International Symposium on Nuclear Physics in Asia
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Microscopic theory for heavy-ion optical potentials:

- present status and future perspective -

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with

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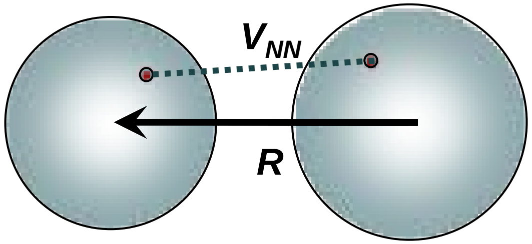
(*For publications, Y. Sakuragi is used as the pen name.)

- *Understanding the interactions between composite nuclei (AA interactions), starting from NN interaction :*



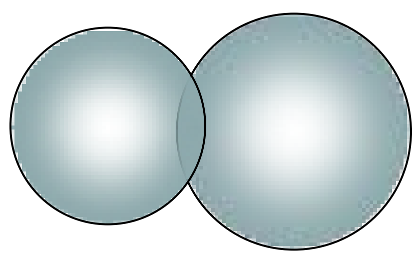
- ✓ *one of the fundamental subject in nuclear physics*
- ✓ *one of the key issue to understand various nuclear reactions:*
  - ➢ *optical potentials: elastic scattering*
  - ➢ *distorting potentials as doorway to various reactions (inelastic, transfer, knockout, breakup ···)*
- ✓ *important to survey unknown nuclear structures/reaction of unstable nuclei far from stability lines (N>>Z, Z>>N), for which*
  - ➢ *few/no elastic-scattering data & phenom. potential informations available.*

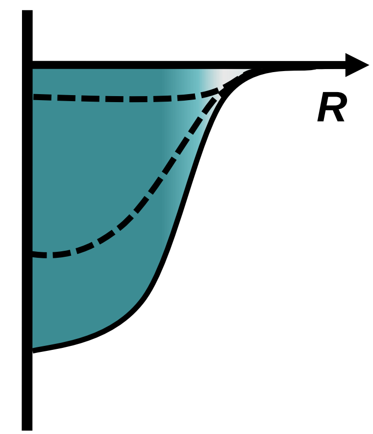
$U_{opt}(R) = V_{opt}(R) + i\,W_{opt}(R)$: complex potential

- Phenomenolocical optical potentials:
  - ✓ needs Exp. Data (elastic scattering)
    to determine potential parameters
    (e.g. Woods-Saxon form)

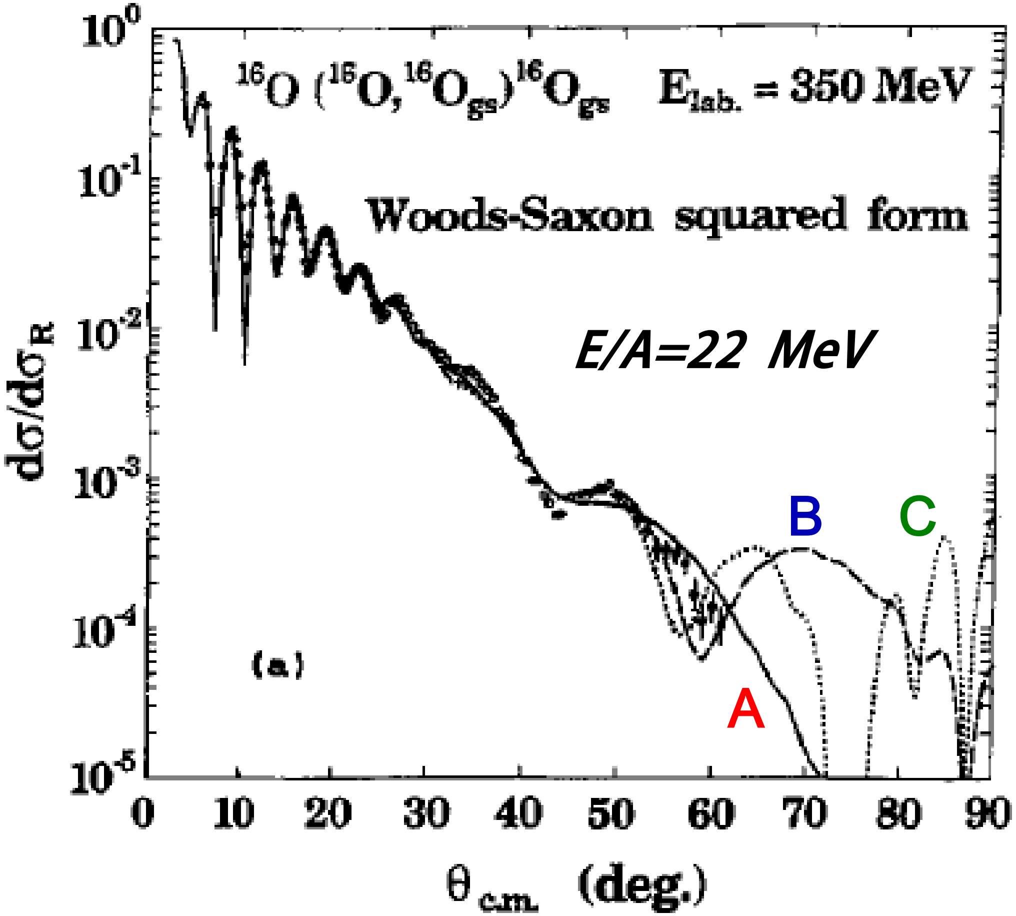
  - ✓ optical potential for heavy-ion systems (AA) has
    large ambiguity in depth & shape
    due to strong absorption (in most cases)

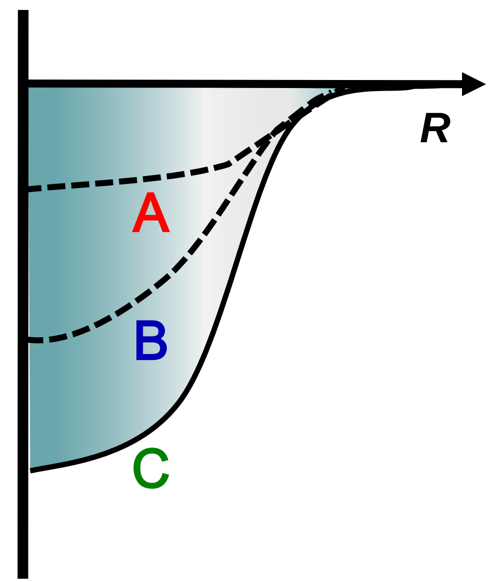
  - ✓ → only sensitive to potential at nuclear surface





discrete ambiguity of optical potential → which is correct ?





Y. Kondō, F. Michel and G. Reidemeister, Phys. Lett. B 242 (1990) 340.

- ✓ *In general, it is rather difficult to probe the short-range part of H.I. potentials, dut to strong absorption.*

- ✓ Can we probe H.I. potential at short distances?

→ ***Yes, we can!***

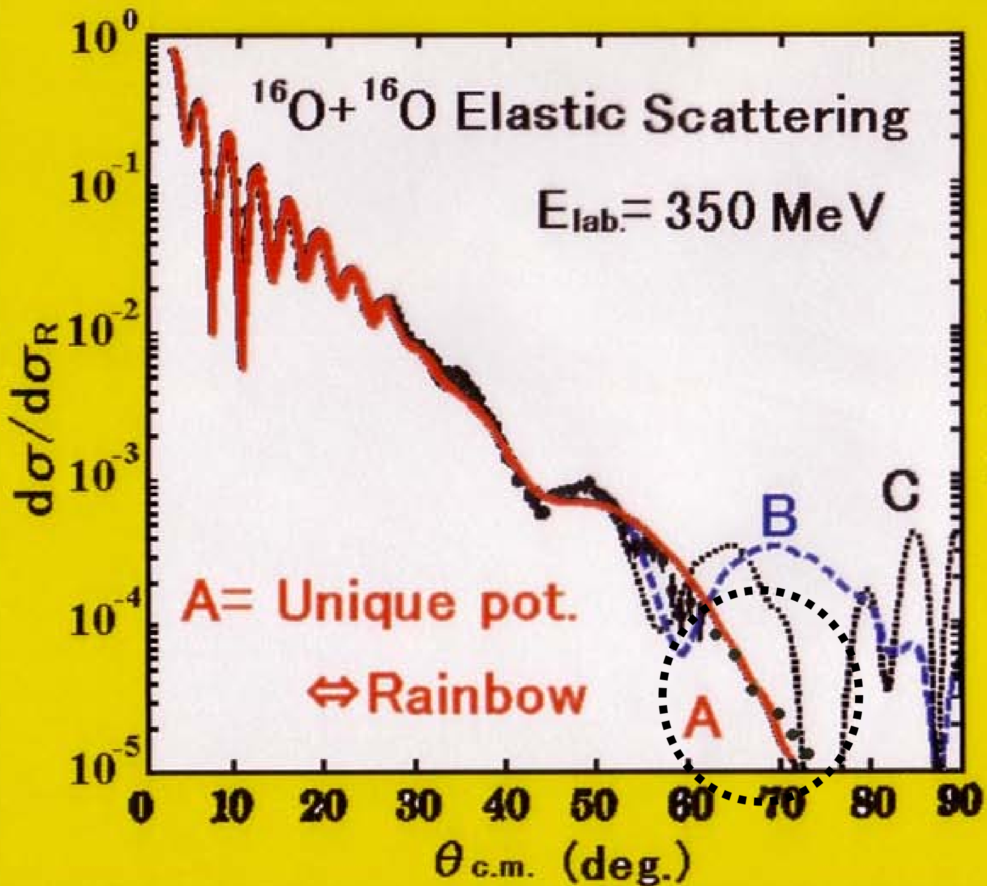
(at least for light heavy-ions)

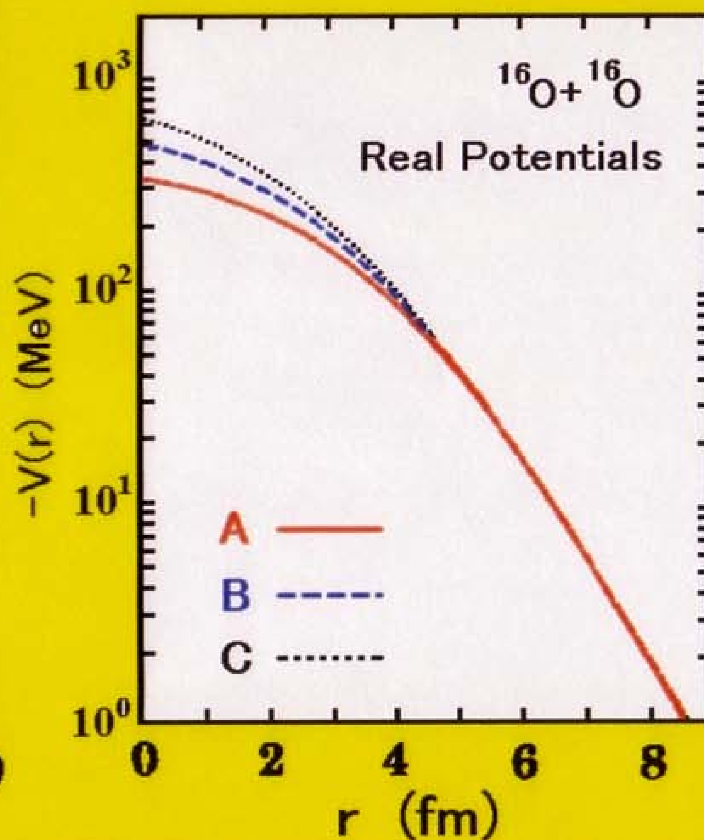
by the measurements of

refractive scattering at high-q region (backward) , such as nuclear-rainbow phenomena.

Phenomenological Analysis of the Nuclear Rainbow

- $^{16}O+^{16}O$ E_{lab} = 350 MeV (HMI 1989)
- The data up to 61° are reproduced by A, B and C.
- "A" pot. is found to be a unique deep potential for this system by the fits to the data up to 73°.





*But, **good quality of exp. data** are **not always** in our hands.*

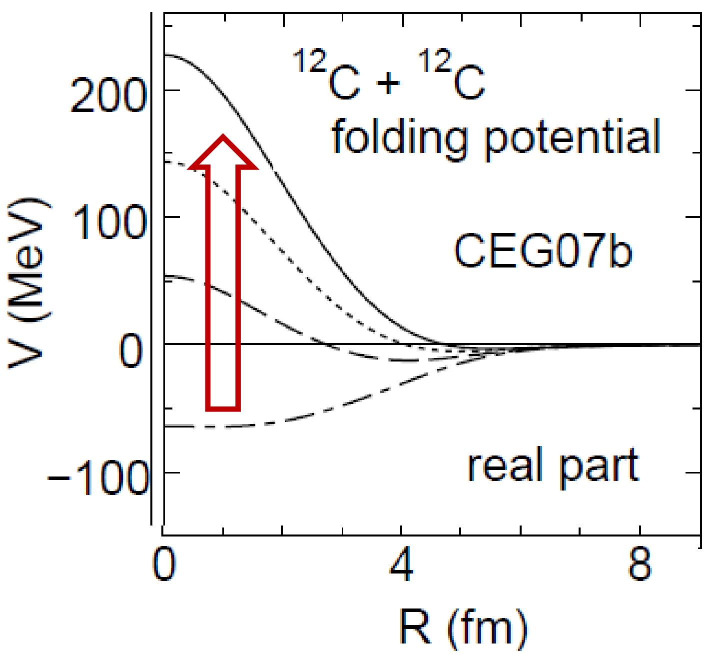
→ *We need a **microscopic theory** that **explains** & **predicts***

- ✓ *correct depth & shape of **heavy-ion optical potentials**, (hopefully ,of both the real and imaginary parts)*
- ✓ *including **unstable nuclei** (n-rich & p-rich isotopes)*
- ✓ *correct **energy dependence** over the wide range of incident energy, up to a few hundred MeV/u*

*starting from **bare NN interaction** in free space*

key word of the present talk

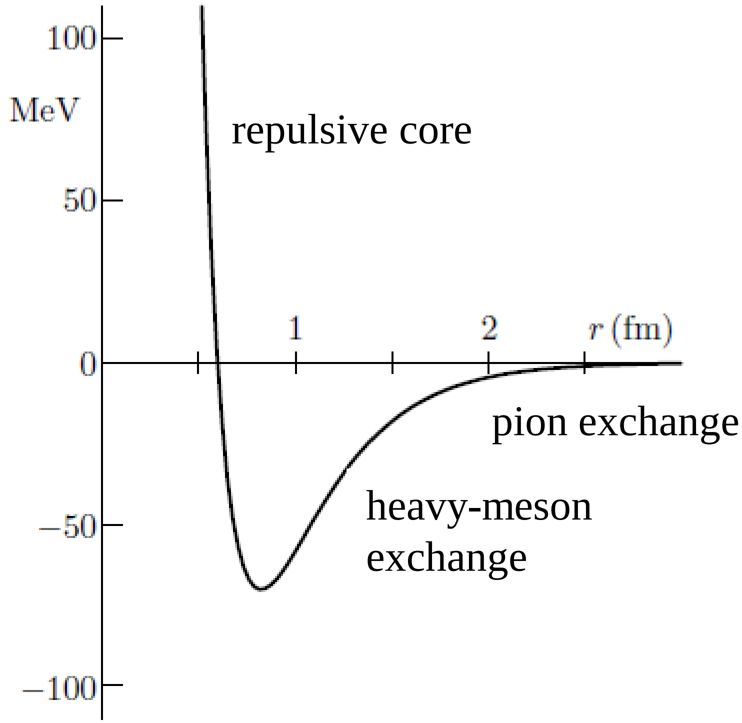
- ***attractive-to-repulsive transition*** *of the optical potentials for **heavy-ion** systems* ***with the increasing energy***



E/A=100～400 MeV

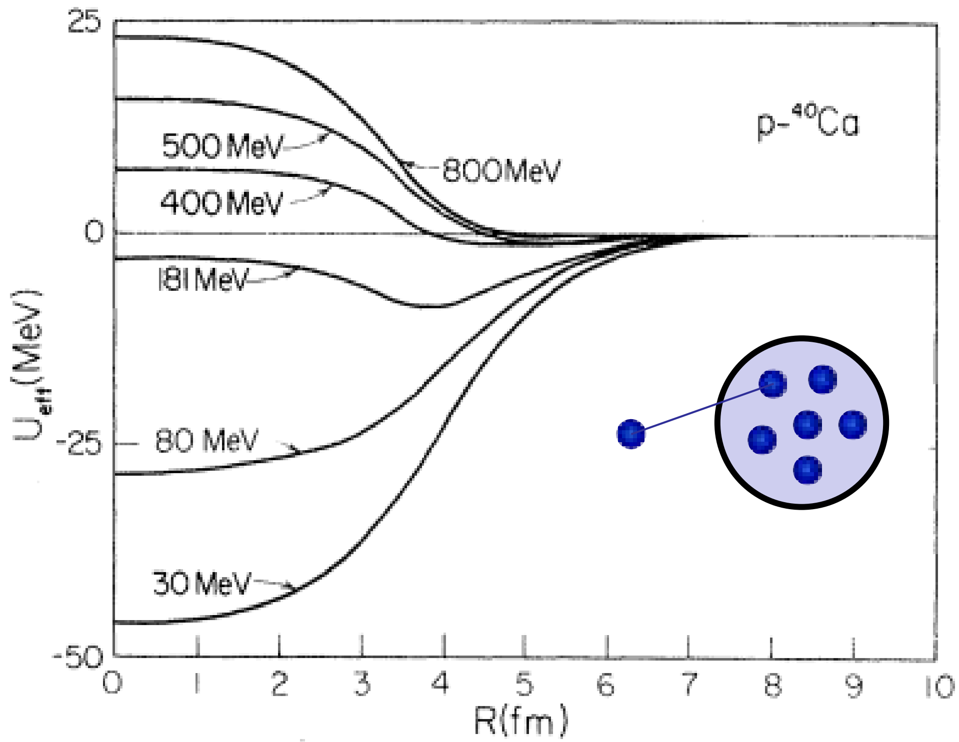
◆ ***NN interaction :***

- *long-range* ***attraction***
- *short-range* ***repulsive core***



◆ *nucleon-nucleus (**NA**) interaction :*

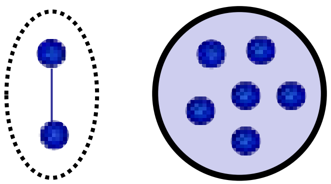
- *attractive at low energies (E<200* MeV)
- *wine-bottle-bottom (WBB)*
  around transitional energies
- *repulsive at high energies (E>500* MeV *)*



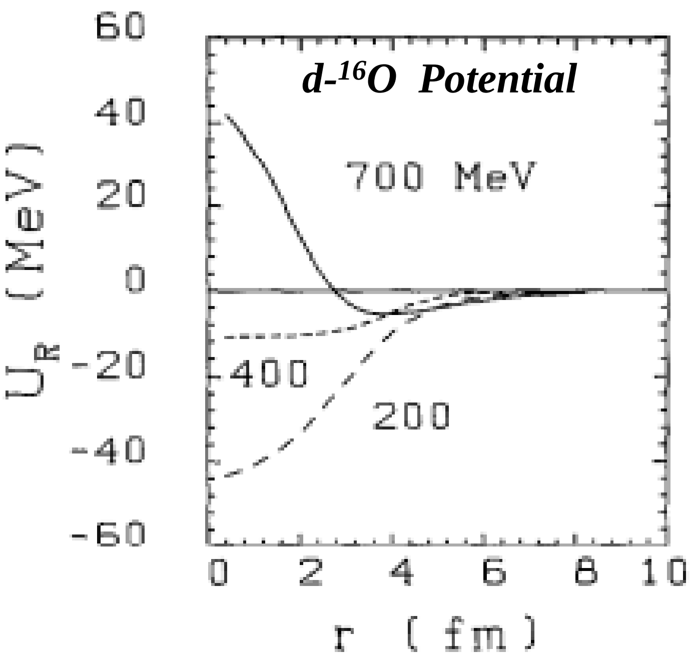
L.G.Arnold, (Phys.Rev.C25(1982)936

◆ d-A interaction :

- *similar behavior to NA int.*
- *f (d-A) ~ f (p-A)+ f (n-A)*



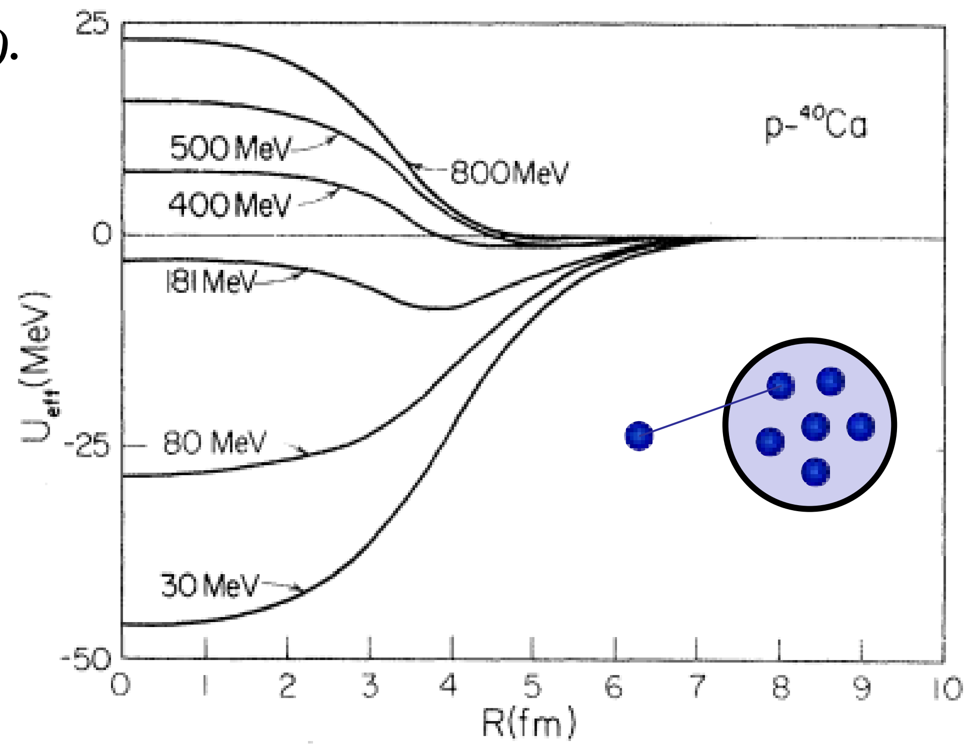
Y. Sakuragi, M. Tanifuji, NPA560, 945(1993).



N.V.Sen, NPA464 (1987) 717

◆ nucleon-nucleus (NA) interaction :

- *attractive at low energies (E<200* MeV)
- *wine-bottle-bottom (WBB)*
  around transitional energies
- *repulsive at high energies (E>500* MeV*)*



L.G.Arnold, (Phys.Rev.C25(1982)936

Q: How about optical potential for heavy ions?

A: according to the predictions of microscopic theory,

- ✓ attractive-to-repulsive transition occurs ?

  → *Yes, but thus far we have no experimental evidence.*

- ✓ if so, in what energy region?

  → *the transition occurs around E/A = 300～400 MeV*

- ✓ how can we observe the transition, if it really occurs?

  → *measure the evolution of elastic scattering angular distribution with increasing energy in the energy range of E/A = 200～400 MeV.*

- ✓ what are the new ingredients we can learn, if we observe the transition?

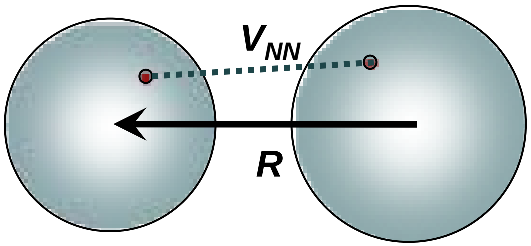
  → *① repulsive three-body force (TBF) in nuclear medium*

  & ② tensor force effects

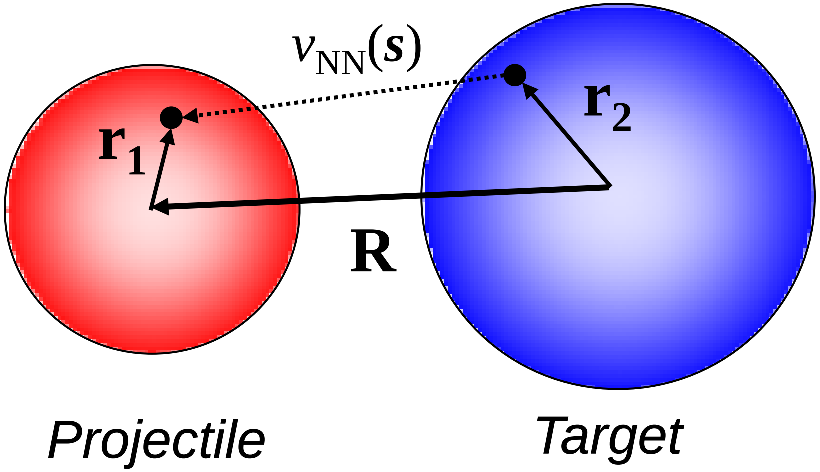
  besides the genuine repulsive core of NN int.

Microscopic / semi-microscopic models :

✓ *starting from **NN interactions** (V_{NN})*



Double-Folding Model (DFM)

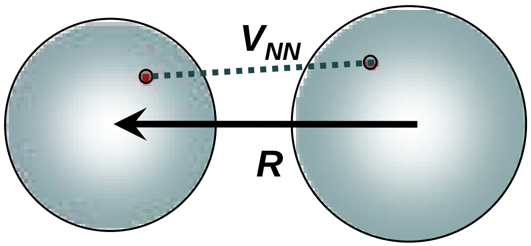


$$U_{DFM}(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)\underline{v_{NN}(\mathbf{s};\rho,E)}d\mathbf{r}_1 d\mathbf{r}_2$$

effective ***NN*** interaction in **nuclear medium**

Microscopic / semi-microscopic models :

✓ starting from NN interactions (V_{NN})



◆ G-matrix with scattering b.c.

✓ V_{NN} : effective NN interaction in nuclear medium

- ✓ should have proper density-dependence (ρ-dep) consistent with nuclear saturation properties
- ✓ should have proper energy-dependence (E-dep)
- ✓ should be complex (real-part + imaginary part)

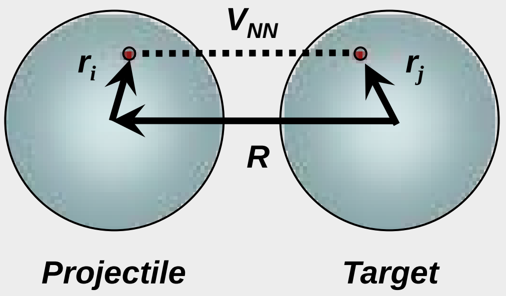
However, no such ideal effective V_{NN} exists so far !

Simple M3Y (1975～1985)

- ✓ real part only (add a phenom. imag. pot)
- ✓ zero-range exchange term

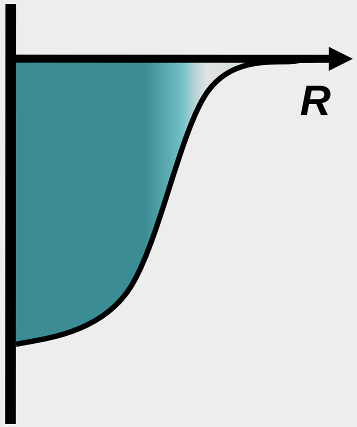
$$v_{\mathrm{NN}}(\mathbf{r}) = 7999\frac{e^{-4r}}{4r} - 2134\frac{e^{2.5r}}{2.5r} - \hat{J}_{00}\delta(\mathbf{r})$$

Double-Folding Model (DFM)



- ✓ no density-dependence

⇒ too deep at short distances, but gives a reasonable strength at nuclear surface



- ◆ due to strong absorption for Heavy Ions (HI)

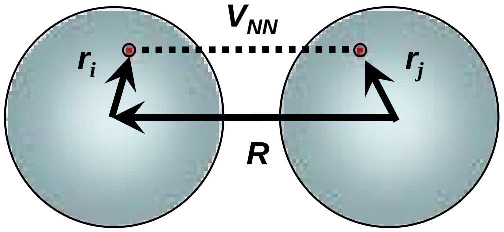
⇒ sensitive only to nuclear surface

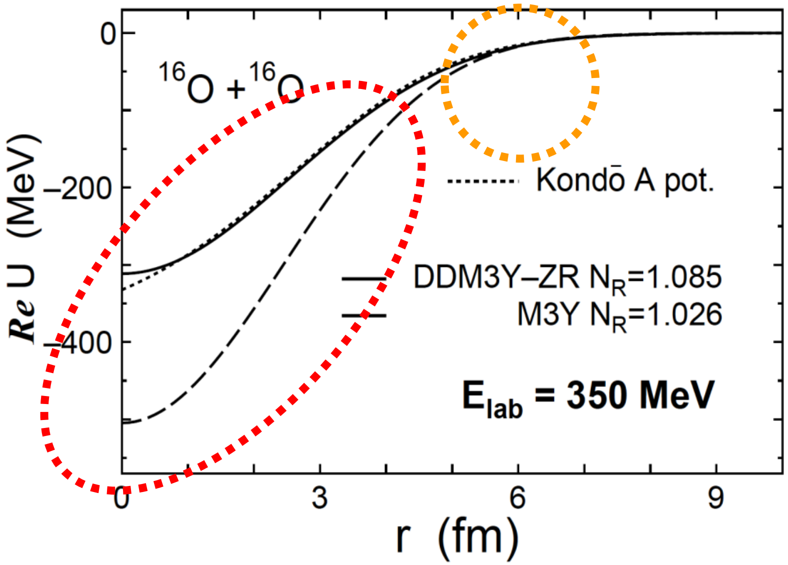
⇒ "Successful" for low-energy (E/A<30 MeV) scattering of heavy-ion (HI) projectiles with A_p<40

[G.R.Satchler and W.G.Love, **Phys.Rep.**55,183(1979)]

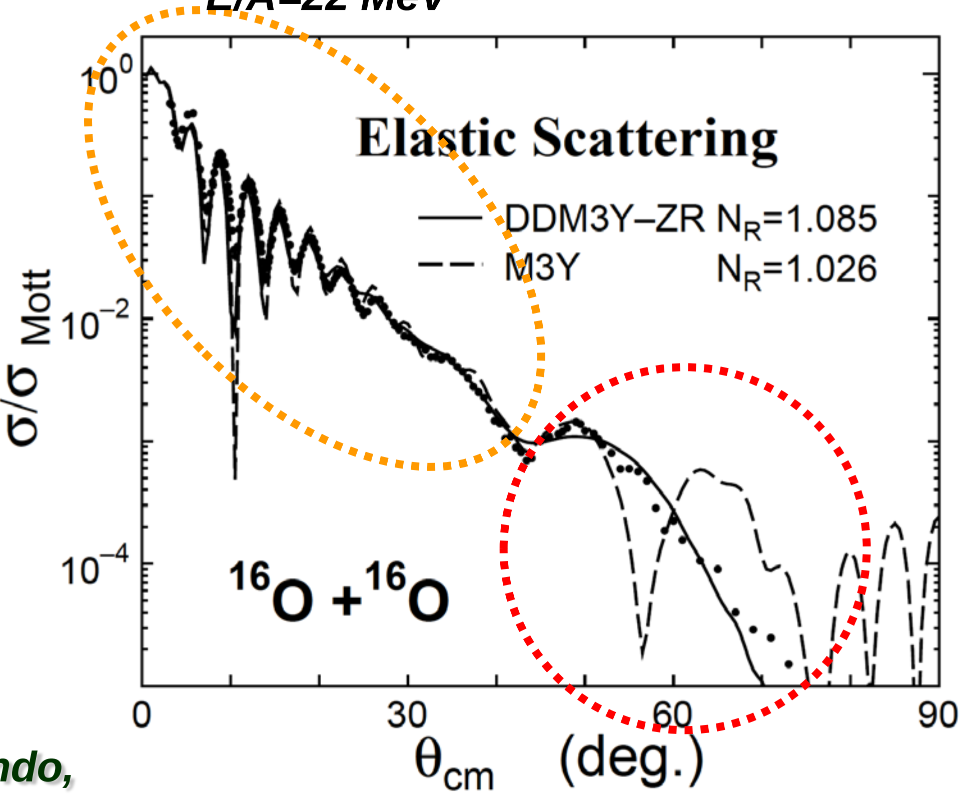
Double-Folding-model potentials with M3Y (density-independent)

Double-Folding Model (DFM)





E/A=22 MeV



M.Katsuma, Y.Sakuragi, S.Okabe, Y.Kondo, Prog.Theor.Phys. 107 (2002) 377

- ***Introduction of density-dependence*** :

DDM3Y-ZR ***(with zero-range exchange term)***

$$v_{NN}(E,\rho;\mathbf{s}) = g(E,\mathbf{s})f(E,\rho)$$

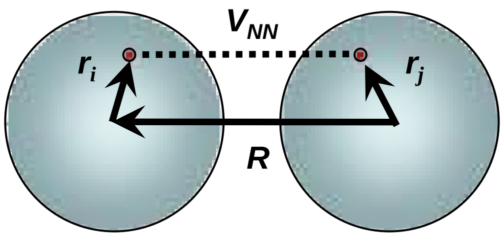
$$f(E,\rho) = C(E)[1+\alpha(E)e^{-\beta(E)\rho}]$$

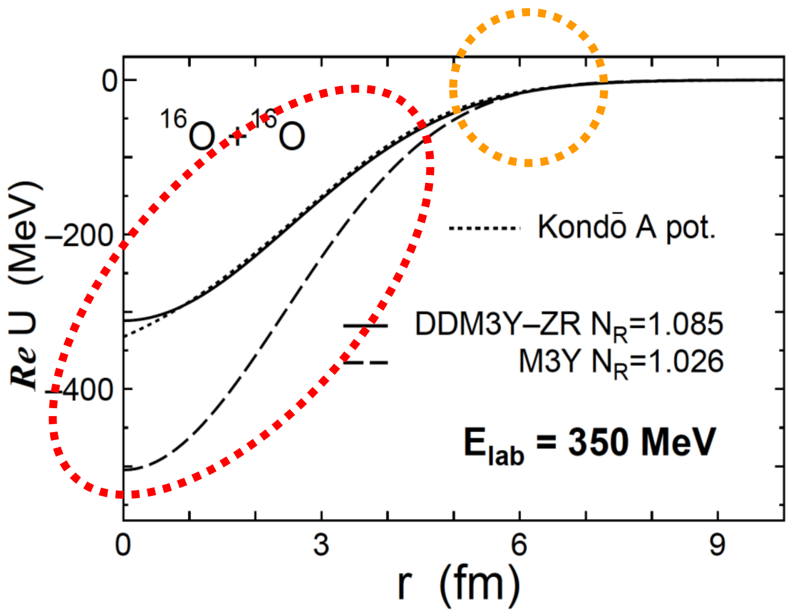
⇒ ***greatly reduce the potential strength at short distances***

⇒ ***reproduce refractive phenomena, such as nuclear-rainbow (eg.^{4}He+A, ^{16}O+^{16}O)***

Double-Folding-model potentials
with M3Y (density-independent)
with DDM3Y (density-dependent)

Double-Folding Model (DFM)





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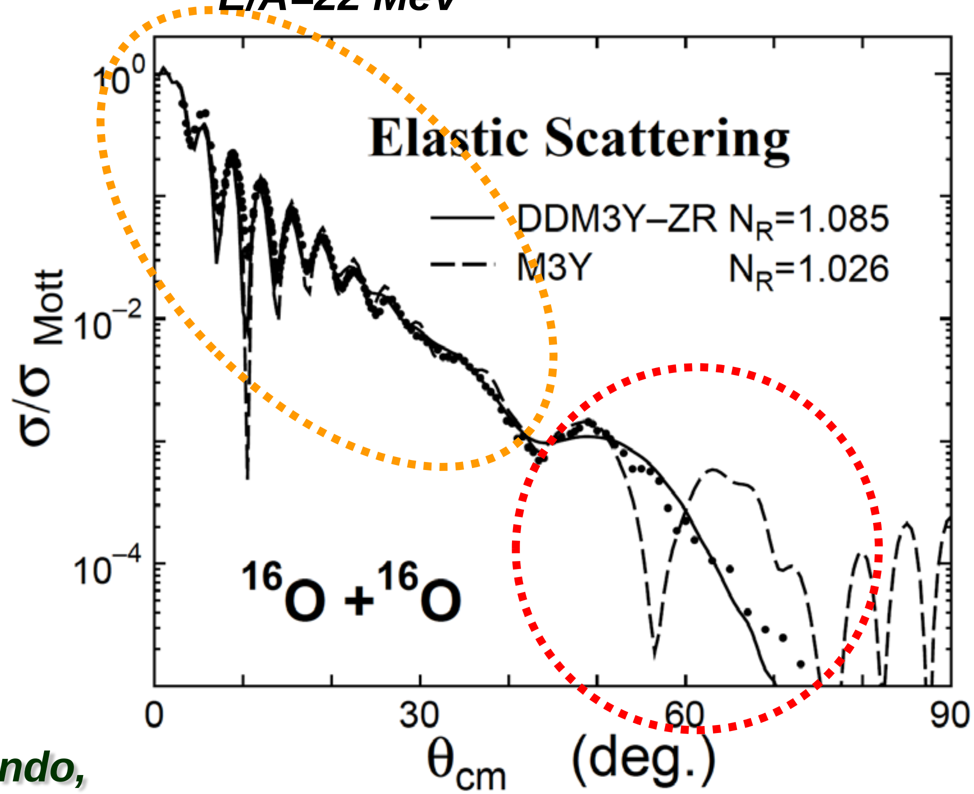

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New complex G-matrix interaction (CEG07)

1. derived from **ESC04**

"**ESC04**" : the latest version of **Extended Soft-Core** force designed for *NN*, *YN* and *YY* systems

Th. Rijken, Y. Yamamoto, Phys. Rev. C 73 (2006) 044008

2. **Three body force**

Three-body attraction (TBA) : Fujita-Miyazawa type

Three-body repulsion (TBR) : triple-meson correl.

3. **up to higher density region**

for the local density prescription in the case of DFM

- *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC78 (2008) 044610,*
- *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC79 (2009) 011601(R),*
- *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC80 (2009) 044614*
- *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 029908(E)*
- *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) (in press)*

Complex G-matrix interaction（CEG07）

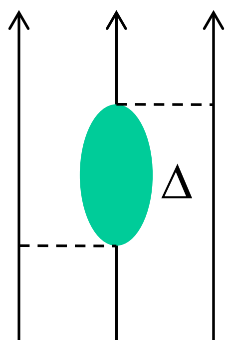
T.Furumoto, Y. Sakuragi and Y. Yamamoto, Phys. Rev. C 78 (2008) 044610

Extended Soft-Core model : “**ESC04**” force
designed for NN, YN and YY interactions

Th. Rijken, Y. Yamamoto, Phys.Rev.C 73 (2006) 044008

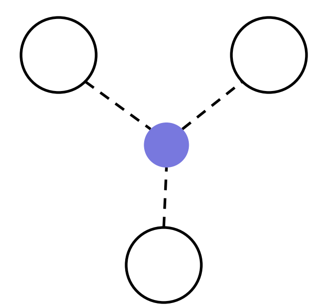
1. Three-body attractive (TBA)

- originated from **Fujita-Miyazawa** diagram
- important at low density region

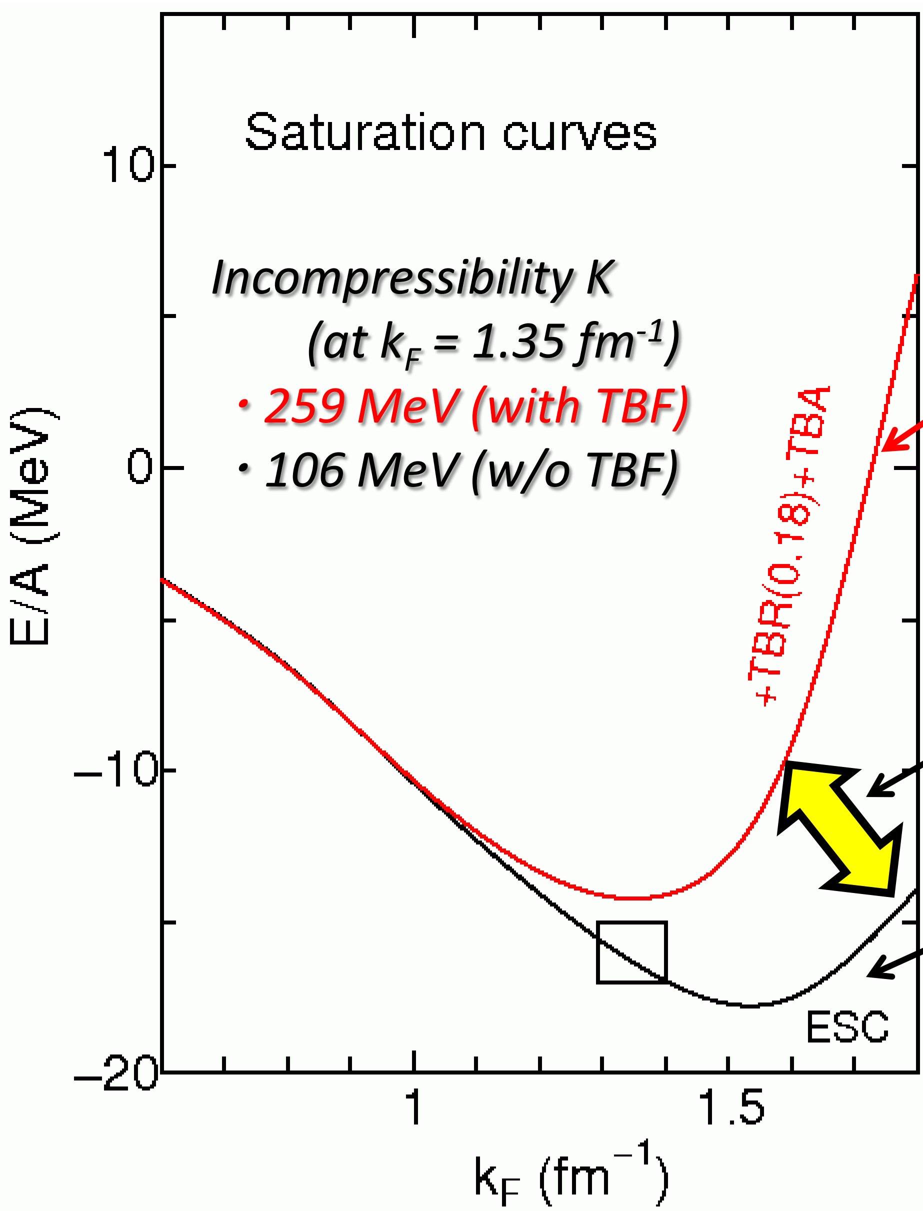


2. Three-body repulsive (TBR)

- universal three-body repulsion (NNN, NNY, NYY) originated from **triple-meson correlation**
- important at **high-density** region



New complex G-matrix interaction （CEG07）



$$\frac{E}{A} = \frac{3}{5}\frac{k_F^2}{2m} + \frac{1}{2}\sum_{k_1,k_2<k_F} \langle k_1 k_2 | G(\omega) | k_1 k_2 \rangle$$

CEG07b
+Three body repulsive (TBR)
+Three body attractive (TBA)

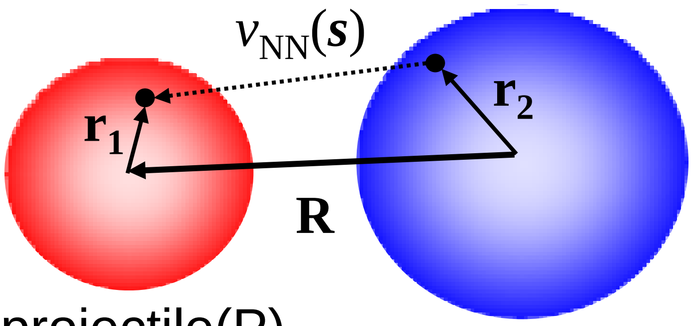
Decisive role to make the saturation curve realistic

CEG07a
With only Two-Body Force

T.Furumoto, Y. Sakuragi , Y. Yamamoto,
Phys. Rev. C 78 (2008) 044610

◆ *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC79 (2009) 011601(R),*
◆ *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC80 (2009) 044614*
◆ *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 029908(E)*
◆ *T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) (in press)*

Double folding Potential with complex-G (CEG07)



$$U(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2) g_D(\mathbf{s};\rho,E)\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

$$+ \int \rho_1(\mathbf{r}_1, \mathbf{r}_1 - \mathbf{s})\rho_2(\mathbf{r}_2, \mathbf{r}_2 + \mathbf{s}) g_{EX}(\mathbf{s};\rho,E)\exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right]\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

➢ Complex G-matrix interaction (**CEG07**)

$$g_{D,EX} = g_{D,EX}^{(real)} + i g_{D,EX}^{(imag)}$$

- T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC79 (2009) 011601(R),
- T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC80 (2009) 044614
- T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 029908(E)
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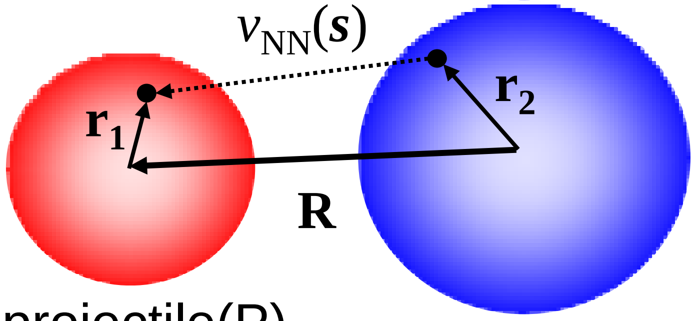
Double folding Potential with complex-G (CEG07)



$$U(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2) g_D(\mathbf{s};\rho,E)\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

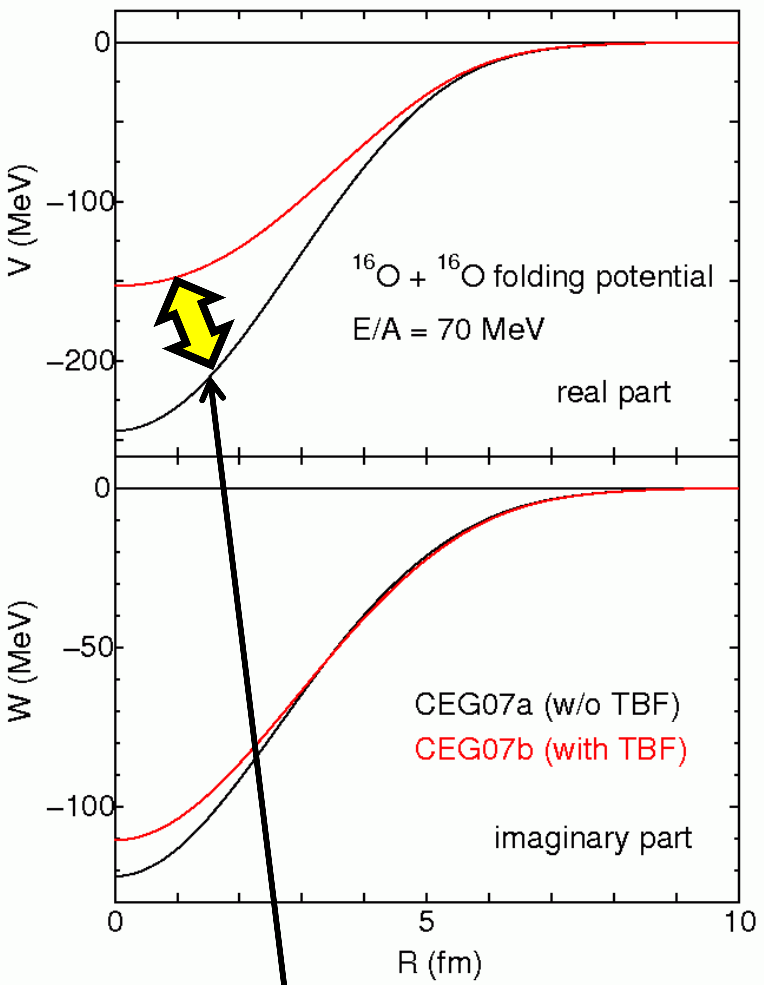
$$+\int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s}) g_{EX}(\mathbf{s};\rho,E)\exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right]\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

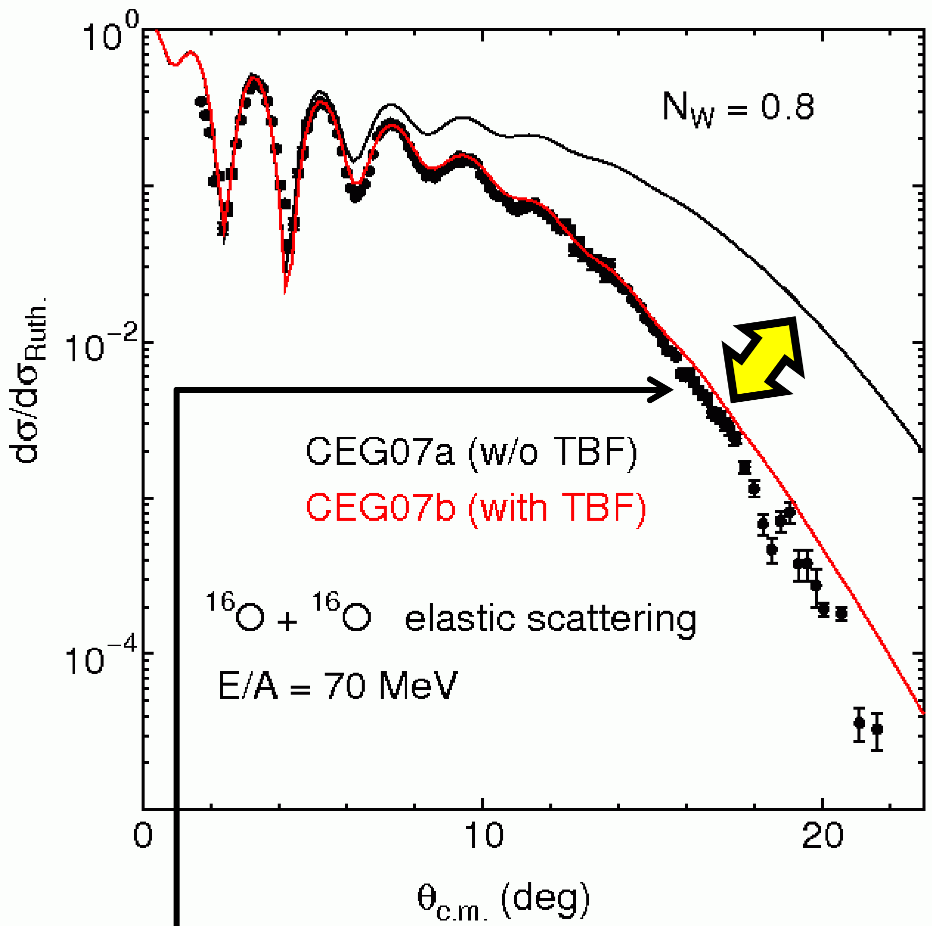
$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

✓Renormalization factor for the imaginary part

$$\rightarrow \quad \boldsymbol{U_{DFM} = V_{DFM} + iN_W W_{DFM}}$$

$^{16}O + ^{16}O$ elastic scattering   *E/A* = 70 MeV



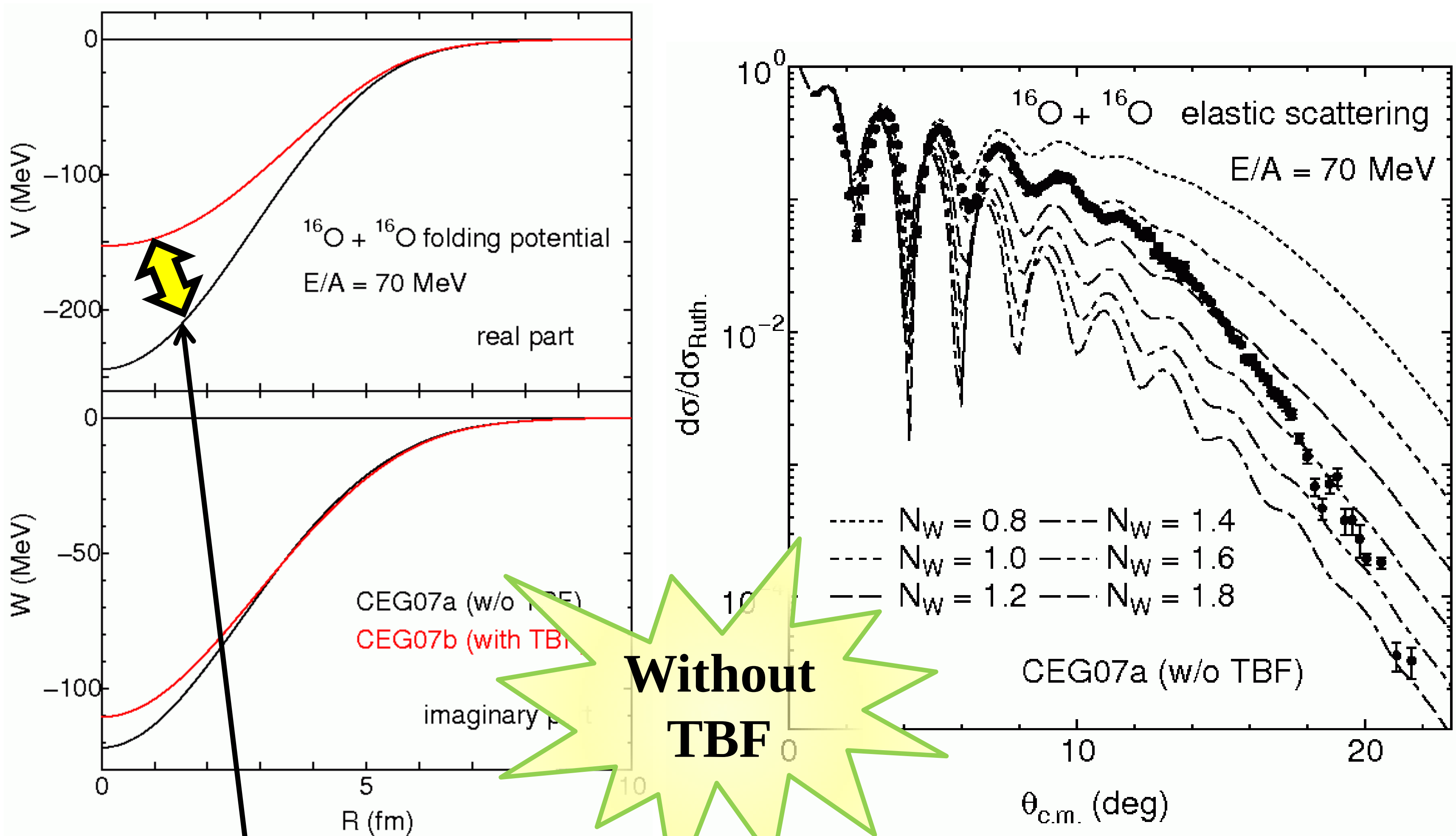


important effect of three-body force

$$U_{DFM} = V_{DFM} + iN_W W_{DFM}$$

T.Furumoto, Y. Sakuragi, Y. Yamamoto, (Phys. Rev. C79 (2009) 011601(R))
T.Furumoto, Y. Sakuragi, Y. Yamamoto, (Phys. Rev. C80 (2009) 044614)

$^{16}O + ^{16}O$ elastic scattering *E/A* = 70 MeV



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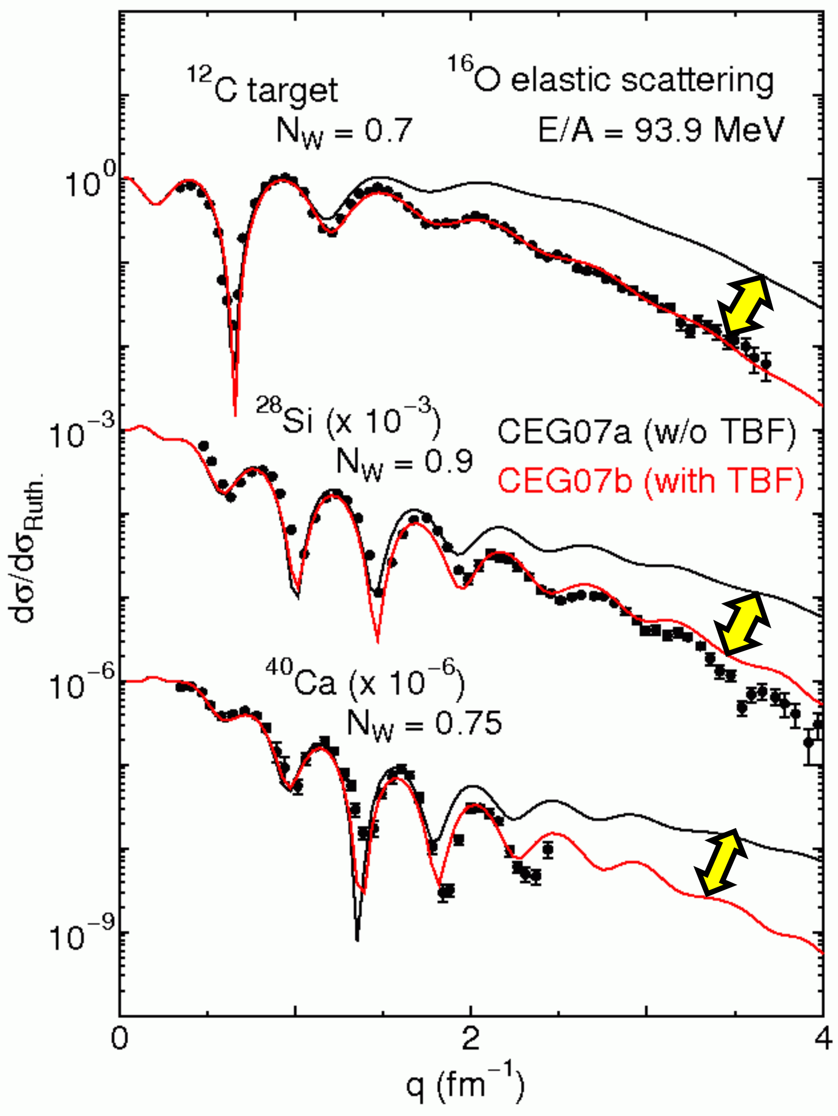
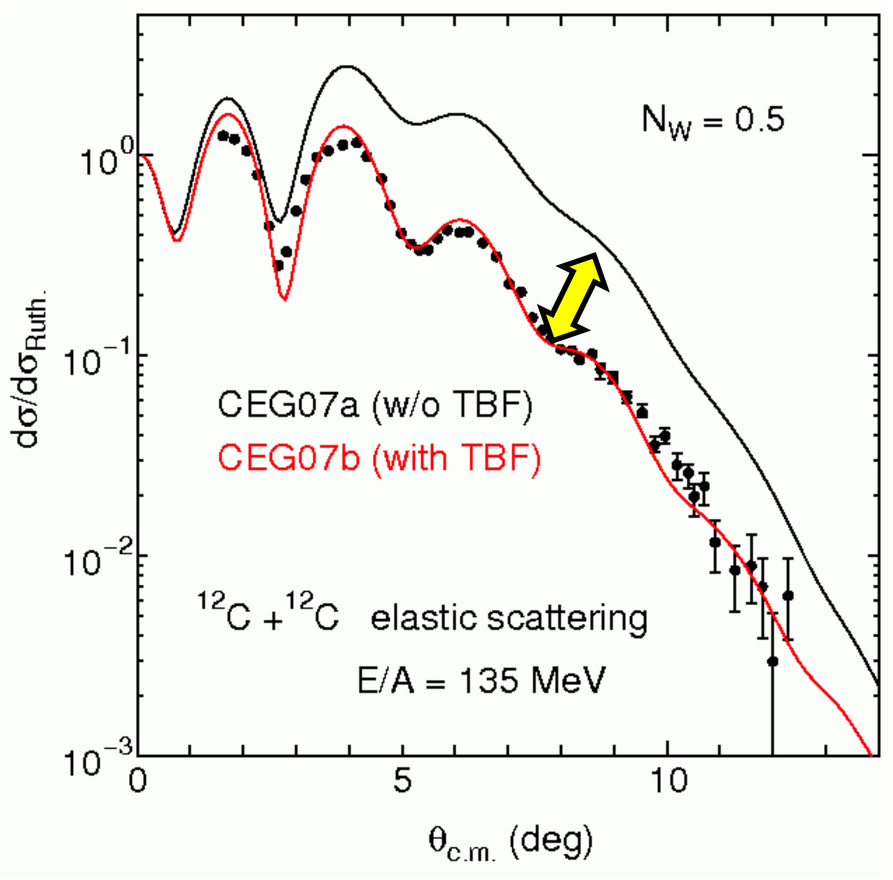
T.Furumoto, Y. Sakuragi, Y. Yamamoto, (Phys. Rev. C79 (2009) 011601(R))
T.Furumoto, Y. Sakuragi, Y. Yamamoto, (Phys. Rev. C80(2009)044614)

$^{16}O + ^{12}C, ^{28}Si, ^{40}Ca$

$^{12}C + ^{12}C$ elastic scattering





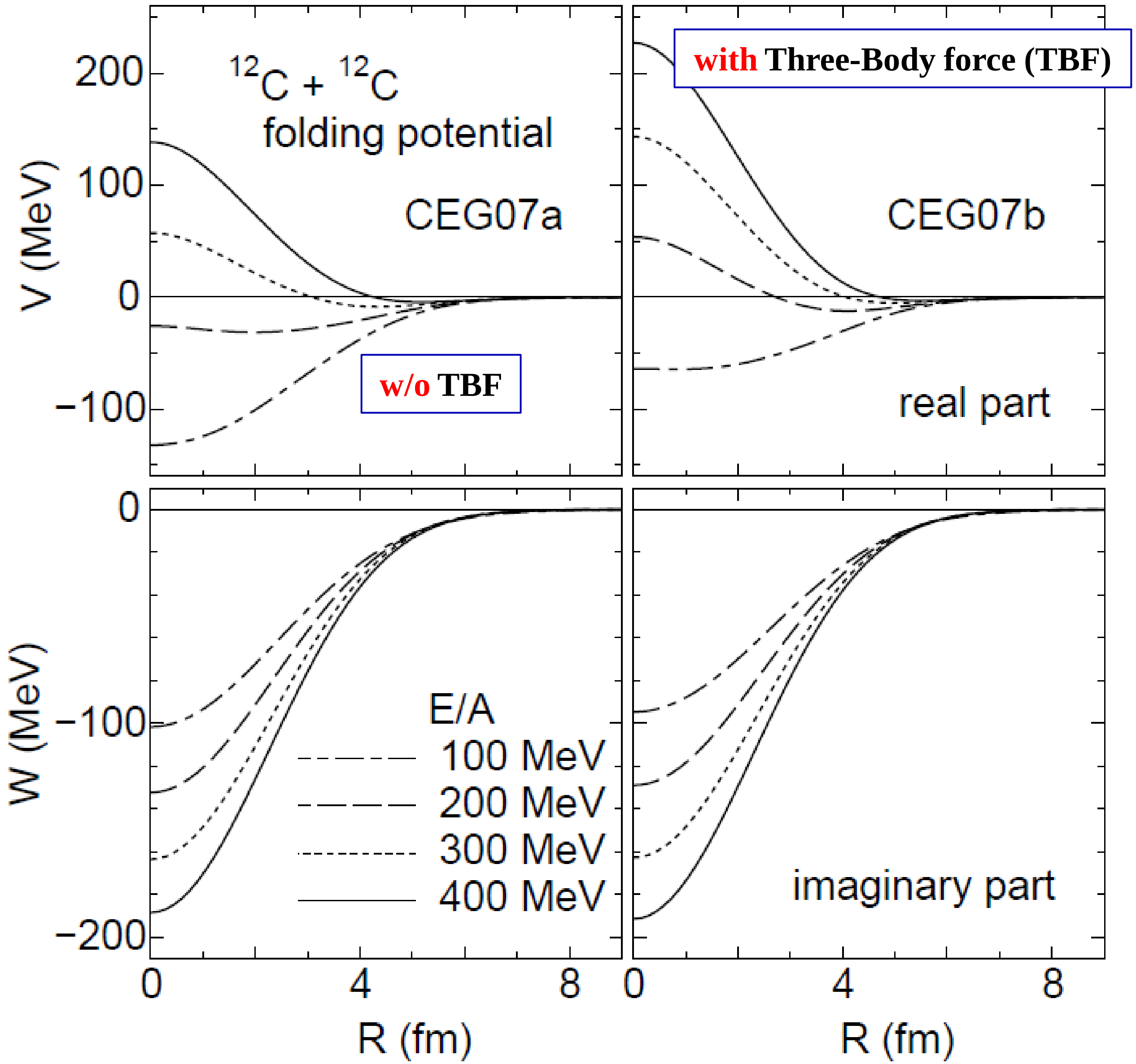
$$U_{DFM} = V_{DFM} + iN_W W_{DFM}$$

important effect of three-body force

T.Furumoto, Y. Sakuragi , Y. Yamamoto, (Phys. Rev. C 80 (2009) 044614)

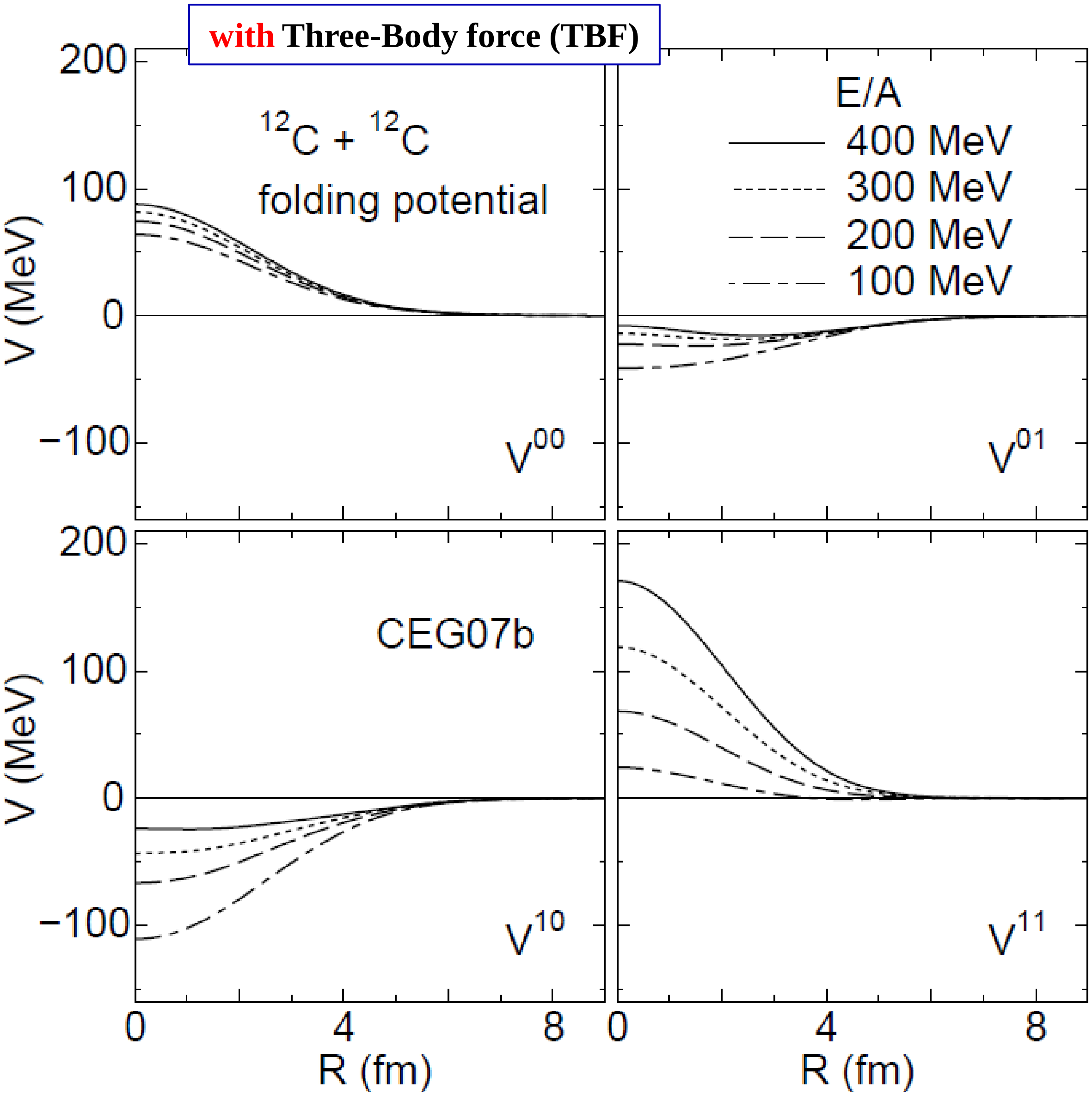
^{12}C + ^{12}C elastic scattering at *E/A* = 100～400 MeV

➢ real potential becomes repulsive around *E/A* = 300～400 MeV



T.Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) (in press)

NN tensor force plays an essential role in the **attractive-to-repulsive transition** of the **A-A potentials**



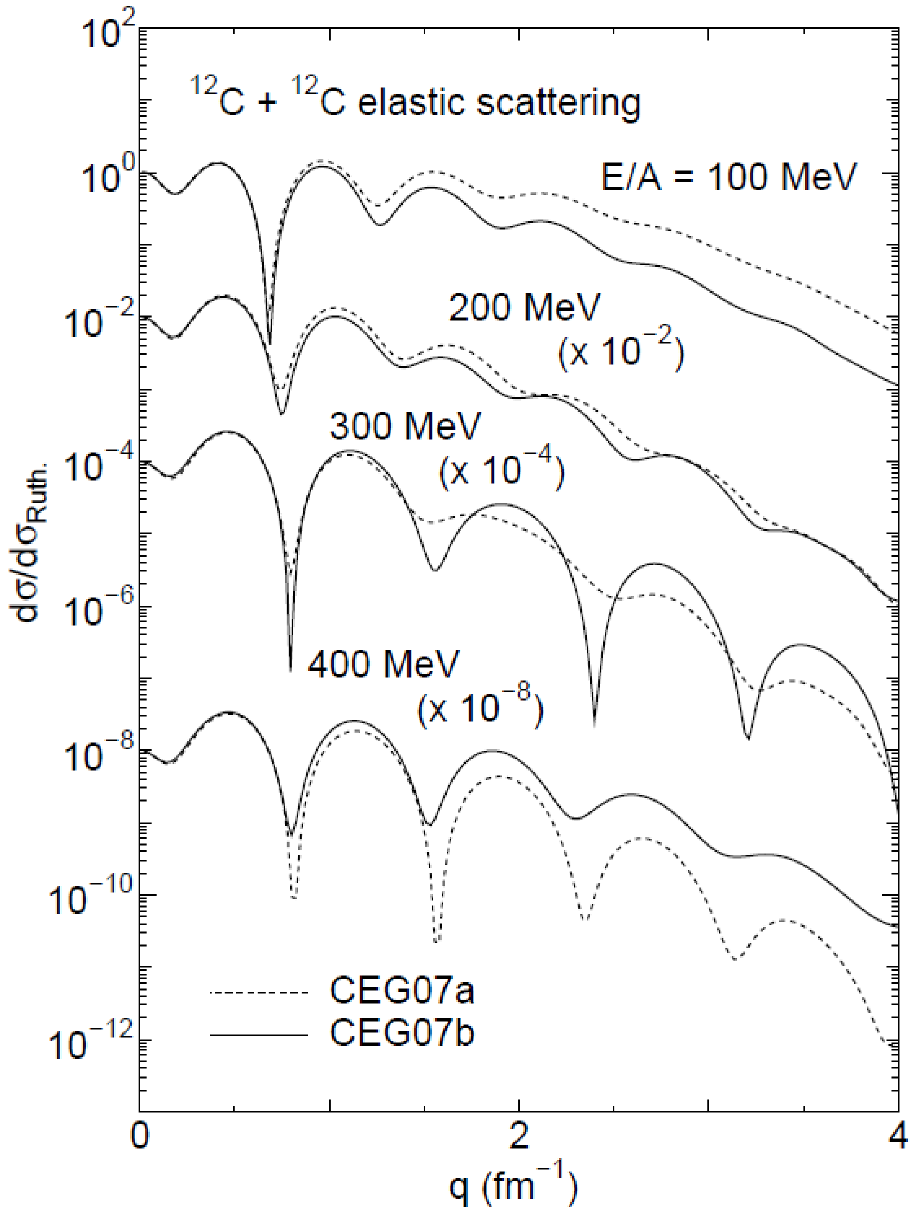
spin(S) and isospin(T) components V^{ST} of folding potential

★ **(S,T) = (0,0) and (0,1) do not include the tensor force.**

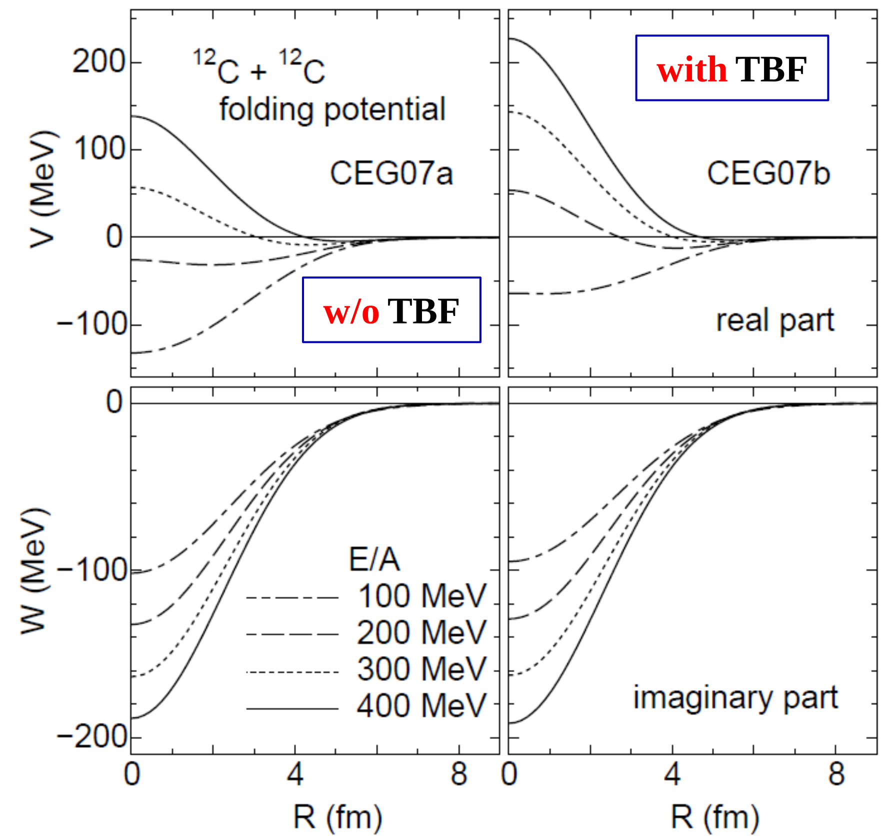
★ **(S,T) = (1,0) and (1,1)** components **include the tensor force**,

T.Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) (in press)

$^{12}C + ^{12}C$ elastic scattering at *E/A* = 100～400 MeV

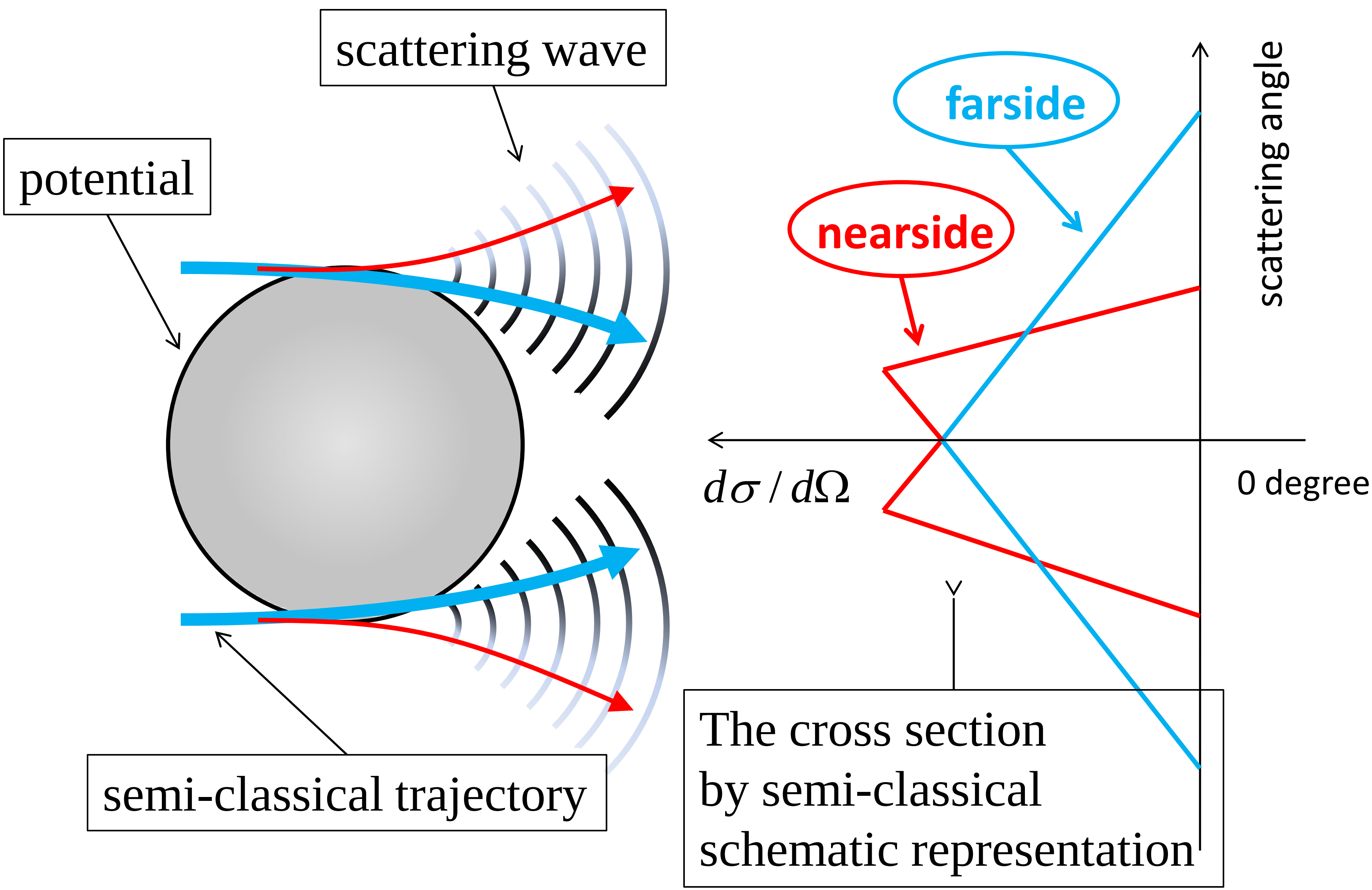


- **real potential : repulsive around *E/A* = 300～400 MeV**

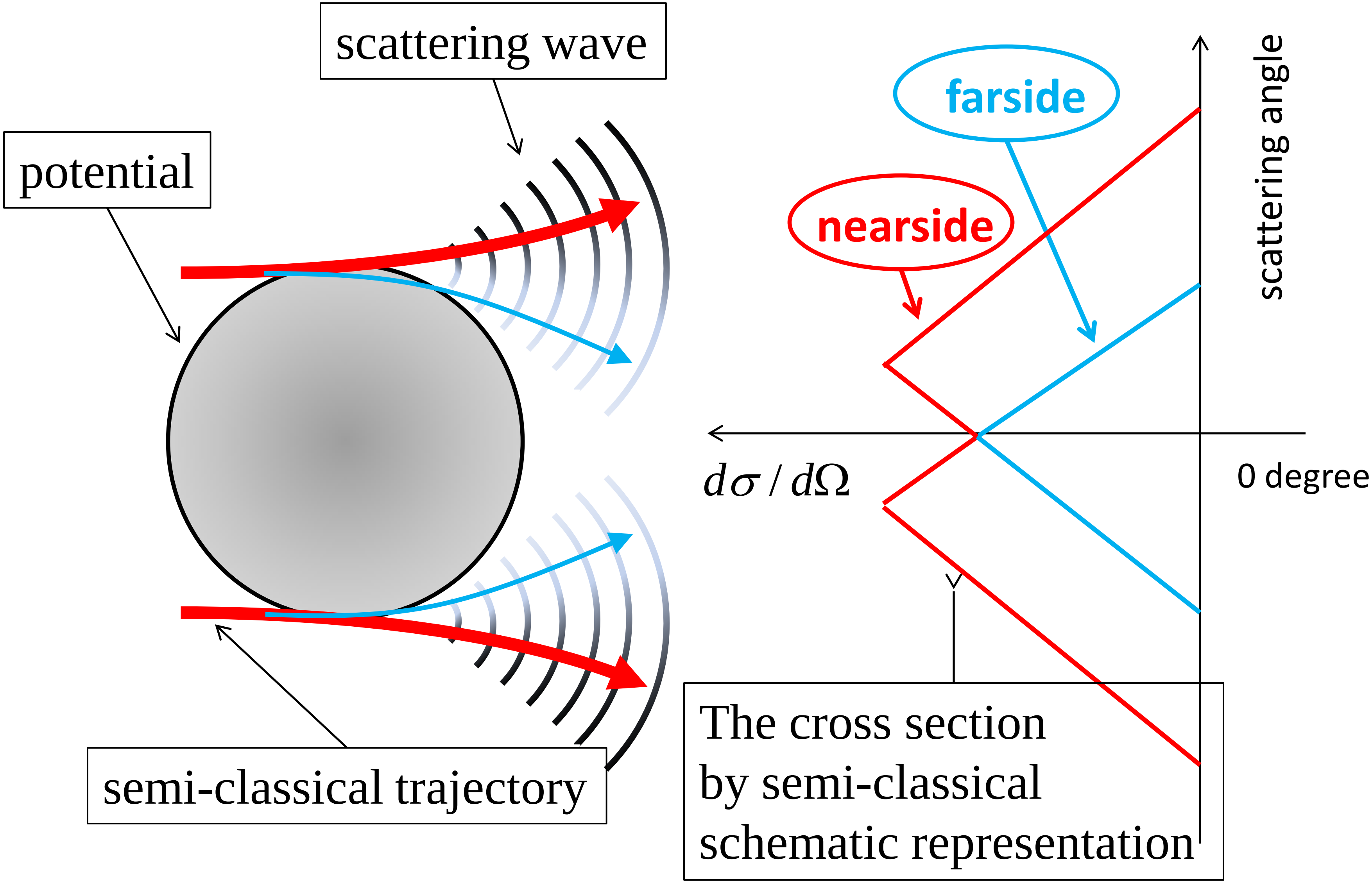


T.Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) (in press)

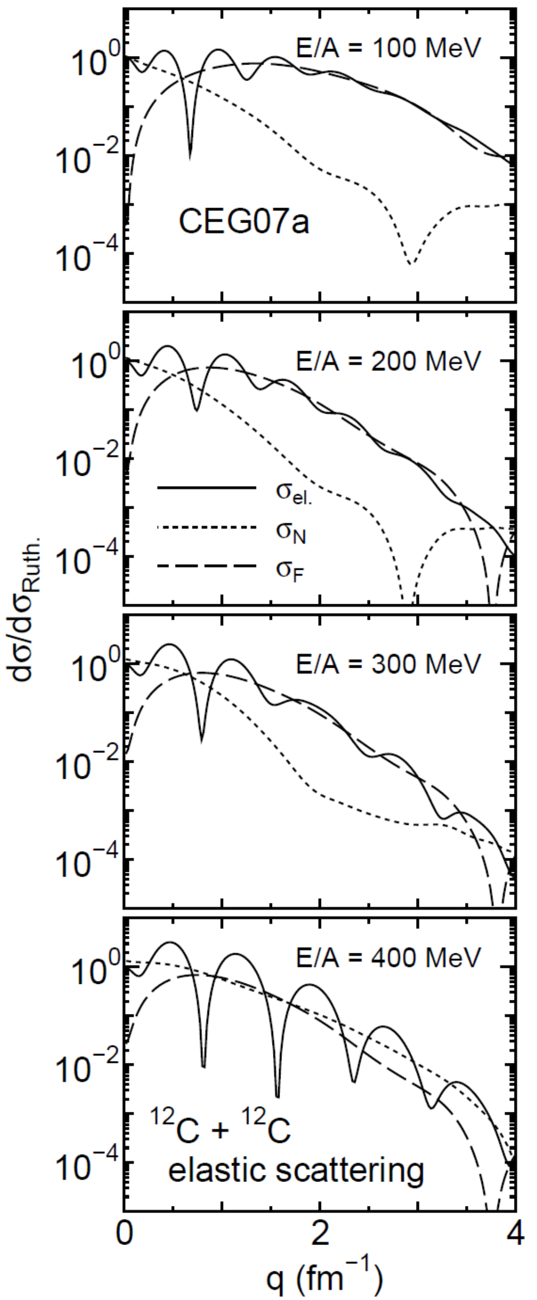
(a) Attractive potential (V < 0)



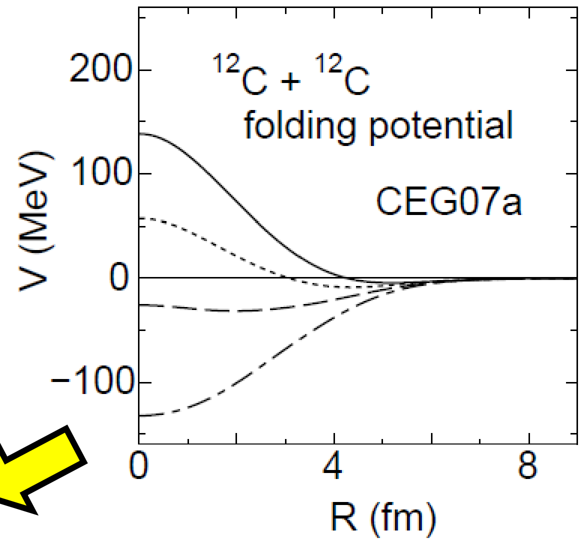
(b) Repulsive potential (V > 0)



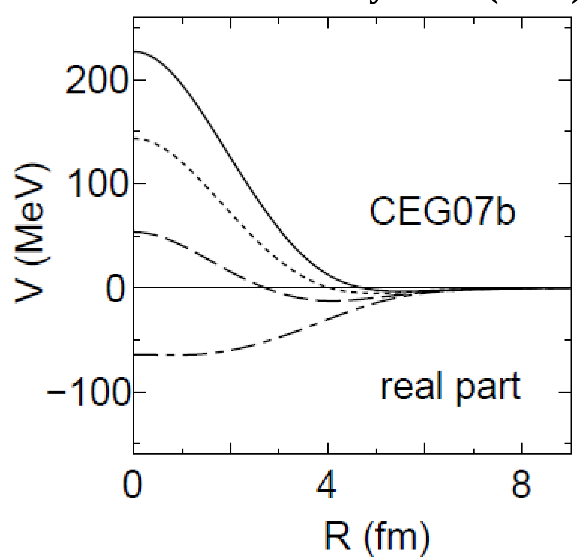
w/o Three-Body force (TBF)



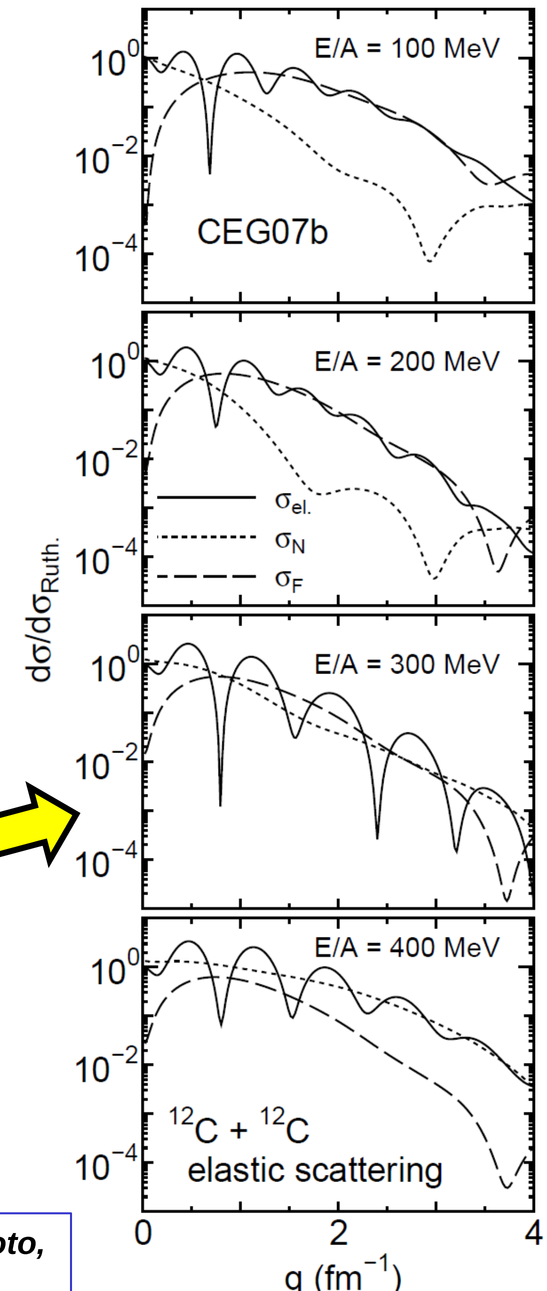
w/o Three-Body force (TBF)



with Three-Body force (TBF)



with Three-Body force (TBF)



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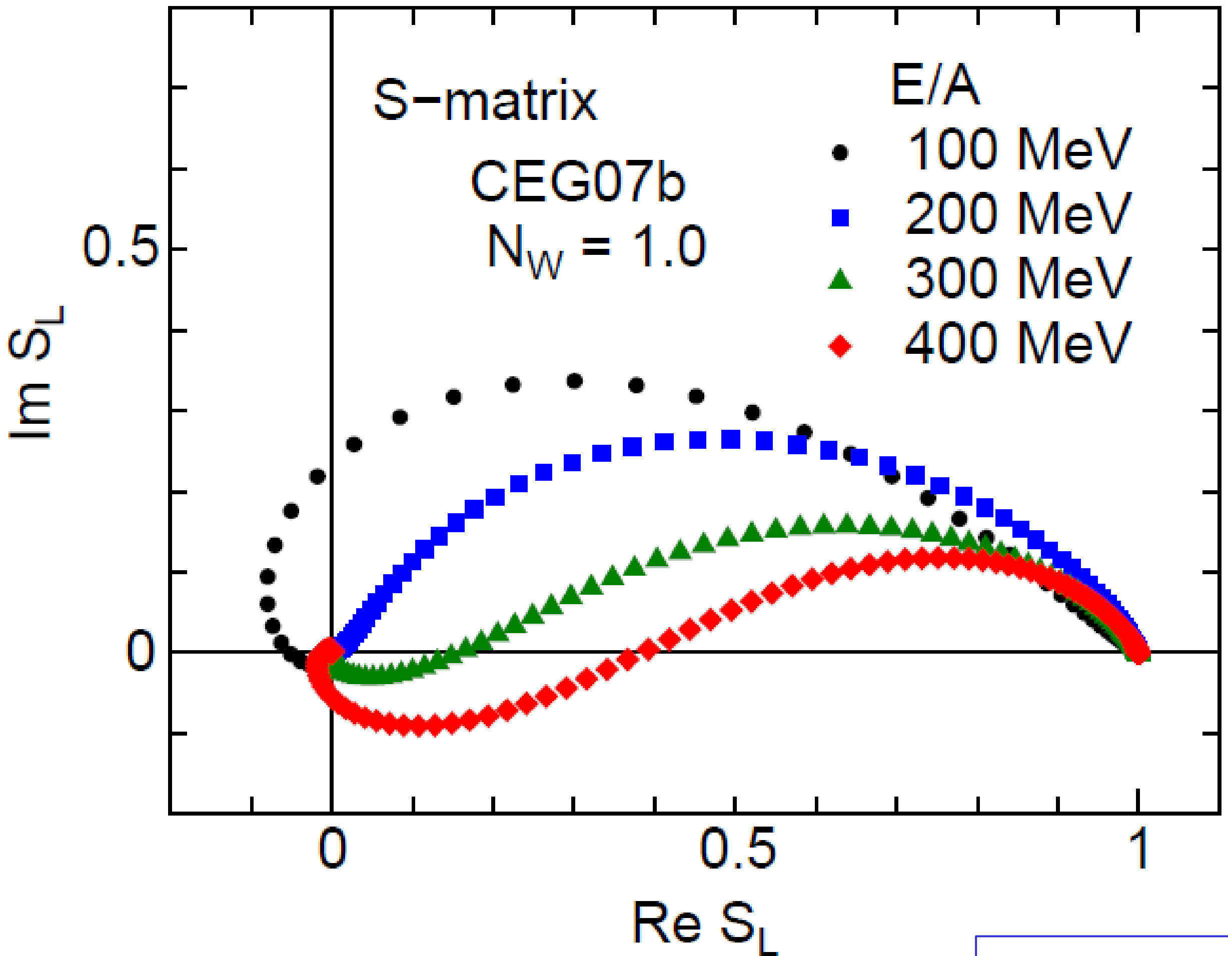
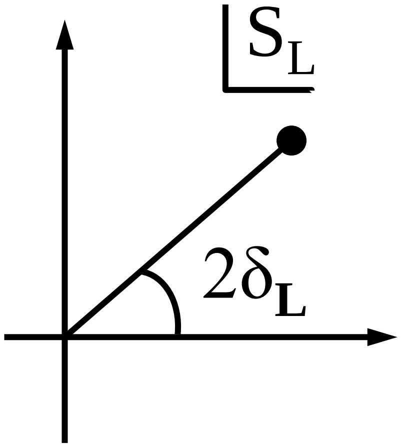
S-matirx elements of the ^{12}C + ^{12}C elastic scattering
at *E/A* = 100～400 MeV with CEG07b (with TBF effects)





$S_L = \exp(2i\delta_L)$

$\delta_L < 0$: repulsive
$\delta_L > 0$: attractive

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Summary & Conclusion

complex G-matrix folding model with a new G-matrix CEG07 predicts that

✓ **attractive-to-repulsive transition occurs also in heavy-ion optical potentials** *around* ***E/A = 300～400 MeV***

→ *but, no experimental evidence* → ***BIG CHALLENGE !***

✓ can be observed by *measuring the energy-evolution of elastic scattering angular distribution in the energy range of E/A = 200～400 MeV.*

✓ **new ingredients** we have learnt are the important roles of

① *repulsive* ***three-body force*** *(TBF) in nuclear medium*

② ***tensor force*** *effects*