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Repulsive aspects of pairing correlation in nuclear fusion reaction

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Simulation of heavy ion collision using TDHF

H.Flocard, S.E.Koonin and M.S.Weiss Phys. Rev. **C17** (1978) 1682

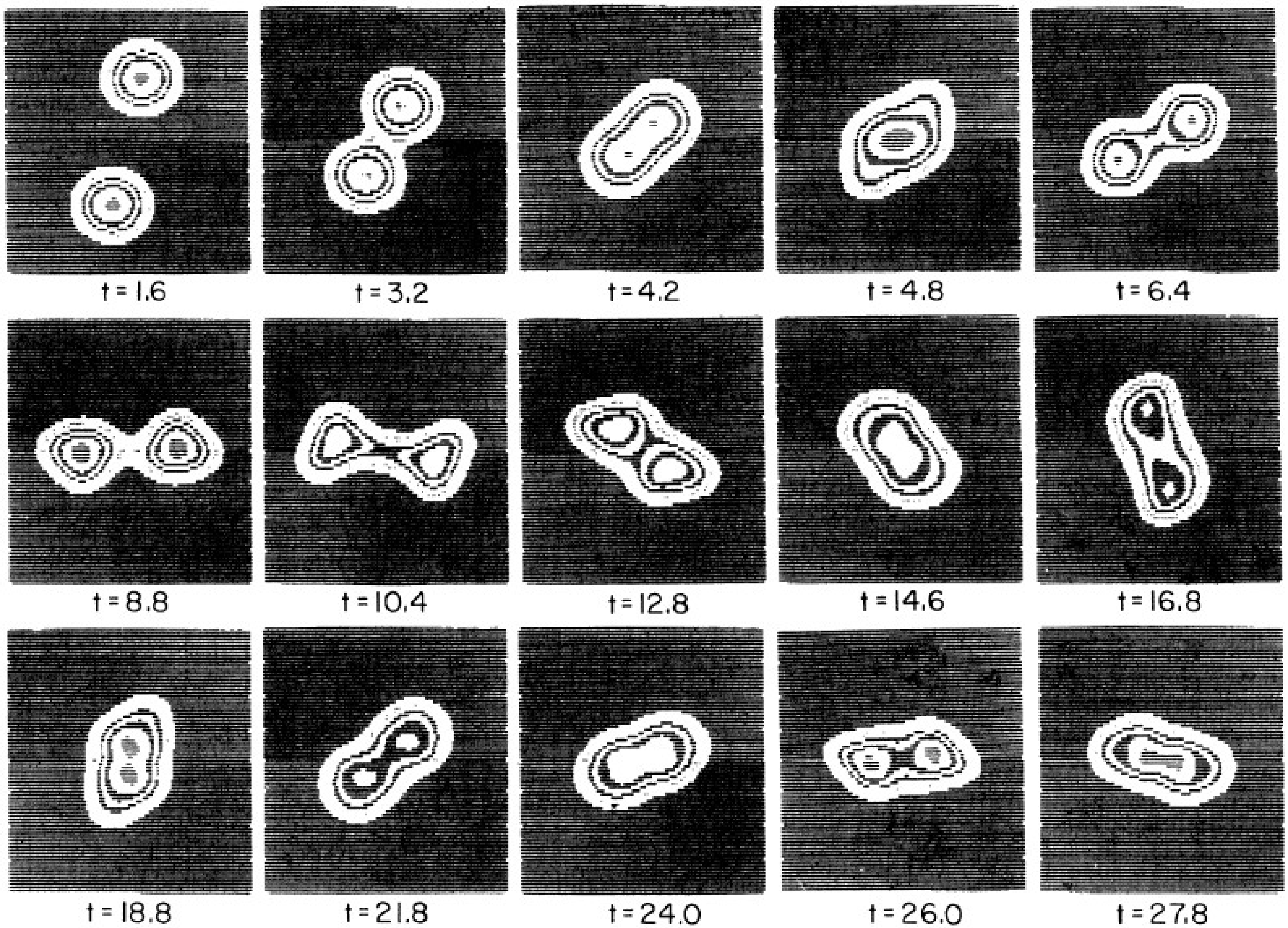


FIG. 2. Contour lines of the density integrated over the coordinate normal to the scattering plane for an $^{16}O + ^{16}O$ collision at $E_{\rm lab} = 105$ MeV and incident angular momentum $L = 13\hbar$. The times t are given in units of 10^{-22} sec.

Several mean-field theories

	For static	For dynamics
No Pairing	Hartree-Fock(HF)	Time-Dependent HF (TDHF, RPA)
With BCS Pairing	HF+BCS	TDHF+BCS
		Cb-TDHFB
With Pairing	Hartree-Fock-Bogoliubov (HFB)	TDHFB (QRPA)

※ RPA: Random-Phase Approximation
※ QRPA: Quasi-particle RPA

What kind of pairing effect is expected in low-energy Heavy ion collision ?

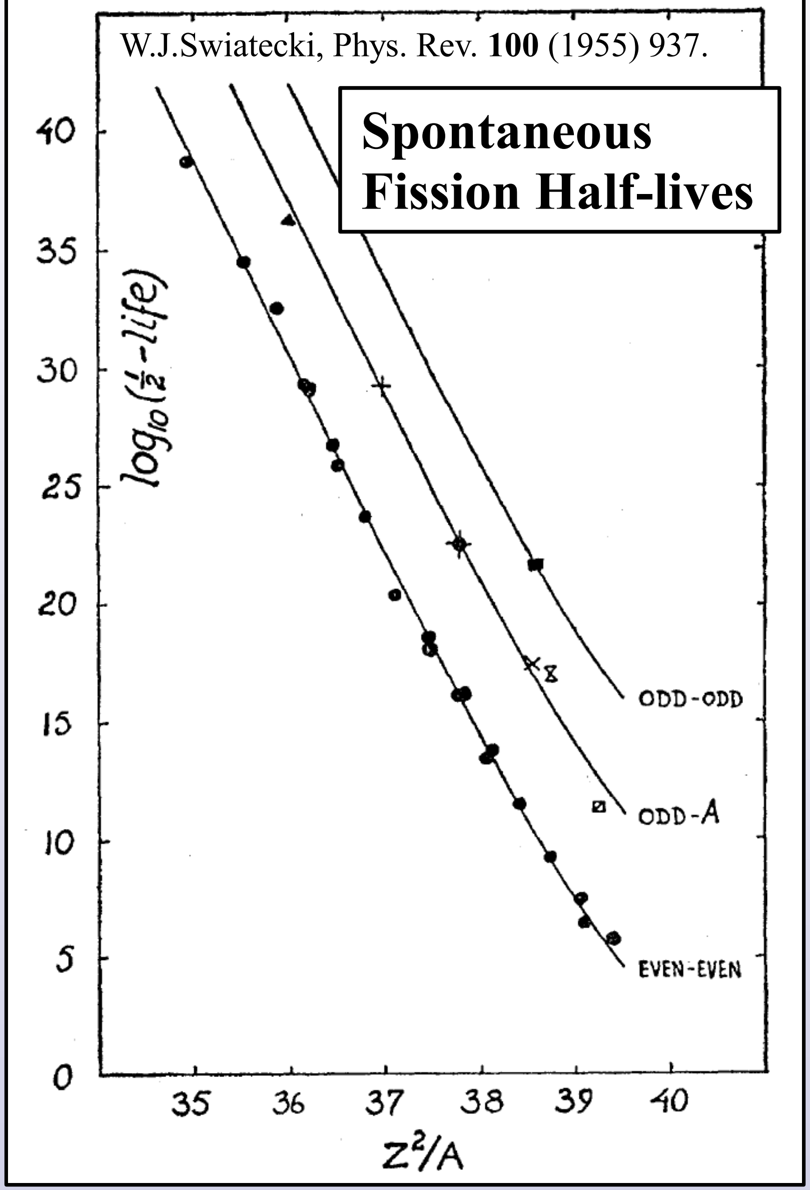
- **Fusion *or* Fission cross section**

- **Level crossing**
  - Energy Dissipation
  - Neck formation
  - Odd-even effects
    for spontaneous fission half-lives ?

- **Pair transfer reaction**

- Nuclear Josephson effect

W.J.Swiatecki, Phys. Rev. **100** (1955) 937.



Method S.E. *et al.*: PRC82 (2010) 034306

Statics: HF+BCS

Dynamics: Cb-TDHFB

ph-channel Int. : Skyrme (SkM*, SLy4d)

pp(*hh*)-channel : δ - *type* (time-reversal)

$$\hat{\mathcal{V}}^\tau(r_1,\sigma_1;r_2,\sigma_2) = V_0^\tau \frac{1-\hat{\sigma}_1\cdot\hat{\sigma}_2}{4}\delta(r_1-r_2)$$

: spin-singlet zero-range interaction

Points:

To solve Cb-TDHFB in **3D space** enable us to study nuclear **dynamics** including ***deformation*** and ***pairing***, **self-consistently**.

For the simulation of collision

Prepare the target and projectile nuclei with HF+BCS, put them with some *b* and distance, also add velocity to them, and their time will be evolved by Cb-TDHFB.

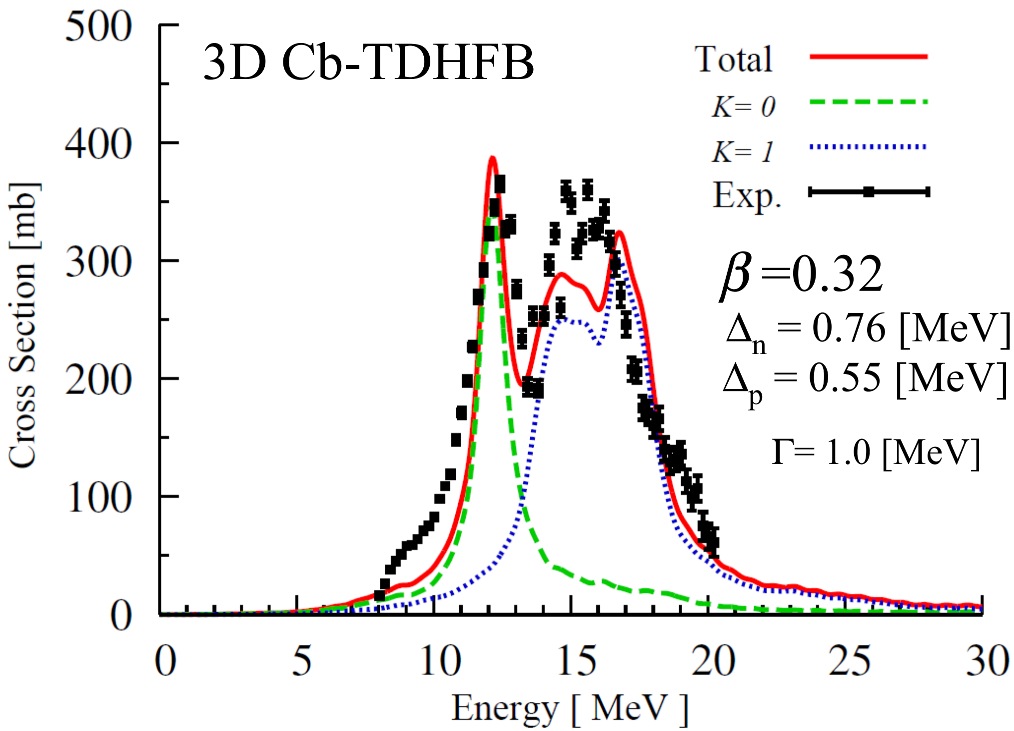
Cb-TDHFB Eqs.

$$i\hbar\frac{\partial}{\partial t}\phi_l(t) = \left\{h(t)-\varepsilon_l(t)\right\}\phi_l(t)$$: Canonical basis (for $\bar{l}$ also)

$$i\hbar\frac{\partial}{\partial t}\ \rho_l(t) = \kappa_l(t)\Delta_l^*(t) - \Delta_l(t)\kappa_l^*(t)$$: Occupation Prob. (for l >0)

$$i\hbar\frac{\partial}{\partial t}\ \kappa_l(t) = \left\{\varepsilon_l(t)+\varepsilon_{\bar{l}}(t)\right\}\kappa_l(t) + \Delta_l(t)\left(2\rho_l(t)-1\right)$$: Pair Prob. (for l >0)

Example : Photo-absorption cross section of ^{172}Yb



Cb-TDHFB can reproduce the photo-absorption cross section of ^{172}Yb.

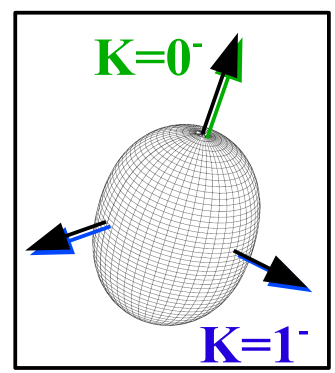
- **Heavy nucleus**
- **Deformed nucleus**
- **Including pairing**

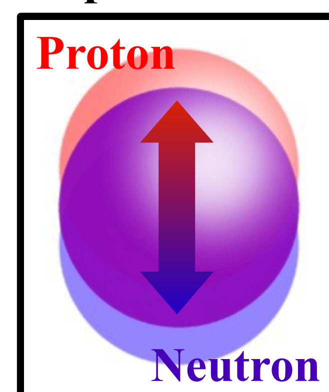
Total cal. cost : **300 CPU hours**
(with **a Single processor**; Intel Core i7 3.0 GHz)

Box size : R=15[fm], mesh=1[fm] (3D-Spherical)
Canonical-basis space (HF+BCS g.s.) :
146 states for neutron,
98 states for proton

Experimental data:
A.M.Goryachev and G.N.Zalesnyy Vopr. Teor. Yad. Fiz. 5, 42 (1976).

Dipole mode





$$\hat{F}^N = -(Ze/A)(\hat{z} + \hat{x} + \hat{y}) \ ,$$
$$\hat{F}^P = (Ne/A)(\hat{z} + \hat{x} + \hat{y})$$

Setup for collision

Incident Energy : 18 - 20 [MeV] ($E_{\rm cm}$ = 9.0 – 10 [MeV], $V_{\rm Coul.}$ ~ 9 MeV)

Impact parameter : 2.8 - 3.1 [fm]

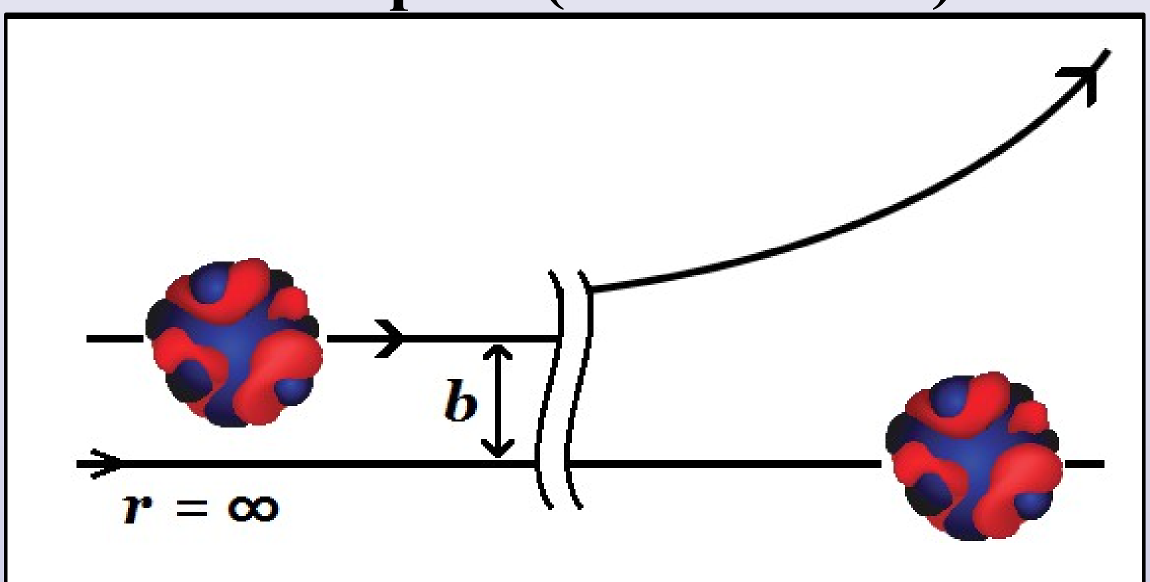
Effective Interaction : Skyrme force (SkM*), Contact pairing

Projectile : ^{22}O, Target : ^{22}O (HF g.s. has also spherical shape)

# of canonical-basis for HF+BCS g.s. ; (N, Z) = (32 (16+16) , 16 (8+8))

Average of gap energy ; $\bar{\Delta}_n = 2.066$ [MeV] $V_0^{\rm n} = -412.5$ [MeV]

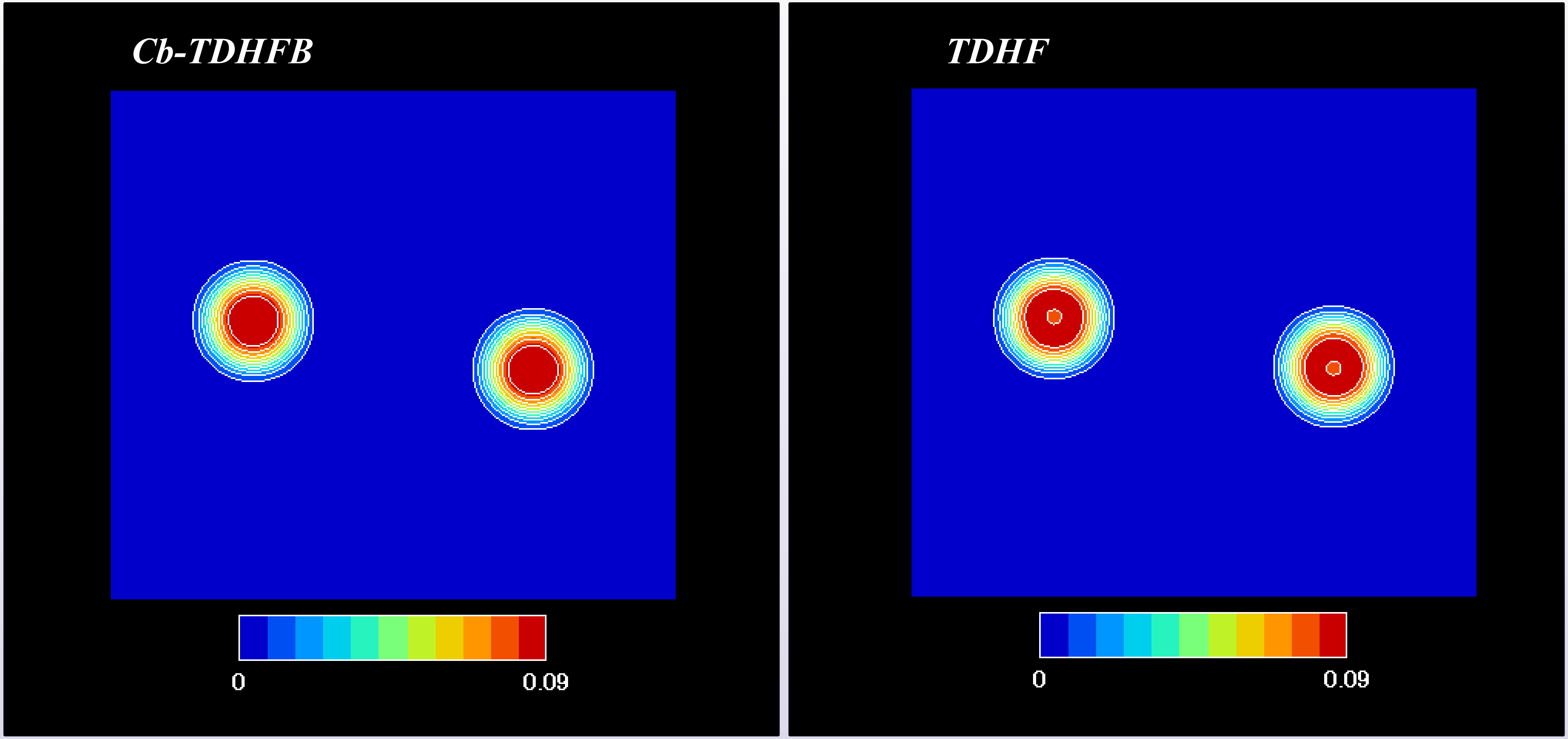
Calculation space (3D meshed box**):**



Length of box for (***x***, ***y***, ***z***) is **36, 20, 40**[fm] meshed by **1.0** [fm]

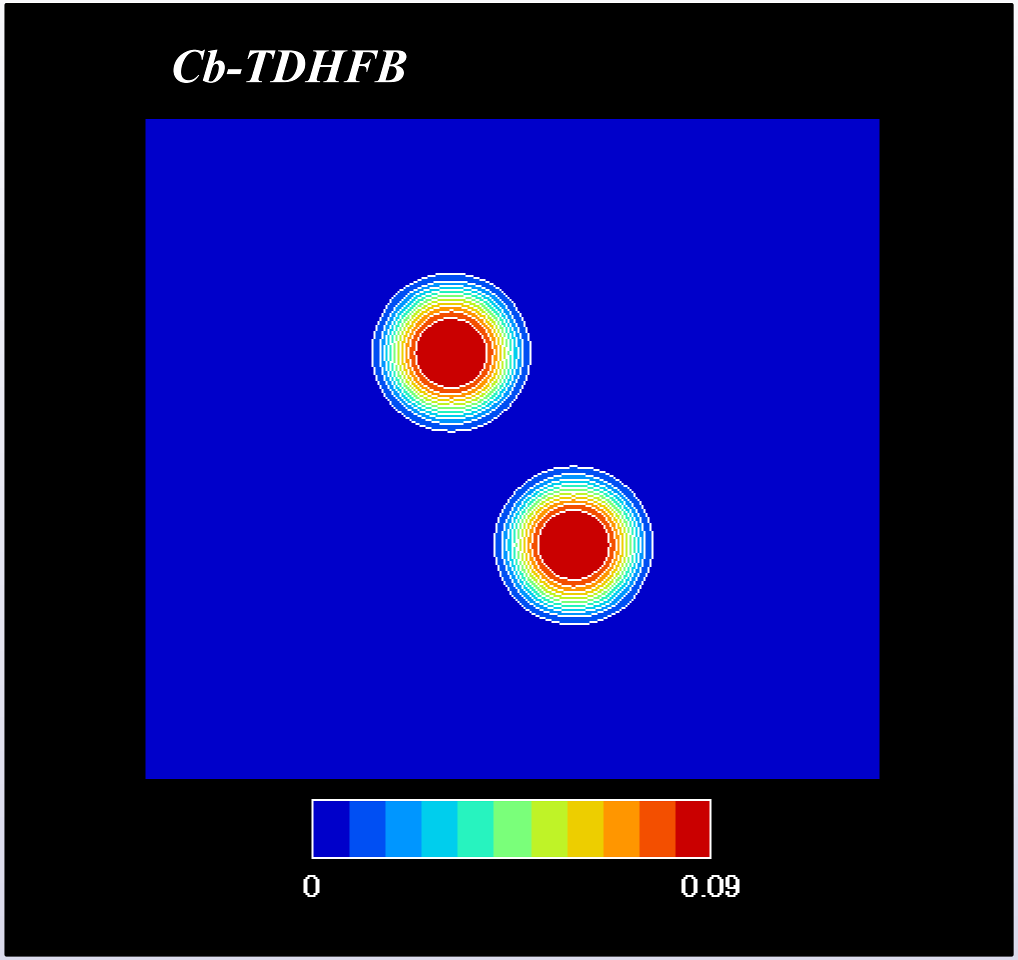
Simulation of $^{22}O + ^{22}O$ collision with $b = 3.0$ [fm] and E_{cm}=10 [MeV]

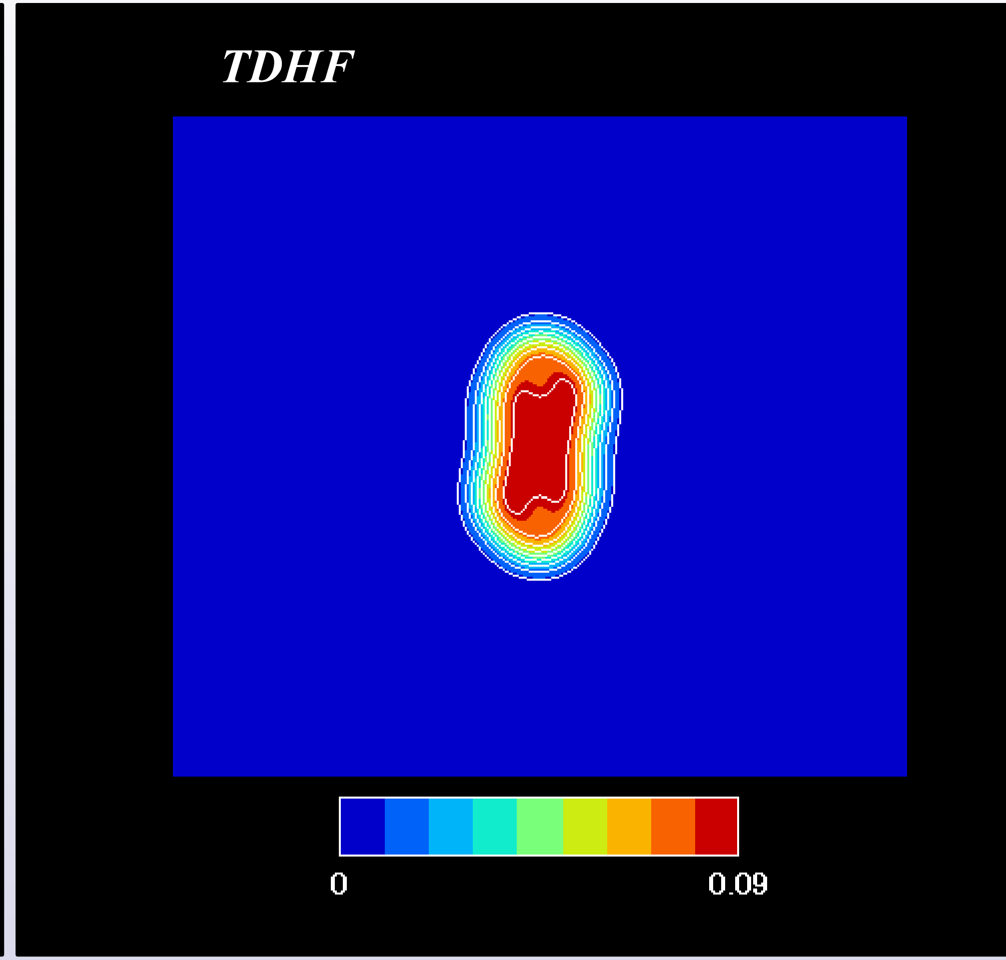
Time-evolution of Neutron density distribution



Simulation of ^{22}O + ^{22}O collision with b = 3.0 [fm] and E_{cm}=10 [MeV]

Time-evolution of Neutron density distribution





$$\sigma_F = 2\pi \int_0^{b_f} db\ b \qquad \sigma_F^{\mathrm{BCS}} < \sigma_F^{\mathrm{HF}}$$

From

simulation of **^{22}O + ^{22}O** collision with $b = 2.8 - 3.1$ [fm] and E_{cm}=10 [MeV],

$$2.8 \text{ fm} < \underline{b_f^{B}} < 2.9 \text{ fm} < \underline{b_f^{Bw}} < 3.0 \text{ fm} < \underline{b_f^{H}} < 3.1 \text{ fm}$$

Pairing correlation ***does not increase*** *the fusion cross section* (in this work).

Up to now

- **Same nuclei collision** with the incident energy around Coulomb barrier
  → Pairing correlation ***can have repulsive aspects*** in fusion reaction.
  $\sigma_H \sim 283$ mb → $\sigma_B \sim 246$ mb be small about 15%
  → The repulsive effects **depends on** the strength of pairing.

From now on

- **In a little bit heavier system?** ← To increase pair number
- **Case of different nuclei collision?** ← Large difference of chemical potential will accelerate Pair transfer.
- **Is the pairing effects visible in much heavier system?**

In a little bit heavier system

Point: increase of pair number

Projectile : **^{52}Ca**, Target : **^{52}Ca**

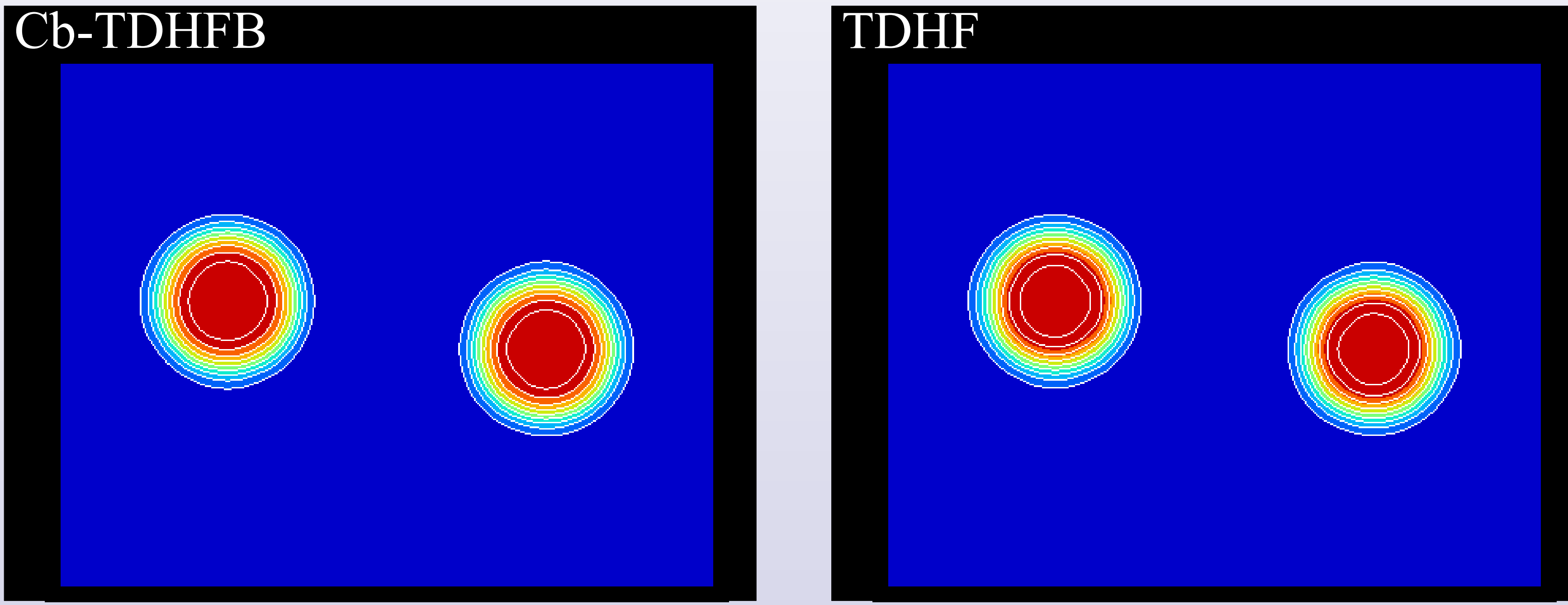
In both methods, the g.s. is spherical shape.

E_{cm} = 51.5 MeV ($V_{\mathrm{Coul.}}$ ~ 49 MeV)

Impact parameter : 2.2 - 2.6 [fm]

Effective Interaction : SkM*, Contact pairing

$V_0^n = -438.1$ MeV ⟵ *To reproduce* Δ_n *of* ^{52}Ca



$$2.4 \text{ fm} < \underline{b_f^{\mathrm{B}}} < 2.45 \text{ fm} < \underline{b_f^{\mathrm{H}}} < 2.5 \text{ fm}$$

→ σ_{H} ~ 189 mb → σ_{B} ~ 181 mb be ***small*** about 5%

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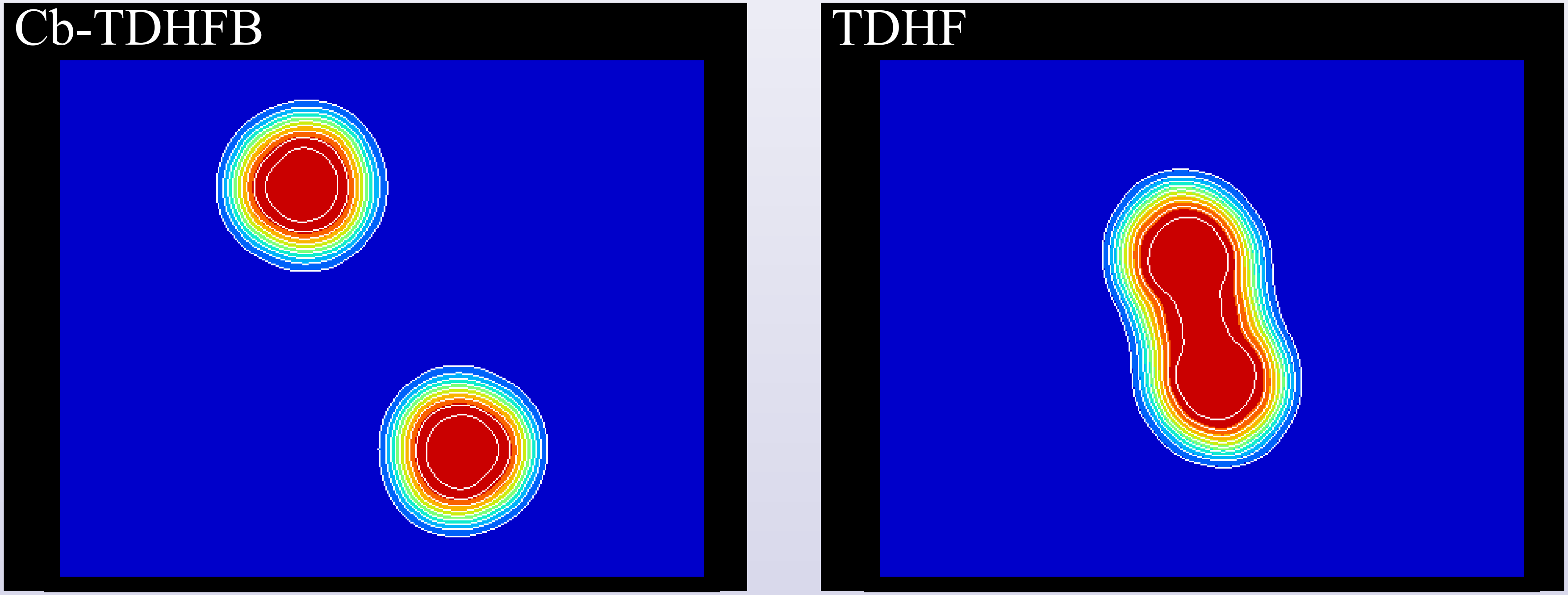


$$2.4\ \text{fm} < b_f^{\text{B}} < 2.45\ \text{fm} < b_f^{\text{H}} < 2.5\ \text{fm}$$

$\rightarrow \sigma_H \sim 189$ mb $\rightarrow \sigma_B \sim 181$ mb be ***small*** about 5%

Case of different nuclei collision

Point:
Difference of chemical potential

Projectile : **^{22}O**, Target : **^{52}Ca**

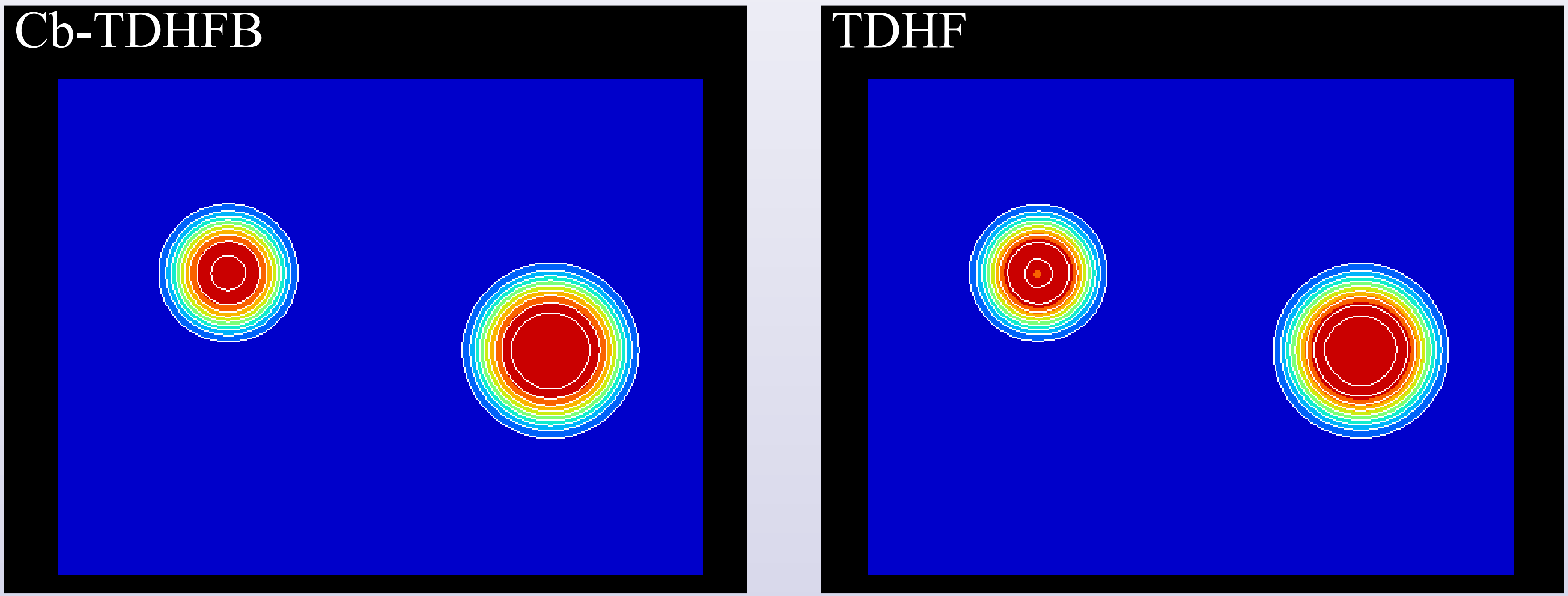
In both methods, the g.s. is spherical shape.

E_{cm} = 25 MeV ($V_{Coul.}$ ~ 20.8 MeV)

Impact parameter : 3.0 - 4.5 [fm]

Effective Interaction : SkM*, Contact pairing

$V_0^n = -425.3$ MeV ⟵ *Average of strength in* ^{22}O *and* ^{52}Ca



$$4.0 \text{ fm} < \underline{b_f^{\mathrm{B}}} < 4.1 \text{ fm} < \underline{b_f^{\mathrm{H}}} < 4.25 \text{ fm}$$

→ σ_H ~ 528 mb → σ_B ~ 503 mb be ***small*** about 5%

Case of different nuclei collision

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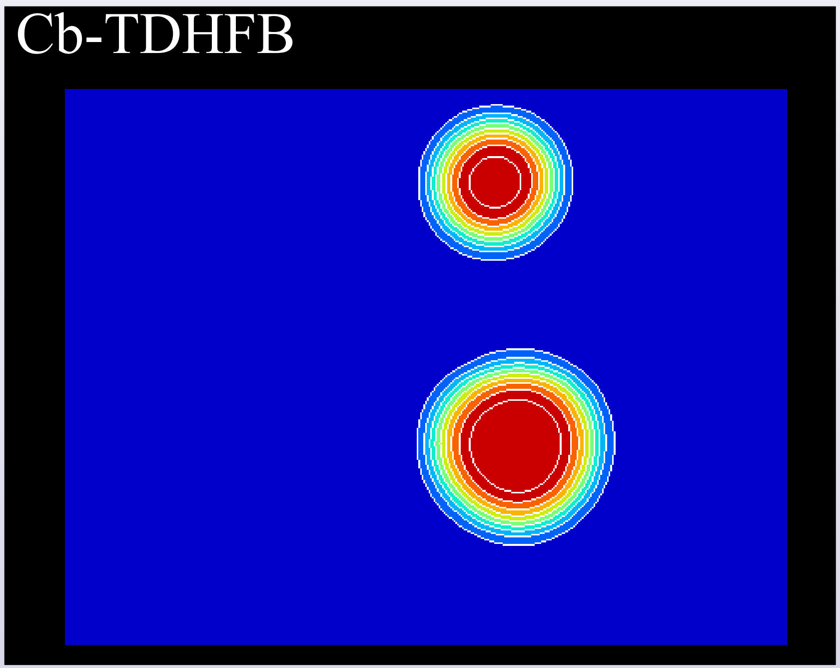
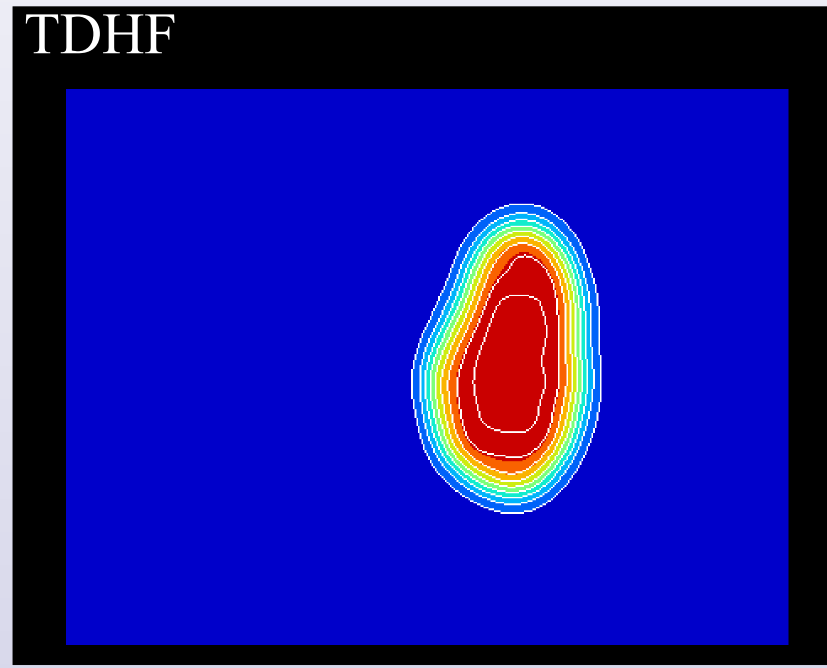




$$4.0\ \text{fm} < \underline{b_f^{\text{B}}} < 4.1\ \text{fm} < \underline{b_f^{\text{H}}} < 4.25\ \text{fm}$$

$\rightarrow \sigma_{\text{H}} \sim 528$ mb $\rightarrow \sigma_{\text{B}} \sim 503$ mb be ***small*** about 5%

Is the pairing effect visible in much heavier system ?

Projectile : ^{96}**Zr**, Target : ^{124}**Sn**

E_{cm} = 228 MeV ($V_{coul.}$ =216, 225 MeV)

Effective Interaction : SLy4d, Contact pairing

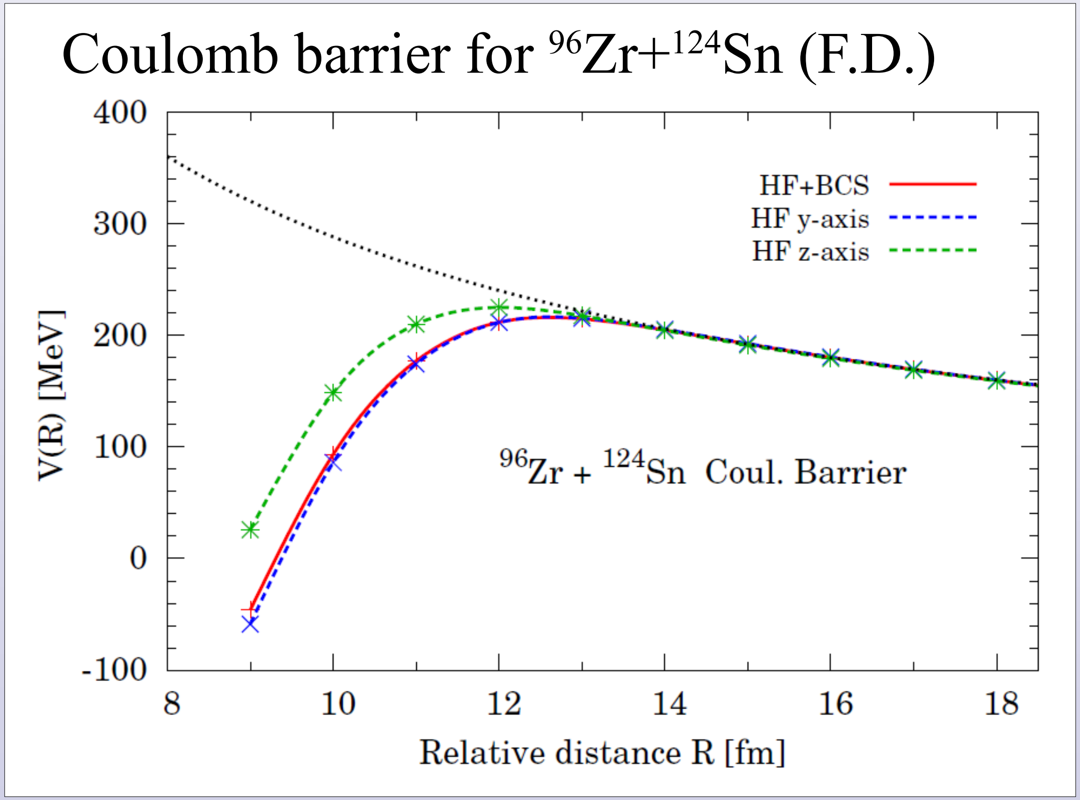
$V_0^n = -412.5$ MeV ← *Very strong in order to check the effect*

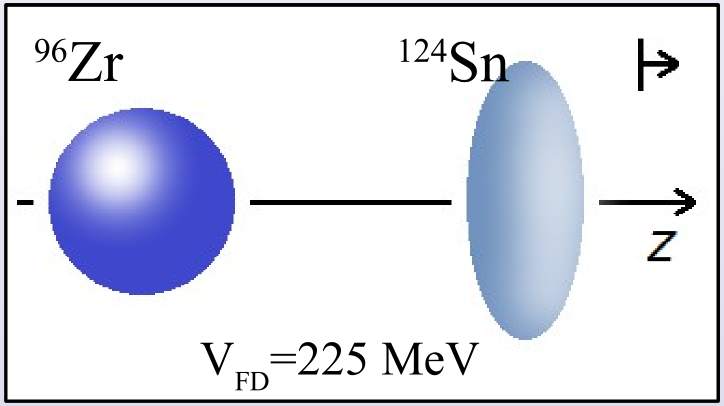
$V_0^p \equiv 0.0$ MeV ← *Neglect proton pairing*

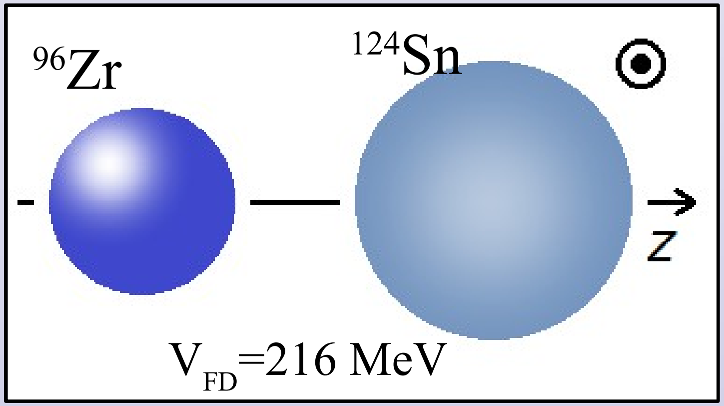
HF+BCS : Both ground states are spherical shape.

HF : ^{96}Zr ; spherical, ^{124}Sn ; oblate shape.

HF g.s. of ^{124}Sn has Oblate shape. β=-0.1







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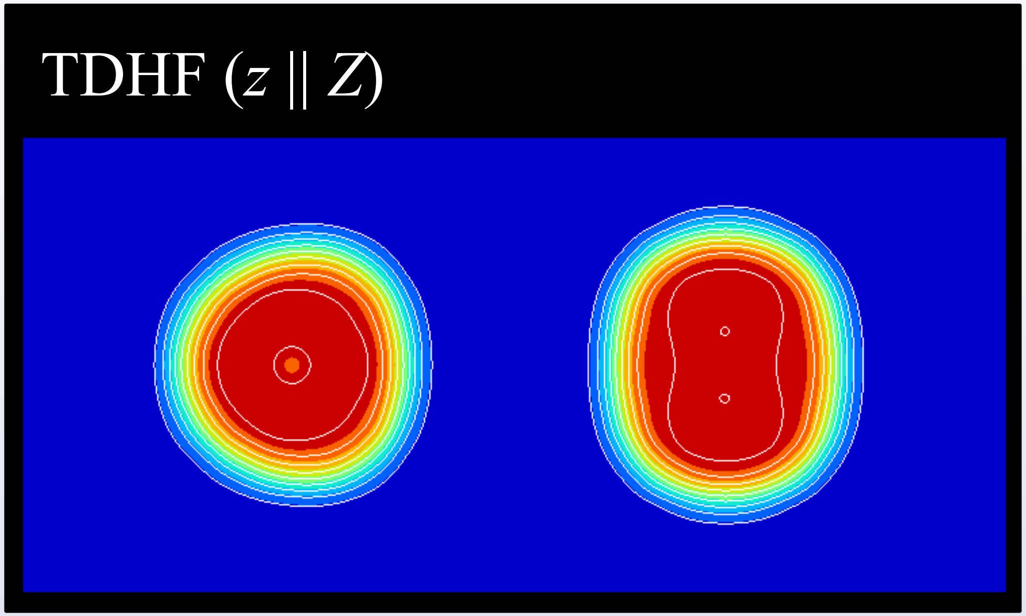
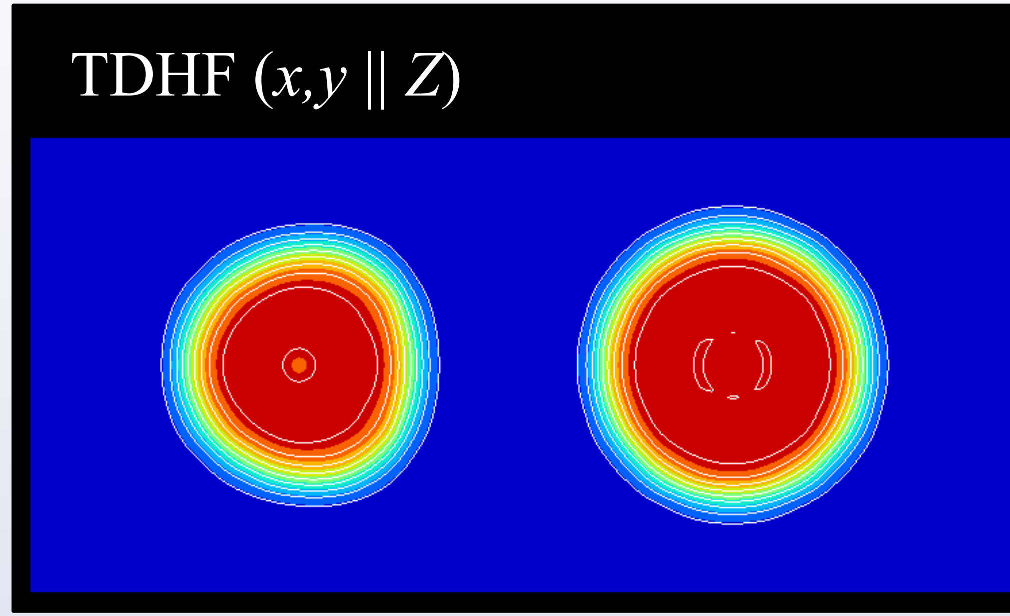
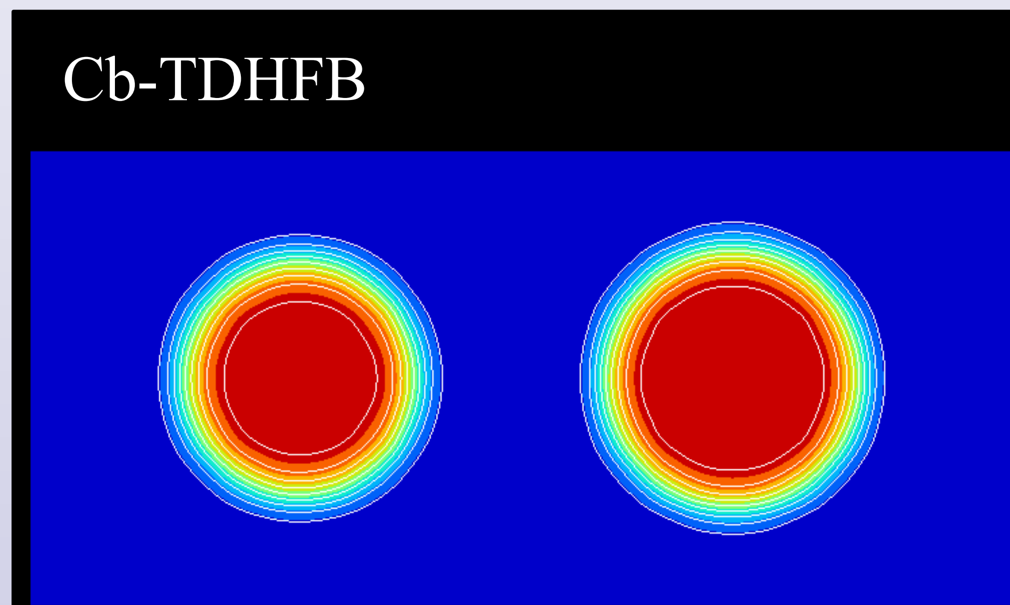
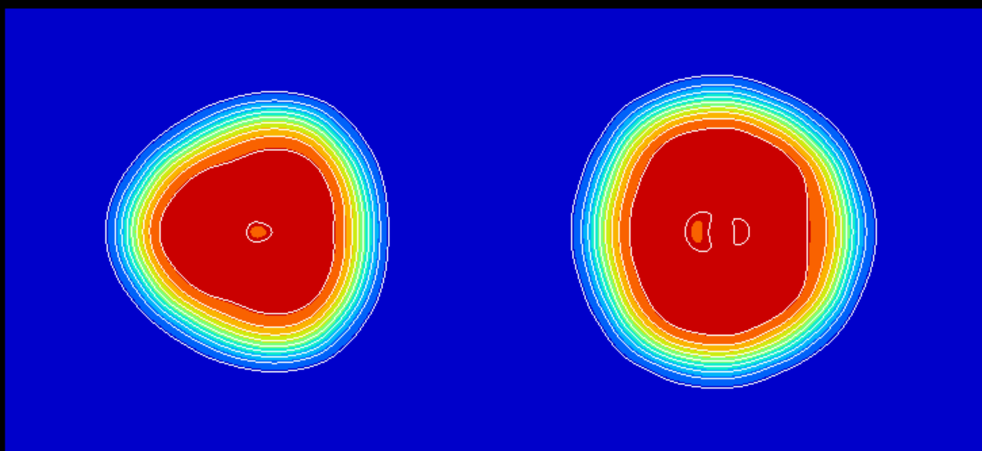




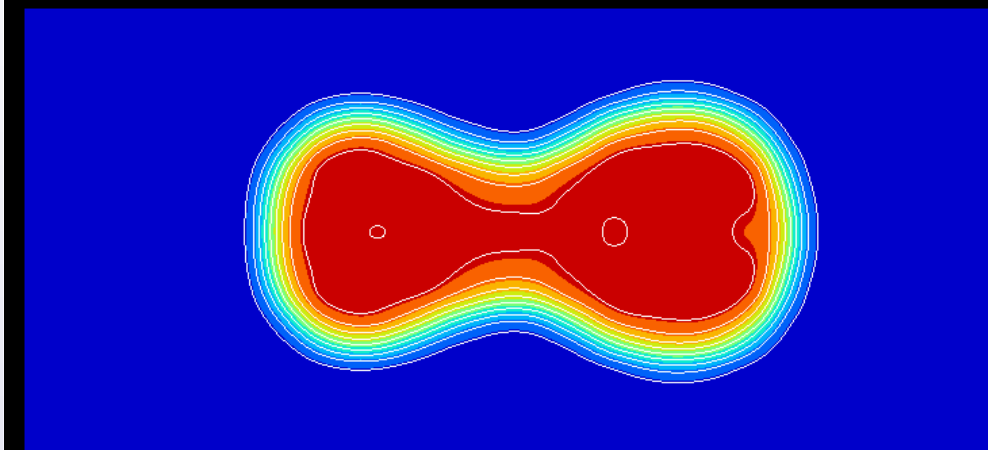


Is the pairing effect visible in much heavier system ?

TDHF ($z \parallel Z$)



TDHF ($x,y \parallel Z$)



Time up to scission

$$T^{\mathrm{Sci.}}_{z||Z} \sim 850\ \mathrm{fm/c}$$

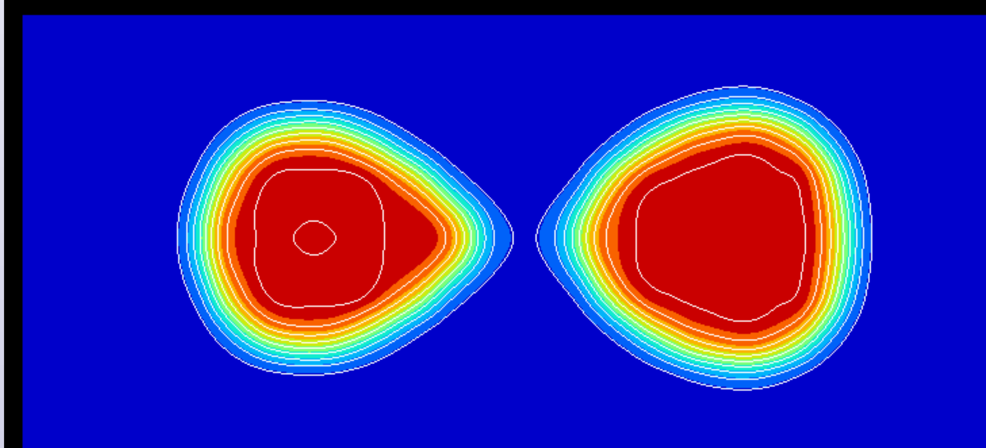
$$T^{\mathrm{Sci.}}_{x,y||Z} \sim 2070\ \mathrm{fm/c}$$

$$\vee$$

$$T^{\mathrm{Sci.}}_{B} \sim 1000\ \mathrm{fm/c}$$

!!

Cb-TDHFB



Summary & Perspective

Simulation of the collision phenomena with Cb-TDHFB

- We apply Cb-TDHFB to large amplitude collective phenomena such as collision, with a contact pairing functional.
- ^{22}O+^{22}O : Pairing effects in fusion reaction, have a ***repulsive*** aspects.
- ^{52}Ca+^{52}Ca : The repulsive aspect appears also, but its contribution becomes small.
- ^{22}O+^{52}Ca : The similar aspects can be seen.
- ^{96}Zr+^{124}Sn : The pairing effects gets the time from a contact to scission to be ***short***.

Perspective

To analyze the detail of internal behavior

- **More accurate calculation**

Behavior of single-particle levels in real-time cal.

- **Energy distribution, Level crossing**

Particle number projection for the multi-particle transfer in real-time cal.

- Nucleon transfer (Pair transfer), Nuclear Josephson effects

Thank you for your attention!