# Systematic analysis of reaction cross section for deuteron induced reaction

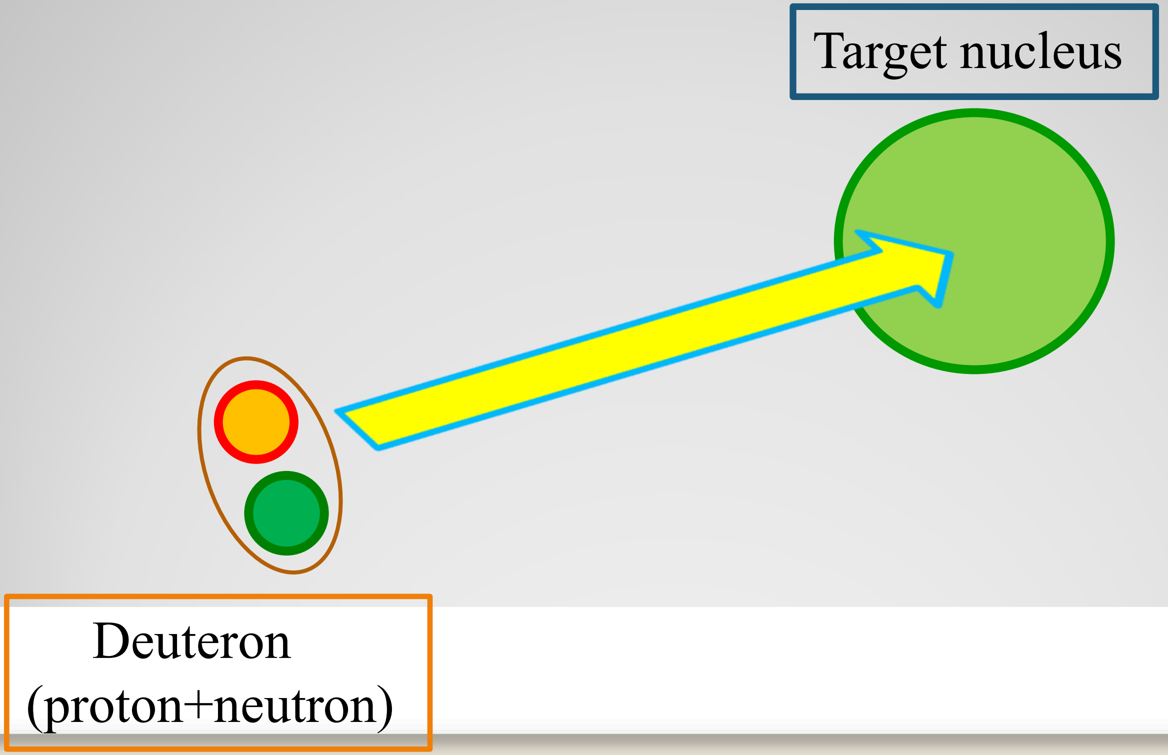
S. Hashimoto, K. Ogata, S. Chiba, M. Yahiro

Second EMMI-EFES Workshop on Neutron-Rich Exotic Nuclei (EENEN 10)

Nishina Hall, RIKEN, June 16–18, 2010.

# Introduction

- The understanding of the reaction mechanism with composite particles is necessary for the study of Neutron-Rich Exotic Nuclei.
- We focus on the reaction cross section for deuteron induced reactions, because the Hamiltonian is well-known.



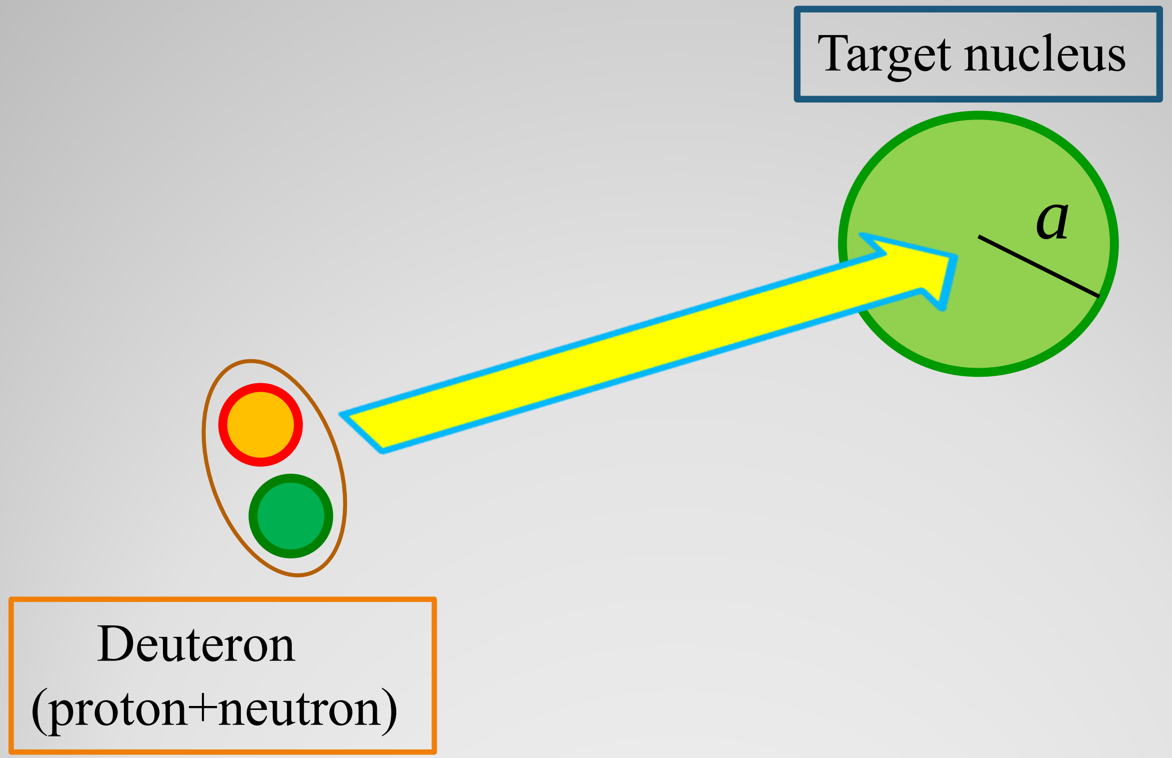
# Introduction

- The understanding of the reaction mechanism with composite particles is necessary for the study of Neutron-Rich Exotic Nuclei.
- We focus on the reaction cross section for deuteron induced reactions, because the Hamiltonian is well-known.

- We show a new and interesting viewpoint for the reaction cross section with the CDCC method.
- Because this idea is on an analogy to "phase transition", you may be surprised. However, if the mechanism is understood, the next stage of the nuclear reaction study will be opened.

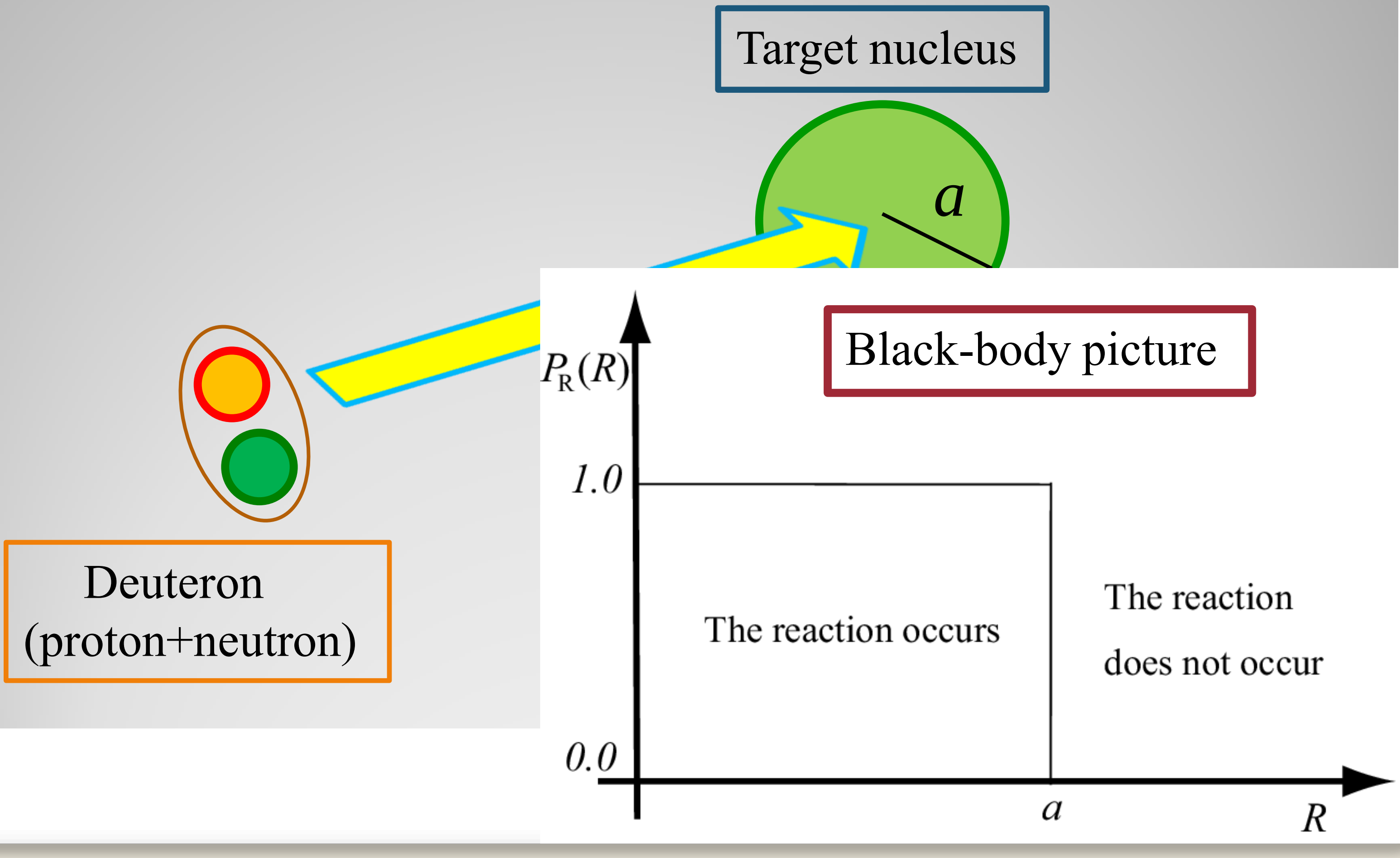
# Reaction cross section

- The reaction cross section is approximately given by
  $$\sigma_R = \pi a^2 \propto A^{2/3}.$$



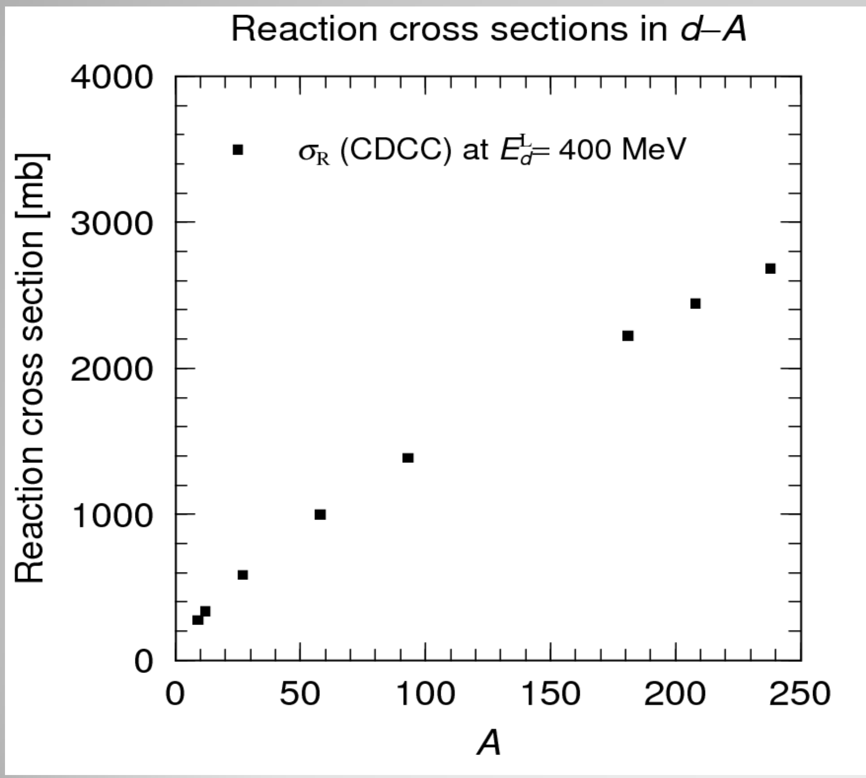
# Reaction cross section

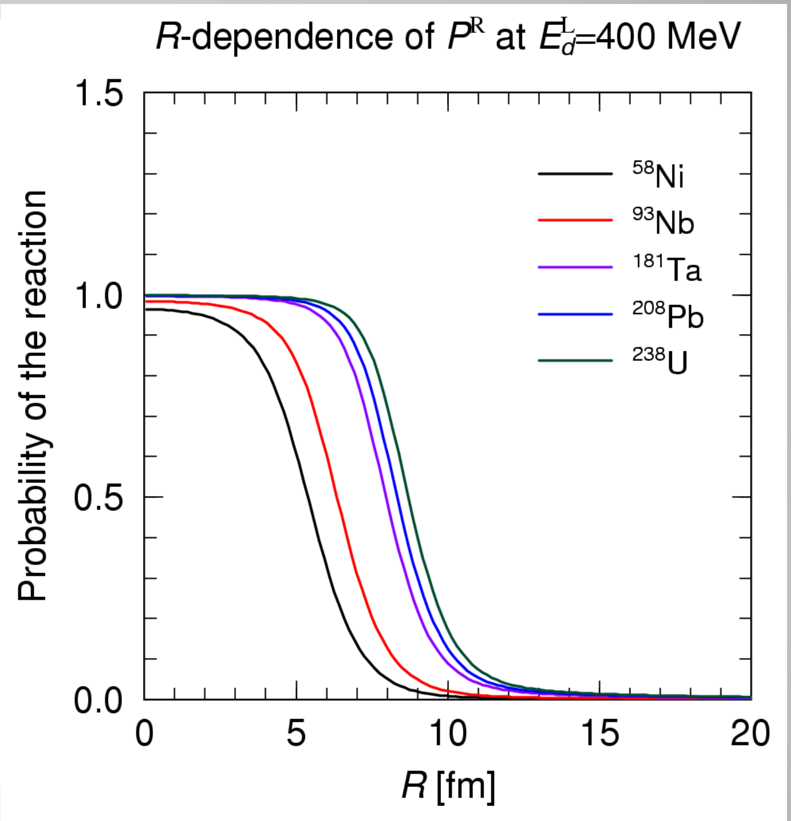
- The reaction cross section is approximately given by $\sigma_R = \pi a^2 \propto A^{2/3}$.



# Reaction cross section

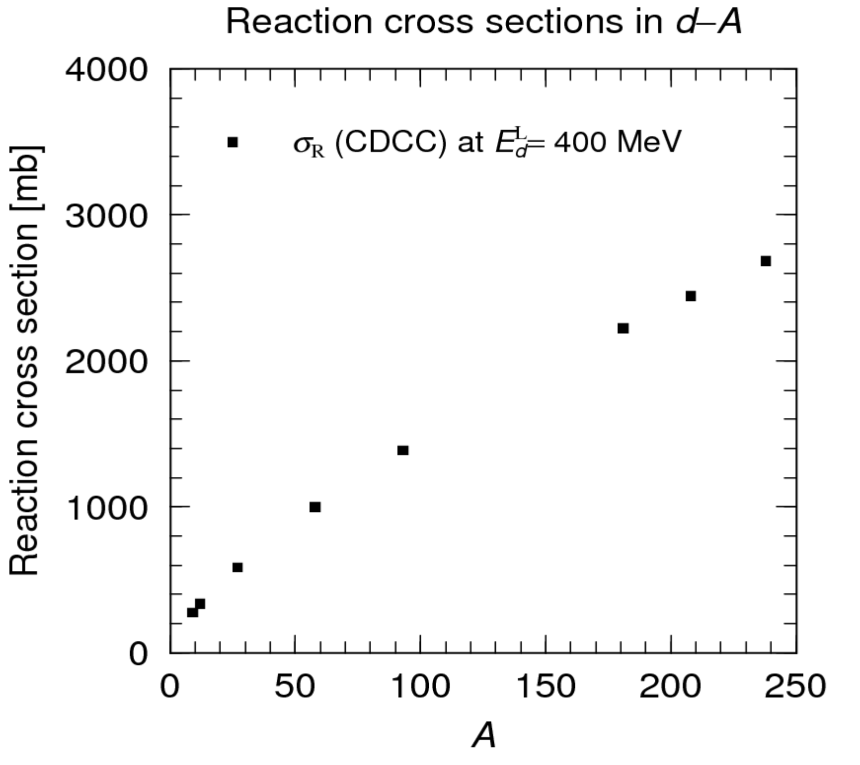
- However, the realistic result of the probability has Fermi distribution.

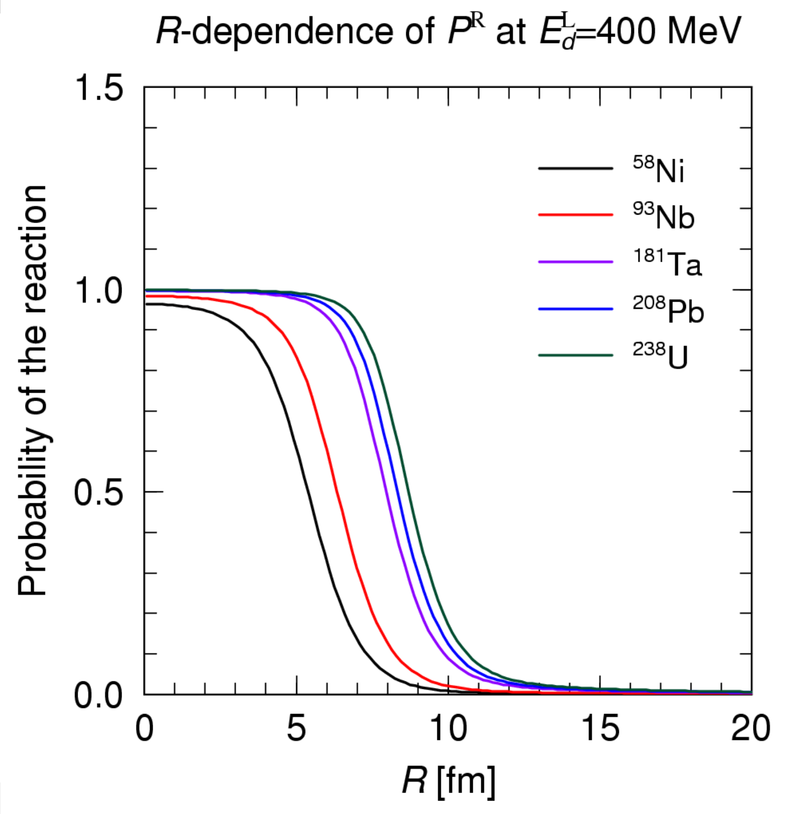


# Reaction cross section

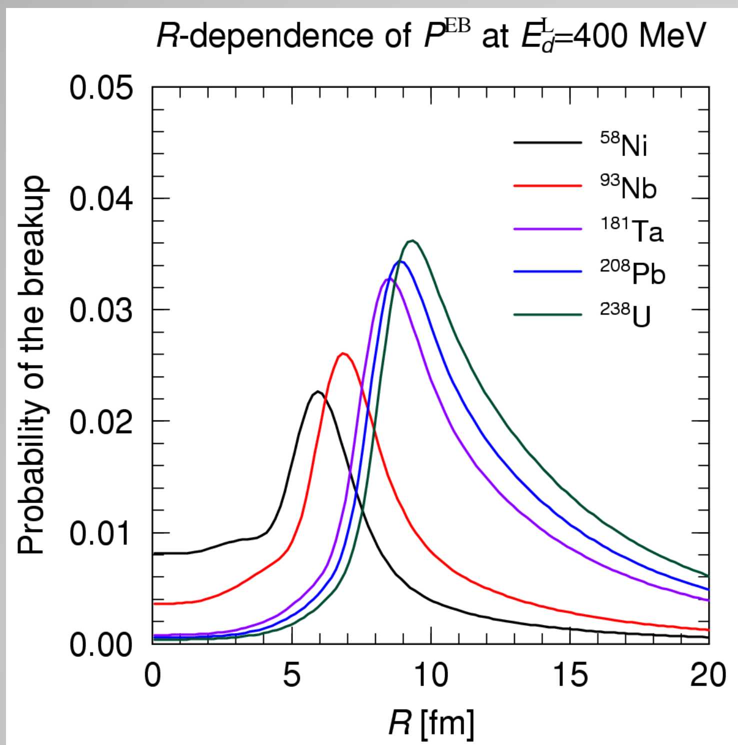
- However, the realistic result of the probability has Fermi distribution.
- How can we determine the radius?

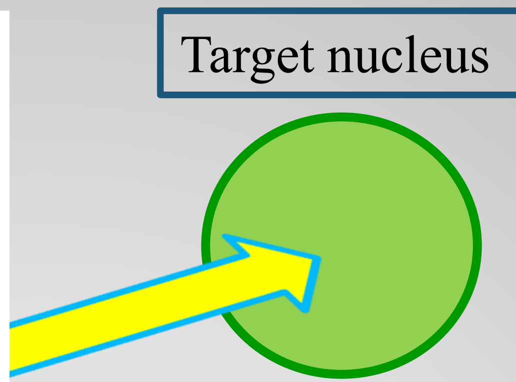


# Reaction cross section

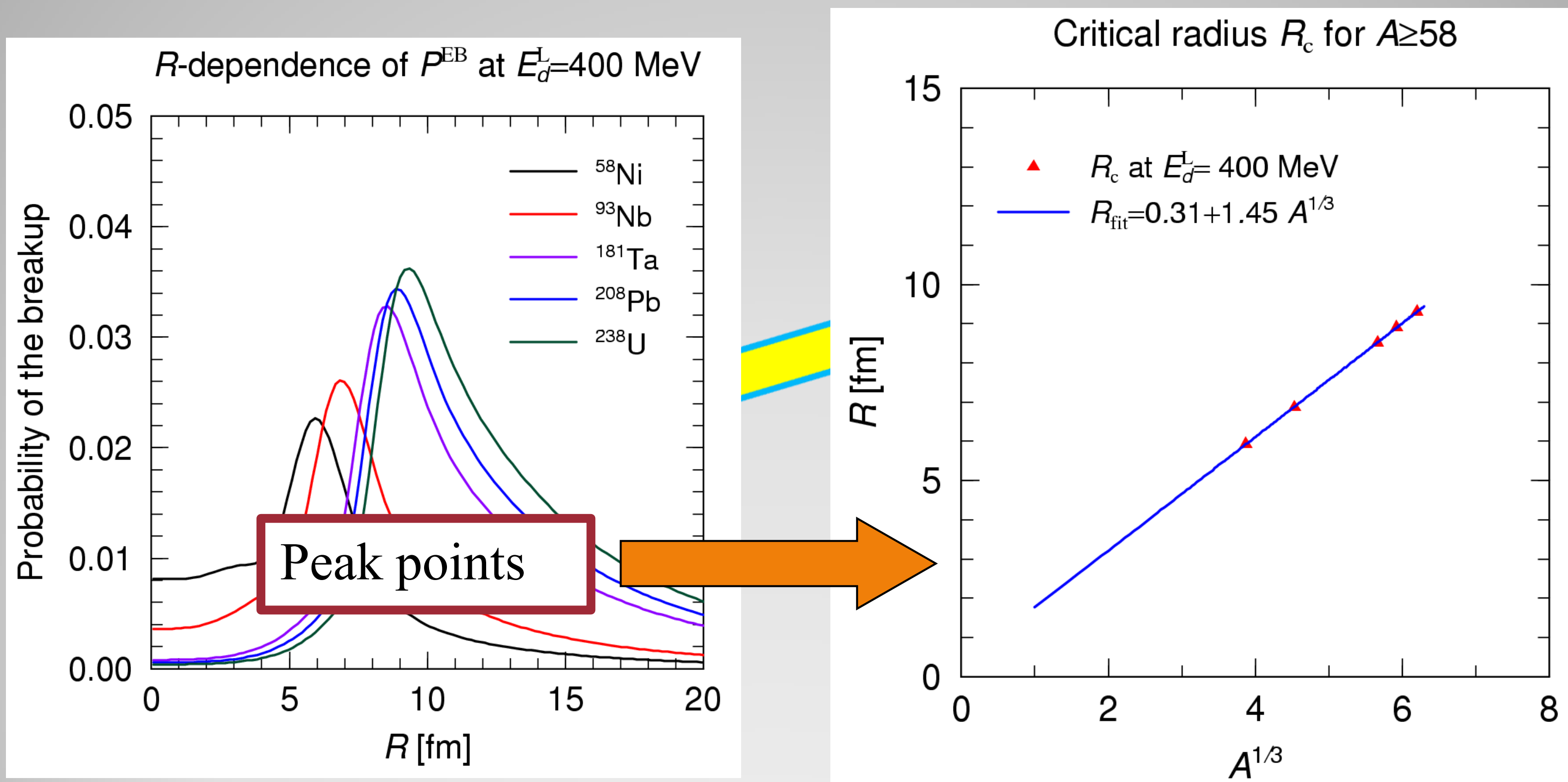
- The probability of the breakup reaction have a peak around surface region of the target.



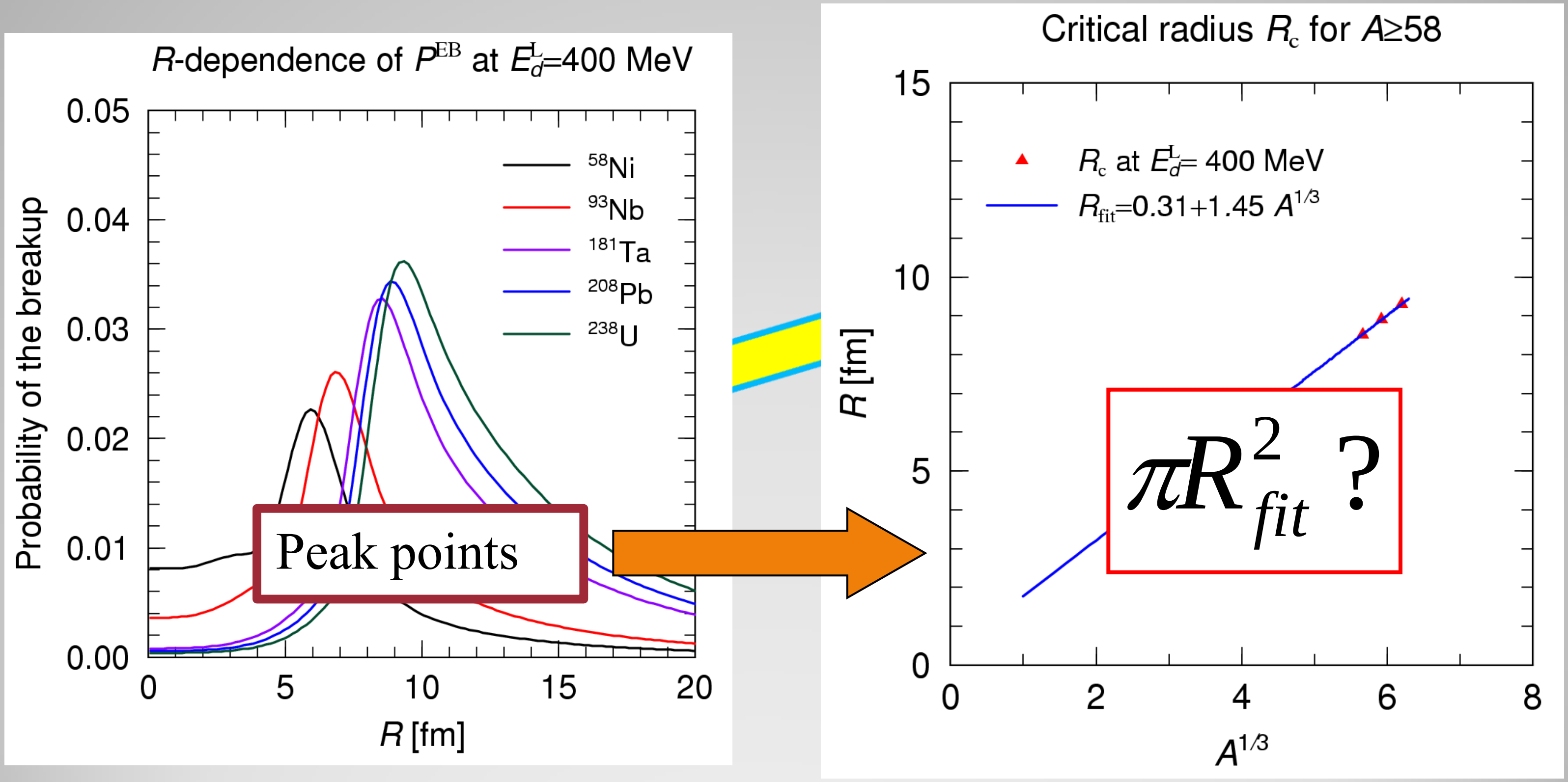
# Reaction cross section

- The probability of the breakup reaction have a peak around surface region of the target.



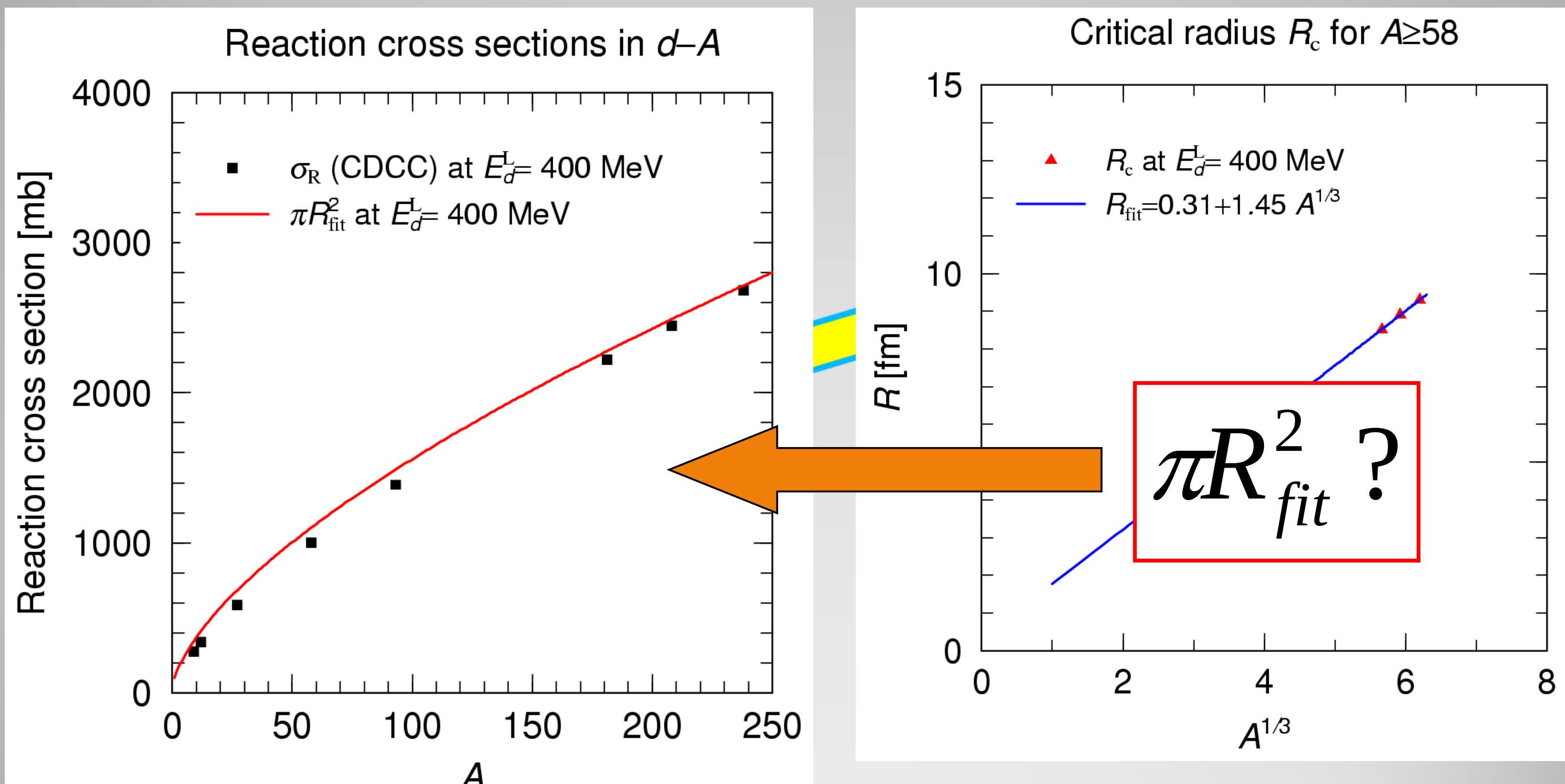
# Reaction cross section

- The probability of the breakup reaction have a peak around surface region of the target.



# Reaction cross section

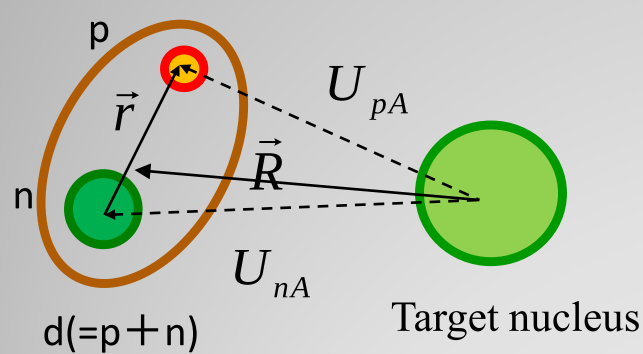
- Surprisingly, the formula with $R_c$ ($R_{fit}$) reproduces the reaction cross section very well.

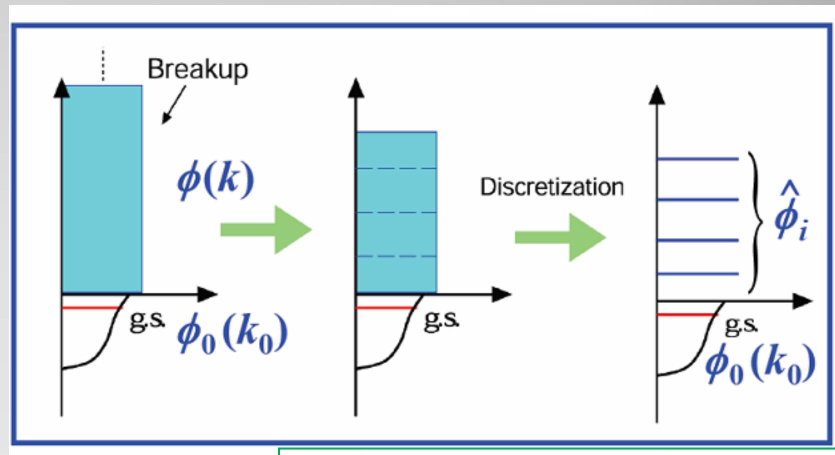


# Frame work

The Continuum-Discretized Coupled-Channels Method (CDCC)
[M. Kamimura, M. Yahiro, Y. Iseri, Y. Sakuragi, H. Kameyama and M. Kawai, Prog. Theo. Phys. Suppl. **89**, 1 (1986).]

■Powerful tool for the analysis of the breakup reaction of composite particle




*Truncation and Discretization*

$$H = T_r + V_{pn}(r) + T_R + U_{pA}(r_p) + U_{nA}(r_n) + V_{Coul}(r_p)$$

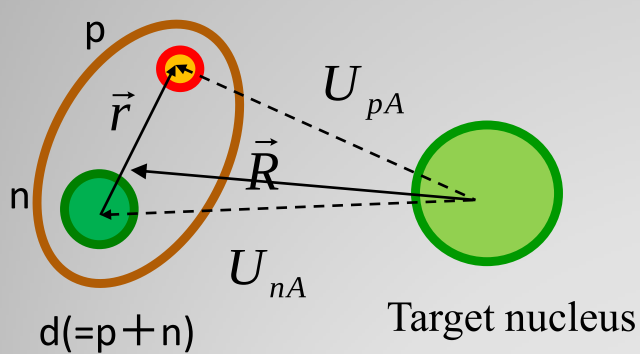
$$\Psi_{CDCC} = \chi_0(R,K)\phi_0(r) + \Sigma\chi_i(R,K_i)\phi_i(r,k_i)$$

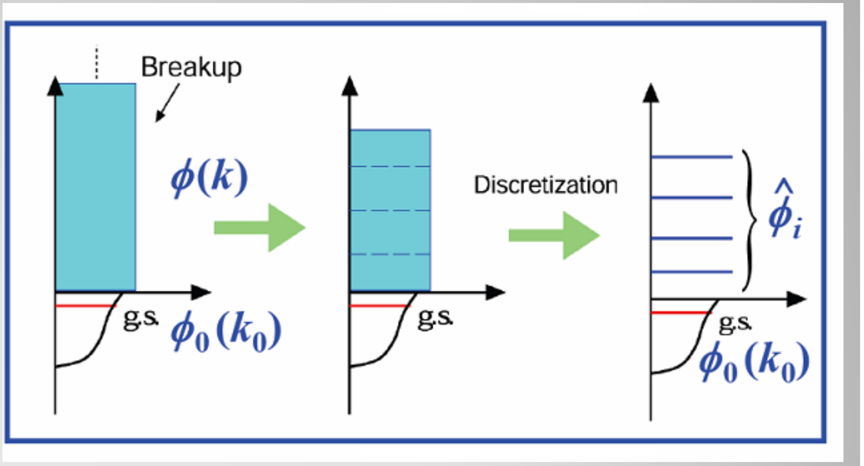
$$\rightarrow U^{(-)}(K_i R)\delta_{i0} - \sqrt{K_0 / K_i}\, S_{iL} U^{(+)}(K_i R)$$ (Asymptotic condition)

# Frame work

The Continuum-Discretized Coupled-Channels Method (CDCC)
[M. Kamimura, M. Yahiro, Y. Iseri, Y. Sakuragi, H. Kameyama and M. Kawai, Prog. Theo. Phys. Suppl. **89**, 1 (1986).]

■Powerful tool for the analysis of the breakup reaction of composite particle



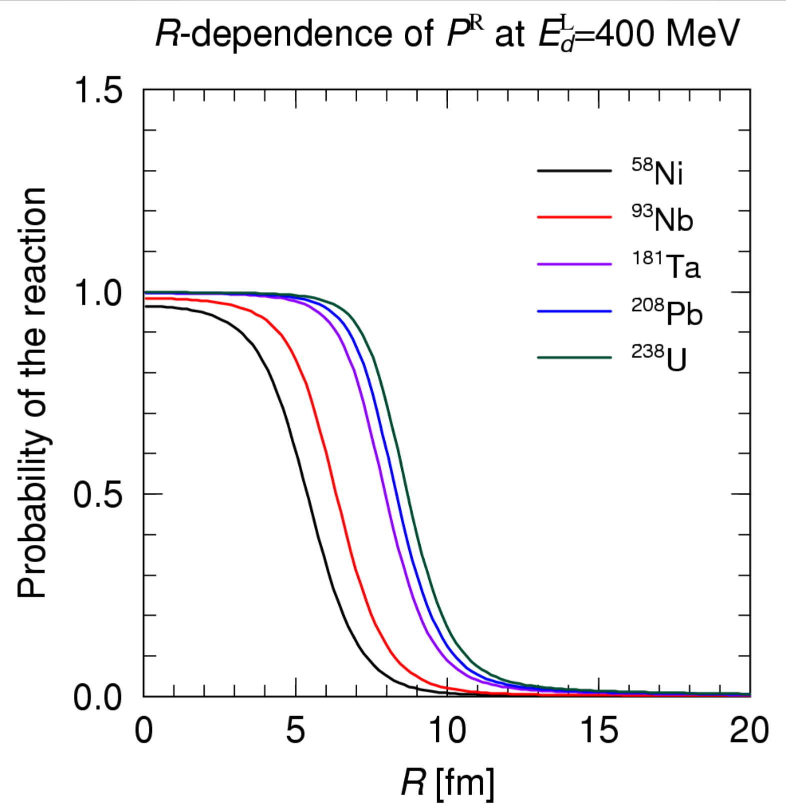

Reaction cross section: $\sigma_R = \sum_L \frac{\pi}{K_0^2}(2L+1)(1-|S_{0L}|^2) = \sum_L \sigma_R(L)$

Breakup cross section: $\sigma_{EB} = \sum_L \frac{\pi}{K_0^2}(2L+1)\sum_{i\neq 0}|S_{iL}|^2 = \sum_L \sigma_{EB}(L)$

- The R-dependence of the probability of the reaction cross section is given from

$$P^R(L) = \frac{\pi}{K_0^2} \frac{\sigma_R(L)}{(2L+1)} = 1 - |S_{0L}|^2$$

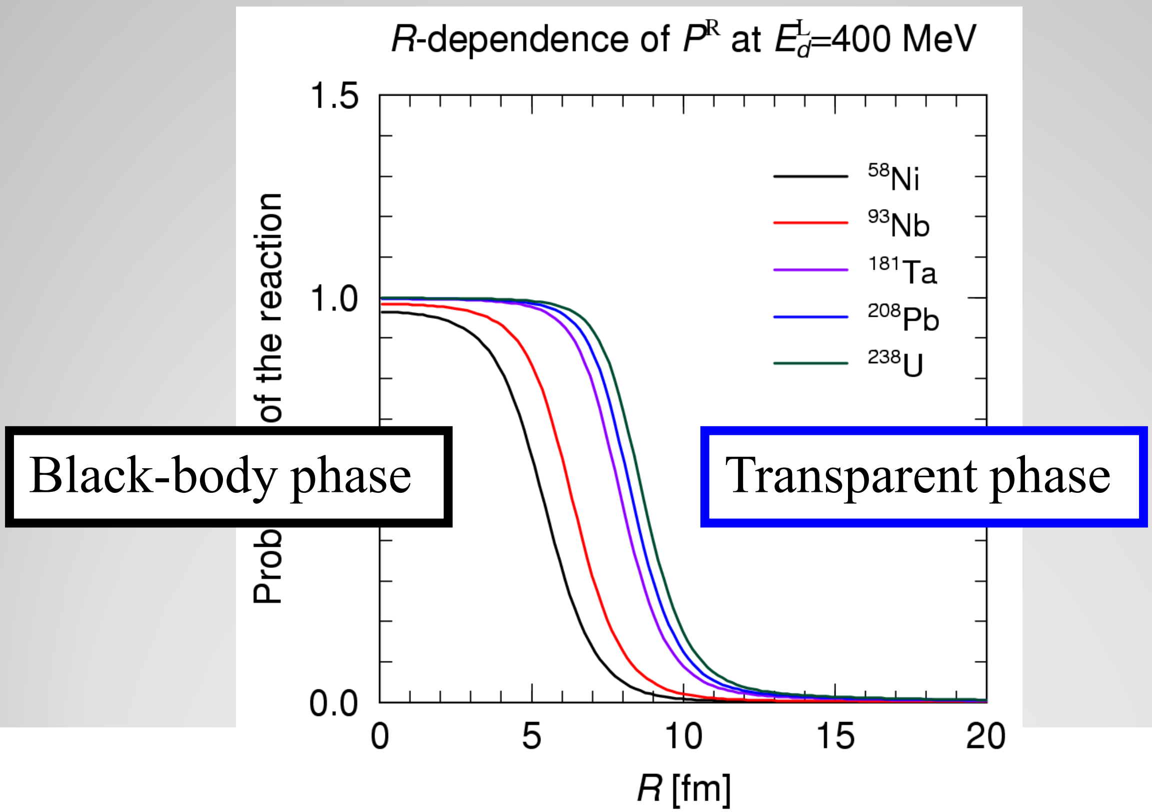
using the semi-classical relation $K_0 R = L + 1/2$



- The R-dependence of the probability of the reaction cross section is given from

$$P^R(L) = \frac{\pi}{K_0^2} \frac{\sigma_R(L)}{(2L+1)} = 1 - |S_{0L}|^2$$

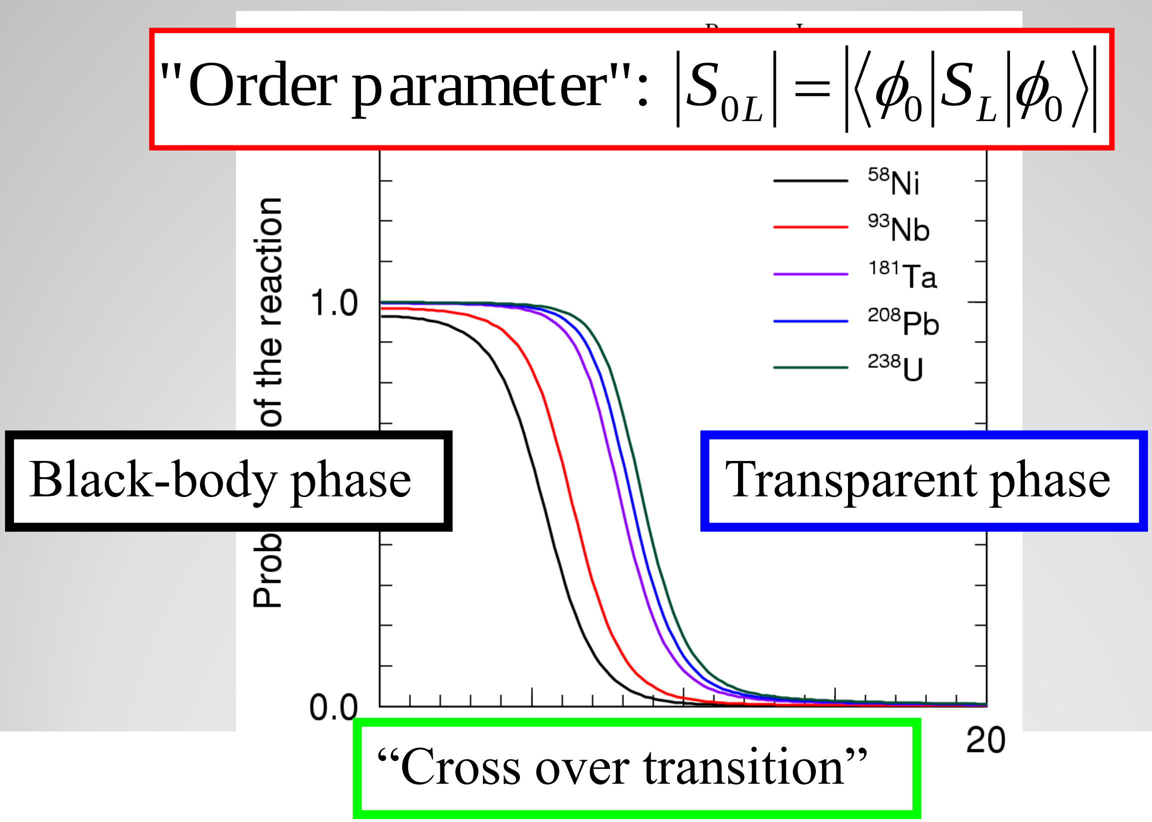
using the semi-classical relation $K_0 R = L + 1/2$



- The R-dependence of the probability of the reaction cross section is given from

$$P^R(L) = \frac{\pi}{K_0^2}\frac{\sigma_R(L)}{(2L+1)} = 1 - |S_{0L}|^2$$

using the semi-classical relation $K_0 R = L + 1/2$



- The fluctuation is given by the following way.

$$\left\langle \phi_0 \middle| S_L^+ S_L \middle| \phi_0 \right\rangle - \left| \left\langle \phi_0 \middle| S_L \middle| \phi_0 \right\rangle \right|^2 = \sum_{i \neq 0} \left\langle \phi_0 \middle| S_L \middle| \phi_i \right\rangle \left\langle \phi_i \middle| S_L \middle| \phi_0 \right\rangle$$

$$\left( \text{complete set} : 1 = \left| \phi_0 \right\rangle \left\langle \phi_0 \right| + \sum_{i \neq 0} \left| \phi_i \right\rangle \left\langle \phi_i \right| \right)$$

- The fluctuation is given by the following way.

$$\left\langle \phi_0 \middle| S_L^+ S_L \middle| \phi_0 \right\rangle - \left| \left\langle \phi_0 \middle| S_L \middle| \phi_0 \right\rangle \right|^2 = \sum_{i \neq 0} \left\langle \phi_0 \middle| S_L \middle| \phi_i \right\rangle \left\langle \phi_i \middle| S_L \middle| \phi_0 \right\rangle$$

$$= \sum_{i \neq 0} \left| \left\langle \phi_i \middle| S_L \middle| \phi_0 \right\rangle \right|^2$$

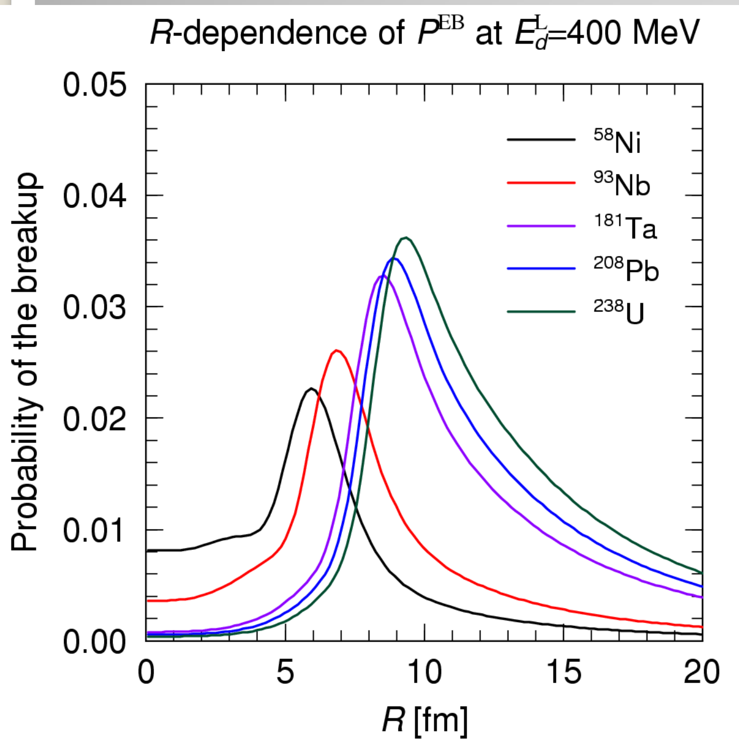
$$= \sum_{i \neq 0} \left| S_{iL} \right|^2 = \frac{K_0^2}{\pi} \sigma_{EB}(L)$$

- The fluctuation is given by the following way.

$$\left\langle \phi_0 \middle| S_L^+ S_L \middle| \phi_0 \right\rangle - \left| \left\langle \phi_0 \middle| S_L \middle| \phi_0 \right\rangle \right|^2 = \sum_{i \neq 0} \left\langle \phi_0 \middle| S_L \middle| \phi_i \right\rangle \left\langle \phi_i \middle| S_L \middle| \phi_0 \right\rangle$$

$$= \sum_{i \neq 0} \left| \left\langle \phi_i \middle| S_L \middle| \phi_0 \right\rangle \right|^2$$

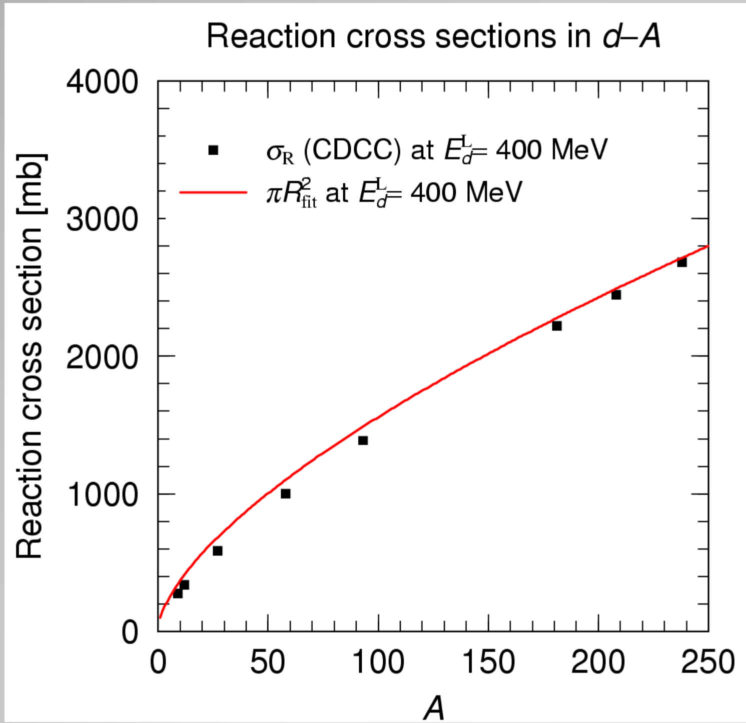
$$= \sum_{i \neq 0} \left| S_{iL} \right|^2 = \frac{K_0^2}{\pi} \sigma_{EB}(L)$$

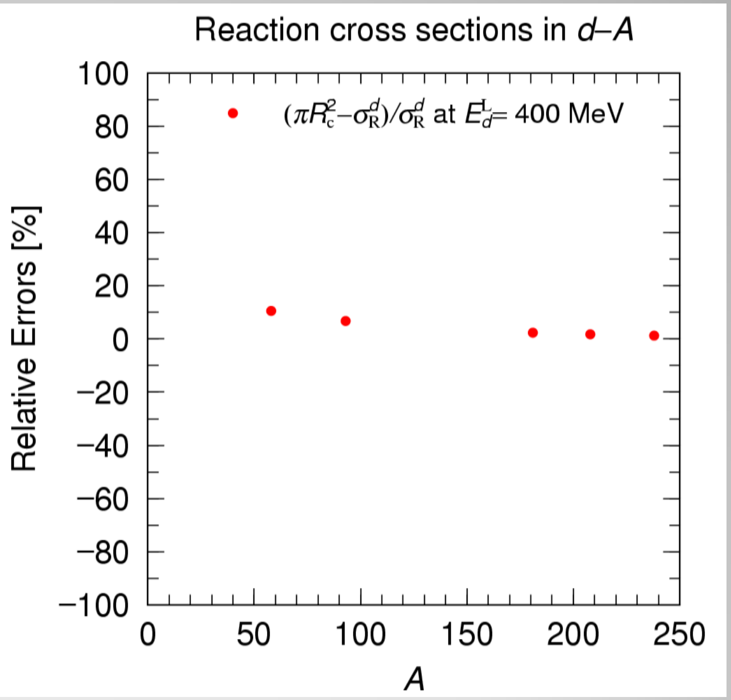



- The "critical radius" is determined as the point of the peak of $P_{EB}(R)$.

# Results

- The deuteron induced reaction on various targets at 400 MeV.

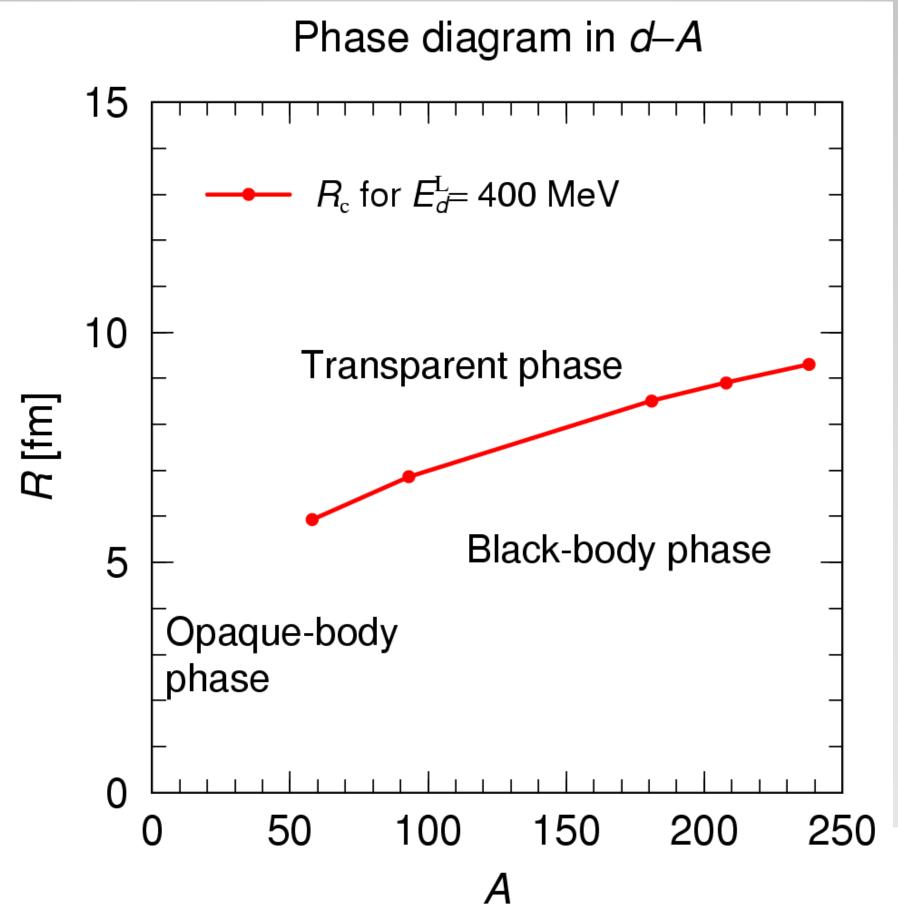



- Using “critical radius” , the results agree with the reaction cross sections within 10%.

# Results

- We can draw the "phase diagram" for the reaction cross section.



# Summary and Future work

- We analyzed the deuteron induced reaction on various targets at 400 MeV.
- We found the "critical radius" describing the scaling of the reaction cross section very well on the analogy of the "phase transition".

- The incident energy dependence of the new idea should be investigated.
- We will analyze the reaction with unstable nuclei, such as $^{8}B$, $^{11}Be$.