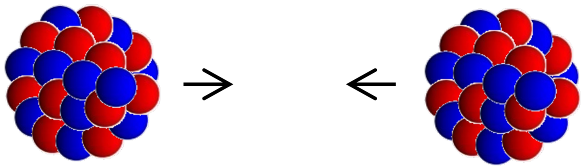
Imaging quantum decoherence in nuclear reactions

Kouichi Hagino
Kyoto University, Kyoto, Japan

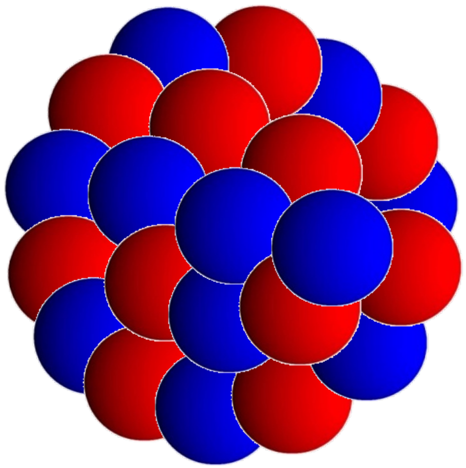


Collaborator: Takuya Yoda (particle theory, Kyoto University)

1. Introduction: interferences in nuclear reactions
2. A new attempt: visualization of nuclear reactions
3. Summary

K. Hagino and T. Yoda, PLB848, 138326 (2024).

Low energy nuclear reactions



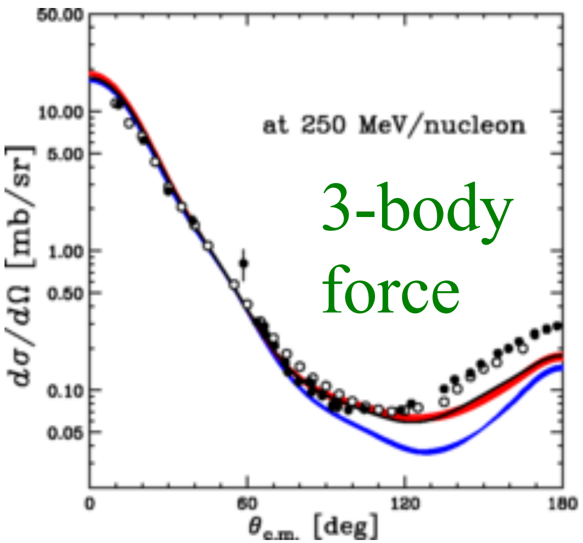
- Nuclei as quantum many-body systems

  ⟵ in terms of nucleon d.o.f.

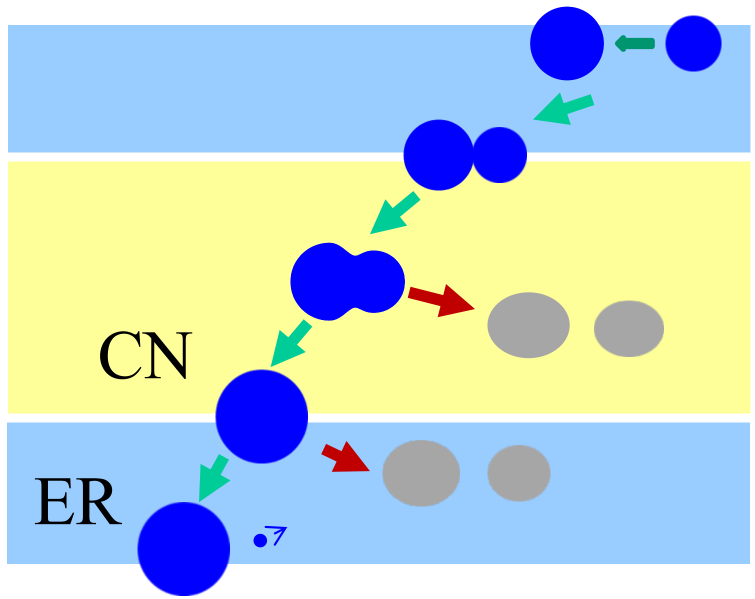
  - static properties: nuclear structure $E < 0$
  - dynamics: nuclear reactions $E > 0$

✓ Nuclear Reactions as a tool to investigate nuclear structure

knock-out reactions



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

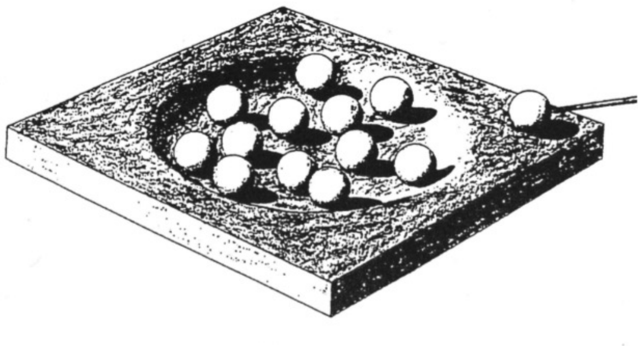


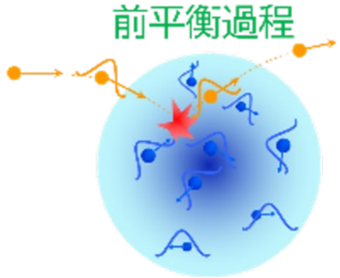
a synthesis of SHE

Two aspects of nuclear reactions

✓ a tool for nuclear structure ← this is often emphasized….

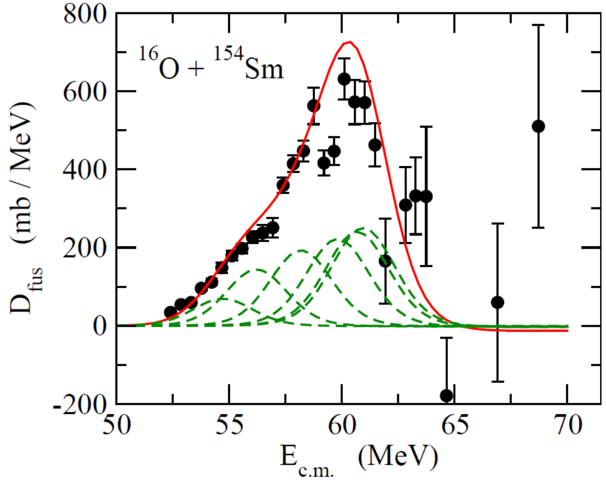
✓ reaction dynamics ⬅ this talk





pre-equilibrium reactions

fusion barrier distribution



nucleus: a composite system

✓ a rich reaction processes

✓ a rich interplay between nuclear structure and reaction

✓ elastic scattering

✓ inelastic scattering

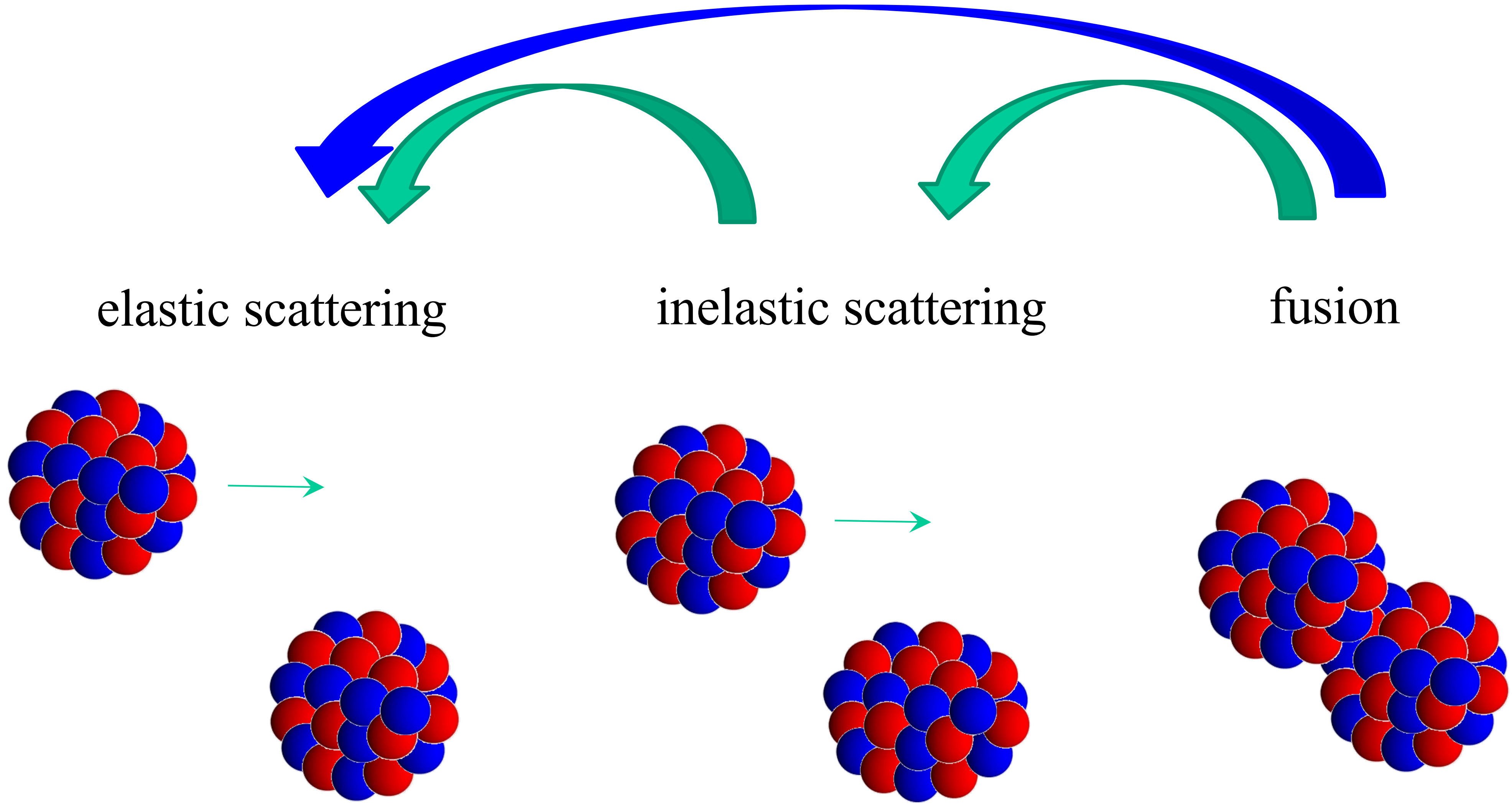
✓ transfer reactions

✓ fusion reactions

✓ g.s. properties (mass, size, shape….)

✓ excitations

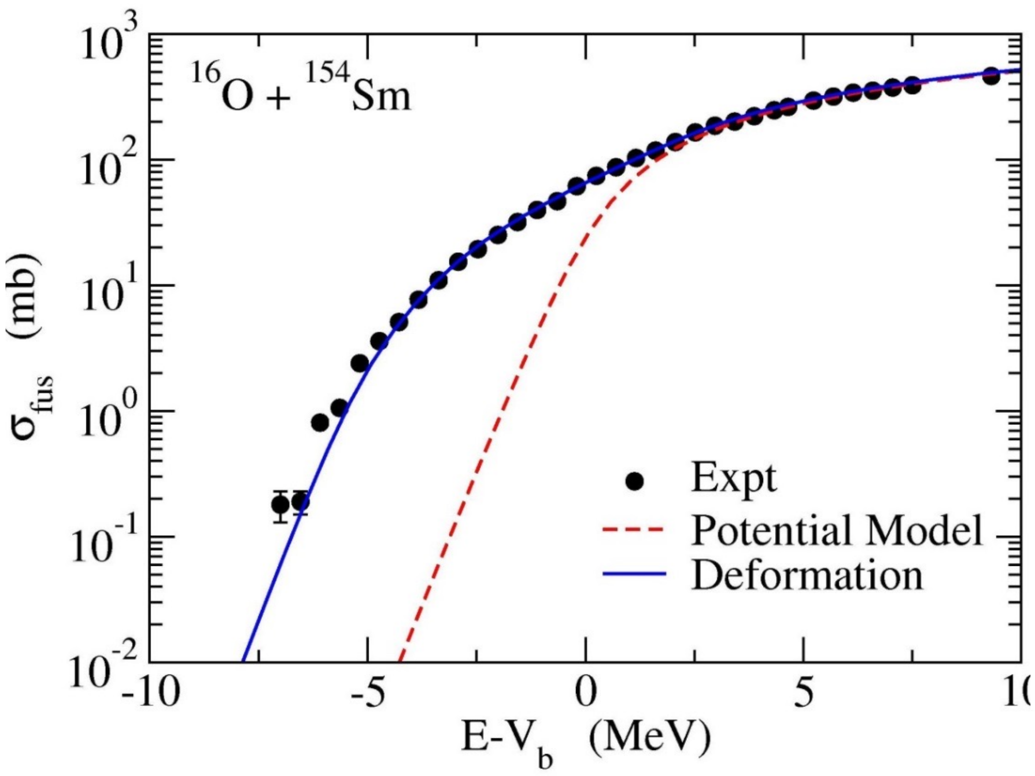
quantum many-body dynamics (nuclear reactions)

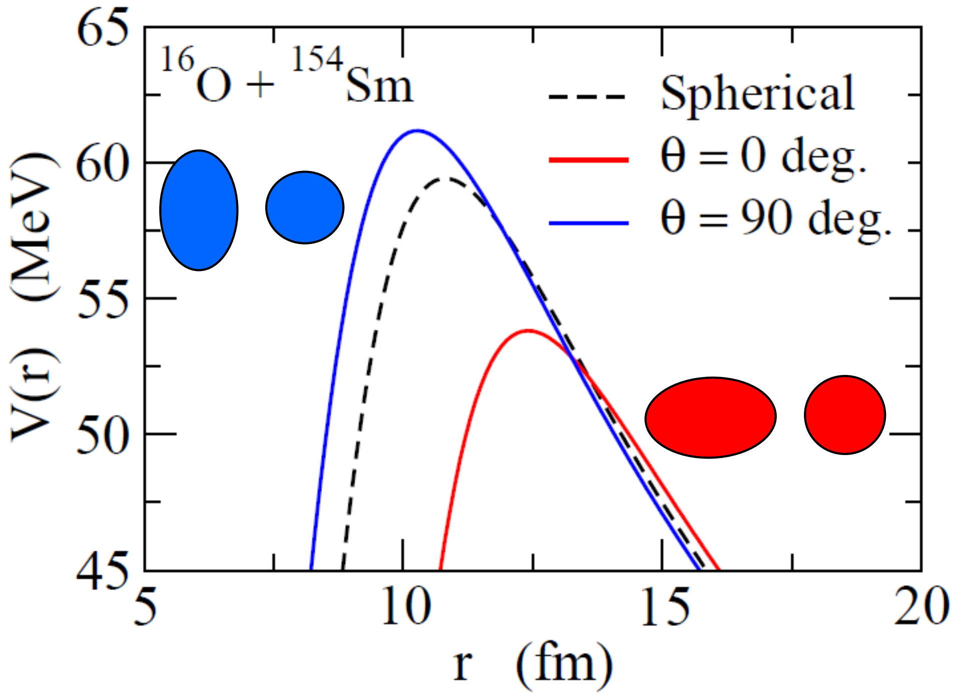


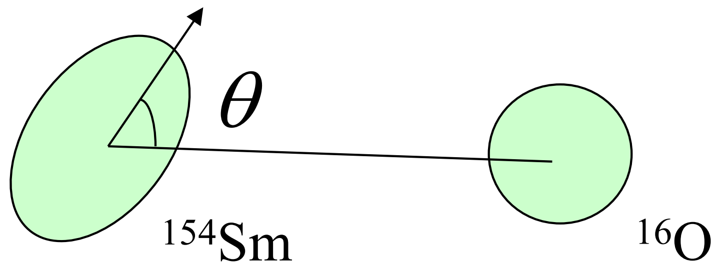
physics of nuclear reactions:
a unified description of these processes

Subbarrier enhancement of fusion cross sections

A typical example of the interplay between structure and reaction



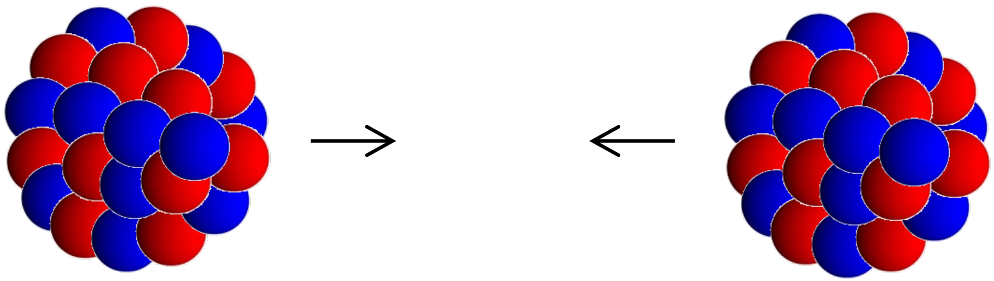




K.H., N. Takigawa, PTP128 (2012) 1061

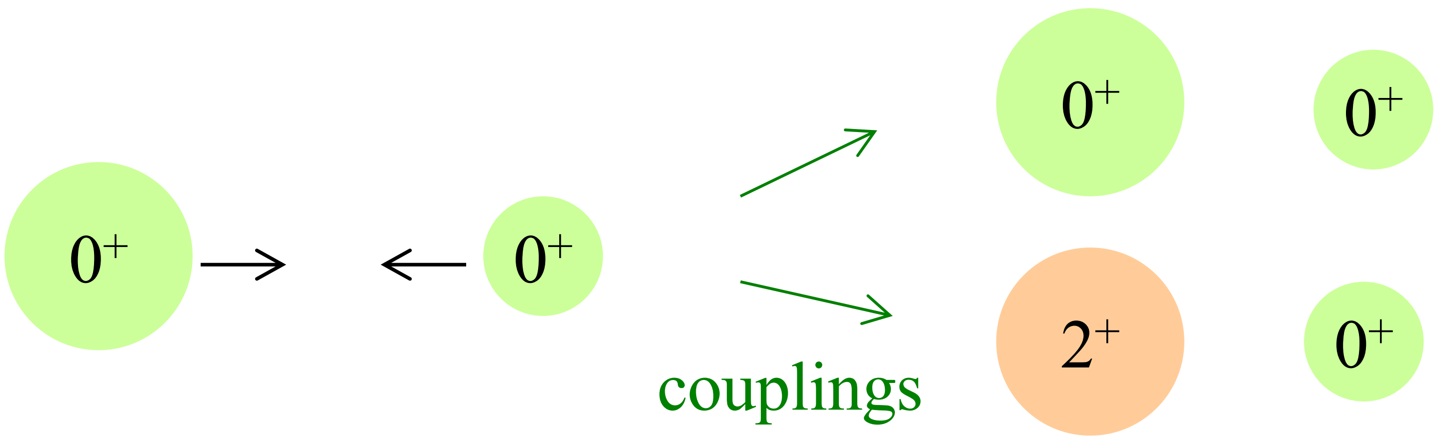
Coupled-channels method: a quantal reaction theory with excitations

a many-particle treatment



still very challenging for low energy scattering
cf. a quantum many-body tunneling

➡ a two-body problem + internal excitations (C.C. approach)



a reduction to the entrance channel → Optical Potential approach a recent review of C.C. approach (Hagino, Ogata, and Moro)

Prog. Part. Nucl. Phys. 125 (2022) 103951

Progress in Particle and Nuclear Physics 125 (2022) 103951

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Review

Coupled-channels calculations for nuclear reactions: From exotic nuclei to superheavy elements

Check for updates

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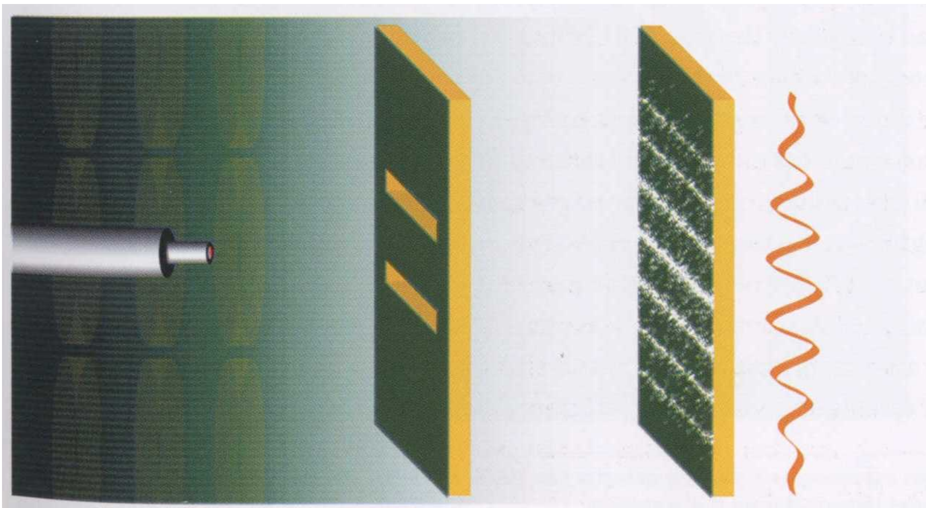
Nuclear Reactions

nucleus: a composite system
- ✓ a rich reaction processes
- ✓ a rich interplay between nuclear structure and reaction

- ✓ elastic scattering
- ✓ inelastic scattering
- ✓ transfer reactions
- ✓ fusion reactions
- ✓ …….

Another aspect of nuclear reactions
: a variety of quantum mechanical natures



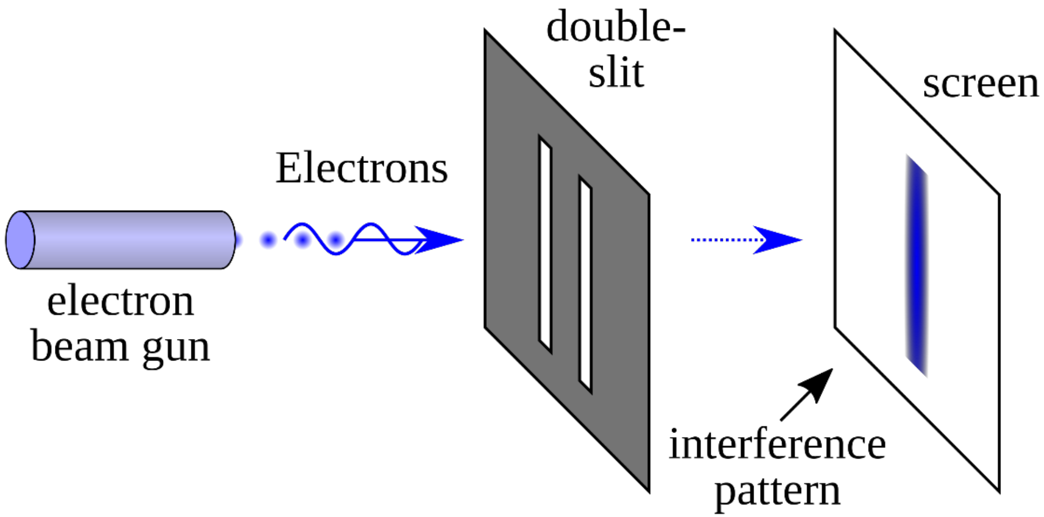
a figure from "Quantum Theory" by Jim Al-Khalili

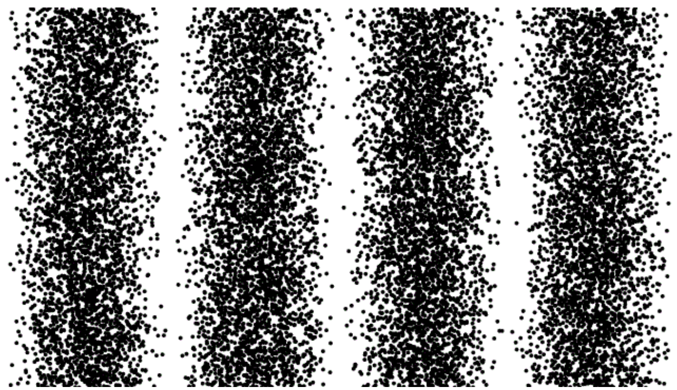
Manifestation of Quantum Nature in Nuclear Reactions

a superposition principle $\quad \psi = \alpha\psi_1 + \beta\psi_2$

$$\rightarrow |\psi|^2 = |\alpha\psi_1|^2 + |\beta\psi_2|^2 + \underbrace{(\alpha\psi_1)^*(\beta\psi_2) + (\alpha\psi_1)(\beta\psi_2)^*}_{\text{interference}}$$

when two processes are in principle indistinguishable
→ take square after adding two amplitudes



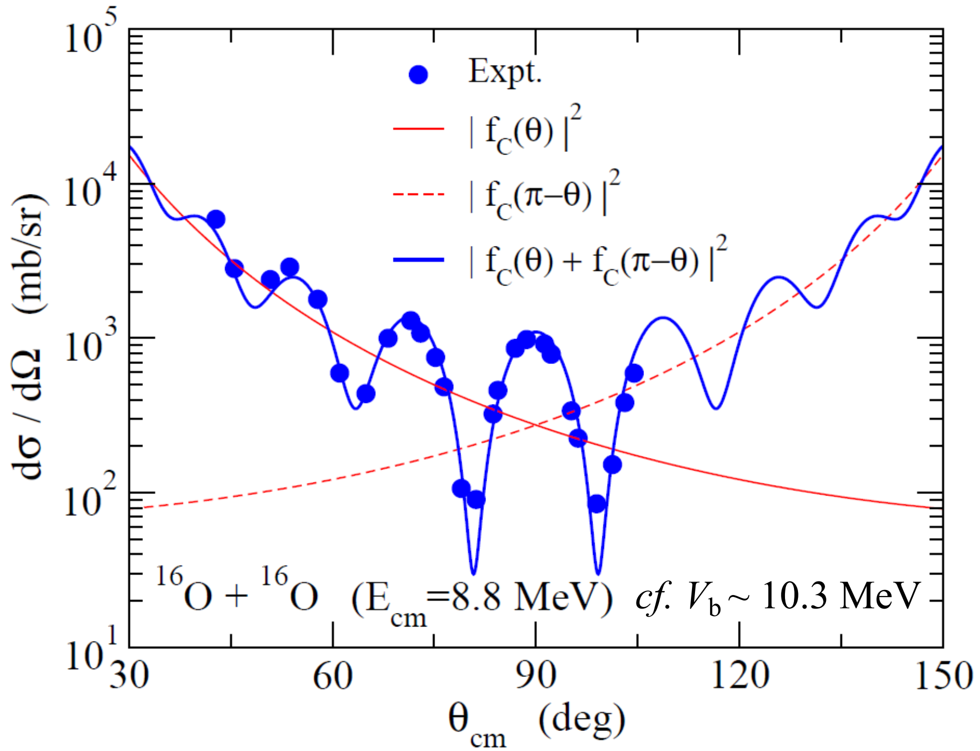


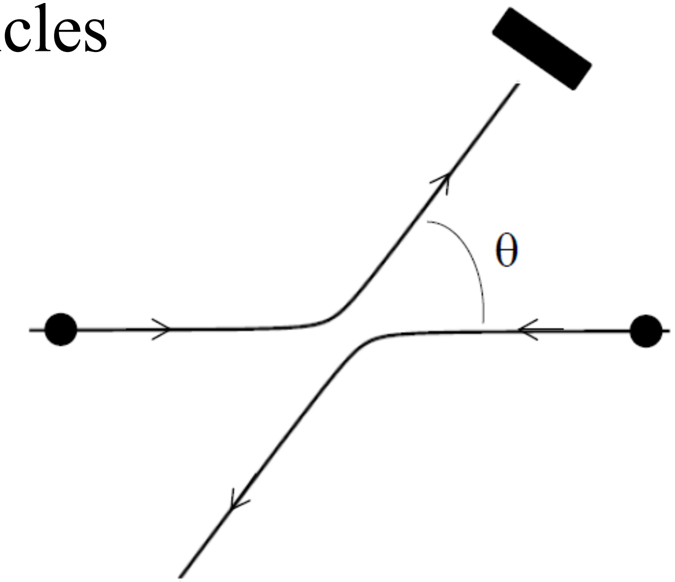
Wikipedia

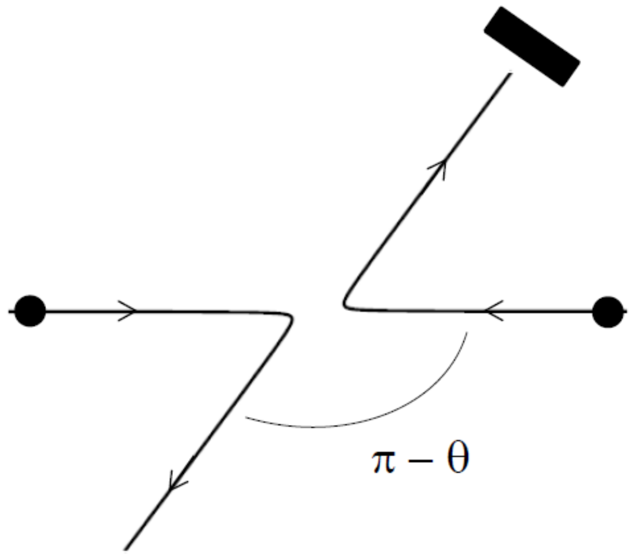
Manifestation of Quantum Nature in Nuclear Reactions

Mott Scattering: scattering of identical particles

$$\frac{d\sigma}{d\Omega} = |f(\theta) \pm f(\pi - \theta)|^2$$



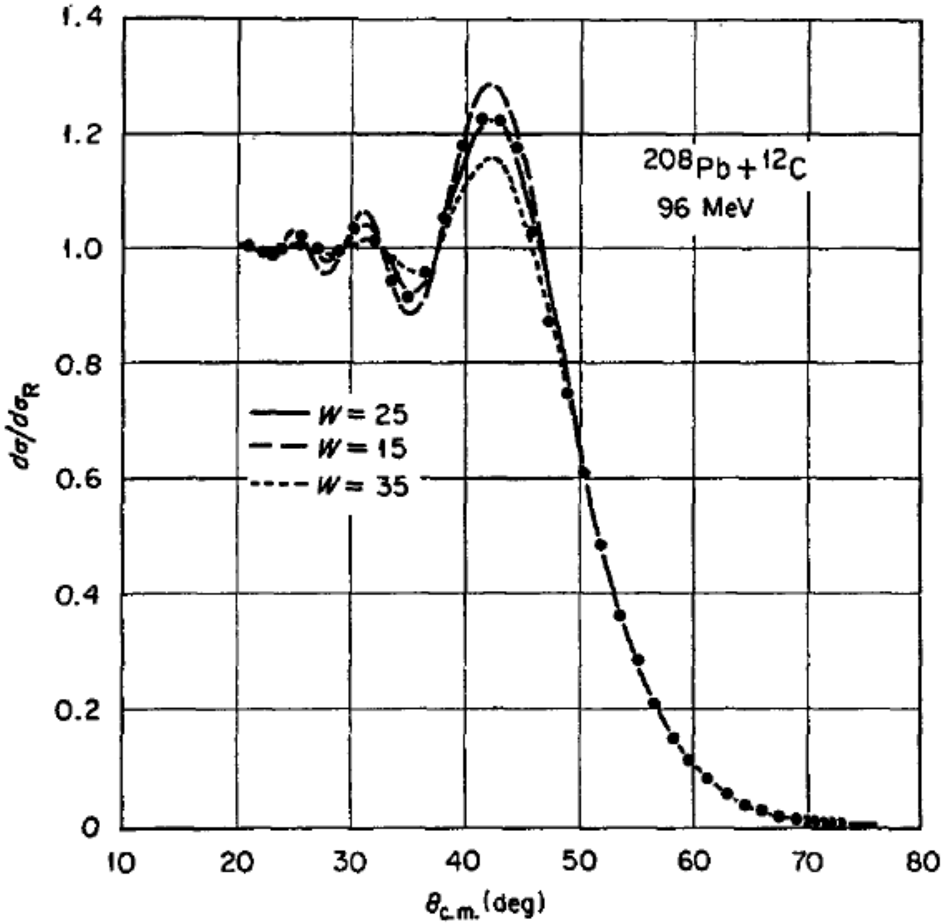




expt: D.A. Bromley et al., Phys. Rev. 123 (‘61)878

- Coulomb-Nuclear interference

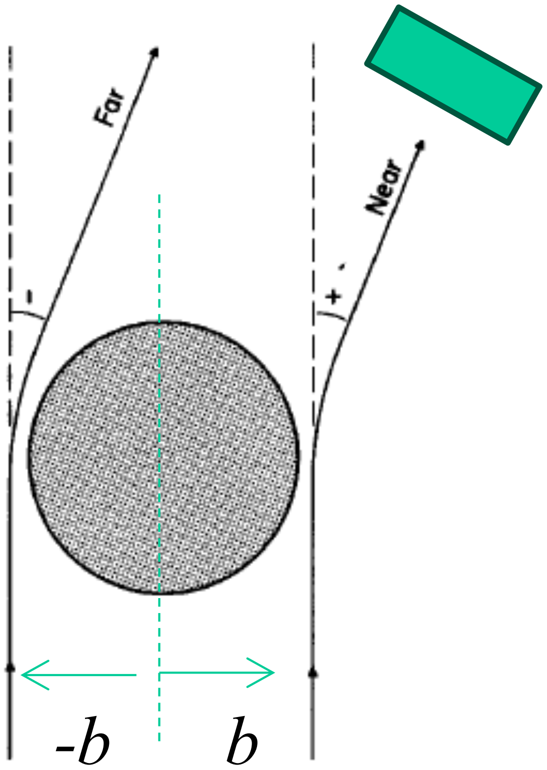
$$f(\theta) = f_C(\theta) + f_N(\theta) \;\rightarrow\; \frac{d\sigma}{d\Omega} = |f(\theta)|^2$$

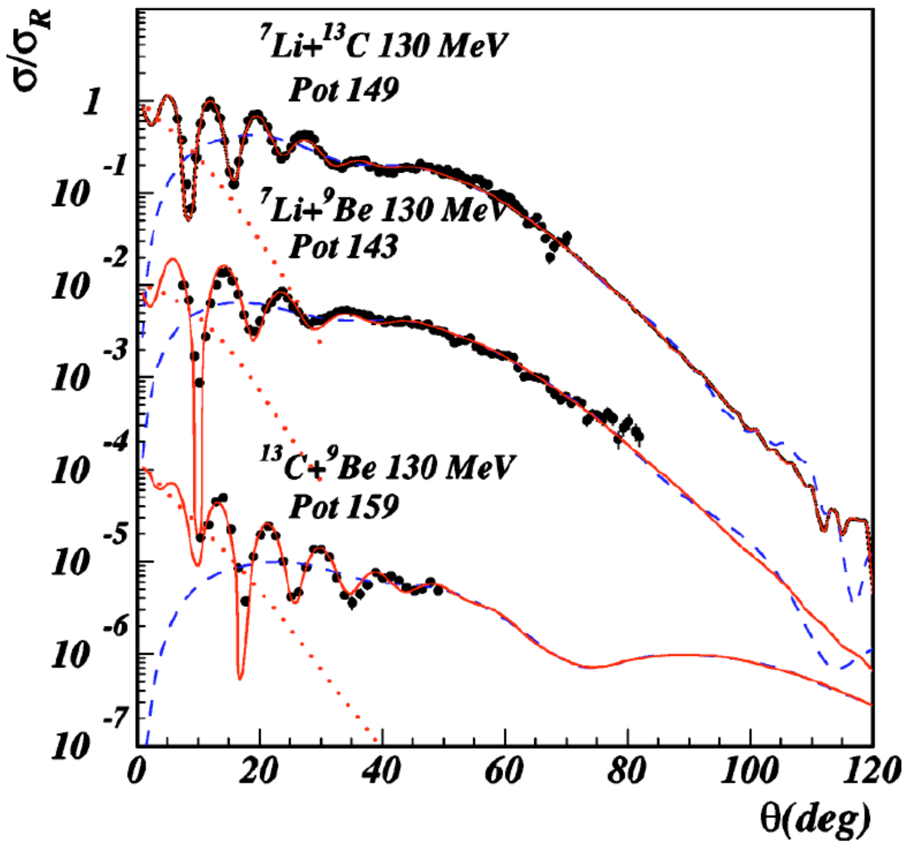


J.B. Ball et al., NPA252 ('75) 208

a special case: Fresnel oscillations ($S_l = 0$ ($l < l_g$); $S_l = e^{2i\sigma l}$ ($l > l_g$))

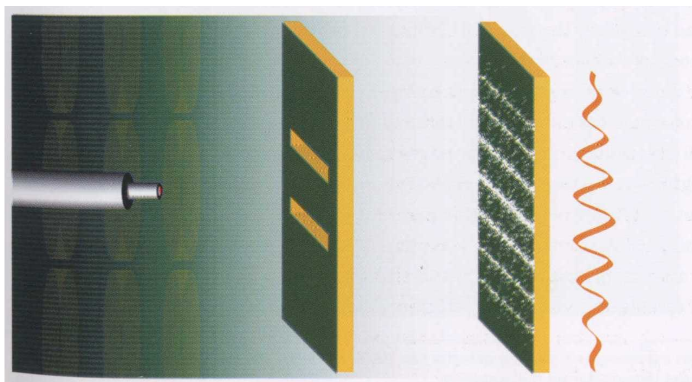
➢ near side - far side interference





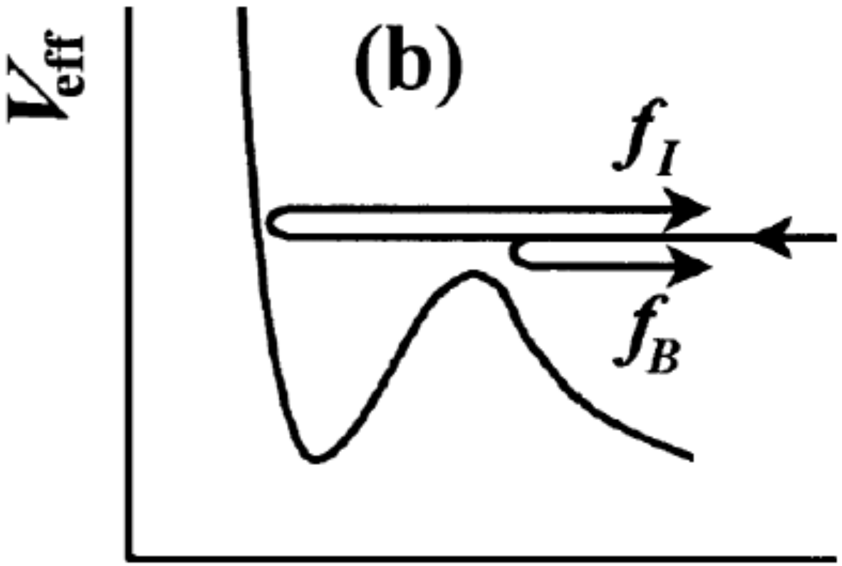
F. Carstoiu et al., PRC70 ('04) 054610

R.C. Fuller, PRC12('75)1561
N. Rowley and C. Marty,
NPA266('76)494
M.S. Hussein and K.W. McVoy,
Prog. in Part. and Nucl. Phys.
12 ('84)103

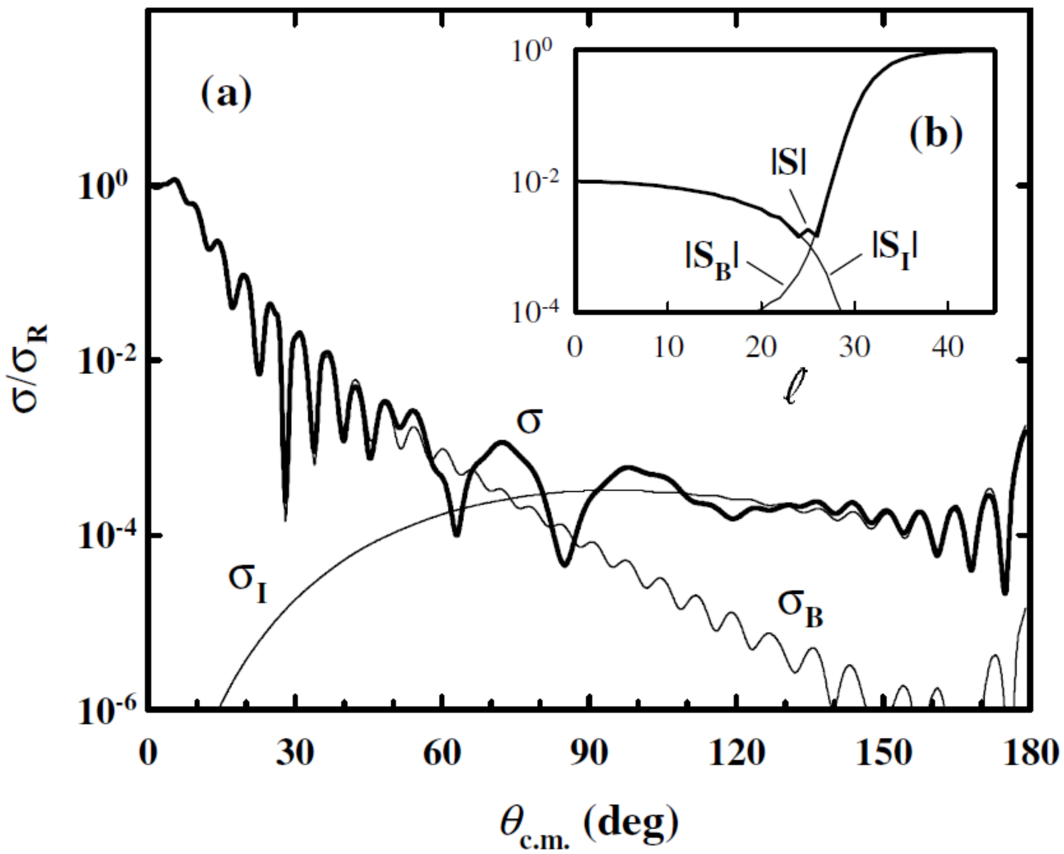


- barrier wave – internal wave interference

cf. D.M. Brink and N. Takigawa, NPA279 ('77) 159



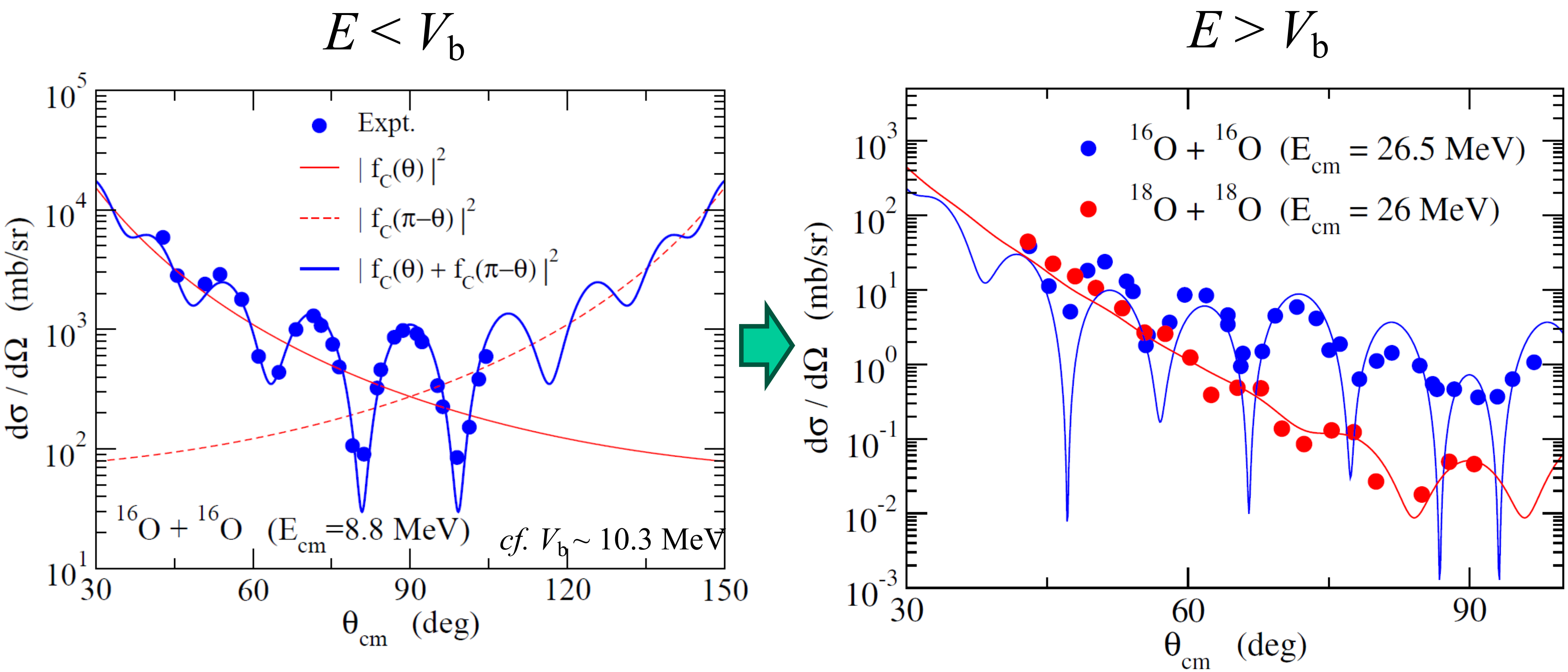
$^{16}O+^{16}O$ at 124 MeV



F. Michel et al., PRL85 ('00) 1823

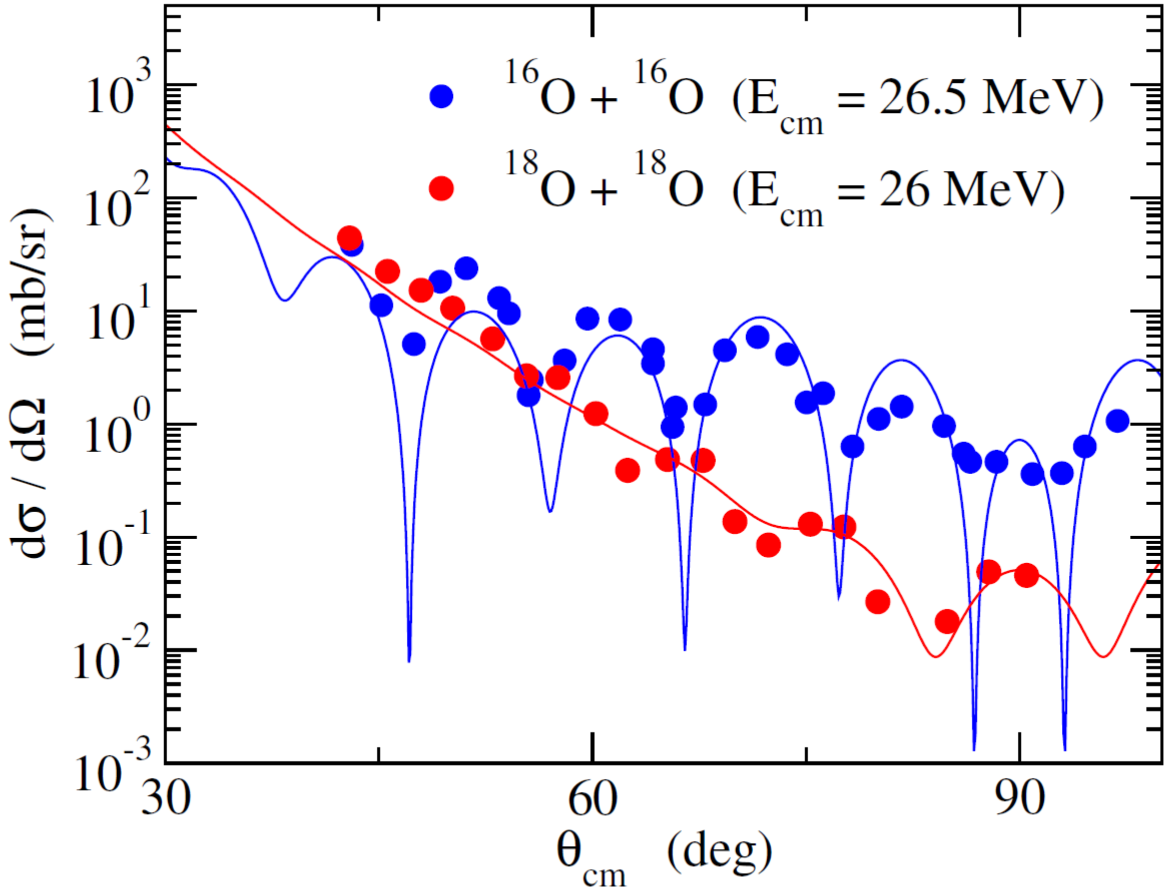
anomalous large angle scattering

$^{16}O+^{16}O$ system



expt: D.A. Bromley et al., Phys. Rev. 123 ('61)878

Comparison between $^{16}O+^{16}O$ and $^{18}O+^{18}O$



^{16}O, ^{18}O: I^π (g.s.) = 0^+ (both are bosons)

$V_b \sim 10.3$ MeV

$\longrightarrow$ $E_{cm} \sim 2.5\, V_b$

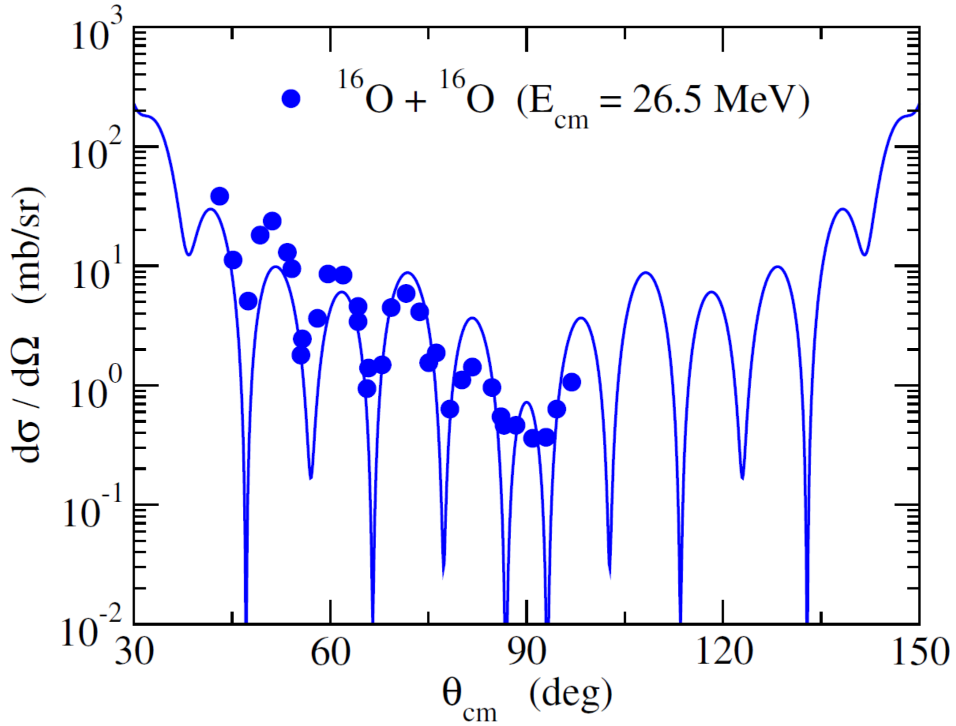
$^{18}O+^{18}O$: much less pronounced interference pattern

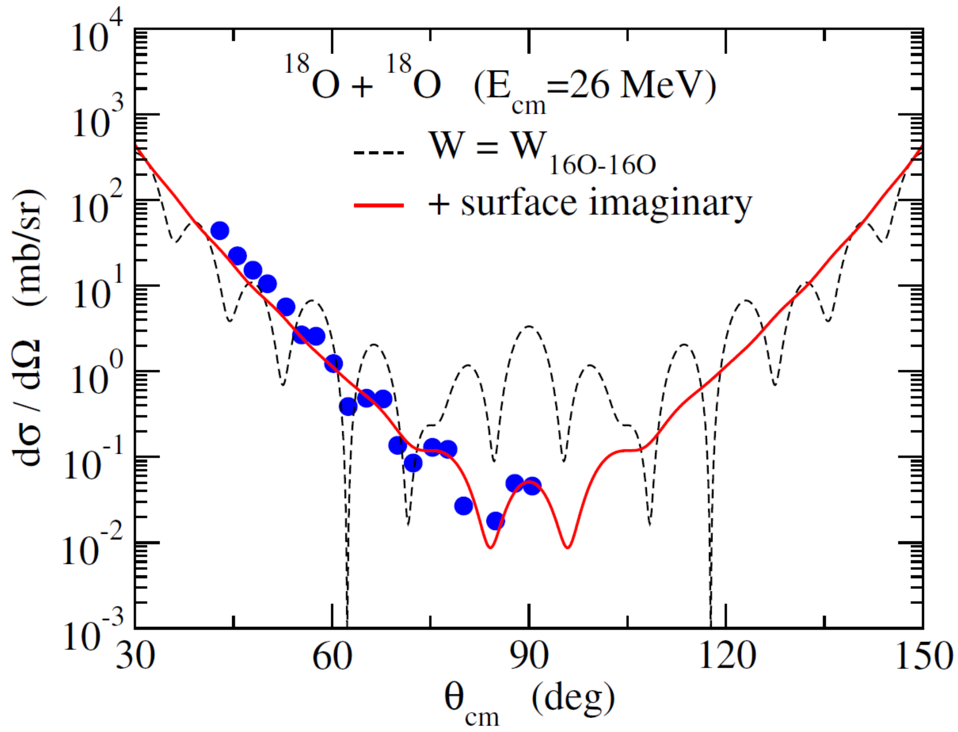
$^{18}O = ^{16}O$ (double closed shell) + 2n

$\longrightarrow$ stronger coupling to environment

$\Rightarrow$ manifestation of environmental decoherence?

Optical potential model calculation





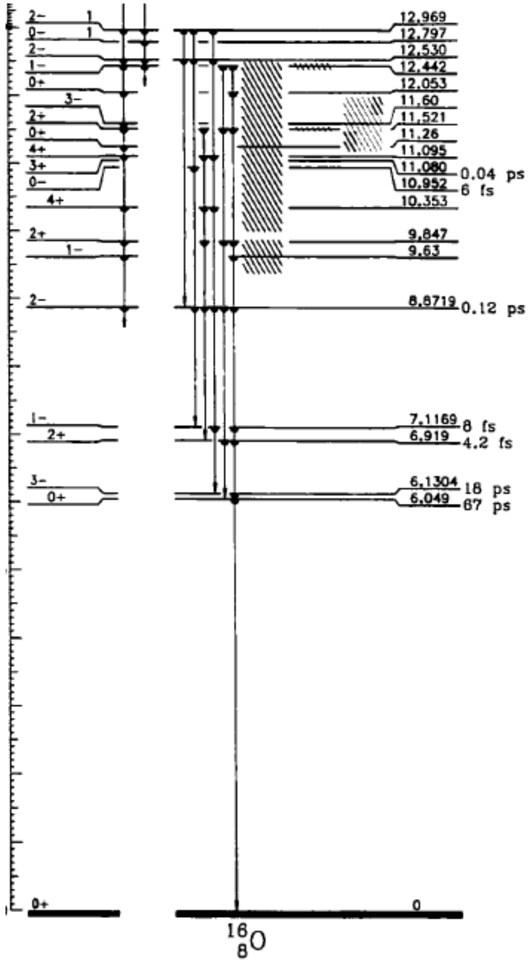
an opt. pot. model calculation with a deep WS^2 potential.

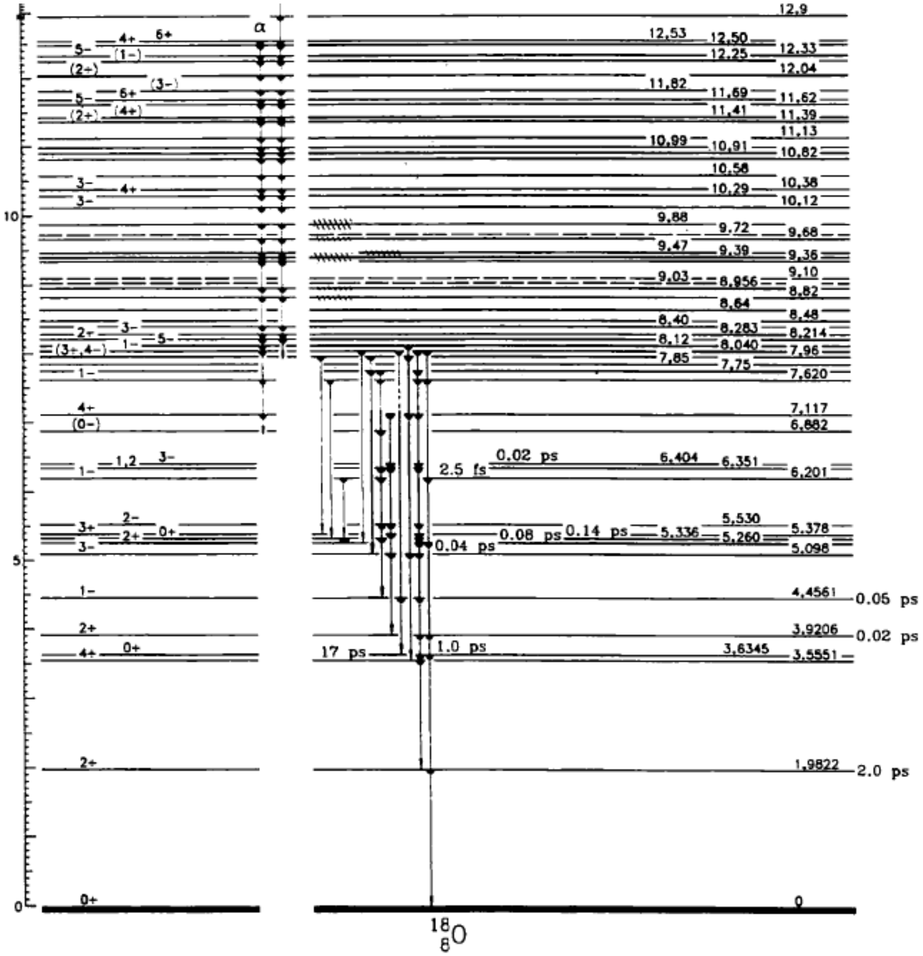
However, the same opt. pot. does not fit $^{18}O+^{18}O$

↓

need to increase *W* (with a surface imaginary pot.)

Spectra up to E* = 13 MeV





^{16}O

20 levels

^{18}O

56 levels

cf. the number of oepn channels, F. Haas and Y. Abe, PRL46('81)1667

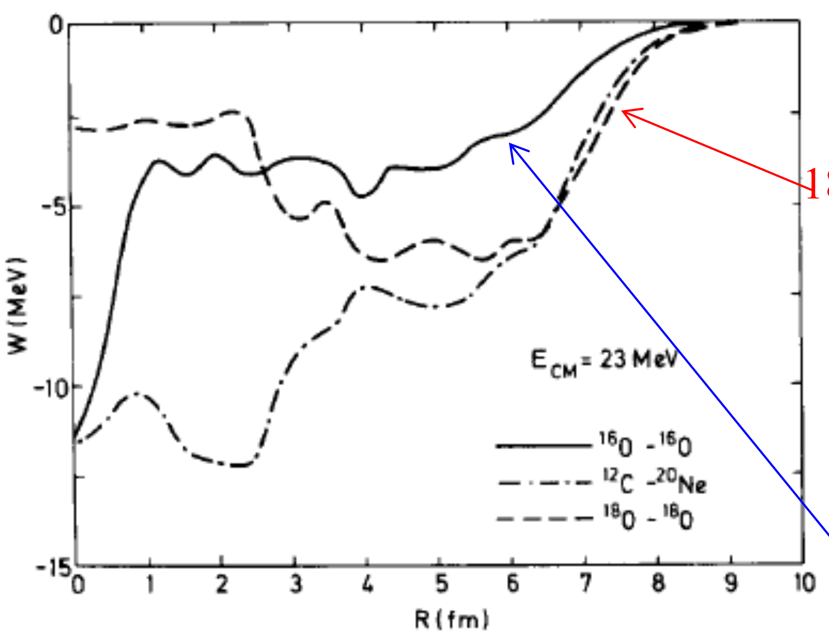
C. Von Charzewski, V. Hnizdo, and C. Toepffer, NPA307('78)309

F. Haas and Y. Abe, PRL46('81)1667

The number of *open channels*

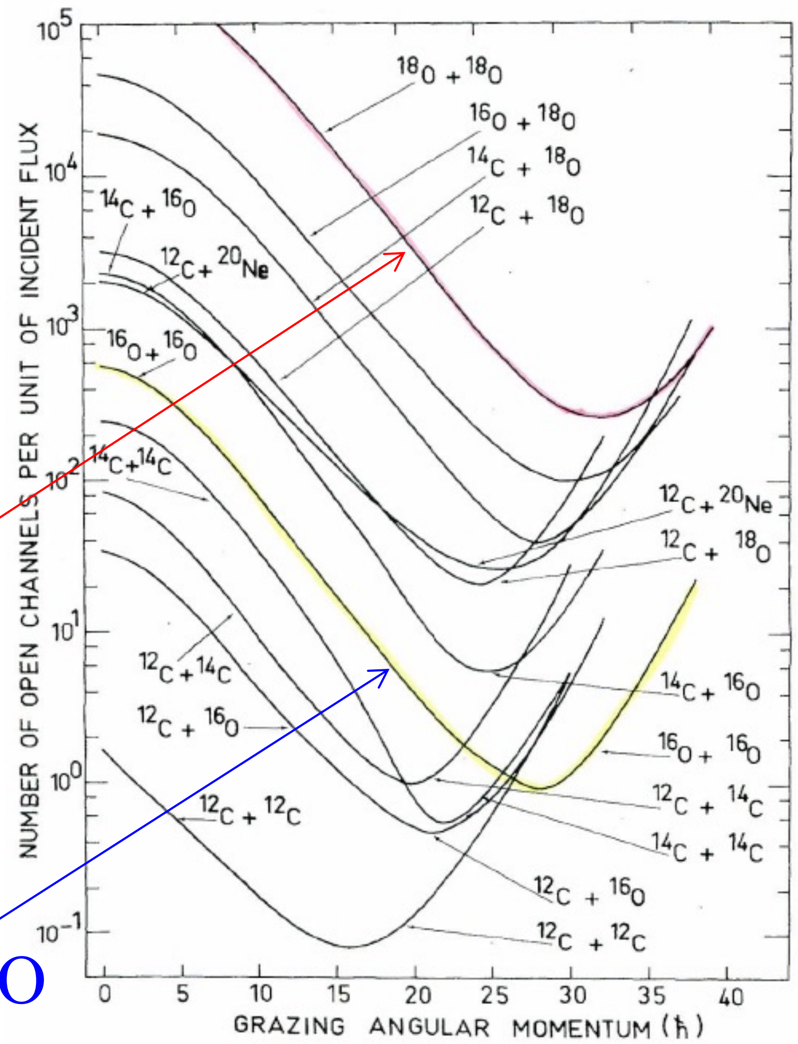
$$W(E,R) = -W_0 f(R) \times \int_0^{E-V(R)} \frac{dN(E^*,R)}{dE^*} e^{-E^*/\Delta E} dE^*$$

N(E*,R): the density of accessible 1p1h states (TCSM)

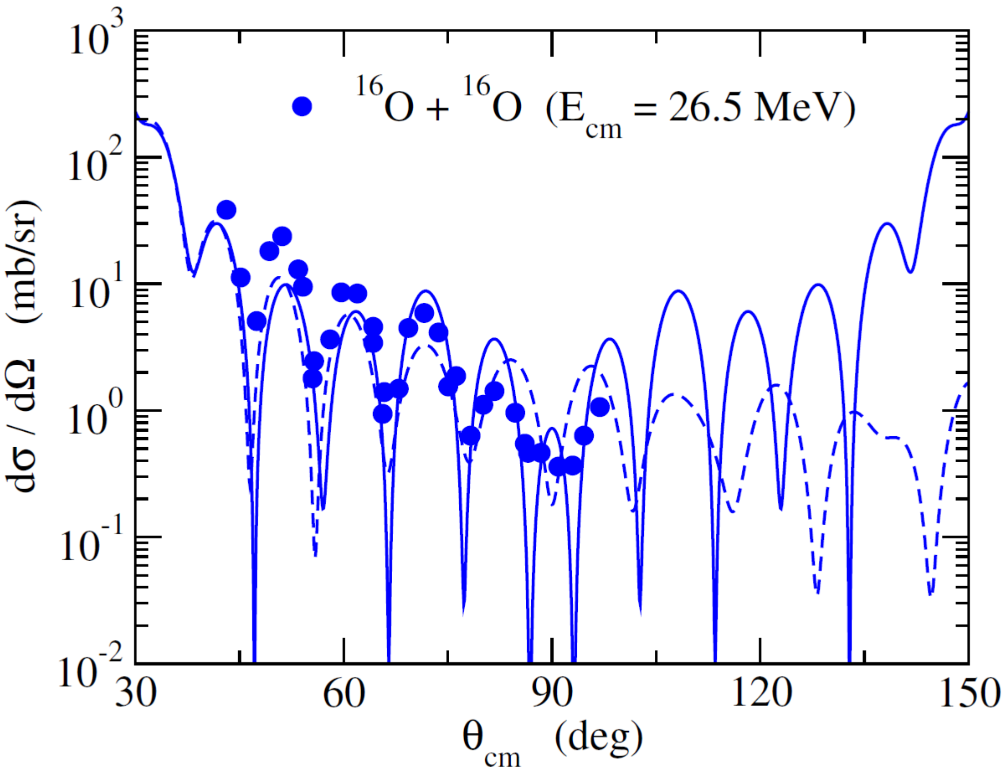


^{18}O+^{18}O

^{16}O+^{16}O



Origins of oscillations

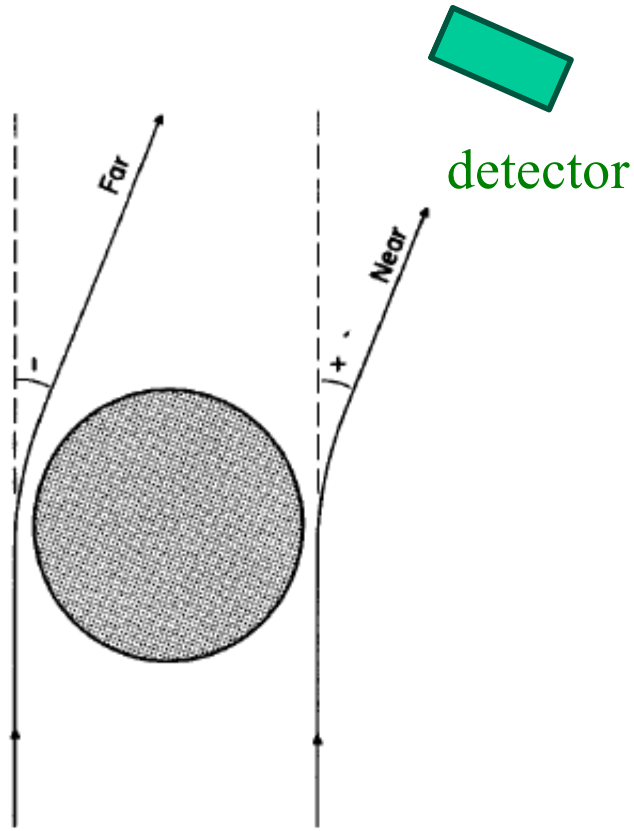


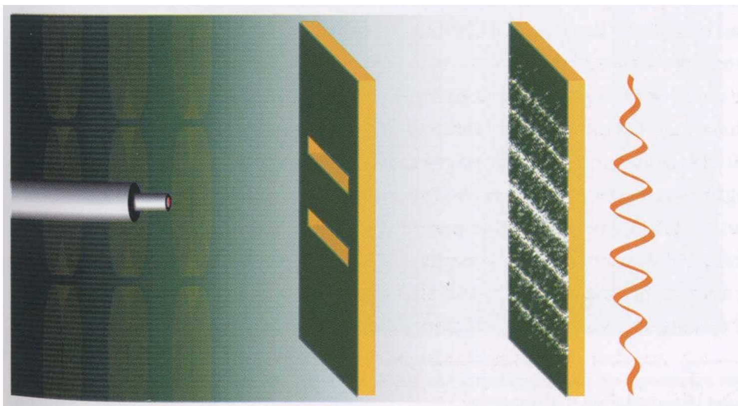
strong oscillations even in unsymmetrized cross sections

↓

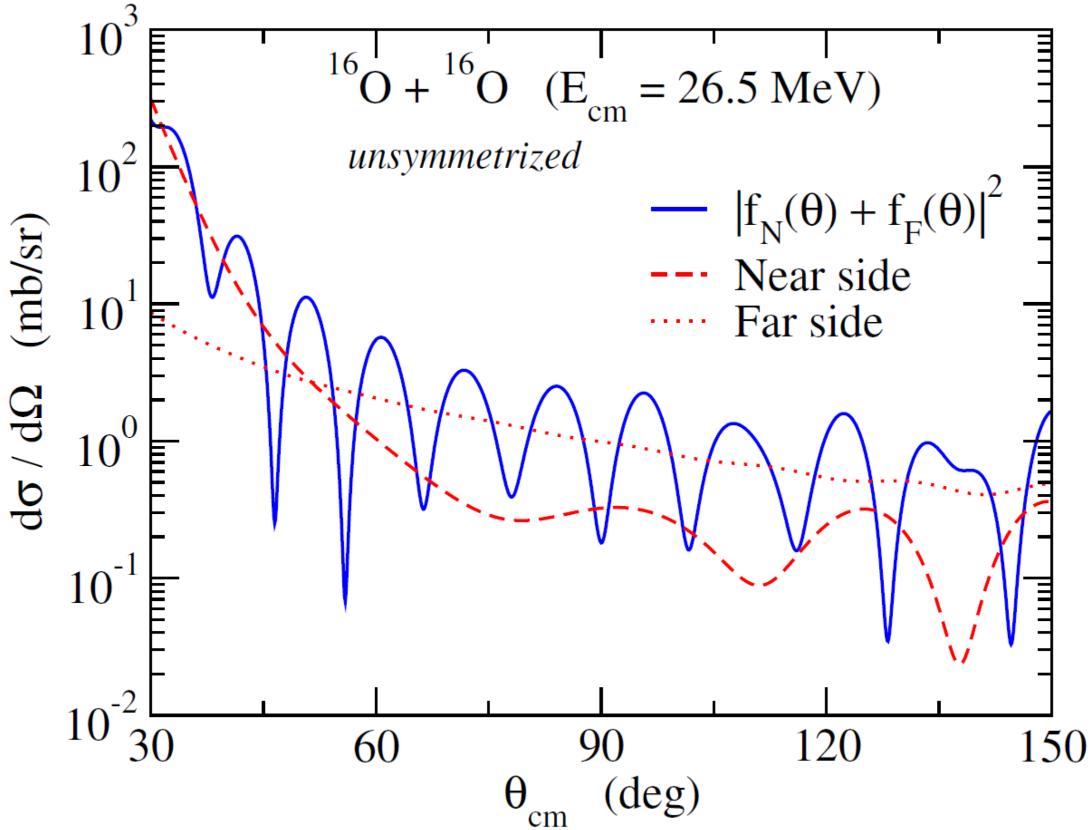
✓ symmetrization: minor

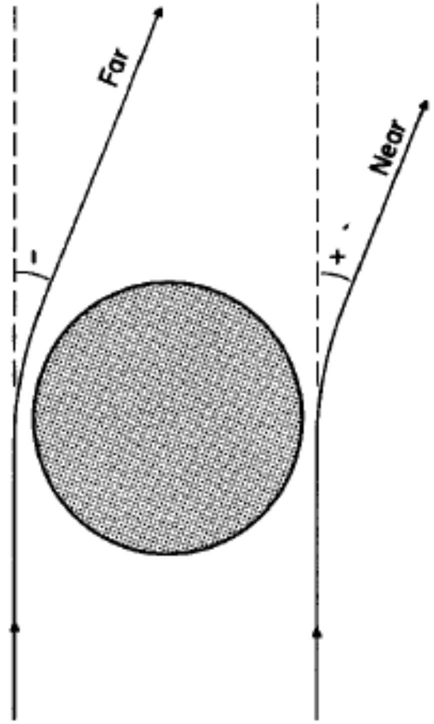
✓ the main origin:
near-side-far-side interference





near side-far side interference



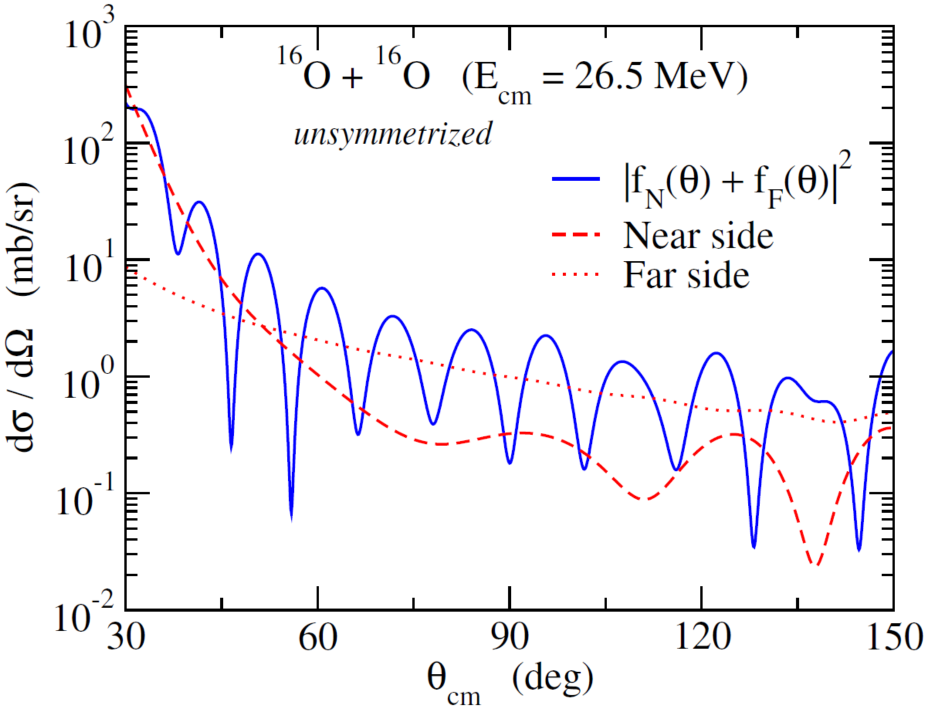


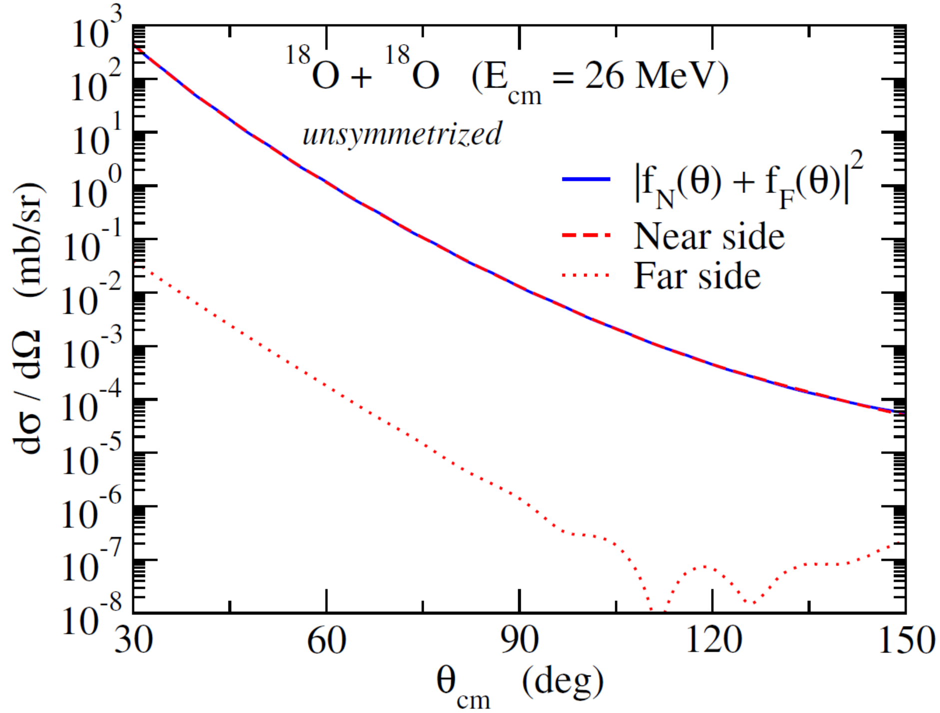
$$P_l(\cos\theta) \to \frac{1}{2}\left[P_l(\cos\theta) \mp i\frac{2}{\pi}Q_l(\cos\theta)\right]$$

N (upper sign), F (lower sign)

R.C. Fuller, PRC12, 1561 (1975)

Q_l: Legendre function of the second kind

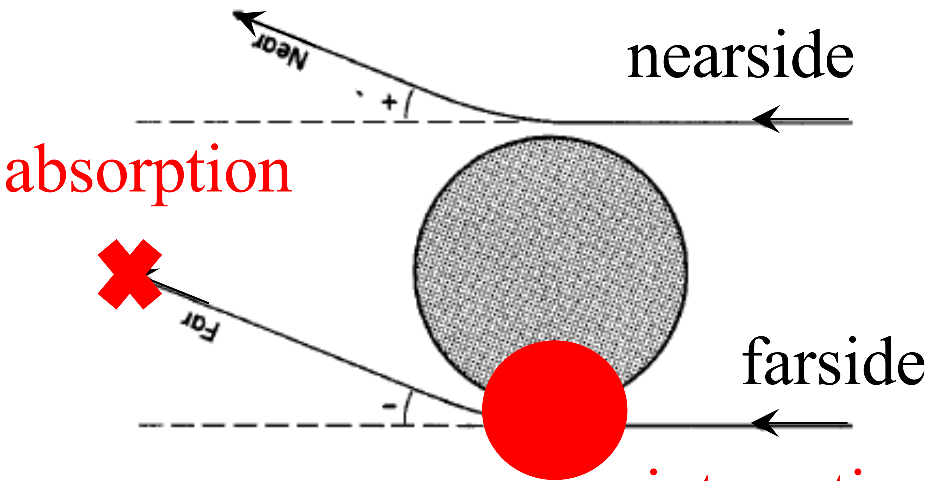


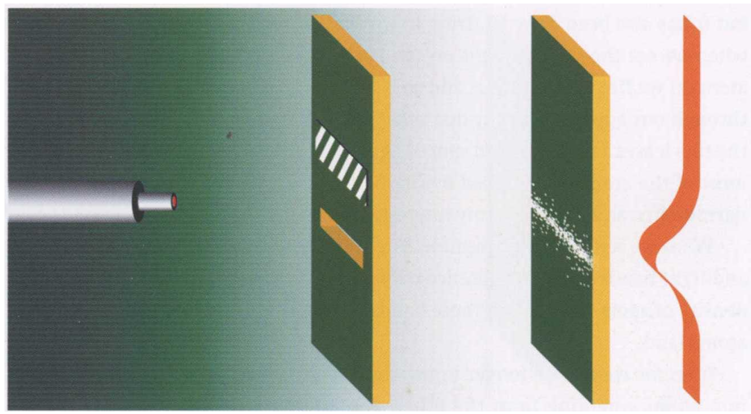


the far-side component is largely damped in $^{18}O+^{18}O$ due to absorption

→almost no interference oscillations

cf. a single slit

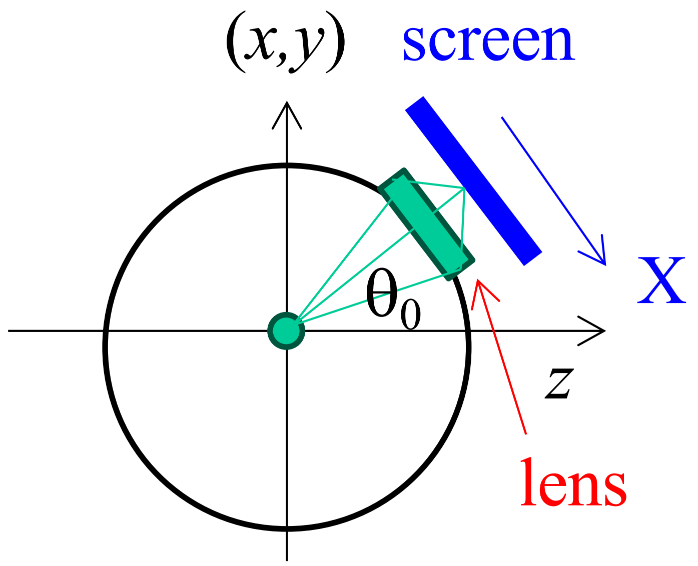




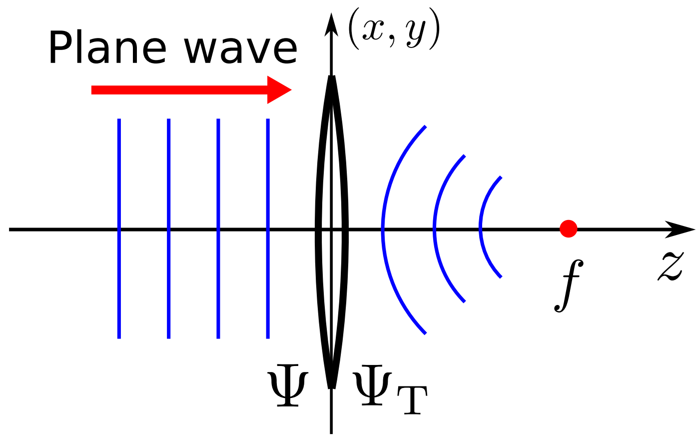
interaction → decoherence

Imaging of nuclear reactions

K. Hagino and T. Yoda,
PLB848, 138326 (2024).



"condensing" scattering waves with a lens



K. Hashimoto et al., PRD101, 066018 (2020)

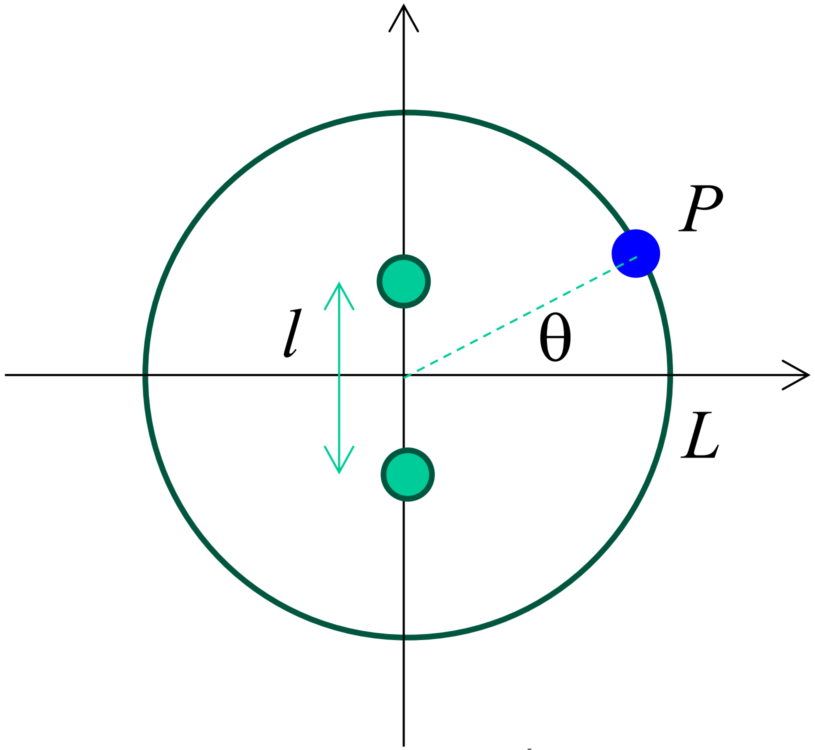
Fourier transform of scattering amplitude

$$\Phi(X,Y) \propto \int_{\theta_0-\Delta\theta}^{\theta_0+\Delta\theta} d\theta \int_{\varphi_0-\Delta\varphi}^{\varphi_0+\Delta\varphi} d\varphi \, e^{ik((\theta-\theta_0)X+(\varphi-\varphi_0)Y)} f(\theta,\varphi)$$

$$I(X,Y) = |\Phi(X,Y)|^2$$

Application to a double slit problem

K. Hashimoto, Y. Matsuo, and
T. Yoda, PTEP2023, 043B04 (2023)



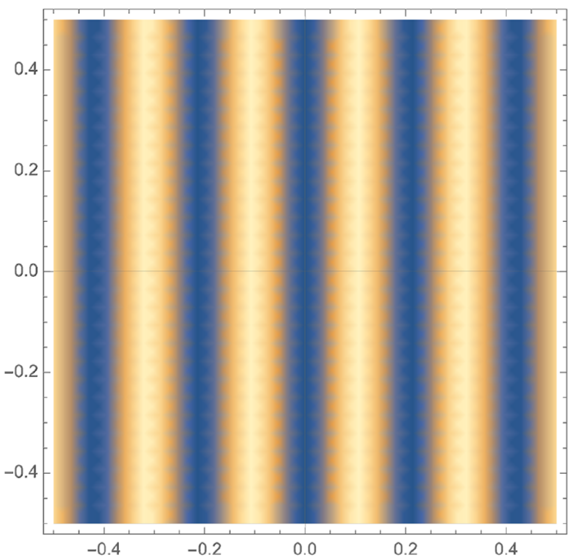
the amplitude at P

$$f(\theta) = f_1 + f_2$$

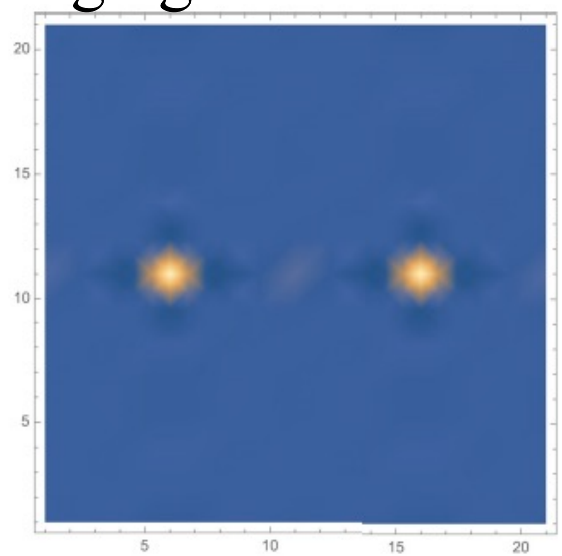
$$f_i = A \sin\left(\frac{2\pi}{\lambda} l_i - \omega t\right)$$

$$l_i \sim L\left(1 \pm \frac{l}{2L} \sin\theta\right)$$

$f(\theta)$



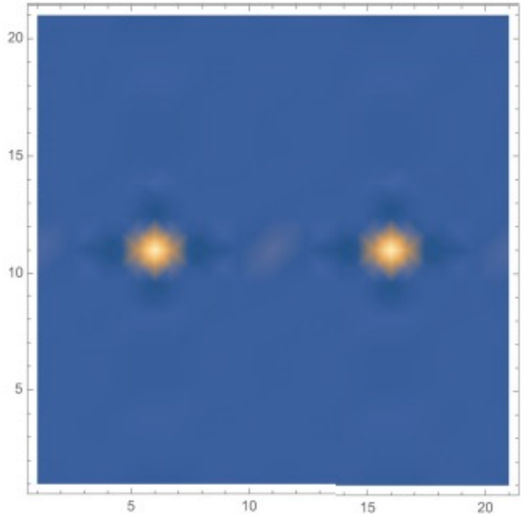
imaging



peaks at

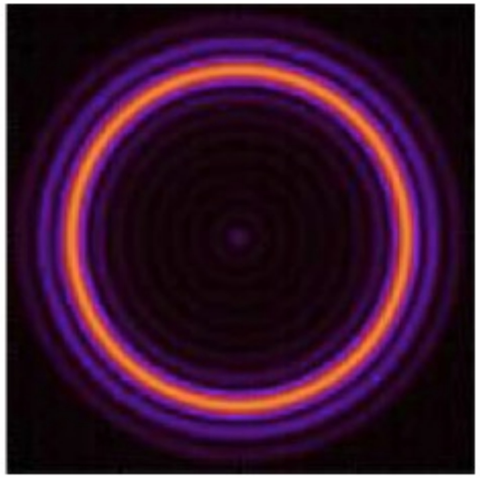
$$\pm\frac{l}{2}\sin\theta_0$$

applications in particle physics



a double slit problem

scattering of string

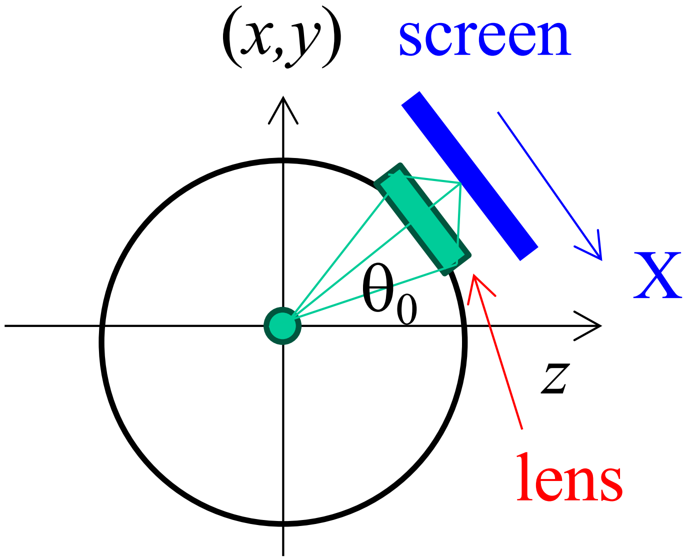


imaging black holes through AdS/CFT

K. Hashimoto, Y. Matsuo, and T. Yoda, PTEP2023, 043B04 (2023)
K. Hashimoto, S. Kinoshita, and K. Murata, PRL123, 031602 (2019)
PRD101, 066018 (2020)

Imaging of nuclear reactions

K. Hagino and T. Yoda, PLB848, 138326 (2024).

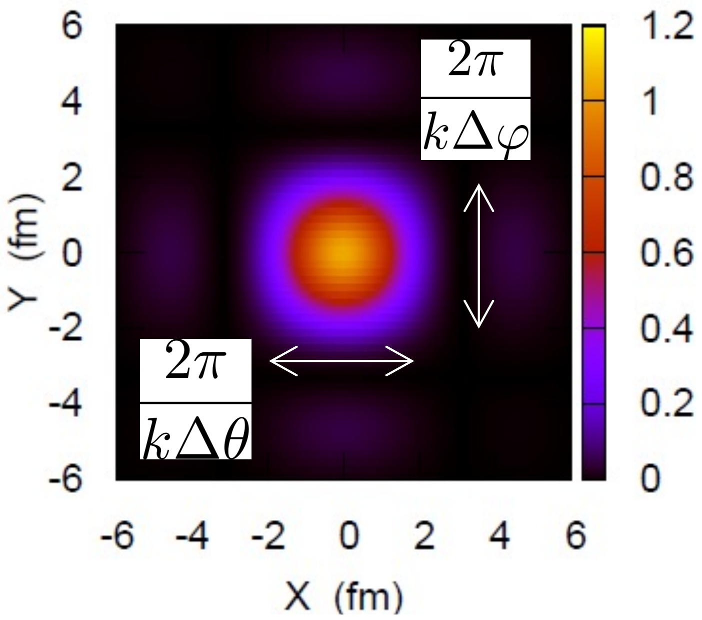


Fourier transform of scattering amplitude

$$\Phi(X,Y) \propto \int_{\theta_0-\Delta\theta}^{\theta_0+\Delta\theta} d\theta \int_{\varphi_0-\Delta\varphi}^{\varphi_0+\Delta\varphi} d\varphi \times e^{ik((\theta-\theta_0)X+(\varphi-\varphi_0)Y)} f(\theta,\varphi)$$

$$I(X,Y) = |\Phi(X,Y)|^2$$

for a flat distribution, $f(\theta,\phi)$ = const.,



$$\int_{\varphi_0-\Delta\varphi}^{\varphi_0+\Delta\varphi} d\varphi e^{ik(\varphi-\varphi_0)Y} = 2\Delta\varphi \frac{\sin(kY\Delta\varphi)}{kY\Delta\varphi}$$

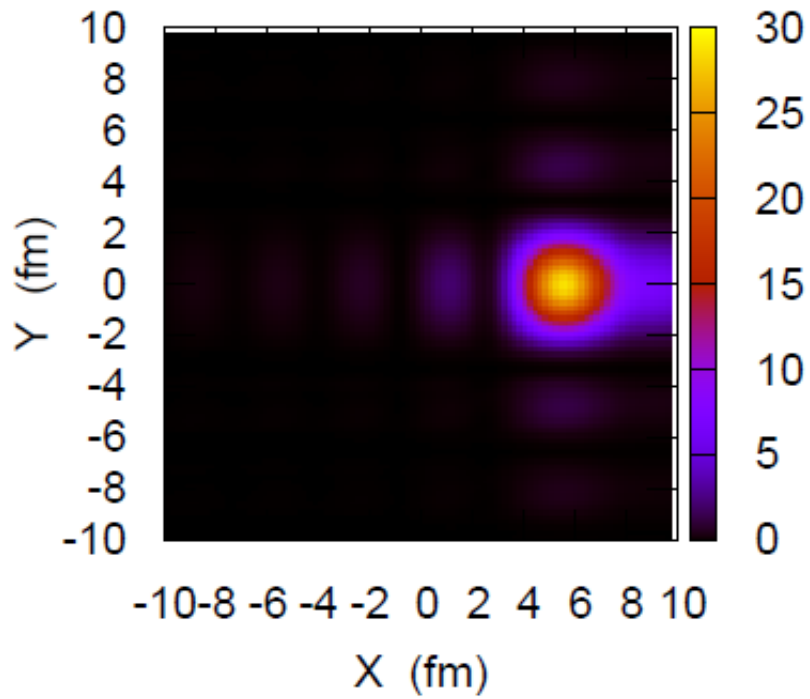
Imaging of nuclear reactions

Fourier transform of scattering amplitude

$$\Phi(X,Y) \propto \int_{\theta_0-\Delta\theta}^{\theta_0+\Delta\theta} d\theta \int_{\varphi_0-\Delta\varphi}^{\varphi_0+\Delta\varphi} d\varphi\, e^{ik((\theta-\theta_0)X+(\varphi-\varphi_0)Y)} f(\theta,\varphi)$$

$$I(X,Y) = |\Phi(X,Y)|^2$$

for the Rutherford scattering, $f(\theta,\phi) = f_C(\theta,\phi)$,



$^{16}O+^{16}O$ at E_{cm} = 8.8 MeV

θ_0= 90 deg.
$\Delta\theta = \Delta\phi$ = 30 deg.

↓

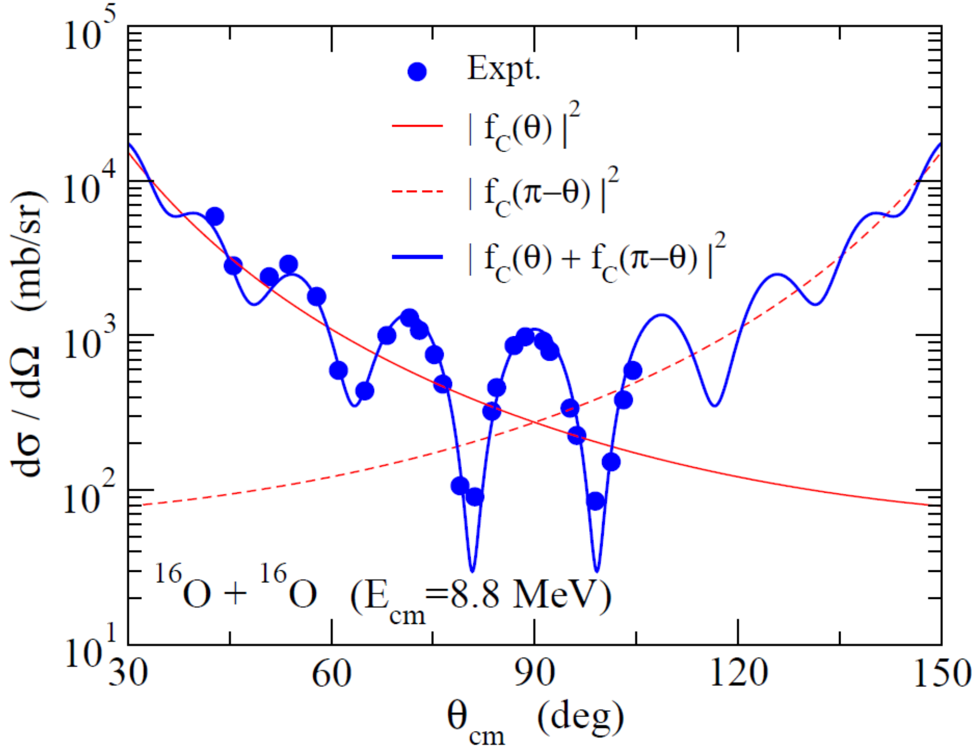
b_{cl} = 5.24 fm ~ X_{peak}

Imaging of nuclear reactions

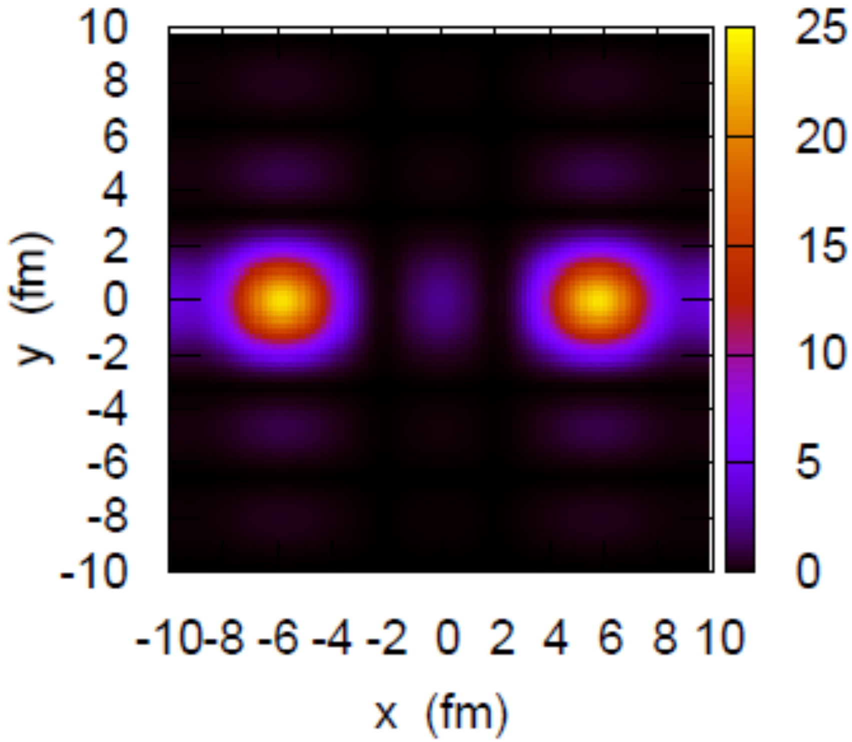
$$\Phi(X,Y) \;\propto\; \int_{\theta_0-\Delta\theta}^{\theta_0+\Delta\theta} d\theta \int_{\varphi_0-\Delta\varphi}^{\varphi_0+\Delta\varphi} d\varphi\, e^{ik((\theta-\theta_0)X+(\varphi-\varphi_0)Y)} f(\theta,\varphi)$$

Imaging of Mott scattering

$$I(X,Y) = |\Phi(X,Y)|^2$$



θ_0=90 deg., $\Delta\theta=\Delta\phi$=30 deg.



(note) for θ_0=90 deg.,

$$\Phi_\theta(X,Y) = \Phi_{\pi-\theta}(-X,Y)$$

Imaging of nuclear reactions

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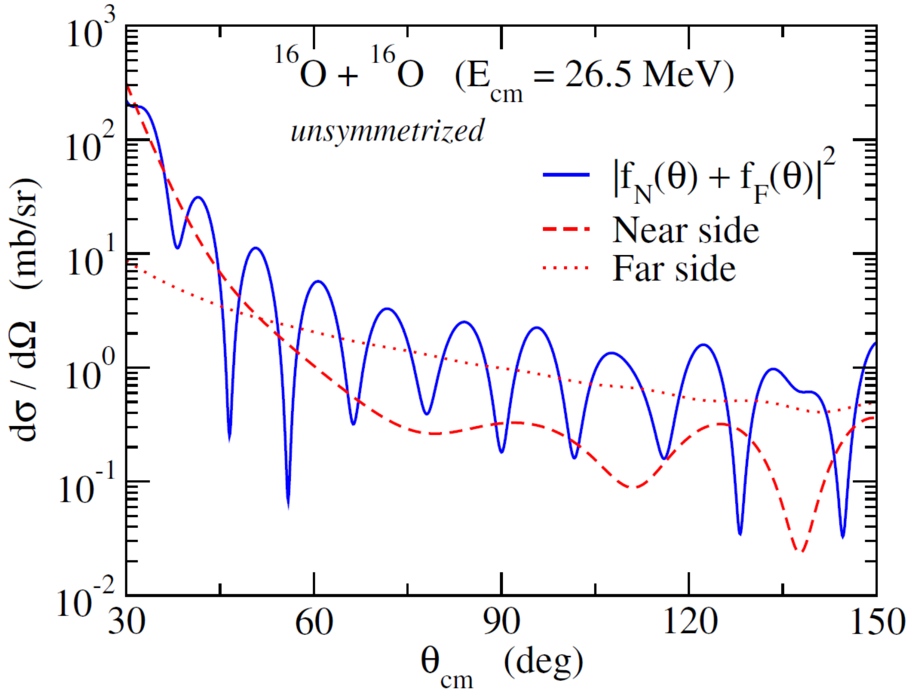
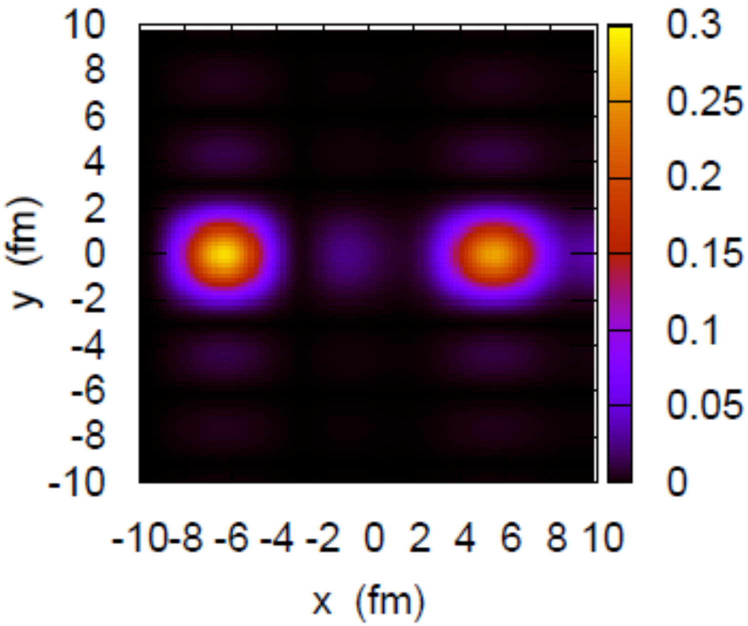
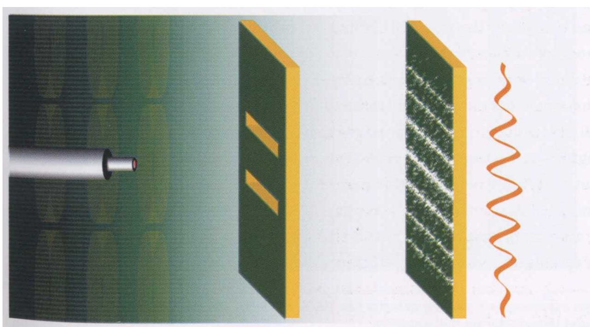
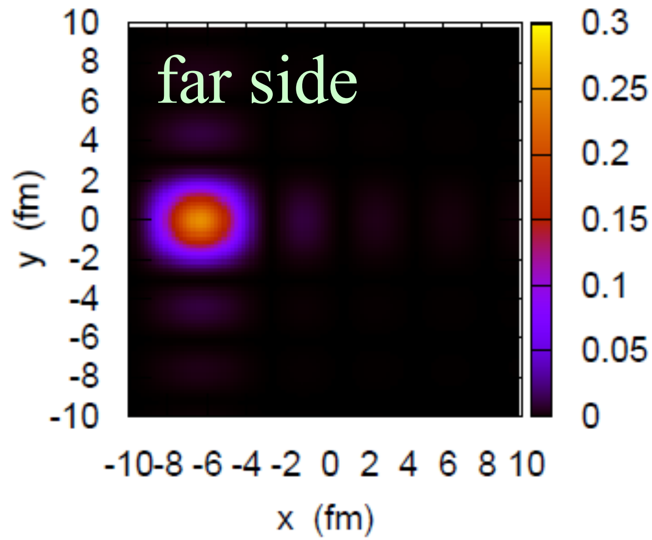
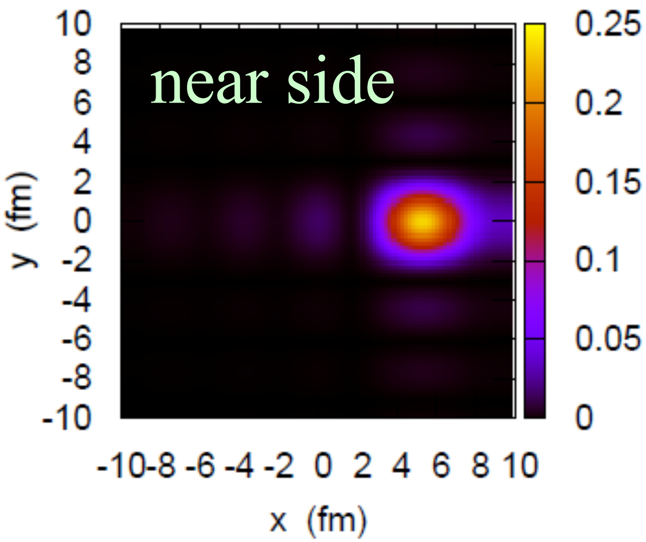


θ_0=55 deg., $\Delta\theta$=15 deg.









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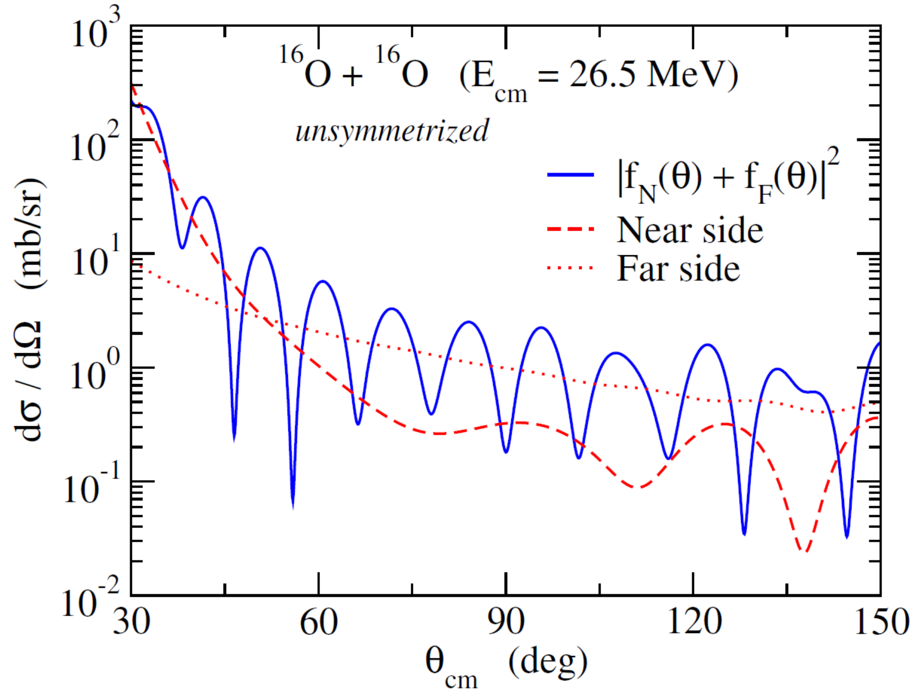
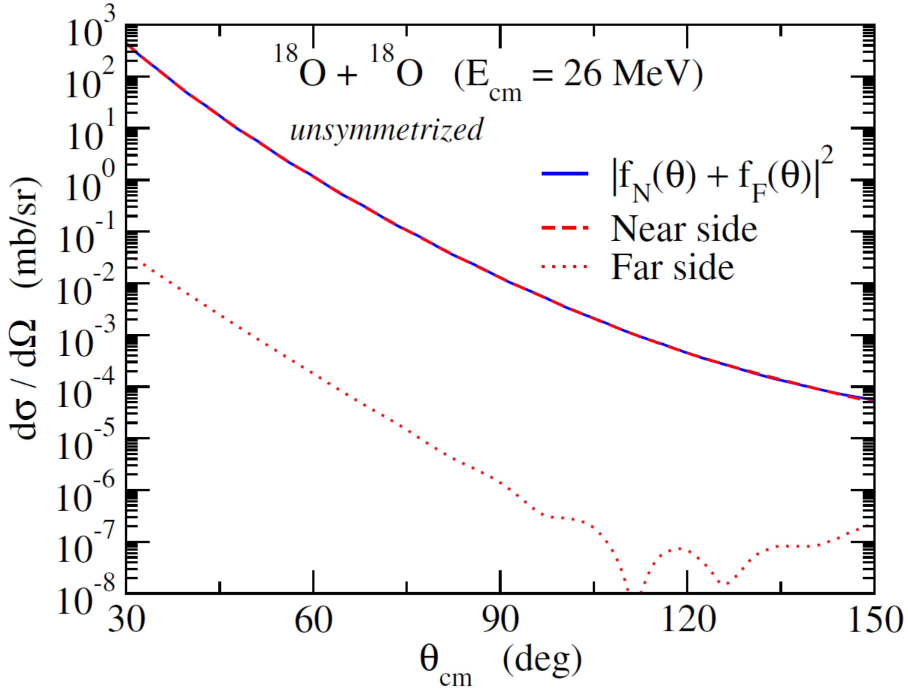
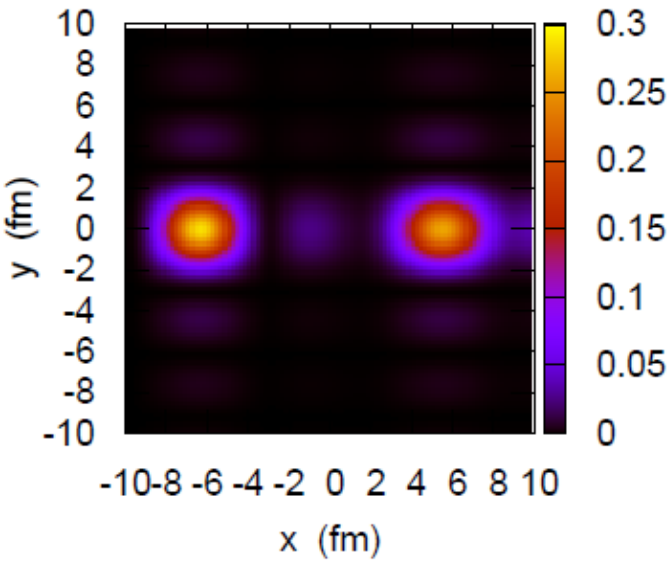
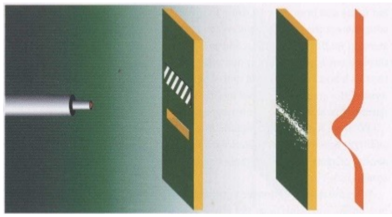
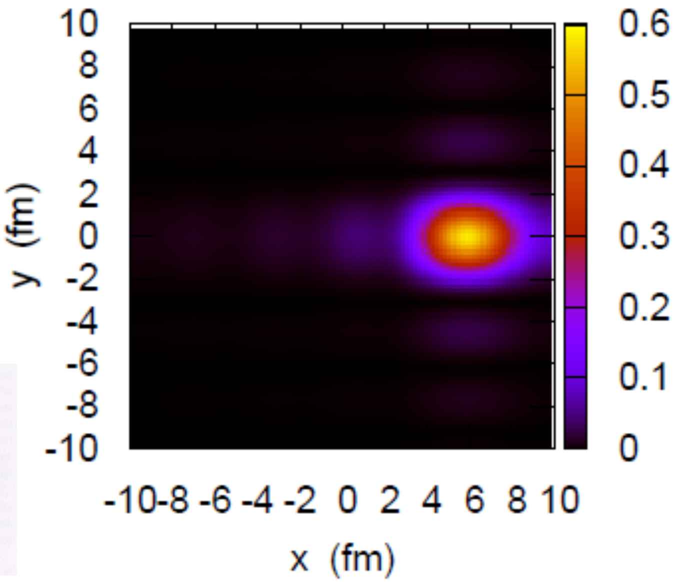






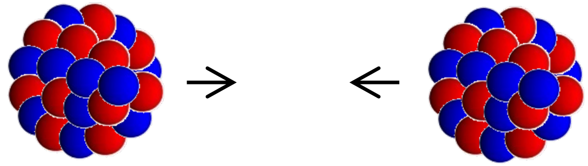




Summary

Nuclear Reactions as quantum many-body phenomena

✓strong interplay with nuclear structure
✓several nuclear intrinsic motions
✓Coupled-channels approach



✓a variety of interference phenomena

- scattering of identical nuclei
- farside-nearside interference
- barrier-wave-internal-wave interference

✓Imaging: a new approach

- a Fourier transform of scatt. amplitudes
- an intuitive way to understand physics of interferences