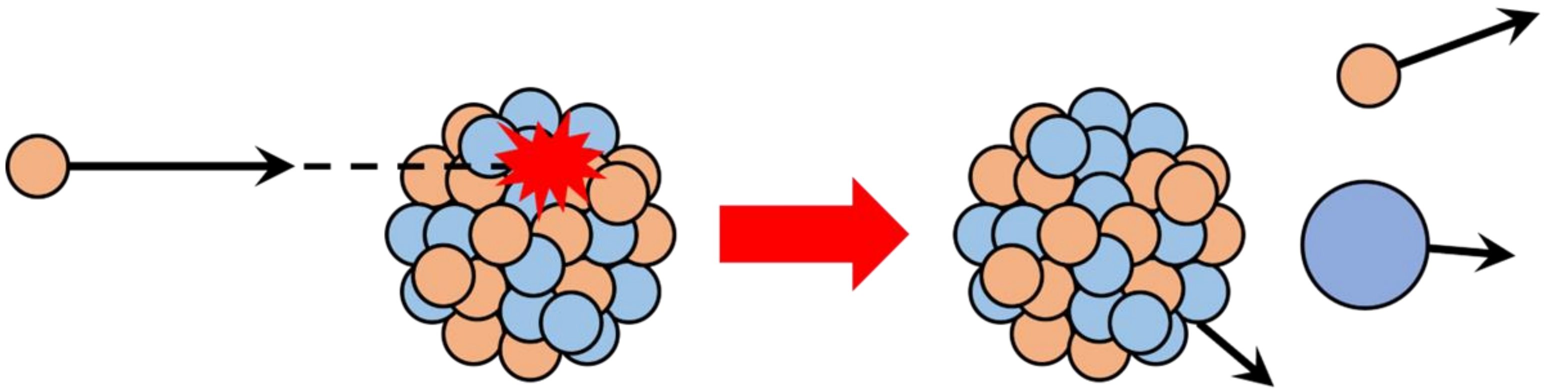
Maris polarization in deuteron knockout reactions

<u>Yoshiki Chazono</u> (Kyushu Univ.)

<u>Acknowledgements</u>:
Shoya Ogawa (Kyushu Univ.)
Kazuki Yoshida (ASRC, JAEA)
Kazuyuki Ogata (Kyushu Univ. / RCNP, Osaka Univ.)

24th – 29th June 2024 DREB2024 @ Wiesbaden, Germany

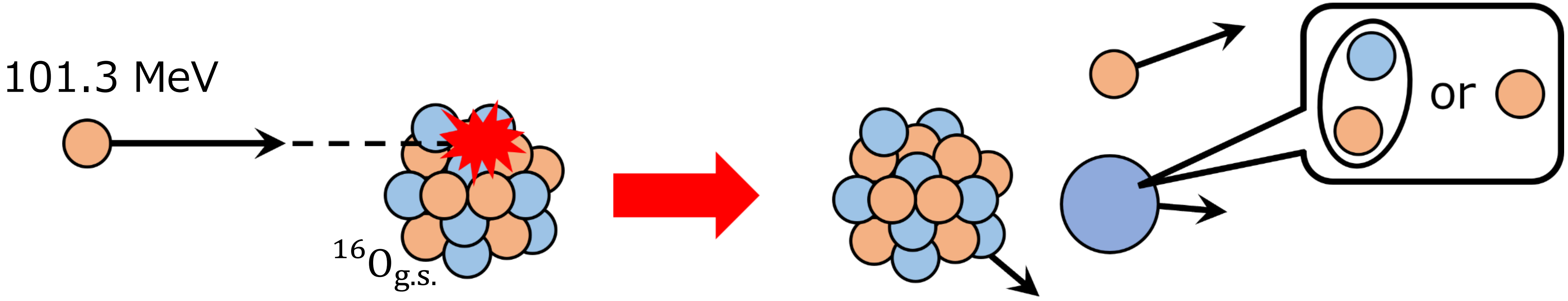
What proton-induced knockout reaction is



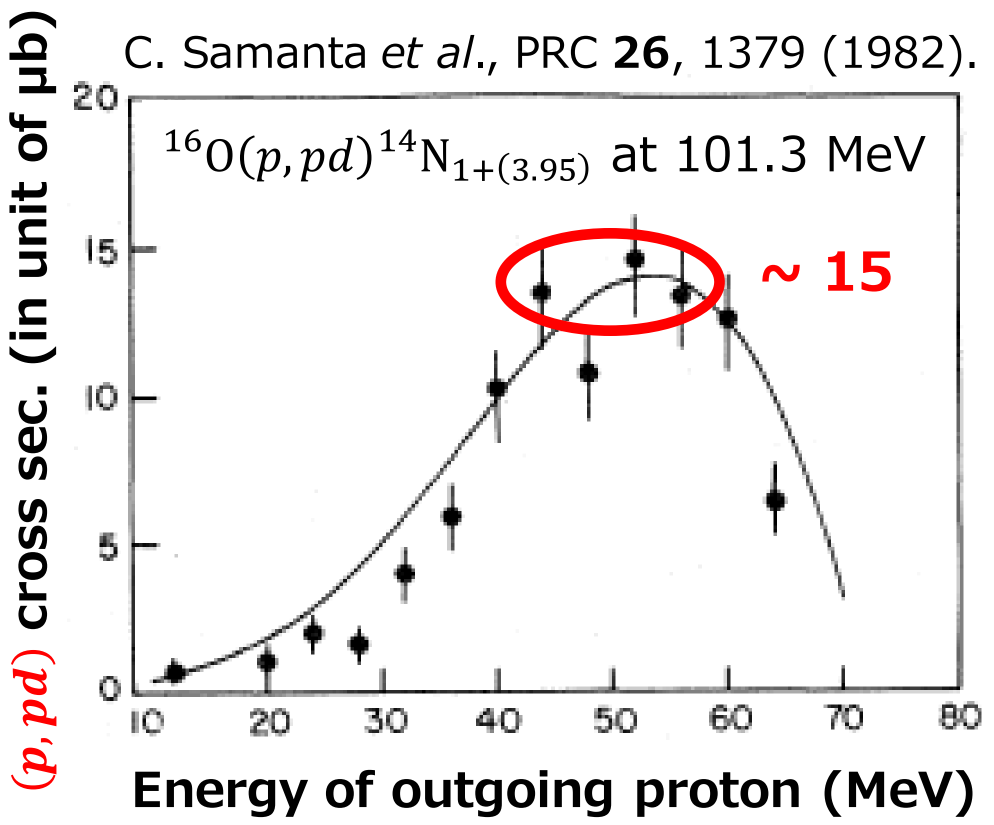
- "In essence, a proton induced knockout reaction is a nuclear reaction in which an incident proton interacts with either a nucleon or a nuclear cluster in a target nucleus and knocks this entity out of the nucleus, ..."
- "..., proton induced knockout reactions, as well as other types of knockout reactions involving incident electrons, provide a uniquely direct means of investigating the single particle structure of a target nucleus."

T. Wakasa, K. Ogata, and T. Noro, PPNP **96**, 32 (2017).

Example of (p, pd) reaction



C. Samanta *et al.*, PRC **26**, 1379 (1982).



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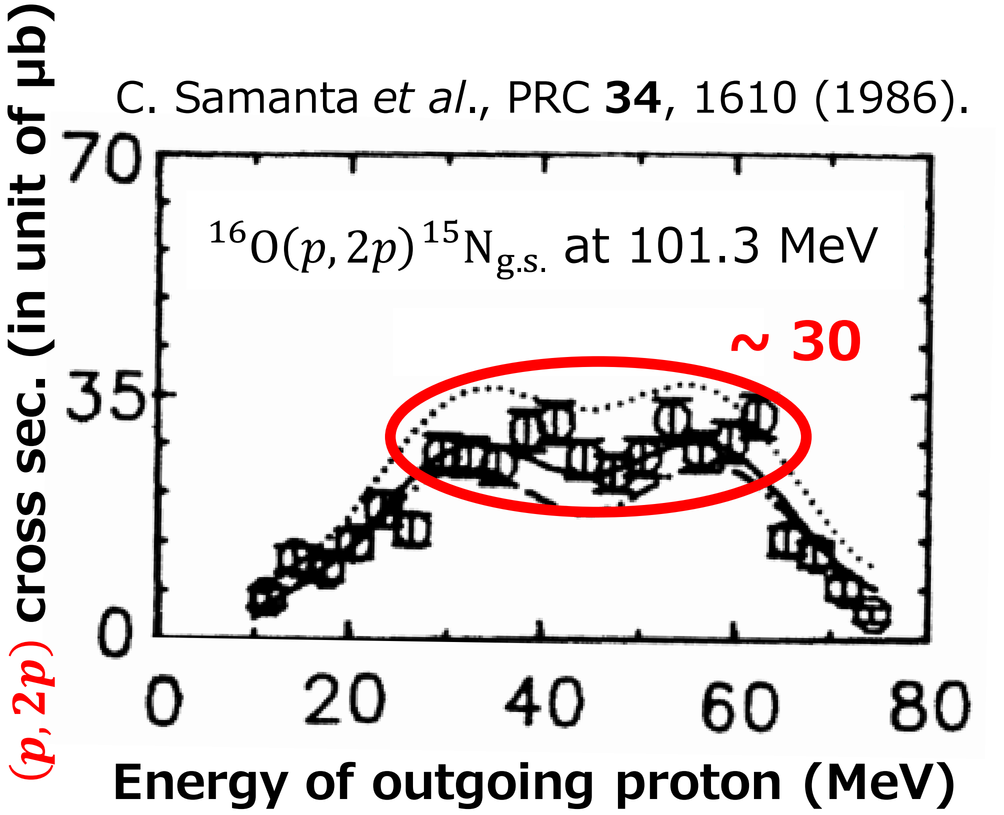

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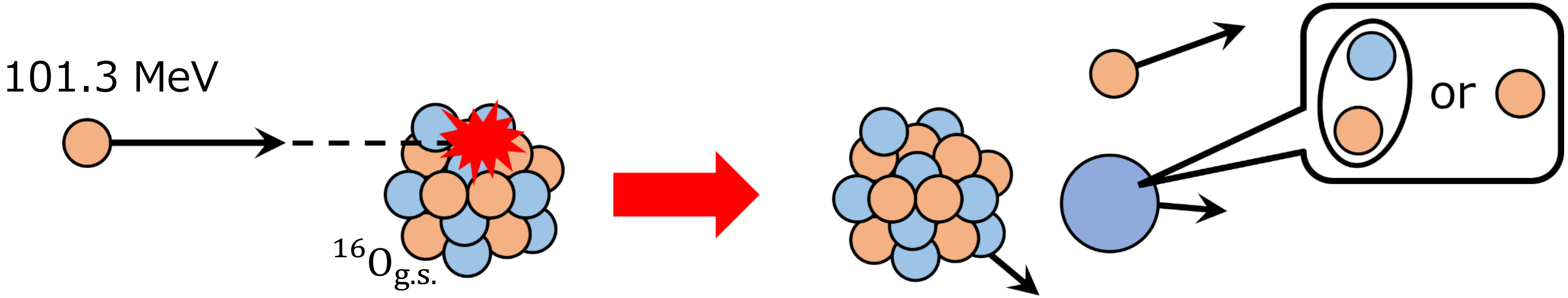

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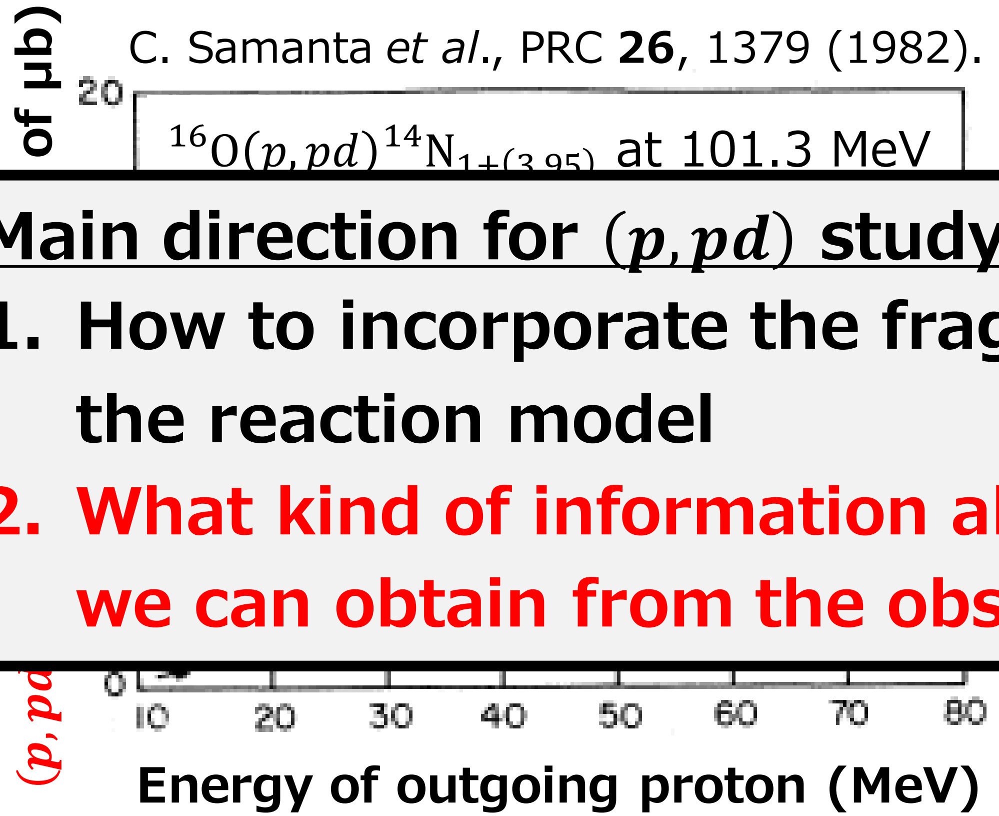

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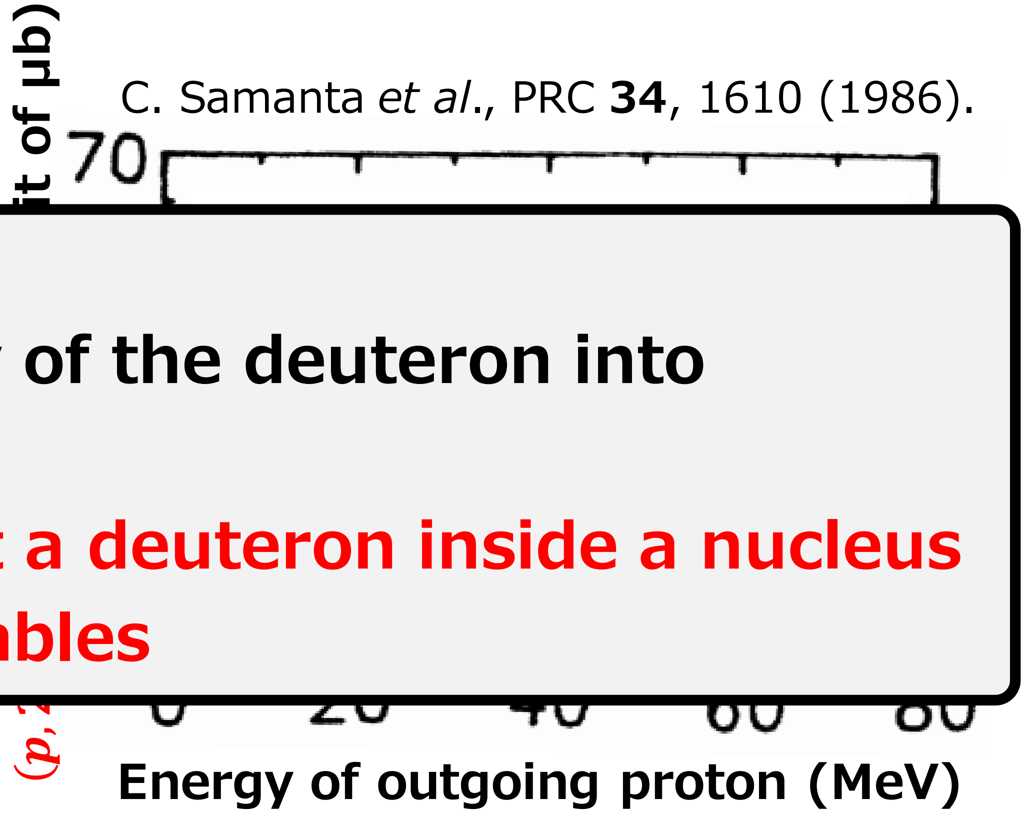
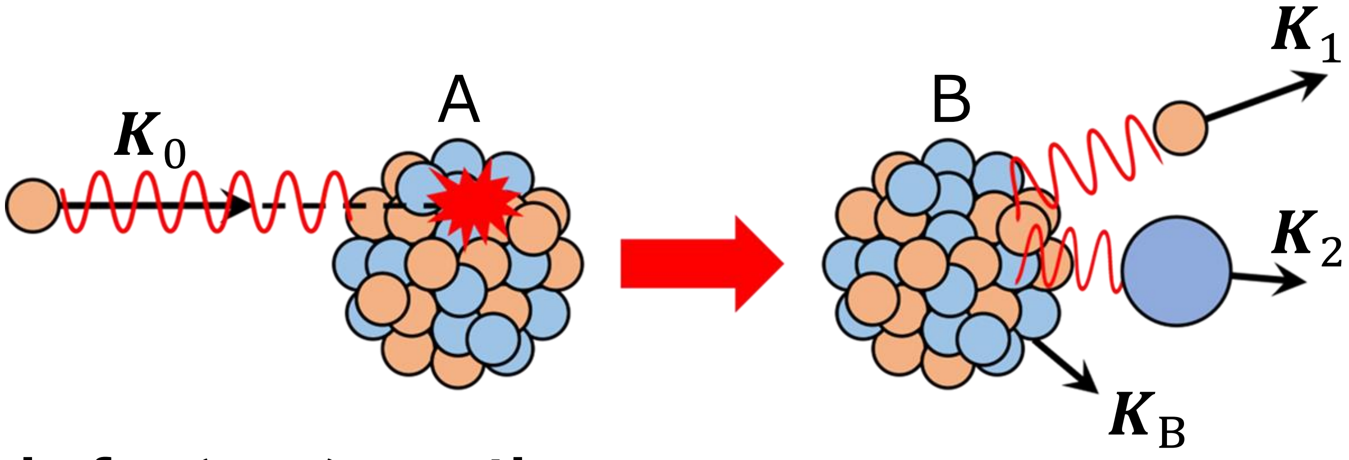


<u>**Main direction for (p, pd) study**</u>

1. **How to incorporate the fragility of the deuteron into the reaction model**
2. **What kind of information about a deuteron inside a nucleus we can obtain from the observables**

Distorted Wave Impulse Approximation (DWIA)

Note: The reaction residue B is assumed to behaves as a spectator.



Transition matrix for (p,pC) reaction

$$T^{\rm DWIA} = \langle \chi_{1,\boldsymbol{K}_1}\chi_{2,\boldsymbol{K}_2} | t_{p\rm C} | \chi_{0,\boldsymbol{K}_0}\varphi_{{\rm C},n\ell j}\rangle$$

$\chi_{i,\boldsymbol{K}_i}$: Distorted wave of particle $i\ (=0,1,2)$

$t_{p\rm C}$: Proton-particle effective int. in free space

$\varphi_{{\rm C},n\ell j}$: Single-particle wave function of particle being knocked out

Triple differential cross section (TDX)

$$\frac{{\rm d}^3\sigma}{{\rm d}E_1{\rm d}\Omega_1{\rm d}\Omega_2} \propto \left|T^{\rm DWIA}\right|^2$$

Plane Wave Impulse Approximation (PWIA)

Transition matrix for $(p,p\mathrm{C})$ reaction

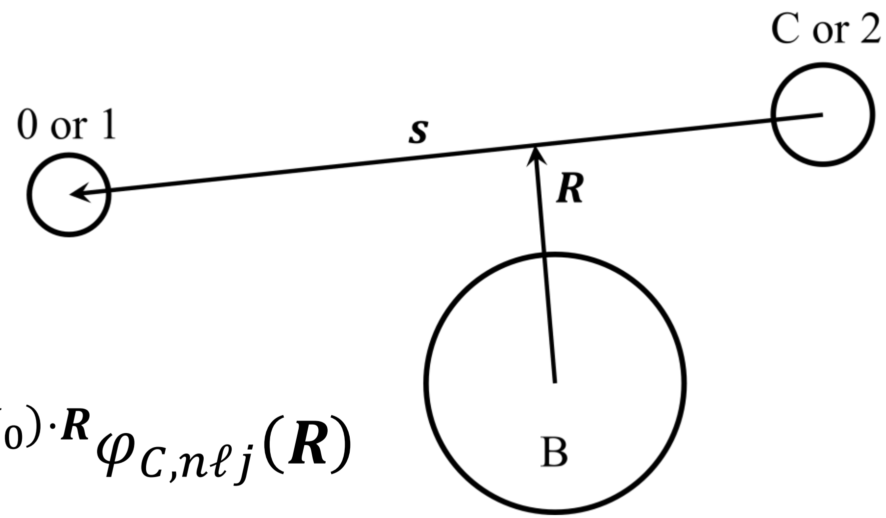
$$T^{\mathrm{DWIA}} = \langle \chi_{1,\boldsymbol{K}_1}\chi_{2,\boldsymbol{K}_2} | t_{p\mathrm{C}} | \chi_{0,\boldsymbol{K}_0}\varphi_{\mathrm{C},n\ell j} \rangle$$

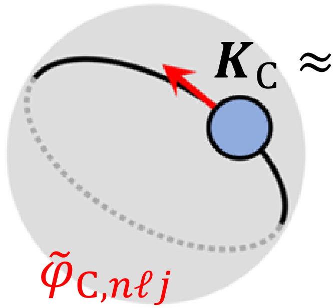
Plane-wave limit (in coordinate space)

$$T^{\mathrm{PWIA}} = \int \mathrm{d}\boldsymbol{s}\, \mathrm{e}^{-i\boldsymbol{\kappa}'\cdot\boldsymbol{s}} t_{p\mathrm{C}}(\boldsymbol{s}) \mathrm{e}^{i\boldsymbol{\kappa}\cdot\boldsymbol{s}} \times \int \mathrm{d}\boldsymbol{R}\, \mathrm{e}^{-i(\boldsymbol{K}_1+\boldsymbol{K}_2-\boldsymbol{K}_0)\cdot\boldsymbol{R}} \varphi_{\mathrm{C},n\ell j}(\boldsymbol{R})$$

$$\approx \int \mathrm{d}\boldsymbol{s}\, \mathrm{e}^{-i\boldsymbol{\kappa}'\cdot\boldsymbol{s}} t_{p\mathrm{C}}(\boldsymbol{s}) \mathrm{e}^{i\boldsymbol{\kappa}\cdot\boldsymbol{s}} \times \tilde{\varphi}_{\mathrm{C},n\ell j}(\boldsymbol{K}_\mathrm{C})$$

p-C collision — Structure



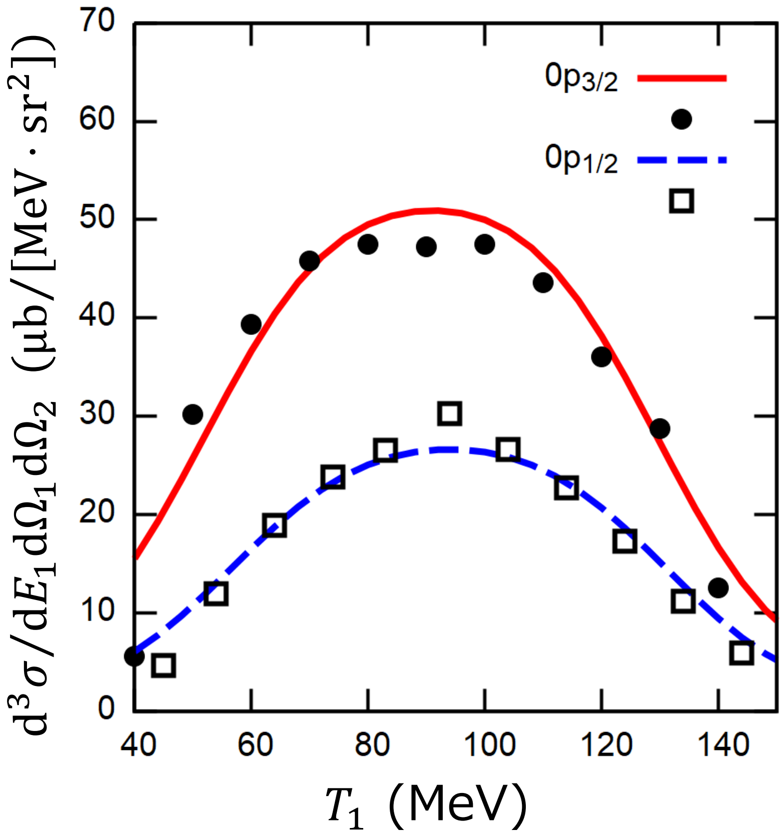


$$\boldsymbol{K}_\mathrm{C} \approx \boldsymbol{K}_1 + \boldsymbol{K}_2 - \boldsymbol{K}_0 = -\boldsymbol{K}_\mathrm{B}$$

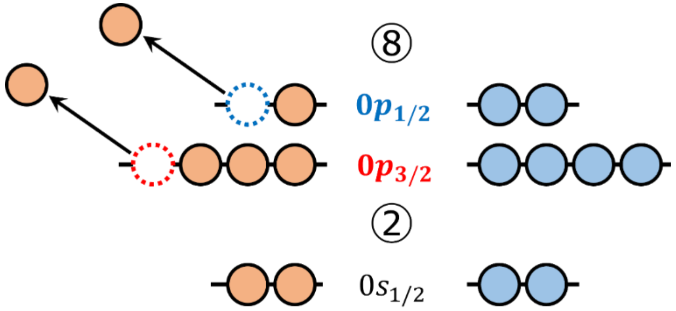
Triple differential cross section (TDX)

$$\left|T^{\mathrm{PWIA}}\right|^2 \approx \frac{\mathrm{d}\sigma_{p\mathrm{C}}}{\mathrm{d}\Omega_{p\mathrm{C}}} \times \left|\tilde{\varphi}_{\mathrm{C},n\ell j}(\boldsymbol{K}_\mathrm{C})\right|^2$$

Single-particle orbit and shape of cross section



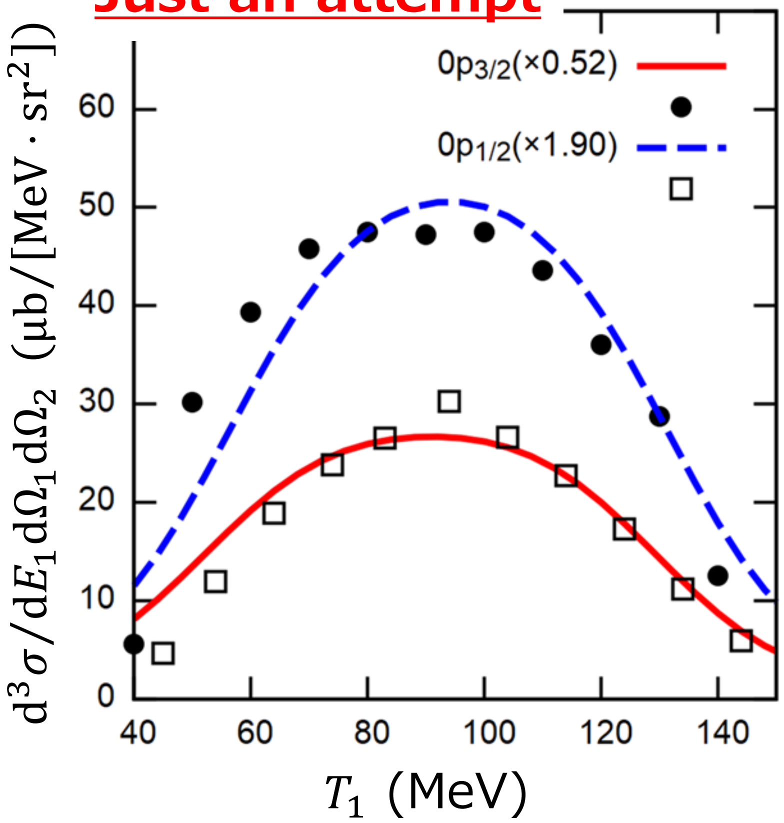
^{16}O$(p, 2p)$^{15}N at 200 MeV



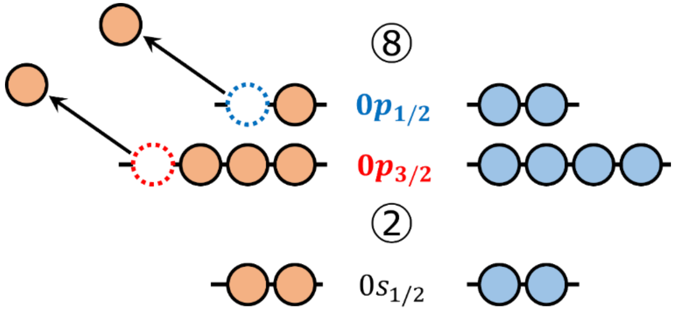
Data: P. Kitching *et al.*, NPA **340**, 423 (1980).

Single-particle orbit and shape of cross section

Just an attempt



$^{16}O(p,2p)^{15}N$ at 200 MeV



- Two lines have the similar shapes.
  - ✓ Two states have the same ℓ.

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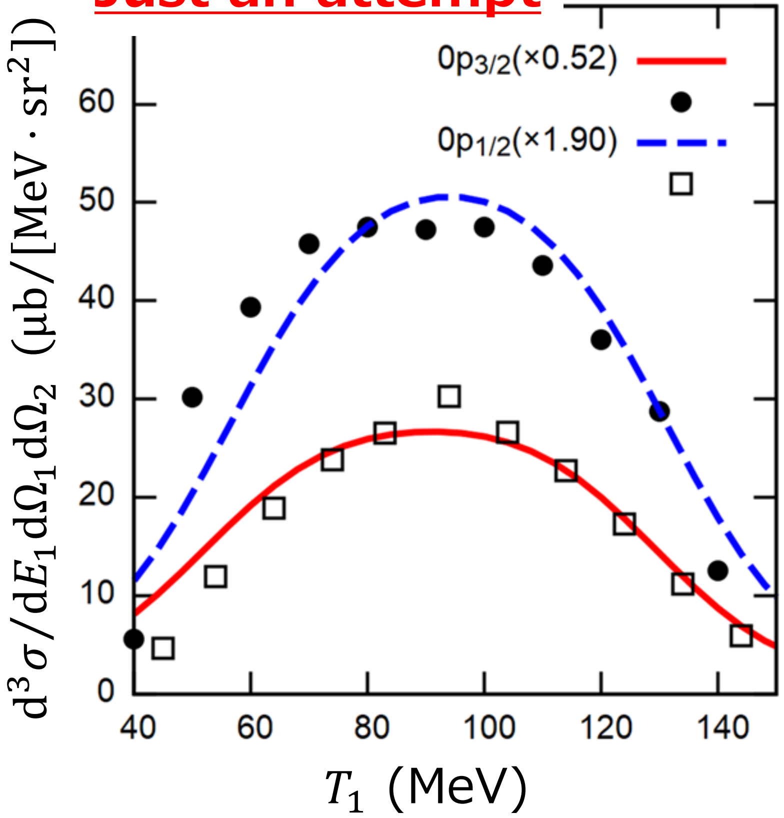

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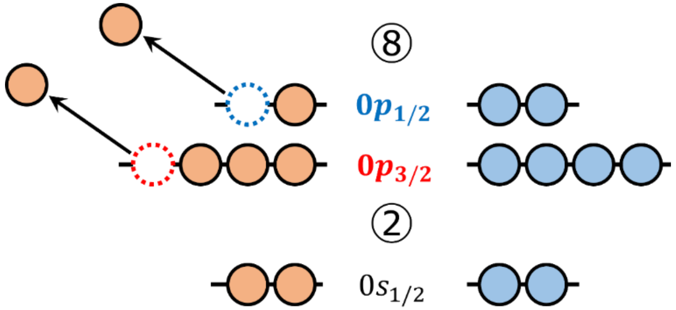

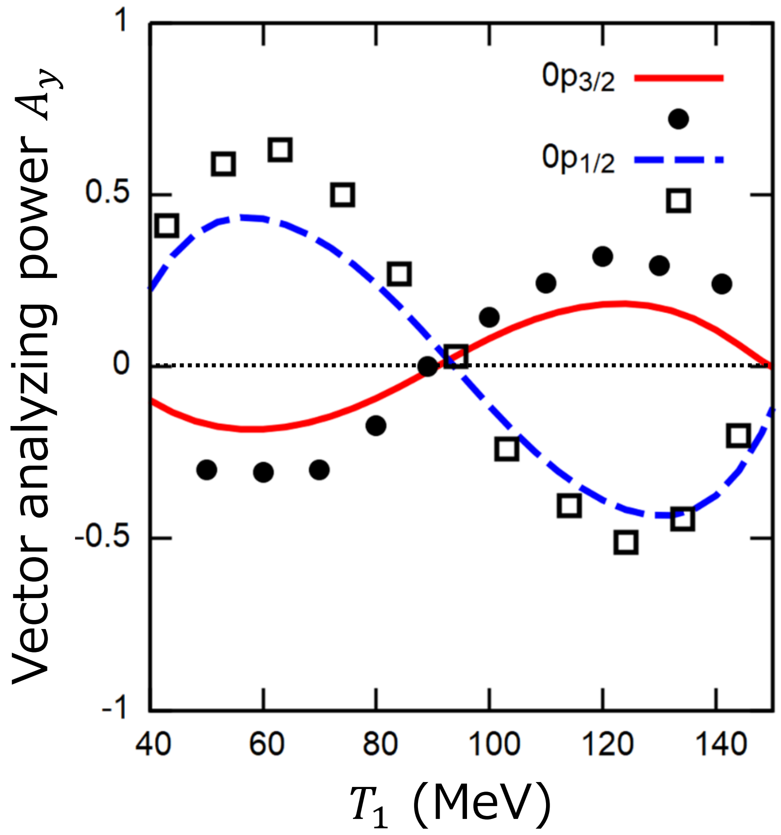

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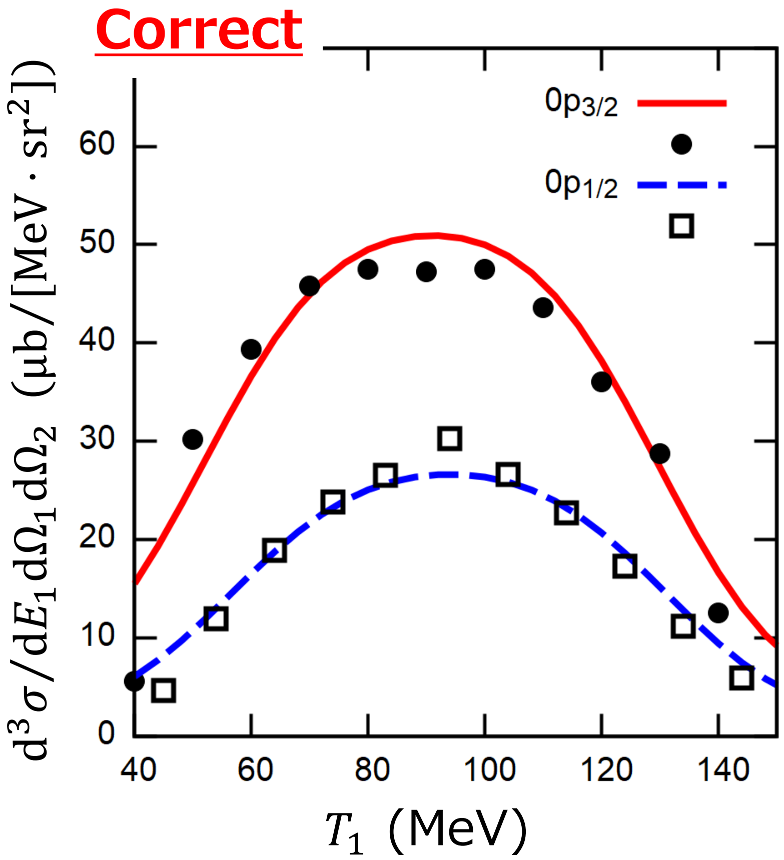

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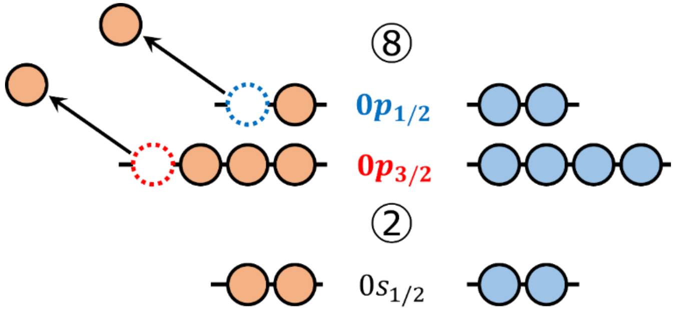

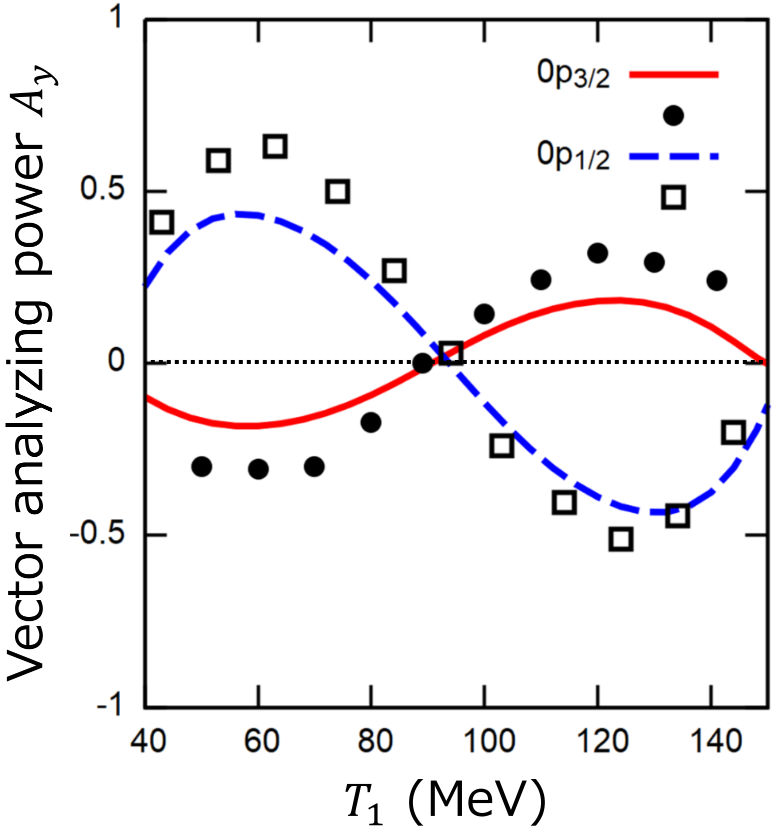

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$d\sigma_\uparrow$ ($d\sigma_\downarrow$): Differential cross sec. (TDX) with spin-up (-down) projectile

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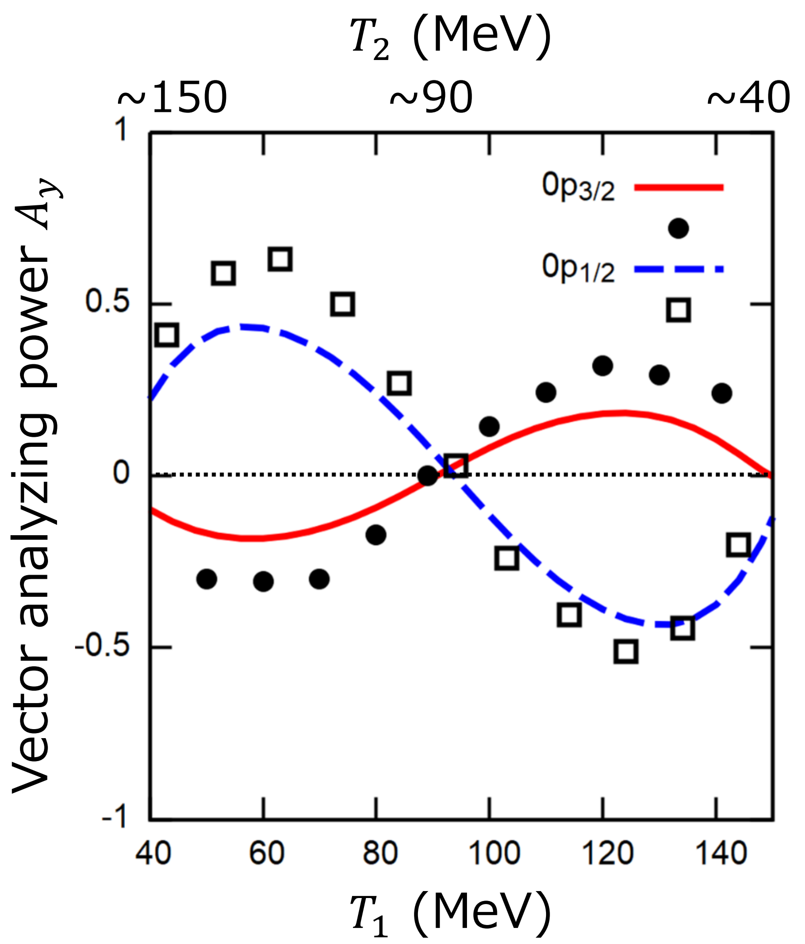

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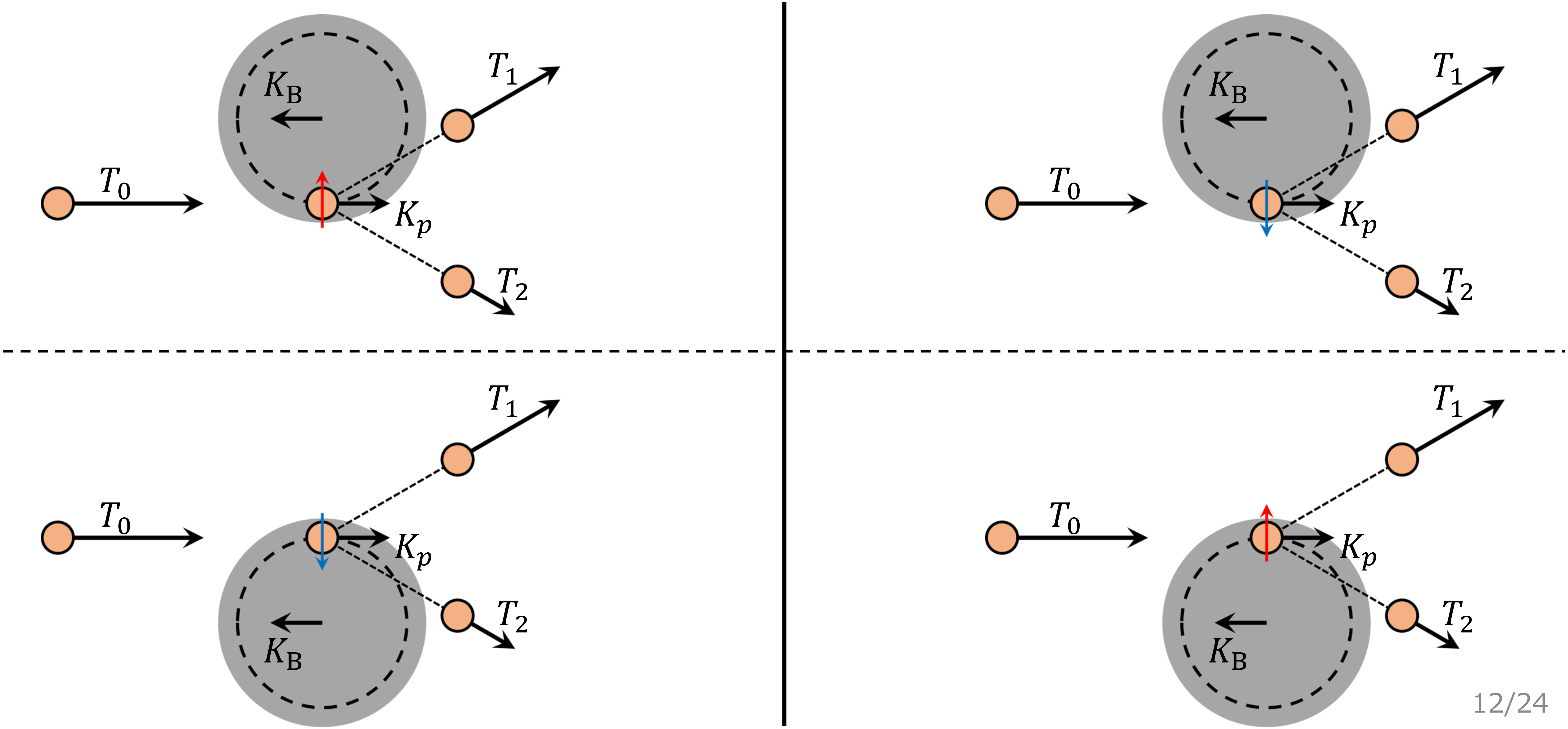
Maris effect in $(p, 2p)$ reaction

Jacob, Maris *et al.*, PLB **45**, 181 (1973).

Knockout from $j_{\uparrow} = \ell + 1/2$ | $\boldsymbol{T_1 > T_2}$ **side** | Knockout from $j_{\downarrow} = \ell - 1/2$



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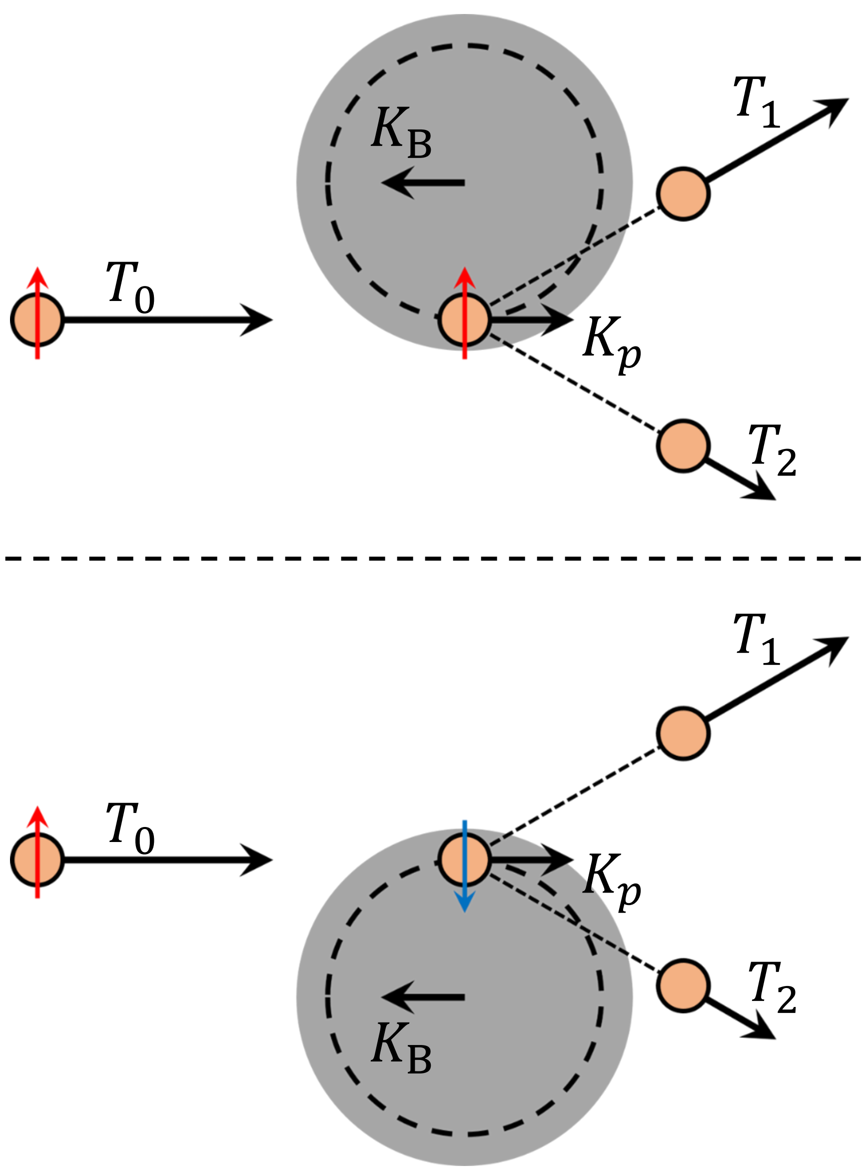

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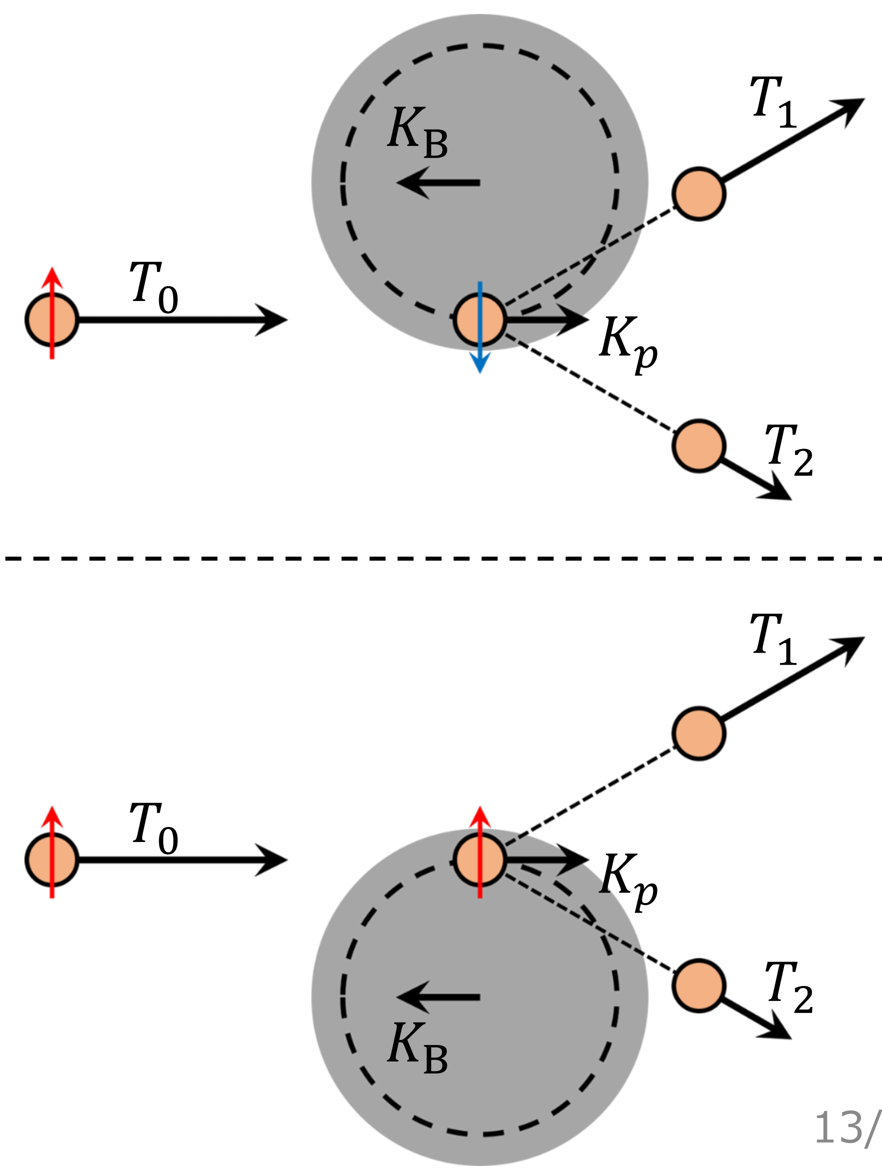
$d\sigma_{\uparrow\uparrow}$ and $d\sigma_{\downarrow\downarrow}$ dominate $d\sigma_{\uparrow\downarrow}$ and $d\sigma_{\downarrow\uparrow}$.



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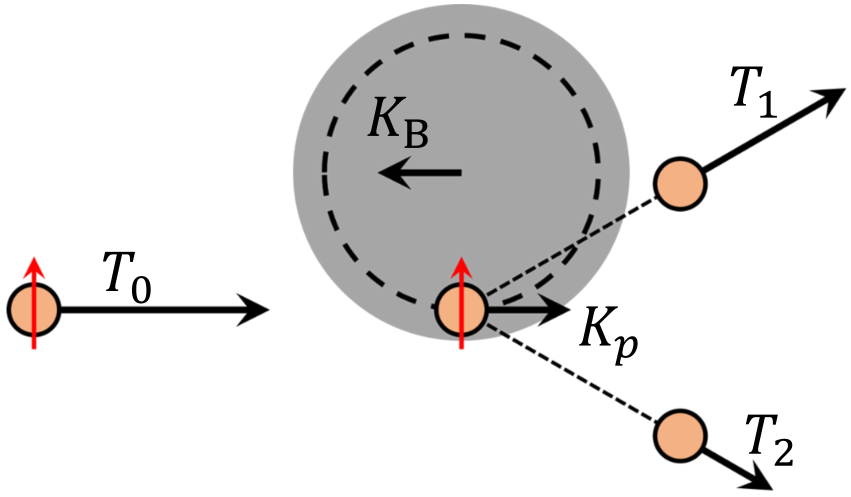

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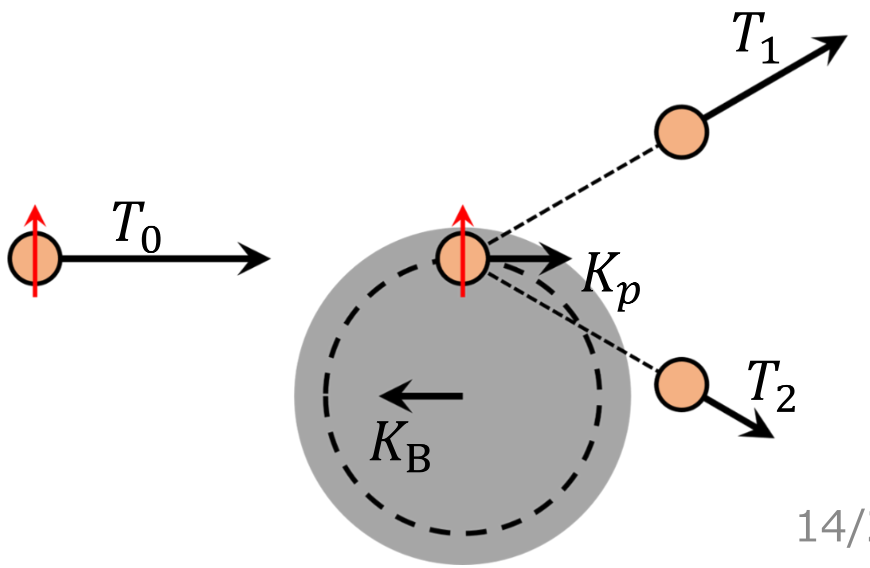

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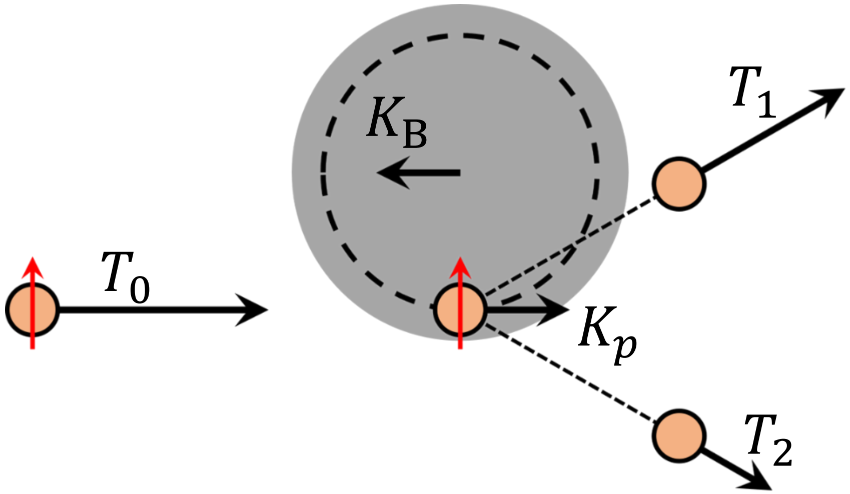

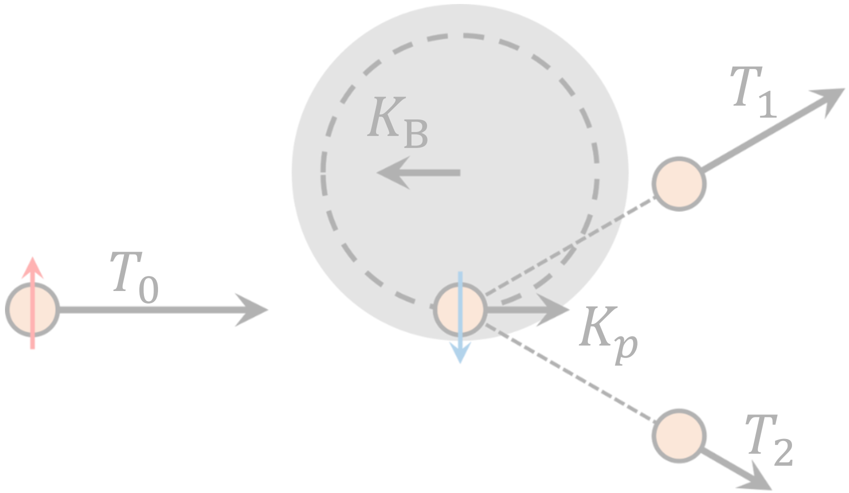

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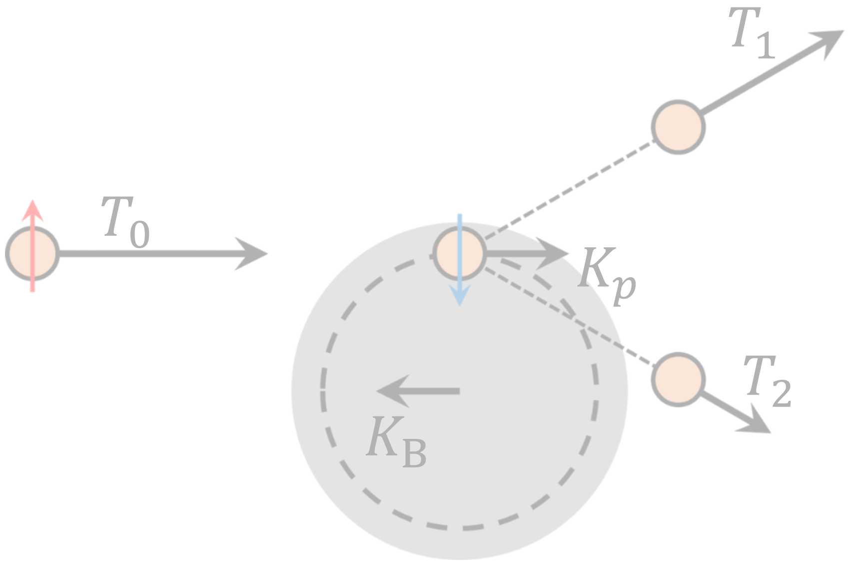
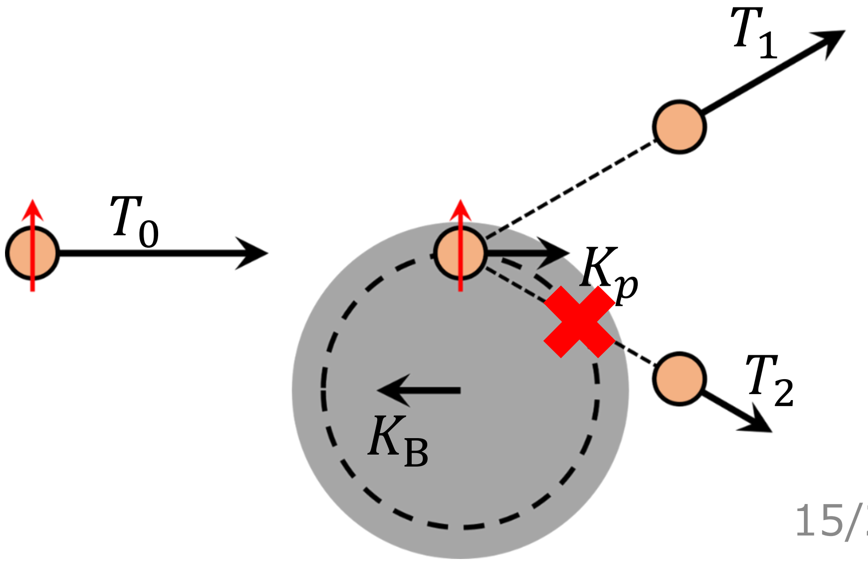
+



<u>Assumption 2</u>:
The mean free path of a low-energy particle is short.



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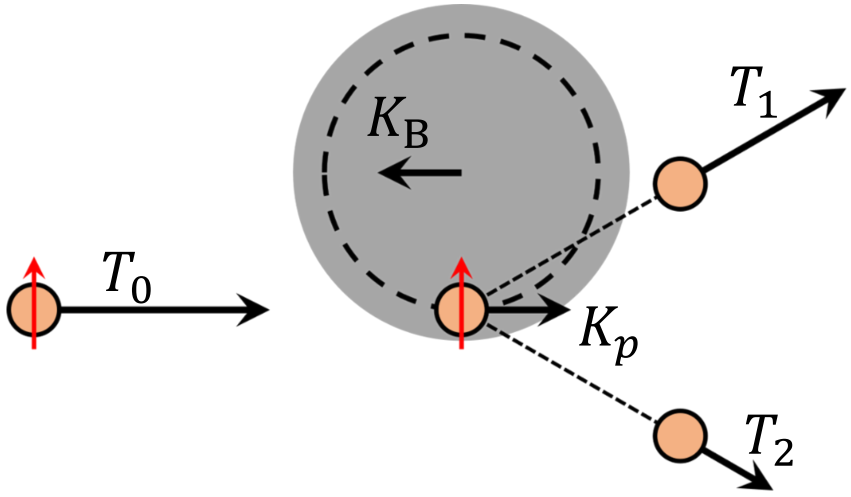

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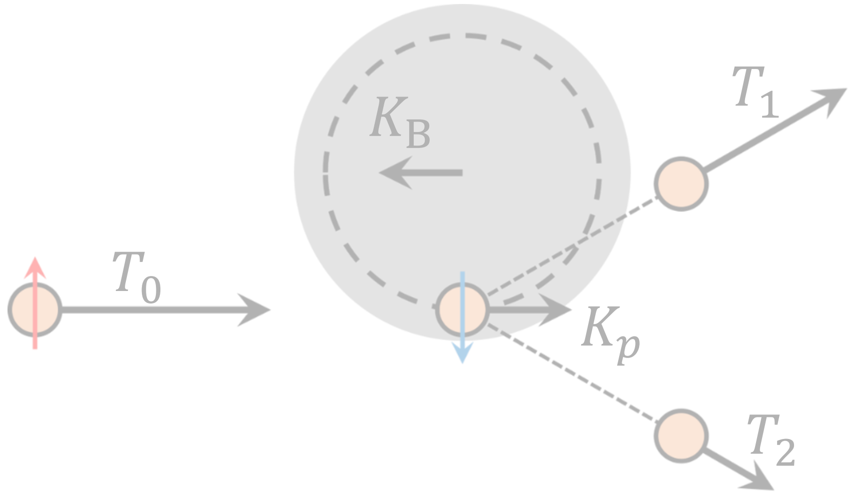

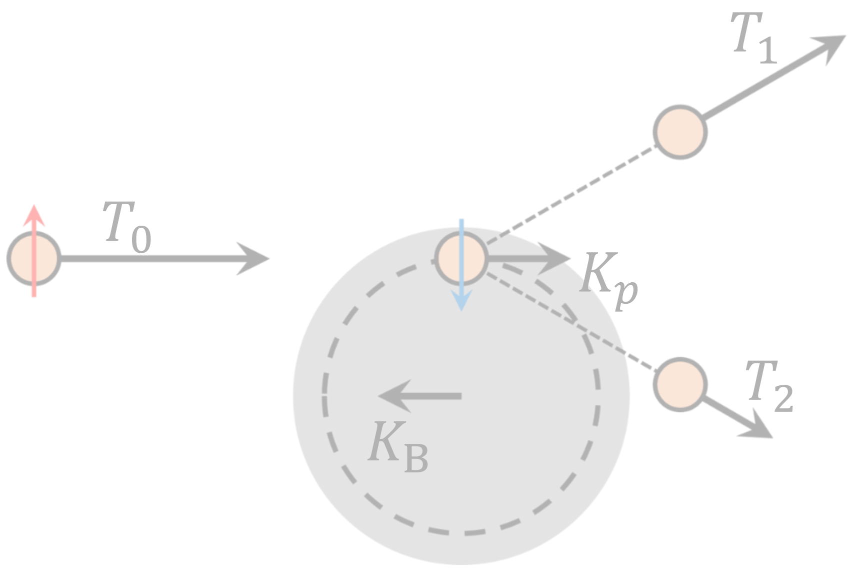

<u>Assumption 2</u>:

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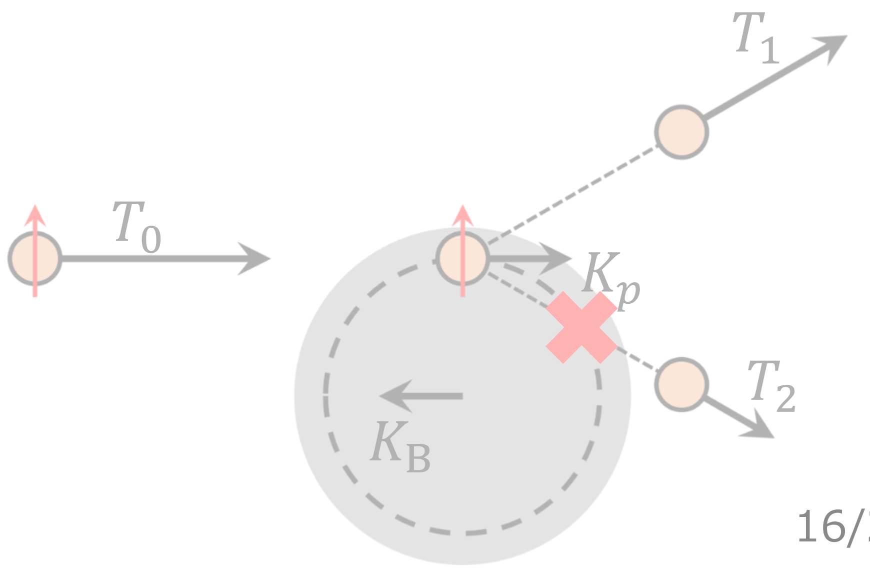

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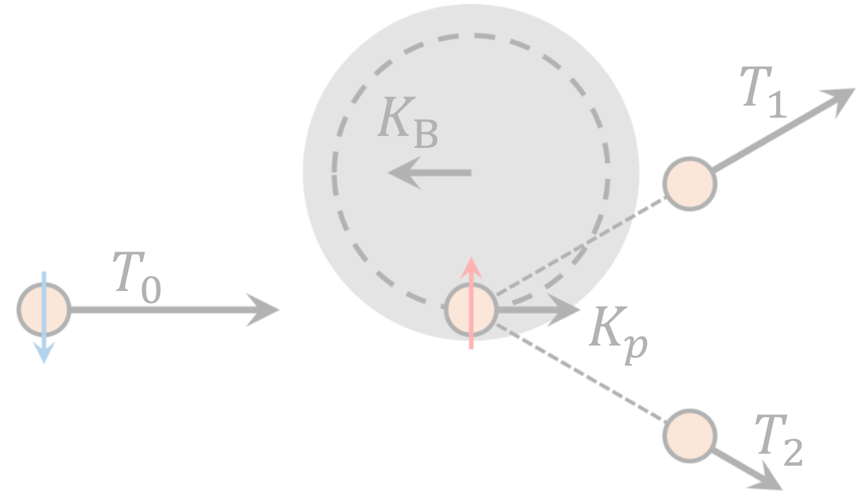

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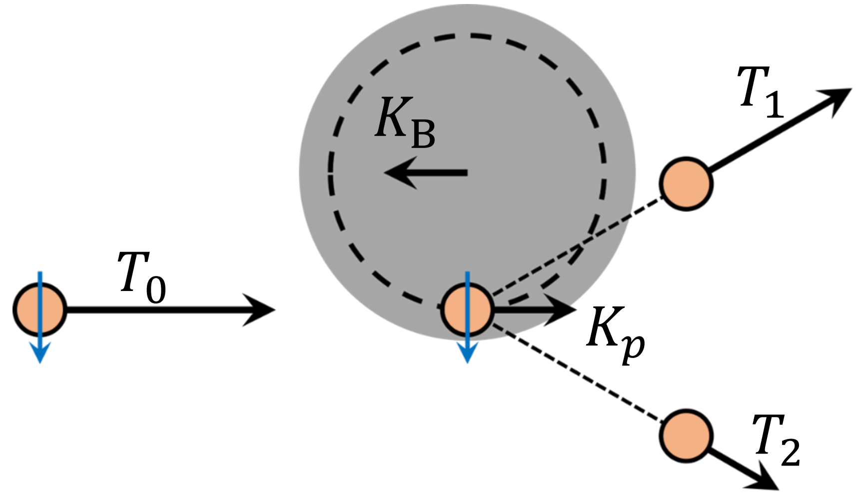

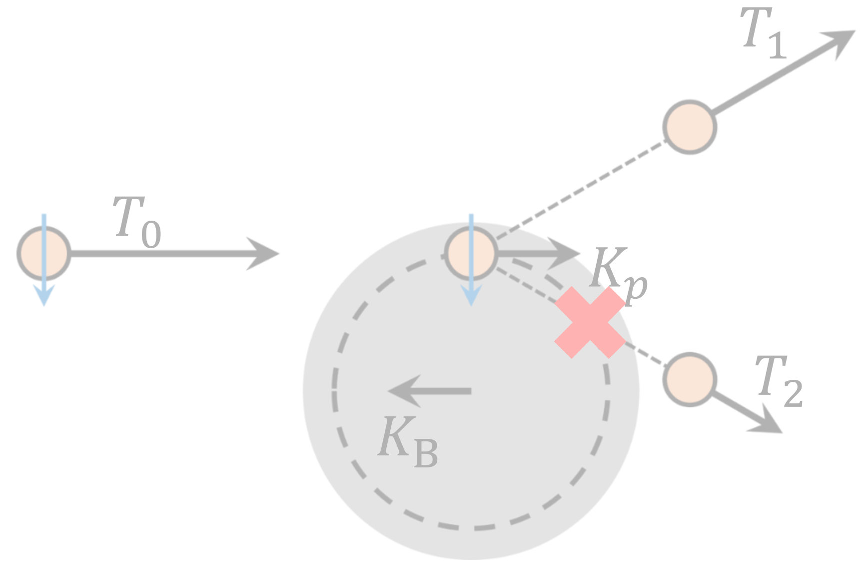

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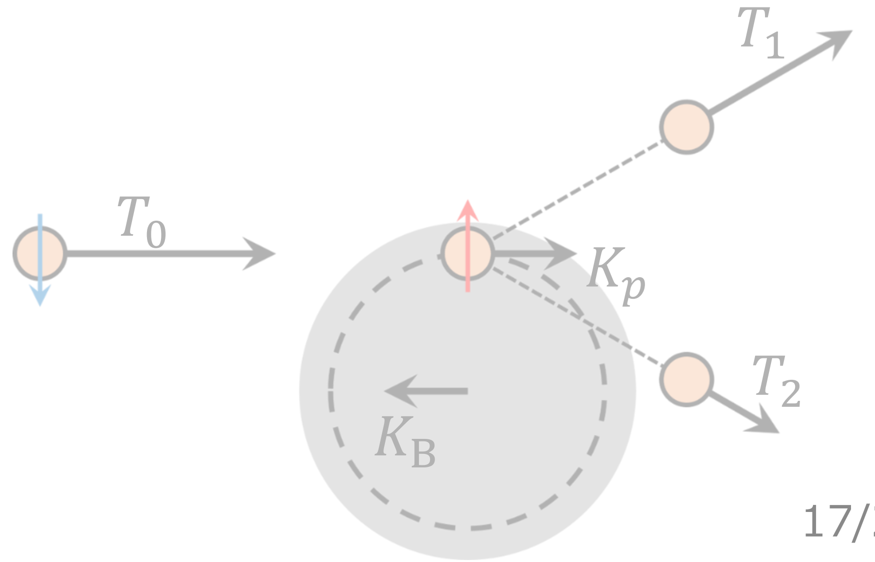

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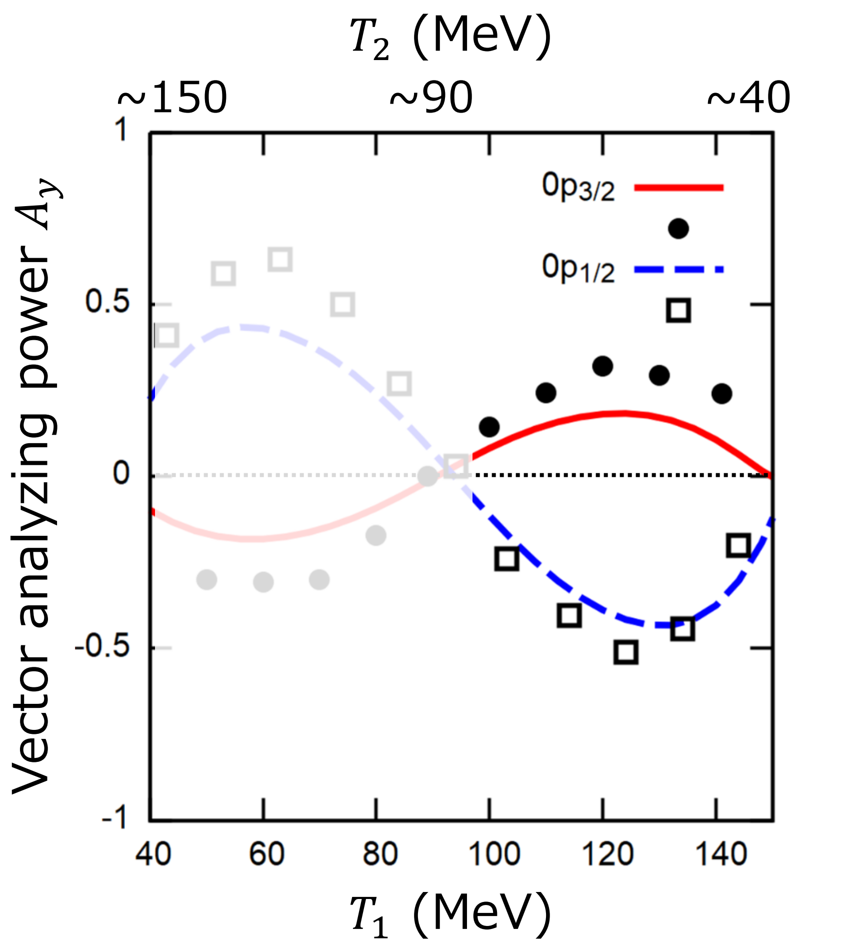

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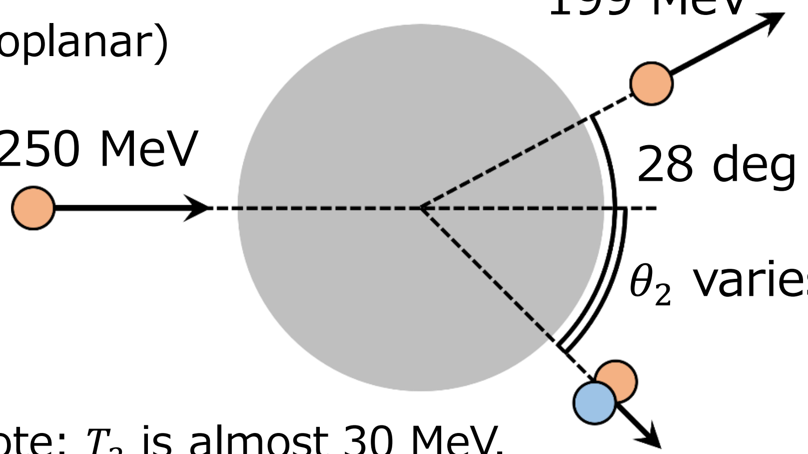
Kinematics

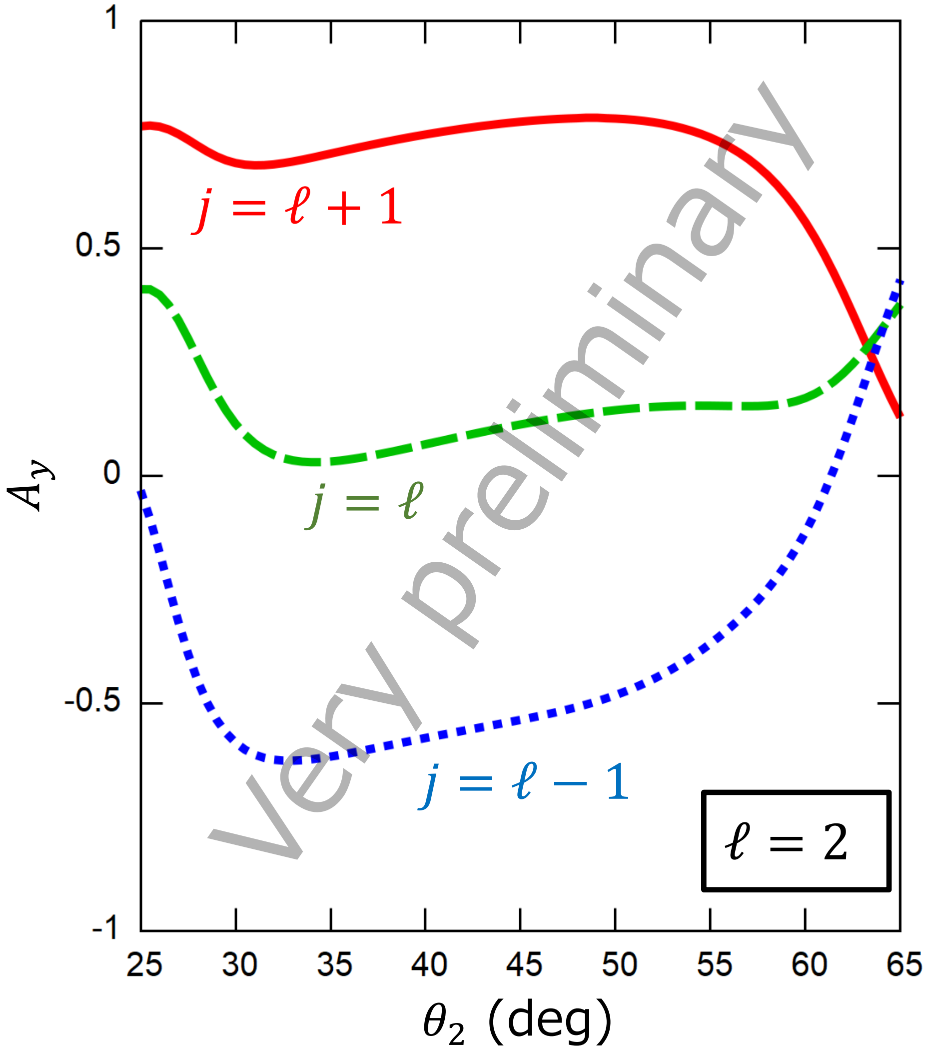
(coplanar)



Note: T_2 is almost 30 MeV.

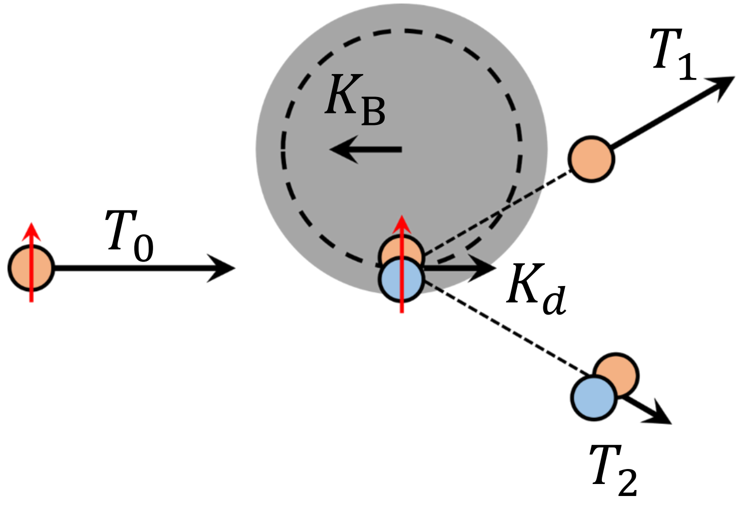
Note: The residue moves to the left.

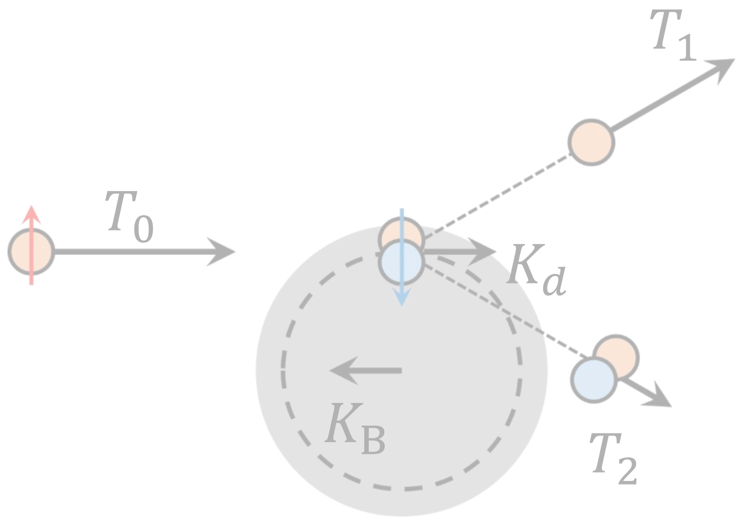
^{56}Ni$(p, pd)^{54}$Co at 250 MeV



Maris effect in (p, pd) reaction

$j = \ell + 1$



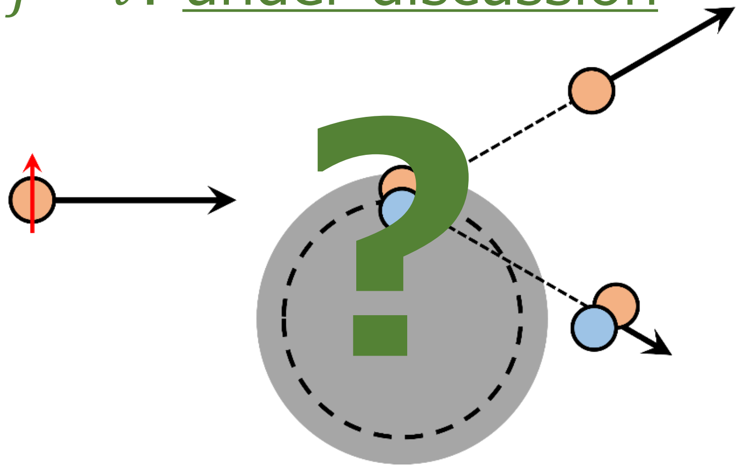


$T_1 > T_2$ case

Assumptions:

1. $\mathrm{d}\sigma_{\uparrow\uparrow}$ and $\mathrm{d}\sigma_{\downarrow\downarrow}$ dominate $\mathrm{d}\sigma_{\uparrow\downarrow}$ and $\mathrm{d}\sigma_{\downarrow\uparrow}$.
2. The mean free path of a low-energy particle is short.

$j = \ell$: under discussion



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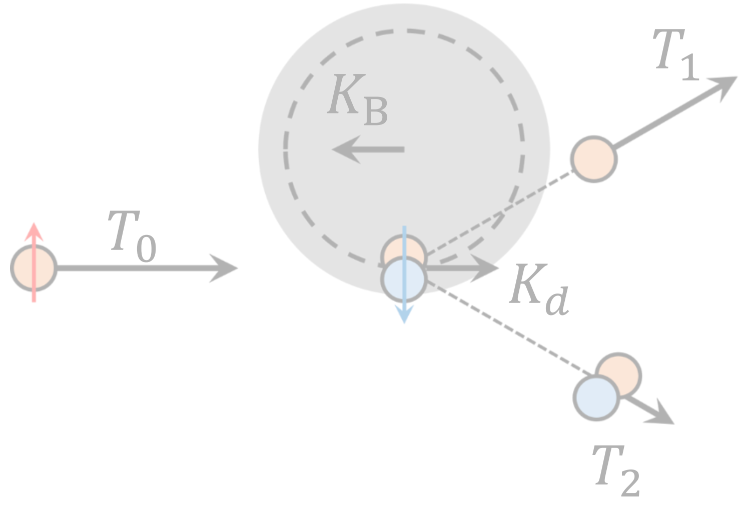

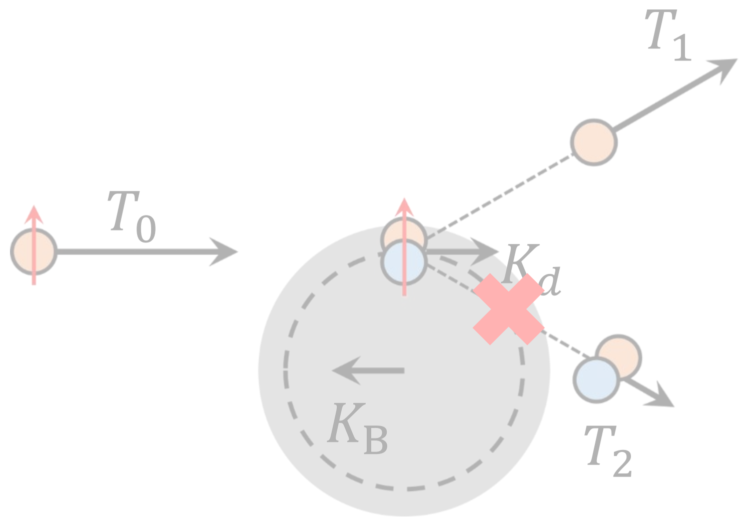

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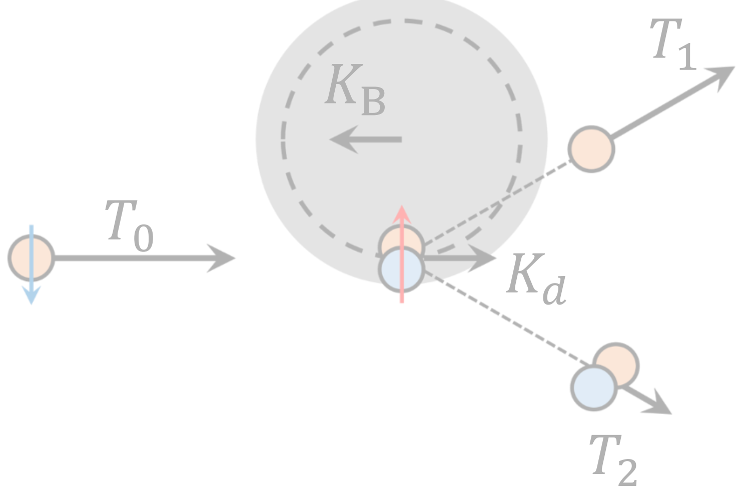

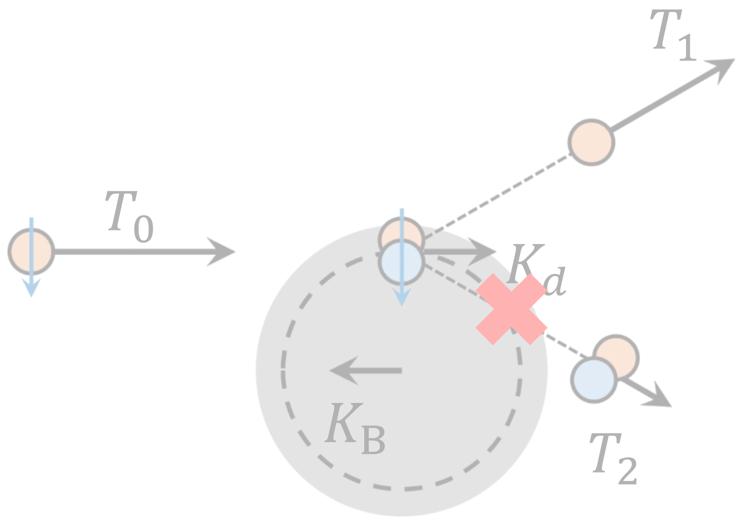

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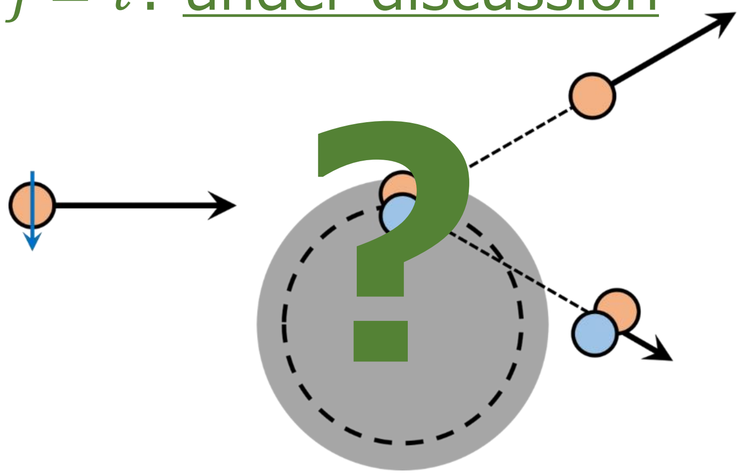
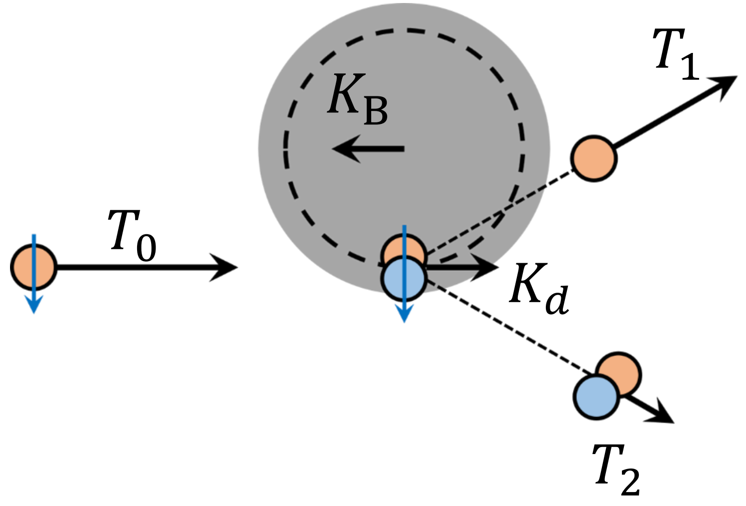
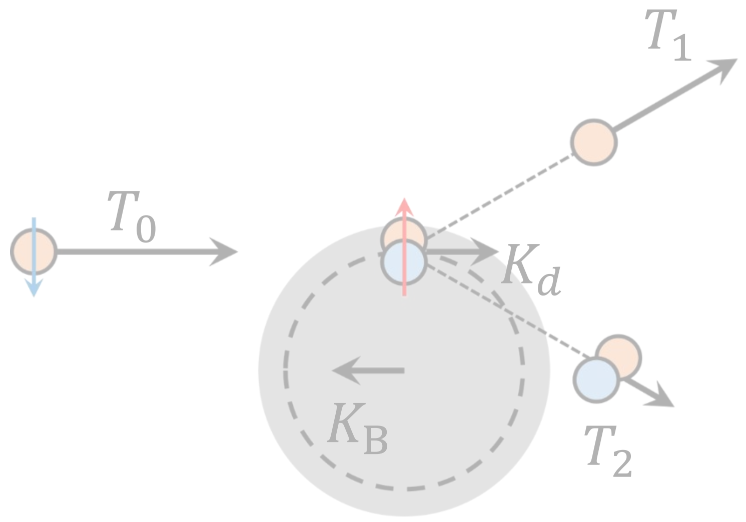


$j = \ell - 1$

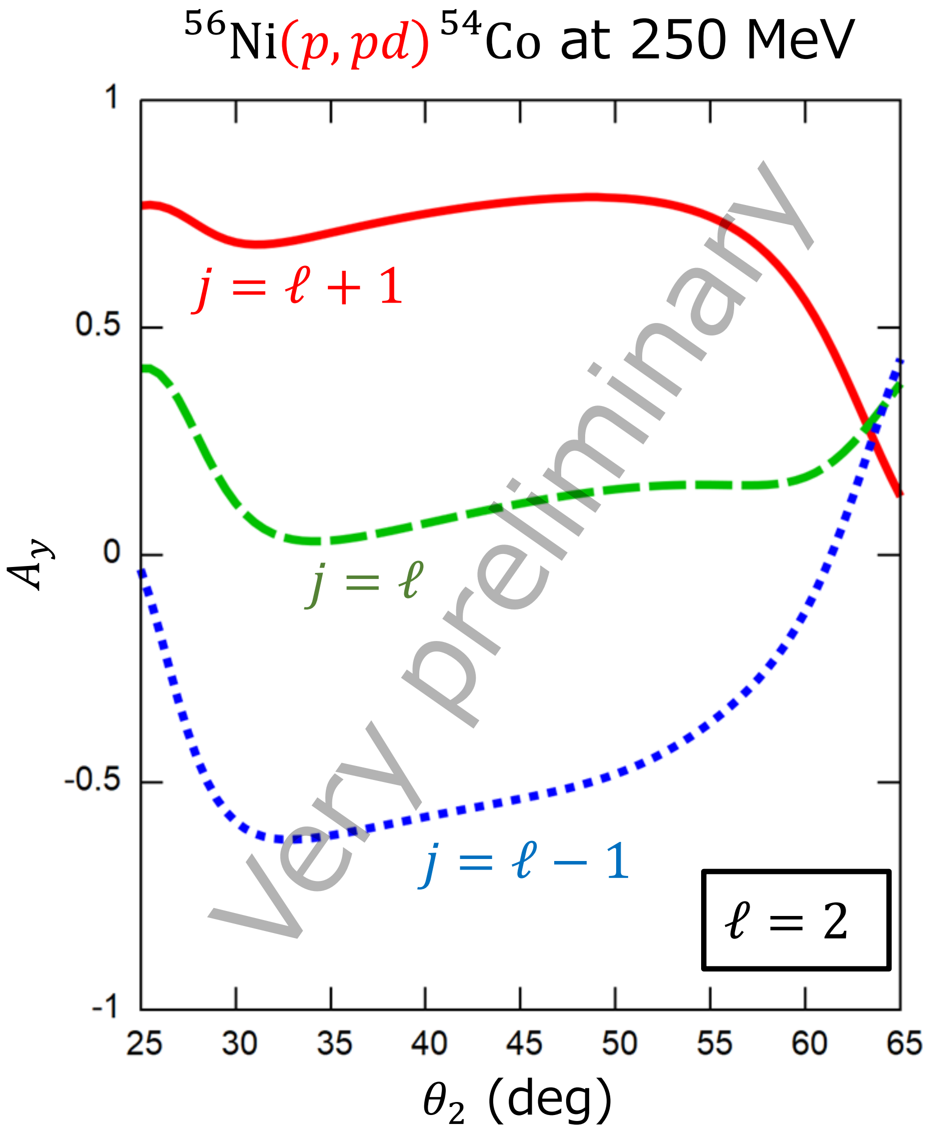




Maris polarization in (p, pd) reaction

$$A_y \equiv \frac{d\sigma_\uparrow - d\sigma_\downarrow}{d\sigma_\uparrow + d\sigma_\downarrow}$$

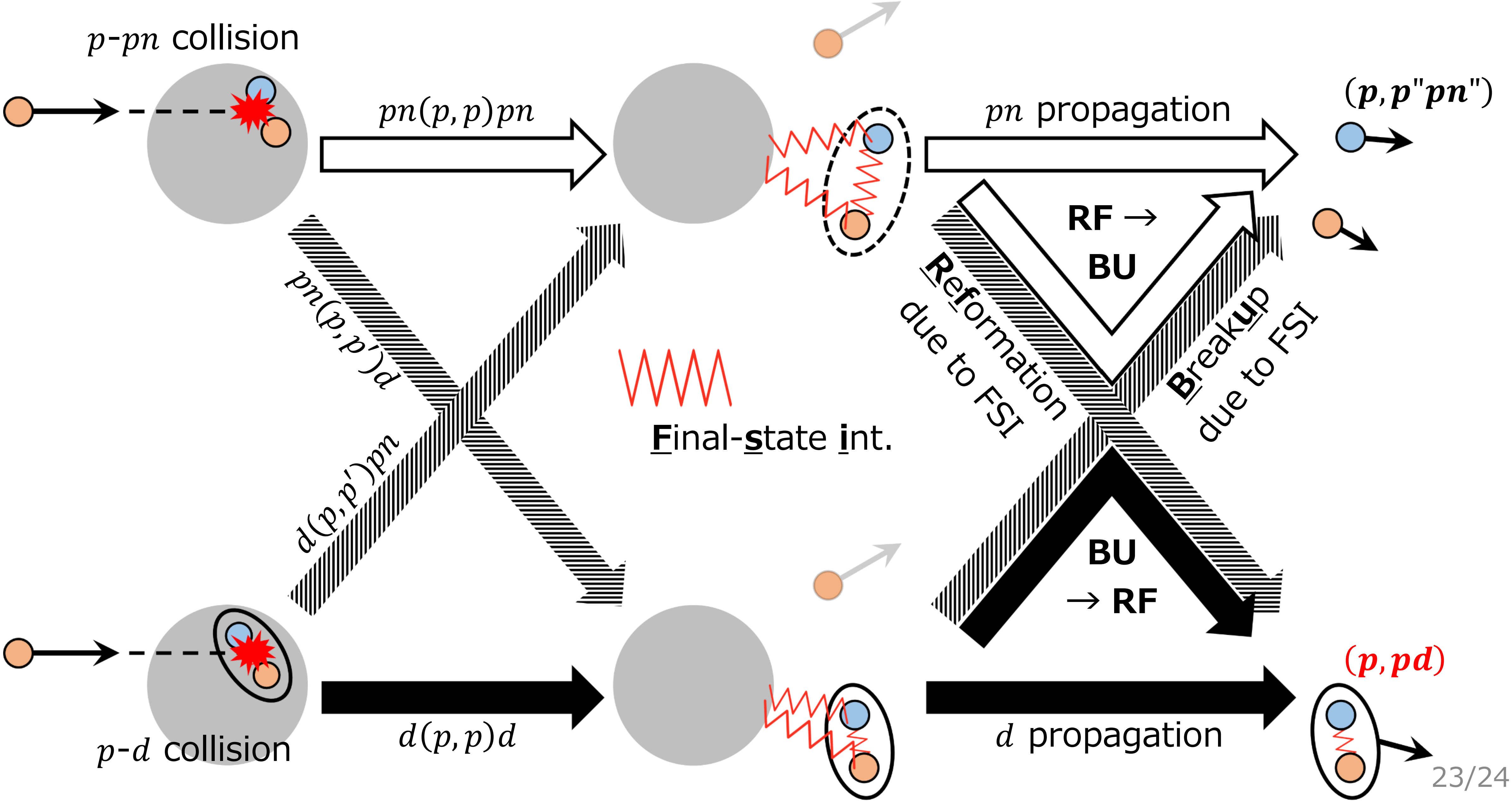
- $A_y > 0$ ($A_y < 0$) represents to what extent a spin-up (-down) projectile contributes the process considered.



<u>**Many future works**</u>

- Interpretation of $j = \ell$
- Use of microscopic pn wave function
- Considering deuteron's fragility
- …

New reaction model for (p, pd) -CDCCIA-



Summary

Purpose

- **[Final goal] To understand the deuteron-like correlation via the (p,pd) reaction**
- **[This talk] To demonstrate numerically the Maris polarization in the (p,pd) reaction**

Result

- **The Maris polarization is observed in $^{56}\mathrm{Ni}(p,pd)^{54}\mathrm{Co}$ calculation at 250 MeV**.
  - ✓ The signs of vector analyzing powers A_y for the $j_+ = \ell + 1$ and $j_- = \ell - 1$ orbits are explained by the Maris effect as in the $(p,2p)$ reaction.

Future work

- Interpretation of $j = \ell$
- Use of microscopic pn wave function
- Considering deuteron's fragility
- …