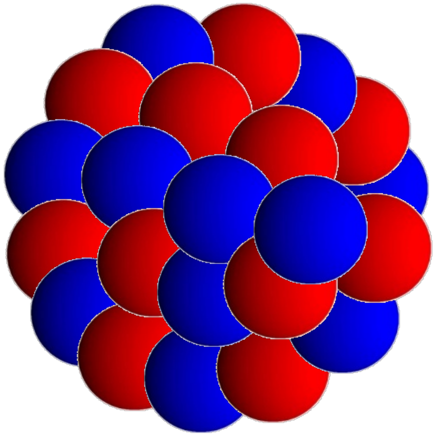
はじめに：低エネルギー原子核物理学のめざすもの



- 核子多体系としての原子核の振る舞い

  ⟵ 核子間相互作用から理解する

- ➢ 静的な振る舞い：原子核構造論
  - ✓ 基底状態の性質
    （質量、大きさ、形など）
  - ✓ 励起状態の性質

- ➢ ダイナミックス：原子核反応論

原子核は複合粒子
✓ 豊富な反応様式

- 弾性散乱
- 非弾性散乱
- 核子移行反応
- 核融合反応

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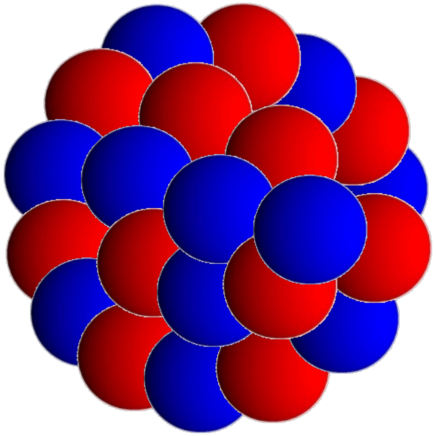

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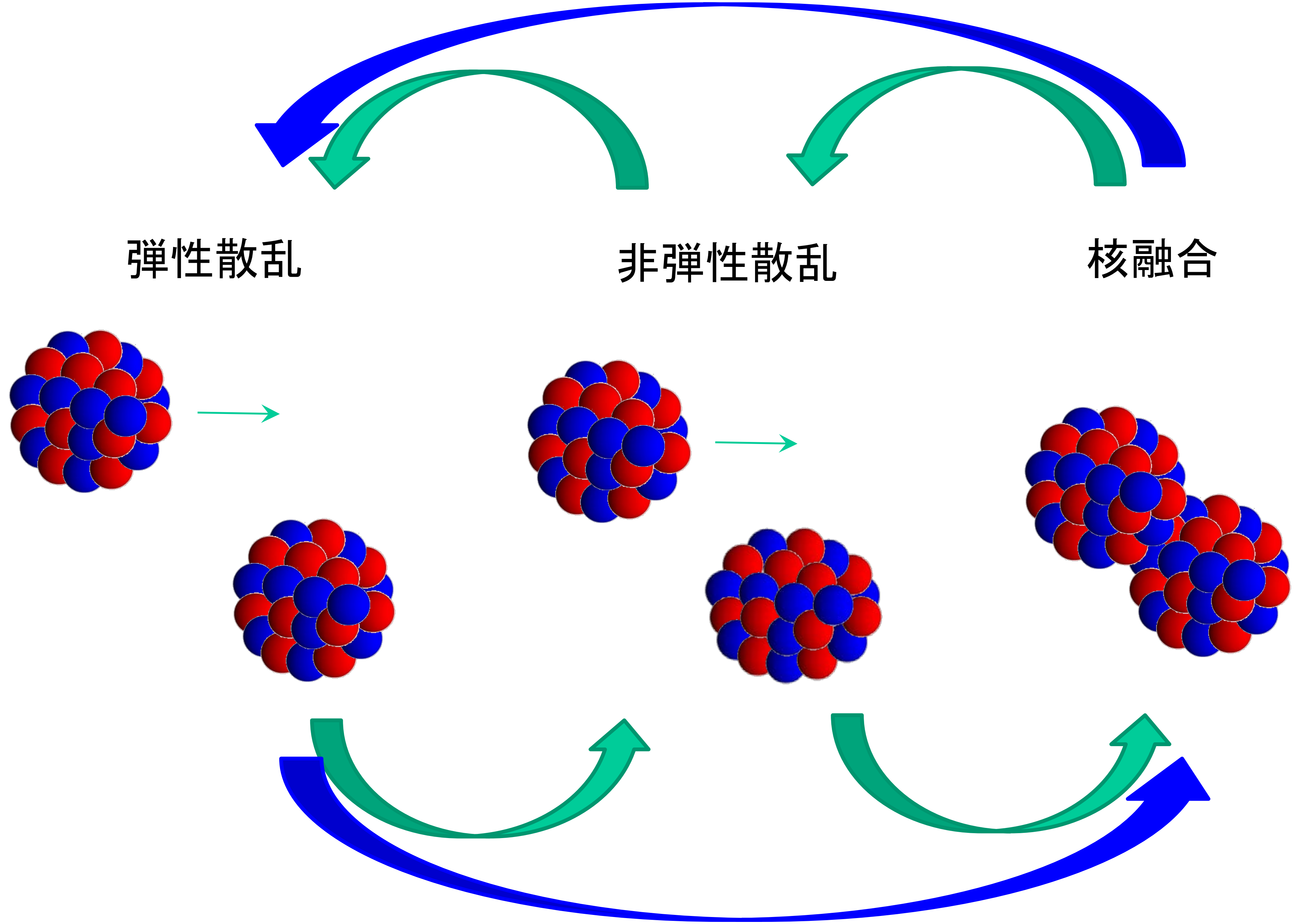
- ダイナミックス：原子核反応論

原子核は複合粒子
✓ 豊富な反応様式
✓ 核構造と核反応の織り成す様々なインタープレイ

- 弾性散乱
- 非弾性散乱
- 核子移行反応
- 核融合反応

量子多体系のダイナミックス（原子核反応）

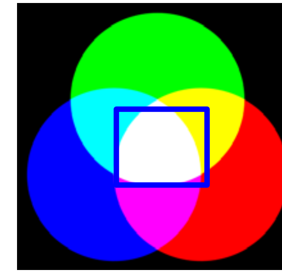


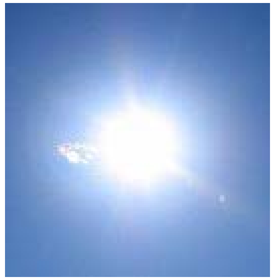
Nuclear Reactions

Shape, interaction, and excitation structures of nuclei $\longleftarrow$ scattering expt.

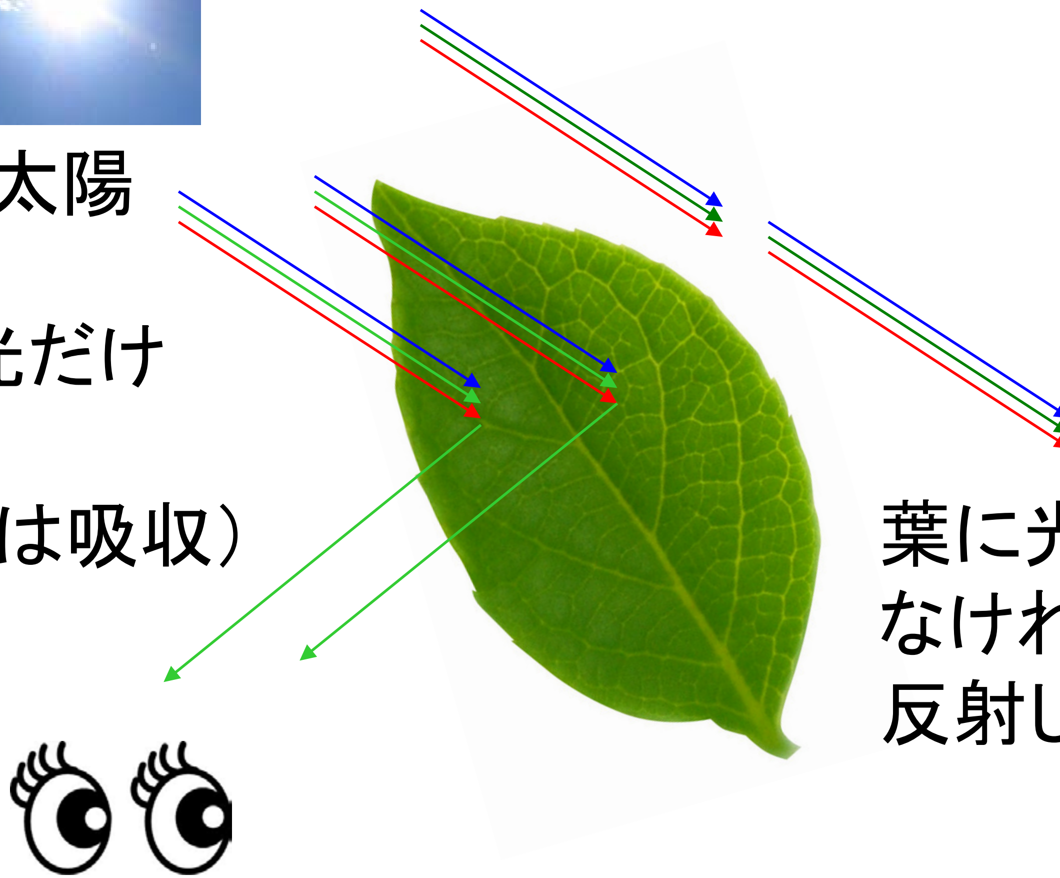
cf. Experiment by Rutherford (α scatt.)

そもそも、ものが見えるとはどういうことか？





太陽



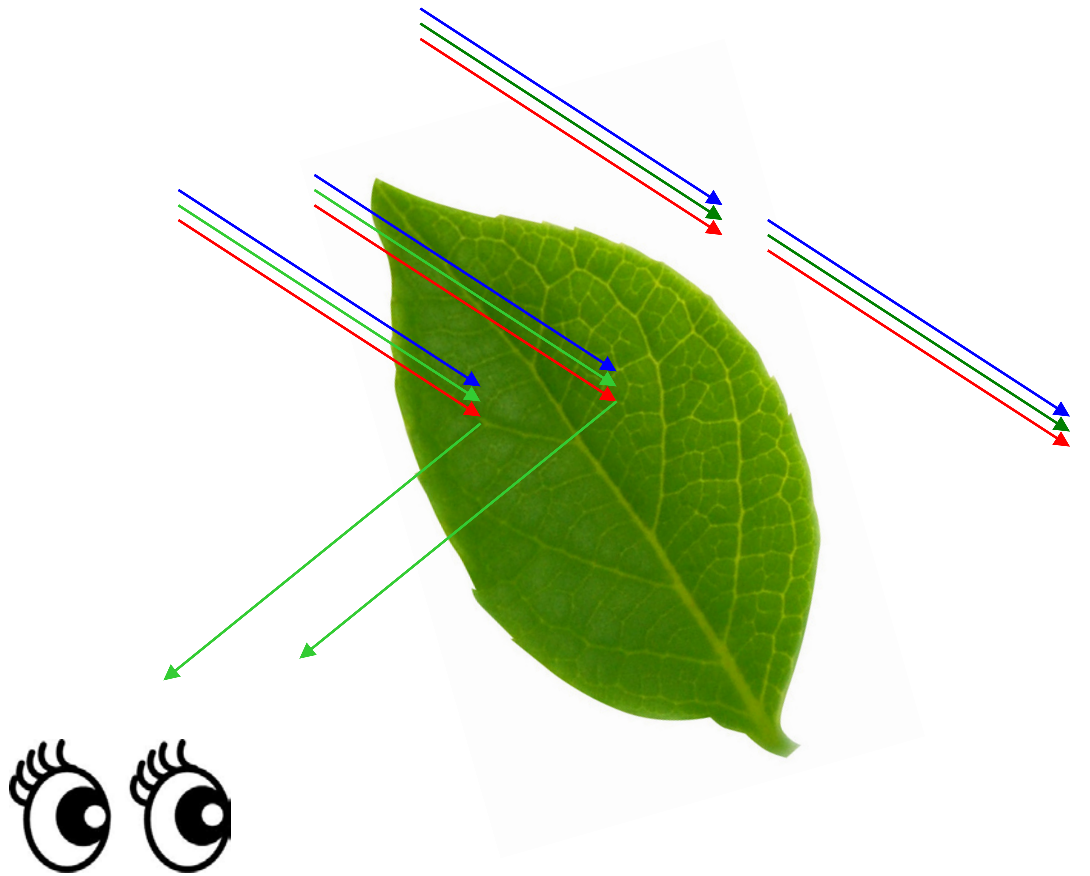
緑色の光だけが反射（他の色は吸収）

葉に光が当たらなければ緑は反射しない

⇩

葉の形

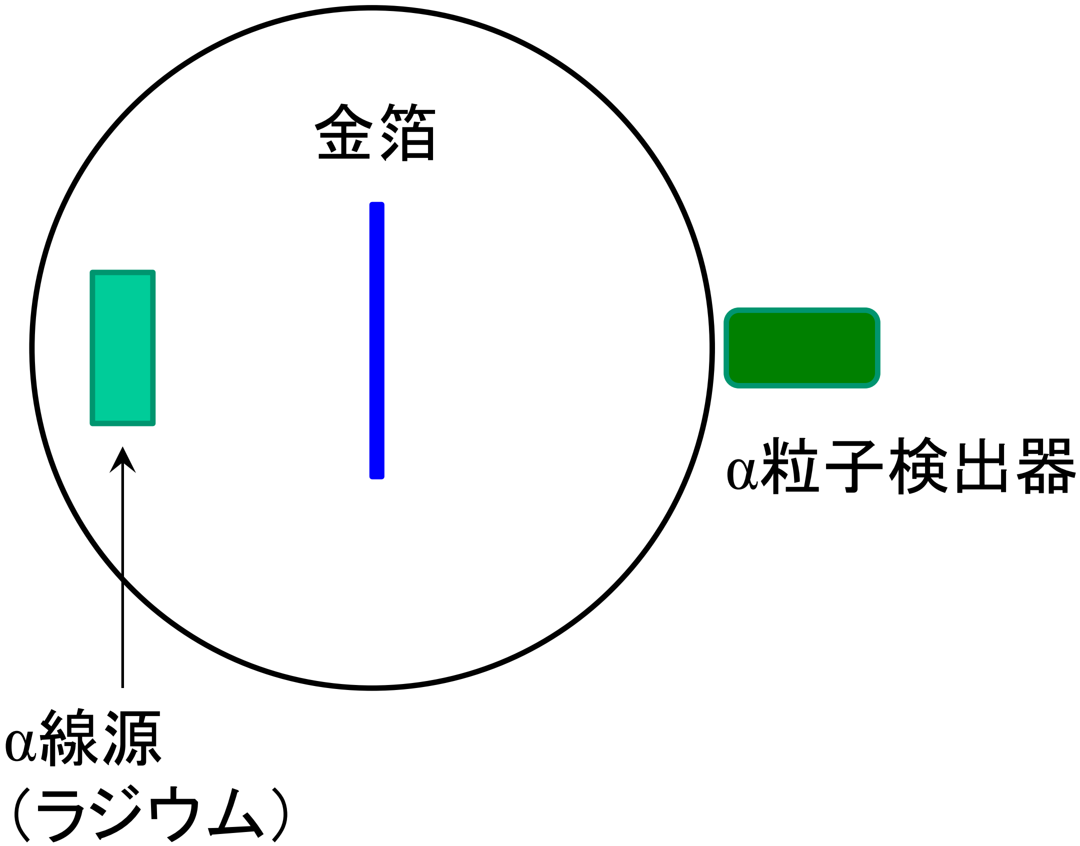
そもそも、ものが見えるとはどういうことか？



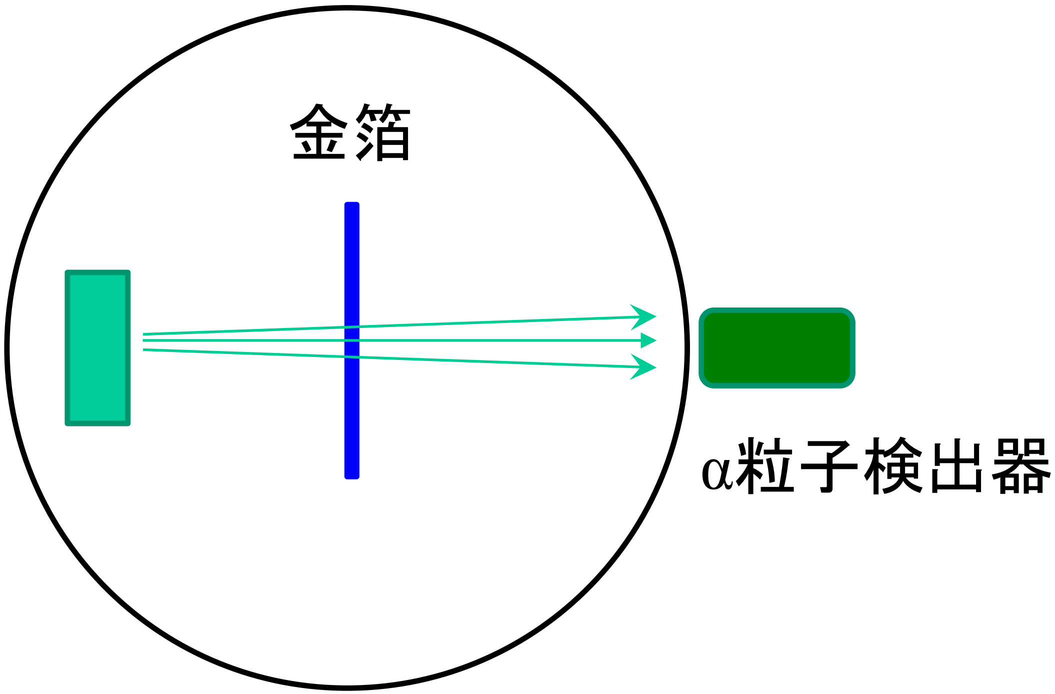
原子核のようなミクロなものの大きさを測るのも基本的には同じ

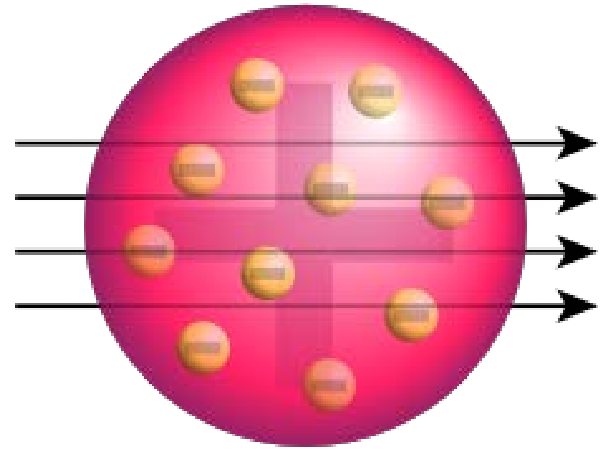
何かをぶつけて、どのように散乱されるか観測する

ラザフォード散乱（ラザフォード、ガイガー、マーースデン ：1909年）



ラザフォード散乱 （ラザフォード、ガイガー、マースデン ：1909年）





J.J.トンプソンのブドウパン模型を検証したい

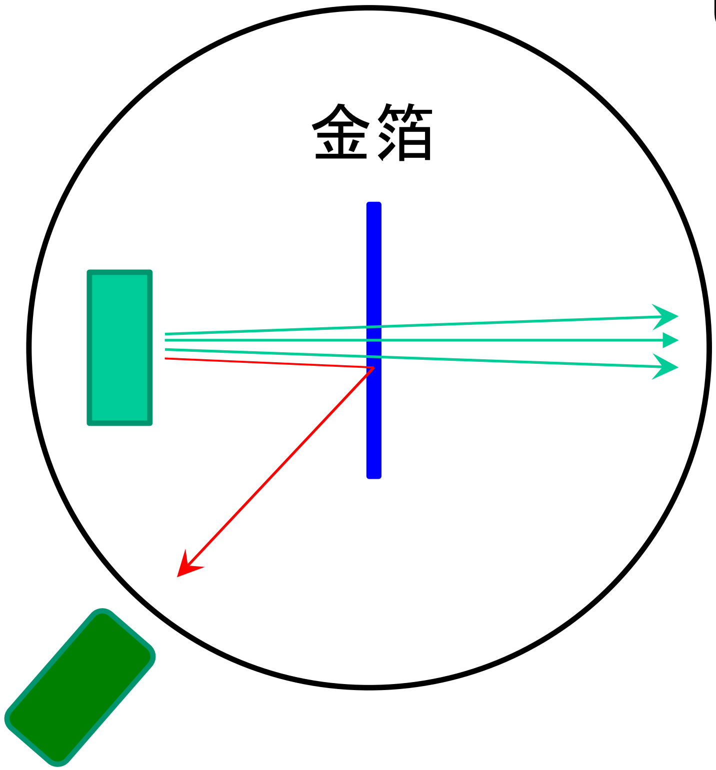
⇩

散乱の角度は高々 0.01 度

観測：たいていのα粒子はほとんど曲げられずに検出器に入る
→ブドウパン模型は正しそうだ（?）

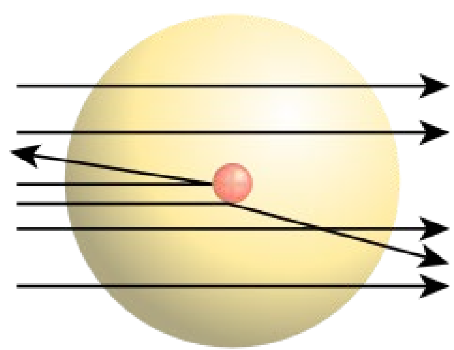
ラザフォード散乱 （ラザフォード、ガイガー、マースデン ：1909年）

試しに検出器を後方角度に置いて見た
（ブドウパン模型が正しければ、何も観測しないはず）



α粒子検出器

8千個に1個の割合で後方に跳ね返ってくるα粒子を観測
（驚愕の事実）



→ 原子核の大きさは約 2×10^{-14} m 以下

Nuclear Reactions

Shape, interaction, and excitation structures of nuclei ⟵ scattering expt.

cf. Experiment by Rutherford (α scatt.)

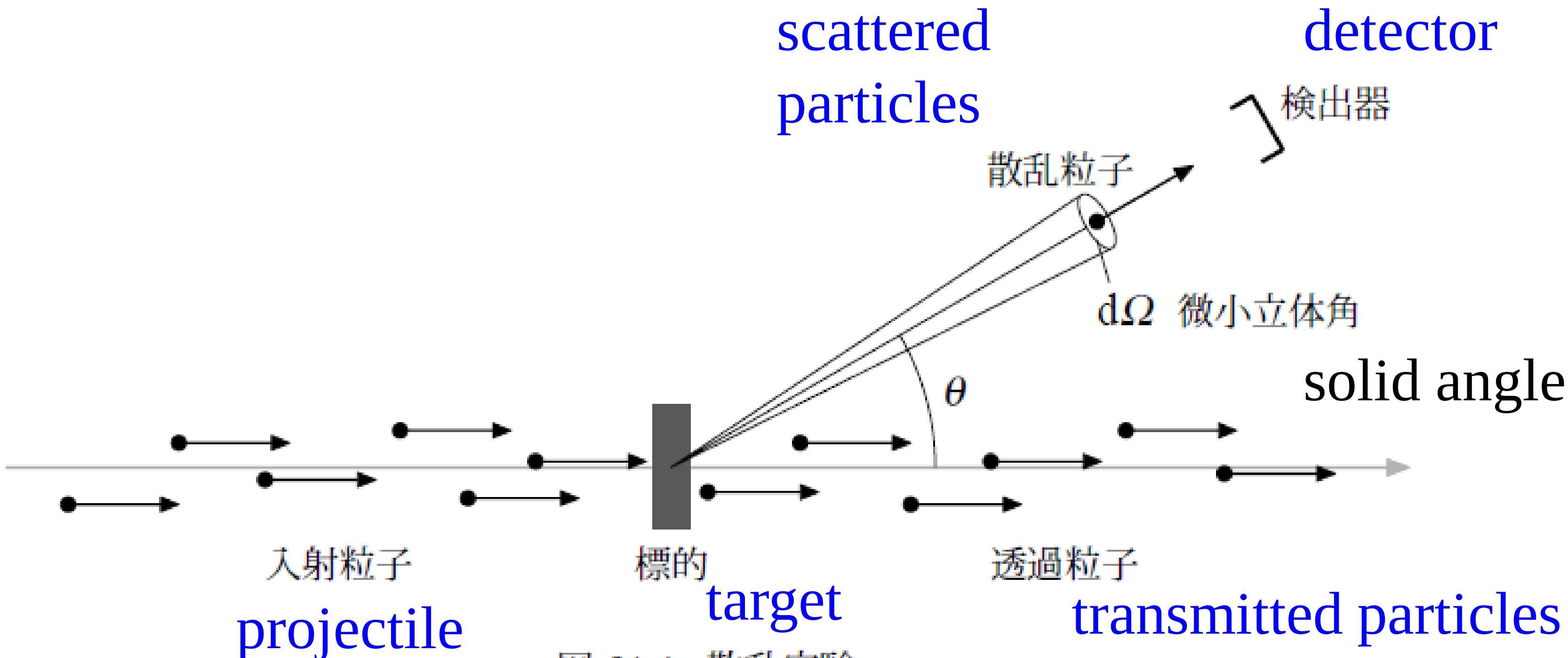


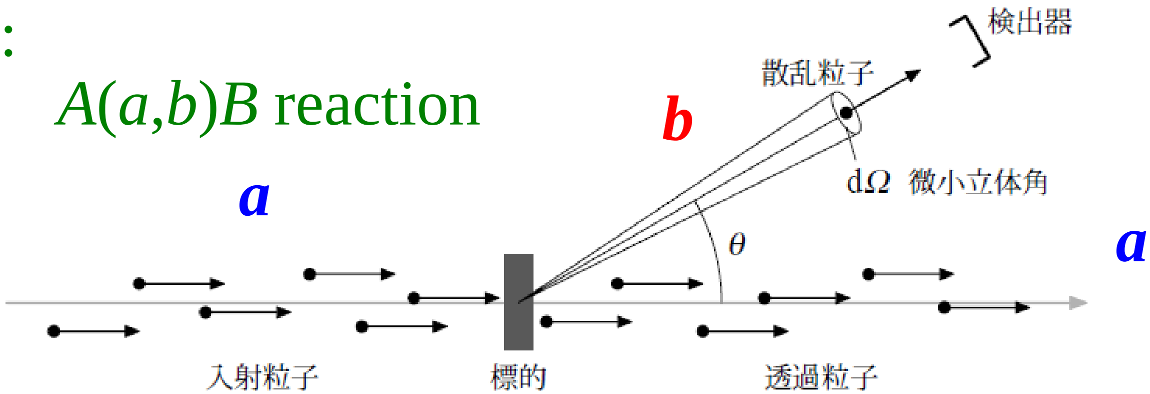
図 21.1: 散乱実験

http://www.th.phys.titech.ac.jp/~muto/lectures/QMII11/QMII11_chap21.pdf

K. Muto (TIT)

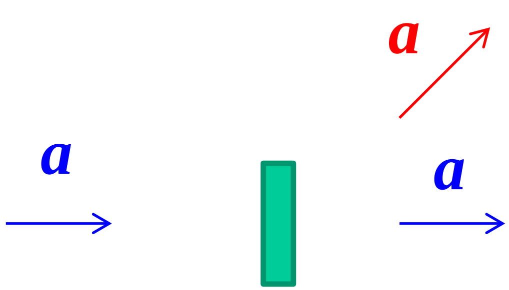
notation:

$A(a,b)B$ reaction



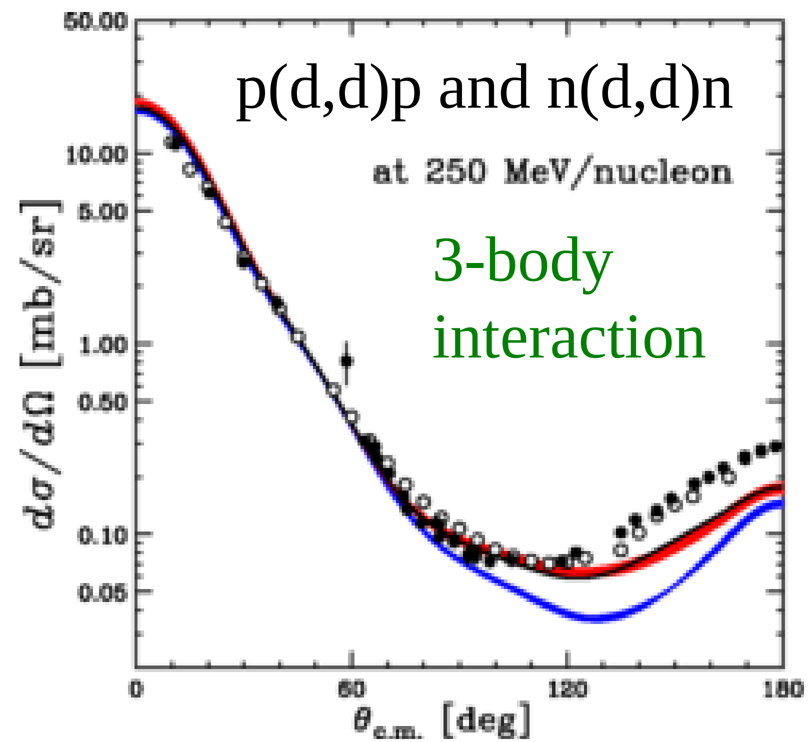
$A \rightarrow B$

✓elastic scattering



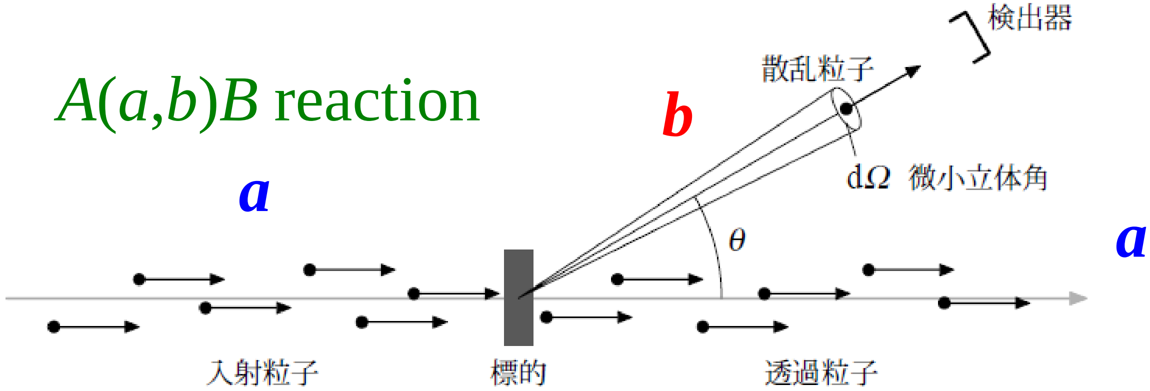
$A_{gs} \rightarrow A_{gs}$

fundamental interaction between a and A



K. Sekiguchi et al., PRC89('14)064007

$A(a,b)B$ reaction



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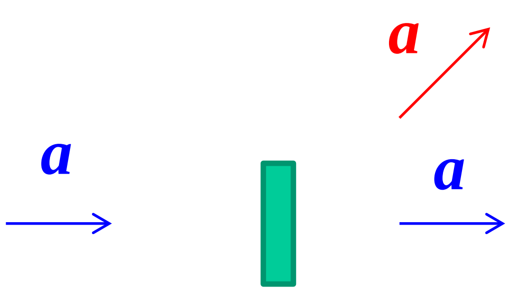

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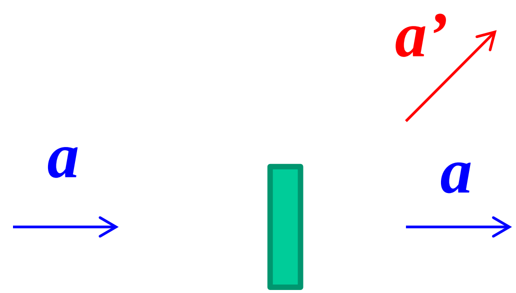
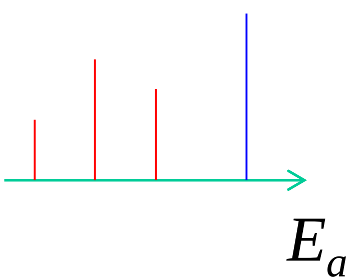
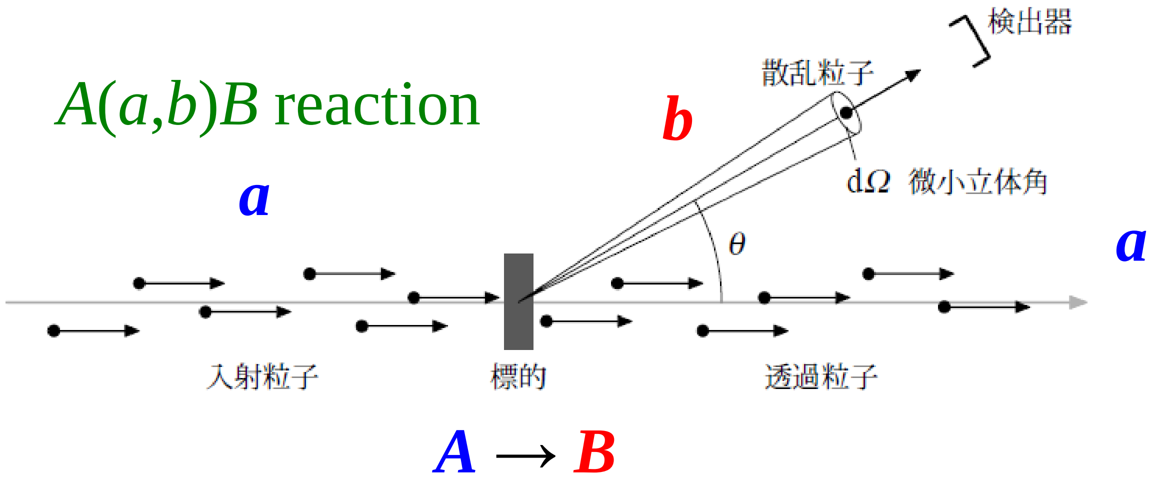


$A_{gs} \rightarrow A^*$

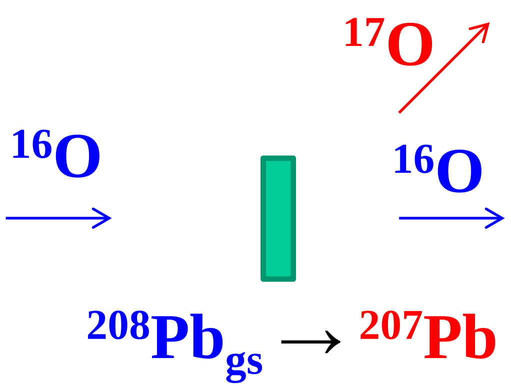
excitation spectrum of a nucleus A





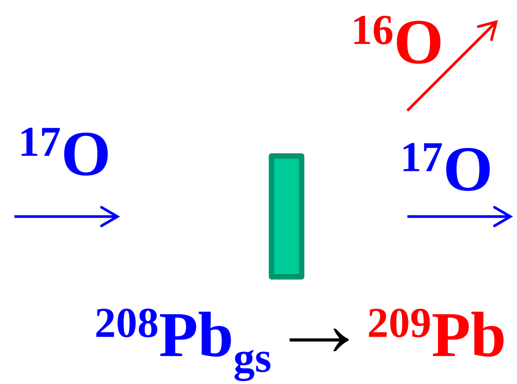
transfer reactions

✓transfer reaction
(pick-up reaction)



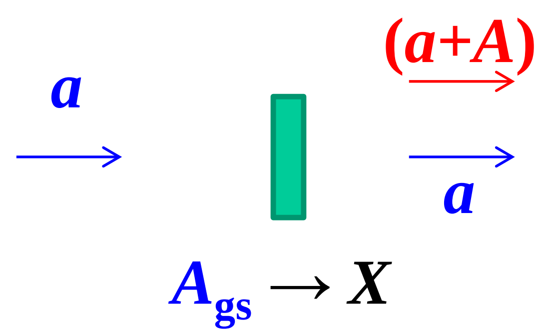
level schem of ^{207}Pb

✓transfer reaction
(stripping reaction)



level schem of ^{209}Pb

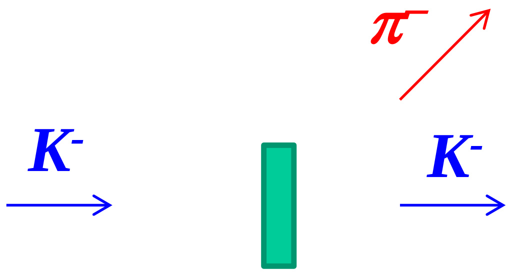
✓fusion reaction



- interaction between *a* and *A*
- structure of *a* and *A*

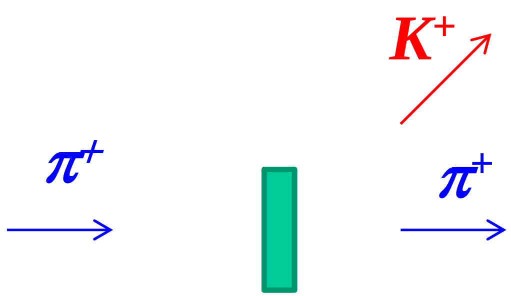
hypernucleus production reactions

✓ (K^-,π^-) reaction



$A_{gs} \rightarrow A_{\Lambda}$

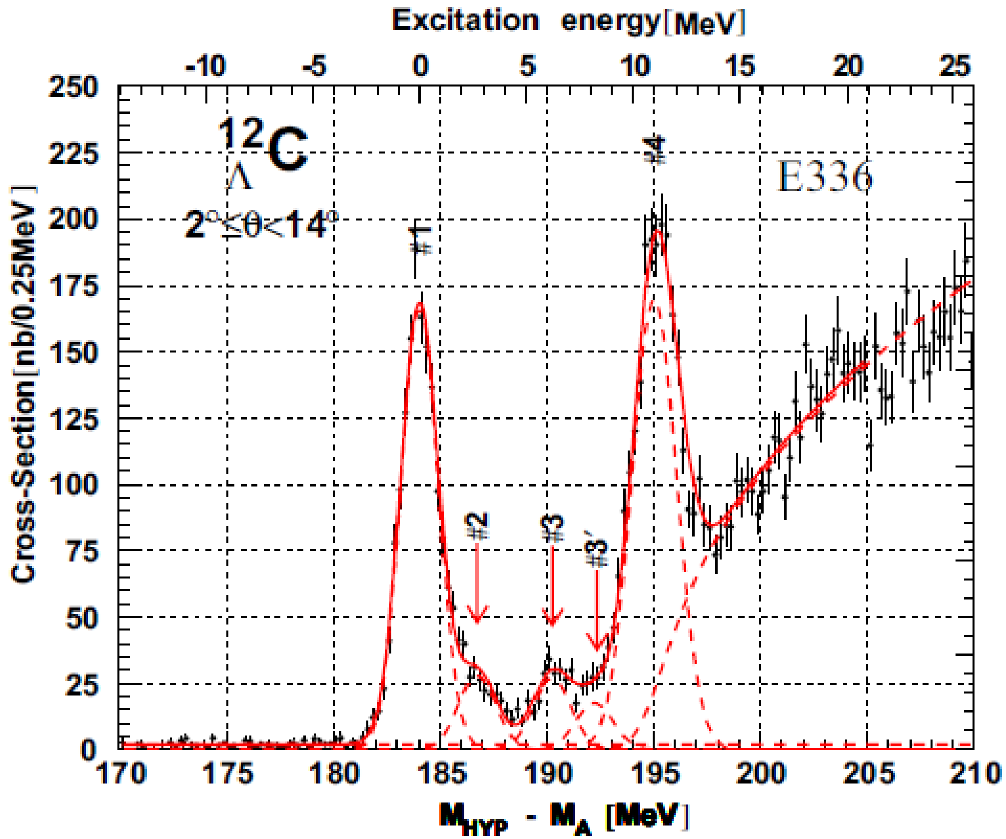
✓ (π^+,K^+) reaction



$A_{gs} \rightarrow A_{\Lambda}$

excitation spectrum
of a hypernucleus A_{Λ}

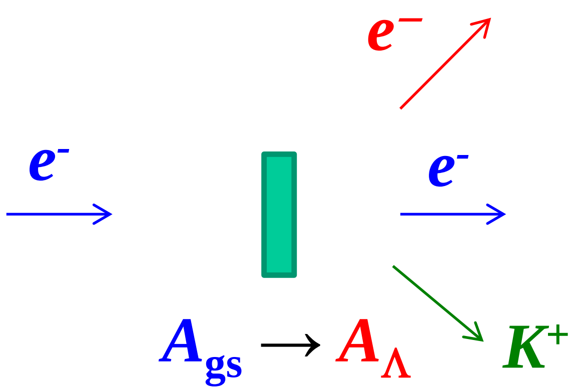
$^{12}C\ (\pi^+,K^+)\ ^{12}{}_{\Lambda}C$ reaction



O. Hashimoto and H. Tamura,
Prog. in Part. and Nucl. Phys. 57 ('06)564

"reaction spectroscopy"

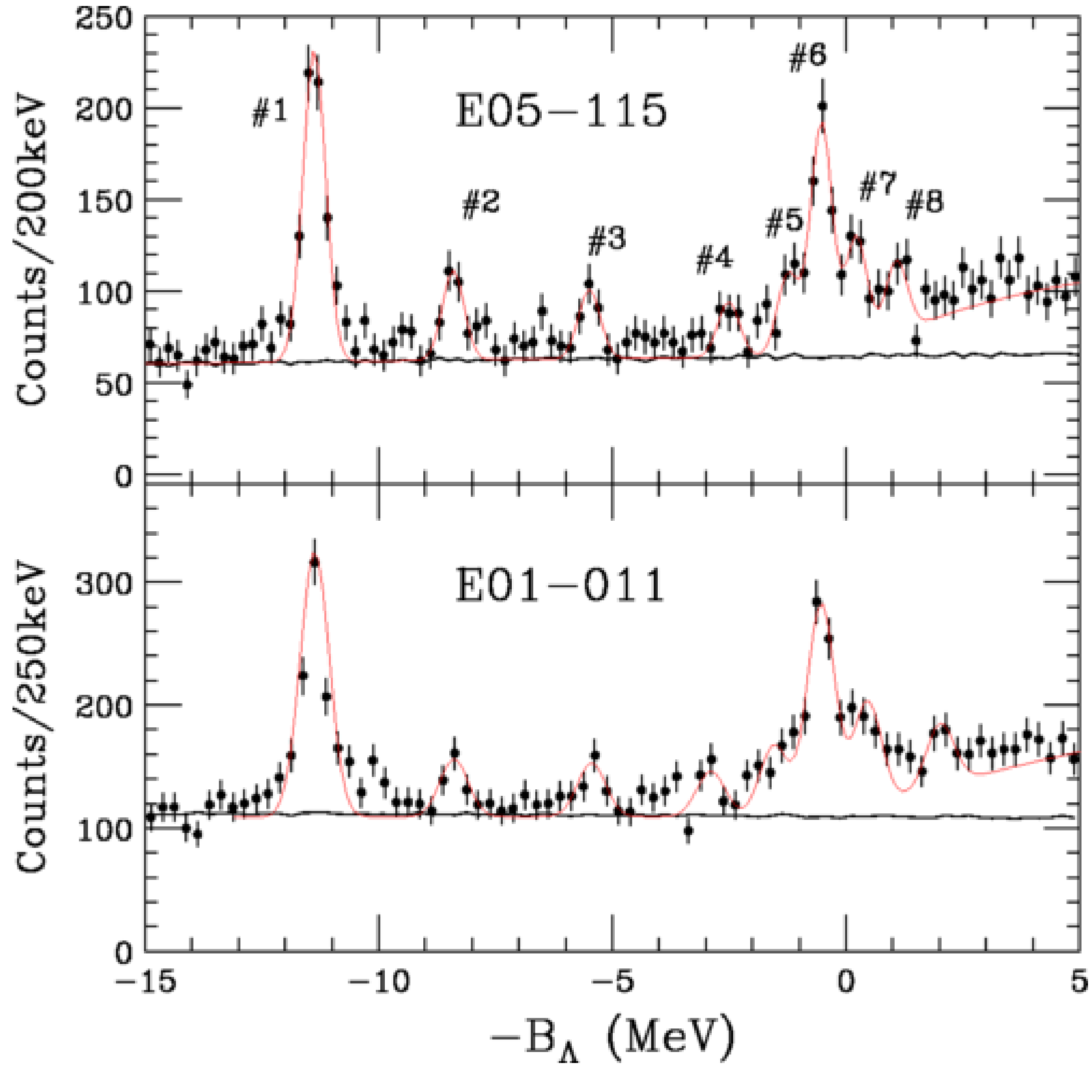
✓(e,e’K$^+$) reaction



S.N. Nakamura et al.,
PRL110(‘13)012502

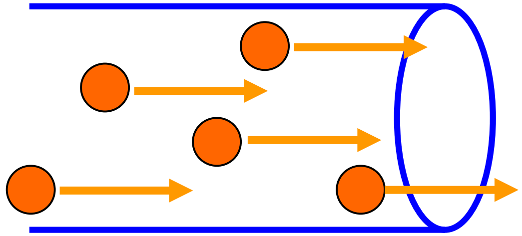
T. Gogami,
Ph.D. Thesis (Tohoku U.)
2014

$^{12}C(e,e'K^+)\ ^{12}_{\Lambda}B$



L. Tang et al., PRC90(‘14)034320

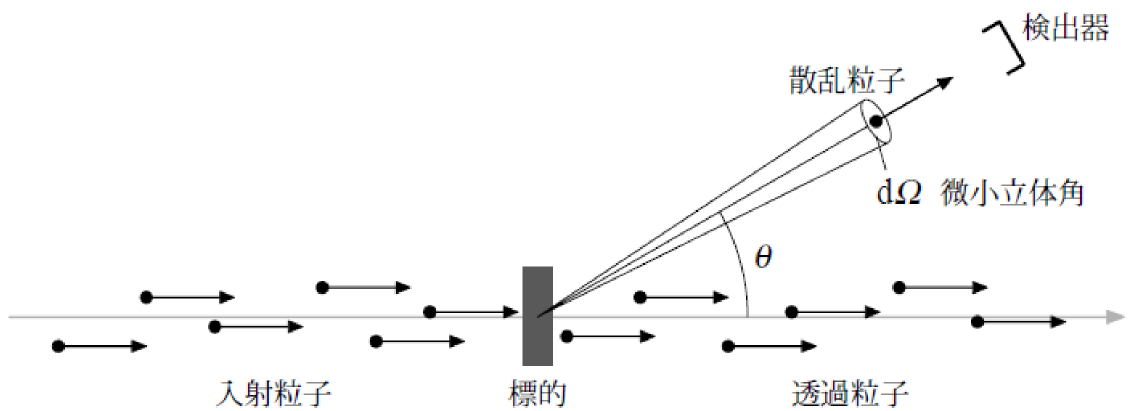
Cross sections



incident beam

flux = the number of particles crossing unit area per unit time

$$j = \rho_{\mathrm{P}} \cdot v$$

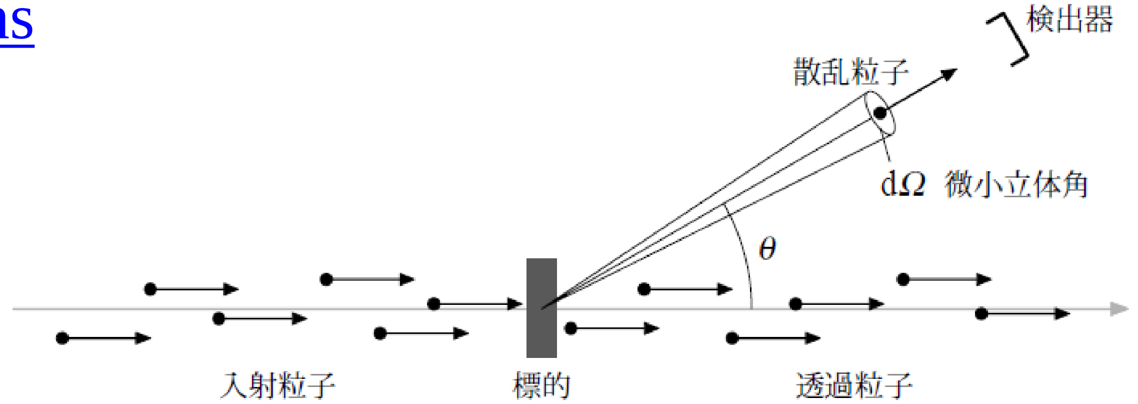


event rate (the number of event per unit time per target nucleus)
: proportional to the incident flux

cross section

$$\longrightarrow \quad R = N_{\mathrm{T}} \cdot \sigma \cdot j$$

Cross sections



event rate (the number of event per unit time per target nucleus)
: proportional to the incident flux

cross section

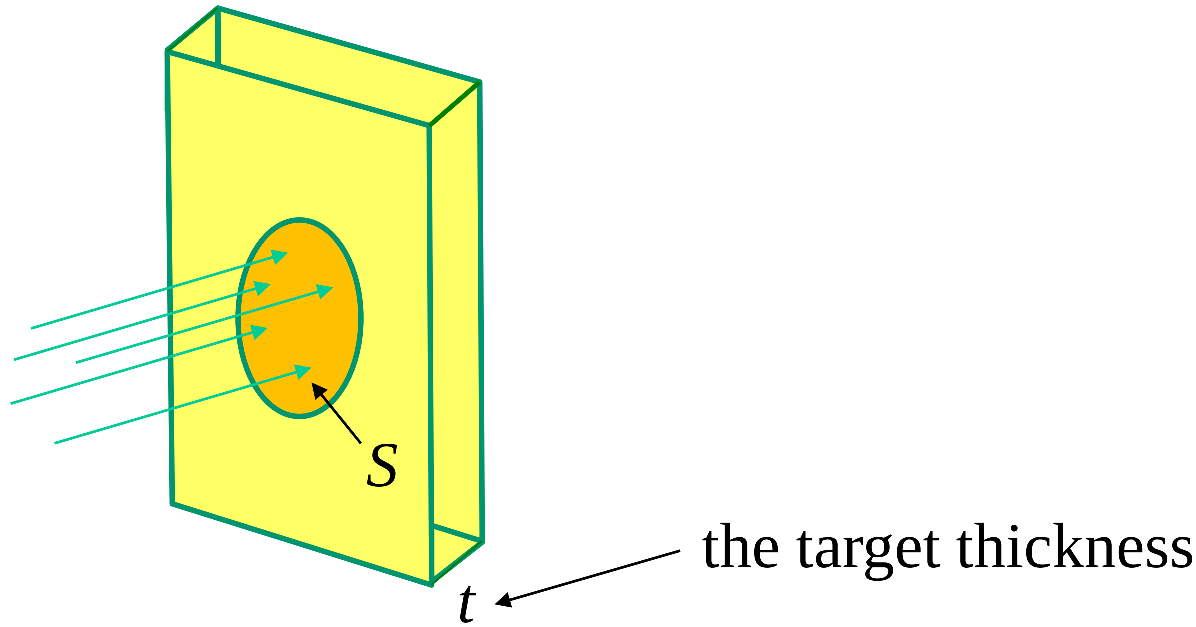
$$\longrightarrow \quad R = N_T \cdot \sigma \cdot j$$

differential cross sections (angular distribution)

$$dR(\theta,\phi) = N_T \cdot \frac{d\sigma}{d\Omega} \cdot j \cdot d\Omega \qquad \sigma = \int d\Omega \frac{d\sigma}{d\Omega}$$

units: 1 barn = 10^{-24} cm^2 = 100 fm^2 (1 mb = 10^{-3} b = 0.1 fm^2)

Cross sections (experiments)



$$dR(\theta,\phi) = N_{\mathsf{T}} \cdot \frac{d\sigma}{d\Omega} \cdot j \cdot d\Omega$$

the number of target nucleus: $N_{\mathsf{T}} = S \cdot t \cdot \rho_{\mathsf{T}}$

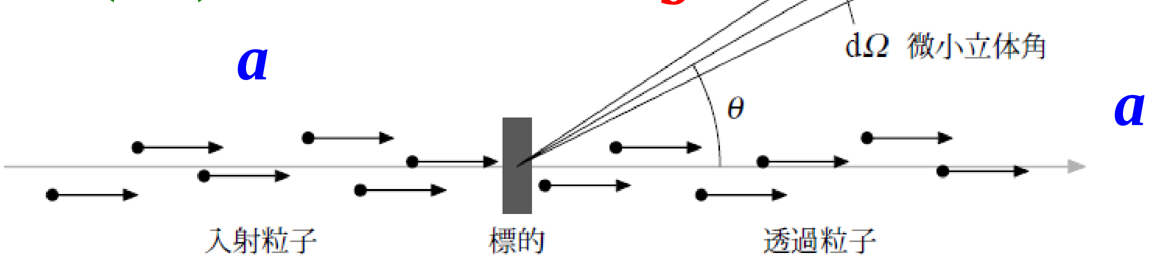
beam intensity: $I = j \cdot S$

$$dR(\theta,\phi) = I \cdot \frac{d\sigma}{d\Omega} \cdot t\rho_{\mathsf{T}} \cdot d\Omega \cdot \epsilon$$

detection efficiency

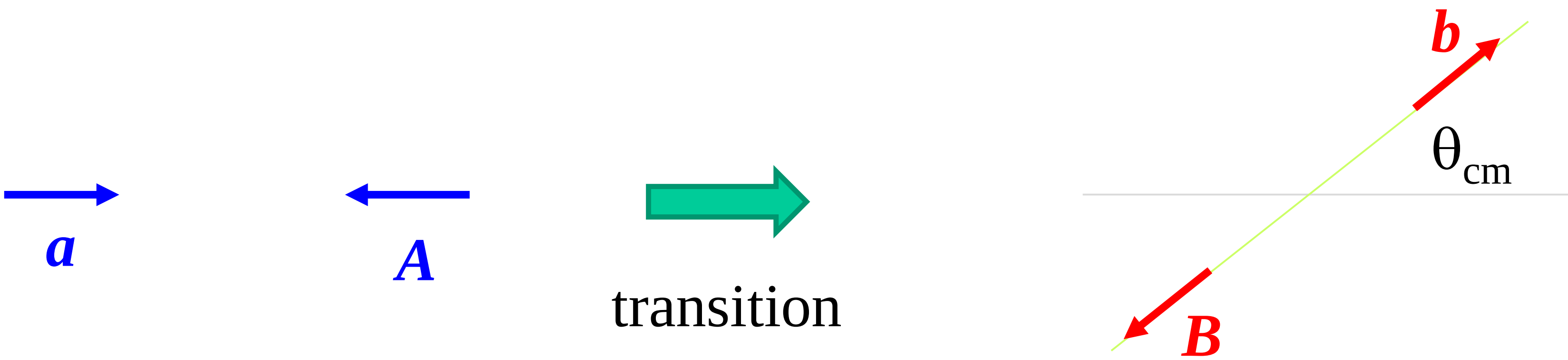
Cross sections (theory)

$A(a,b)B$ reaction



$A \rightarrow B$

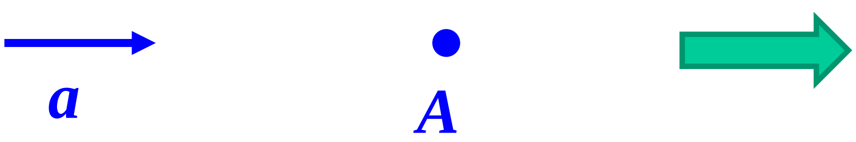
center of mass frame

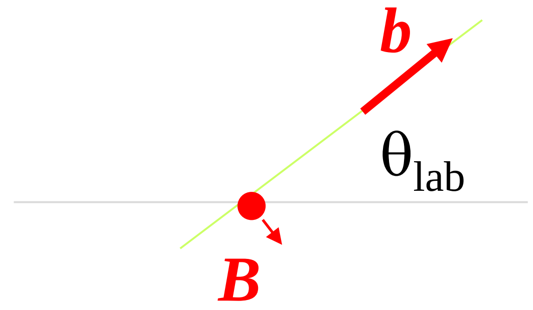


$$\frac{d\sigma}{d\Omega} = \frac{R}{j_{\mathrm{in}}}$$

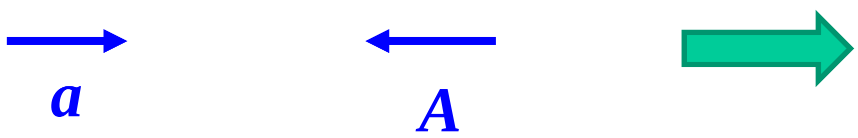
Cross sections

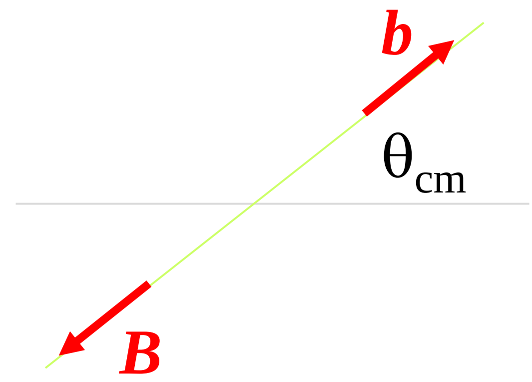
✓ laboratory frame





✓ center of mass frame





☐ transformation ⟵ energy and momentum conservations

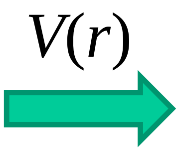
$$\tan\theta_{\mathrm{lab}} = \frac{\sin\theta_{\mathrm{cm}}}{\gamma+\cos\theta_{\mathrm{cm}}}, \qquad d\Omega_{\mathrm{lab}} = \frac{|1+\gamma\cos\theta_{\mathrm{cm}}|}{(1+\gamma^2+2\gamma\cos\theta_{\mathrm{cm}})^{3/2}}\, d\Omega_{\mathrm{cm}}$$

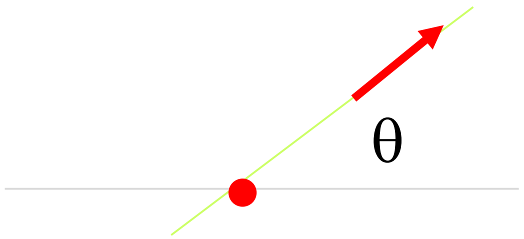
$$E_{\mathrm{cm}} = \frac{M_A}{M_a+M_A} E_{\mathrm{lab}}, \qquad \gamma = \sqrt{\frac{M_a M_b}{M_A M_B}\frac{E_{\mathrm{cm}}}{E_{\mathrm{cm}}+Q}}$$

Born approximation

$$\psi_f(\boldsymbol{r}) = e^{i\boldsymbol{p}_f\cdot\boldsymbol{r}/\hbar}$$

$$\psi_i(\boldsymbol{r}) = e^{i\boldsymbol{p}_i\cdot\boldsymbol{r}/\hbar}$$





$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + \underline{V(r)} - E\right)\psi(\boldsymbol{r}) = 0$$

perturbation

transition rate for elastic scattering:

$$W_{fi} = \frac{2\pi}{\hbar}\int \frac{d\boldsymbol{p}_f}{(2\pi\hbar)^3}\left|\langle\psi_f|V|\psi_i\rangle\right|^2\delta(E_f - E_i)$$

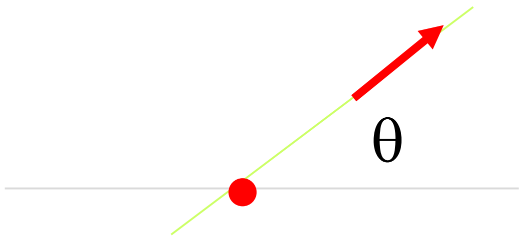
$$= \frac{\mu p_i}{4\pi^2\hbar^4}\int d\Omega\left|\widetilde{V}(\boldsymbol{q})\right|^2$$

$$\widetilde{V}(\boldsymbol{q}) = \int d\boldsymbol{r}e^{i(\boldsymbol{p}_i-\boldsymbol{p}_f)\cdot\boldsymbol{r}/\hbar}V(r) \equiv \int d\boldsymbol{r}e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}V(r)$$

Born approximation

$$\psi_f(\boldsymbol{r}) = e^{i\boldsymbol{p}_f\cdot\boldsymbol{r}/\hbar}$$

$$\psi_i(\boldsymbol{r}) = e^{i\boldsymbol{p}_i\cdot\boldsymbol{r}/\hbar}$$



$$W_{fi} = \frac{\mu p_i}{4\pi^2\hbar^4}\int d\Omega \left|\tilde{V}(\boldsymbol{q})\right|^2$$

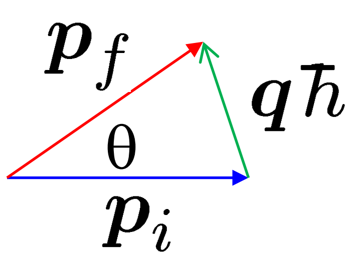
momentum transfer

$$\tilde{V}(\boldsymbol{q}) = \int d\boldsymbol{r} e^{i(\boldsymbol{p}_i-\boldsymbol{p}_f)\cdot\boldsymbol{r}/\hbar} V(r) \equiv \int d\boldsymbol{r} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}} V(r)$$

incident flux: $j_{\text{inc}} = \rho_i v = p_i/\mu$

$$\sigma = \frac{W_{fi}}{j_{\text{inc}}} = \int d\Omega \frac{\mu^2}{4\pi^2\hbar^4}\left|\tilde{V}(\boldsymbol{q})\right|^2$$

$$= \frac{d\sigma}{d\Omega}$$



$$q\hbar = 2p_i \sin\frac{\theta}{2}$$

Electron scattering

$$V(r) = -e^2 \int d\boldsymbol{r}' \frac{\rho_{\text{ch}}(\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|}$$

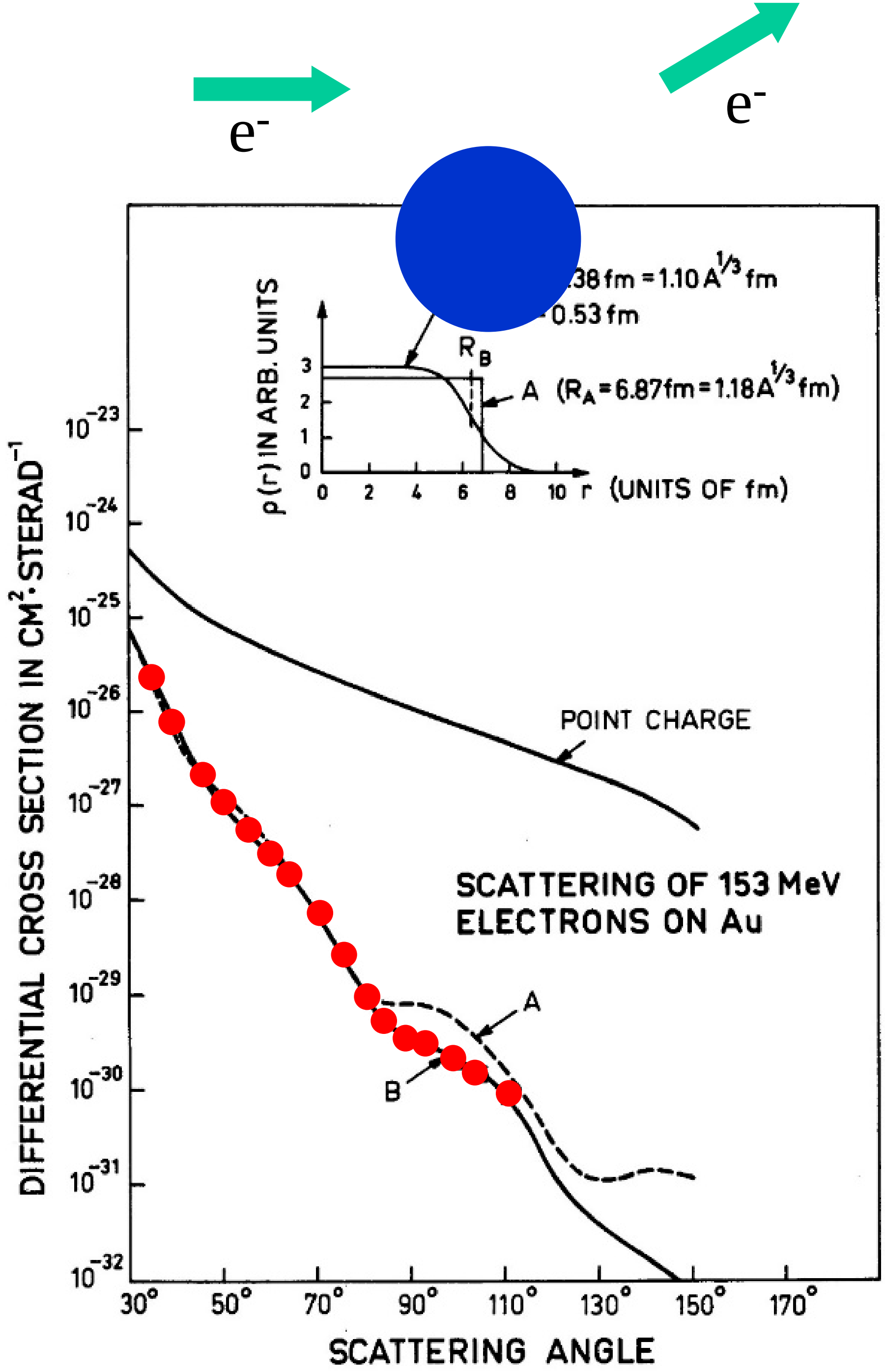
$$\frac{d\sigma}{d\Omega} = \frac{Z_P^2 e^4}{(4E\sin^2\theta/2)^2}|F(\boldsymbol{q})|^2 = \left(\frac{d\sigma_{\text{Ruth}}}{d\Omega}\right)|F(\boldsymbol{q})|^2$$

Form factor

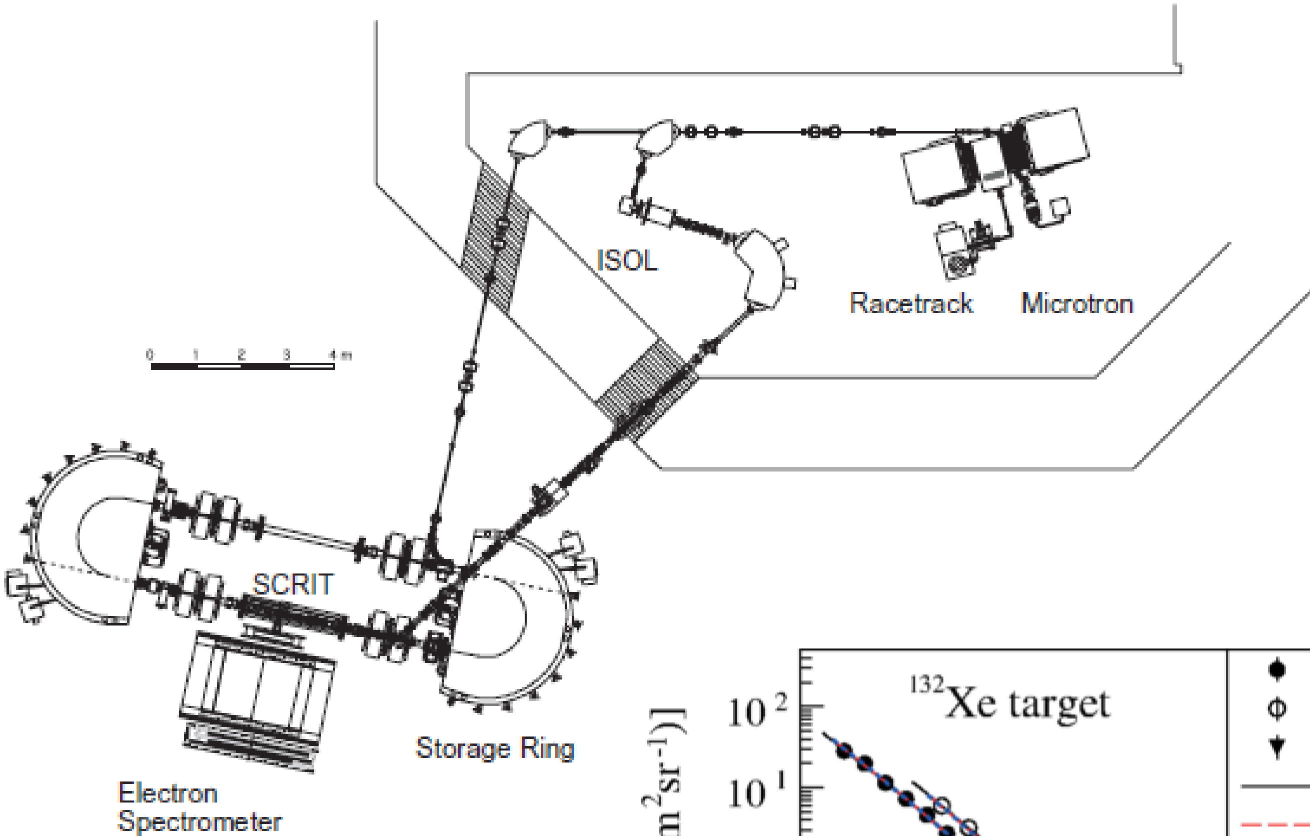
$$F(\boldsymbol{q}) = \int e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}\rho_{\text{ch}}(\boldsymbol{r})\,d\boldsymbol{r}$$

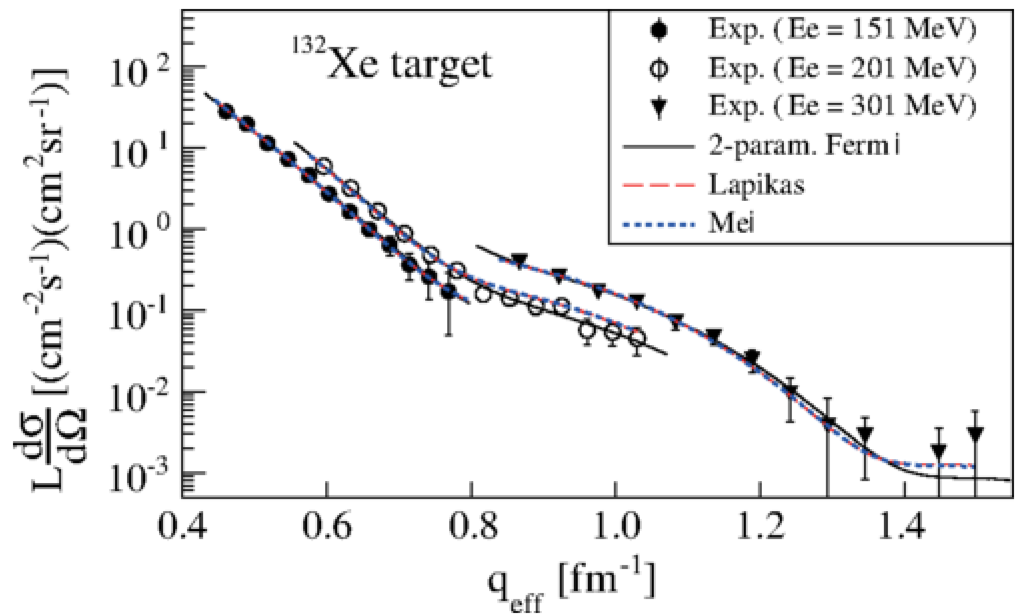
* relativistic correction:

$$\frac{d\sigma_{\text{Ruth}}}{d\Omega} \rightarrow \frac{d\sigma_{\text{Mott}}}{d\Omega} = \frac{d\sigma_{\text{Ruth}}}{d\Omega}\cdot\left(1-\frac{v^2}{c^2}\sin^2\frac{\theta}{2}\right) \sim \frac{d\sigma_{\text{Ruth}}}{d\Omega}\cdot\cos^2\frac{\theta}{2} \qquad (v\rightarrow c)$$



cf. electron scattering off unstable nuclei (SCRIT)

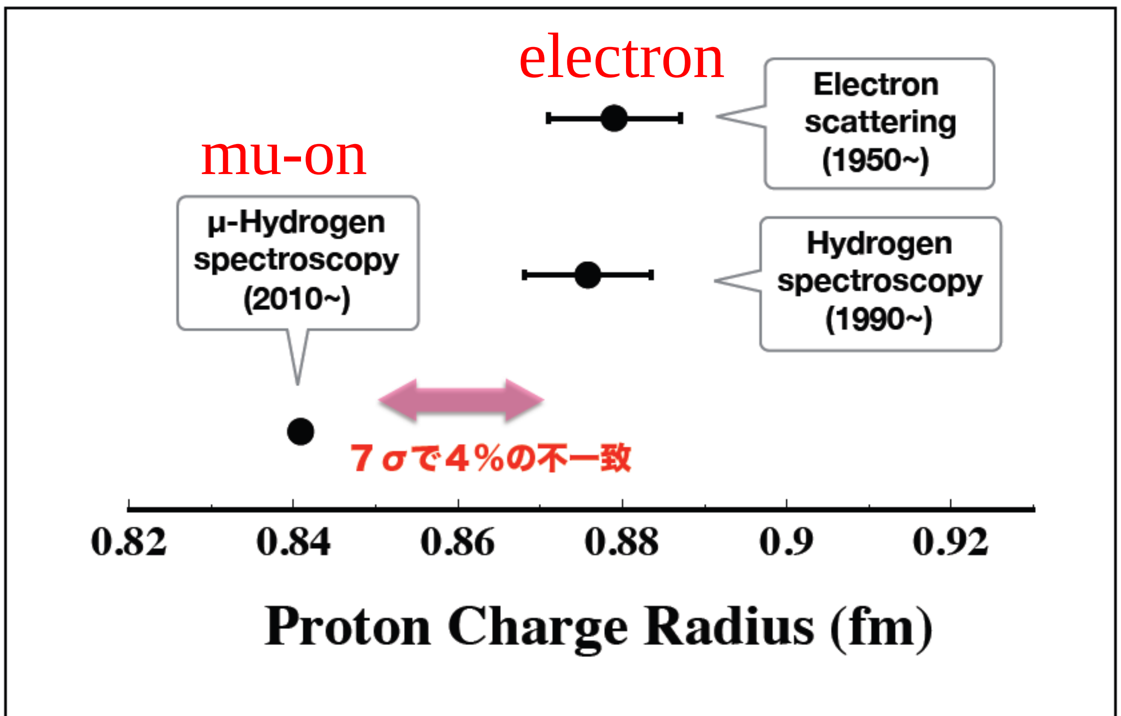




K. Tsukada et al.,
PRL118, 262501 (2017)

proton radius puzzle

$$
\begin{aligned}
F(\boldsymbol{q}) &= \int e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}\,\rho_{\text{ch}}(\boldsymbol{r})\,d\boldsymbol{r} \\
&\sim \int \left(1 - i\boldsymbol{q}\cdot\boldsymbol{r} - \frac{(qr)^2}{2}\cos^2\theta + \cdots\right)\rho_{\text{ch}}(\boldsymbol{r})\,d\boldsymbol{r} \\
&\sim Z\left(1 - \frac{q^2}{6}\langle r^2\rangle + \cdots\right)
\end{aligned}
$$



Distorted Wave Born approximation (DWBA)

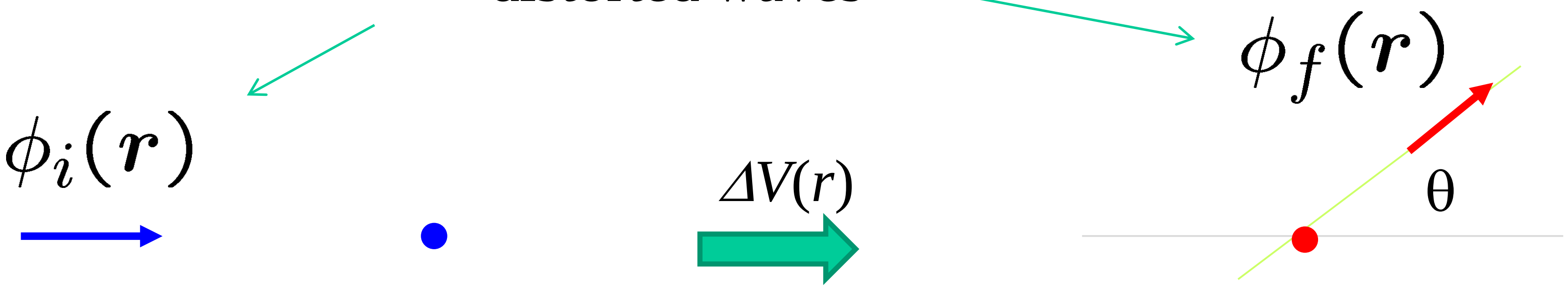
$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + \underline{V(r)} - E\right)\psi(\boldsymbol{r}) = 0$$

perturbation

$$\Rightarrow \left(-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) + \underline{V(r) - V_0(r)} - E\right)\psi(\boldsymbol{r}) = 0$$

perturbation

"distorted waves"

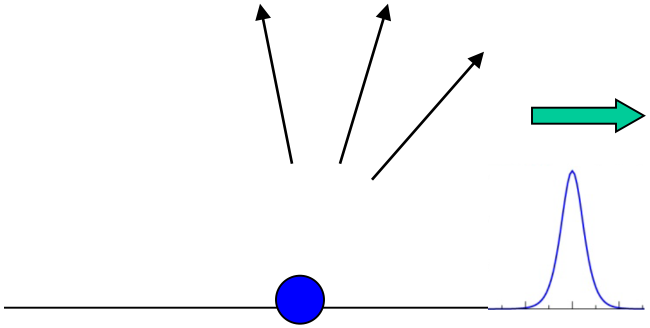


✓inelastic scattering
✓transfer reactions

How to choose $V_0(r)$? : Optical model

Reaction processes

- Elastic scatt.
- Inelastic scatt.
- Transfer reaction
- Compound nucleus formation (fusion)



Loss of incident flux (absorption)

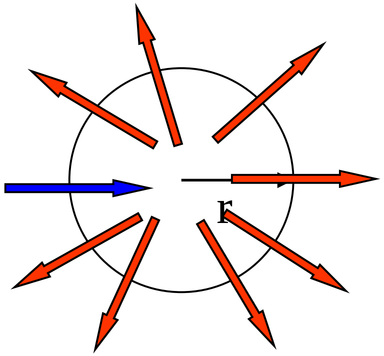
Optical potential

$$V_{\rm opt}(\boldsymbol{r}) = V(\boldsymbol{r}) - iW(\boldsymbol{r}) \qquad (W > 0)$$

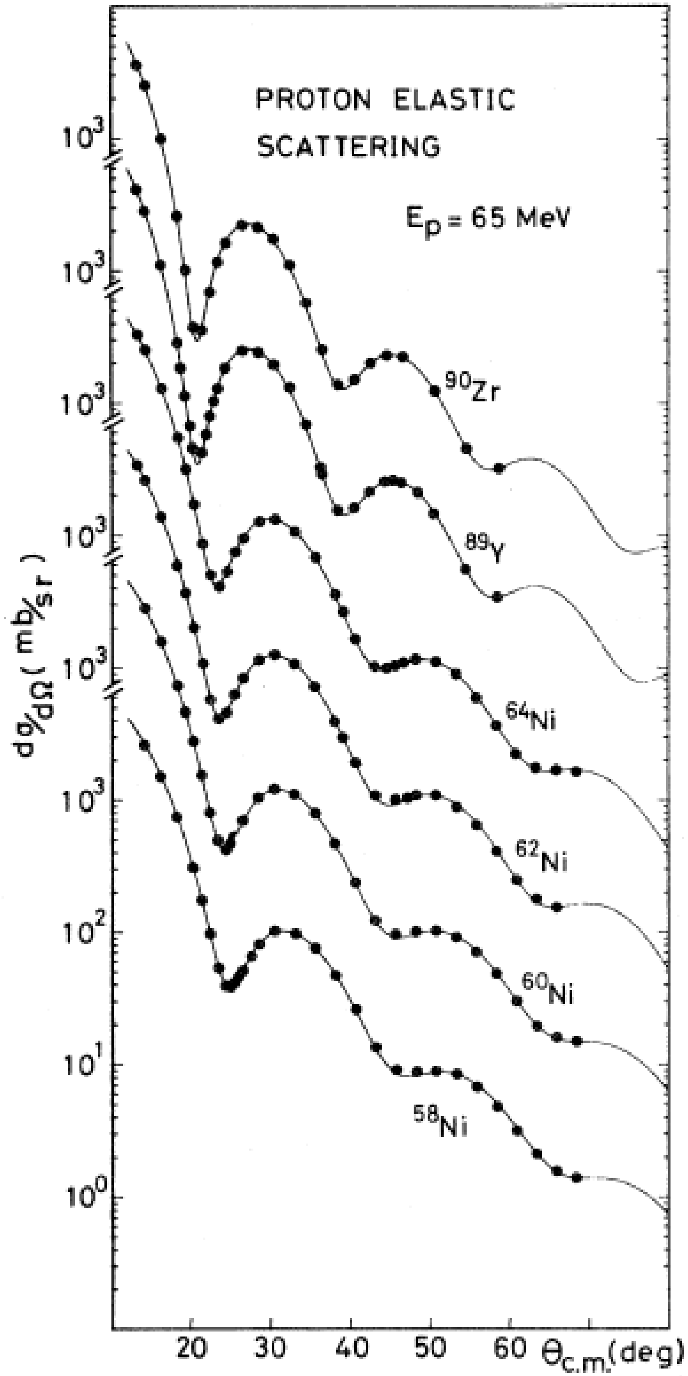
$$\boldsymbol{\nabla}\cdot\boldsymbol{j} = \cdots = -\frac{2}{\hbar}W|\psi|^2$$

(note) Gauss's theorem

$$\int_S \boldsymbol{j}\cdot\boldsymbol{n}\,dS = \int_V \boldsymbol{\nabla}\cdot\boldsymbol{j}\,dV$$



$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + \frac{Z_P Z_T e^2}{r} + V_{\rm opt}(r) - E\right)\psi(\boldsymbol{r}) = 0$$

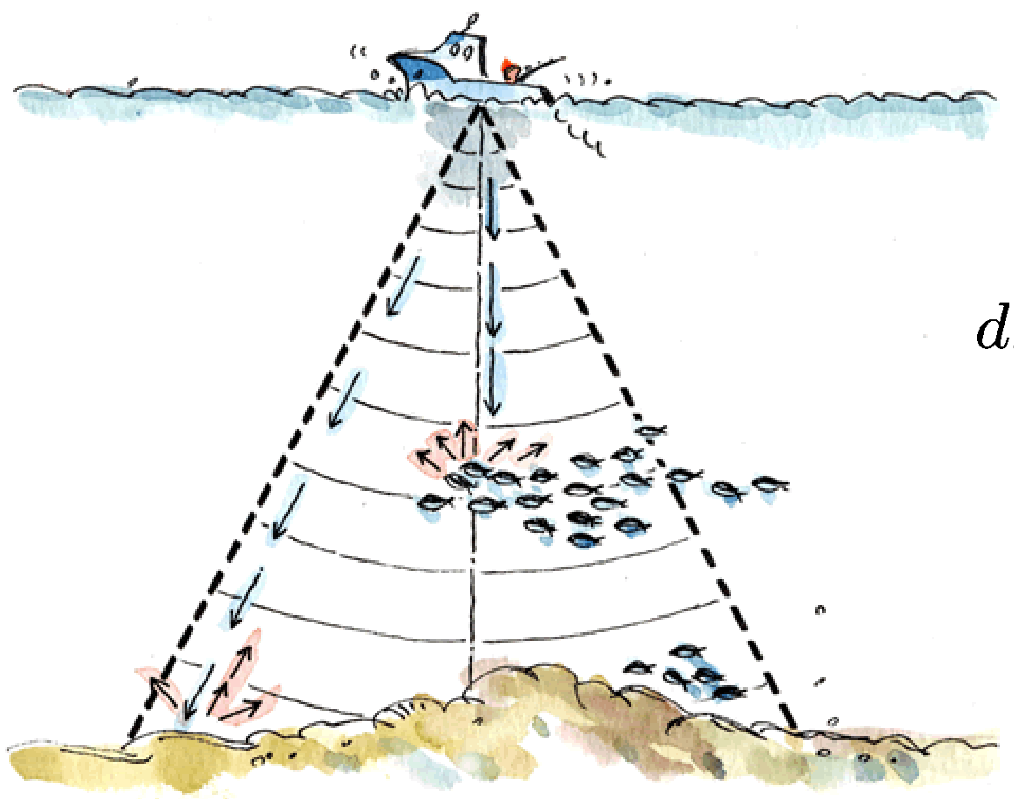


Woods-Saxon + volume &surface imaginary parts

H. Sakaguchi et al., PRC26 (1982) 944

Appendix: DWBA in ocean acoustics

Fishfinder



https://www.furuno.co.jp/technology/about/fishfinder1.html

(backward) scattering of (ultra-)sonic waves due to fish etc.

$$dR(\theta, \phi) = N_{\mathsf{T}} \cdot \frac{d\sigma}{d\Omega} \cdot j \cdot d\Omega$$

$$\downarrow$$

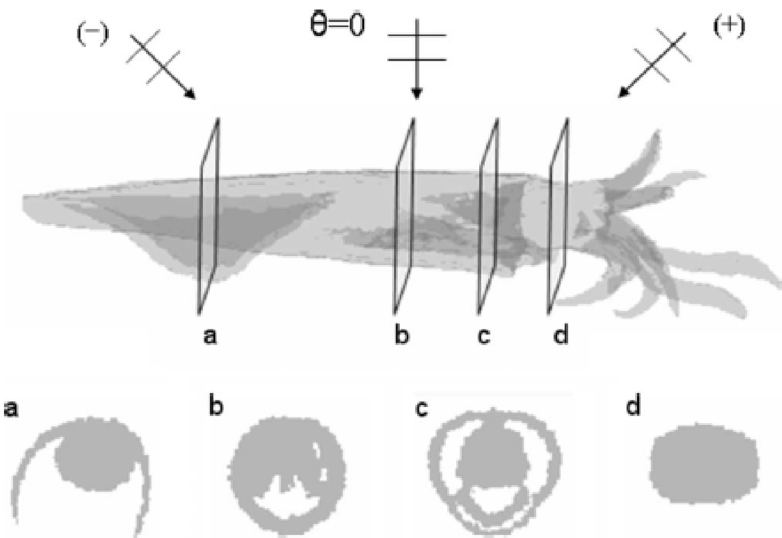
$$N_{\mathsf{T}} = \frac{\frac{dR}{d\Omega}}{j \cdot \frac{d\sigma}{d\Omega}}$$

one can know the number of fish N_{T} if one knows the differential cross sections

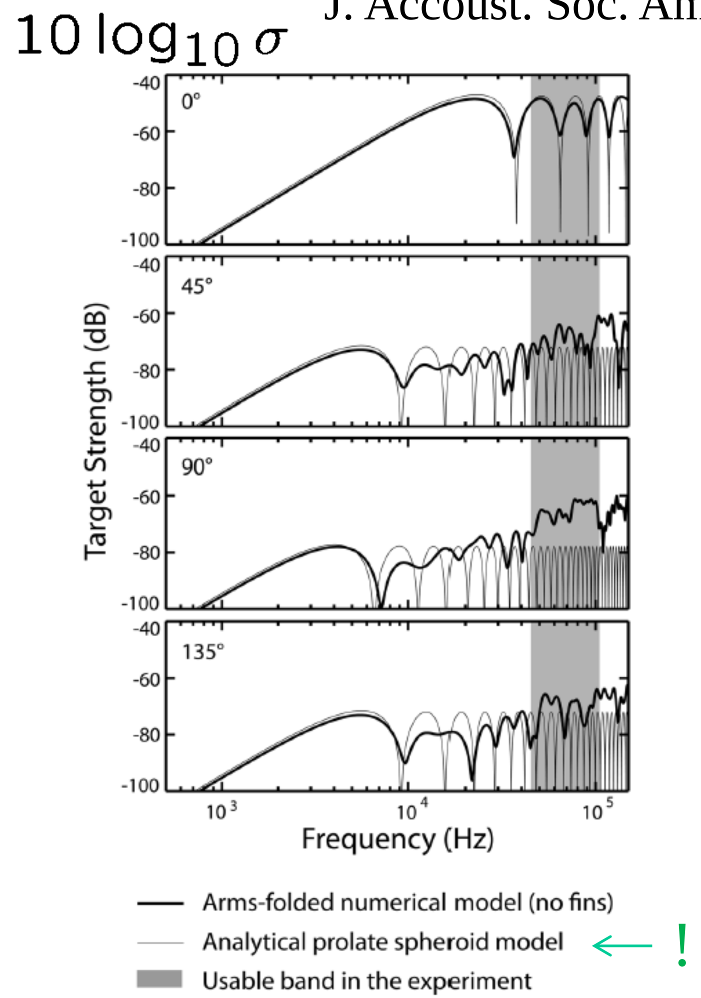
Use of the distorted wave Born approximation to predict scattering by inhomogeneous objects: Application to squid

Benjamin A. Jones,[a] Andone C. Lavery, and Timothy K. Stanton
Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543-1053

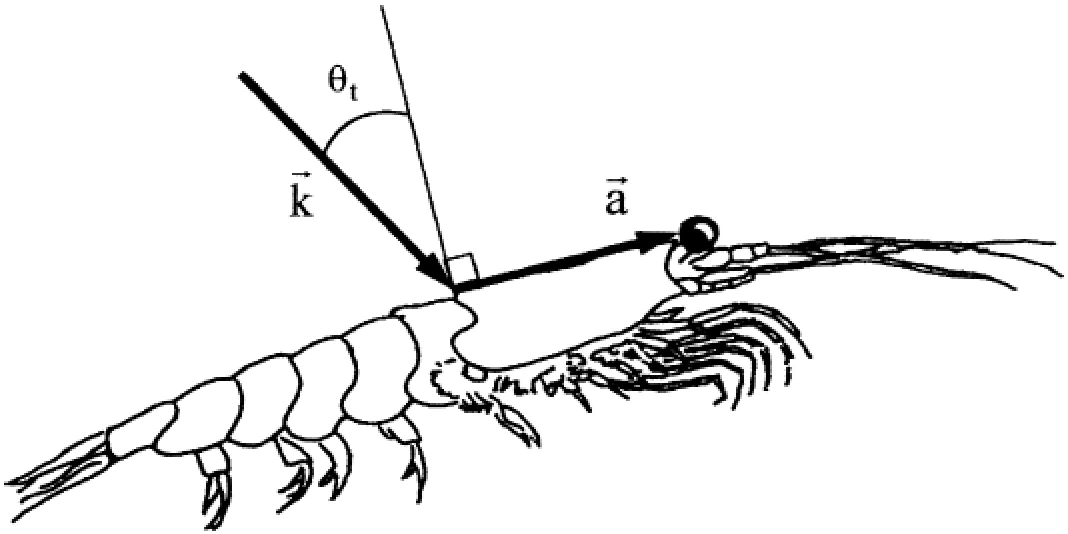
J. Accoust. Soc. Am. 125 ('09) 73



Modeling of squid



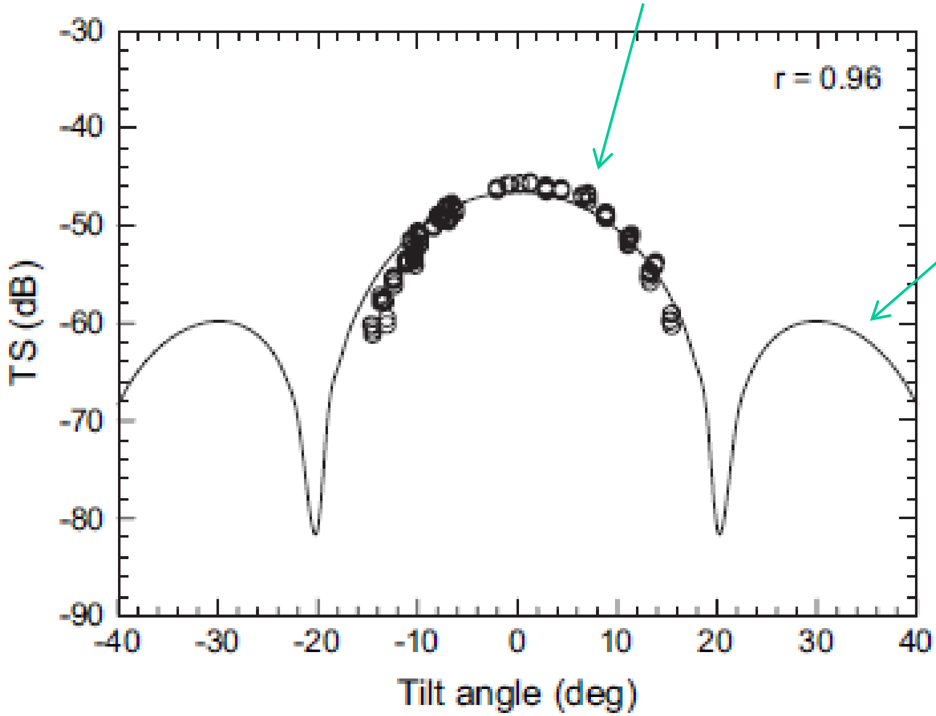
DWBA: local wave number inside a squid



Krill (オキアミ)

measurement

DWBA

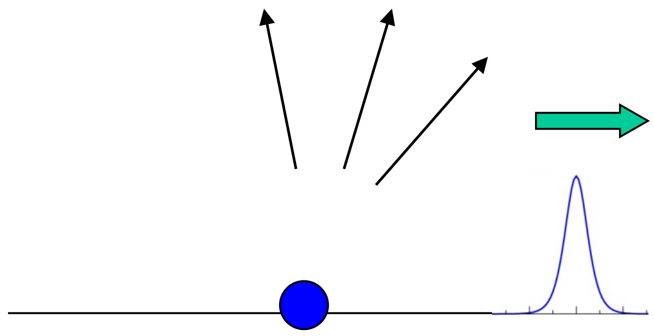


K. Akamatsu and M. Furusawa,
ICES J. of Marine Science 63 (‘06) 36

Absorption cross sections

Reaction processes

- Elastic scatt.
- Inelastic scatt.
- Transfer reaction
- Compound nucleus formation (fusion)



Loss of incident flux (absorption)

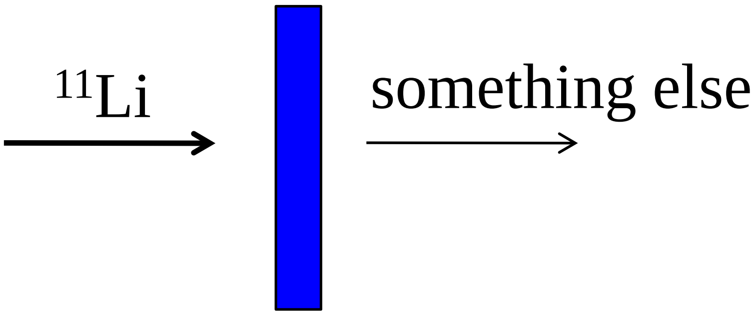
reaction cross sections

total scattering cross section minus elastic cross section

$$\sigma_R = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}}$$

- fusion
- inelastic
- transfer

Interaction cross sections and halo nuclei

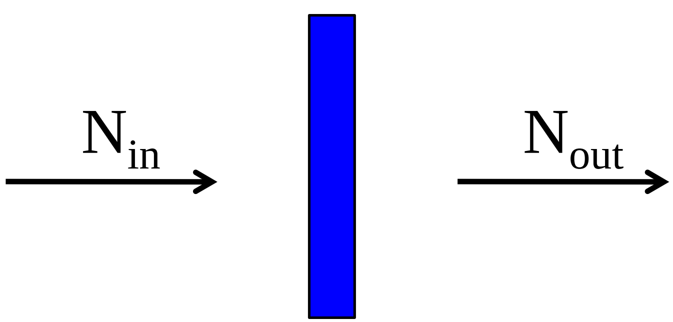


target nuclei

interaction cross section σ_I

= cross section for the change of Z a/o N in the incident nucleus

transmission method

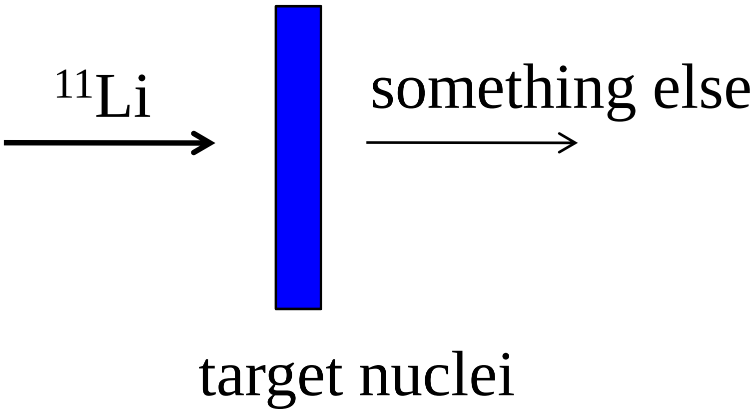


d

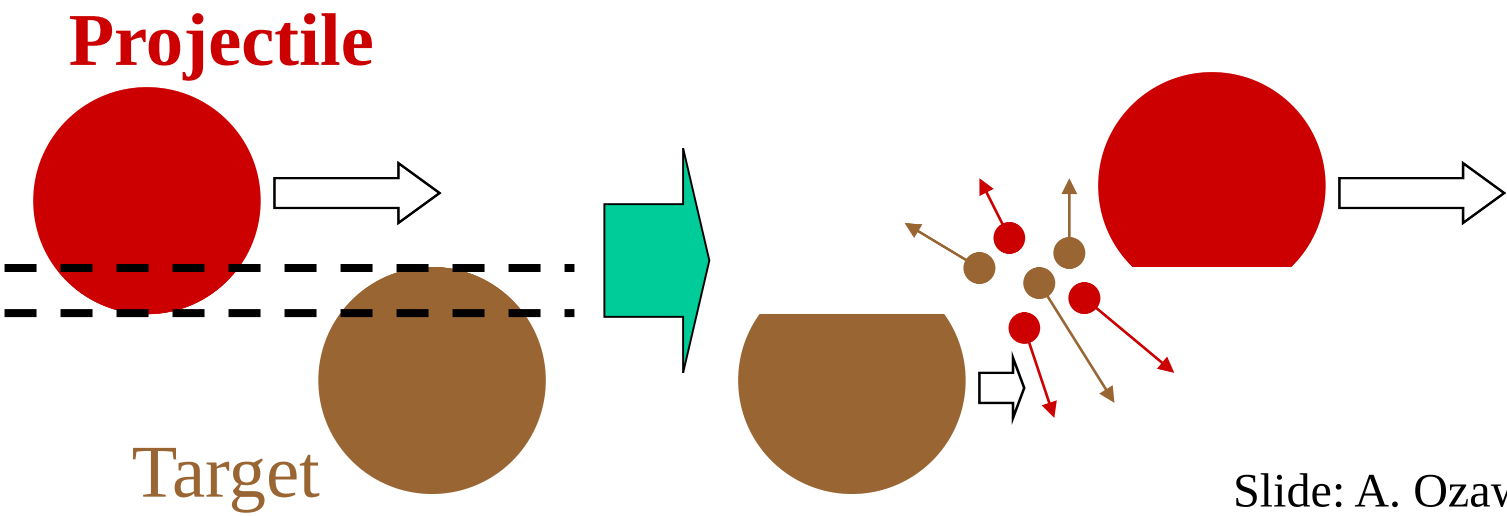
$$\sigma_R = -\frac{1}{t} \ln\left(\frac{N_{\rm out}}{N_{\rm in}}\right)$$

$$t = \rho_T \cdot d \cdot \epsilon$$

Interaction cross sections and halo nuclei



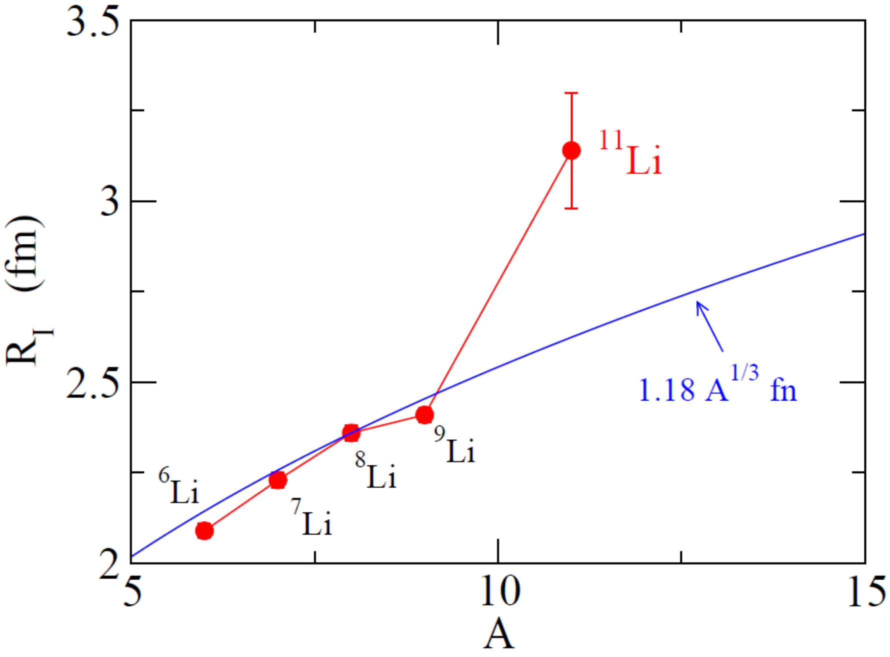
interaction cross section σ_I
= cross section for the change
of Z a/o N in the incident nucleus

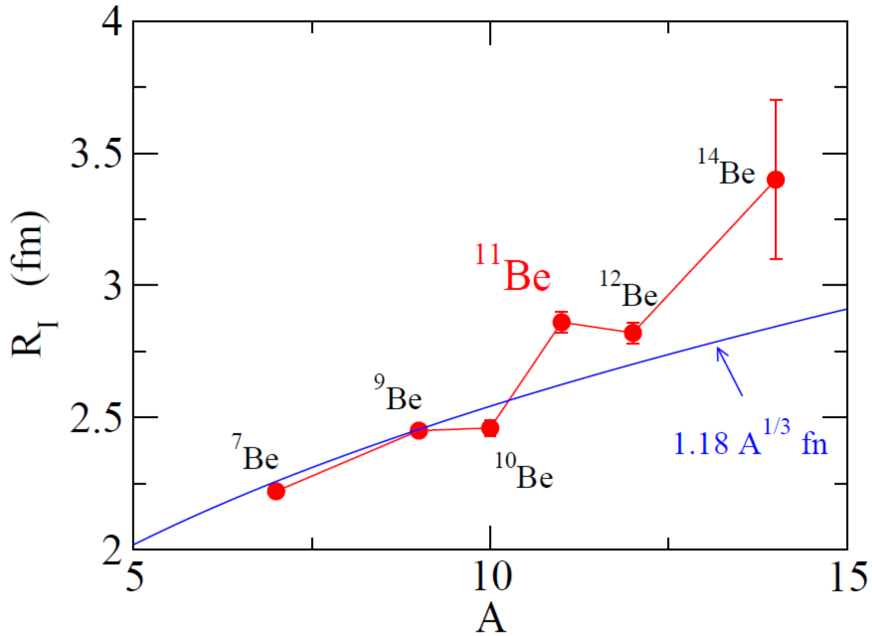


Slide: A. Ozawa

$$\sigma_I \sim \pi[R_I(P) + R_I(T)]^2 \longrightarrow R_I(P)$$

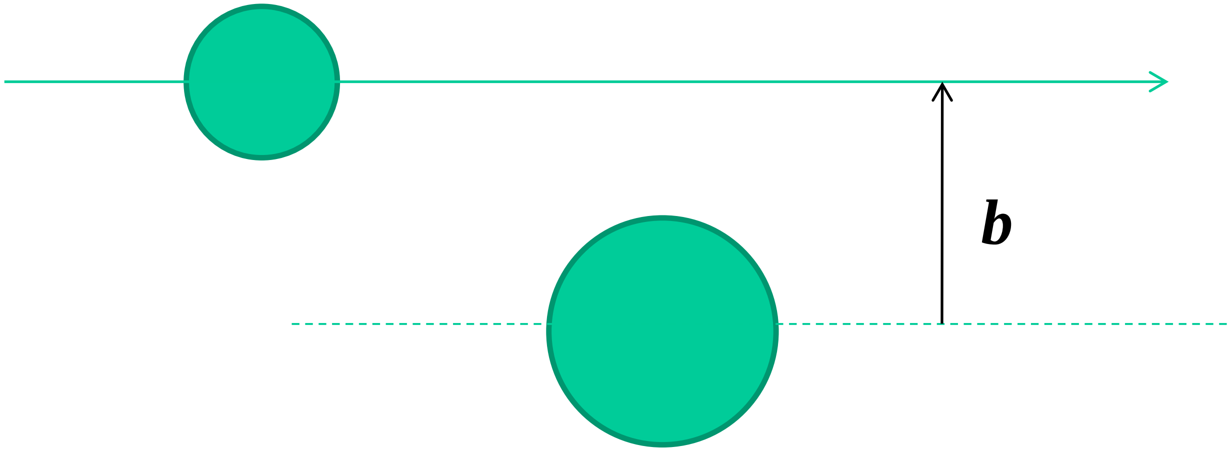
Discovery of **halo nuclei**





I. Tanihata, T. Kobayashi, O. Hashimoto et al., PRL55('85)2676; PLB206('88)592

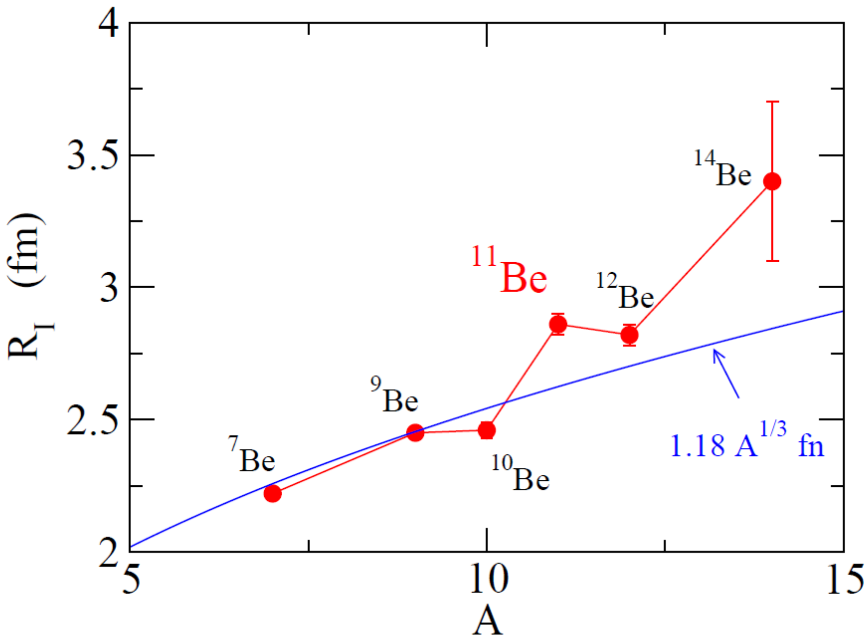
Reaction cross sections



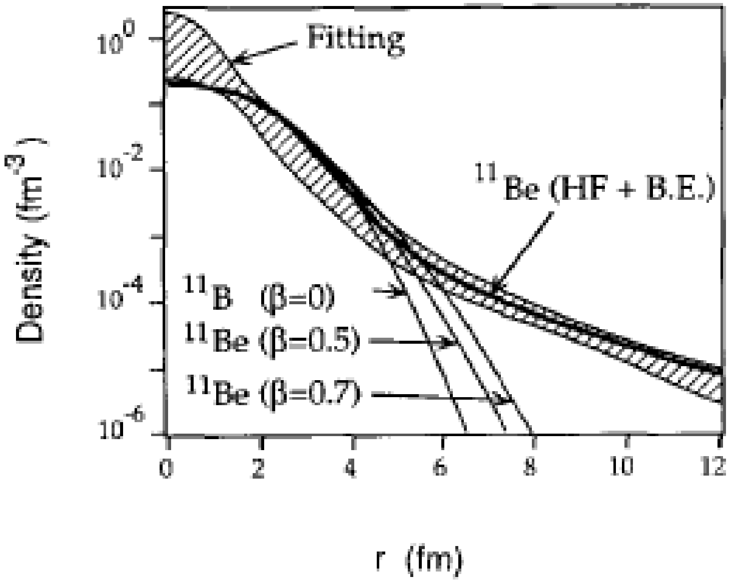
Glauber theory (optical limit approximation : OLA)

$$\sigma_R \sim 2\pi \int_0^\infty b\,db \left[1 - \exp\left(-\sigma_{NN} \int d^2 s \rho_P^{(z)}(\boldsymbol{s}) \rho_T^{(z)}(\boldsymbol{s} - \boldsymbol{b})\right)\right]$$

- straight-line trajectory (high energy scattering)
- adiabatic approximation
- simplified treatment for multiple scattering: $(1-x)^N \to e^{-Nx}$



Density distribution which explains the experimental σ_R



M. Fukuda et al., PLB268('91)339

$$\sigma_R \sim 2\pi \int_0^\infty bdb \left[1 - \exp\left(-\sigma_{NN} \int d^2s \rho_P^{(z)}(\boldsymbol{s}) \rho_T^{(z)}(\boldsymbol{s} - \boldsymbol{b})\right)\right]$$