Dynamics and Correlations in Exotic Nuclei (DCEN2011)
(Sept.20—Oct.28, 2011, @ Yukawa Institute for Theoretical Physics, Kyoto,)
(seminar talk on 19th October)

Microscopic interaction models for nuclear reactions with exotic beams:

- present status and future perspective -

Y. Sakuragi **(Osaka City Univ.)**

collaborators:

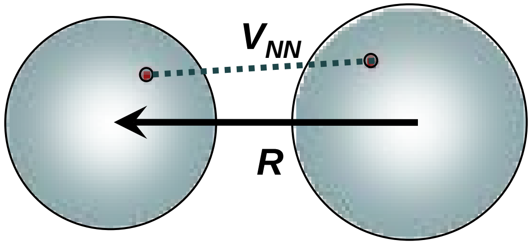
T. Furumoto (YITP, Kyoto Univ.)

Y. Yamamoto (Tsuru Univ.)

M. Takashina (Osaka Univ.)

W. Horiuchi (RIKEN)

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

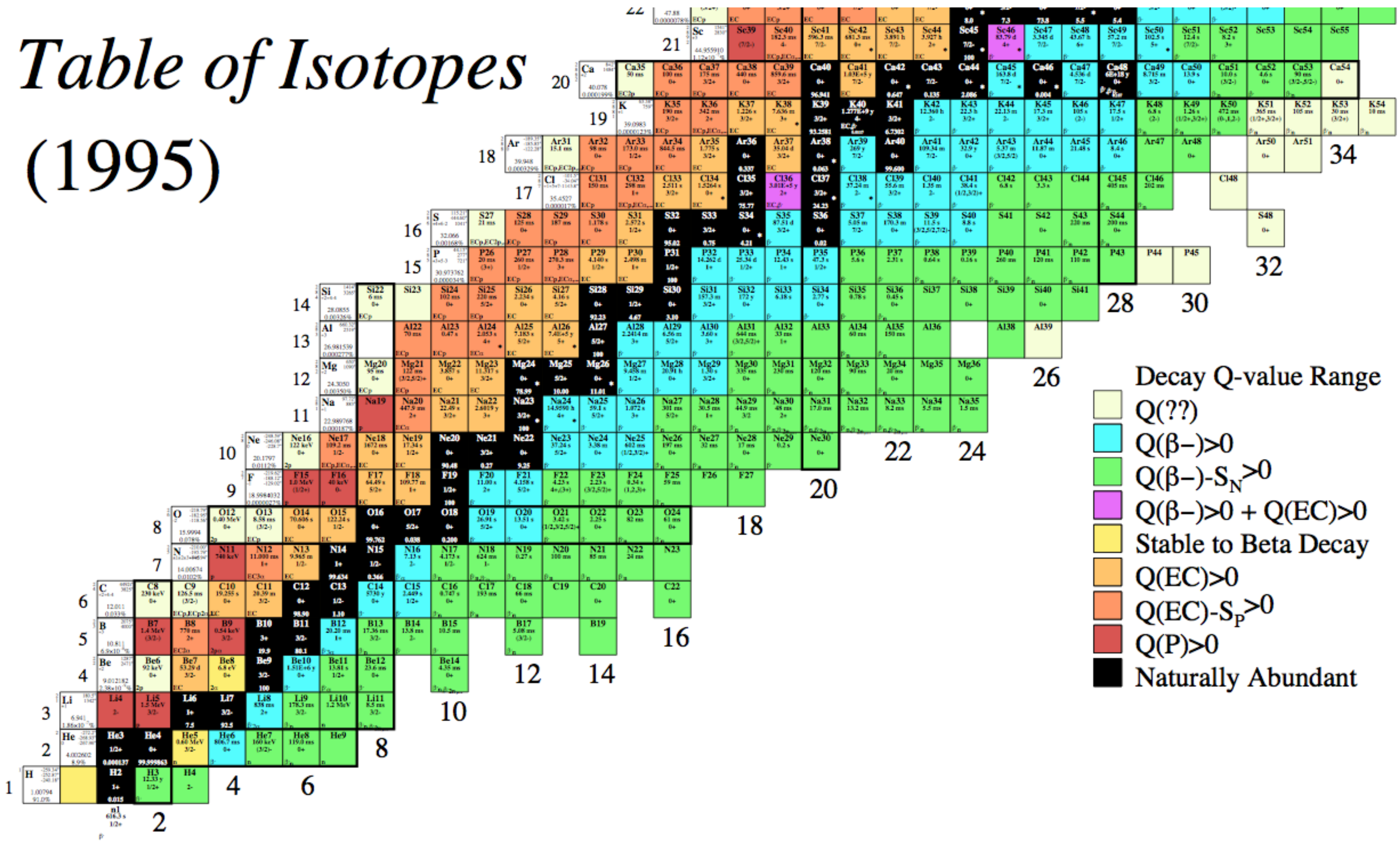


- ✓ ***one of the fundamental subject** in nuclear physics*

- ✓ ***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 information is available.*

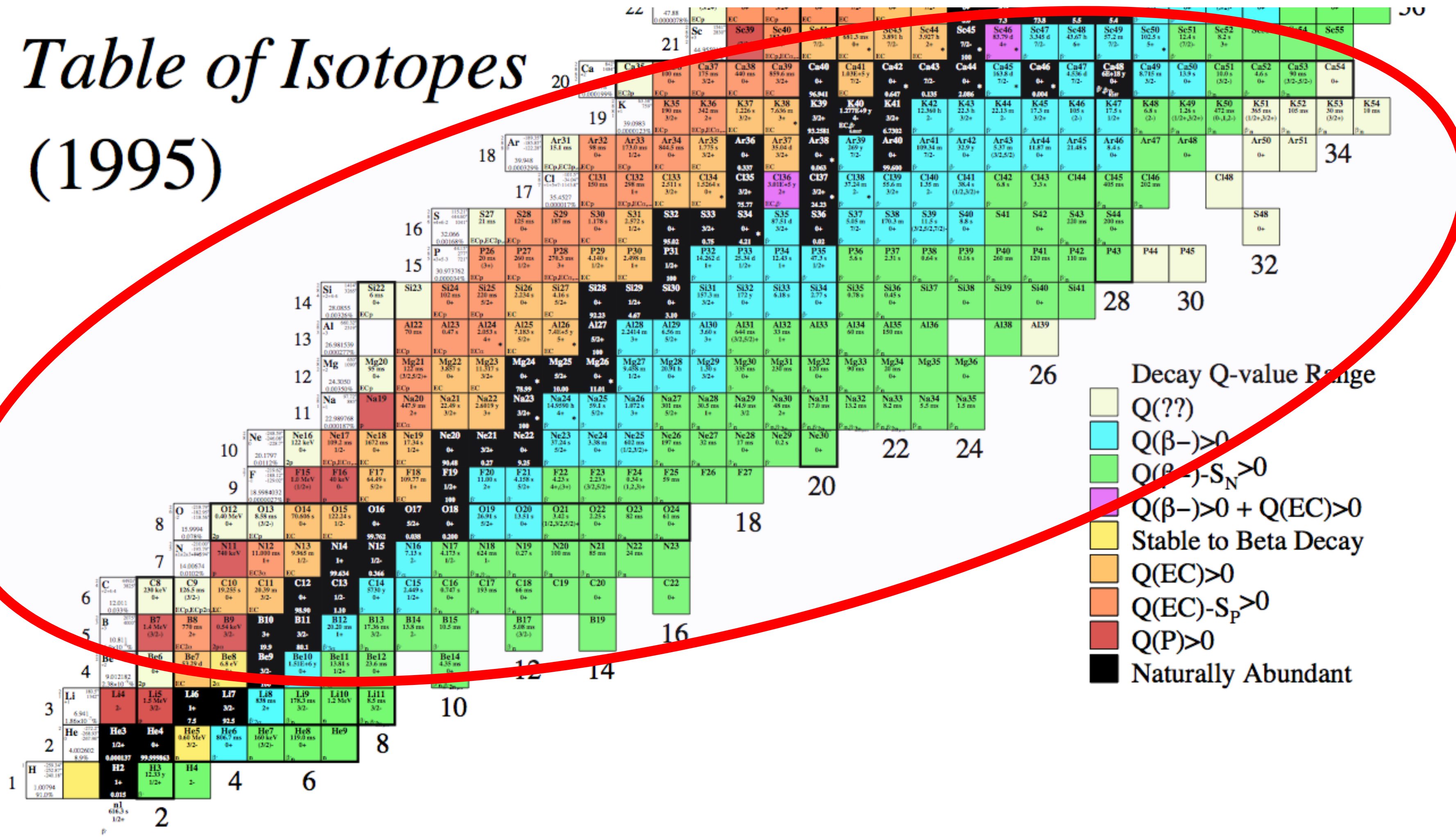
Table of Isotopes (1995)



for which

- *few/no elastic-scattering data & phenom. potential information is available.*

Table of Isotopes (1995)



Global potential for projectiles of unstable nuclei up to driplines

T. Furumoto, W. Horiuchi, M. Takashina, Y. Yamamoto, Y. Sakuragi (in preparation)

Global potential for projectiles of unstable nuclei up to driplines

T. Furumoto, W. Horiuchi, M. Takashina, Y. Yamamoto, Y. Sakuragi (in preparation)

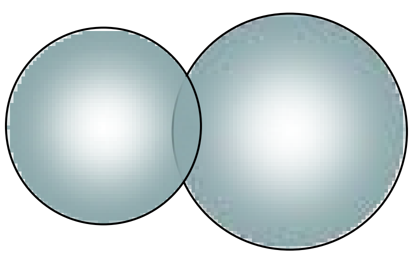
With CEG07b						^{34}Ca	^{36}Ca	^{38}Ca	^{40}Ca	^{42}Ca	^{44}Ca	^{46}Ca	^{48}Ca	^{50}Ca	^{52}Ca	^{54}Ca	^{56}Ca	^{58}Ca	^{60}Ca	^{62}Ca	^{64}Ca	^{66}Ca	^{68}Ca	^{70}Ca
					^{30}Ar	^{32}Ar	^{34}Ar	^{36}Ar	^{38}Ar	^{40}Ar	^{42}Ar	^{44}Ar	^{46}Ar	^{48}Ar	^{50}Ar	^{52}Ar	^{54}Ar	^{56}Ar	^{58}Ar	^{60}Ar	^{62}Ar			
				^{26}S	^{28}S	^{30}S	^{32}S	^{34}S	^{36}S	^{38}S	^{40}S	^{42}S	^{44}S	^{46}S	^{48}S	^{50}S	^{52}S							
			^{22}Si	^{24}Si	^{26}Si	^{28}Si	^{30}Si	^{32}Si	^{34}Si	^{36}Si	^{38}Si	^{40}Si	^{42}Si	^{44}Si	^{46}Si	^{48}Si								
			^{20}Mg	^{22}Mg	^{24}Mg	^{26}Mg	^{28}Mg	^{30}Mg	^{32}Mg	^{34}Mg	^{36}Mg	^{38}Mg	^{40}Mg											
		^{16}Ne	^{18}Ne	^{20}Ne	^{22}Ne	^{24}Ne	^{26}Ne	^{28}Ne	^{30}Ne	^{32}Ne	^{34}Ne	^{36}Ne	^{38}Ne											
	^{12}O	^{14}O	^{16}O	^{18}O	^{20}O	^{22}O	^{24}O																	
^{8}C	^{10}C	^{12}C	^{14}C	^{16}C	^{18}C	^{20}C	^{22}C																	

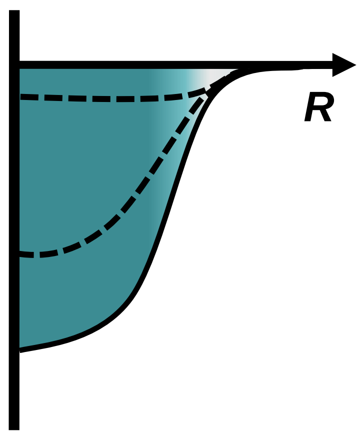
Global parameterization of the CEG07 folding-model potentials

- ✓ **projectiles : Z = 6 (C isotope) ~ 20 (Ca isotope) (even-even)**
- ✓ **targets : ^{12}C ~ ^{208}Pb (closed or sub-closed shell nuclei)**
- ✓ **energy range : E/A = 30 ~ 400 MeV**

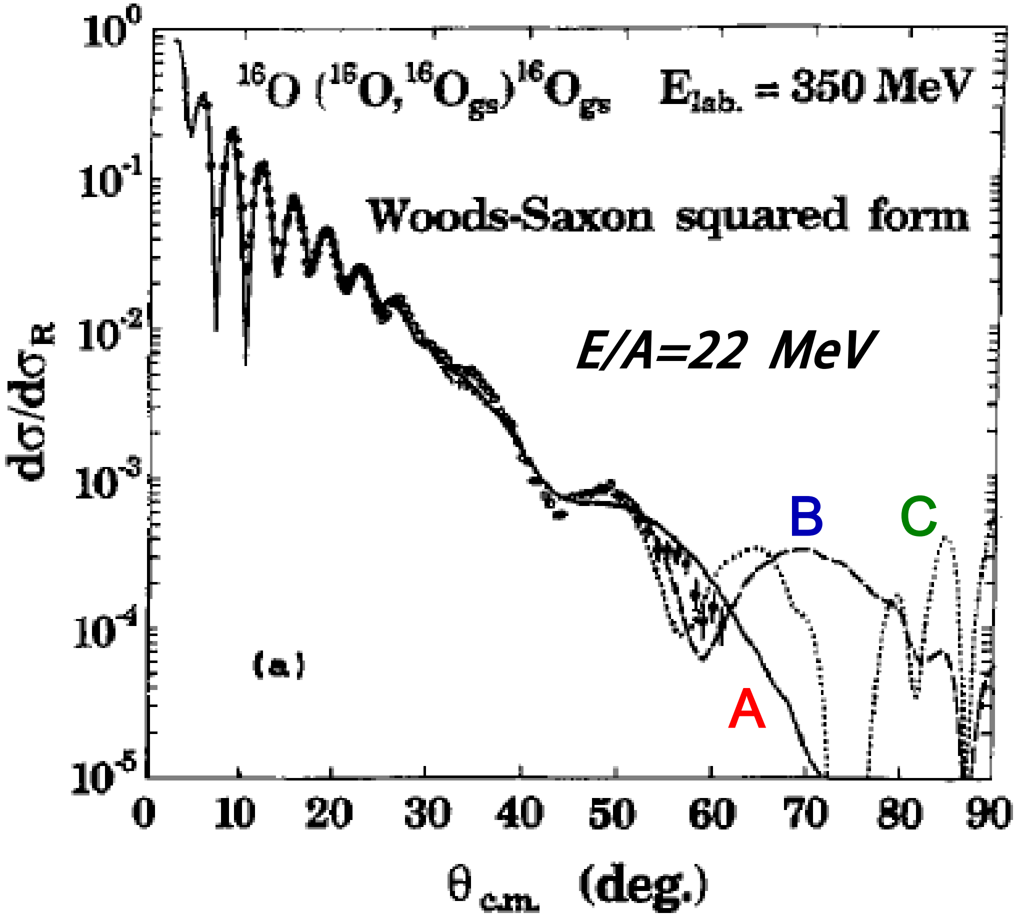
$U_{opt}(R) = V_{opt}(R) + i\, W_{opt}(R)$: complex potential

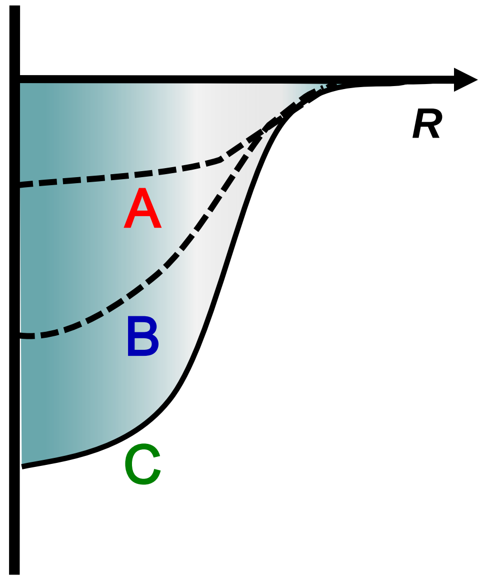
- Phenomenolocical optical potentials:
  - ✓ needs Exp. Data (elastic scattering) to determine potential parameters (e.g. Woods-Saxon form)
  - ✓ optical potential for heavy-ion systems (AA) has large ambiguity in depth & shape due to strong absorption (in most cases)
  - ✓ → only sensitive to potential 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!***

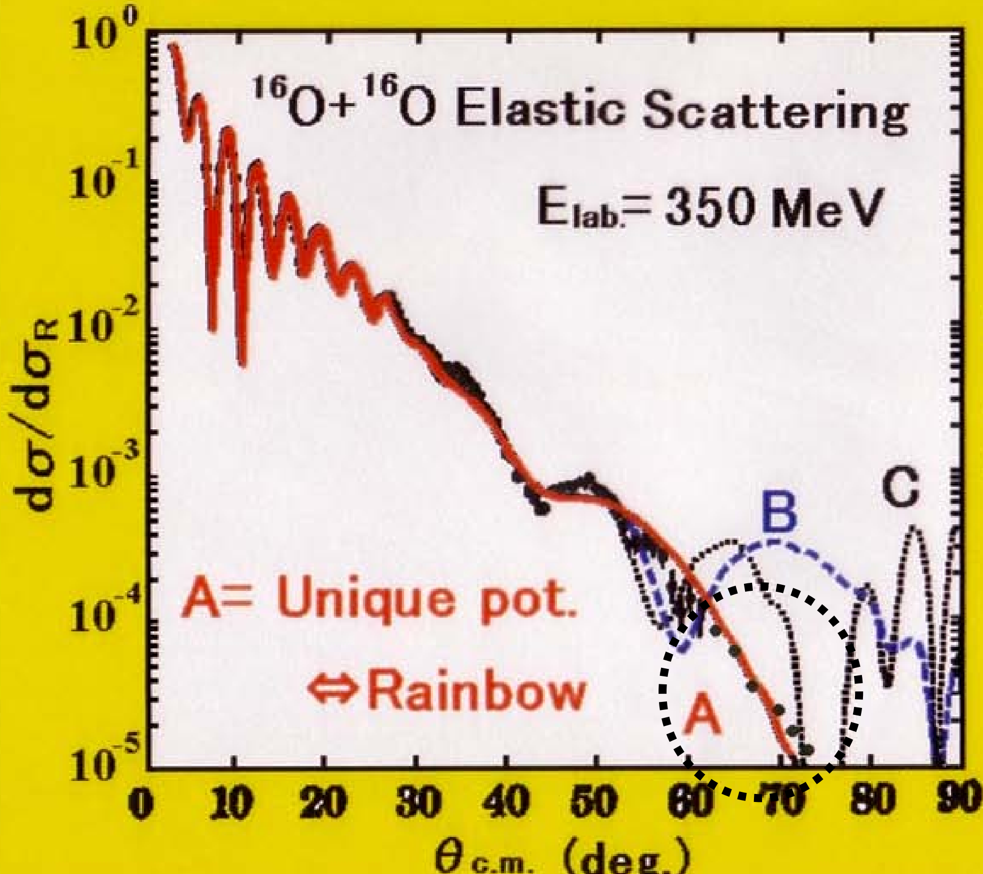
(at least for light heavy-ions)

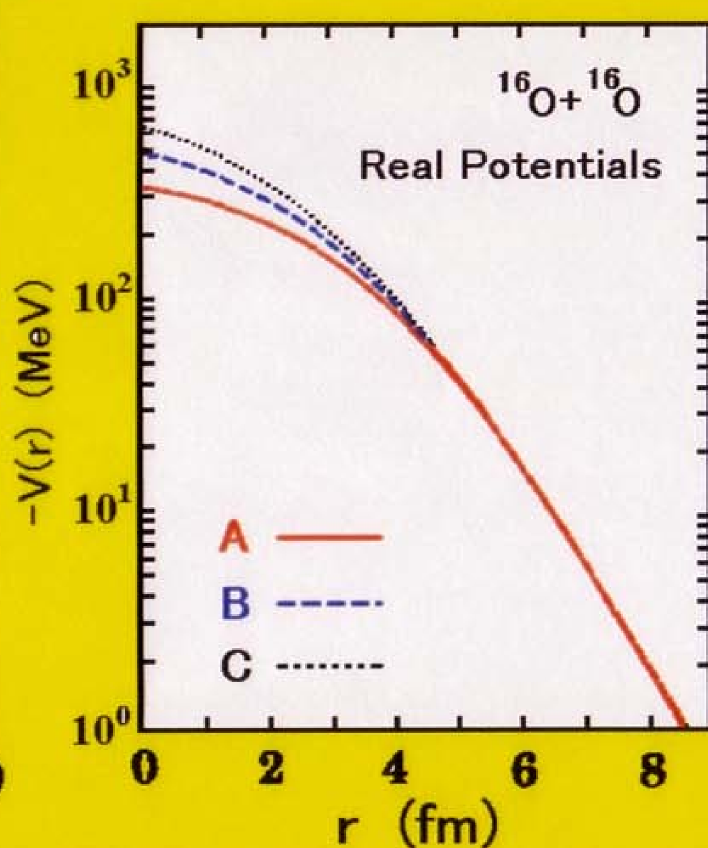
by the measurements of

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)*

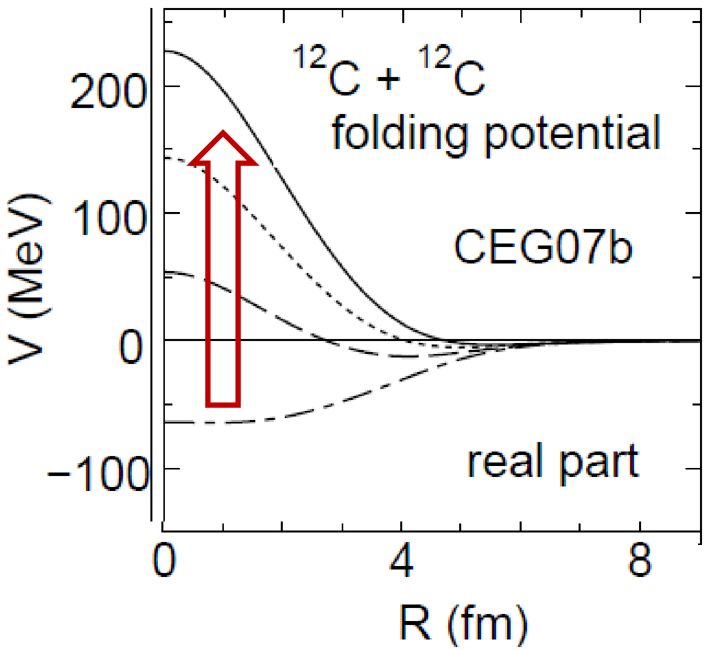
- ✓ *including **unstable nuclei** (n-rich & p-rich isotopes)*

- ✓ *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* *one of the*

key word of the present talk

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

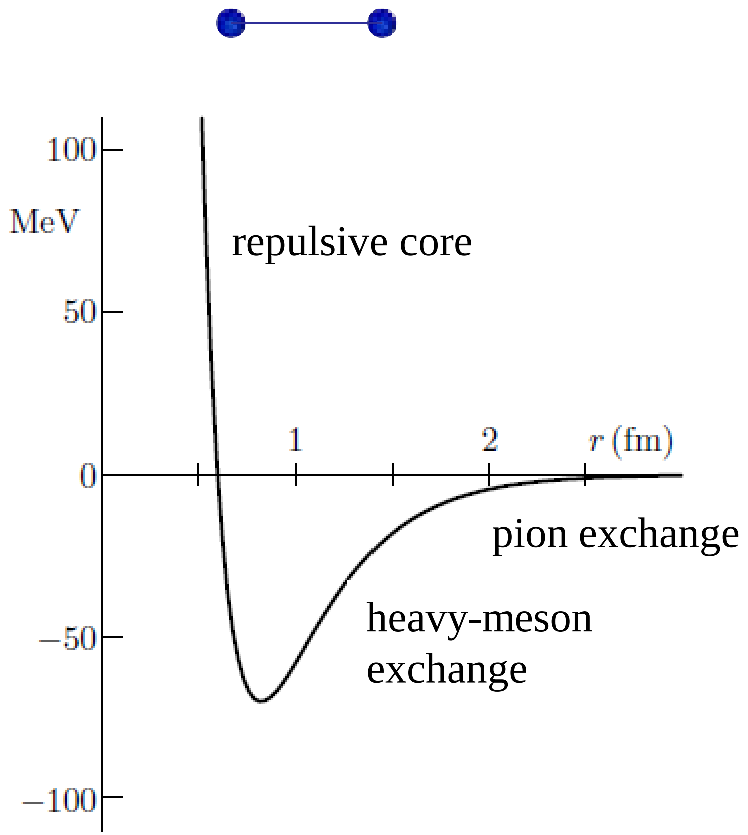


E/A=100～400 MeV

T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 044612

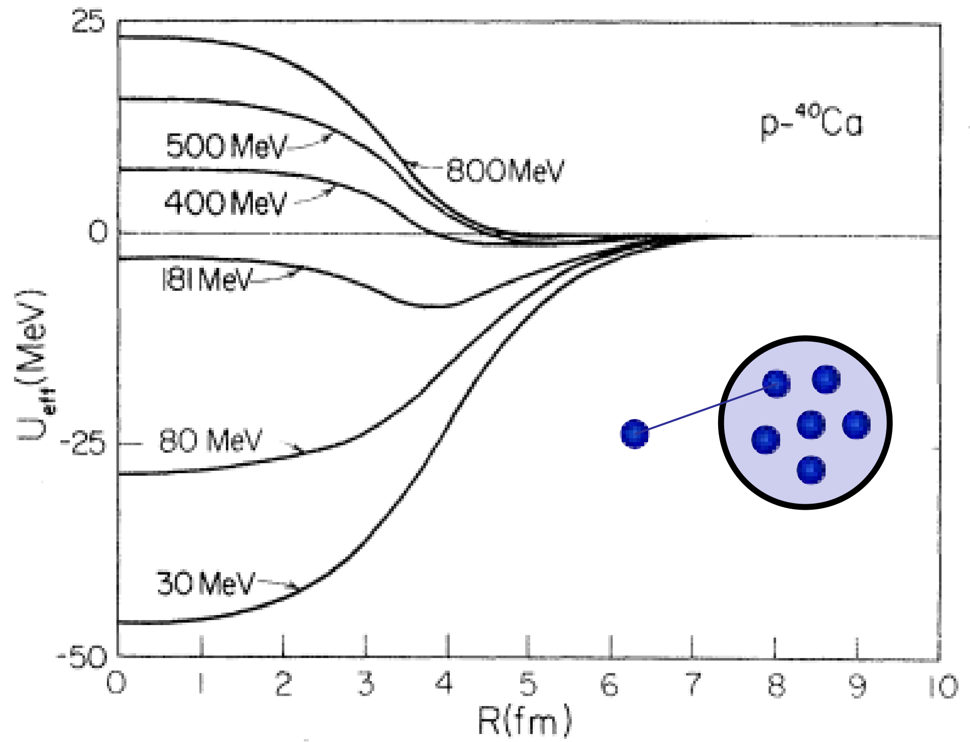
◆ NN interaction :

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



◆ nucleon-nucleus (NA) interaction :

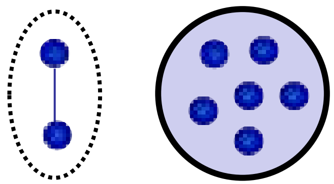
- *attractive at low energies (E<200* MeV)
- *wine-bottle-bottom (WBB)*
  around transitional energies
- *repulsive at high energies (E>500* MeV *)*



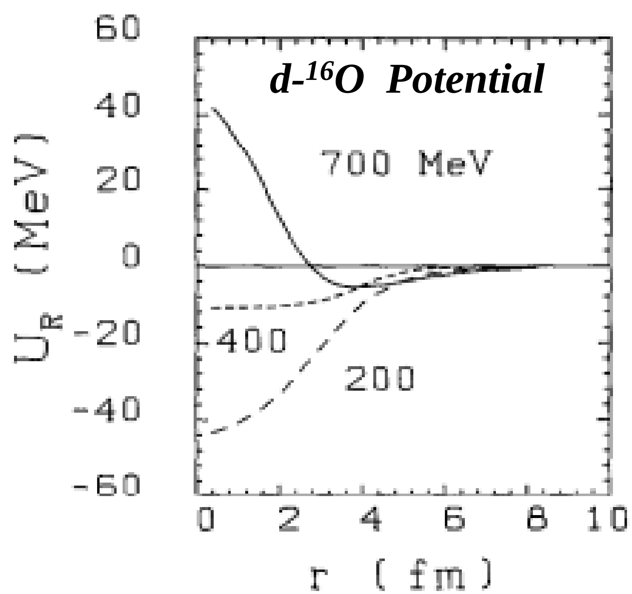
L.G.Arnold, (Phys.Rev.C25(1982)936

◆ d-A interaction :

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



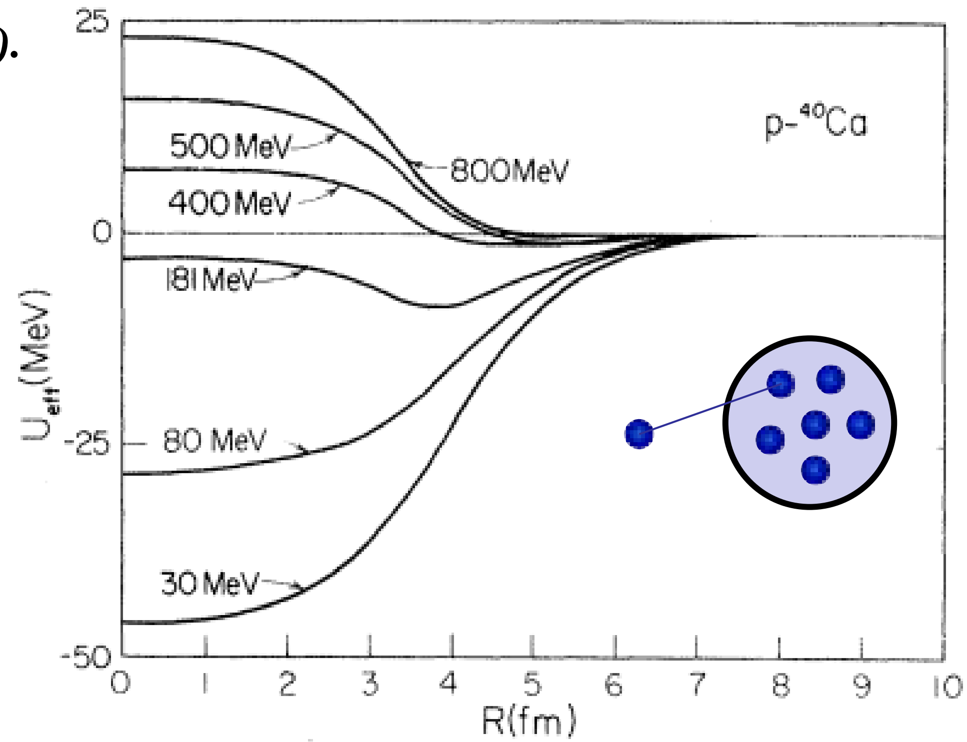
Y. Sakuragi, M. Tanifuji, NPA560, 945(1993).



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?

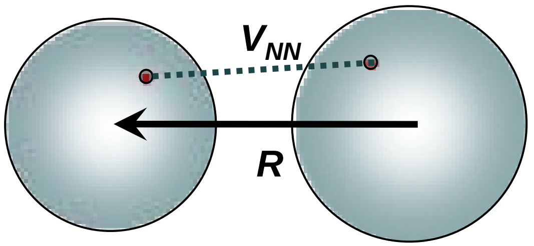
→ *measure the evolution of elastic scattering angular distribution with increasing energy in the energy range of E/A = 200～400 MeV.*

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

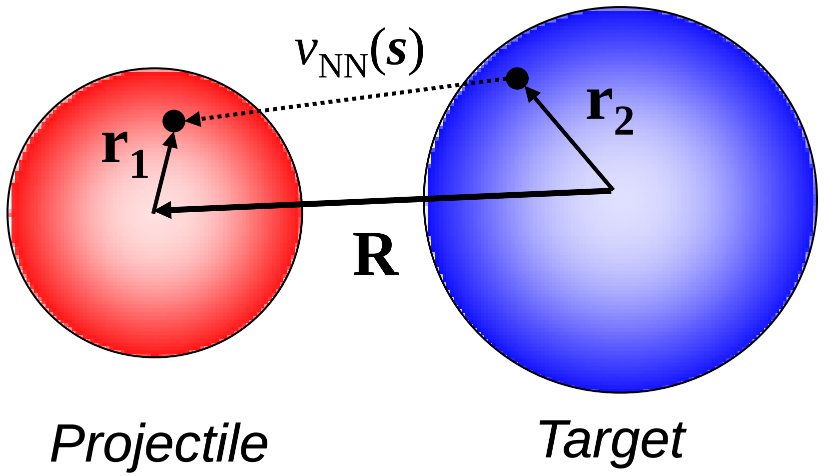
→ *① repulsive three-body force (TBF) in nuclear medium & ② tensor force effects besides the genuine repulsive core of NN int.*

Microscopic / semi-microscopic models :

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



Double-Folding Model (DFM)

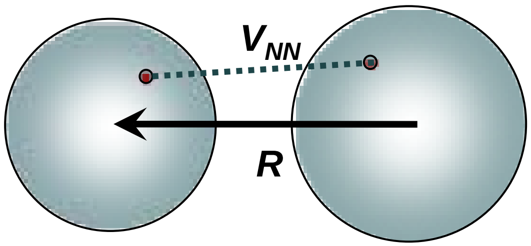


$$U_{DFM}(\mathbf{R}) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)\underline{v_{NN}(\mathbf{s};\rho,E)}d\mathbf{r}_1 d\mathbf{r}_2$$

effective *NN* interaction in nuclear medium

Microscopic / semi-microscopic models :

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

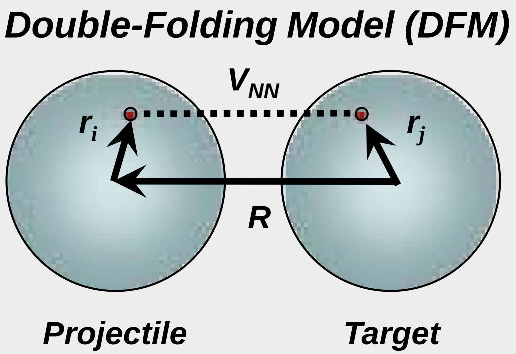


◆ ***G-matrix** with scattering b.c.*

- ✓ ***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)

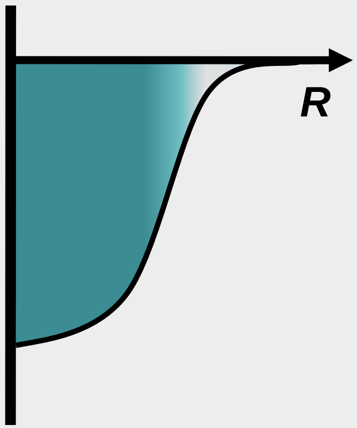


- ✓ *real part only (add a phenom. imag. pot)*
- ✓ *zero-range exchange term*

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

- ✓ *no density-dependence*

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



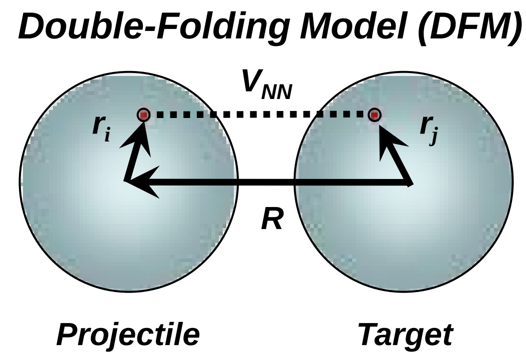
- ◆ *due to strong absorption for Heavy Ions (HI)*

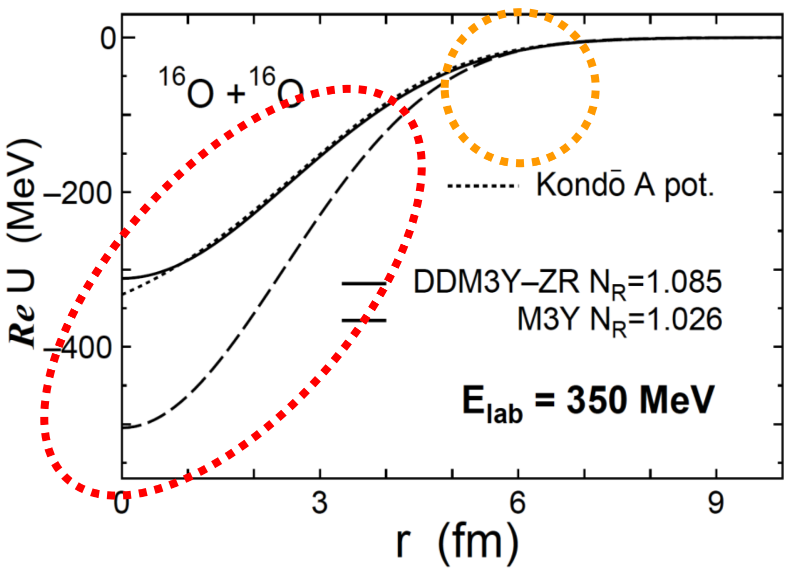
  ⇒ *sensitive only to nuclear surface*

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

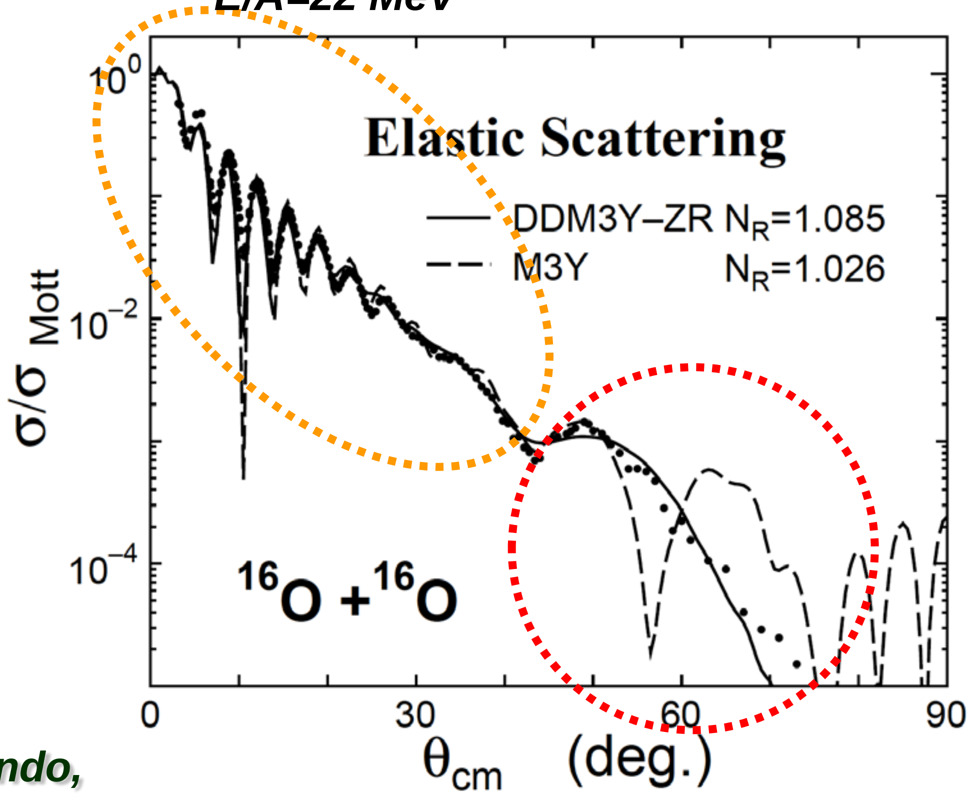
[*G.R.Satchler and W.G.Love,* **Phys.Rep.**55,183(1979)]

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





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)

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

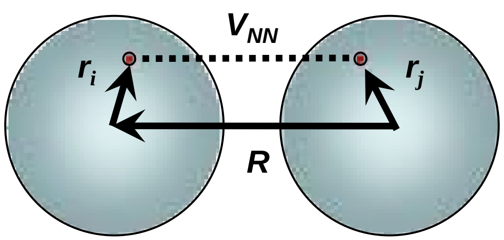
$$f(E,\rho) = C(E)[1+\alpha(E)e^{-\beta(E)\rho}]$$

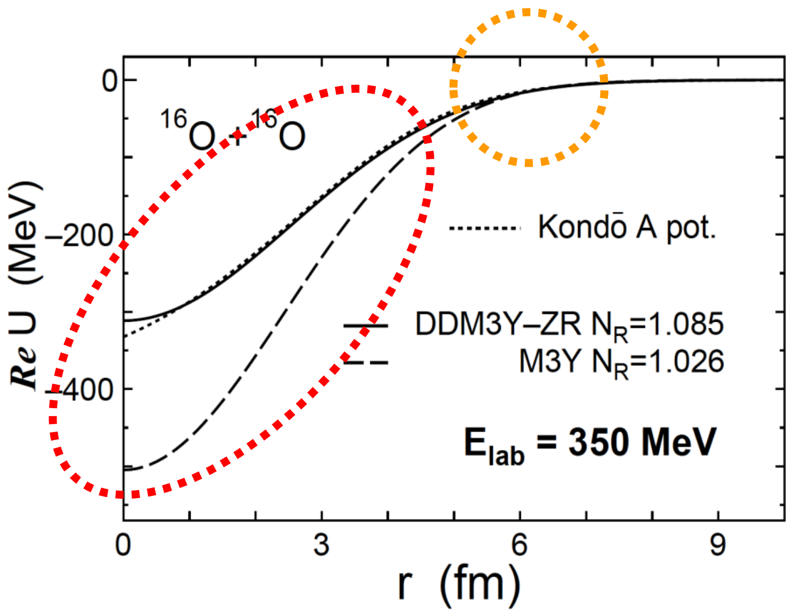
⇒ greatly reduce the potential strength at short distances

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

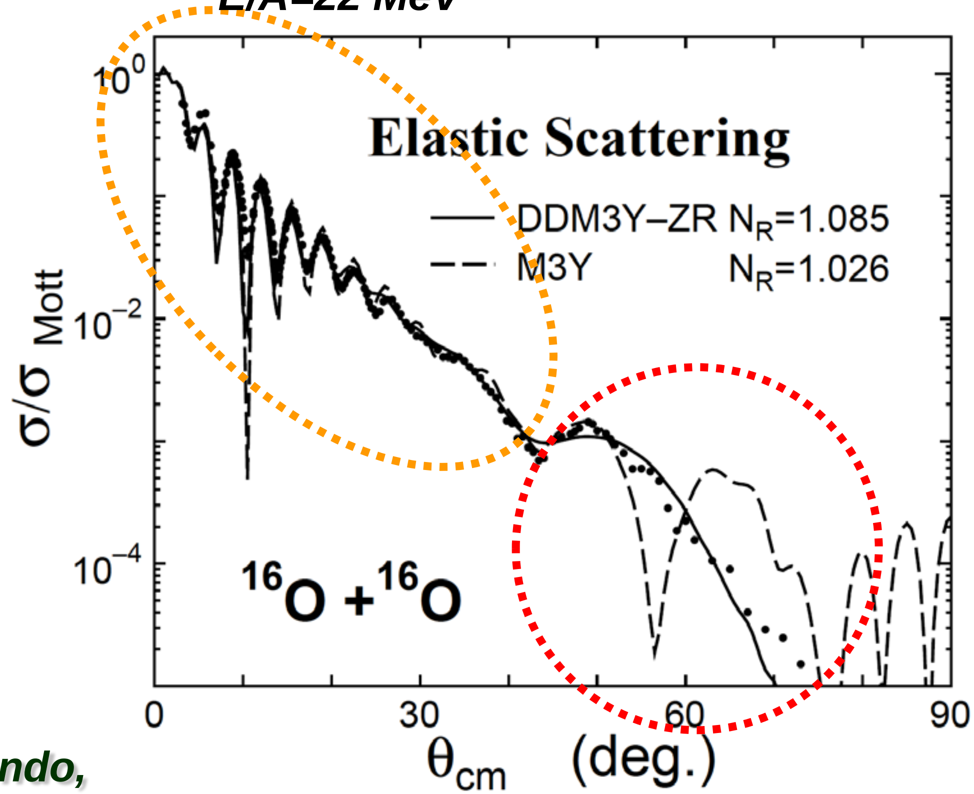
Double-Folding-model potentials
with *M3Y (density-independent)*
with *DDM3Y (density-dependent)*

Double-Folding Model (DFM)





E/A=22 MeV



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

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) 044612*

Complex G-matrix interaction（CEG07）

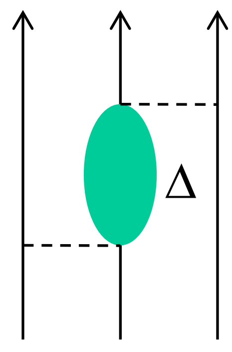
T.Furumoto, Y. Sakuragi and Y. Yamamoto, Phys. Rev. C 78 (2008) 044610

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

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

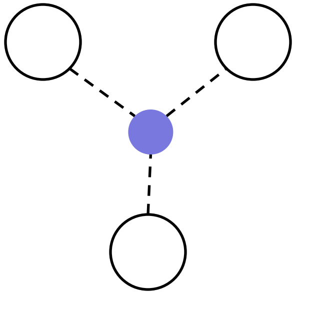
1. Three-body attractive (TBA)

- originated from **Fujita-Miyazawa** diagram
- important at <u>low density</u> region

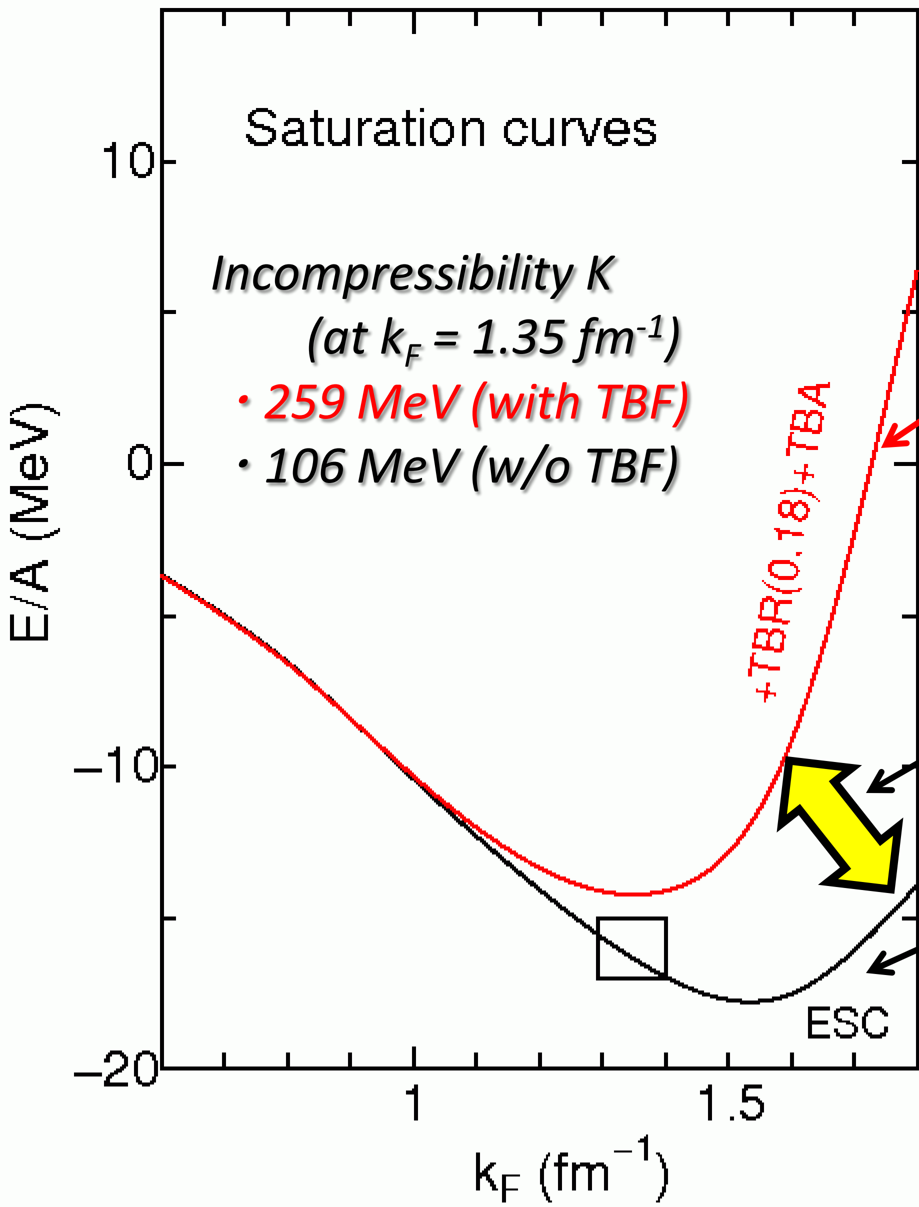


2. Three-body repulsive (TBR)

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

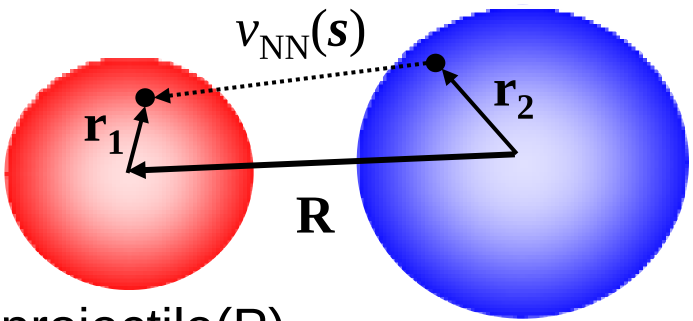
Decisive role to make the saturation curve realistic

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) 044612

Double folding Potential with complex-G (CEG07)



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

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

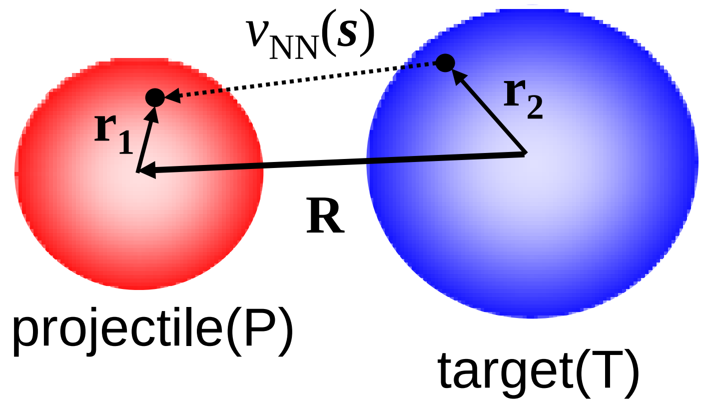
$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

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

Double folding Potential with complex-G (CEG07)



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

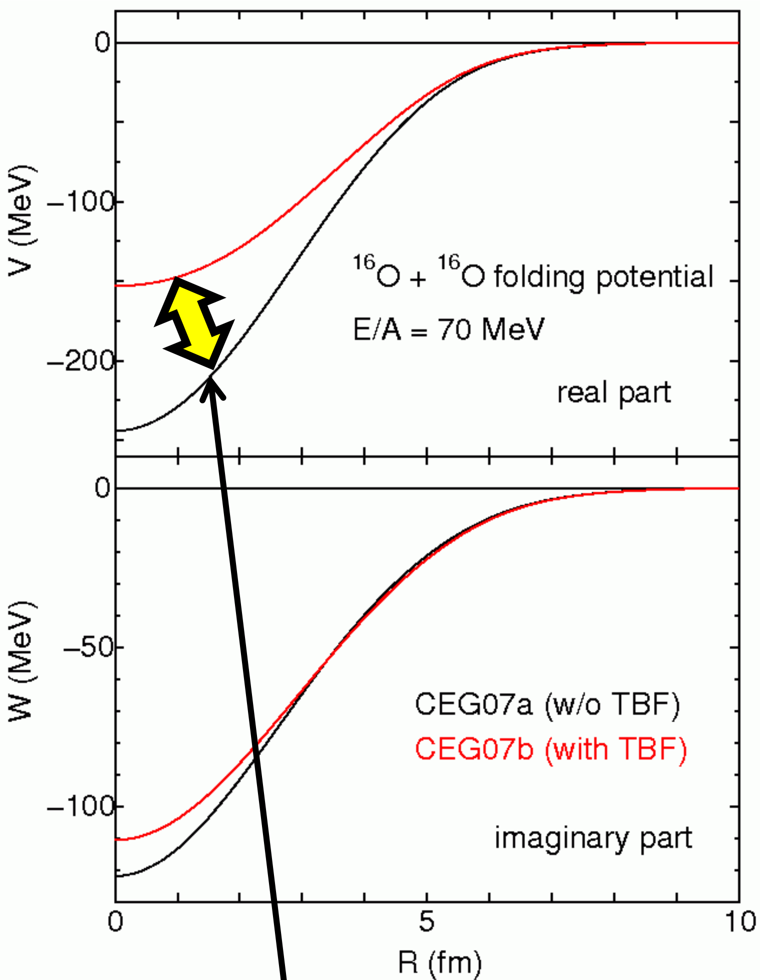
$$+ \int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s}) g_{EX}(\mathbf{s};\rho,E) \exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right] d\mathbf{r}_1 d\mathbf{r}_2$$

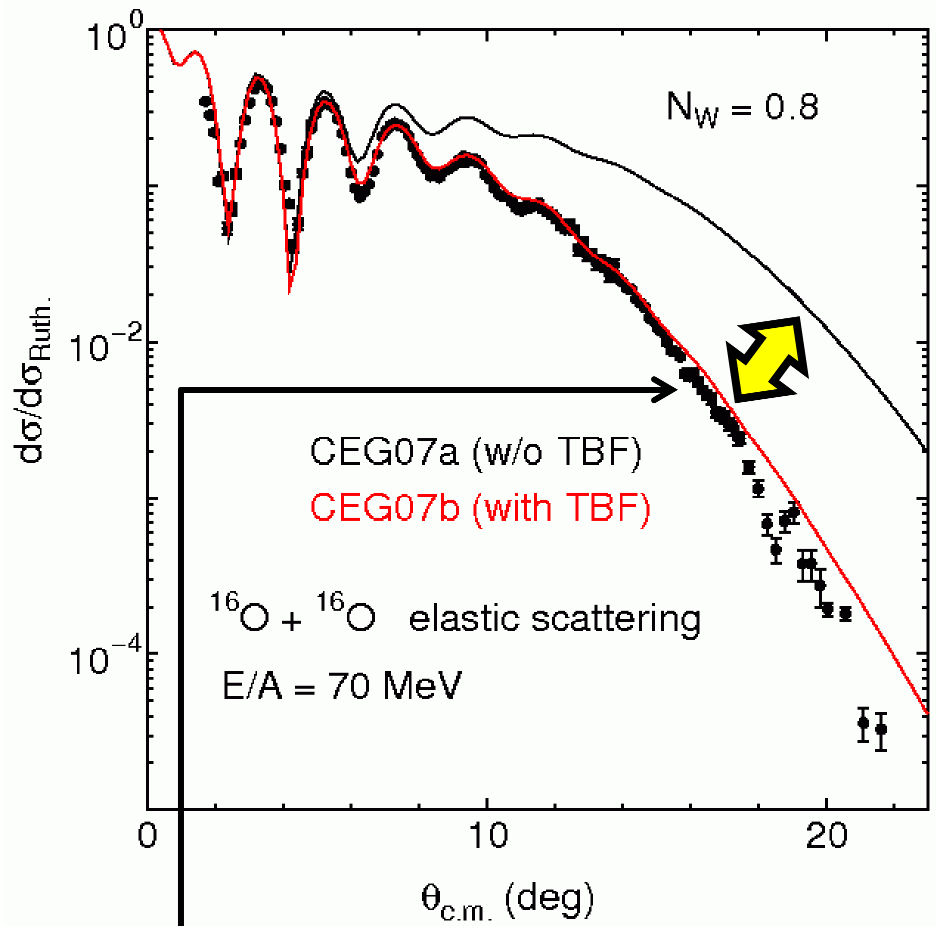
$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

✓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



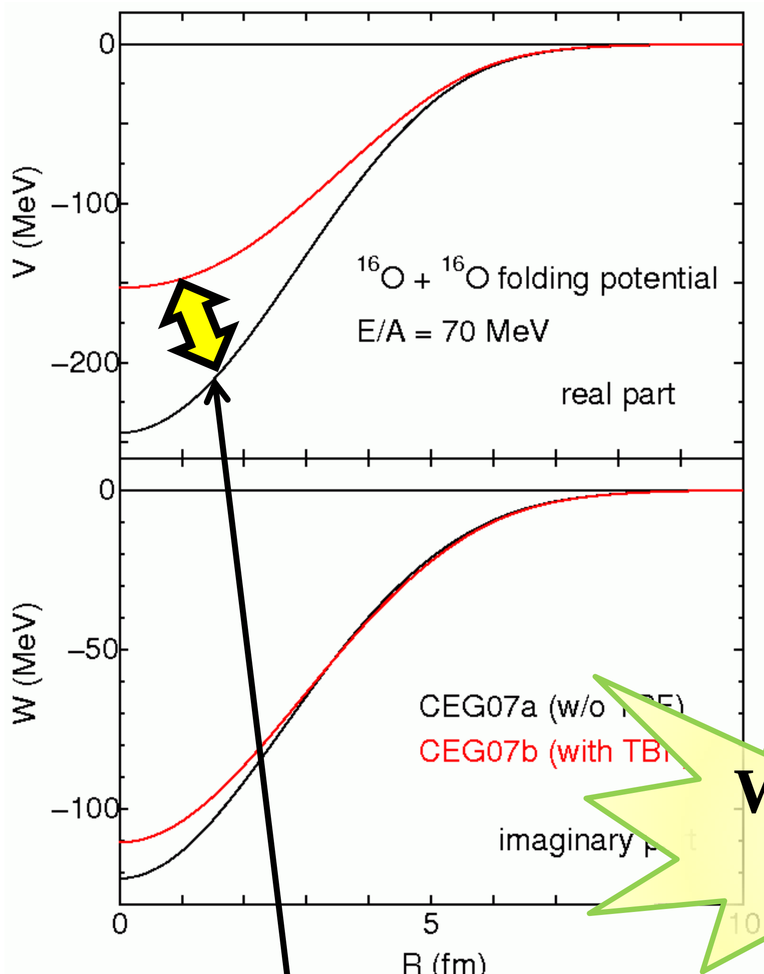


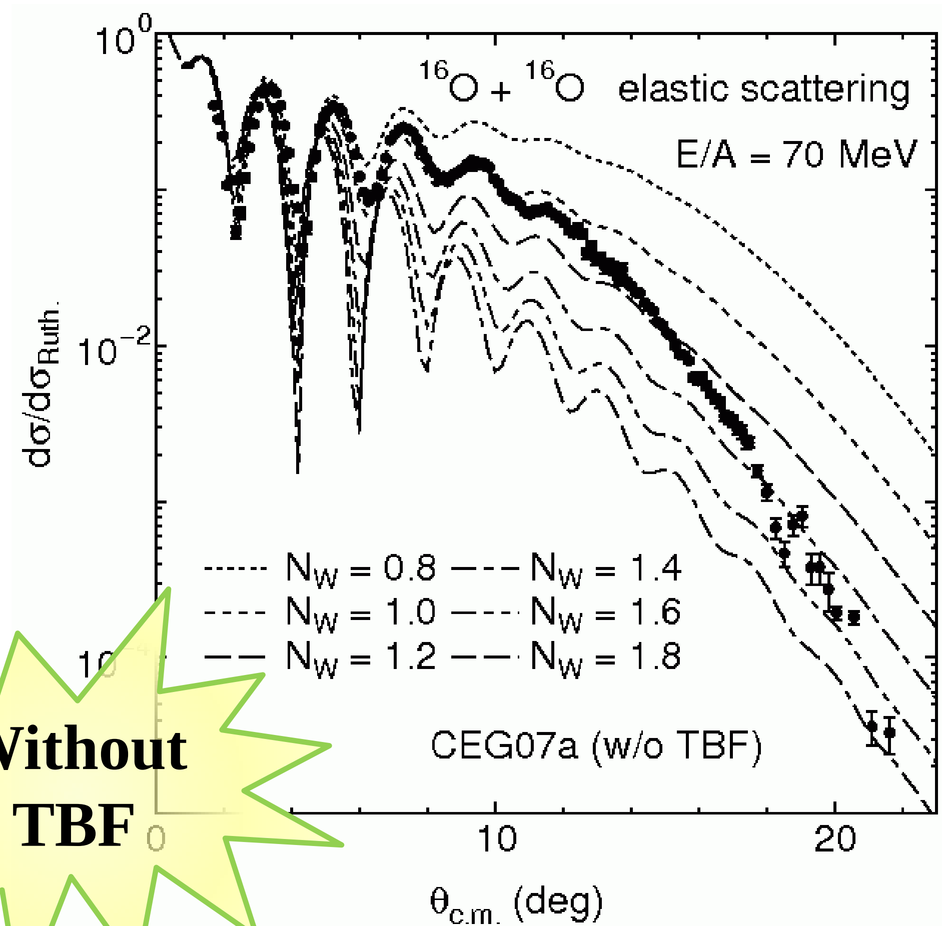
important effect of three-body force

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

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





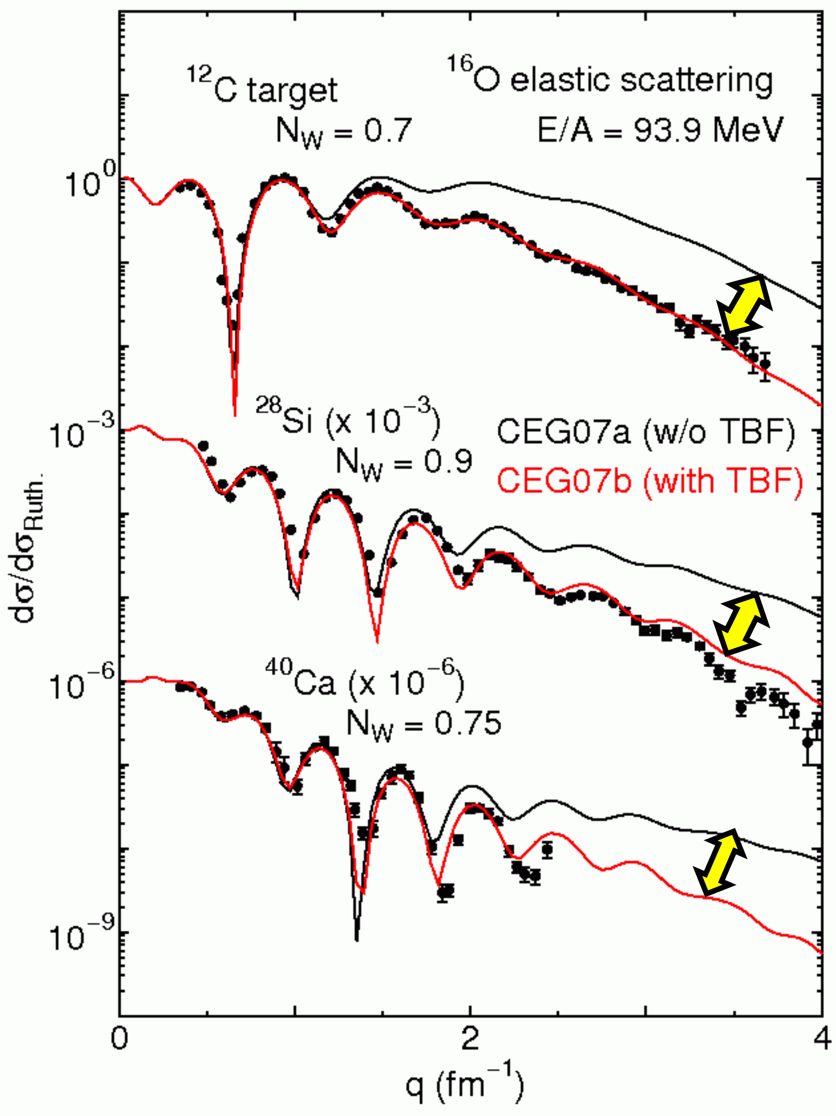
Without TBF

important effect of three-body force

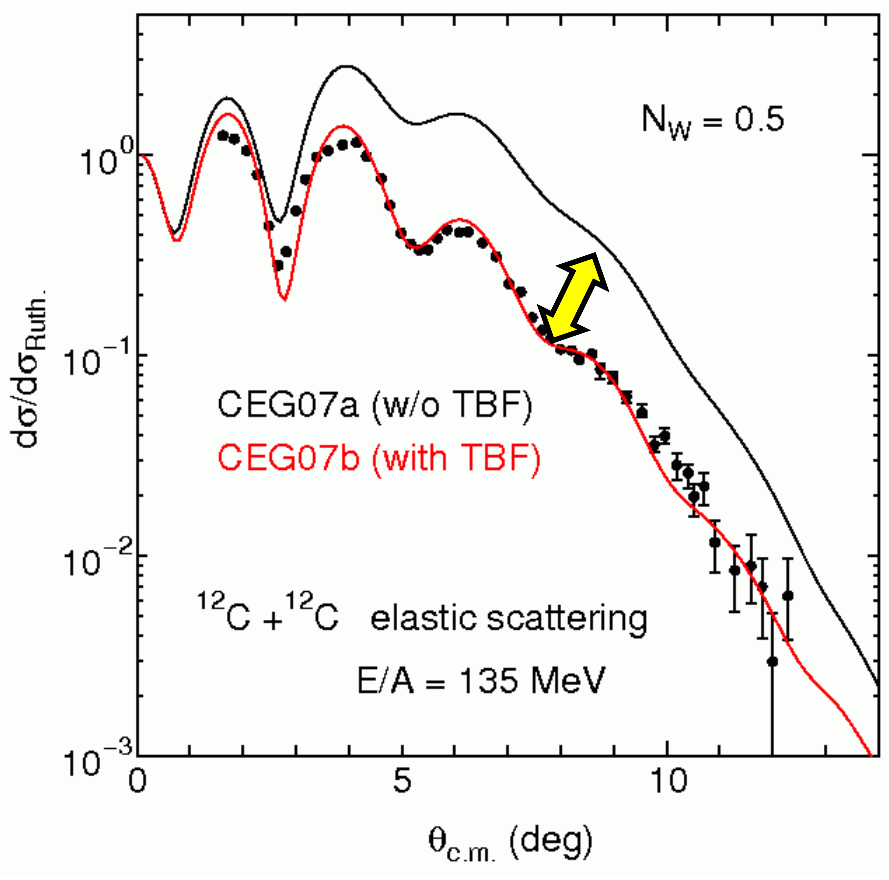
$$U_{DFM} = V_{DFM} + iN_W W_{DFM}$$

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

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



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



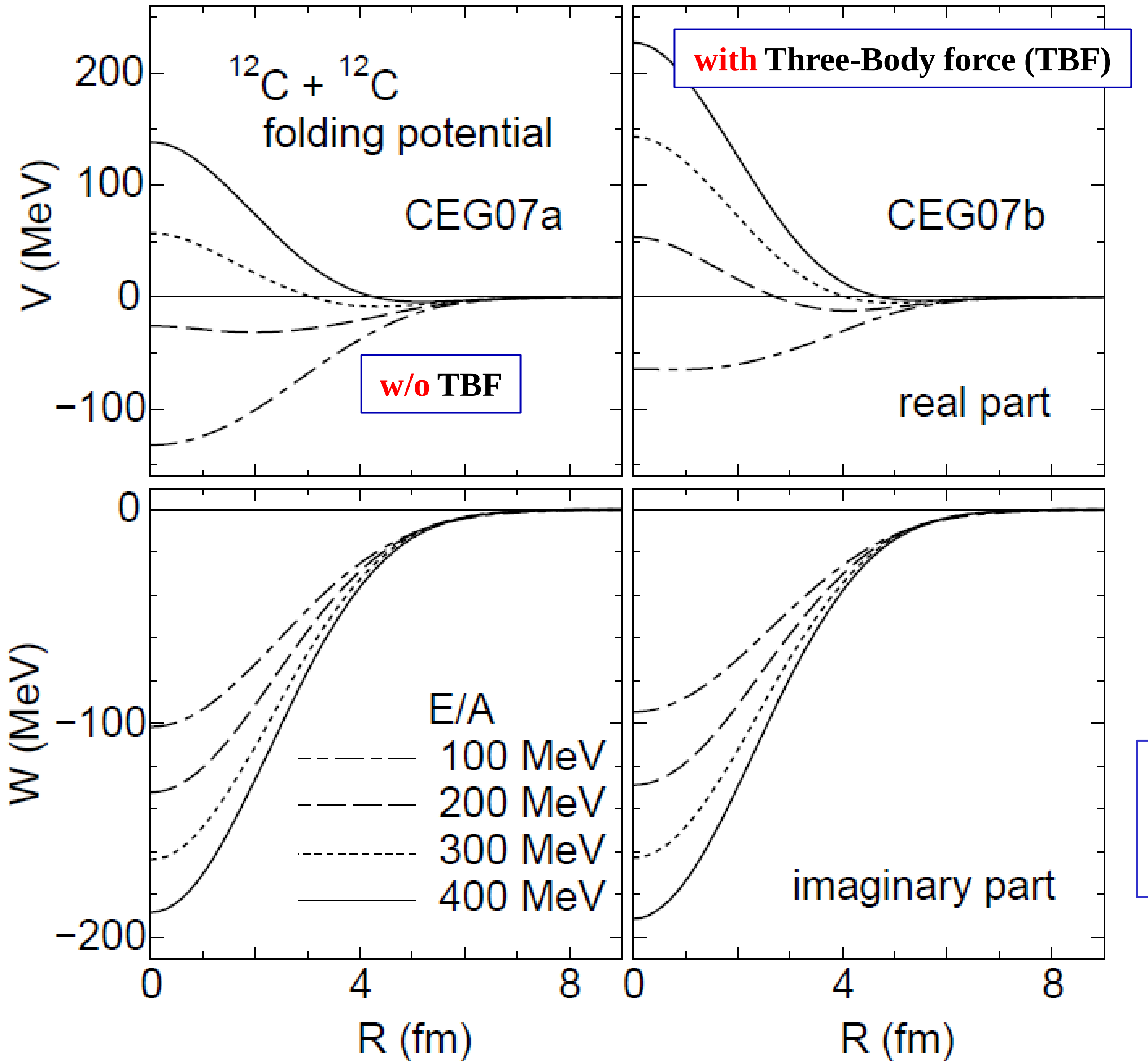
$$U_{DFM} = V_{DFM} + iN_W W_{DFM}$$

important effect of three-body force

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

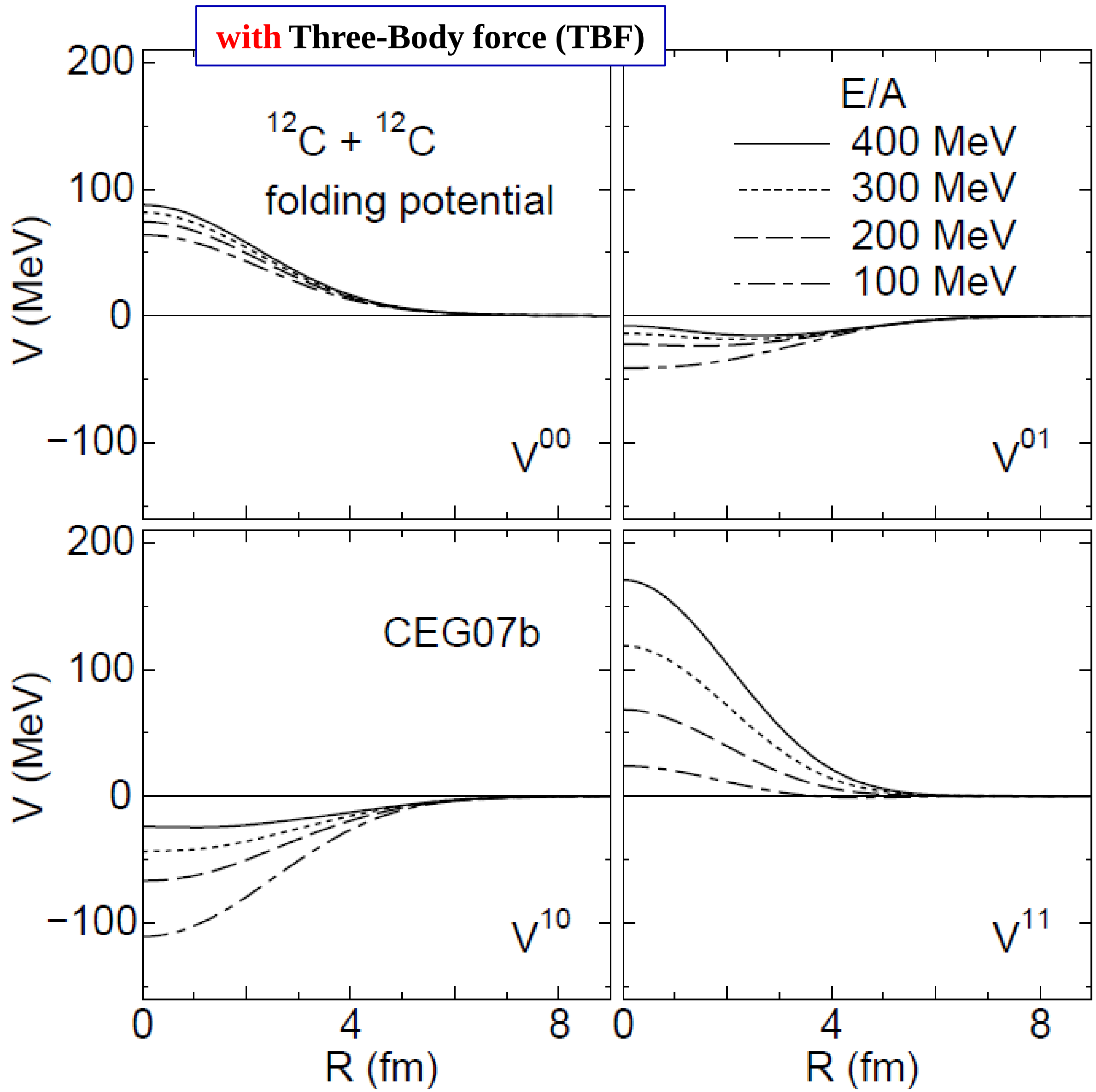
$^{12}C + ^{12}C$ elastic scattering at E/A = 100～400 MeV

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



T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 044612

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



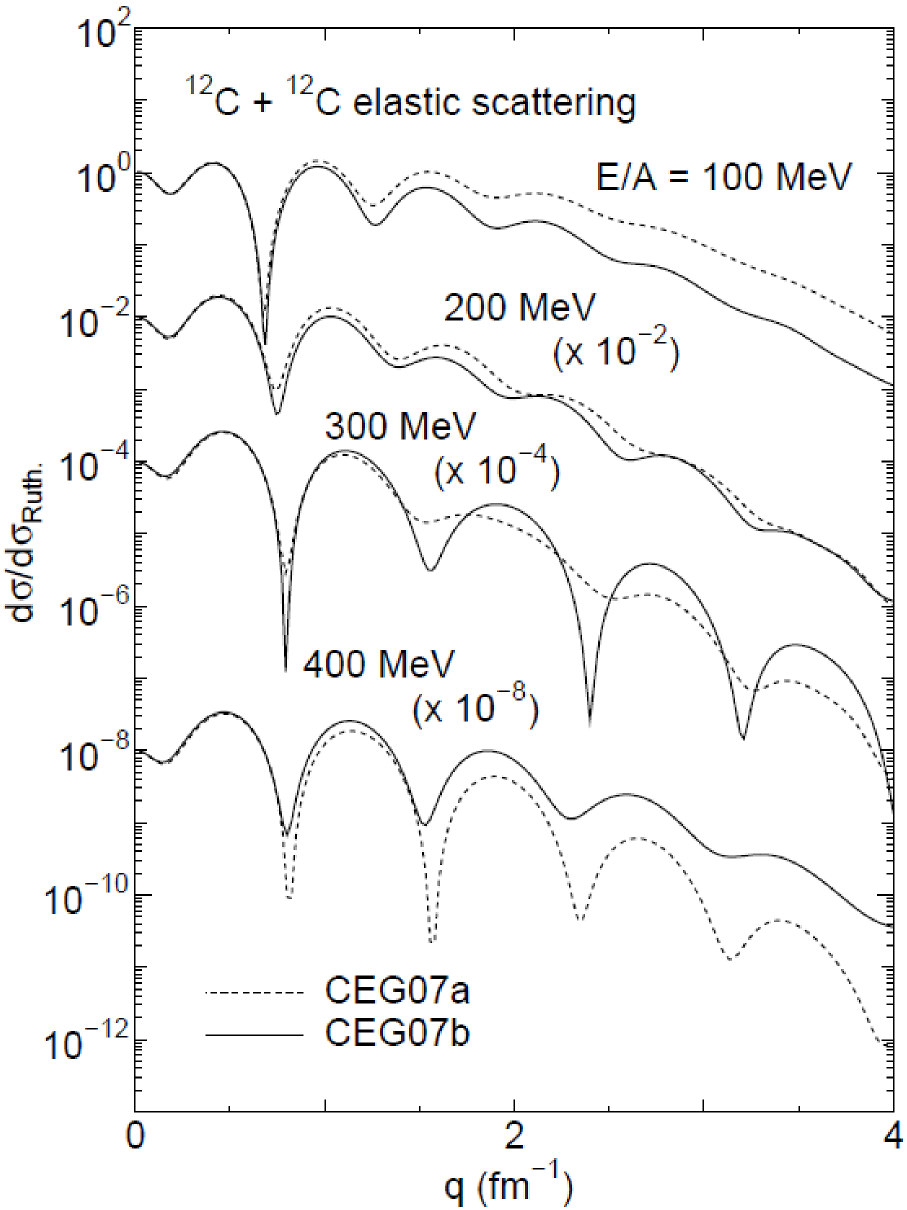
spin(S) and isospin(T) components V^{ST} of folding potential

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

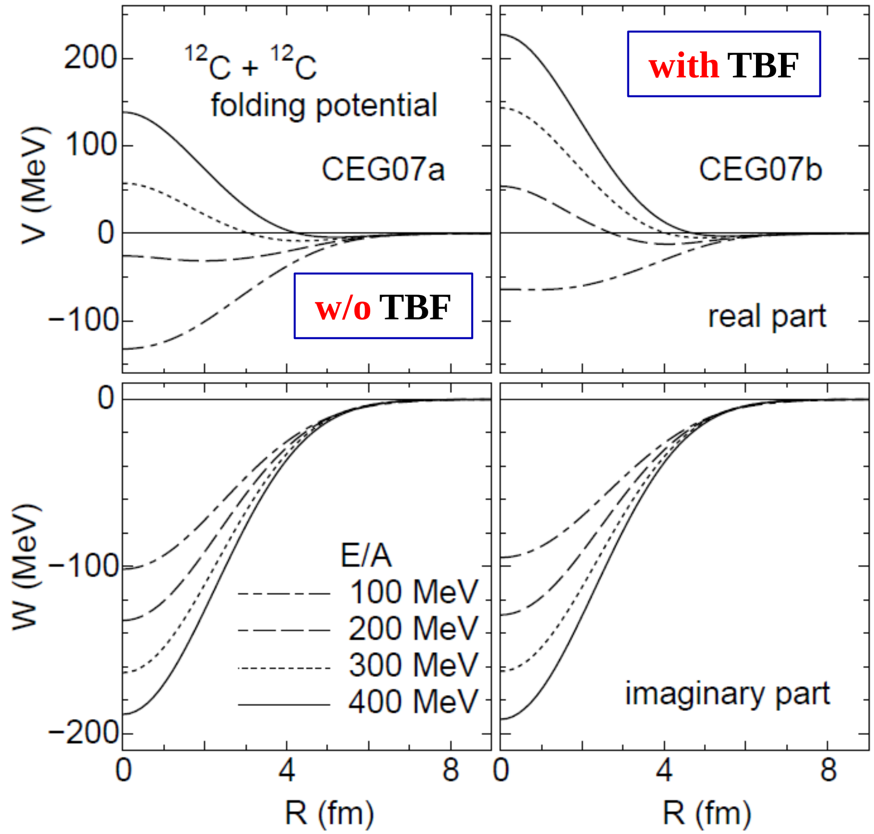
★ **(S,T) = (1,0) and (1,1)** components **include the tensor force**,

T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 044612

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

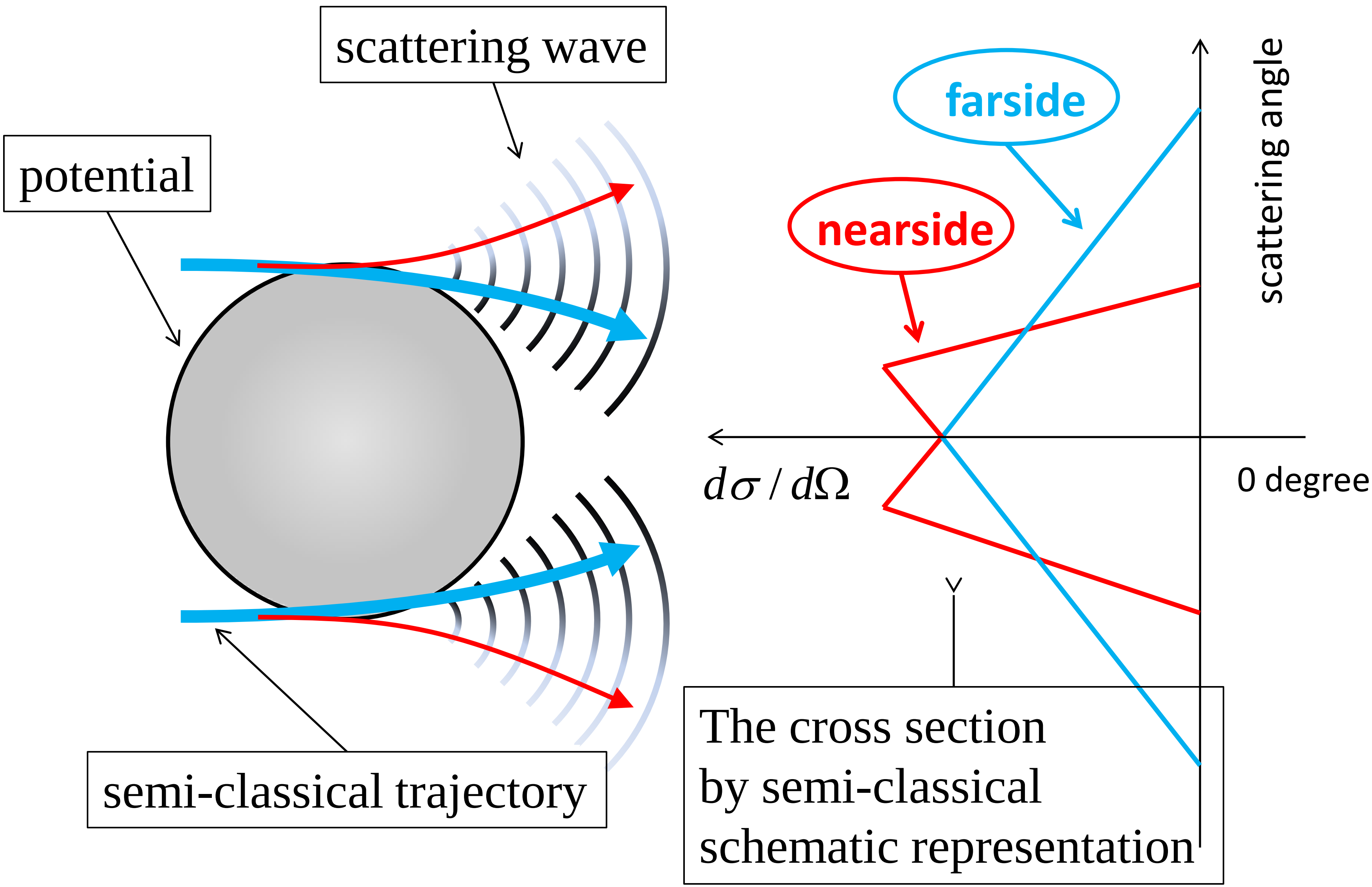


- **real potential : repulsive around *E/A* = 300～400 MeV**

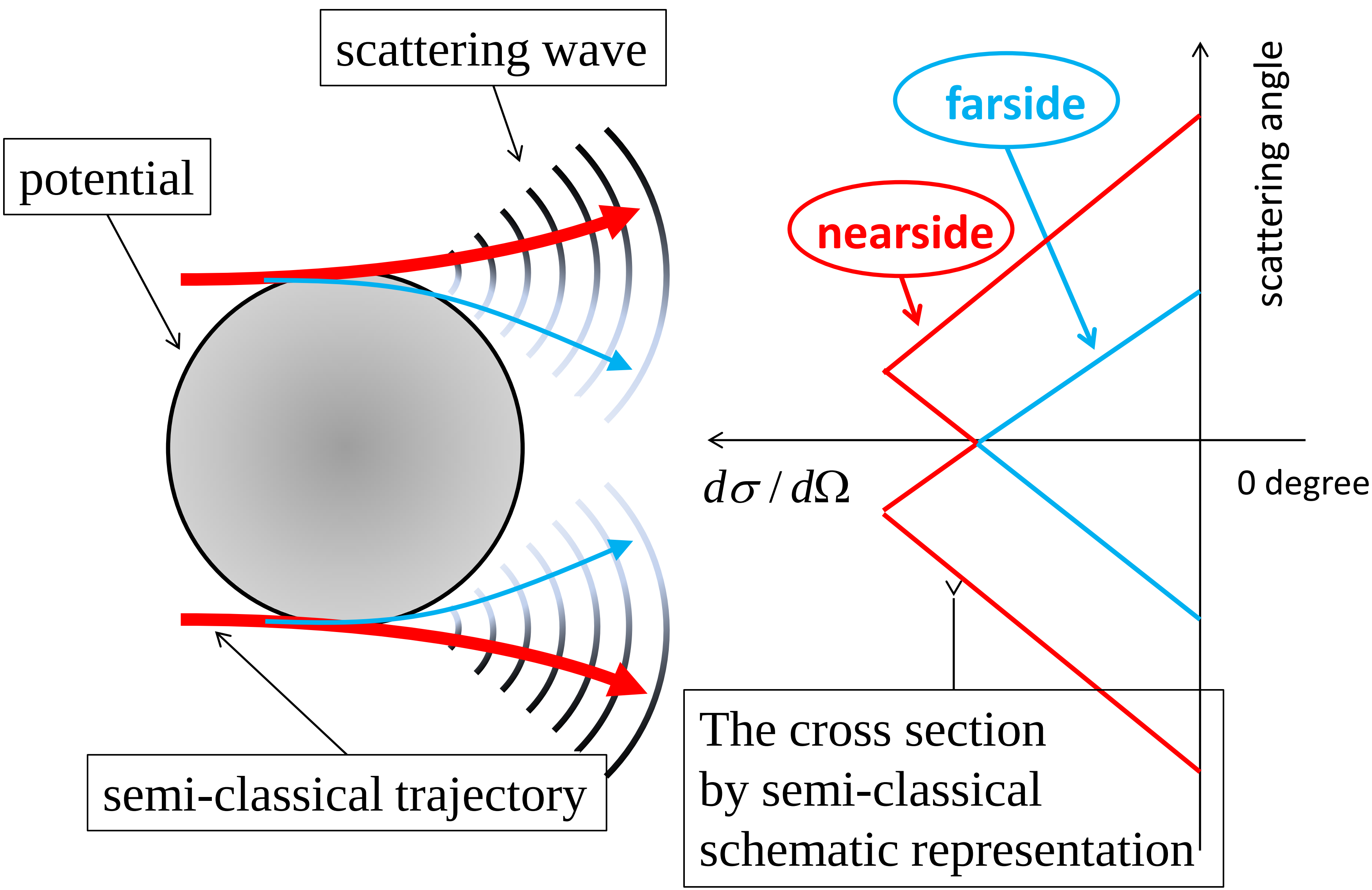


T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 044612

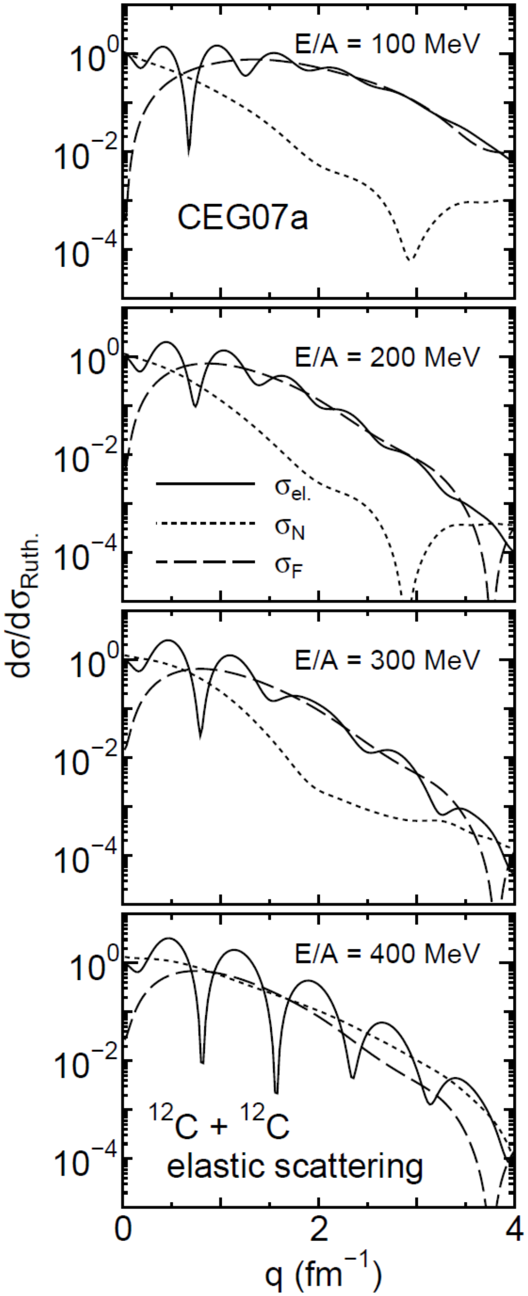
(a) Attractive potential (V < 0)



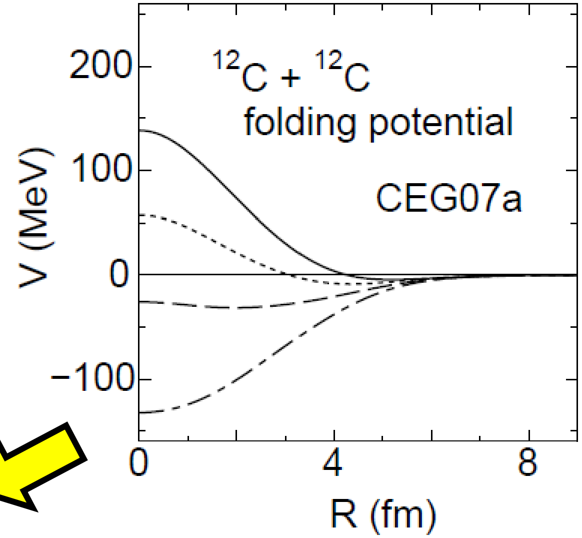
(b) Repulsive potential (V > 0)



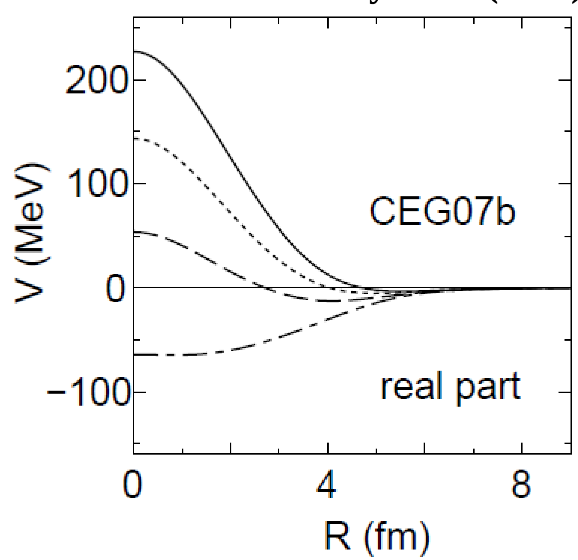
w/o Three-Body force (TBF)



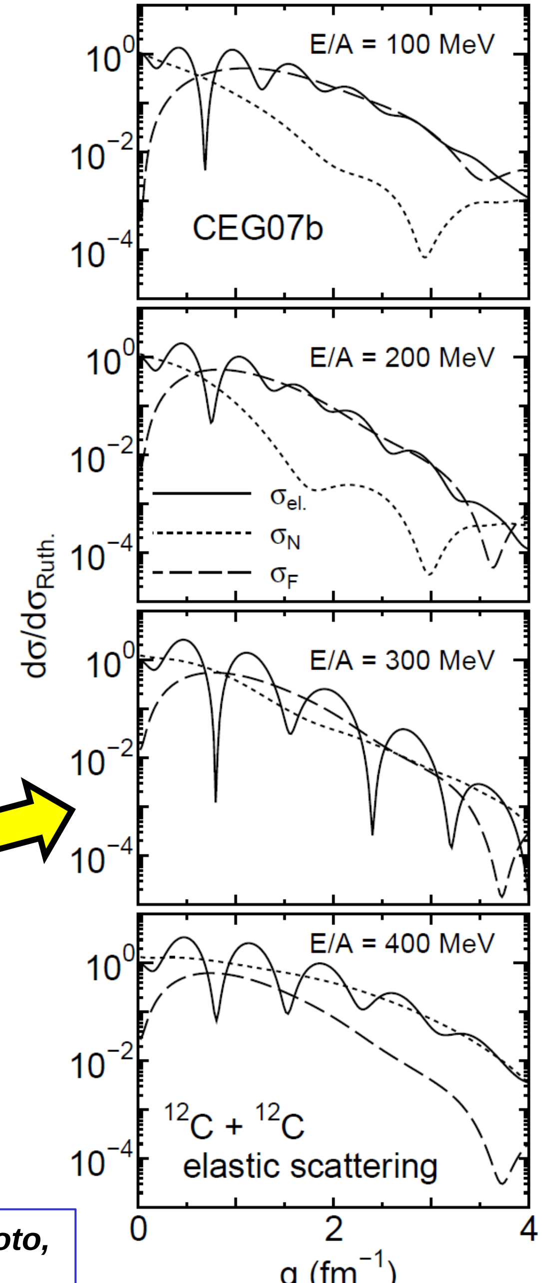
w/o Three-Body force (TBF)



with Three-Body force (TBF)



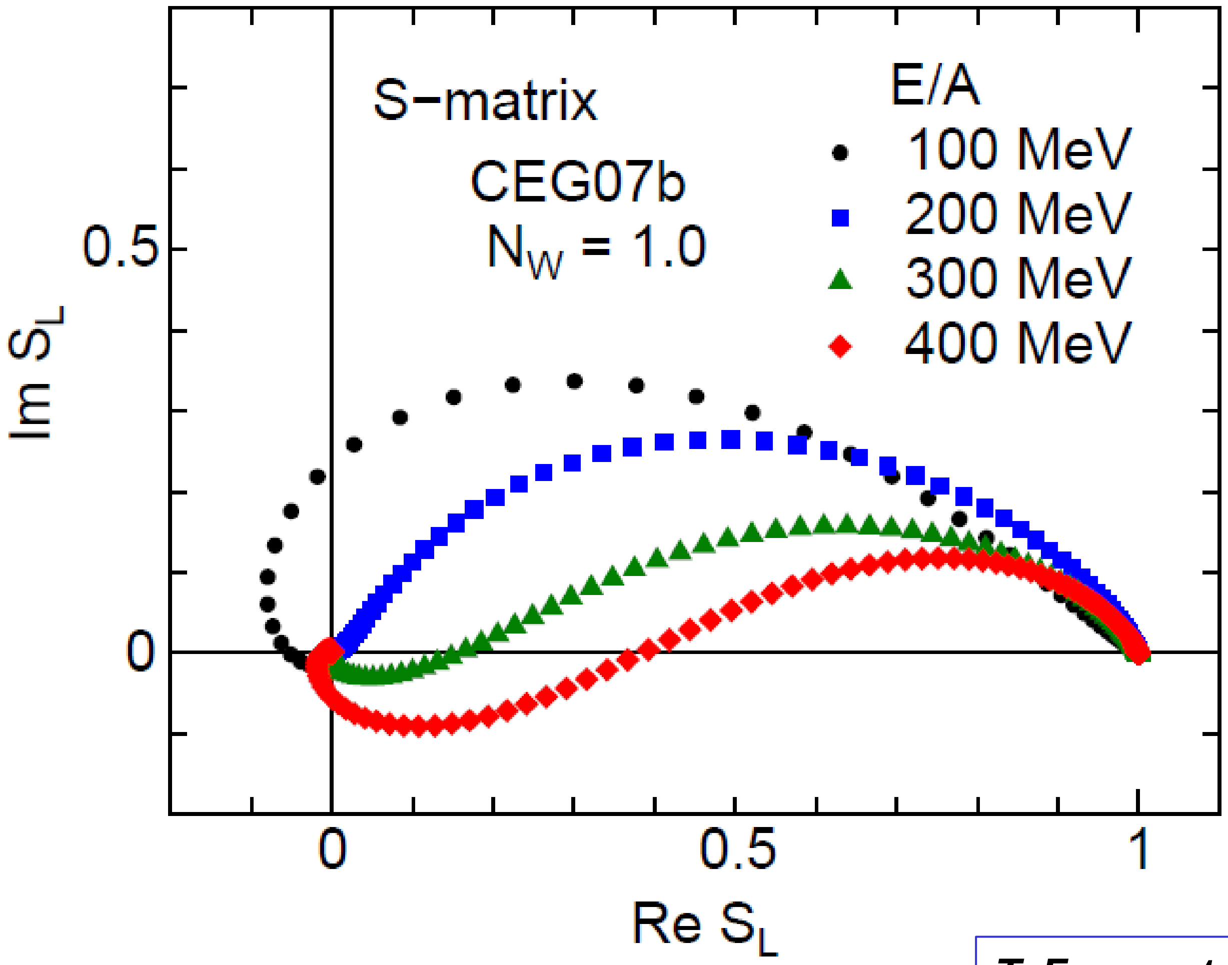
with Three-Body force (TBF)

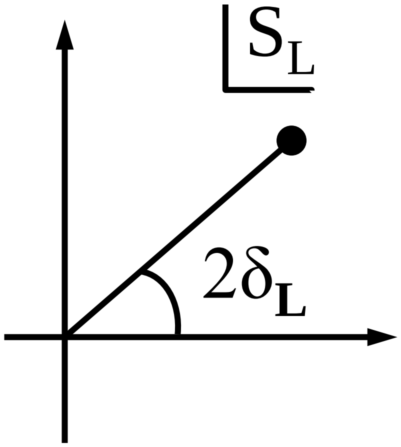


T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 044612

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

T. Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 (2010) 044612

Summary & Conclusion of **part 1**

complex G-matrix folding model with a <u>new G-matrix</u> <u>CEG07</u> predicts that

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

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

✓ can be observed by *measuring the energy-evolution of elastic scattering <u>angular distribution</u> 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*

Part 2:

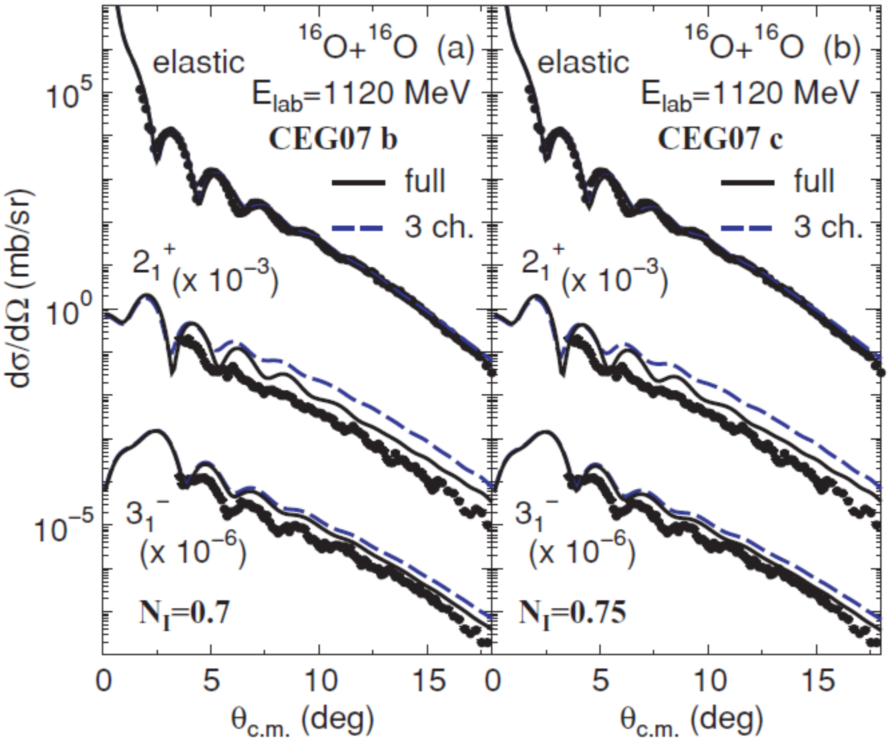
Applications of microscopic FMP to

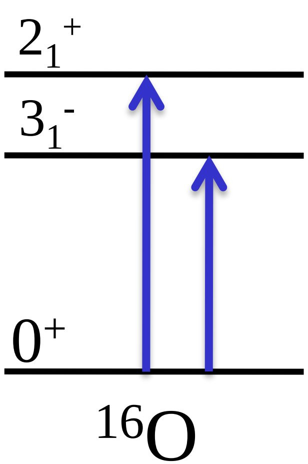
1. *reaction calculations (CC, CDCC etc.)*
2. *scattering of unstable nuclei*
3. *global parameterization*

$^{16}O + ^{16}O$ inelastic scattering studied by a complex *G-matrix interaction* *(@ E/A=70 MeV)*

by M.Takashina, T. Furumoto, Y.Sakuragi

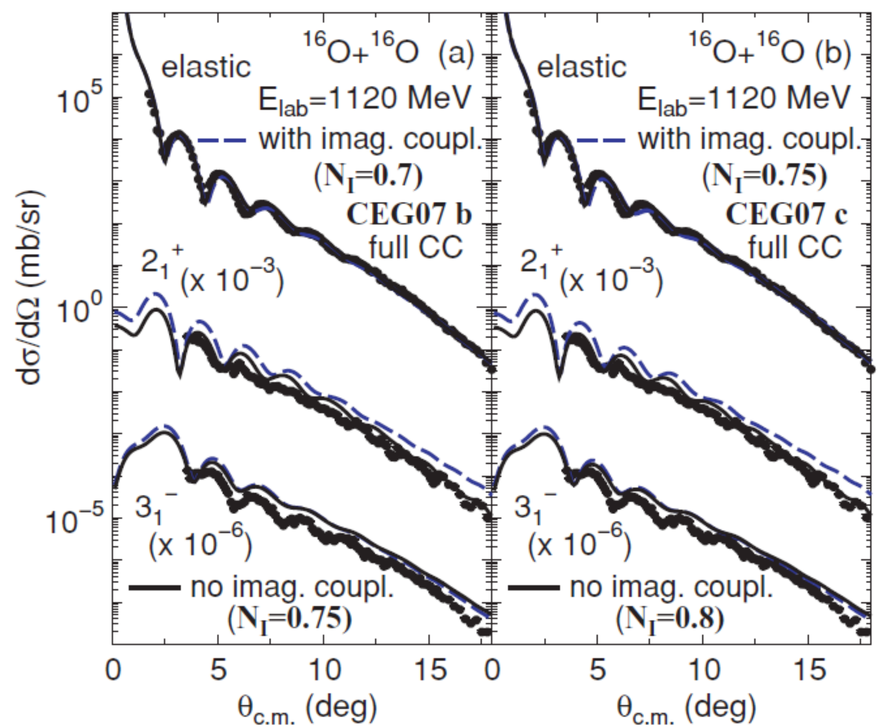
PRC **81, 047605 (2010)**





CC cal. with complex-G (CEG07)

$$U_{ij}^{DFM}(\mathbf{R}) = V_{ij}^{DFM}(\mathbf{R}) + iN_W W_{ij}^{DFM}(\mathbf{R})$$



^{9,11}Li + ^{12}C "quasi-elastic" scattering

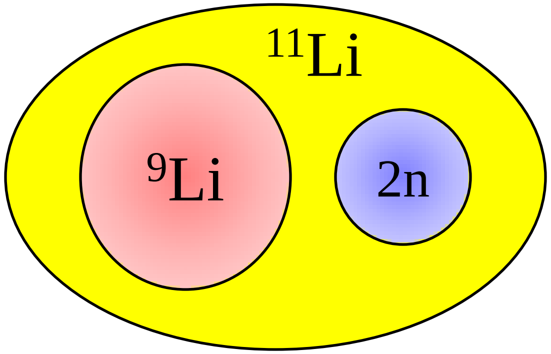
- **^{9}Li density** : proton, neutron ⇒ single Gaussian form

$$\begin{cases} R^{p}_{\mathrm{r.m.s}} = 2.18\,(\mathrm{fm}) \\ R^{n}_{\mathrm{r.m.s}} = 2.39\,(\mathrm{fm}) \end{cases}$$

- **^{11}Li density :** ^{9}Li + di-neutron model

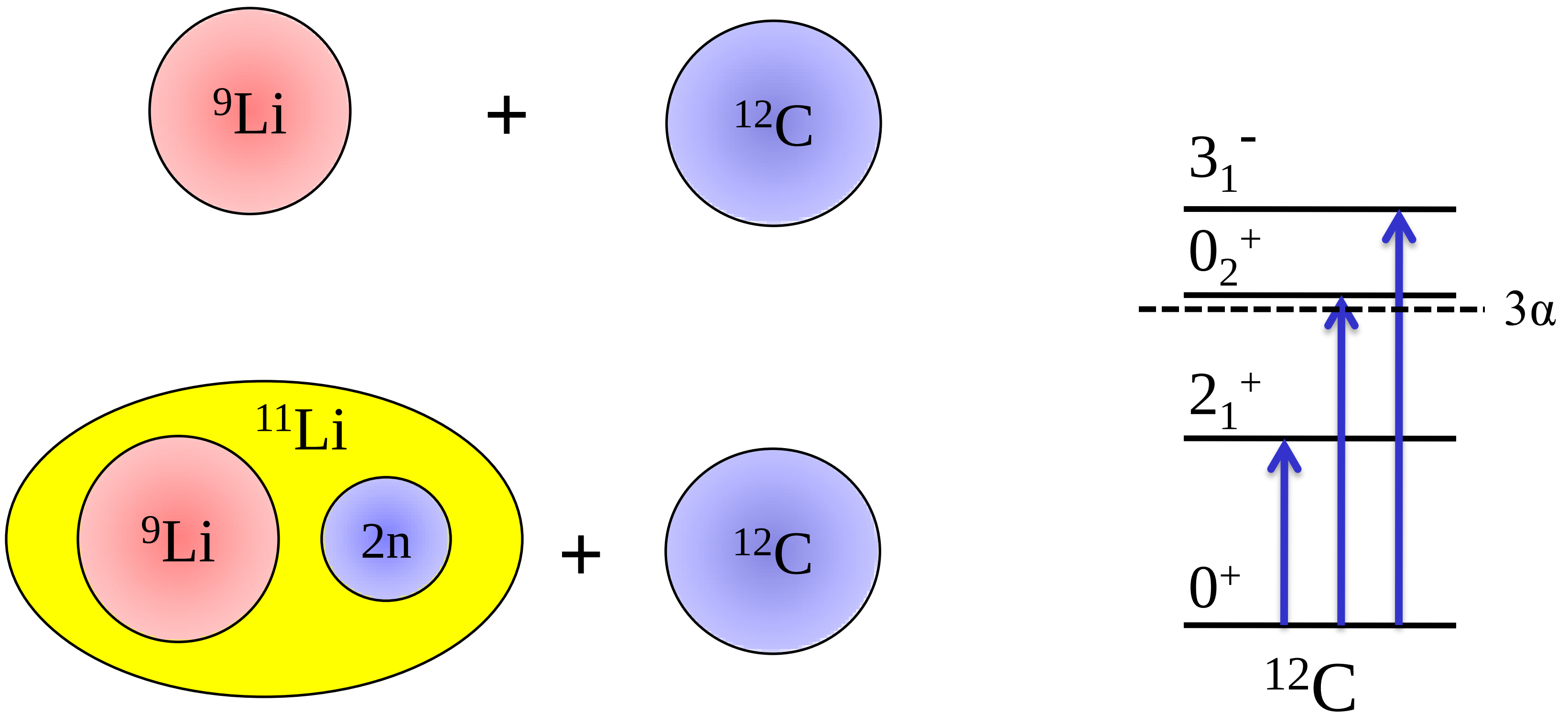
$$\rho^{(^{11}\mathrm{Li})}(r) = \left\langle \psi_0(R) \,|\, \rho^{(^{9}\mathrm{Li})}(\vec{r} - \frac{2}{11}\vec{R}) + \rho^{(2\mathrm{n})}(\vec{r} + \frac{9}{11}\vec{R}) \,|\, \psi_0(R) \right\rangle$$

$$R_{\mathrm{r.m.s}} = 3.16\,(\mathrm{fm})$$



Y.Hirabayashi, S.Funada and Y. Sakuragi
(Proceedings of International Symposium on Structure and Reactions of Unstable Nuclei, pp227-pp232 (1991))

$^{9,11}Li + ^{12}C$ "quasi-elastic" scattering

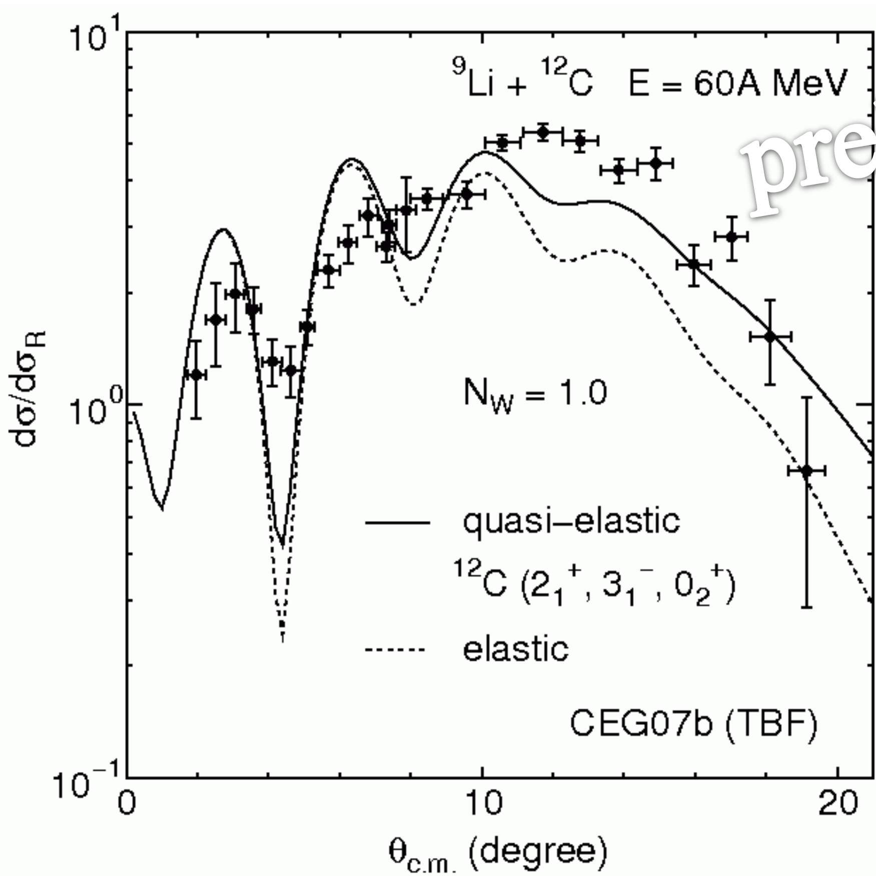


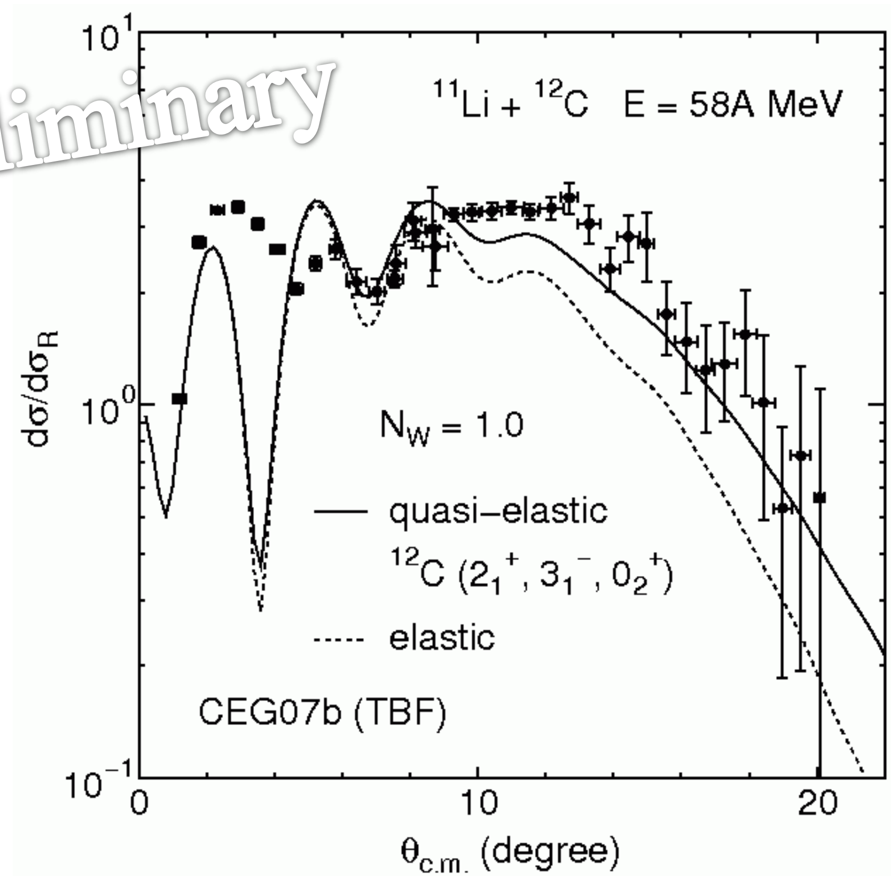
$$U_{ij}^{DFM}(\mathbf{R}) = V_{ij}^{DFM}(\mathbf{R}) + iN_W W_{ij}^{DFM}(\mathbf{R})$$

^{9,11}Li + ^{12}C "quasi-elastic" scattering   E/A ~ 60 MeV

coupled-channel (CC)
calculation with
complex-G (CEG07)

$$U_{DFM}(\mathbf{R}) = V_{DFM}(\mathbf{R}) + iN_W W_{DFM}(\mathbf{R})$$

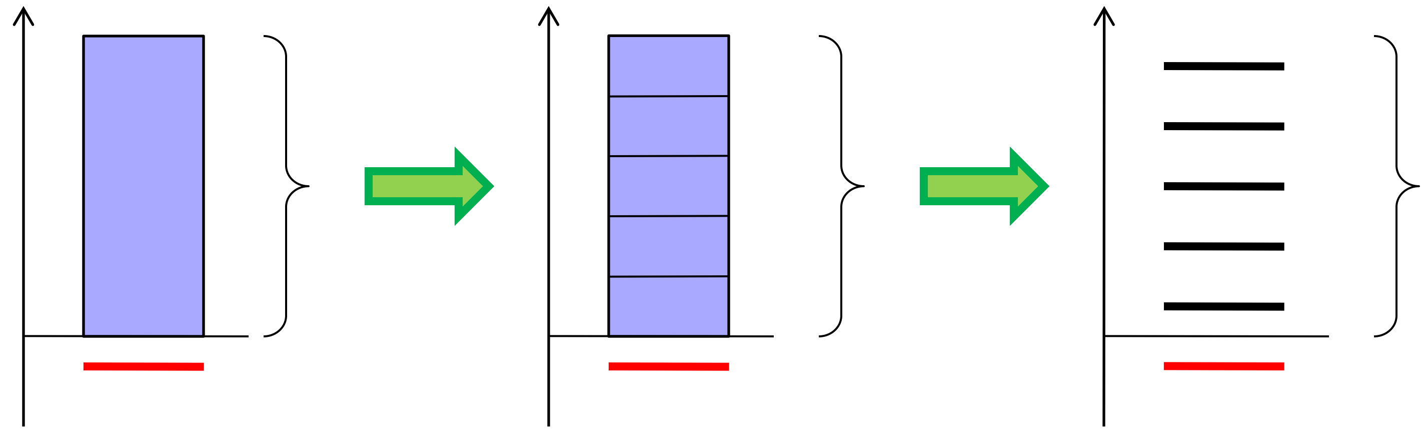


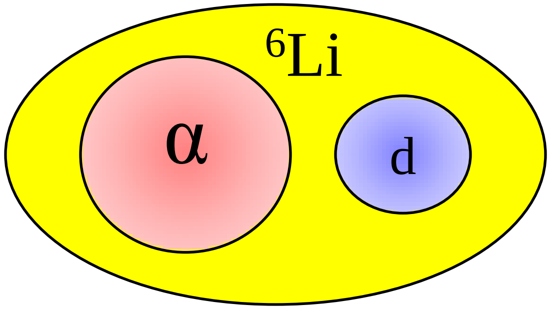


Exp. data : J. J. Kolata et al., (Phys. Rev. Lett. 69 (1993) 2631

^{6}Li elastic scattering with ^{6}Li→α+d break-up

⇒ Continuum-Discretized Coupled-Channels (CDCC) method





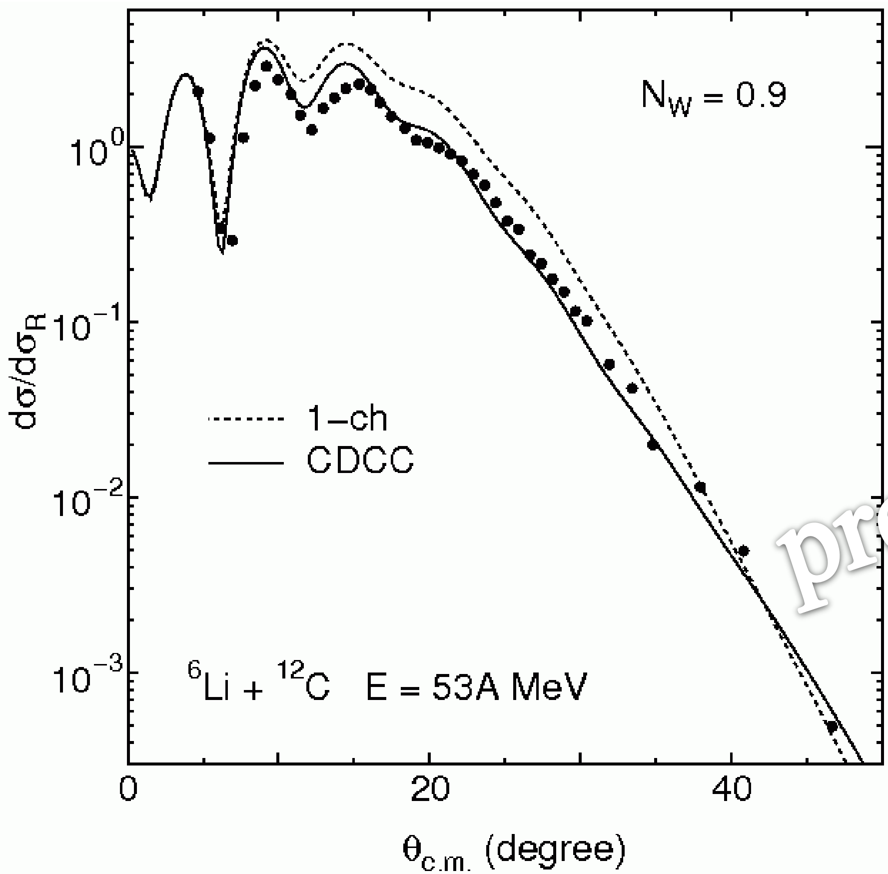
$$U_{ij}^{DFM}(\mathbf{R}) = V_{ij}^{DFM}(\mathbf{R}) + iN_W W_{ij}^{DFM}(\mathbf{R})$$

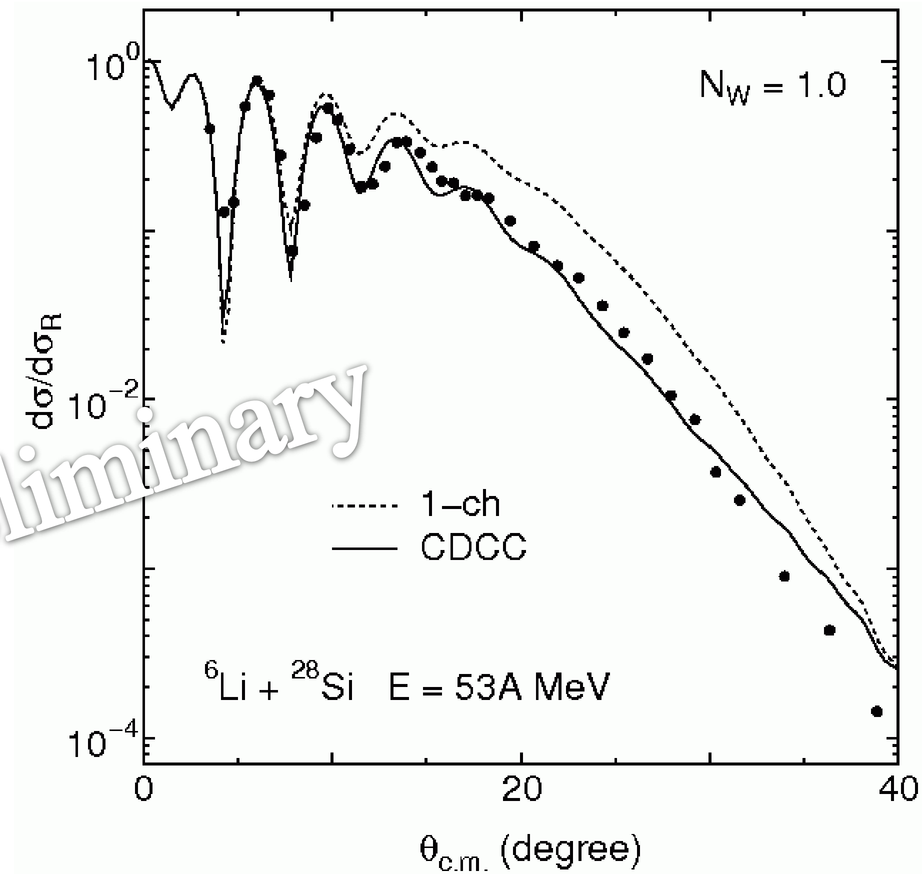
Y. Sakuragi, M, Ito, Y. Hirabayashi , C. Samanta (Prog. Theor. Phys. 98 (1997) 521)

elastic scattering of ^{6}Li by ^{12}C, ^{28}Si at E/A = 53 MeV

- ***CDCC cal. with complex-G (CEG07) folding model***

$$U_{ij}^{DFM}(\mathbf{R}) = V_{ij}^{DFM}(\mathbf{R}) + iN_W W_{ij}^{DFM}(\mathbf{R})$$





Exp. data : A. Nadasen et al., (Phys. Rev. C. 47 (1993) 674

Global potential for projectiles of unstable nuclei up to driplines

T. Furumoto, W. Horiuchi, M. Takashina, Y. Yamamoto, Y. Sakuragi (in preparation)

With CEG07b						^{34}Ca	^{36}Ca	^{38}Ca	^{40}Ca	^{42}Ca	^{44}Ca	^{46}Ca	^{48}Ca	^{50}Ca	^{52}Ca	^{54}Ca	^{56}Ca	^{58}Ca	^{60}Ca	^{62}Ca	^{64}Ca	^{66}Ca	^{68}Ca	^{70}Ca
					^{30}Ar	^{32}Ar	^{34}Ar	^{36}Ar	^{38}Ar	^{40}Ar	^{42}Ar	^{44}Ar	^{46}Ar	^{48}Ar	^{50}Ar	^{52}Ar	^{54}Ar	^{56}Ar	^{58}Ar	^{60}Ar	^{62}Ar			
				^{26}S	^{28}S	^{30}S	^{32}S	^{34}S	^{36}S	^{38}S	^{40}S	^{42}S	^{44}S	^{46}S	^{48}S	^{50}S	^{52}S							
			^{22}Si	^{24}Si	^{26}Si	^{28}Si	^{30}Si	^{32}Si	^{34}Si	^{36}Si	^{38}Si	^{40}Si	^{42}Si	^{44}Si	^{46}Si	^{48}Si								
			^{20}Mg	^{22}Mg	^{24}Mg	^{26}Mg	^{28}Mg	^{30}Mg	^{32}Mg	^{34}Mg	^{36}Mg	^{38}Mg	^{40}Mg											
		^{16}Ne	^{18}Ne	^{20}Ne	^{22}Ne	^{24}Ne	^{26}Ne	^{28}Ne	^{30}Ne	^{32}Ne	^{34}Ne	^{36}Ne	^{38}Ne											
	^{12}O	^{14}O	^{16}O	^{18}O	^{20}O	^{22}O	^{24}O																	
^{8}C	^{10}C	^{12}C	^{14}C	^{16}C	^{18}C	^{20}C	^{22}C																	

Global parameterization of the CEG07 folding-model potentials

- ✓projectiles : Z = 6 (C isotope) ~ 20 (Ca isotope) (even-even)
- ✓targets : ^{12}C ~ ^{208}Pb (closed or sub-closed shell nuclei)
- ✓energy range : E/A = 30 ~ 400 MeV

◆ Folding-model potential with CEG07a, CEG07b

$$U_{\mathrm{D}}(R) = \int \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2)v_{\mathrm{D}}(s;\rho,E/A)d\boldsymbol{r}_1 d\boldsymbol{r}_2$$

$$= \int \{\rho_1^{(\mathrm{p})}(\boldsymbol{r}_1)\rho_2^{(\mathrm{p})}(\boldsymbol{r}_2)v_{\mathrm{D}}^{(\mathrm{pp})}(s;\rho,E/A) + \rho_1^{(\mathrm{p})}(\boldsymbol{r}_1)\rho_2^{(\mathrm{n})}(\boldsymbol{r}_2)v_{\mathrm{D}}^{(\mathrm{pn})}(s;\rho,E/A)$$

$$+\rho_1^{(\mathrm{n})}(\boldsymbol{r}_1)\rho_2^{(\mathrm{p})}(\boldsymbol{r}_2)v_{\mathrm{D}}^{(\mathrm{np})}(s;\rho,E/A) + \rho_1^{(\mathrm{n})}(\boldsymbol{r}_1)\rho_2^{(\mathrm{n})}(\boldsymbol{r}_2)v_{\mathrm{D}}^{(\mathrm{nn})}(s;\rho,E/A)\}d\boldsymbol{r}_1 d\boldsymbol{r}_2,$$

$$U_{\mathrm{EX}}(R) = \int \rho_1(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}(s;\rho,E/A)\exp\left[\frac{i\boldsymbol{k}(R)\cdot\boldsymbol{s}}{M}\right]d\boldsymbol{r}_1 d\boldsymbol{r}_2$$

$$= \int \{\rho_1^{(\mathrm{p})}(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2^{(\mathrm{p})}(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}^{(\mathrm{pp})}(s;\rho,E/A) + \rho_1^{(\mathrm{p})}(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2^{(\mathrm{n})}(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}^{(\mathrm{pn})}(s;\rho,E/A)$$

$$+\rho_1^{(\mathrm{n})}(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2^{(\mathrm{p})}(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}^{(\mathrm{np})}(s;\rho,E/A) + \rho_1^{(\mathrm{n})}(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2^{(\mathrm{n})}(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}^{(\mathrm{nn})}(s;\rho,E/A)\}$$

$$\times\exp\left[\frac{i\boldsymbol{k}(R)\cdot\boldsymbol{s}}{M}\right]d\boldsymbol{r}_1 d\boldsymbol{r}_2,$$

◆ Globally-parameterized density (“Sao Paolo density”)

L. C. Chamon, B. V. Carlson, L. R. Gasques, D. Pereira, C. D. Conti, M. A. Alvarez, M. S. Hussein, M. A. C. Ribeiro, E. S. Rossi, Jr., et al., Phys. Rev. C **66**, 014610 (2001).

◆ Globally-parameterized density ("Sao Paolo density")

L.C.Chamon et al., PRC66, 014601 (2001)

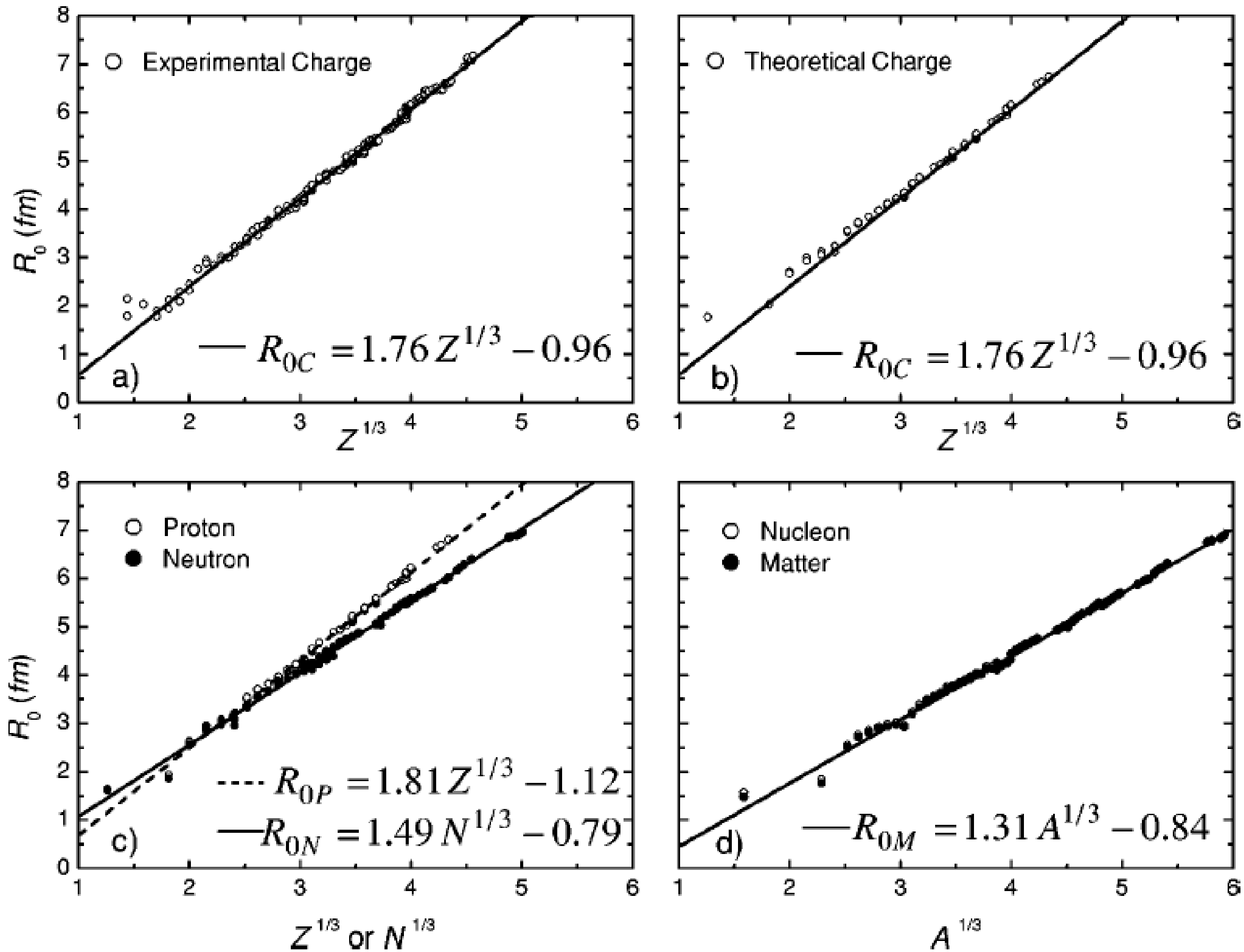


FIG. 3. The R_0 parameter obtained for charge distributions extracted from electron scattering experiments and for theoretical densities obtained from Dirac-Hartree-Bogoliubov calculations.

◆ Globally-parameterized density ("Sao Paolo density")

L.C.Chamon et al., PRC66, 014601 (2001)

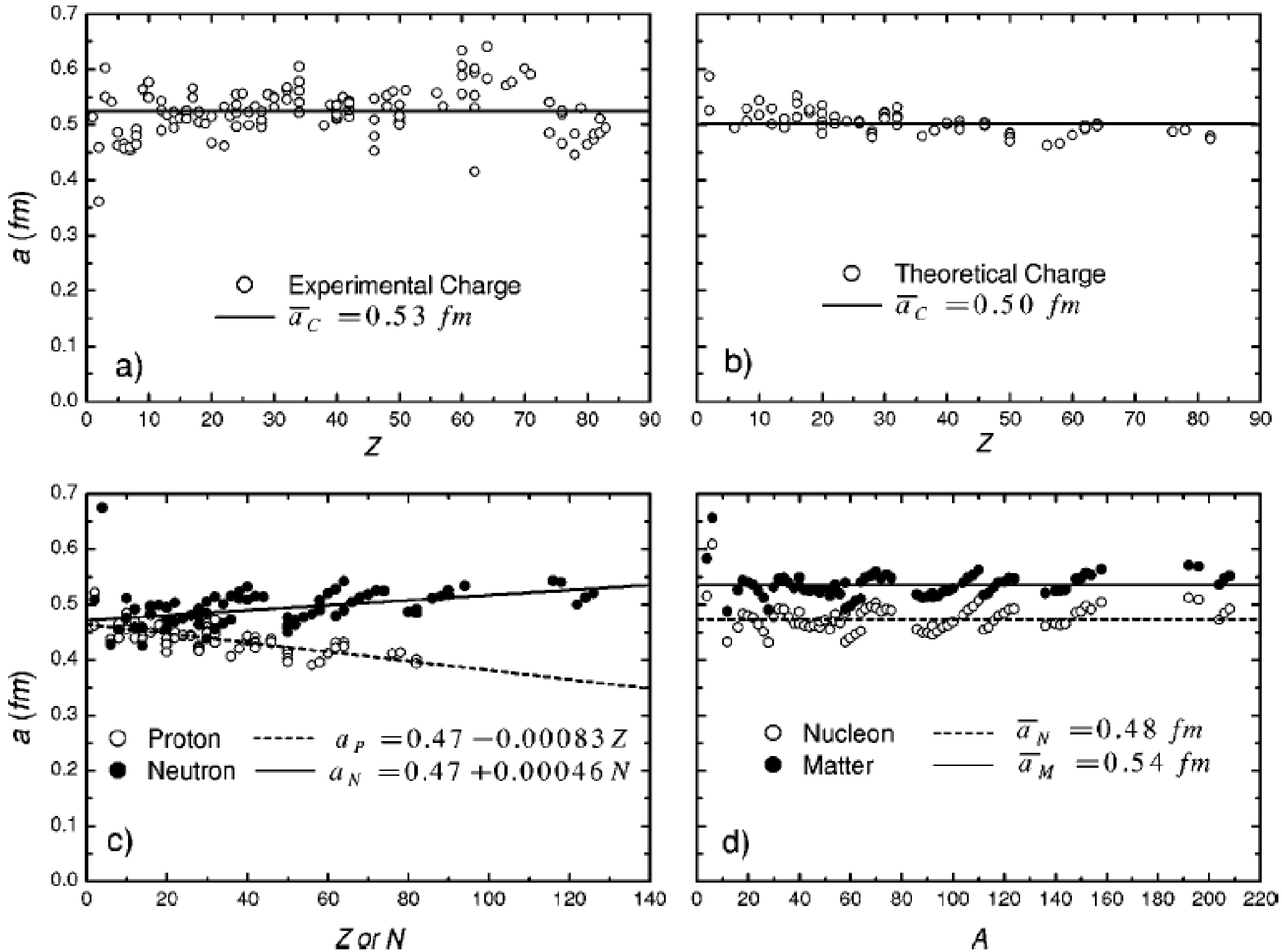


FIG. 2. Equivalent diffuseness values obtained for charge distributions extracted from electron scattering experiments and for theoretical densities obtained from Dirac-Hartree-Bogoliubov calculations.

Global parameterization of the CEG07 folding-model potentials

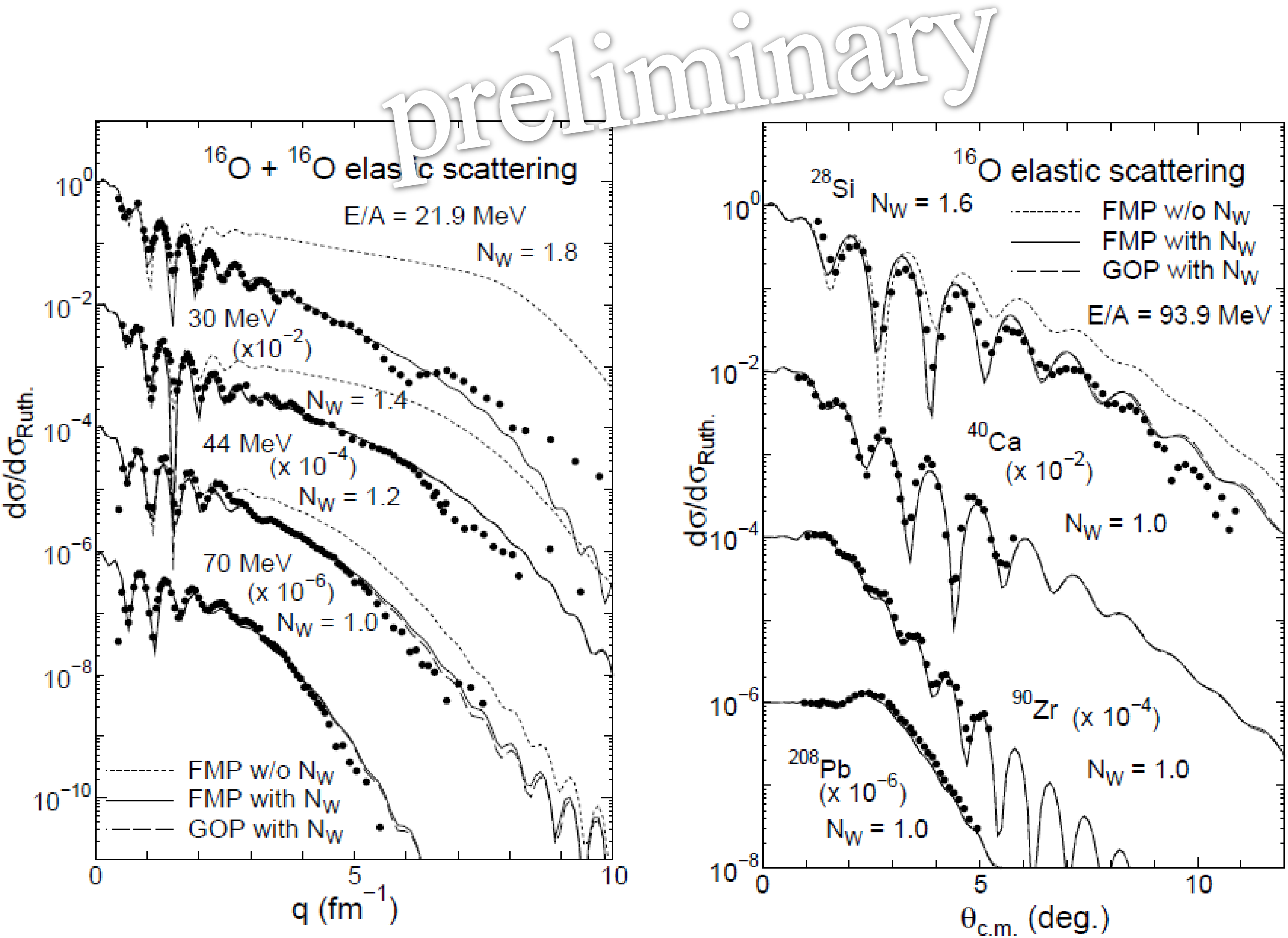
T. Furumoto, W. Horiuchi, M. Takashina, Y. Yamamoto, Y. Sakuragi (in preparation)

- ✓ **projectiles : Z = 6 (C isotope) ~ 20 (Ca isotope) (even-even)**
- ✓ **targets : ^{12}C ~ ^{208}Pb (closed or sub-closed shell nuclei)**
- ✓ **energy range : E/A = 30 ~ 400 MeV**

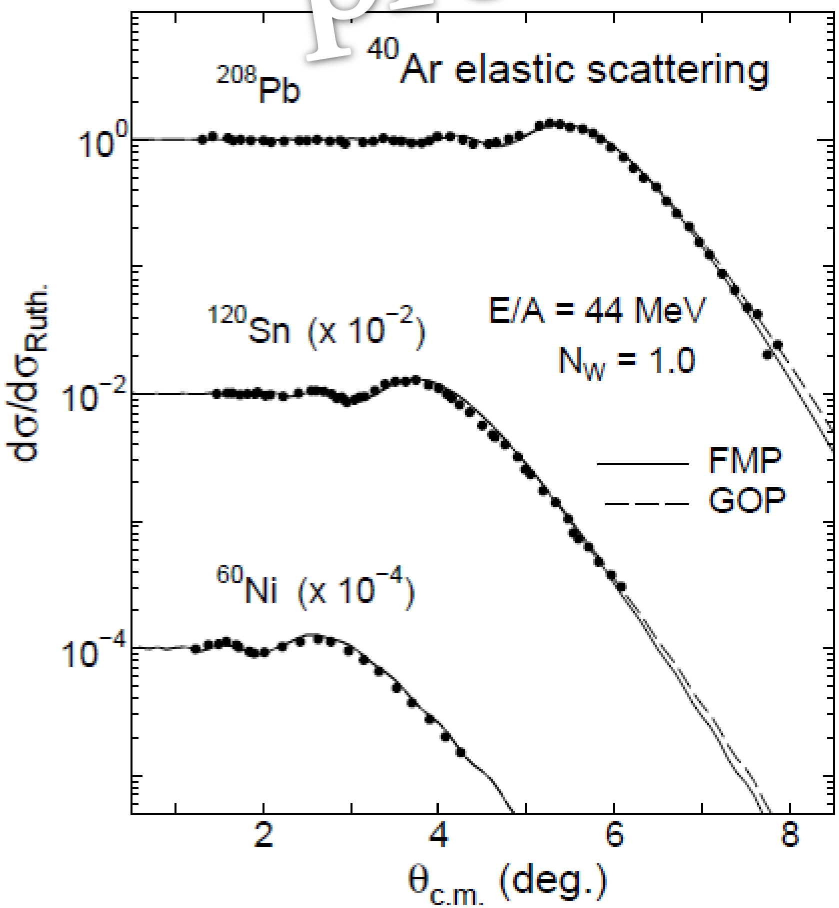
$$V_F(R) = \sum_{n=1}^{10} \left\{ \alpha_n \exp\left(-\frac{R^2}{\gamma_n^2} \right) \right\} ,$$

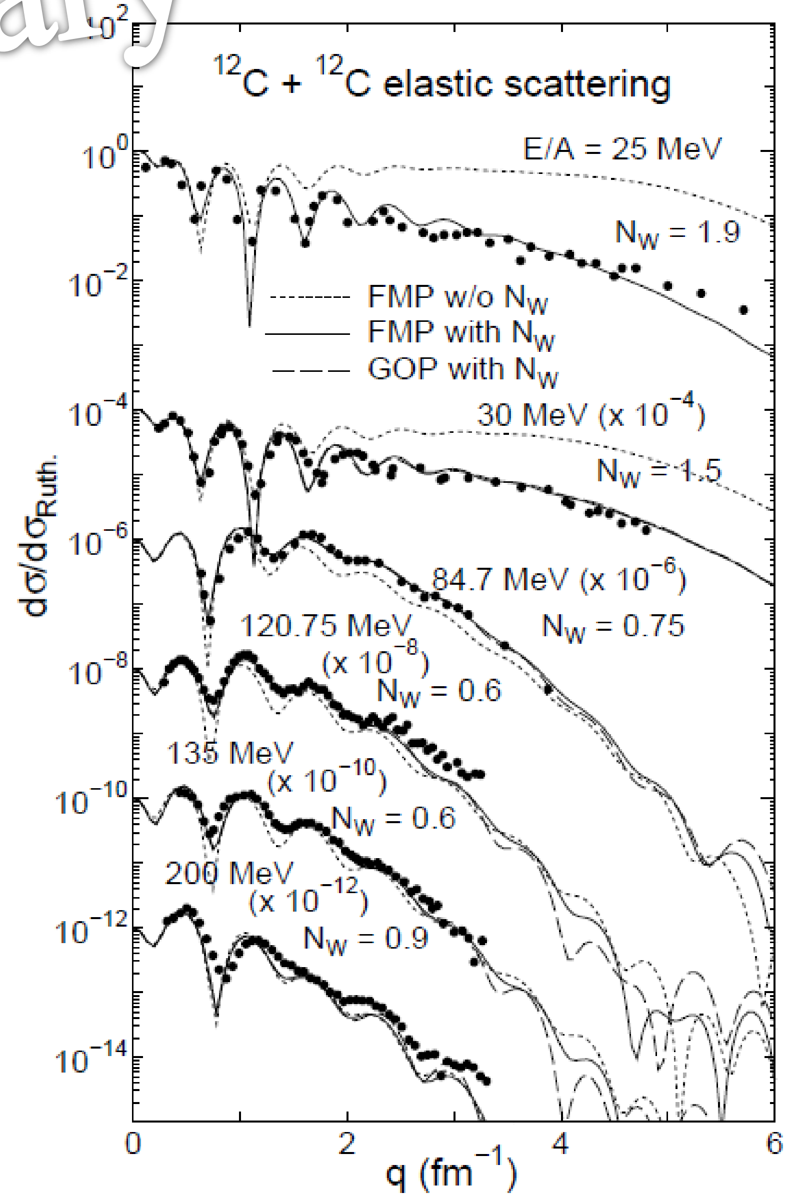
$$W_F(R) = \sum_{n=1}^{10} \left\{ \beta_n \exp\left(-\frac{R^2}{\gamma_n^2} \right) \right\} ,$$

$$\begin{aligned} \alpha_n &= \alpha_n(A_p, Z_p, A_t, E/A) , \\ \beta_n &= \beta_n(A_p, Z_p, A_t, E/A) , \\ \gamma_n &= 0.45 \left(\frac{n+8}{18} \right) (A_p^{1/3} + A_t^{1/3} + 1) \end{aligned}$$

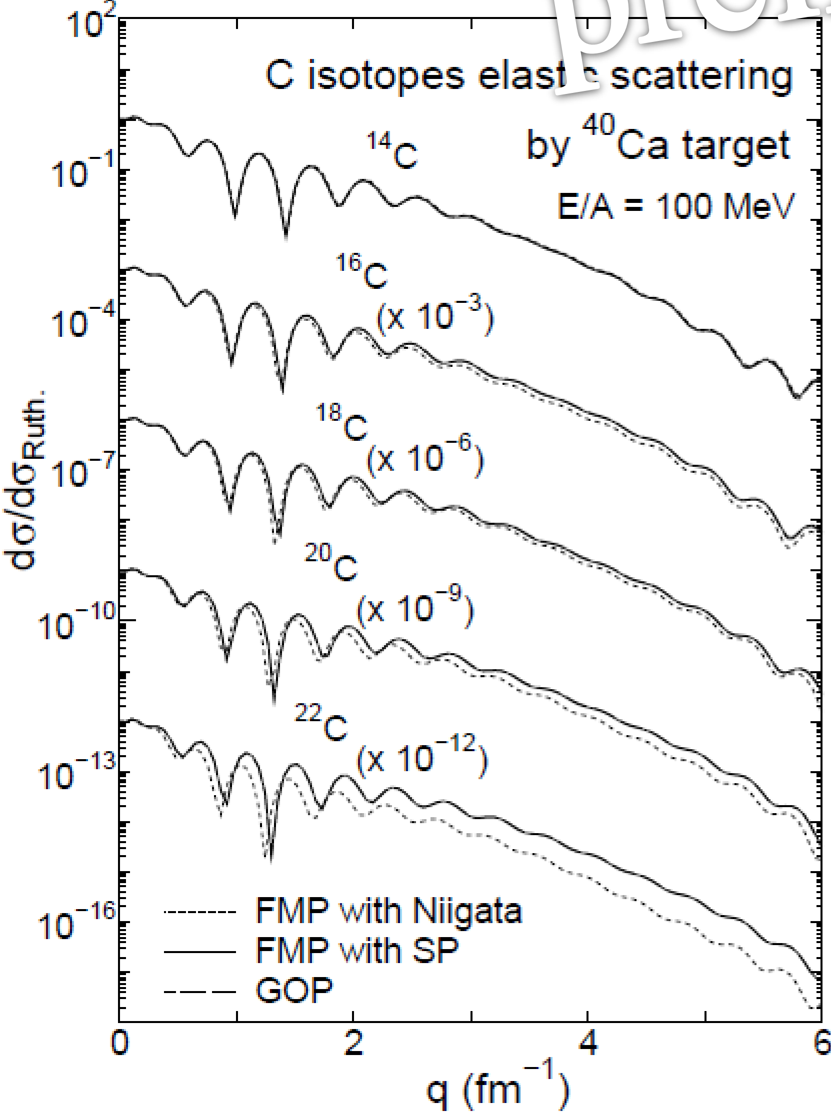

preliminary
16O + 16O elastic scattering
E/A = 21.9 MeV
NW = 1.8
30 MeV
(x10-2)
NW = 1.4
44 MeV
(x 10-4)
NW = 1.2
70 MeV
(x 10-6)
NW = 1.0
FMP w/o NW
FMP with NW
GOP with NW
dσ/dσRuth.
q (fm-1)
16O elastic scattering
28Si
NW = 1.6
E/A = 93.9 MeV
40Ca
(x 10-2)
NW = 1.0
90Zr (x 10-4)
NW = 1.0
208Pb
(x 10-6)
NW = 1.0
θc.m. (deg.)

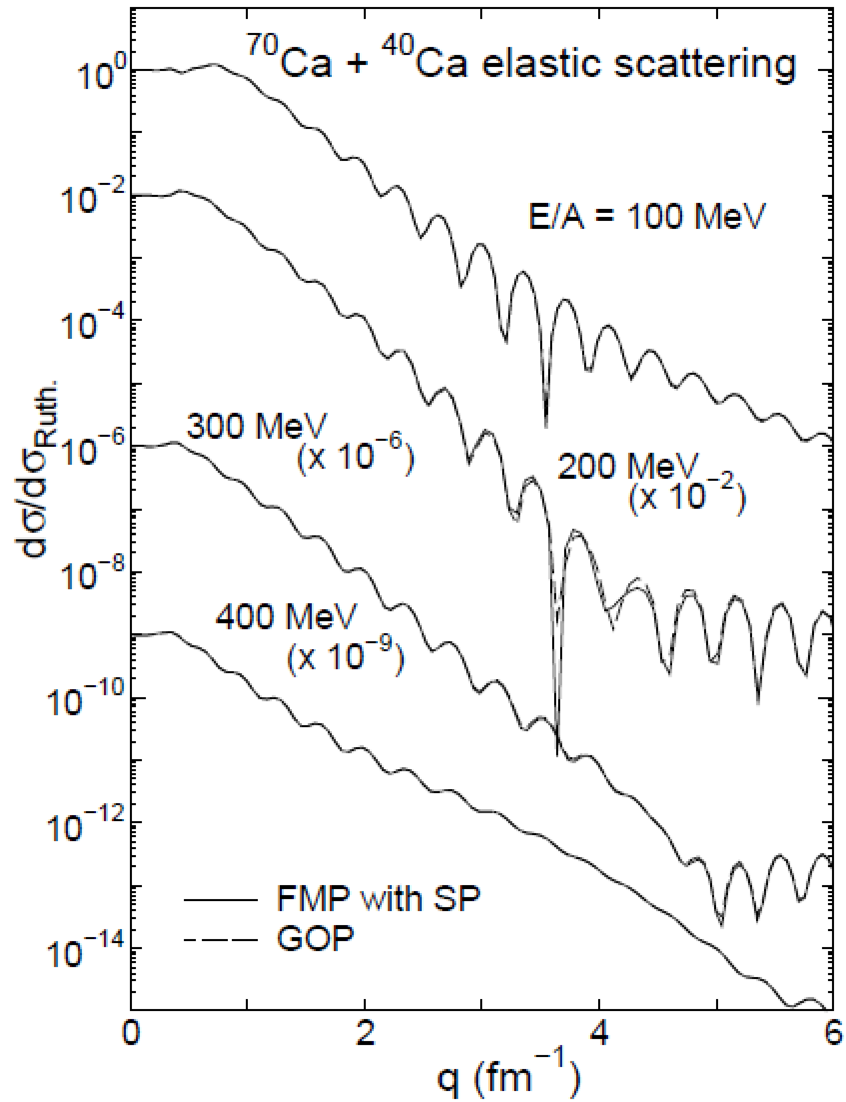
preliminary





preliminary





Summary

- We have proposed a new complex G-matrix ("CEG07"),
  - derived from ESC04(extended soft-core) NN force
  - include three-body force (TBF) effect
  - calculated up to higher density (about twice the normal density)

- We have applied DFM with new complex G-matrix ("CEG07") to nucleus-nucleus (AA) elastic/inelastic scattering & breakup

- CEG07 is successful for nucleus-nucleus elastic scattering
  - reproduce cross section data for ^{12}C, ^{16}O elastic scattering by ^{12}C, ^{16}O, ^{28}Si, ^{40}Ca targets at various energies.

- We have found a decisive role of Three-body repulsive force effect

- We also demonstrated possible applications to nuclear reactions (inelastic/breakup) including those with unstable nuclei

- We constructed Global potentials for projectiles of unstable nuclei up to driplines, based on the microscopic CEG07 folding potentials.