Imaging quantum decoherence in nuclear reactions

Kouichi Hagino

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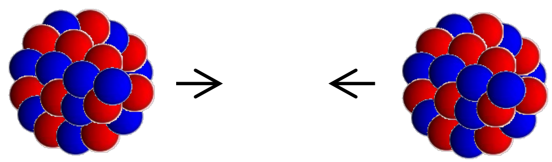


- ✓ nuclear reactions as a tool
- ✓ nuclear reactions as many-body phenomena

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

New Frontiers in Nuclear Physics and Astrophysics-2, Akdeniz Univ., Antalya, Turkey, September 5-10, 2023

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
- ✓ …….

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

physics of nuclear reactions:
a unified description of these nuclear reaction processes

cf. Francesco Cappuzzello's talk

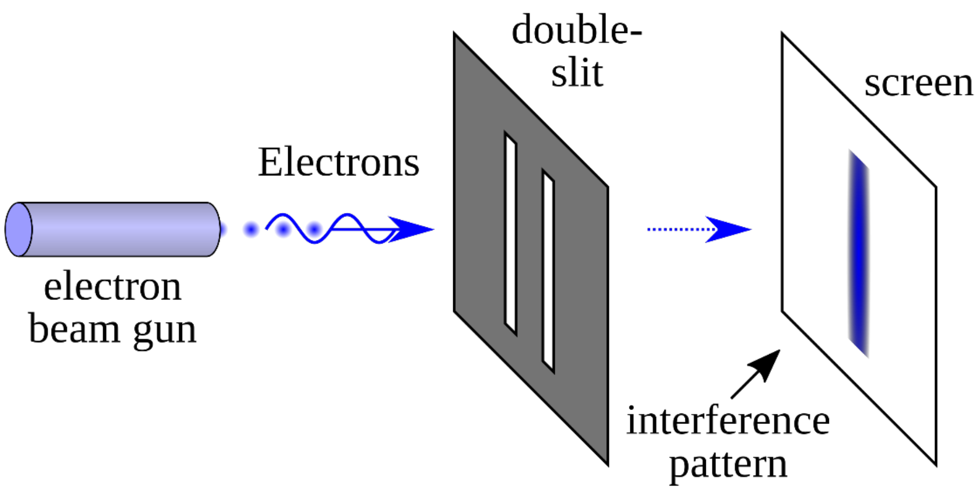
Nuclear Reactions: a variety of quantum mechanical natures

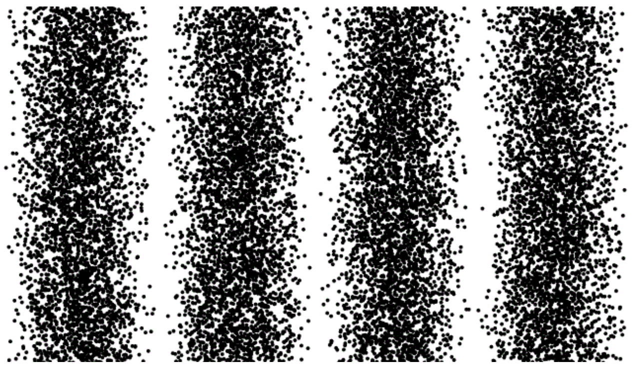
Manifestation of Quantum Nature in Nuclear Reactions

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

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

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



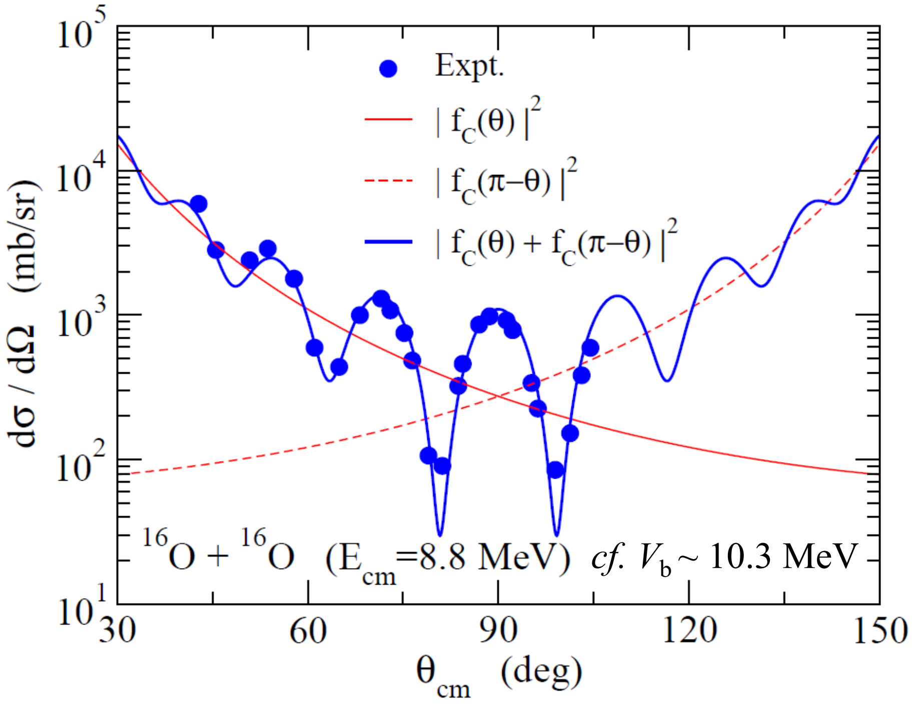


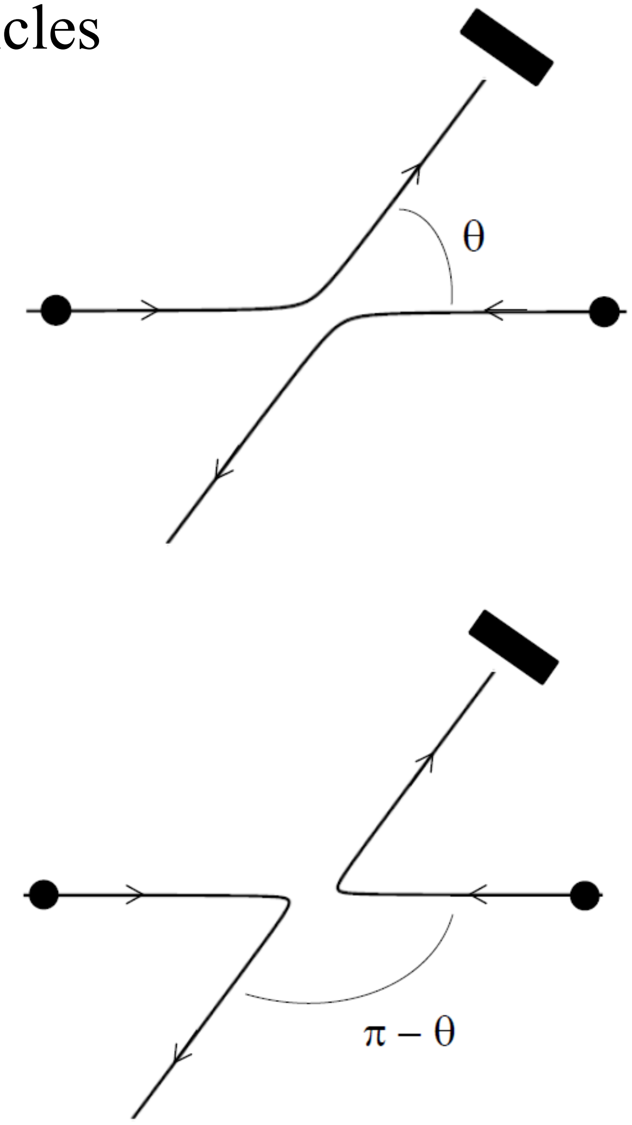
Wikipedia

Manifestation of Quantum Nature in Nuclear Reactions

Mott Scattering: scattering of identical particles

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

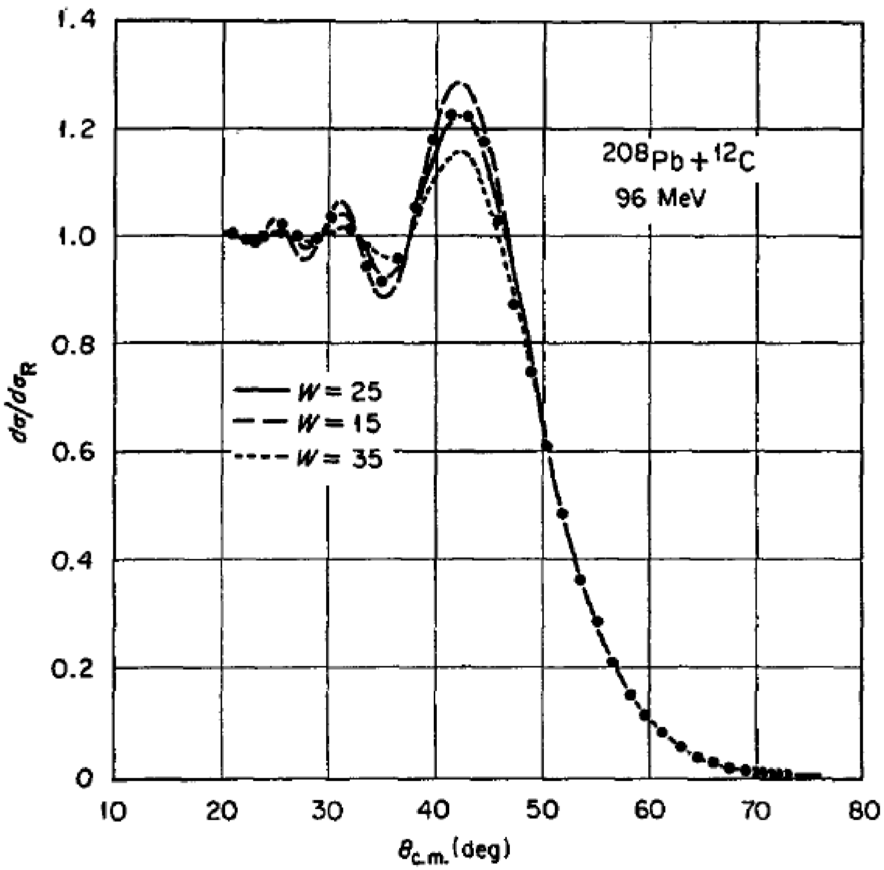




expt: D.A. Bromley et al., Phys. Rev. 123 (‘61)878

- Coulomb-Nuclear interference

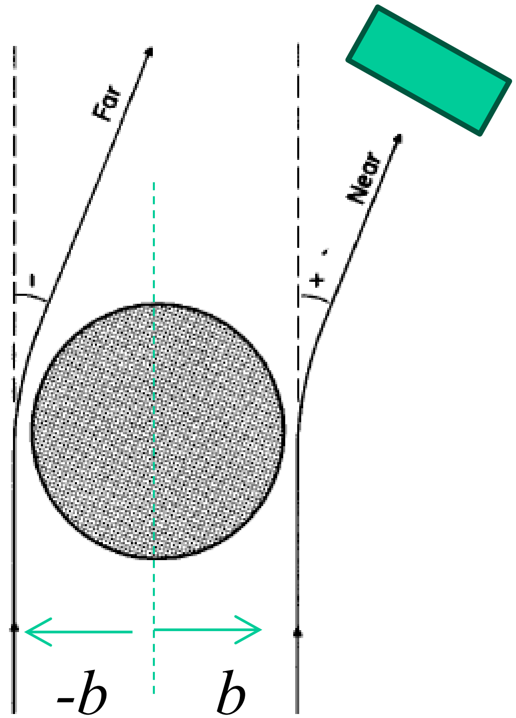
$$f(\theta) = f_C(\theta) + f_N(\theta) \ \rightarrow \ \frac{d\sigma}{d\Omega} = |f(\theta)|^2$$

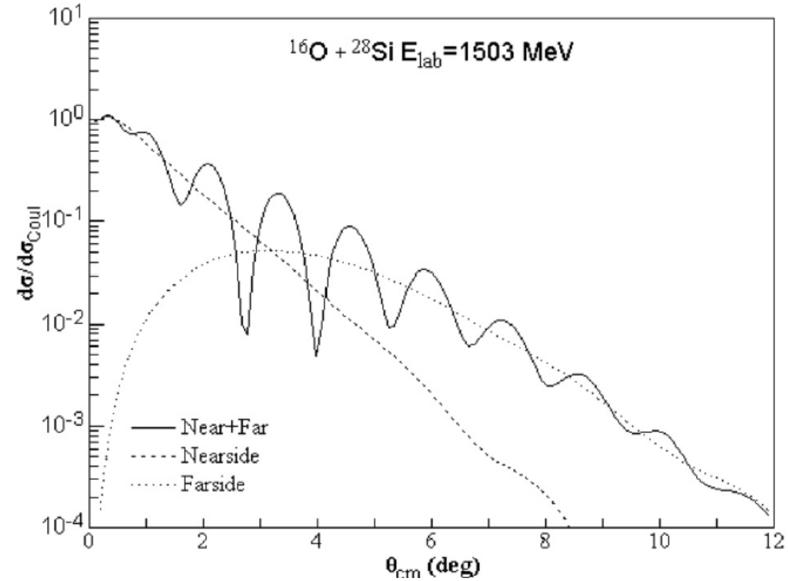


J.B. Ball et al., NPA252 ('75) 208

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

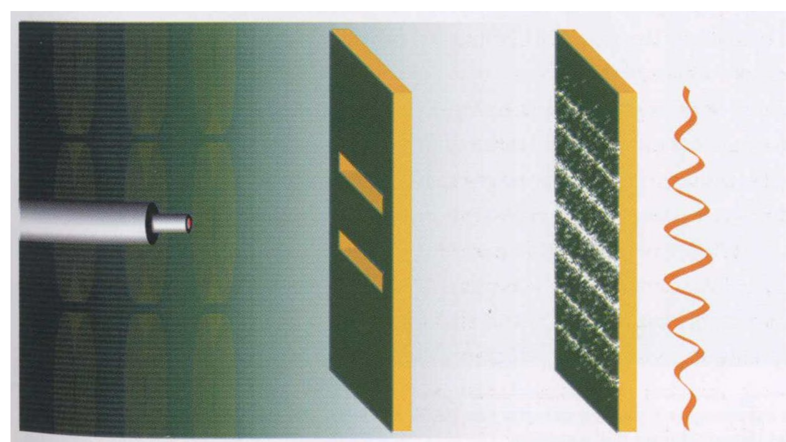
➢ near side - far side interference





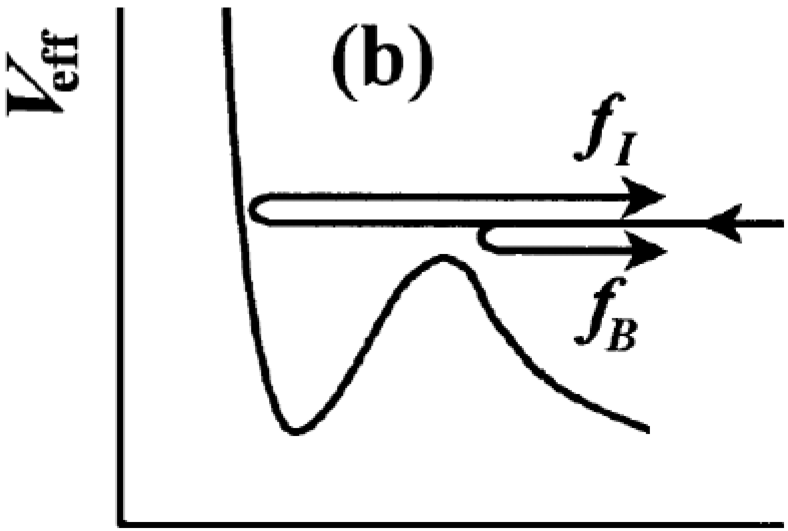
M.H. Cha,
Comp. Phys. Comm. 176 (‘07) 318

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

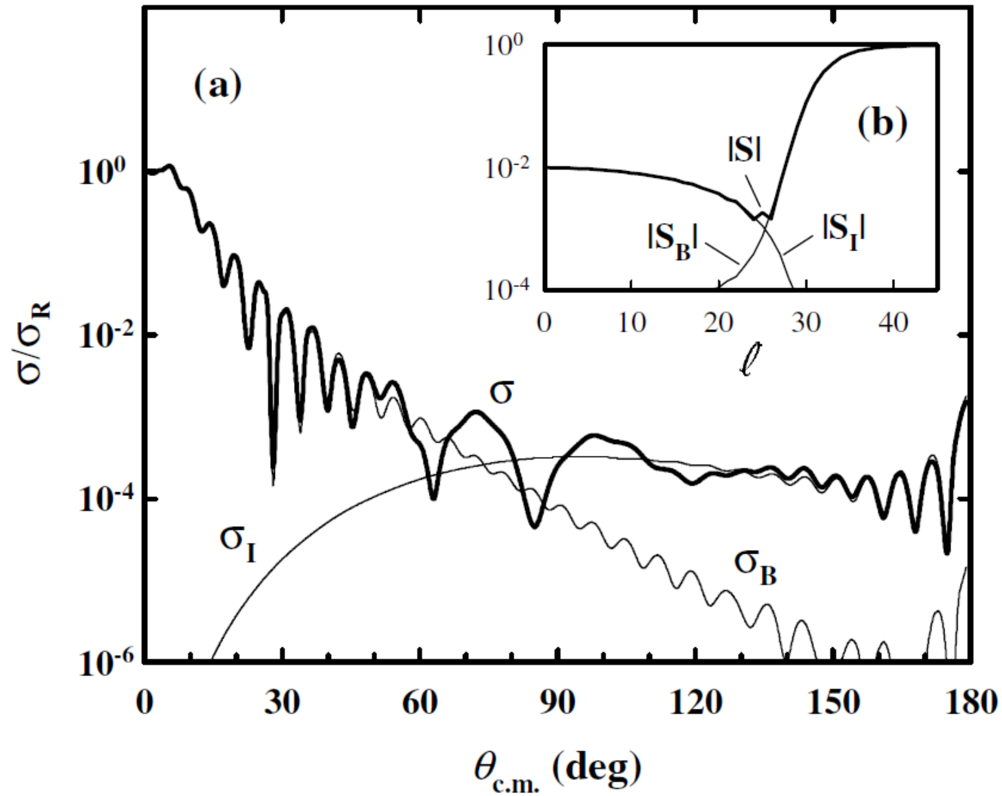


- barrier wave – internal wave interference

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



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

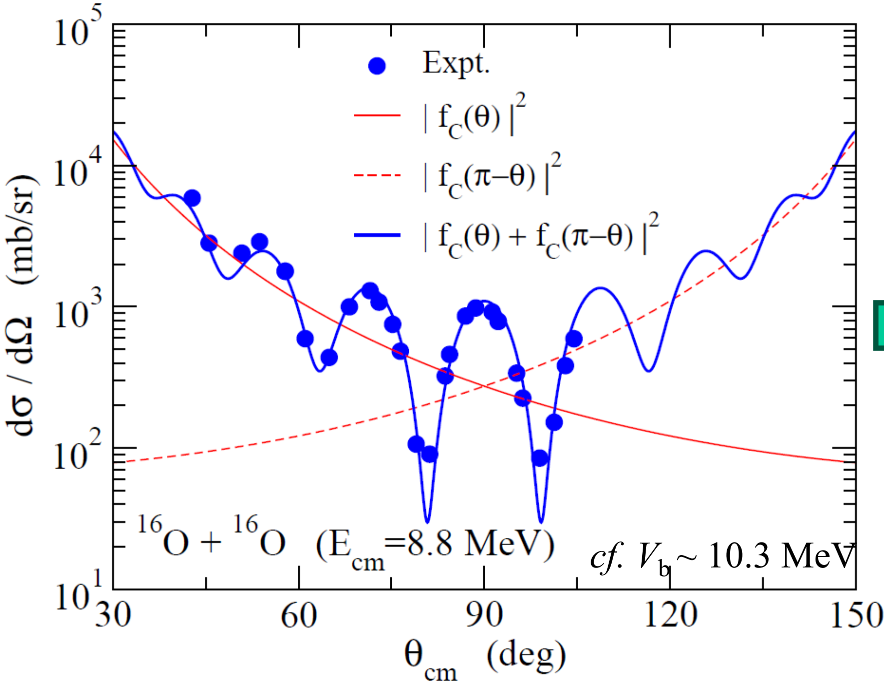


F. Michel et al., PRL85 ('00) 1823

anomalous large angle scattering

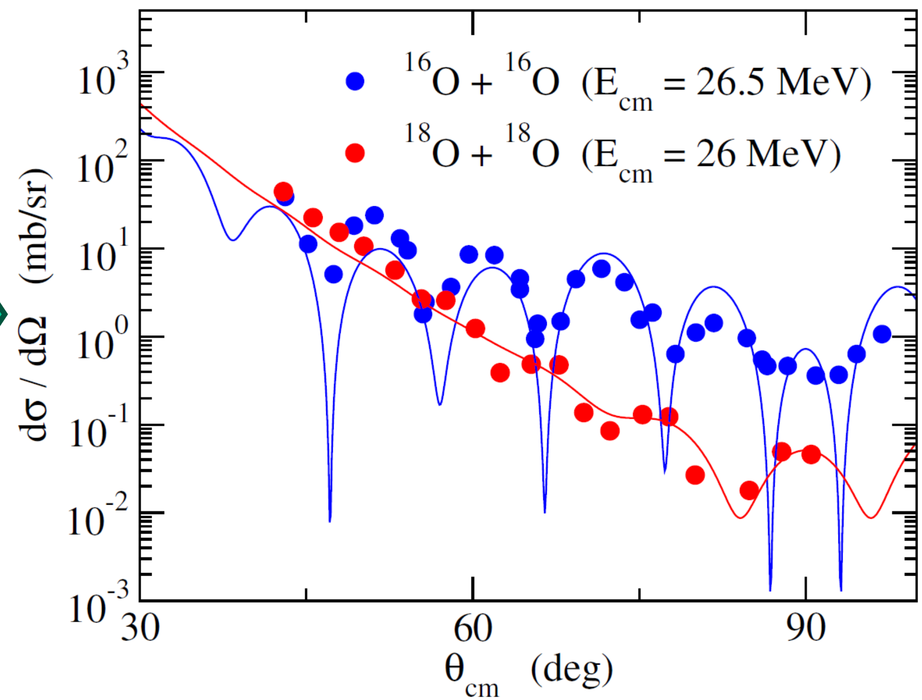
$^{16}O+^{16}O$ system

$E < V_b$



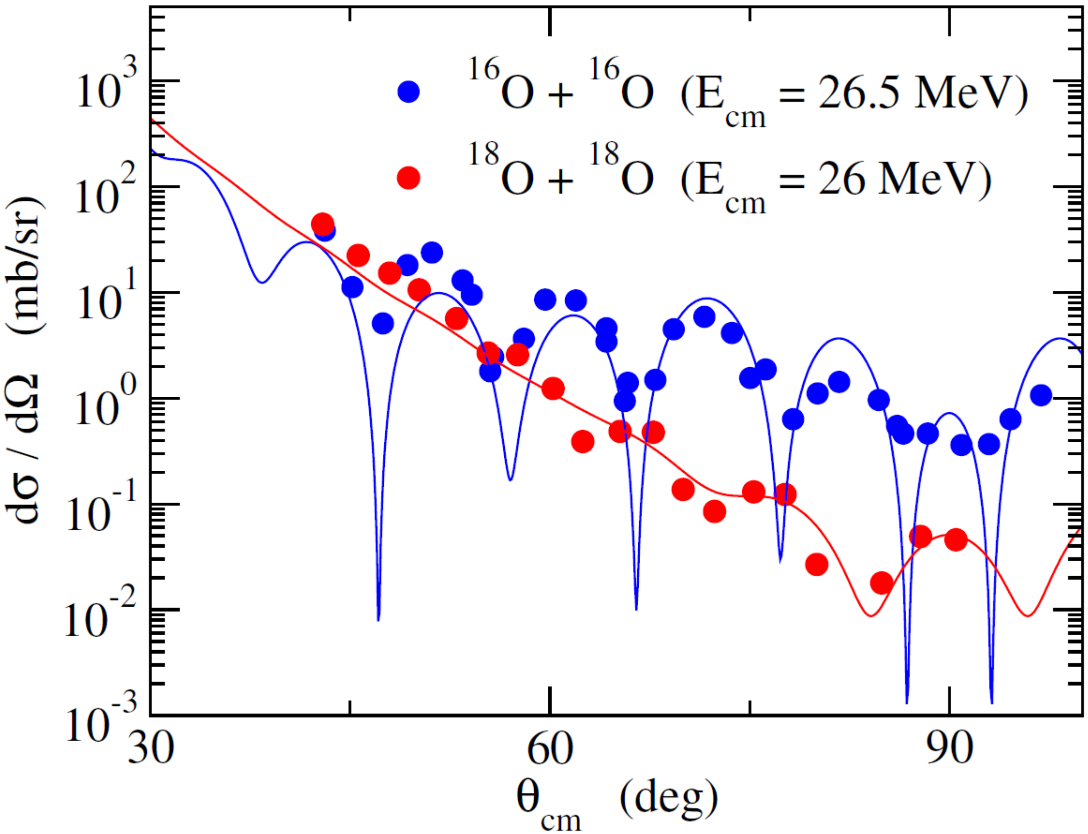
expt: D.A. Bromley et al., Phys. Rev. 123 (‘61)878

$E > V_b$



R.H. Siemessen et al., PRL19 (‘67) 369
R. Vandenbosch et al., NPA230 (‘74) 59

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

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

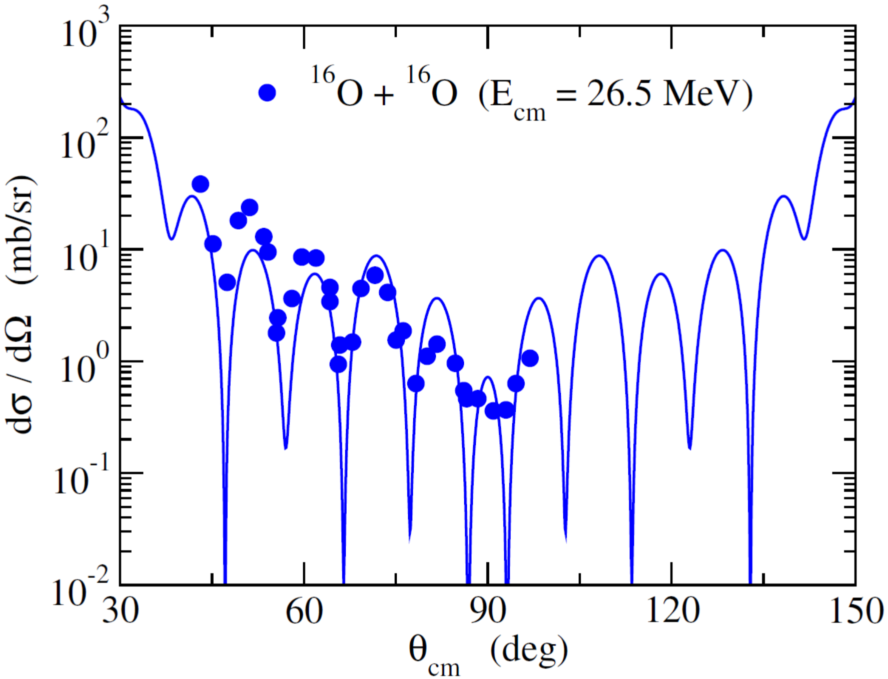
$^{18}O+^{18}O$: much less pronounced interference pattern

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

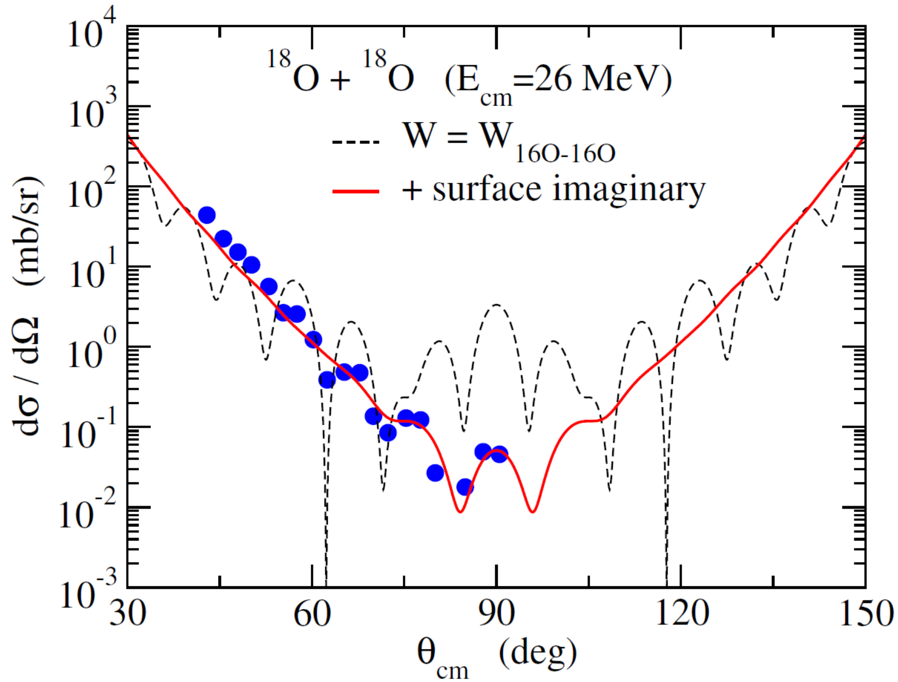
$\longrightarrow$ stronger coupling to environment

➡ manifestation of environmental decoherence?

Optical potential model calculation



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

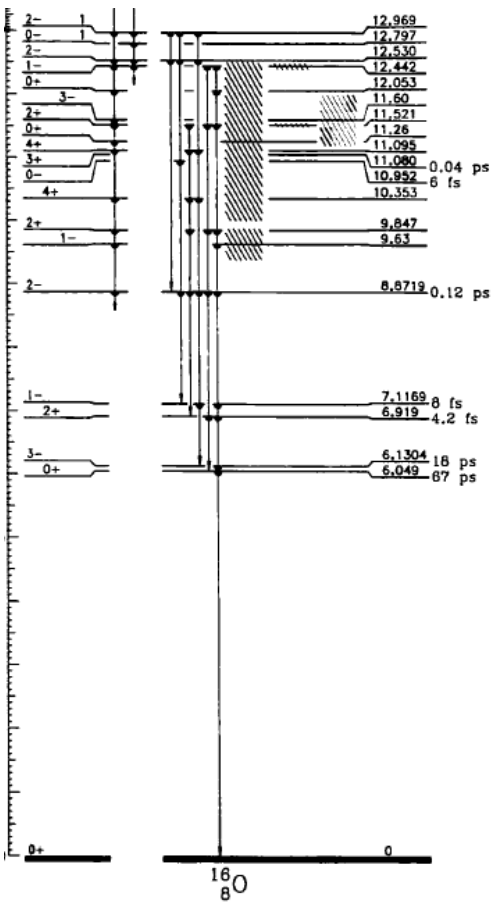


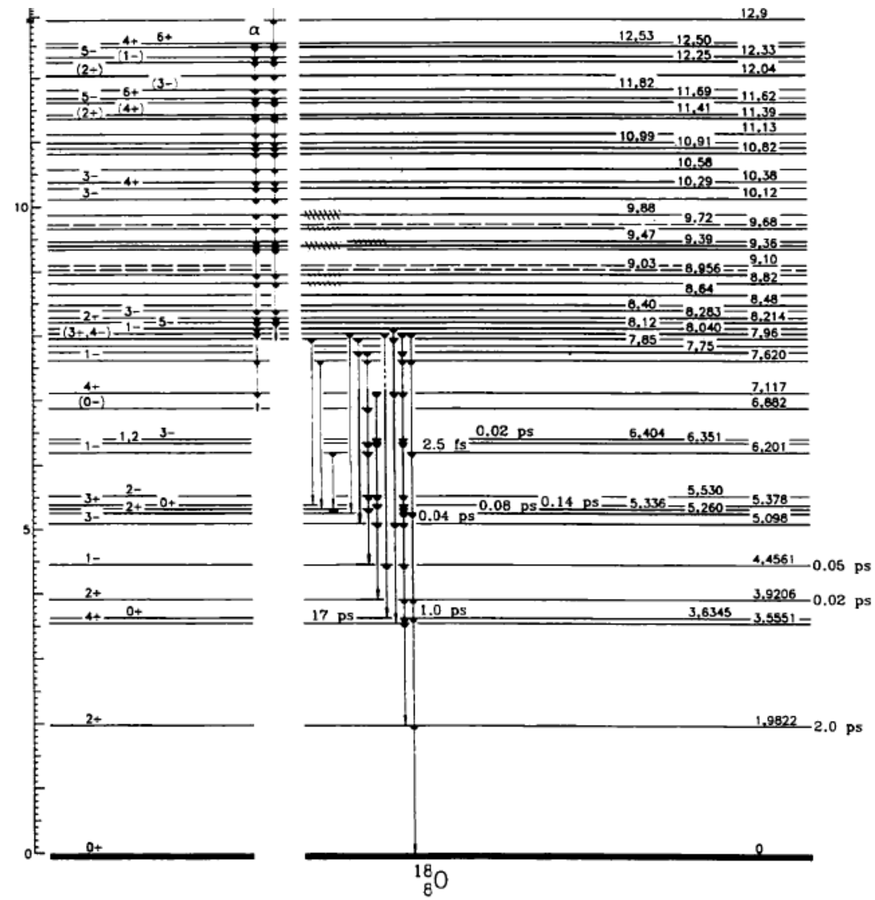
However, the same opt. pot. does not fit $^{18}O+^{18}O$

↓

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

Spectra up to E* = 13 MeV





^{16}O

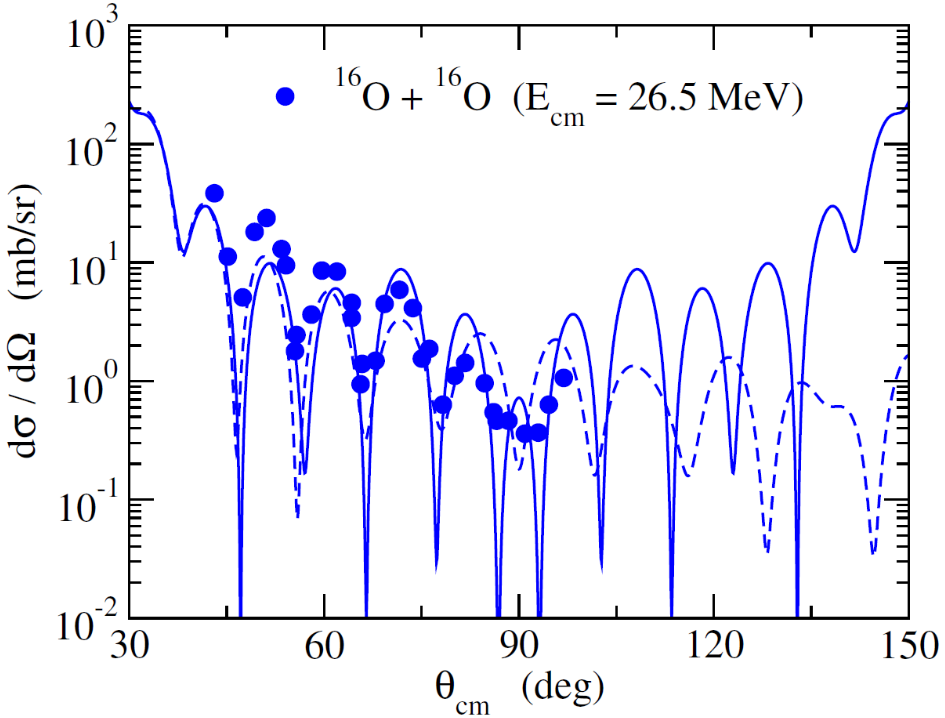
20 levels

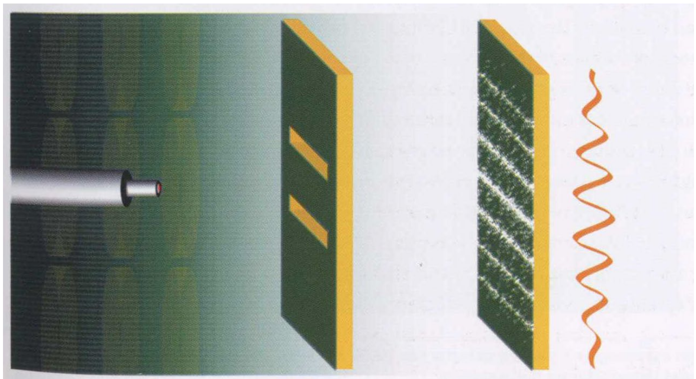
^{18}O

56 levels

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

Origins of oscillations



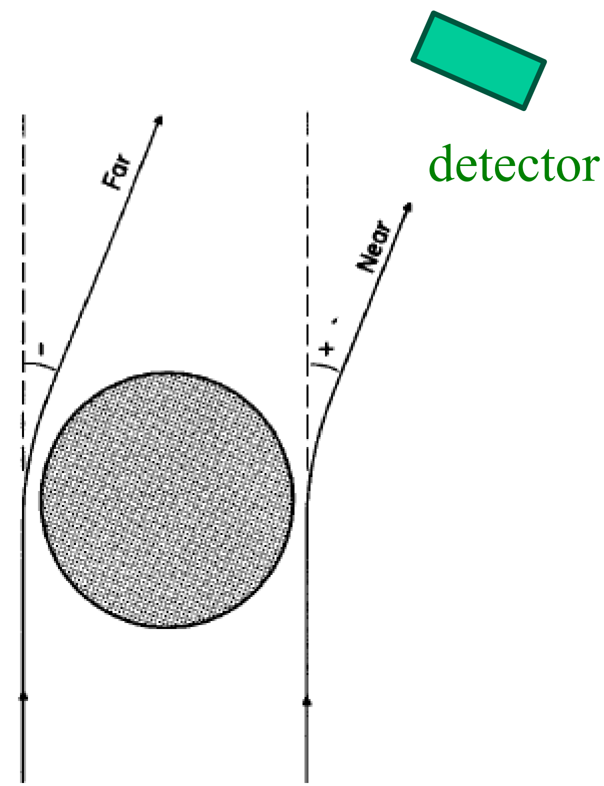


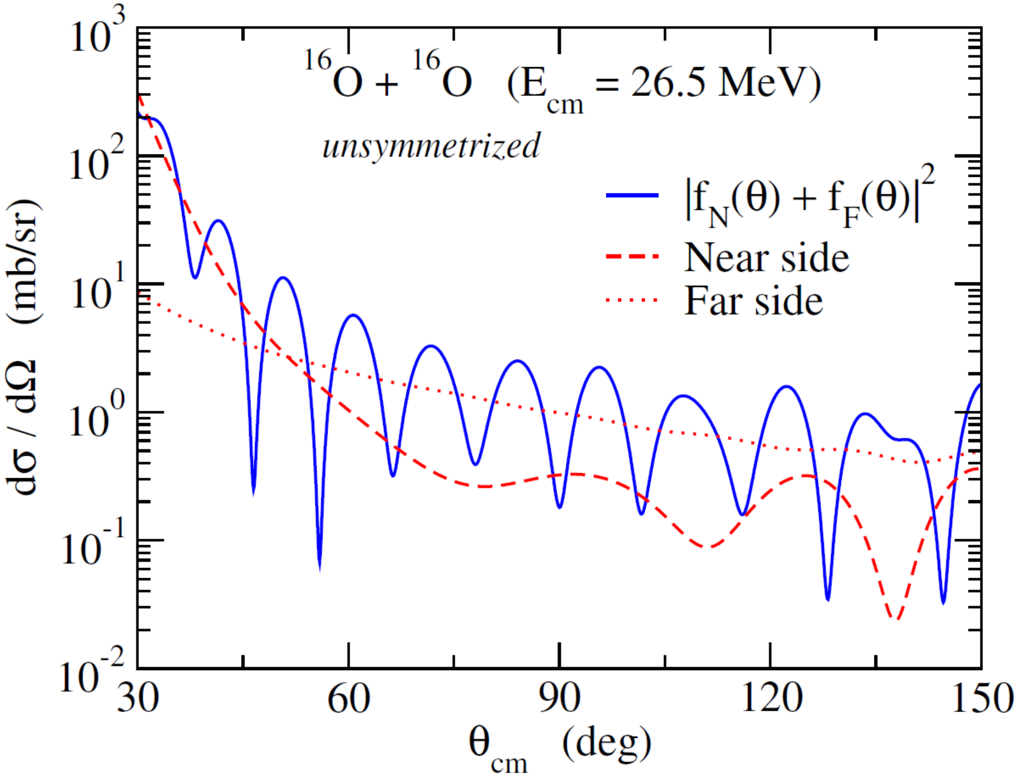
strong oscillations even in unsymmetrized cross sections

↓

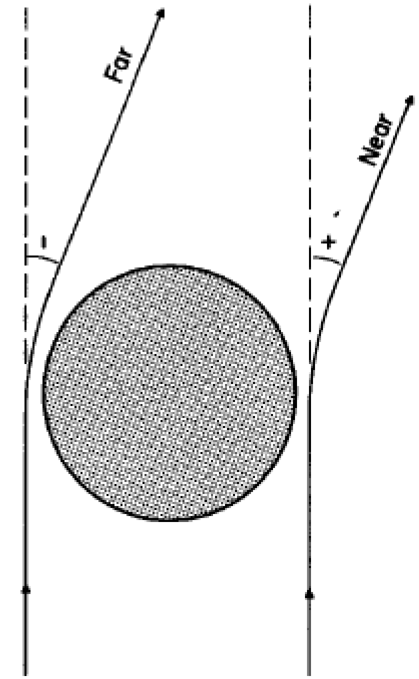
✓ symmetrization: minor

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





near side-far side interference

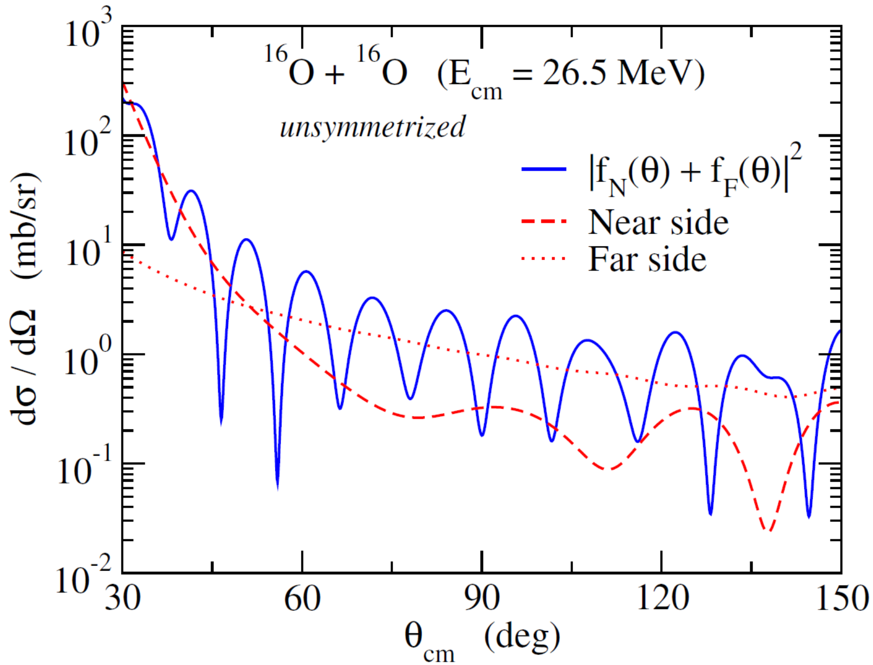


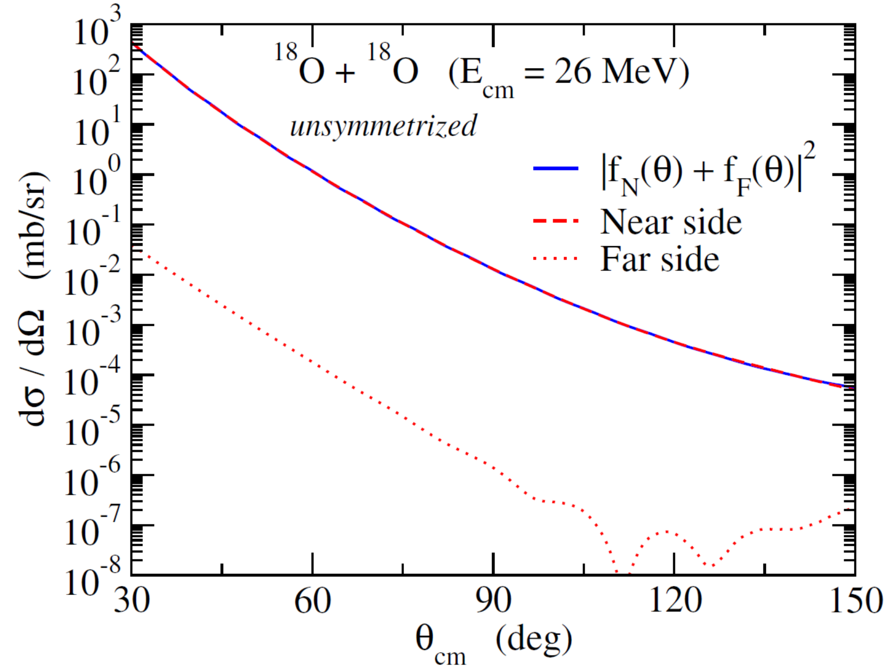
$$P_l(\cos\theta) \to \frac{1}{2}\left[P_l(\cos\theta) \mp i\frac{2}{\pi}Q_l(\cos\theta)\right]$$

N (upper sign), F (lower sign)

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

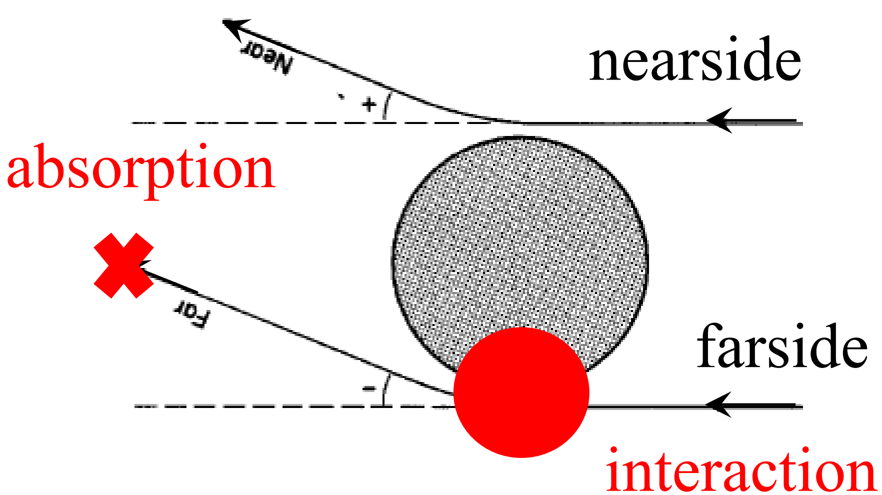
Q_l: Legendre function of the second kind



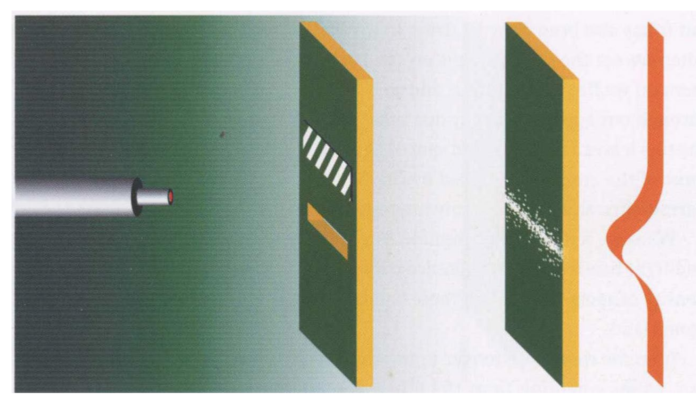


the far-side component is largely damped in $^{18}O+^{18}O$ due to absorption

→almost no interference oscillations

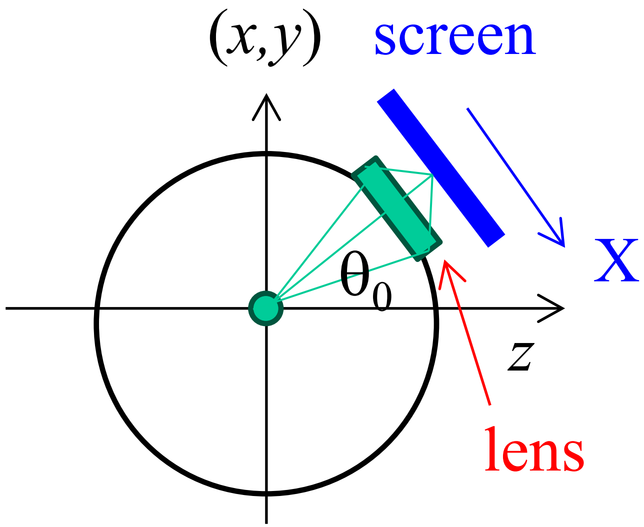


cf. a single slit

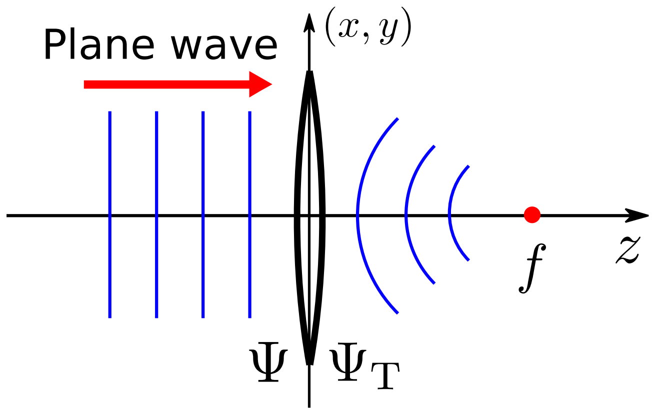


Imaging of nuclear reactions

K. Hagino and T. Yoda, in preparation



"condensing" scattering waves with a lens



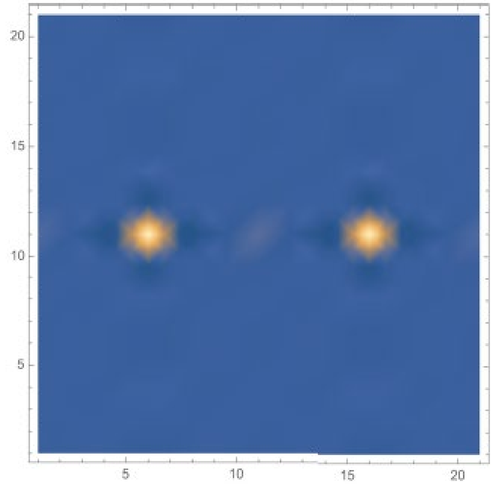
K. Hashimoto et al., PRD101, 066018 (2020)

Fourier transform of scattering amplitude

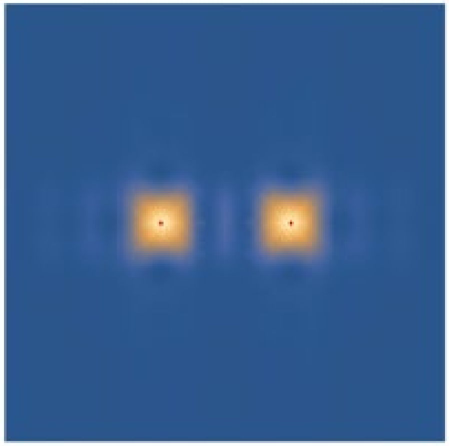
$$\Phi(X,Y) \propto \int_{\theta_0-\Delta\theta}^{\theta_0+\Delta\theta} \sin\theta d\theta \int_{\varphi_0-\Delta\varphi}^{\varphi_0+\Delta\varphi} d\varphi \times e^{i\alpha((\theta-\theta_0)X+(\varphi-\varphi_0)Y)} f(\theta,\varphi)$$

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

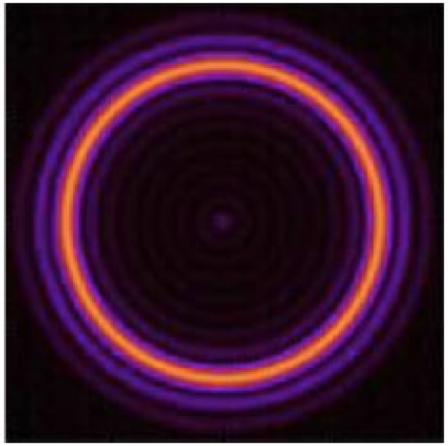
applications in particle physics



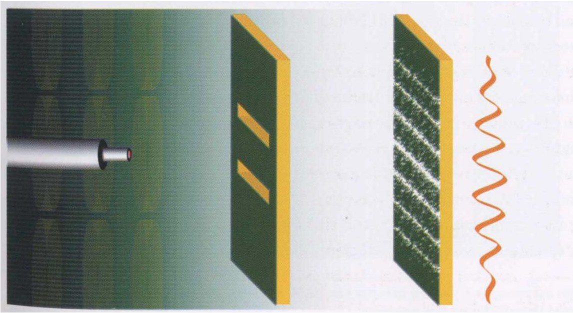
a double slit problem



scattering of string



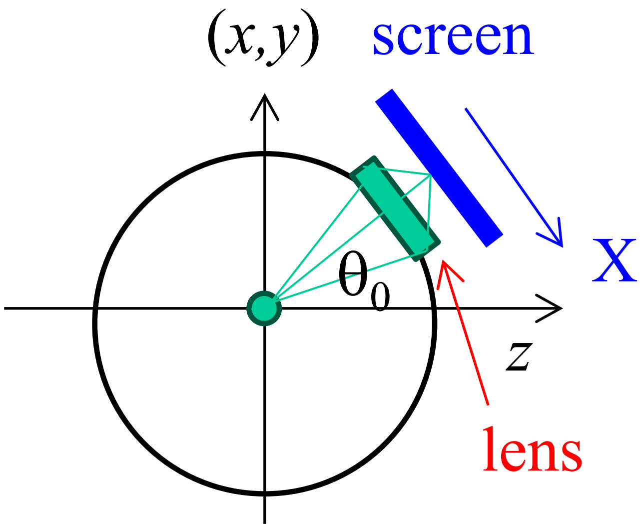
imaging black holes through AdS/CFT



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,
in preparation

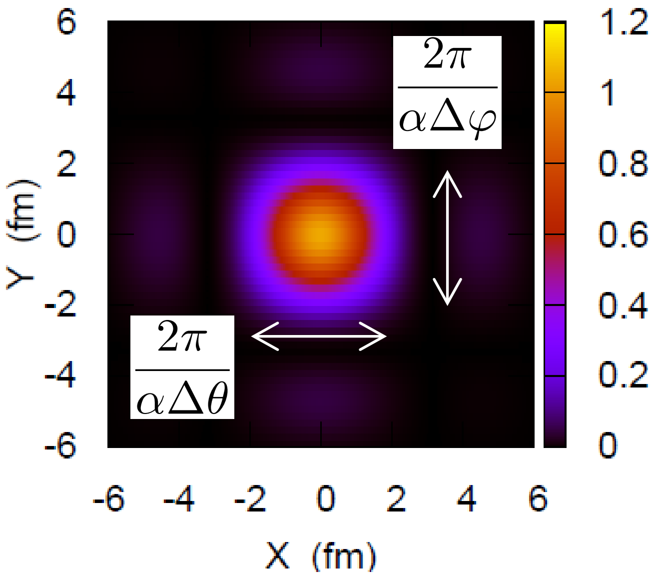


Fourier transform of scattering amplitude

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

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

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



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

Imaging of nuclear reactions

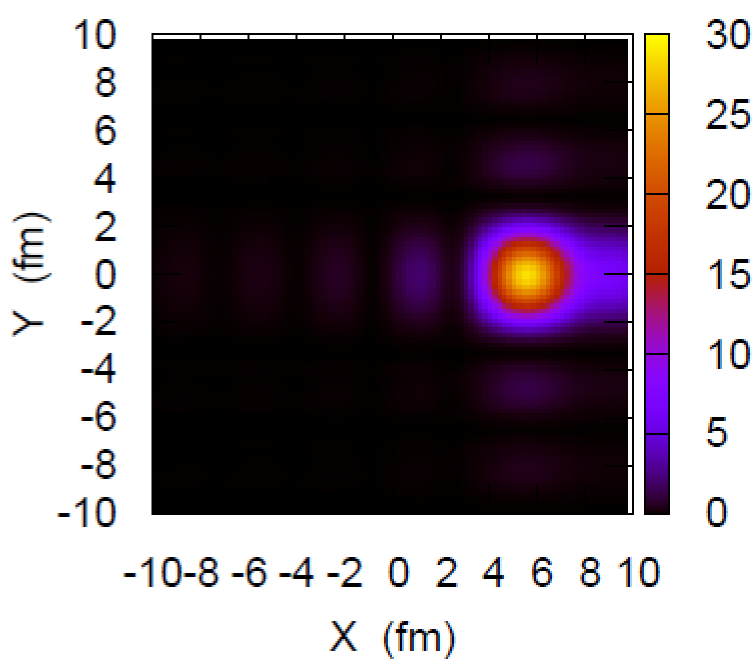
K. Hagino and T. Yoda,
in preparation

Fourier transform of scattering amplitude

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

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

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



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

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

↓

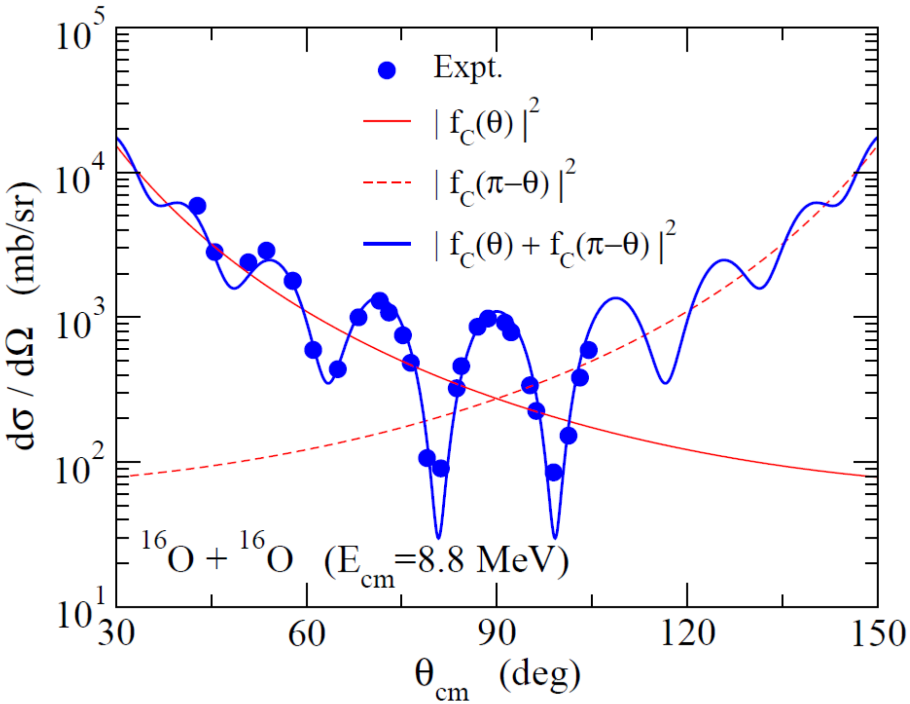
b_{cl} = 5.24 fm ~ X_{peak}

Imaging of nuclear reactions

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

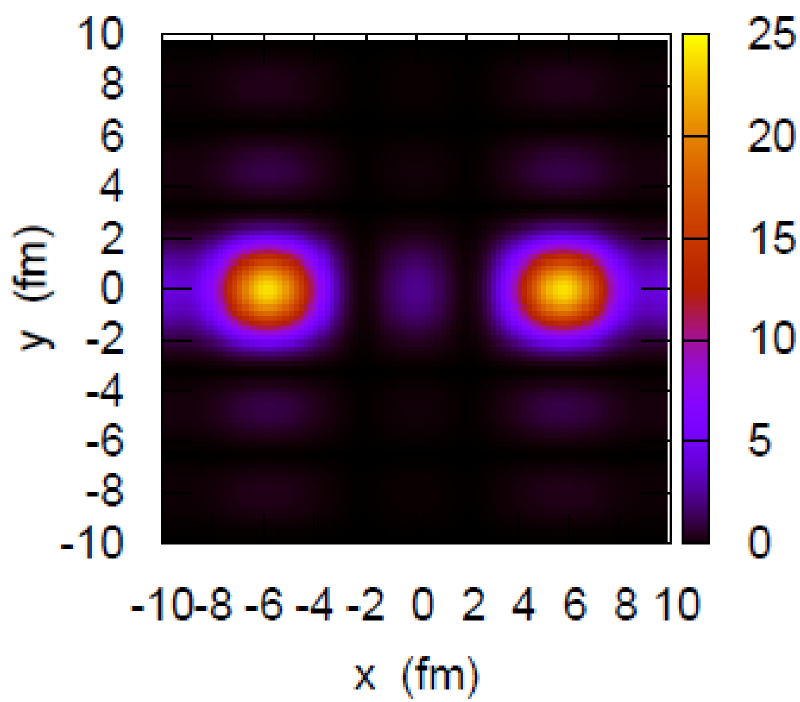
Imaging of Mott scattering

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



$\alpha = k$

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

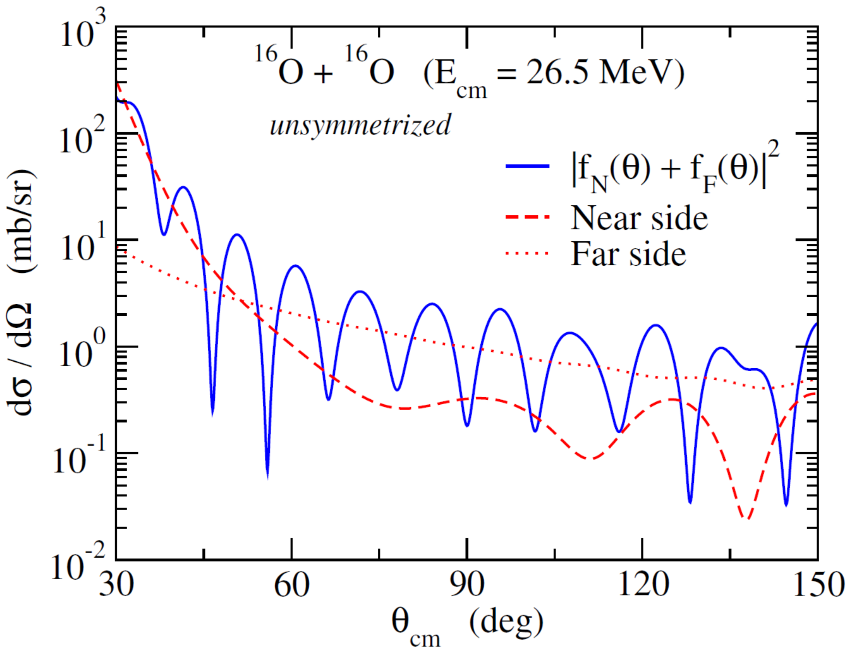


(note) for θ_0=90 deg.,

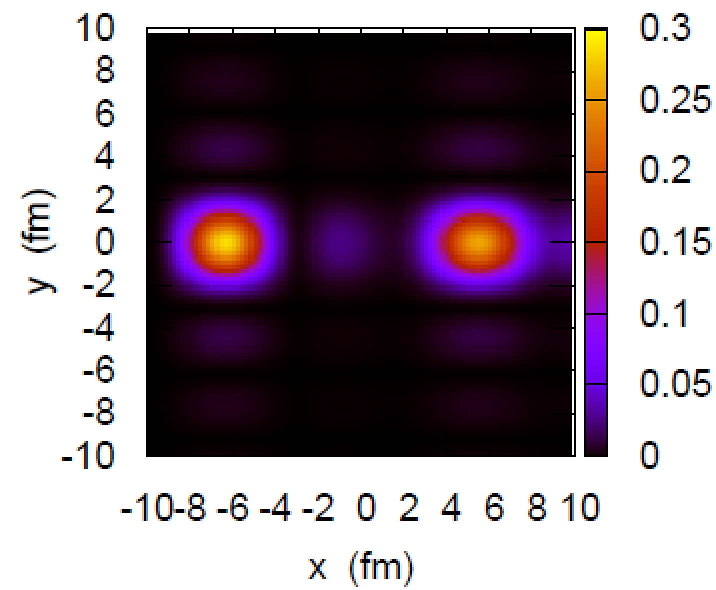
$$\Phi_\theta(X,Y) = \Phi_{\pi-\theta}(-X,Y)$$

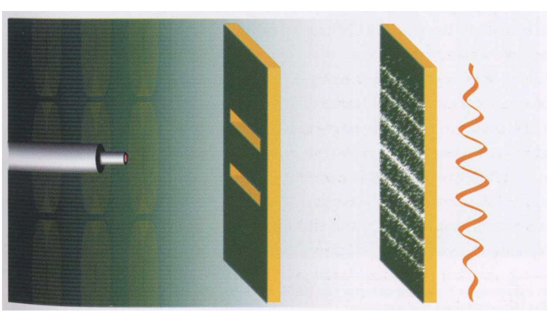
Imaging of nuclear reactions

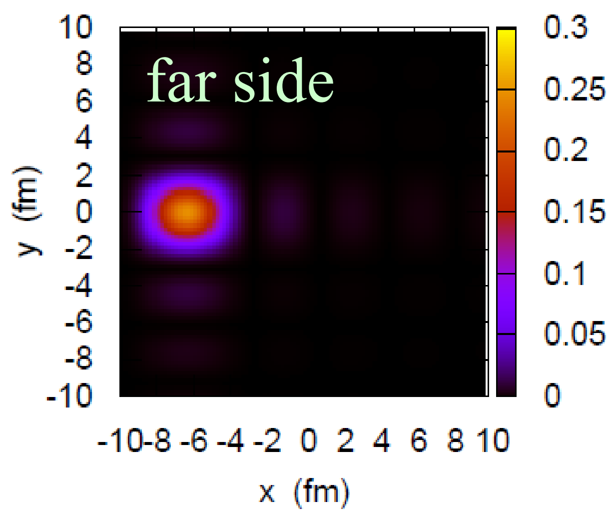
K.H. and T. Yoda, in preparation

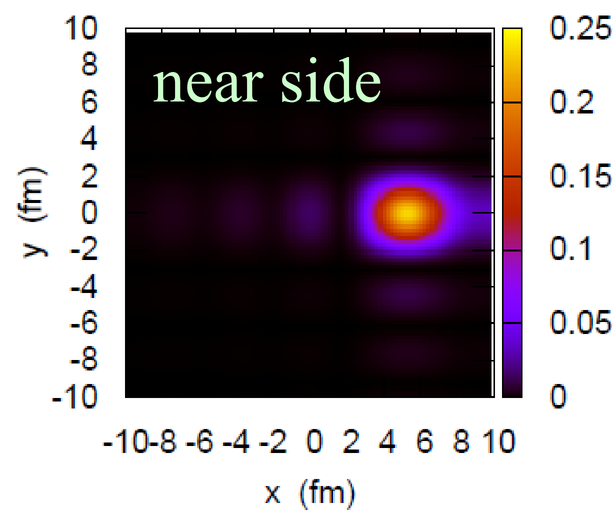


$\alpha = k$, θ_0=55 deg., $\Delta\theta$=15 deg.









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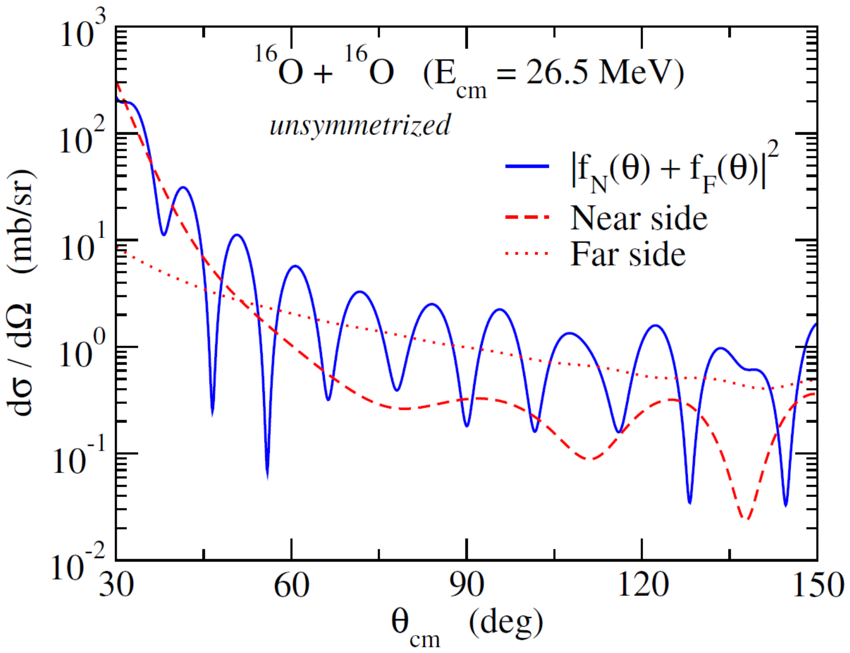
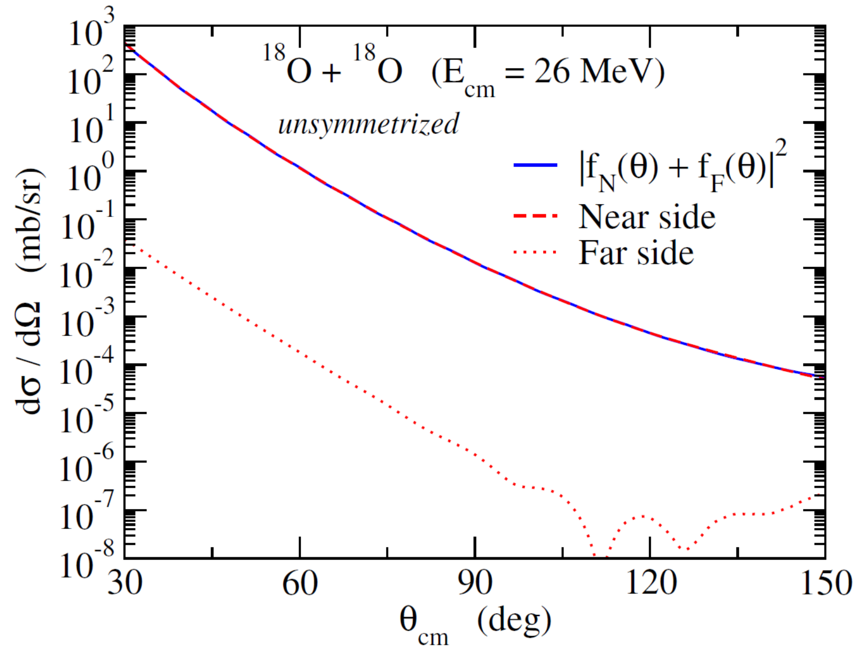
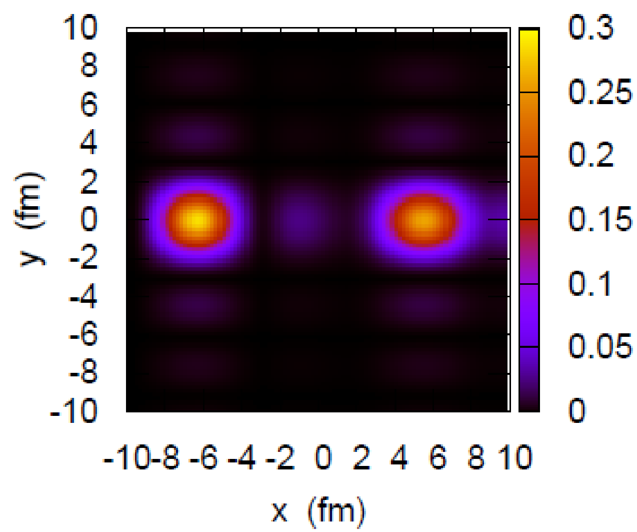
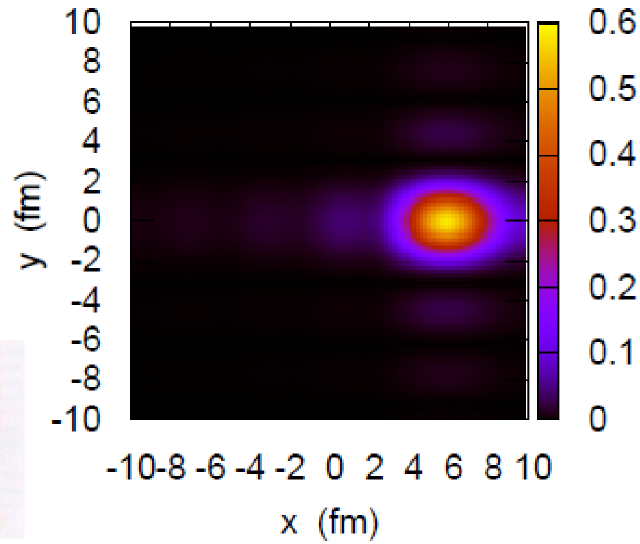




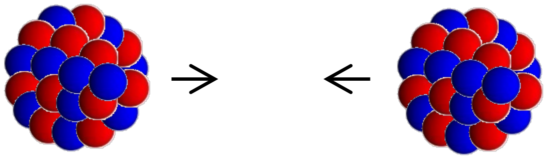




Summary

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