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Pairing effects in fusion phenomena utilizing a time-dependent mean field theory

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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

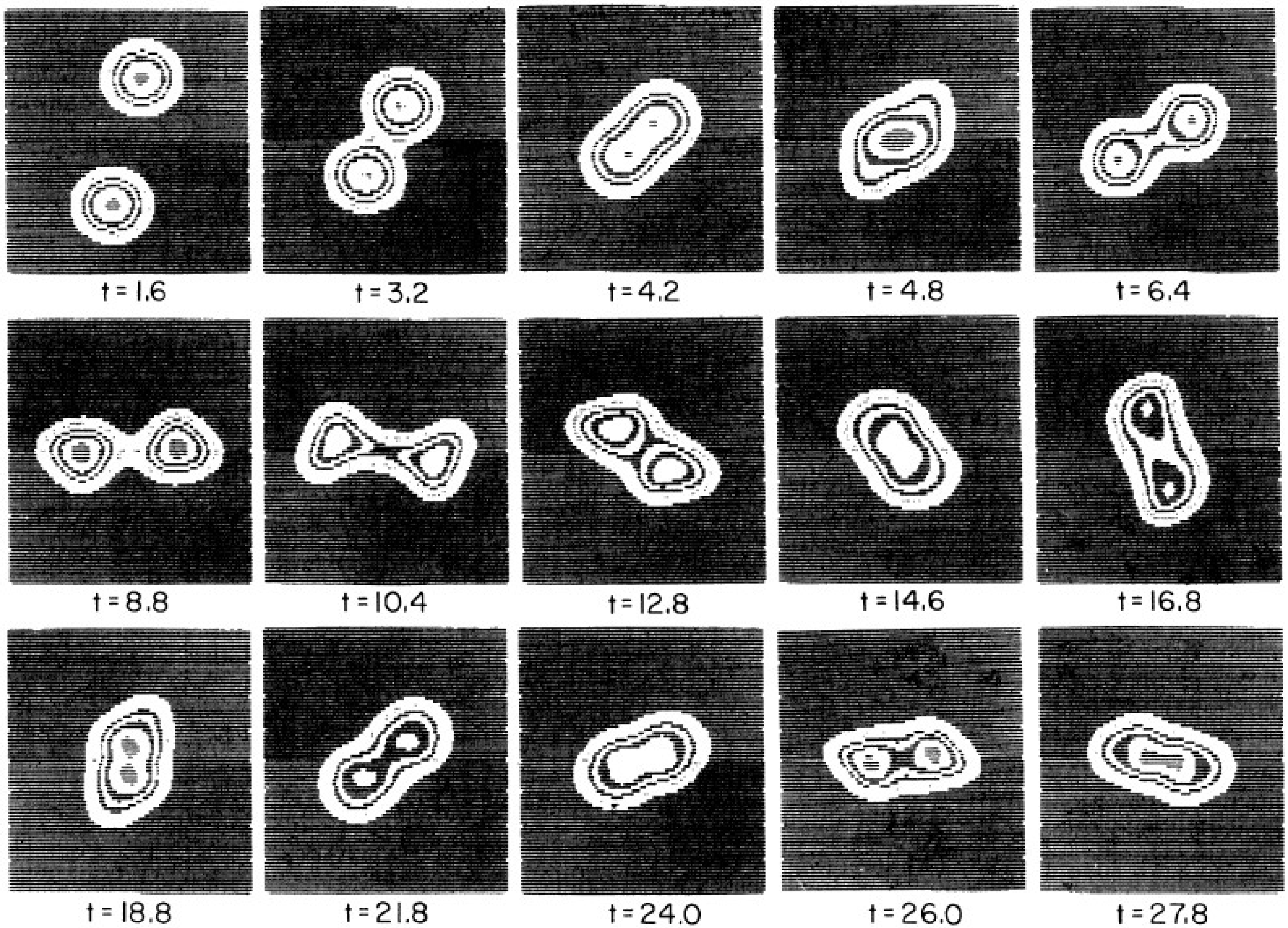
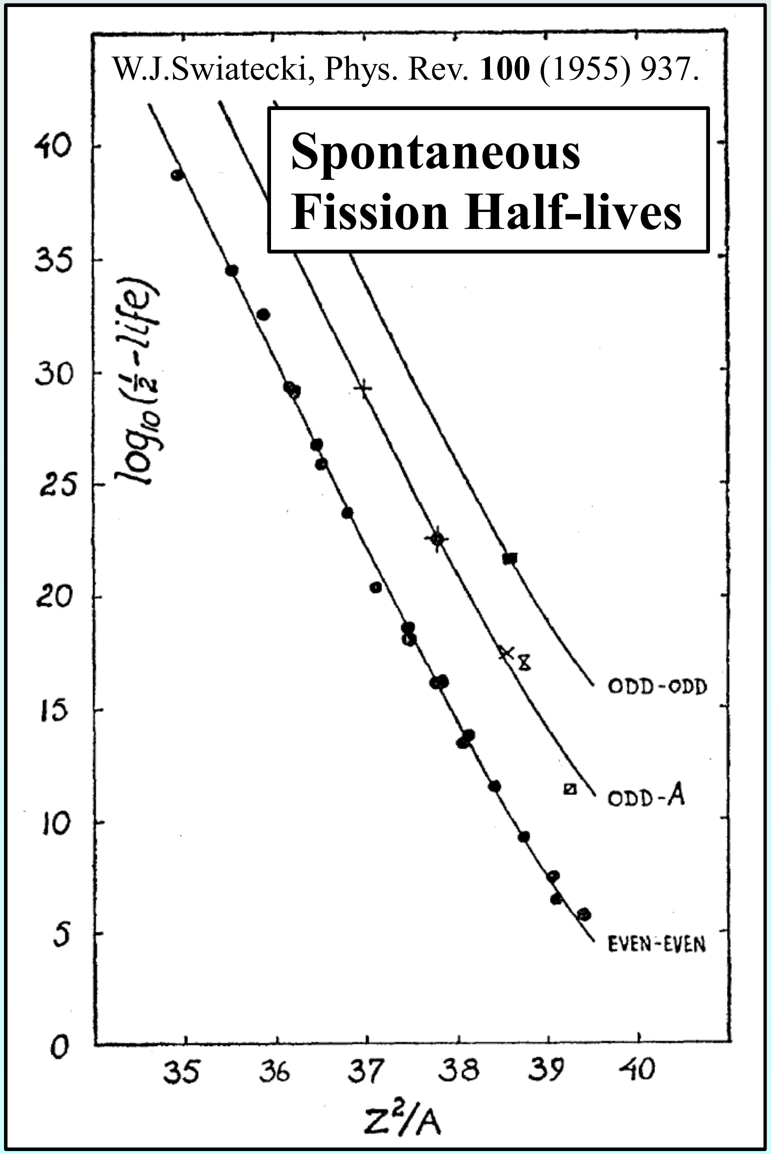


FIG. 2. Contour lines of the density integrated over the coordinate normal to the scattering plane for an $^{16}O + ^{16}O$ collision at $E_{lab} = 105$ MeV and incident angular momentum $L = 13\hbar$. The times t are given in units of 10^{-22} sec.

Expected pairing correlation effects in Heavy ion collision ?

- **Level crossing**
  - Energy Dissipation
  - Neck formation
  - Odd-even effects
    for spontaneous fission half-lives ?
- **Fusion *or* Fission cross section**
- **Pair transfer reaction**
- **Nuclear Josephson effect**



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 is Cb-TDHFB ?

More detail … **S. Ebata et al., PRC82, 034306**

Cb-TDHFB can be derived from **TDHFB** represented in **canonical basis***, with an **approximation** of pairing potential which is **diagonal** as like **BCS**.

$$|\Psi(t)\rangle = \prod_{k>0} \left(v_k(t) + u_k(t) \hat{c}_k^\dagger \hat{c}_{\bar{k}}^\dagger \right) |0\rangle$$

$\bar{k}$ **: Pair of *k*-state**
(**no restriction of time-reversal**)

*Canonical basis diagonalize density matrix.

$\rho_k(t) = |v_k(t)|^2$ **: Occupation probability**

$\kappa_k(t) = u_k(t) v_k(t)$ **: Pair probability**

Cb-TDHFB is a time-dependent scheme including pairing correlations as in the BCS approximation.

Cb-TDHFB equations

$$i\hbar \frac{\partial}{\partial t} |\phi_k(t)\rangle = \left(h(t) - \eta_k(t)\right) |\phi_k(t)\rangle$$

$$i\hbar \frac{\partial}{\partial t} \rho_k(t) = \kappa_k(t) \Delta_k^*(t) - \Delta_k(t) \kappa_k^*(t)$$

$$i\hbar \frac{\partial}{\partial t} \kappa_k(t) = \left(\eta_k(t) + \eta_{\bar{k}}(t)\right) \kappa_k(t) + \Delta_k(t) \left(2\rho_k(t) - 1\right)$$

$$\eta_k(t) \equiv \langle \phi_k(t) | h(t) | \phi_k(t) \rangle + i\hbar \left\langle \frac{\partial \phi_k}{\partial t} \middle| \phi_k(t) \right\rangle$$

Properties of Cb-TDHFB

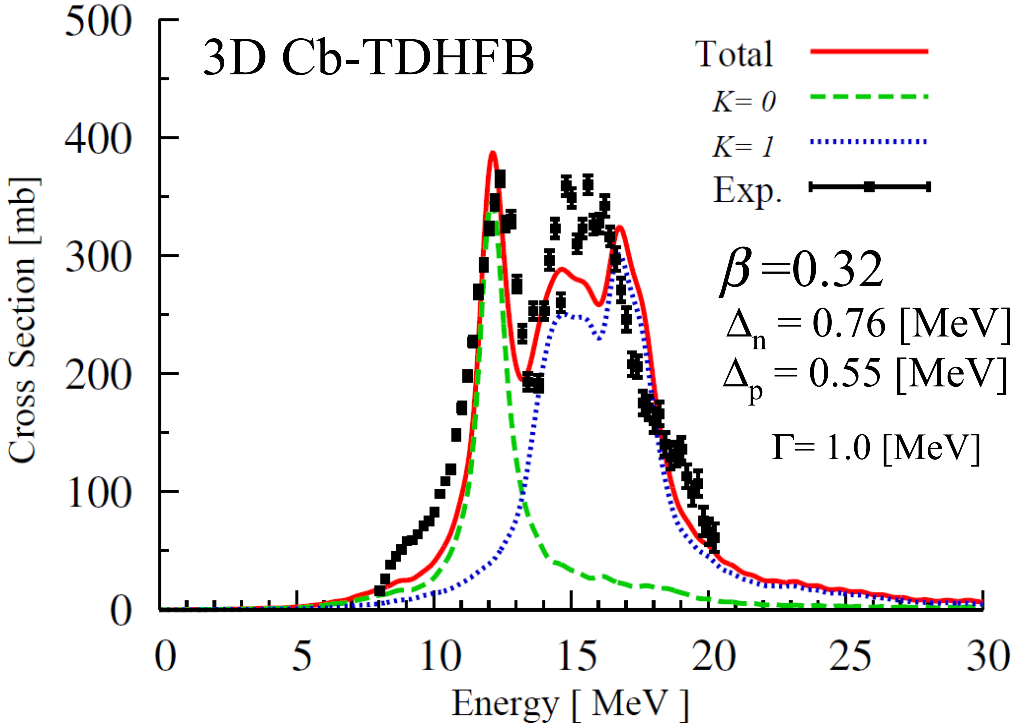
$d/dt\langle \phi_k(t) | \phi_{k'}(t) \rangle = 0,$

$d/dt\langle \hat{N} \rangle = 0, \; d/dt E_{\text{Total}} = 0$

In the limit of $\Delta = 0$, → **TDHF**

In the static limit, → **HF+BCS**

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



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

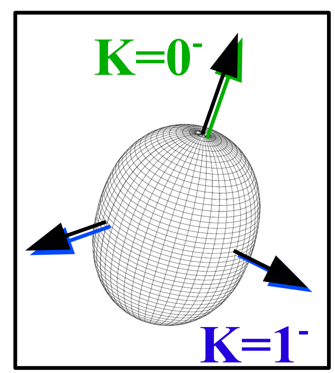
- **Heavy nucleus**
- **Deformed nucleus**
- Including pairing

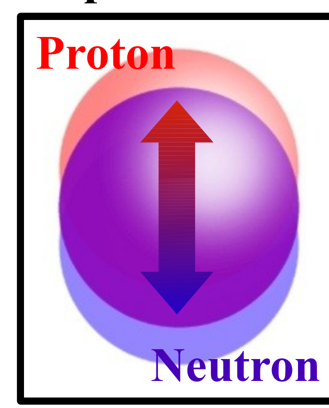
Total cal. cost : **300 CPU hours**
(with **a Single processor**; Intel Core i7 3.0 GHz)

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



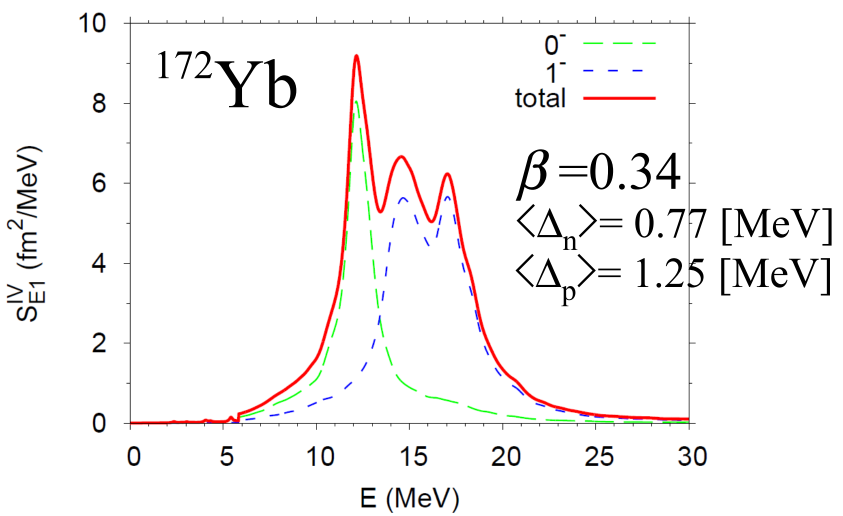


$$\hat{F}^N = -(Ze/A)(\hat{z} + \hat{x} + \hat{y}) \ ,$$
$$\hat{F}^P = (Ne/A)(\hat{z} + \hat{x} + \hat{y})$$

Example of Cb-TDHFB (for ^{172}Yb ; numerical cost)

Cb-TDHFB can reproduce the similar results of QRPA with very small numerical cost.

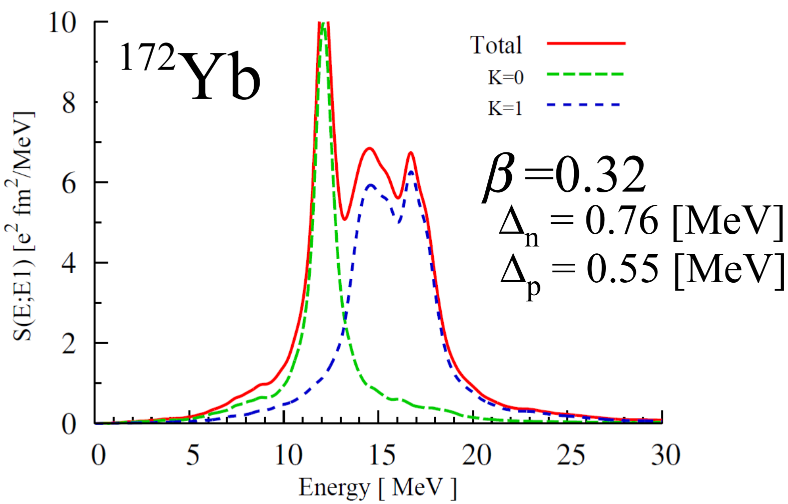
J. Terasaki and J. Engel
PRC**82**, 034326



Total cal. cost : **100,000 CPU hours**
(with **Kraken**; Super computer of ORNL)

Box Size : $\rho = z_{\pm}$=20[fm], b-spline (Cylindrical)
Single-quasiparticle space (HFB g.s.) :
5348 states for neutron,
4648 states for proton

S. Ebata using Cb-TDHFB
(based on PRC**82**, 034306)



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

Setup for collision

Incident Energy : 20, **40** [MeV] (Coulomb Barrier ~9.7 [MeV])

Impact parameter : 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0 [fm]

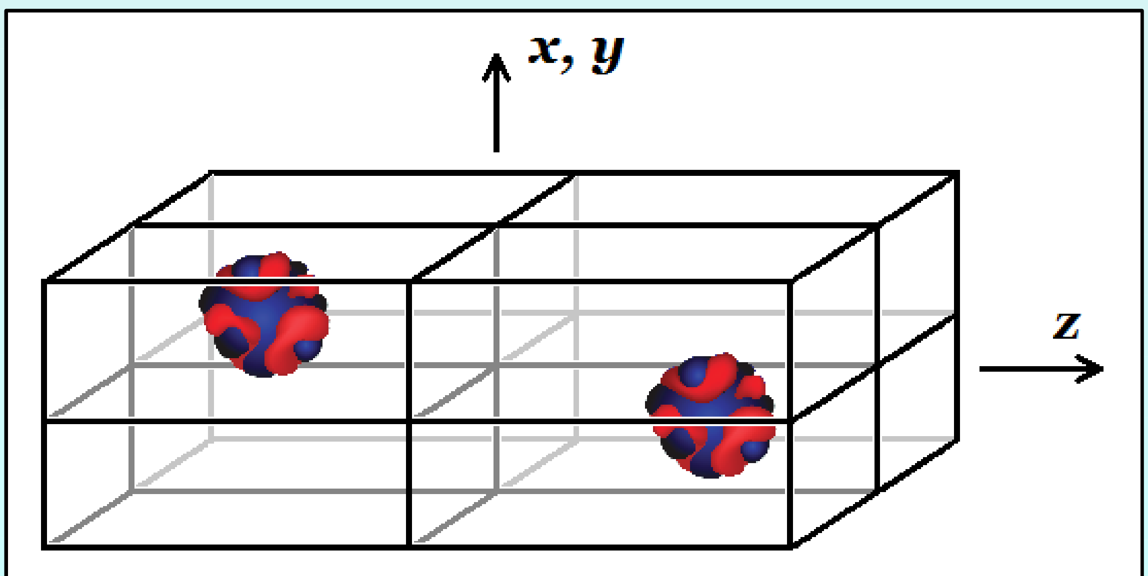
Effective Interaction : Skyrme force (SkM*), Contact pairing

Projectile : ^{20}O, Target : ^{20}O

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

Average of gap energy ; $\bar{\Delta}_{\rm n} = 1.901$ [MeV] $V_0^{\rm n} = -321.0$ [MeV]

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

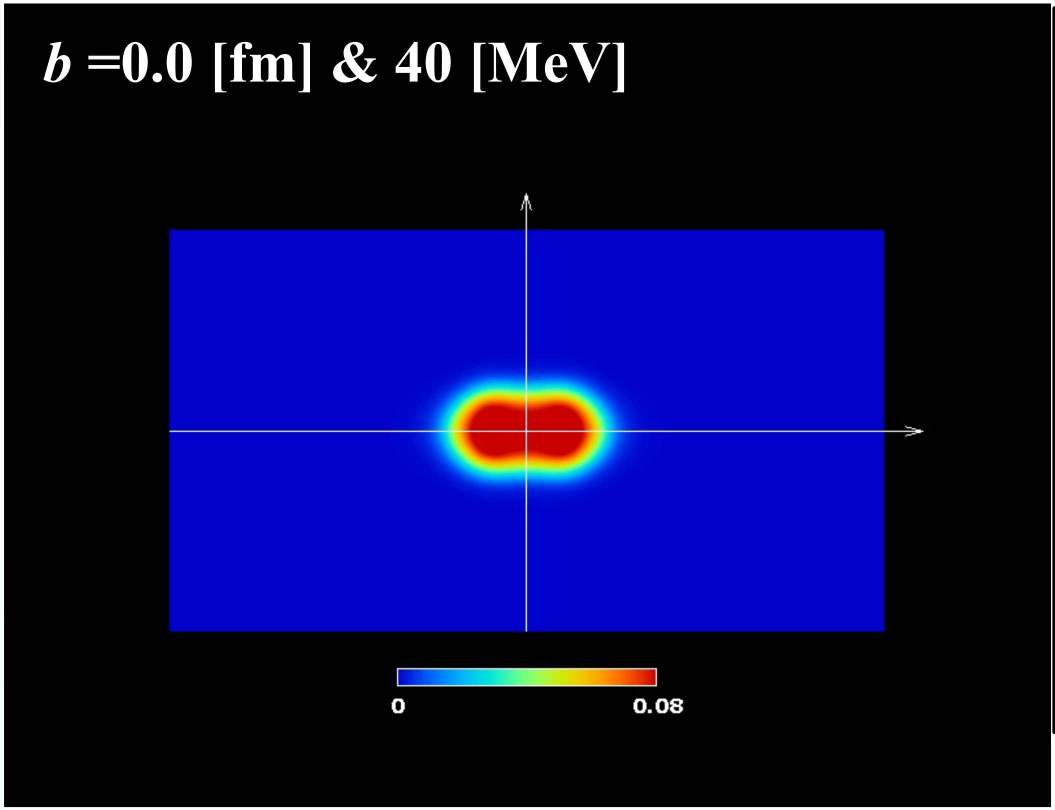


Length of box for z is **50**[fm] meshed by **1.0** [fm]

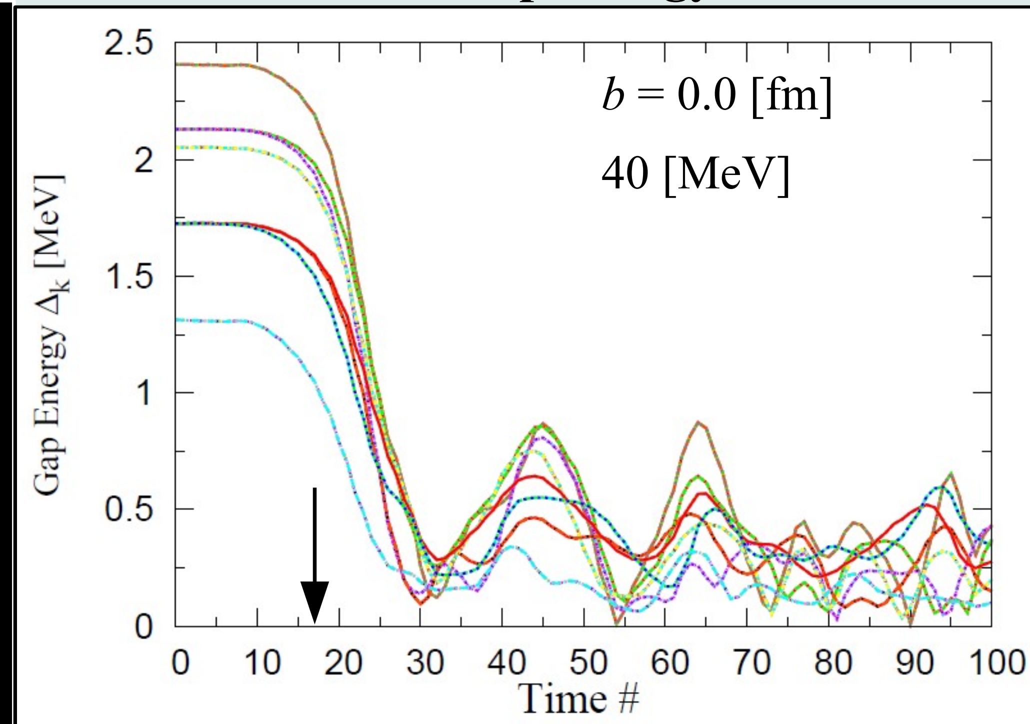
Lengths of box for x,y are **30**[fm] meshed by **1.0** [fm]

Simulation of ^{20}O + ^{20}O collision with b = 0.0 [fm] and E_{in}=40 [MeV]

Time-evolution of Neutron density



Time-evolution of Gap energy



Nuclear density vibrate with keeping deformed shape.
Gap energy is dumping at contact and
vibration while neutron density vibration.

Setup for collision

Incident Energy : 18 - 20 [MeV] (E_{cm} = 9.0 – 10 [MeV], V_{FD} ~ 9 MeV)

Impact parameter : 0.0, 2.8 - 3.1 [fm]

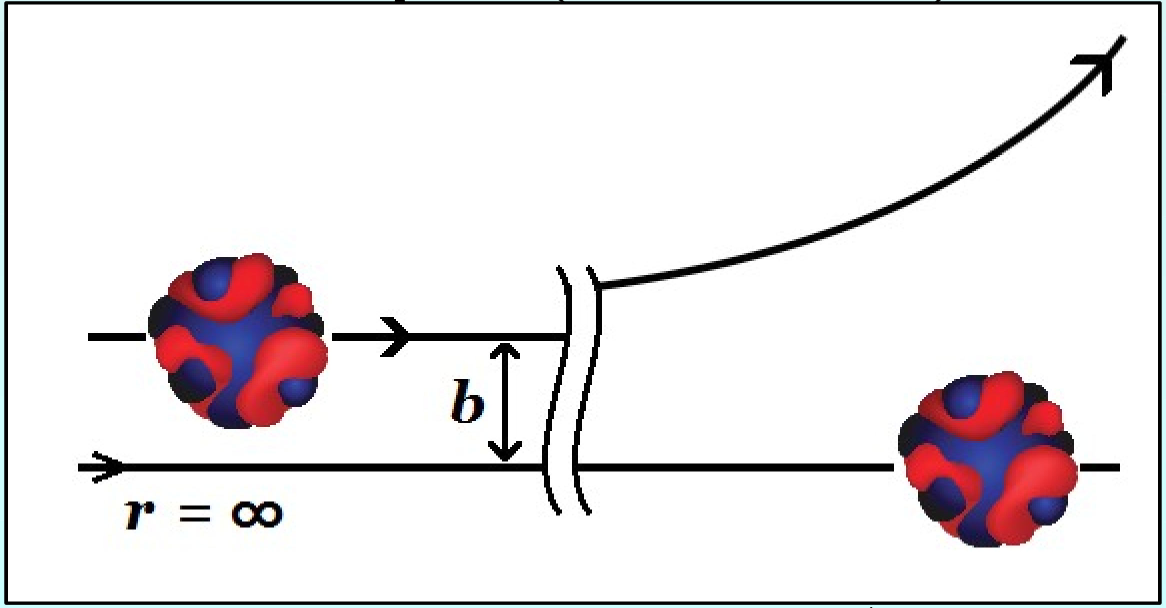
Effective Interaction : Skyrme force (SkM*), Contact pairing

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] $V_0^{\mathrm{n}} = -412.5$ [MeV]

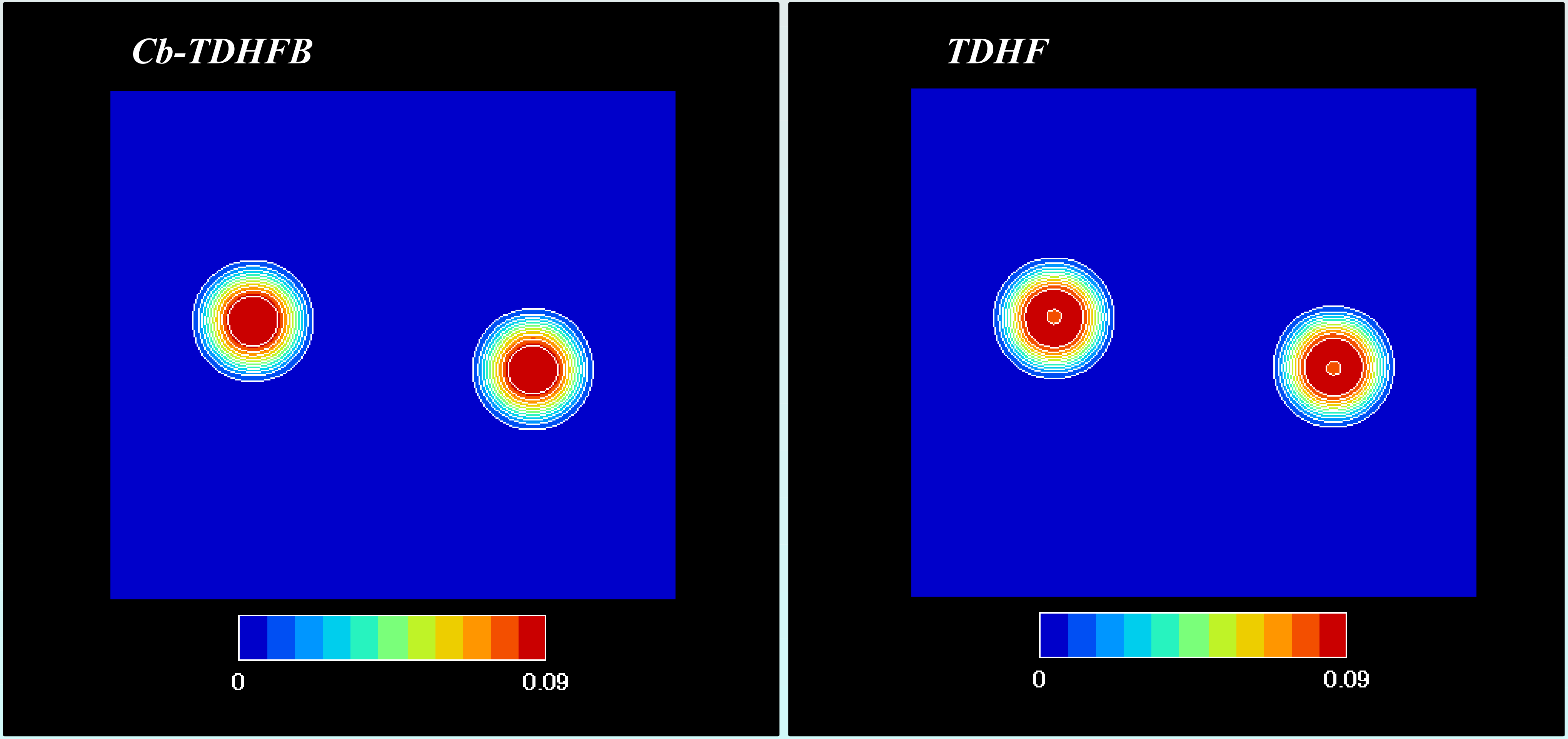
Calculation space (3D meshed box**):**



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

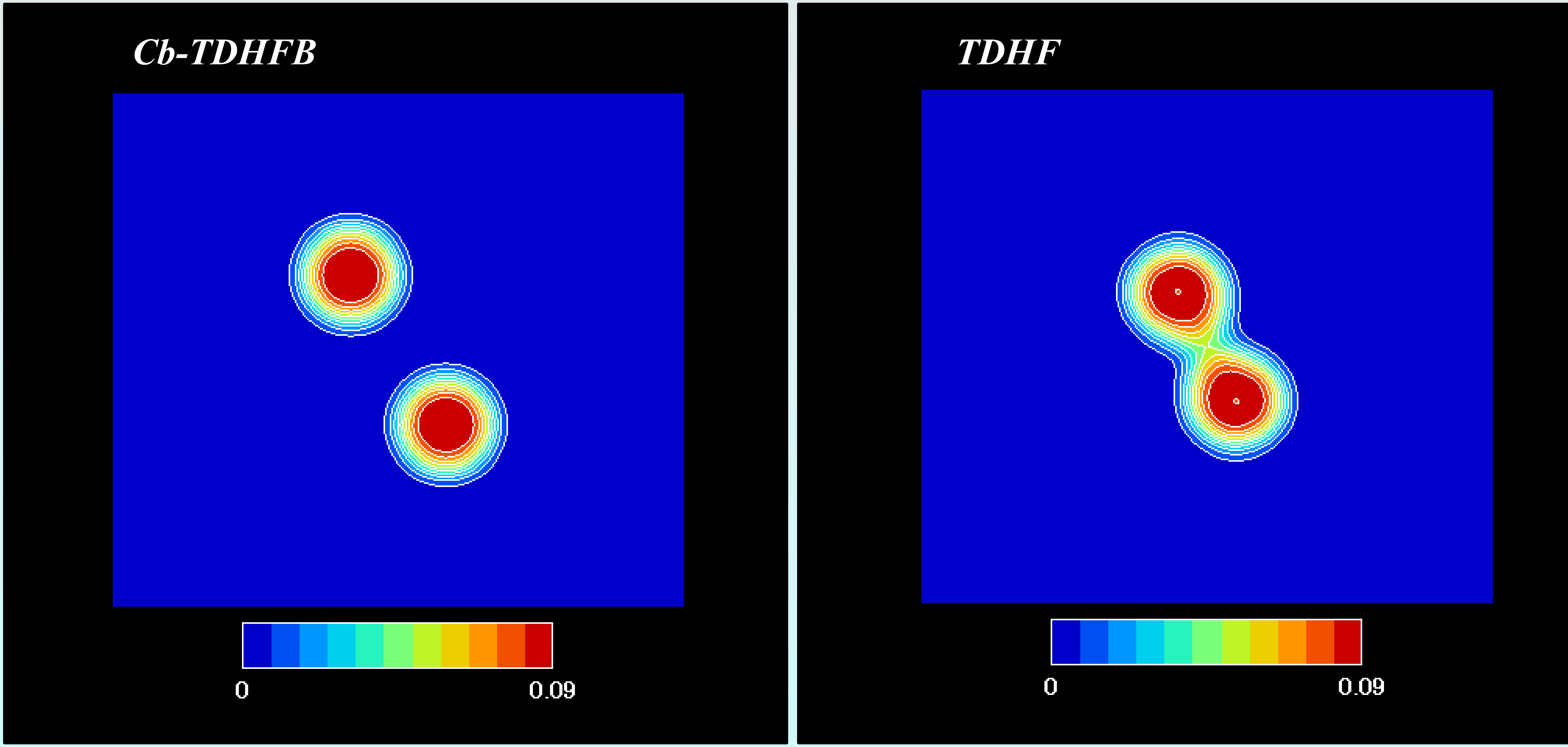
Simulation of ^{22}O + ^{22}O collision with b = 3.0 [fm] and E_{cm}=10 [MeV]

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



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

!?

Summary & Perspective

Summary

- Apply the **Cb-TDHFB** to heavy-ion collision, including a ***pairing***.
- Execute the simulation of **^{22}O+^{22}O collision** with $b \geqq 0.0$ [fm], E_{cm} = 9 - 10 [MeV]

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

$$2.8\ \mathrm{fm} < \underline{b_f^{\mathrm{Bs}}} < 2.9\ \mathrm{fm} < \underline{b_f^{\mathrm{Bw}}} < 3.0\ \mathrm{fm} < \underline{b_f^{\mathrm{H}}} < 3.1\ \mathrm{fm}$$

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

Perspective

- About some physical values (gap, s.p.-states, Q-moment, etc.)
- Particle number projection for the nucleon transfer
- More heavy system (^{52}Ca + ^{52}Ca) → it can be compare TDHF.
- Different nuclei collision phenomena (^{22}O + ^{52}Ca)
- Realistic system (Ni isotope)