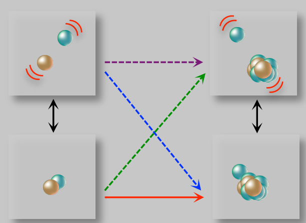
T. Fukui *et al.*, Prog. Theor. Phys. 125, 1193 (2011)
T. Fukui *et al.*, Phys. Rev. C **91**, 014604 (2015).

CCBA analyses

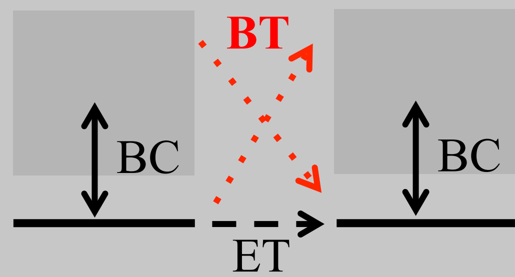
$^{8}B(d, n)^{9}C$

$^{16}O(^{6}Li, d)^{20}Ne$

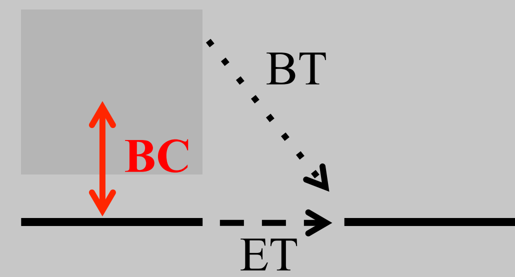
Analyses of $^{8}B(d, n)^{9}C$ and $^{16}O(^{6}Li, d)^{20}Ne$ with **CCBA**



Small BC effect.
The BT is important.



Only the BC plays an important role.



Why is the breakup effect large?

Why opposite?

→ **Explained in detail in T. Fukui *et al*., Phys. Rev. C 91, 014604 (2015).**

Transfer reaction to unbound state (ex. ^{4}He(d, p)^{5}He)

✓ The transition matrix of the post-form representation for (d, p) reaction

$$T_{\rm DWBA}^{\rm (post)} = \left\langle \chi_\beta^{(-)} \psi_n \middle| V_{pn} \middle| \psi_d \chi_\alpha^{(+)} \right\rangle$$

$$= \int d\boldsymbol{r}_\alpha \int d\boldsymbol{r}_d \chi_\beta^{*(-)}(\boldsymbol{r}_\alpha, \boldsymbol{r}_d) \underbrace{\psi_n^*(\boldsymbol{r}_\alpha, \boldsymbol{r}_d)}_{\text{oscillate}} \underbrace{V_{pn}(\boldsymbol{r}_d)\psi_d(\boldsymbol{r}_d)}_{\text{attenuate}} \chi_\alpha^{(+)}(\boldsymbol{r}_\alpha).$$

The r_α integration does not converge.

✓ **The prior form**

$$T_{\rm DWBA}^{\rm (prior)} = \left\langle \tilde{\chi}_\beta^{(-)} \psi_n \middle| V_{n\alpha} \middle| \psi_d \chi_\alpha^{(+)} \right\rangle$$

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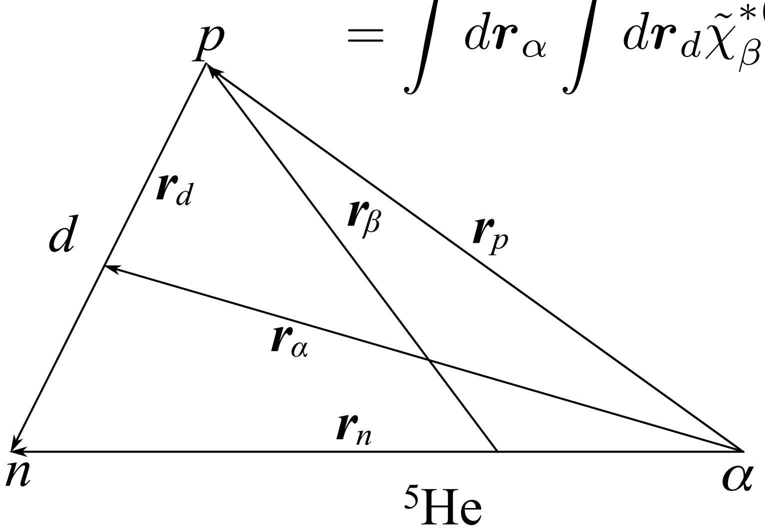

These respectively attenuate for two independent coordinates.
→ The integration does converge.

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oscillate attenuate

The r integration does not converge.

> The distorted wave $\tilde{\chi}_\beta^{(-)}$ should be exact.
>
> → **The CCBA approach is necessary** for the final channel.
>
> $$T_{\rm DWBA}^{\rm (prior)} \to T_{\rm CCBA}^{\rm (prior)}$$

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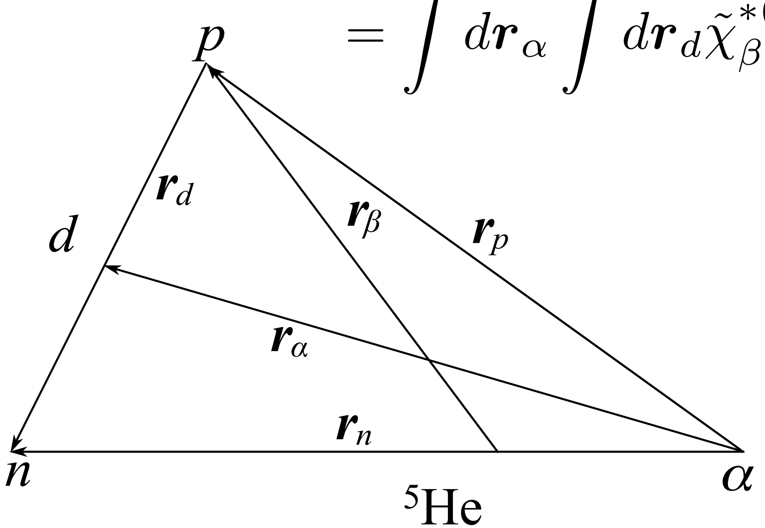

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→ **The integration does converge.**