RIKEN Nishina Center Monthly Colloquium
(14th February 2012)

重イオン核反応のための微視的相互作用モデル
Microscopic interaction models for HI reactions

ー現状と今後の展望ー
- present status & future perspective -

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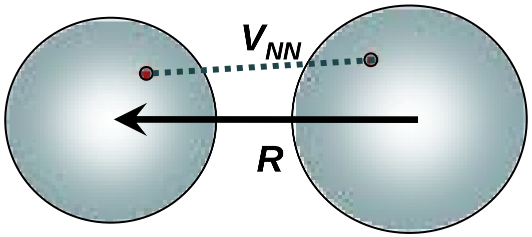
menu

1. Introduction
2. Microscopic theory for nucleus-nucleus interaction with a new complex G-matrix interaction, CEG07
   I. Application to proton-nucleus scattering
   II. Application to heavy-ion (HI) scattering/reactions
   ⇒ Importance of repulsive three-body force effect
3. Attractive-to-repulsive transition of HI optical potential around E/A=200～300 MeV
4. Global optical potential for exotic heavy ions
5. future perspectives

1. Introduction

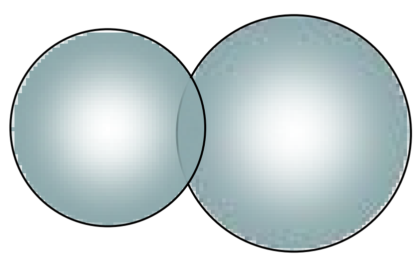
- ***Understanding the interactions between composite nuclei (AA interactions), starting from NN interaction :***

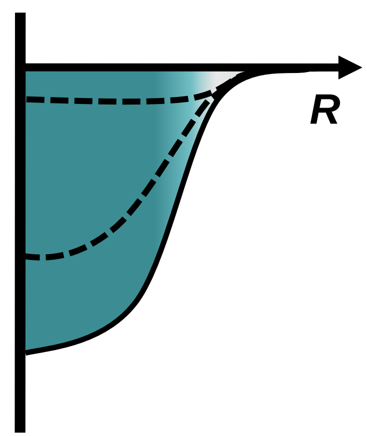


  - ✓ ***one of the most fundamental subjects in nuclear physics***
  - ✓ ***one of the key issues to understand various nuclear reactions:***
    - ➢ *optical potentials: elastic scattering*
    - ➢ *distorting potentials as doorway to various reactions (inelastic, transfer, knockout, breakup ···)*
  - ✓ ***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.*

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

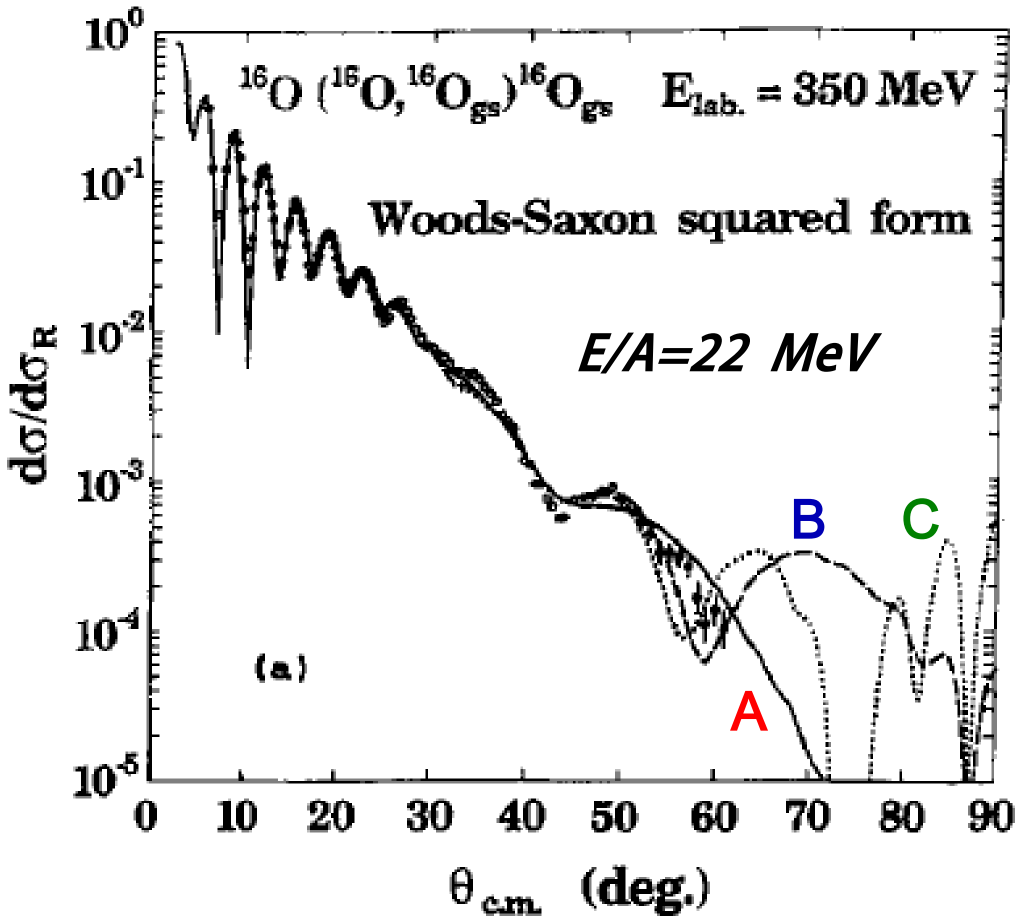
- *Phenomenolocical optical potentials:*
  - ✓ *needs Exp. Data (elastic scattering)*
    to determine potential parameters
    (e.g. Woods-Saxon form)
  - ✓ *optical potential for heavy-ion systems (AA) has*
    large ambiguity in depth & shape
    due to strong absorption (in most cases)
  - ✓ *→ only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

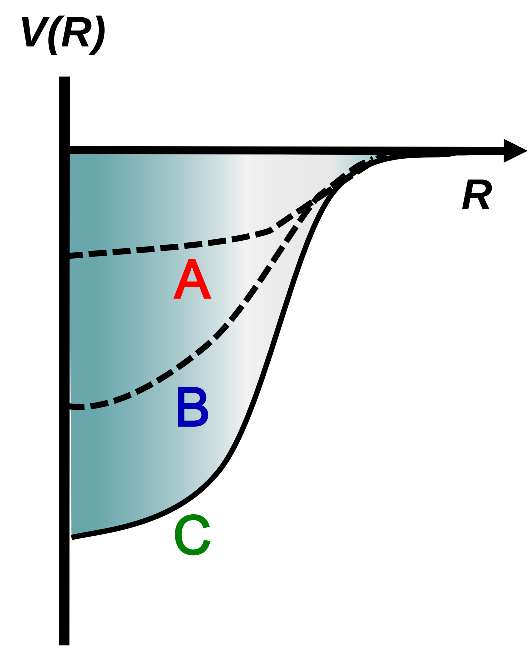




✓ *Discrete ambiguity of the potential depth :*

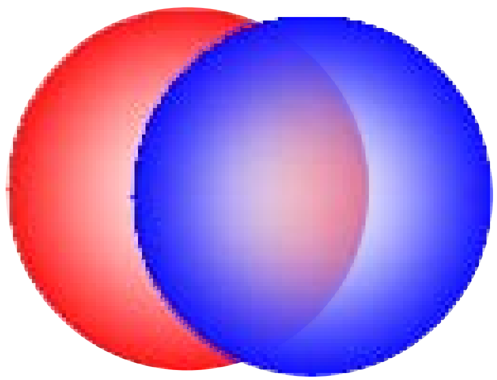
→ *which is correct ?*

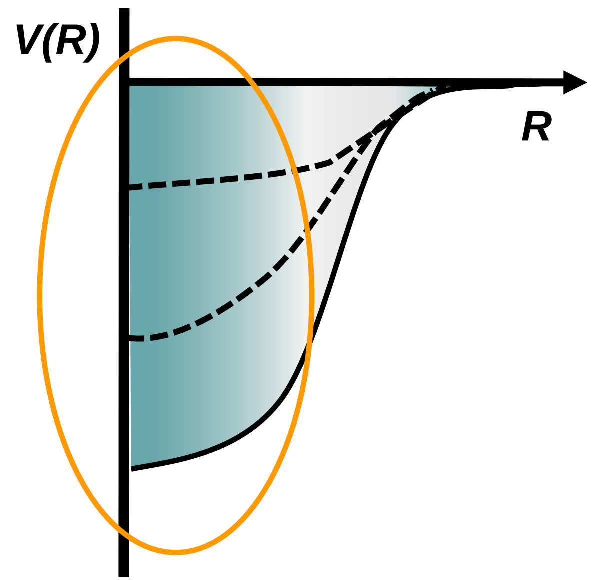




Y. Kondō, F. Michel and G. Reidemeister, Phys. Lett. B 242 (1990) 340.

✓*How deep is the nucleus-nucleus potential at short distances ?*





✓*Can we probe the depth ?*

- ✓ *In general, it is very difficult to probe the central depth of the H.I. potentials, due to strong absorption.*

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

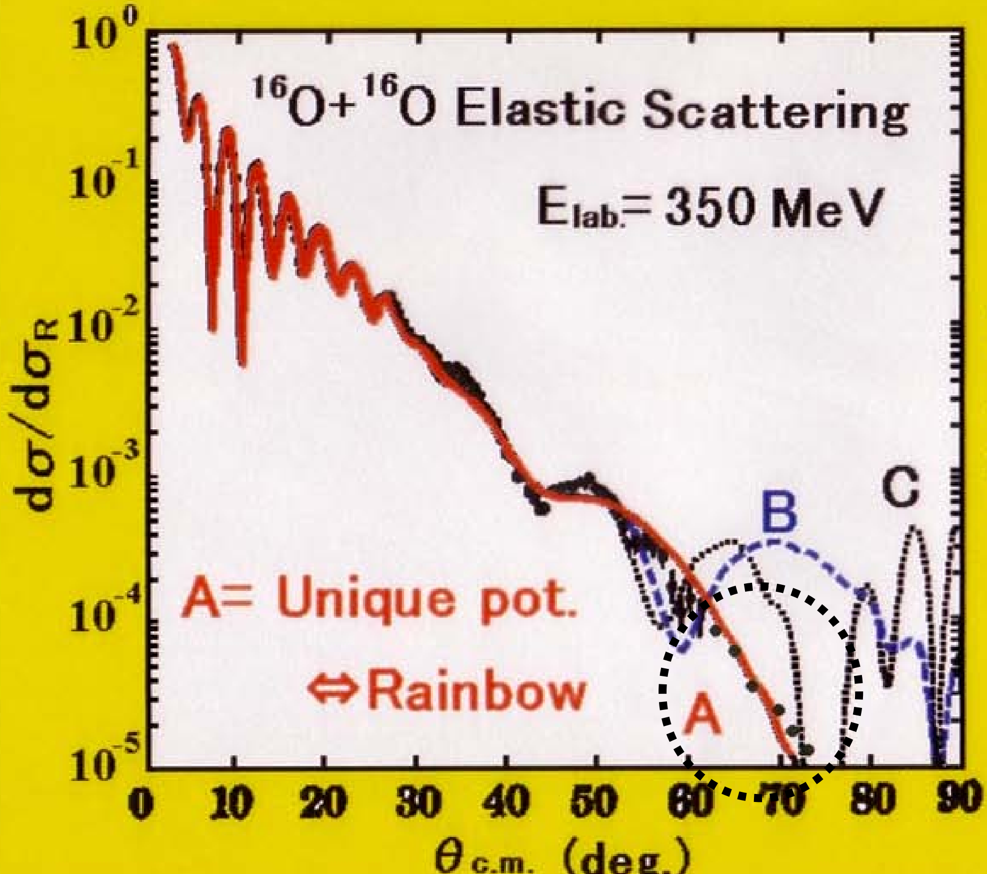
→ ***Yes, we can!***

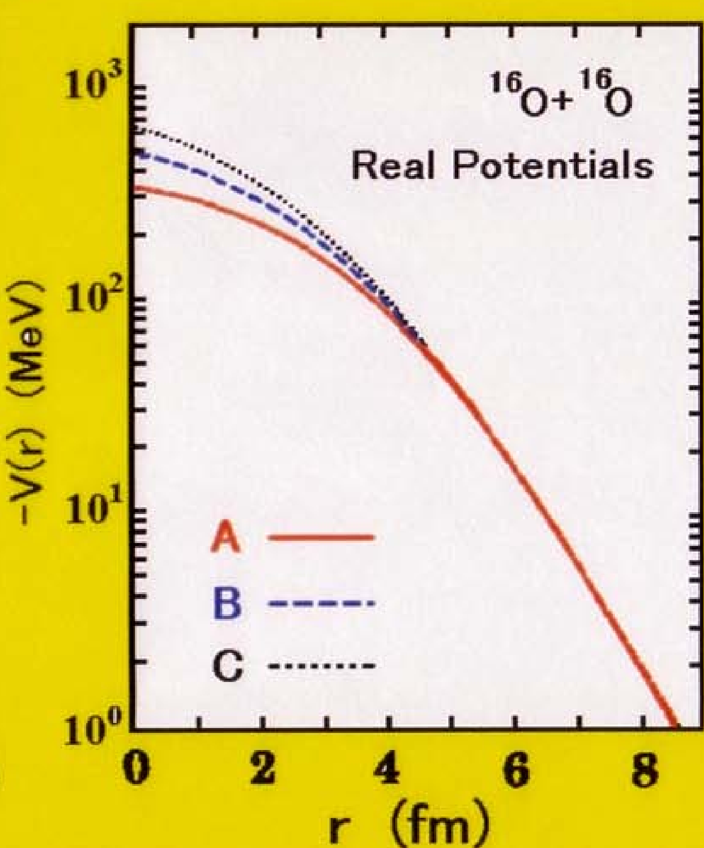
(at least for light heavy-ions)

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°.

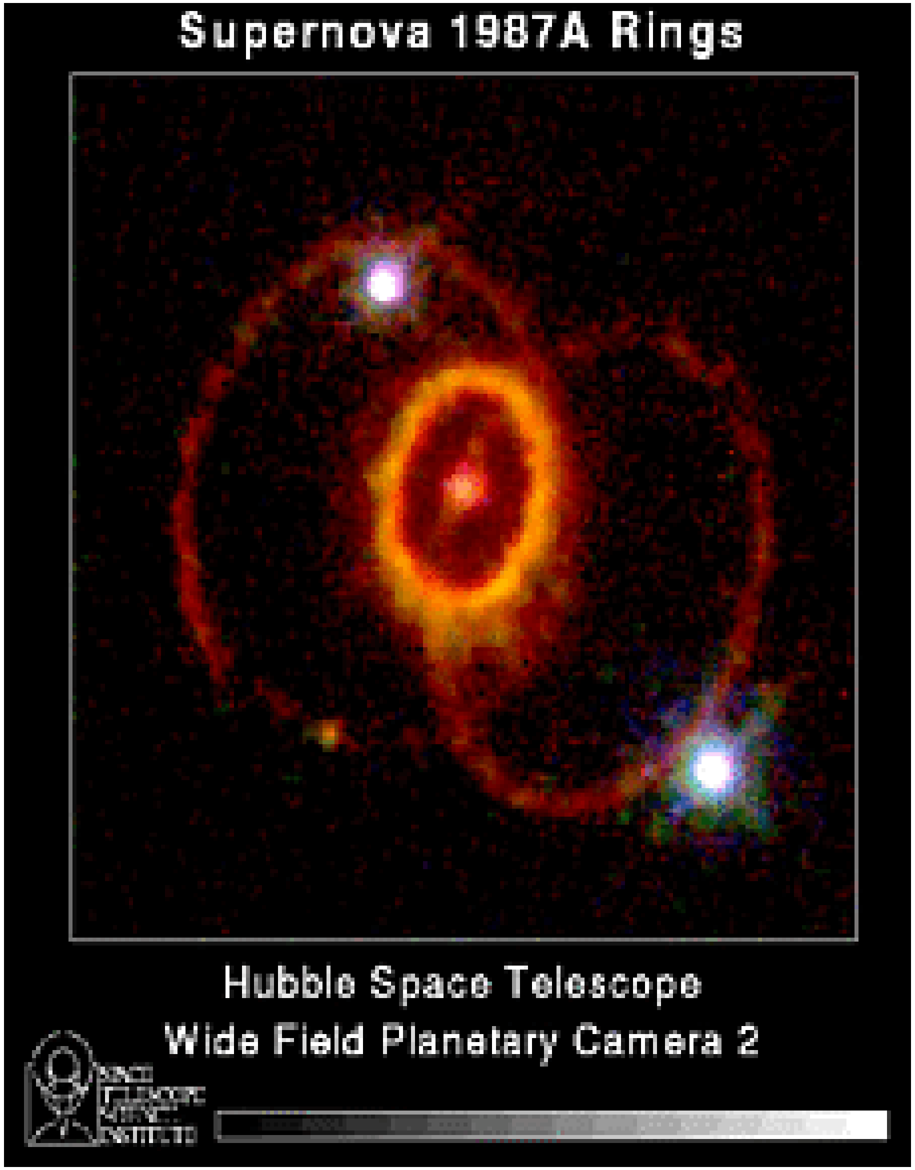




By the way,

Q: Why do we need to know the central depth of the potential ?

A: We can study the property of high-density nuclear matter, such as that in neutron stars, in laboratory experiments.



赤色巨星・超巨星における
元素合成の終焉（Fe, Ni）

→　重力崩壊

→　高密度核物質／超新星爆発

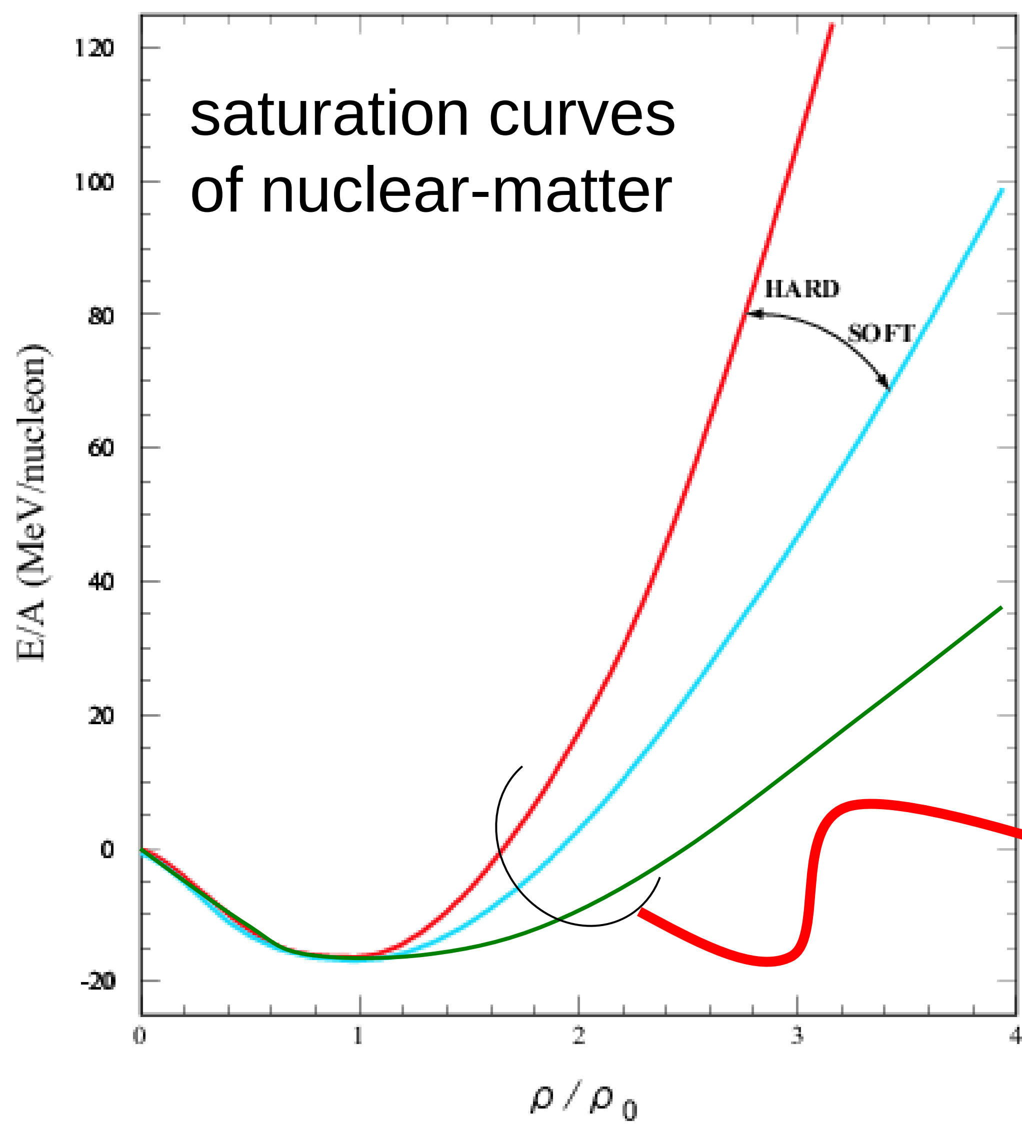
→　中性子星

　ハイペロン星／クォーク星

高密度核物質の性質、　特に、
非圧縮率 (Incompressibility)
が重要

$$K_{\mathrm{nm}} = 9\rho_0^2 \left. \frac{d^2(E/A)}{d^2\rho} \right|_{\rho_0}$$

核物質(Nuclear Matter)の飽和曲線



核物質の非圧縮率
(Incompressibility
of nuclear matter)

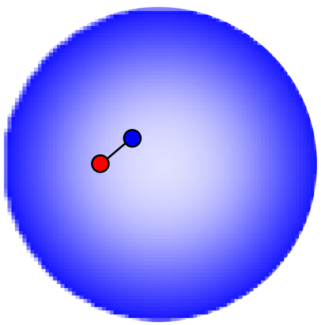
$$K_{\mathrm{nm}} = 9\rho_0^2 \left. \frac{d^2(E/A)}{d^2\rho} \right|_{\rho_0}$$

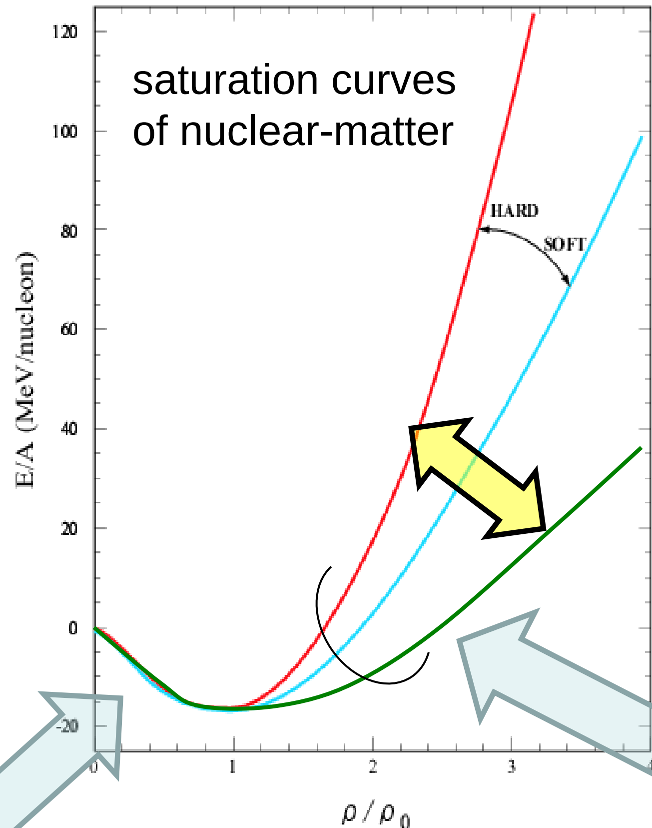
- 超新星爆発→中性子星
- 原子核のGiant Monopole振動
- 高エネルギー重イオン衝突から放出されるγ線

K_{nm} = 100 ～300 MeV
： 不定性が大きい

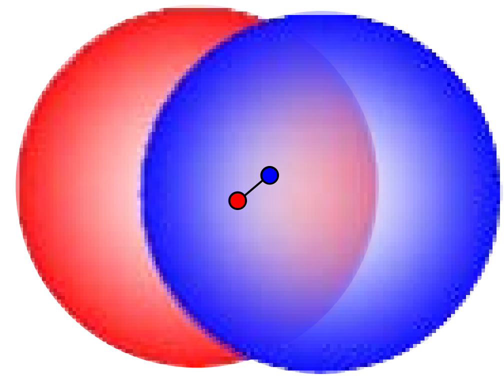
How can we probe the property of high-density nuclear matter at $\rho > \rho_0$?

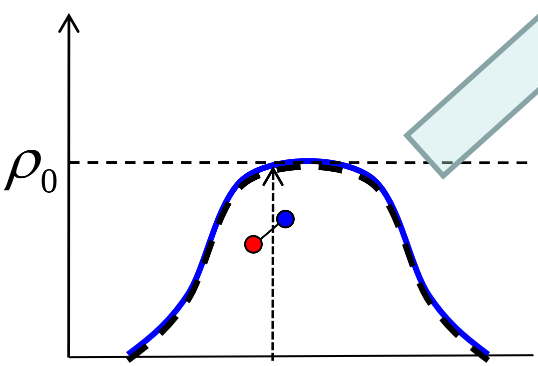
nucleon-nucleus system
(one nuclear matter)



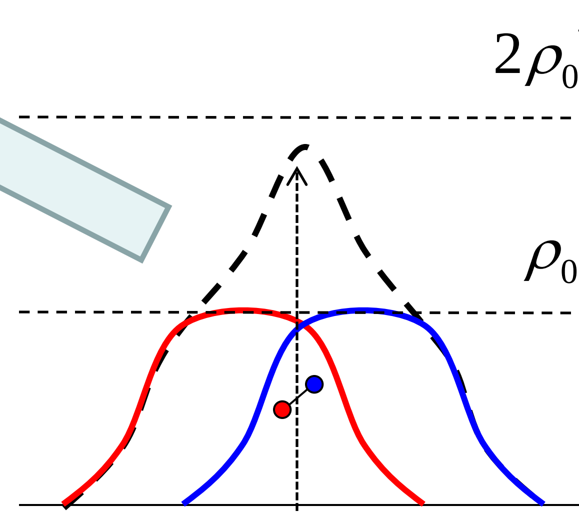


nucleus-nucleus system
(two nuclear matters)

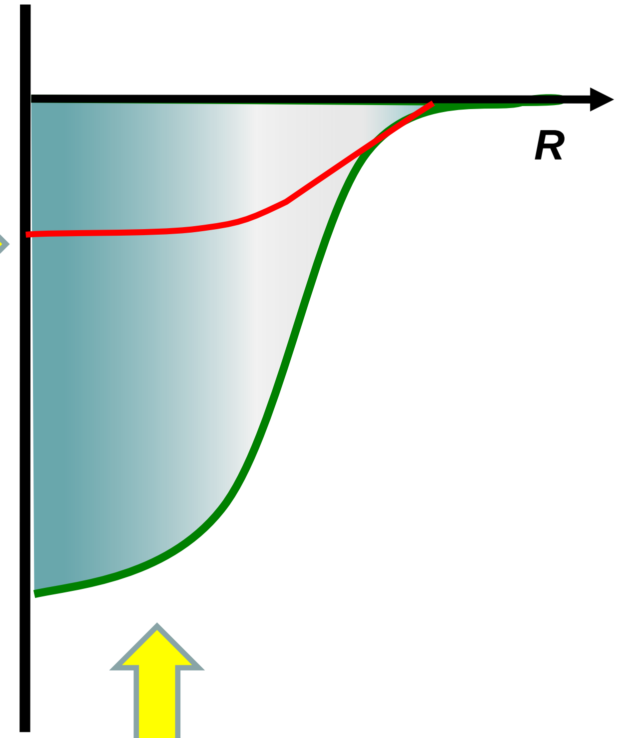


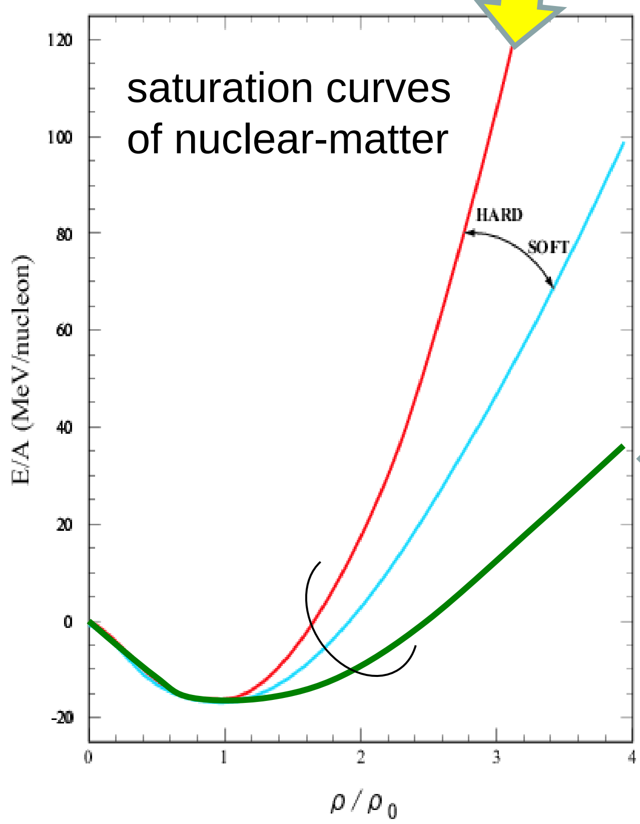


低密度 ⇔ 高密度



- *If the nuclear matter is* ***hard****, the central depth of the potential may become* ***shallow****.*





- *If the nuclear matter is* ***soft****, the central depth of the potential may become* ***deep****.*

*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)*

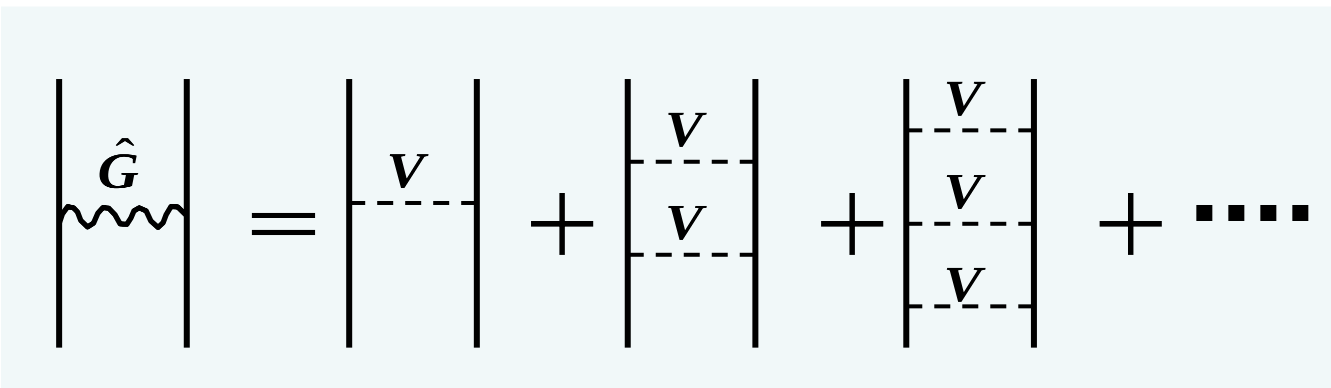
- ✓ *correct **energy dependence** over the wide range of incident energy, up to a few hundred MeV/u*

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

2. Microscopic theory for nucleus-nucleus interaction with a new complex G-matrix interaction, CEG07

Breuckner Theory (G-matrix theory)

- **無限核物質中**での**有効相互作用**を導出する理論
- 密度ρの核物質中で、Bethe-Goldstone方程式を解く
  ⇒媒質効果（Pauli effects, Binding effect etc.）を考慮した
  ladder diagram をすべて足しあげる。



$$G(\omega) = V + \sum_{\boldsymbol{q}_1, \boldsymbol{q}_2} V \frac{Q(\boldsymbol{q}_1, \boldsymbol{q}_2)}{\omega - e(q_1) - e(q_2) + i\varepsilon} G(\omega)$$

$Q(\boldsymbol{q}_1, \boldsymbol{q}_2)$: Pauli-Projection Operator

Complex G-matrix interaction（CEG07）

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

"**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

References:

- ✓ ***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）

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

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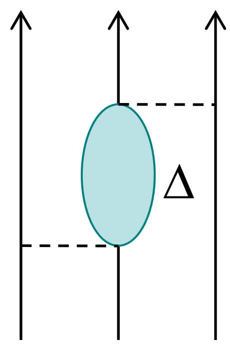
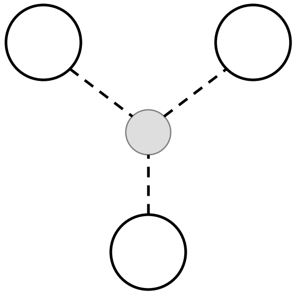
1. Three-body attraction (三体引力)

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



2. Three-body repulsion (三体斥力)

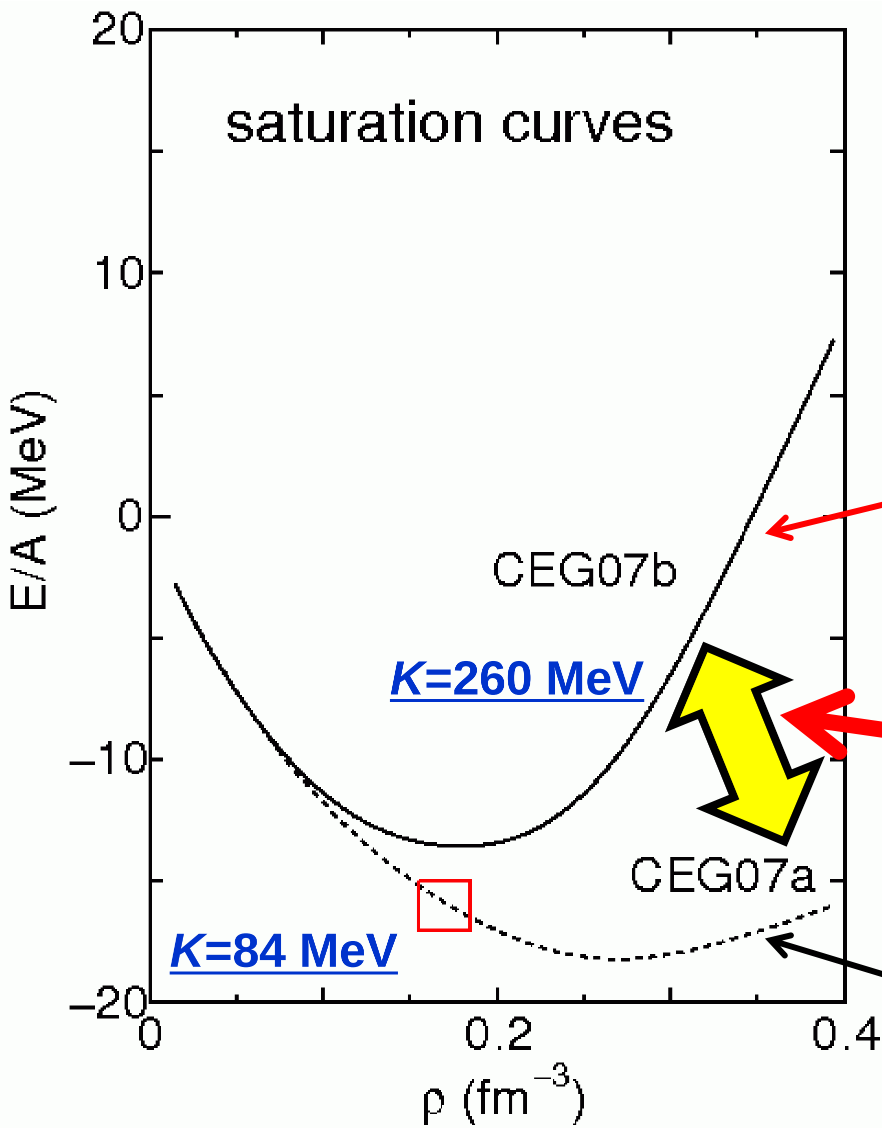
- originated the **triple-meson correlation**
- important at **high-density** region



In the ESC04 model

⇒ density-dependent effective two-body force

saturation curve in nuclear matter
with G-matrix interaction (CEG07)



ESC04 NN force
(Extended Soft-Core)
includes ***Three body force***

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

⇕

三体核力の効果が重要！

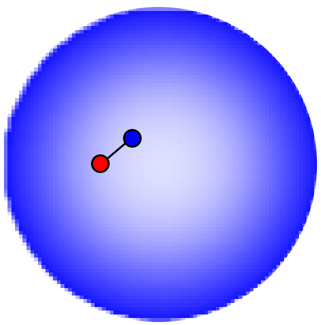
⇕

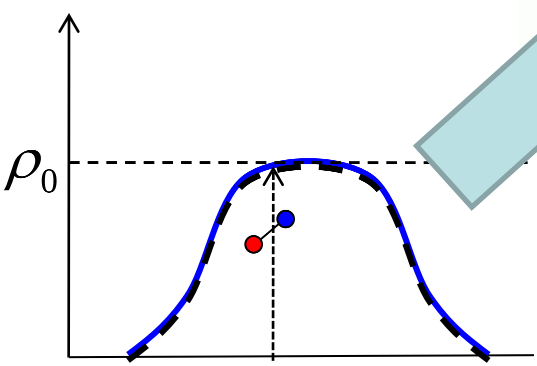
Two body force only

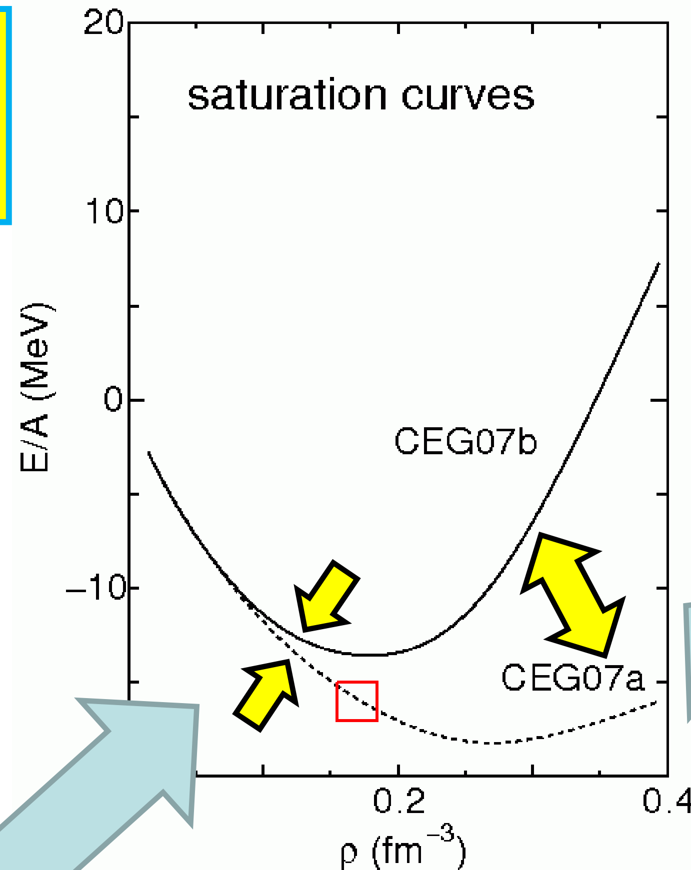
※ *K*=100 ～300 MeV : 不定性が大きい

有限核への適用 ⇒ 無限系で求めた有効核力を、有限系の核子密度でfolding

nucleon-nucleus system
(one nuclear matter)

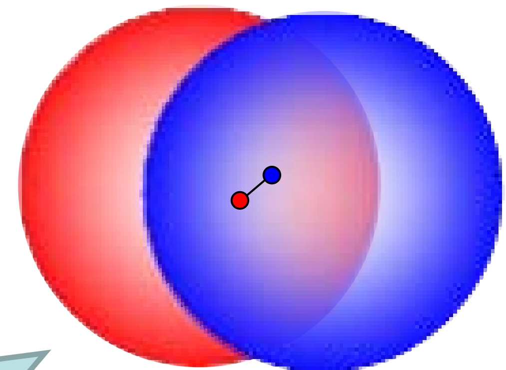


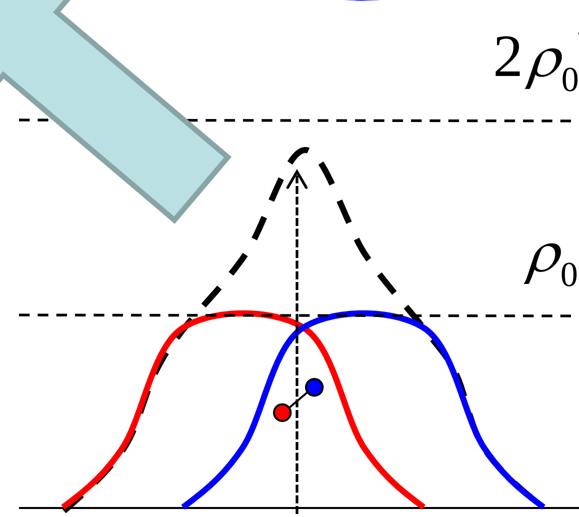




低密度 ⇔ 高密度

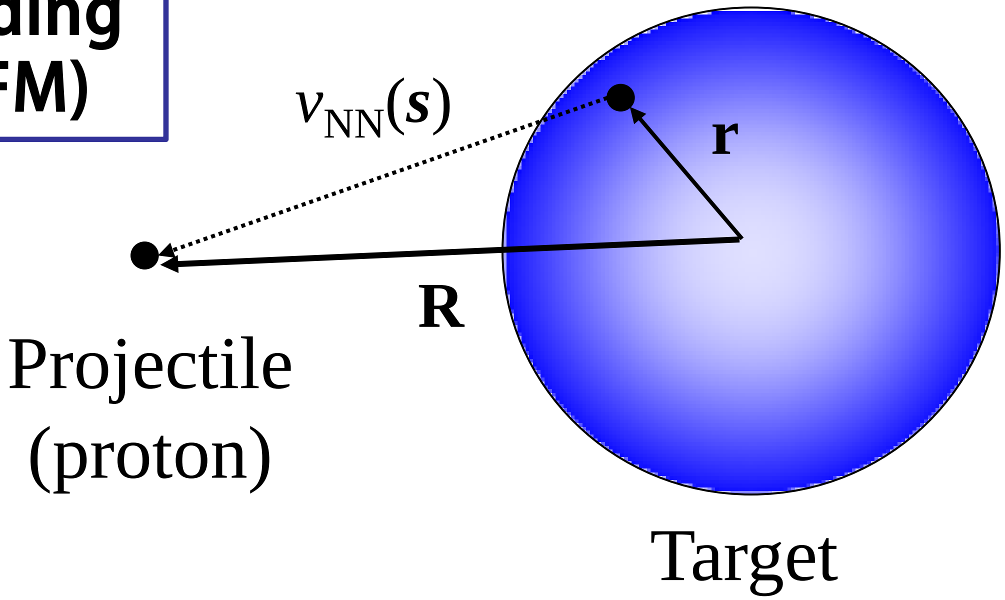
nucleus-nucleus system
(two nuclear matters)





I. Application to proton-nucleus scattering

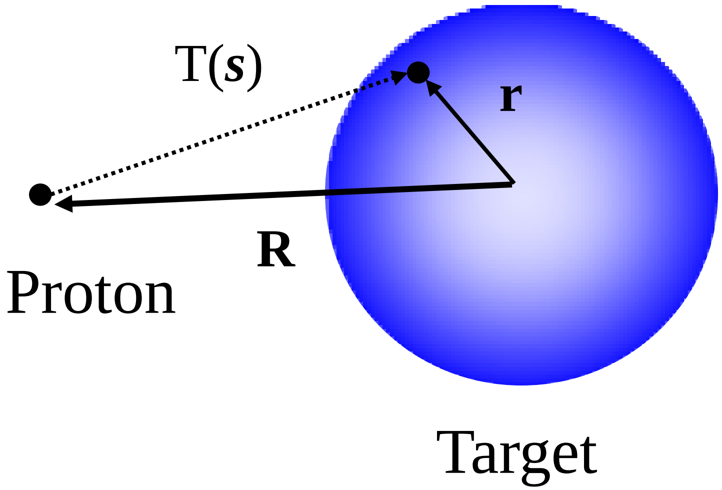
Single-Folding Model (SFM)



$$U_{SFM}(\mathbf{R}) = \int \rho(\mathbf{r}) v_{NN}(\mathbf{s}; \rho, E) d\mathbf{r}$$

CEG07

Single folding Potential
(Central part)

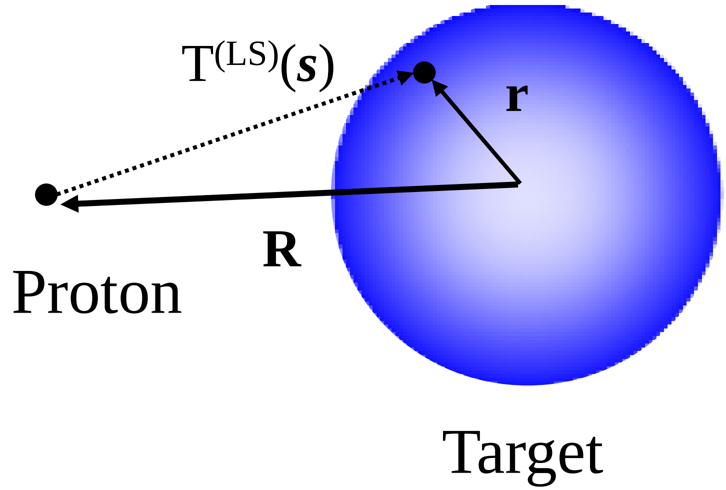


$$U_C(\mathbf{R}) = \int \rho(\mathbf{r}) T_D(\mathbf{R}, \mathbf{r}; k_F, E) d\mathbf{r}$$
$$+ \int \rho(\mathbf{R}, \mathbf{r}) T_{EX}(\mathbf{R}, \mathbf{r}; k_F, E) \exp(i\mathbf{k}_0 \cdot \mathbf{s}) d\mathbf{r}$$
$$= V_C(\mathbf{R}) + iW_C(\mathbf{R})$$

Complex G-matrix interaction (CEG07)

$$T_{D,EX} = T_{D,EX}^{(real)} + iT_{D,EX}^{(imag)}$$

Single folding Potential (LS part)



$$U_{LS}(\mathbf{R})\ell\cdot\sigma=\sum_i\int\varphi_i^*(\mathbf{r})T_D^{(LS)}(\mathbf{R},\mathbf{r};k_F,E)\mathbf{L}\cdot\mathbf{S}\varphi_i(\mathbf{r})d\mathbf{r}$$

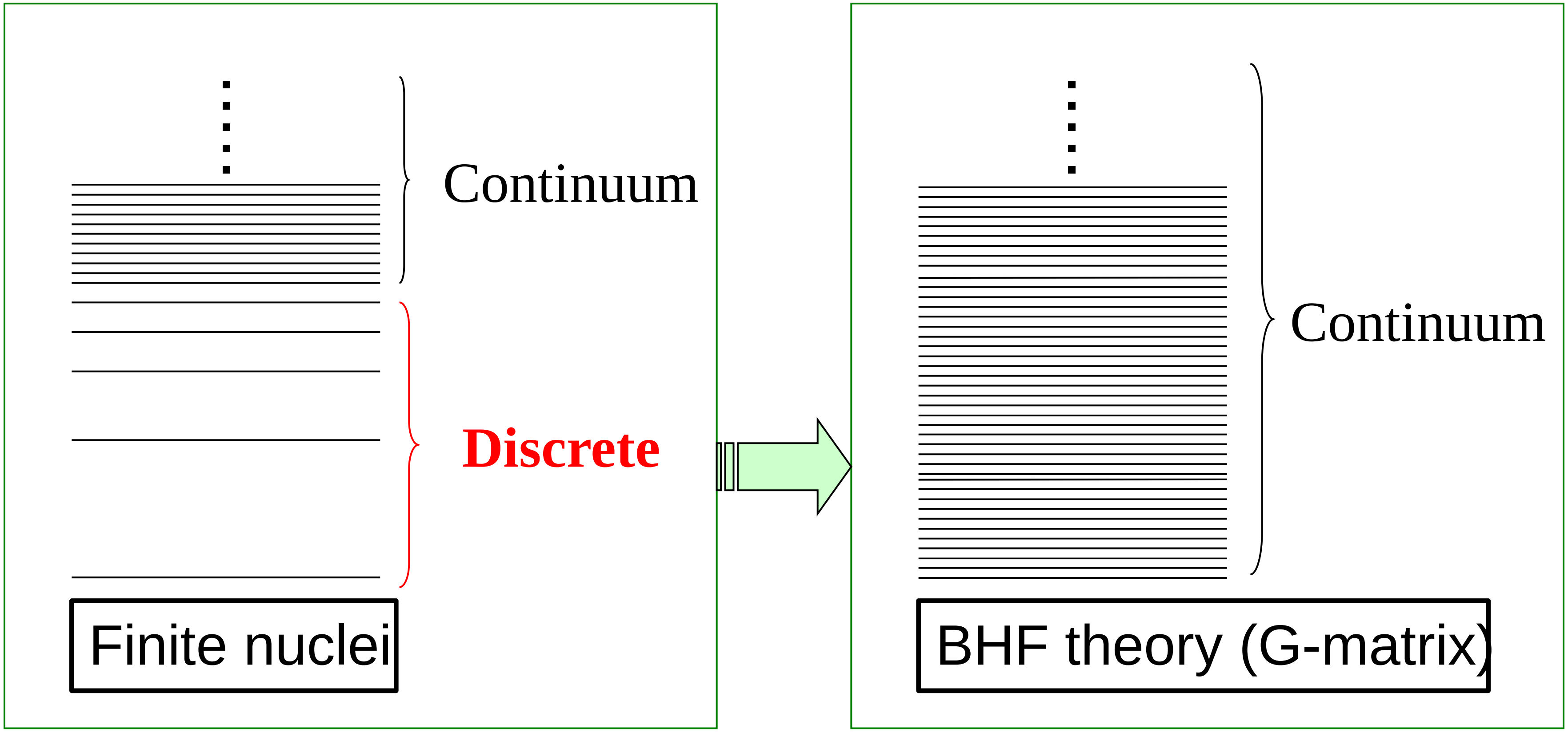
$$+\sum_i\int\varphi_i^*(\mathbf{r})T_{EX}^{(LS)}(\mathbf{R},\mathbf{r};k_F,E)\mathbf{L}\cdot\mathbf{S}\varphi_i(\mathbf{R})\exp(i\mathbf{k}_0\cdot\mathbf{s})d\mathbf{r}$$

$$=\left(V_{LS}(\mathbf{R})+iW_{LS}(\mathbf{R})\right)\ell\cdot\sigma$$

Complex G-matrix interaction (CEG07)

$$T_{D,EX}^{(LS)}=T_{D,EX}^{(LS,real)}+iT_{D,EX}^{(LS,imag)}$$

Renormalization of the imaginary part strength

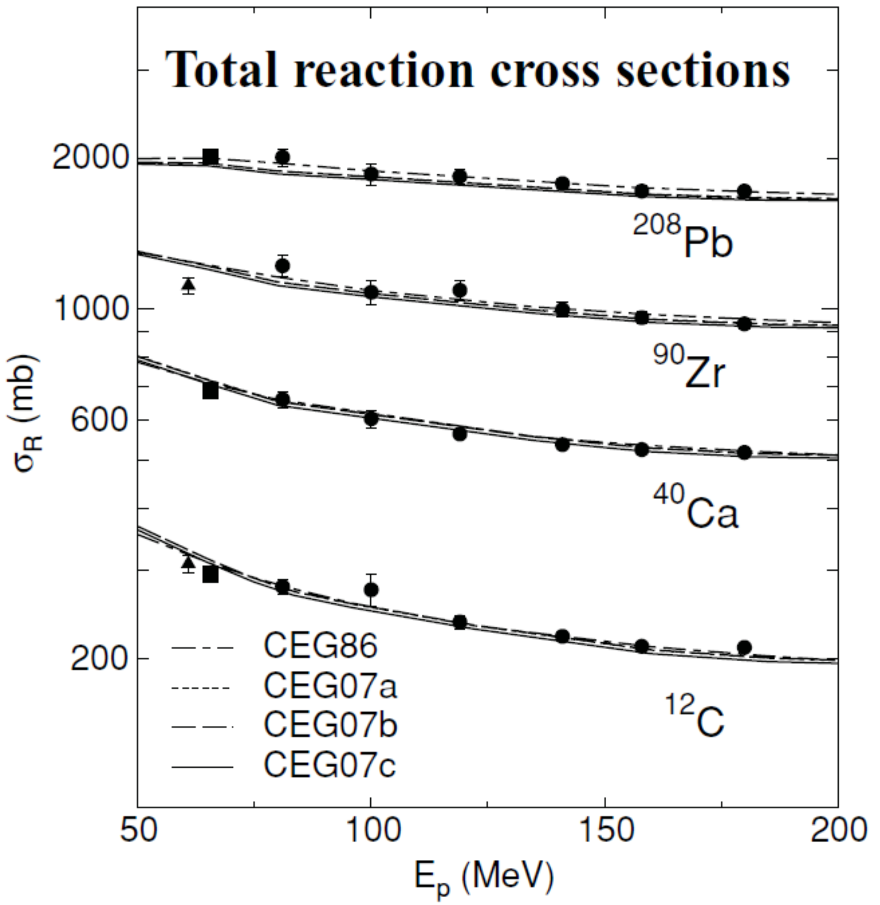


So, we renormalize (suppress) the imaginary part strength

$$V(\mathbf{R}) + iN_W W(\mathbf{R}) + \left(V_{LS}(\mathbf{R}) + iN_W W_{LS}(\mathbf{R})\right)\ell \cdot \sigma$$

Renormalized factor N_W is fixed to reproduce measured <u>total reaction cross sections</u>

$$V(\mathbf{R}) + i\underline{N_W W}(\mathbf{R}) + \left(V_{LS}(\mathbf{R}) + i\underline{N_W W_{LS}}(\mathbf{R})\right)\ell\cdot\sigma$$



CEG07a(two-body only)

$N_W = 0.60$

CEG07b(TBR+TBA)

$N_W = 0.60$

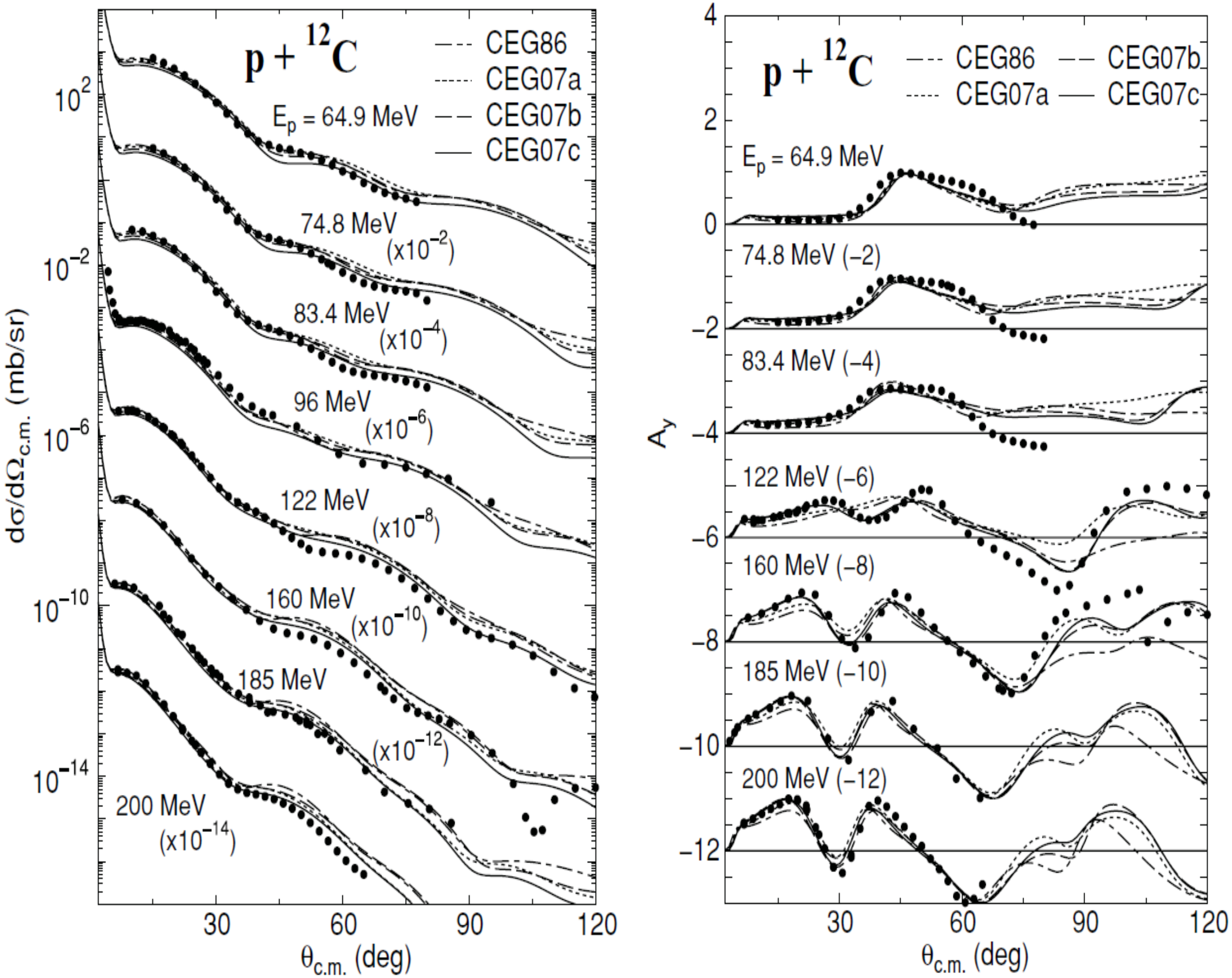
CEG07c(TBR+TBA+ω)

$N_W = 0.65$

CEG86 (two-body only)

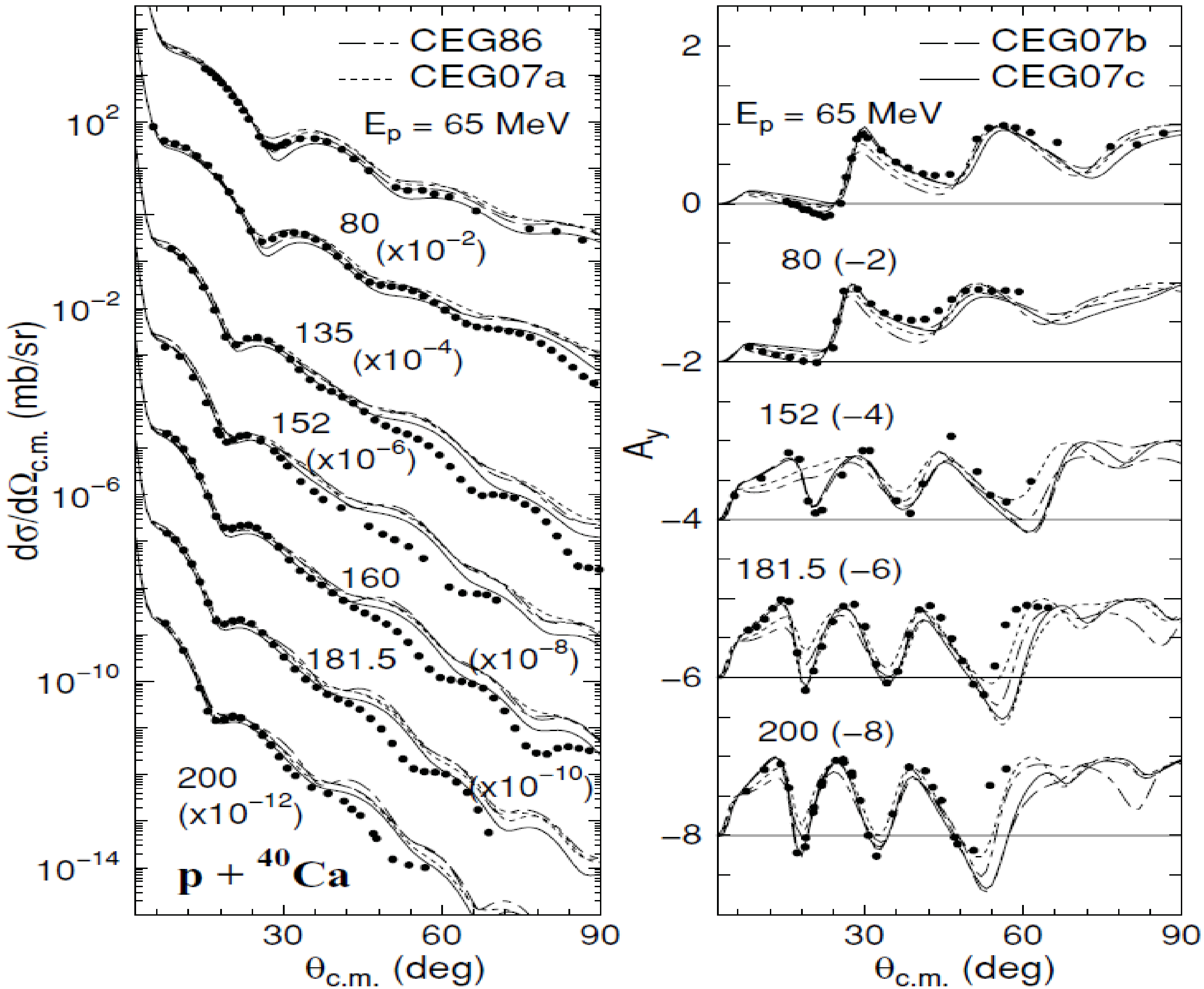
$\mathbf{N_W = 0.80}$

CEG07 folding-model cal. of proton scattering by ^{12}C



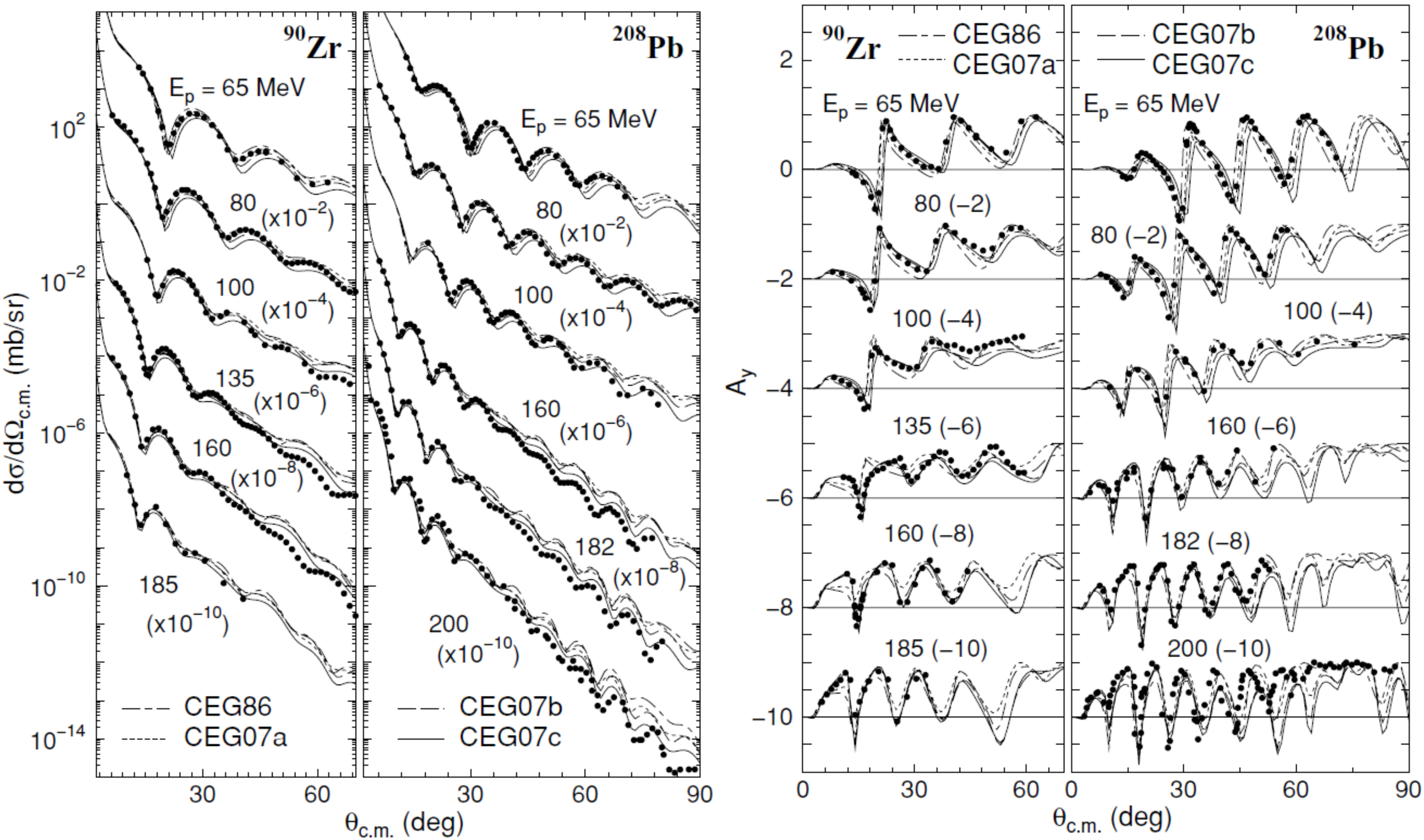
T.Furumoto, Y. Sakuragi and Y. Yamamoto, Phys.Rev.C 78 (2008) 044610

CEG07 folding-model cal. of proton scattering by ^{40}Ca



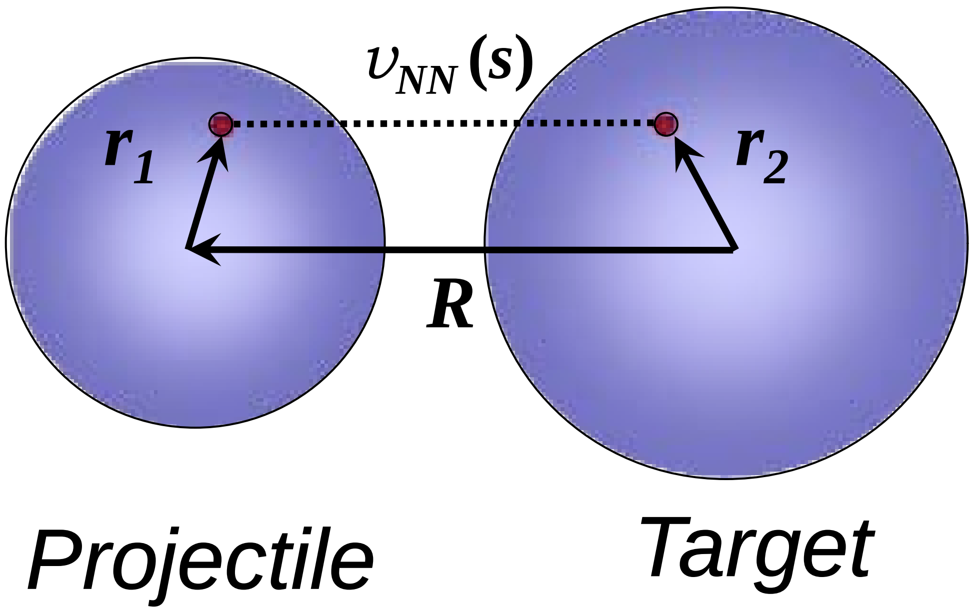
T.Furumoto, Y. Sakuragi and Y. Yamamoto, Phys.Rev.C 78 (2008) 044610

CEG07 folding-model cal. of proton scattering by ^{90}Zr & ^{208}Pb



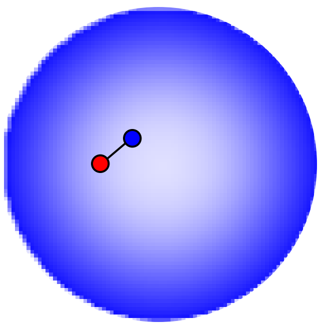
T.Furumoto, Y. Sakuragi and Y. Yamamoto, Phys.Rev.C 78 (2008) 044610

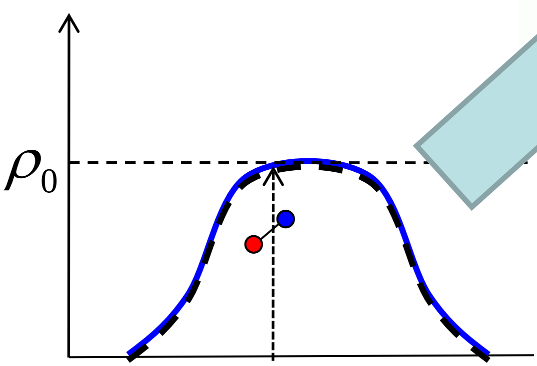
II. Application to heavy-ion scattering/reractions

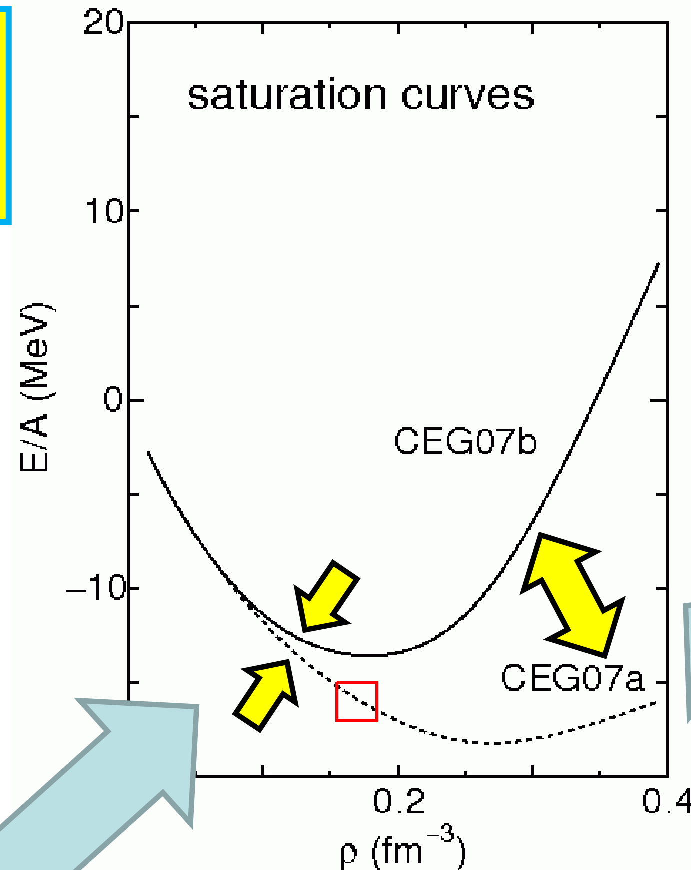


有限核への適用 ⇒ 無限系で求めた有効核力を、有限系の核子密度でfolding

nucleon-nucleus system
(one nuclear matter)

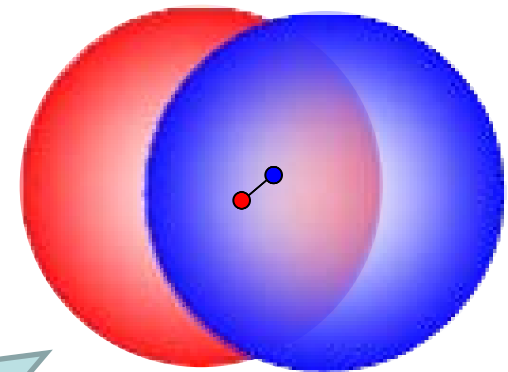


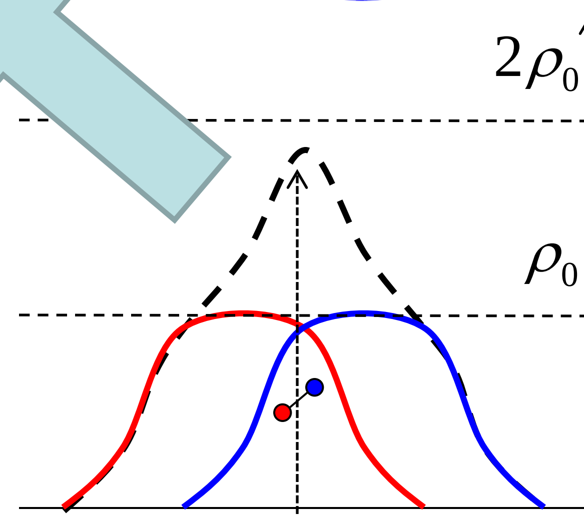




低密度 ⇔ 高密度

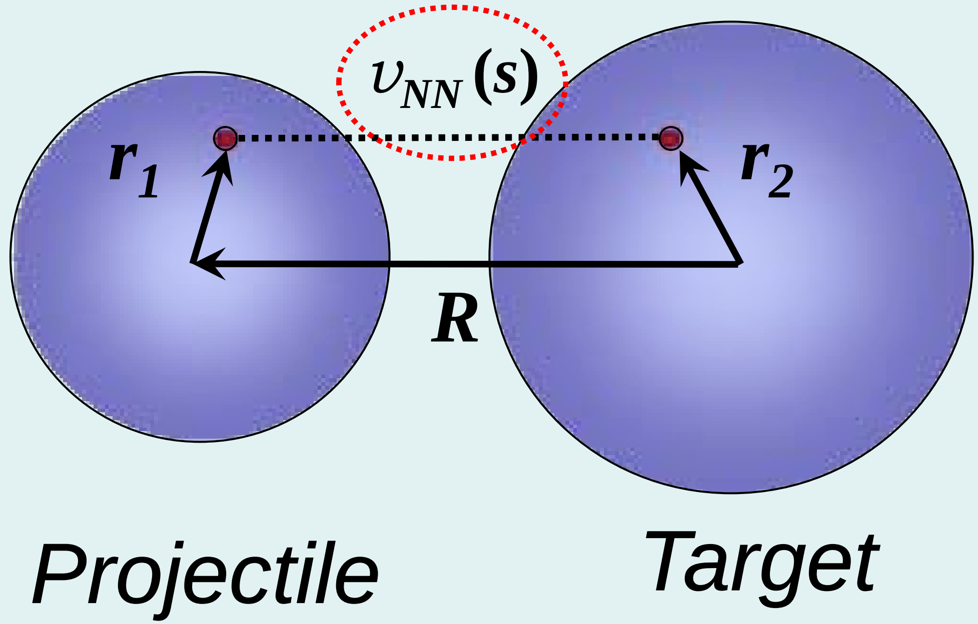
nucleus-nucleus system
(two nuclear matters)





有限核への適用　⇒　無限系で求めた有効核力を、有限系の核子密度でfolding

Double-Folding Model (DFM)

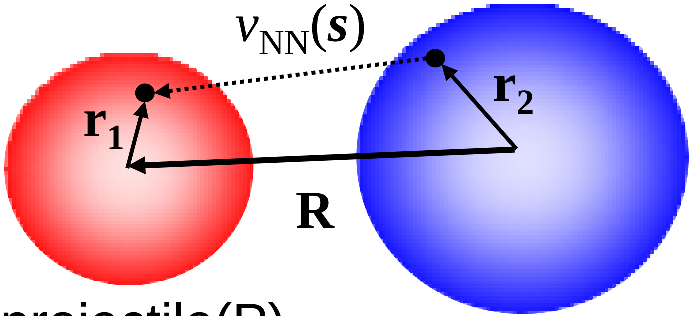


$$U_{DF}(\boldsymbol{R}) = \int \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2)\upsilon_{NN}(\boldsymbol{s};\rho,E)d\boldsymbol{r}_1 d\boldsymbol{r}_2$$

三体力を含んだ有効核力（CEG07）

- 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)



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

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

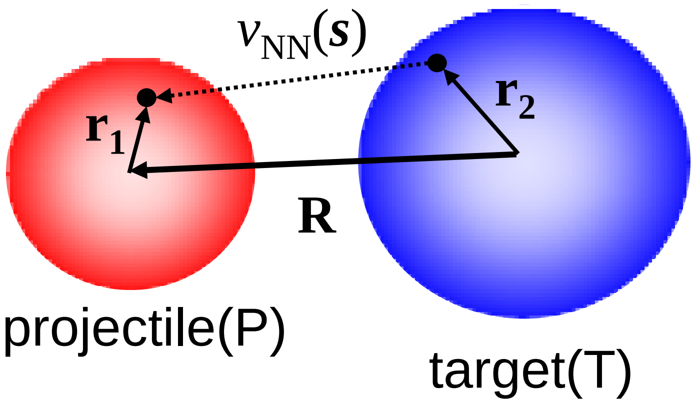
$$= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})$$

- 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) 044612

Double folding Potential with complex-G (CEG07)



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

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

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

✓Renormalization factor for the **imaginary** part

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

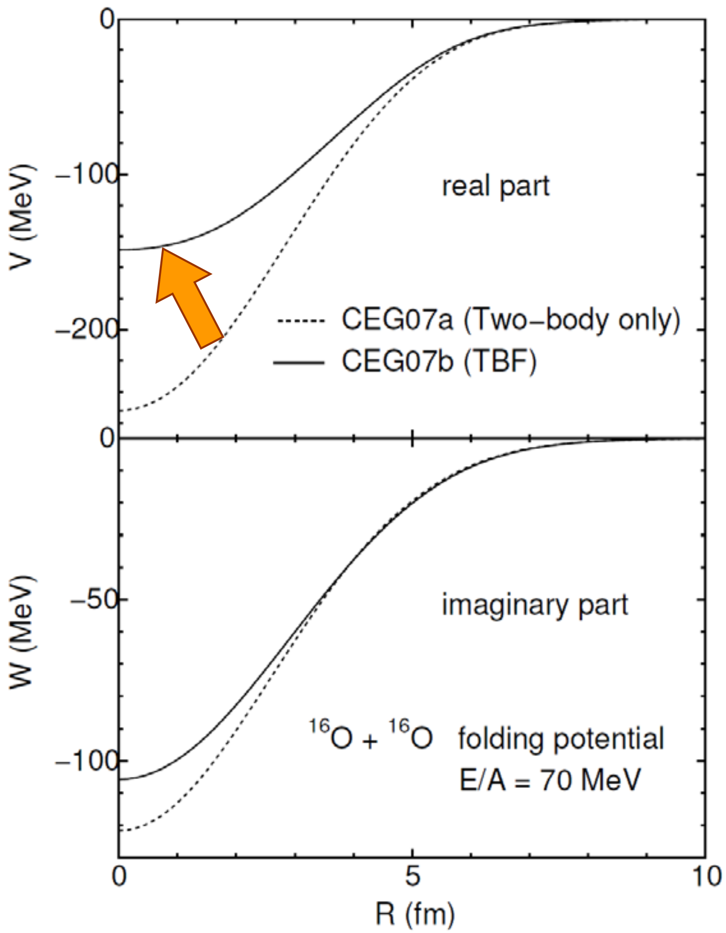
$^{16}O+^{16}O$: bench-mark system to test DFM

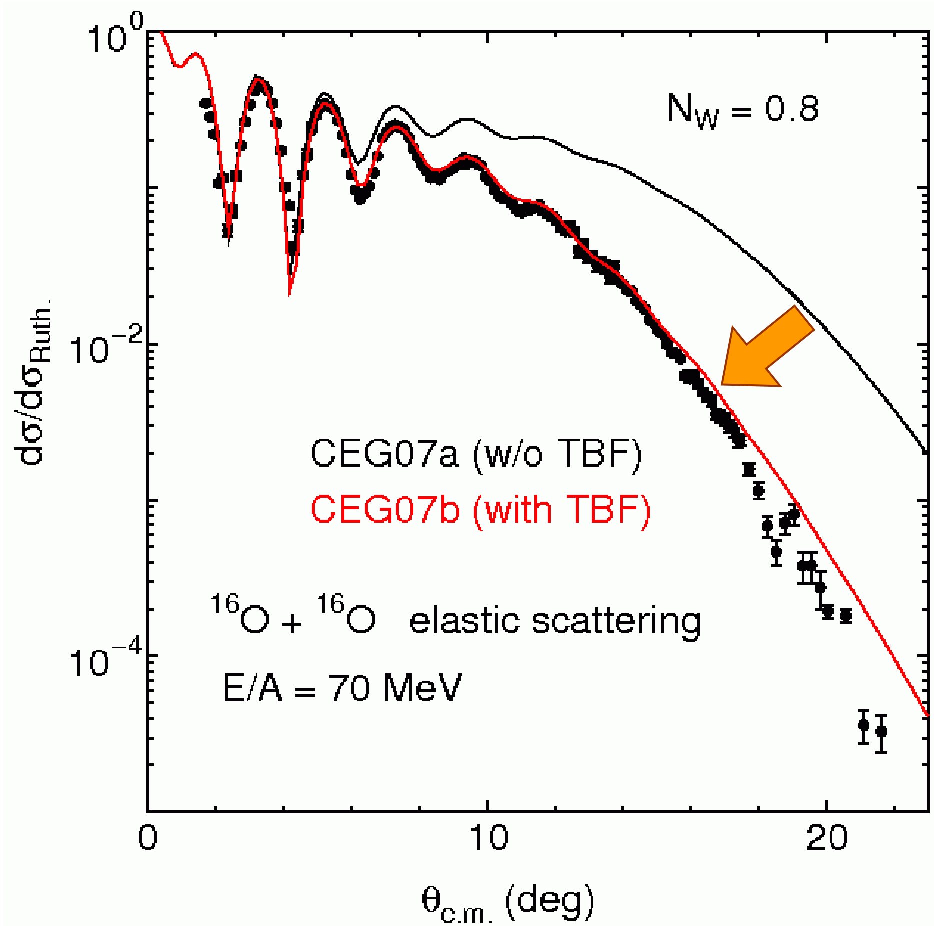
Frozen-density approx. (FDA)

$$\rho = \rho_1 + \rho_2$$

$^{16}O+^{16}O$ Elastic Scattering at ***E/A* = 70** MeV : DFM with CEG07

⇒ decisive effect of Three-body force (mainly TBR) is clearly observed !





T.Furumoto, Y. Sakuragi , Y. Yamamoto, (Phys. Rev. C 80 (2009) 04461

三体核力が決定的に重要

$^{16}O+^{16}O$: bench-mark system to test DFM

Frozen-density approx. (FDA)

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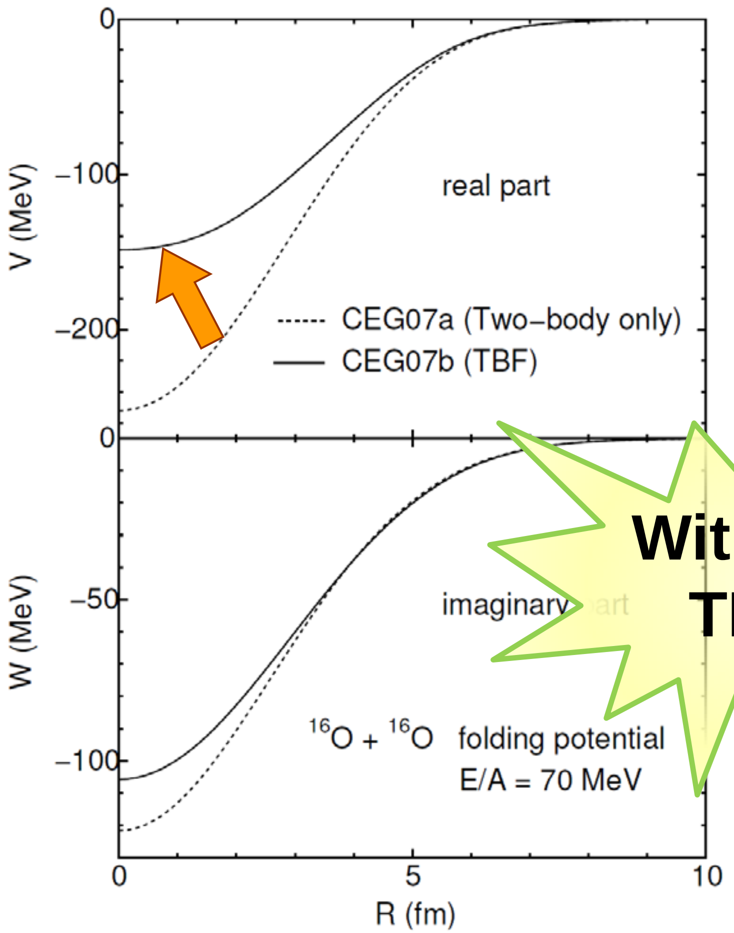
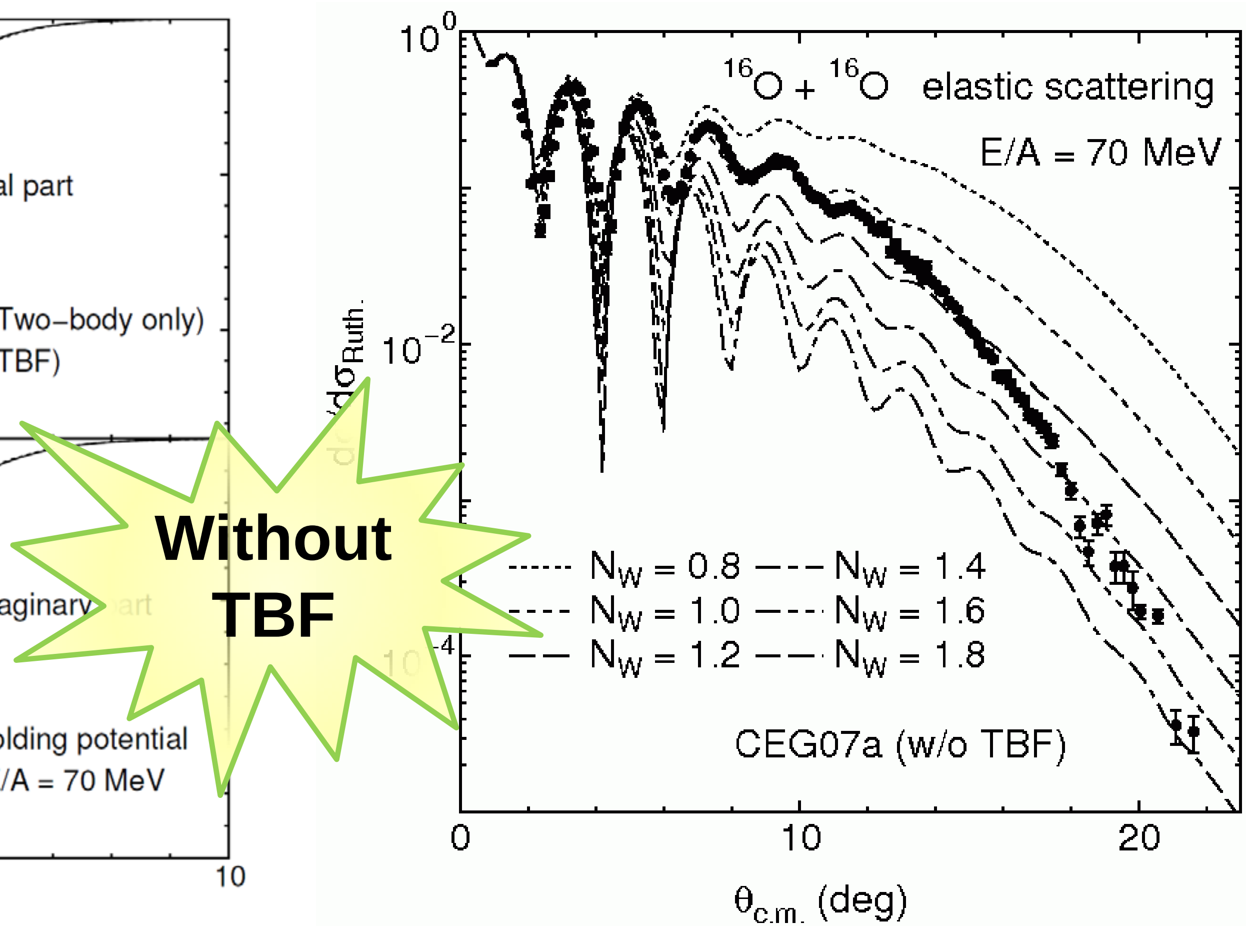
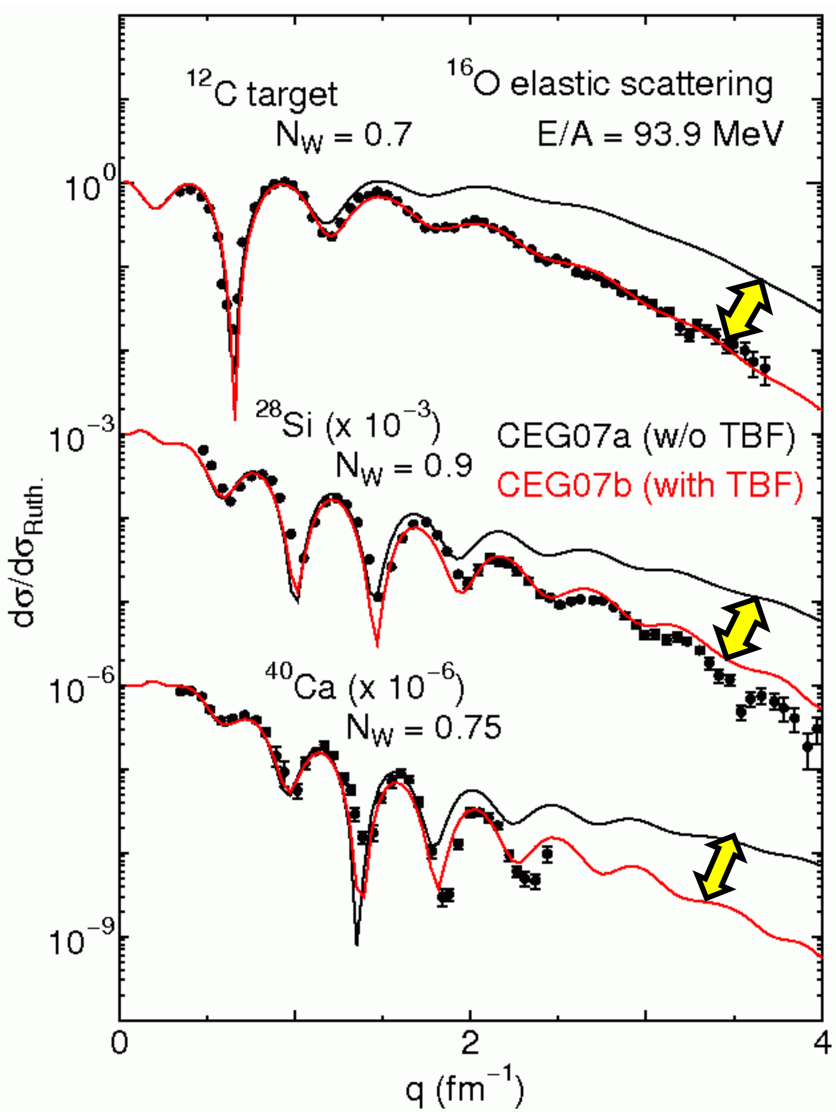




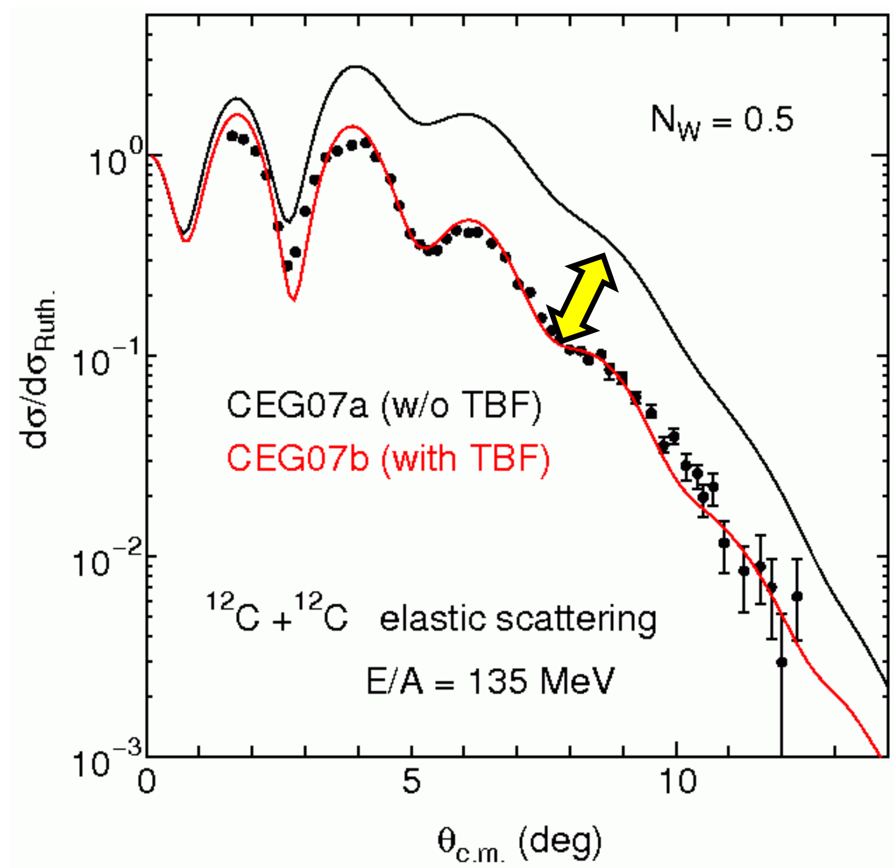
T.Furumoto, Y. Sakuragi , Y. Yamamoto, (Phys. Rev. C 80 (2009) 04461

三体核力が決定的に重要

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



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



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

三体核力が決定的に重要

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

Applications of microscopic FMP to

1. *reaction calculations (CC, CDCC etc.)*

2. *scattering of unstable nuclei*

Microscopic Coupled Channel (MCC) with CEG07

Coupled Channel equation

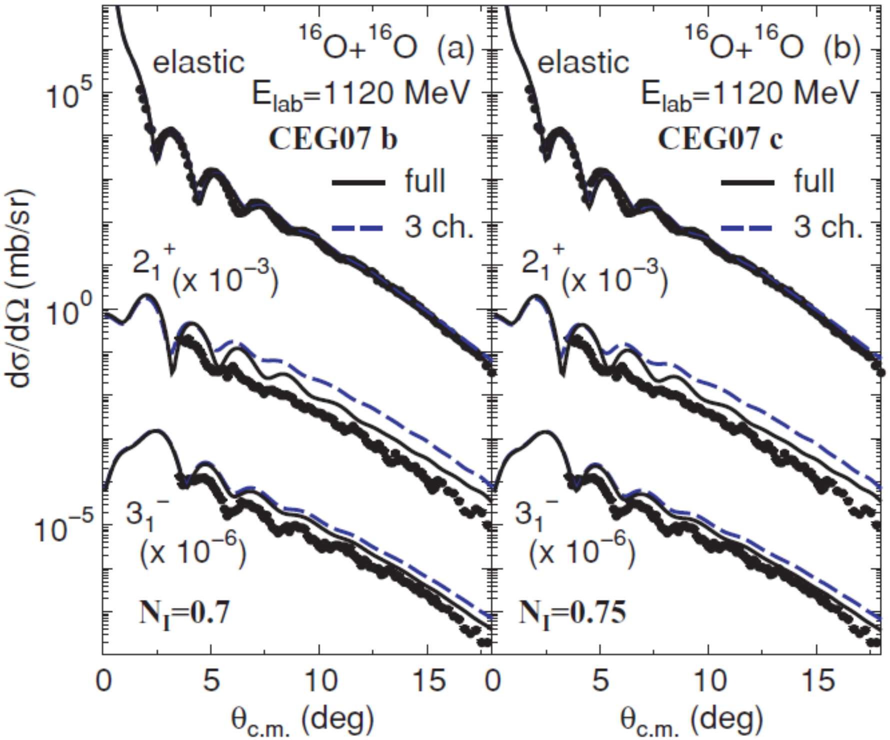
$$\left[T_R + U_{\alpha\alpha}(\mathbf{R}) - E_\alpha\right]\chi_\alpha(\mathbf{R}) = -\sum_{\beta\neq\alpha}^{N} U_{\alpha\beta}(\mathbf{R})\,\chi_\beta(\mathbf{R})$$

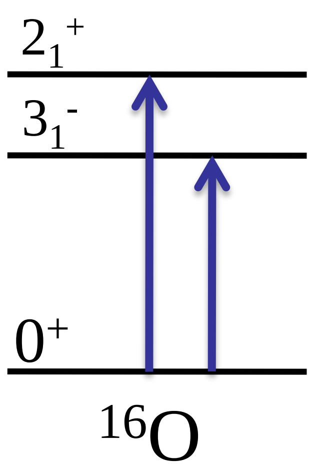
$$U_{\alpha\beta}(\boldsymbol{R}) = \int \underline{\rho_{00}^{(P)}(\boldsymbol{r}_1)}\,\underline{\rho_{\alpha\beta}^{(T)}(\boldsymbol{r}_2)}\,\boxed{v_{NN}(\boldsymbol{s};\rho,E)}\,d\boldsymbol{r}_1 d\boldsymbol{r}_2 = V_{\alpha\beta} + iW_{\alpha\beta}$$

transition density CEG07

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

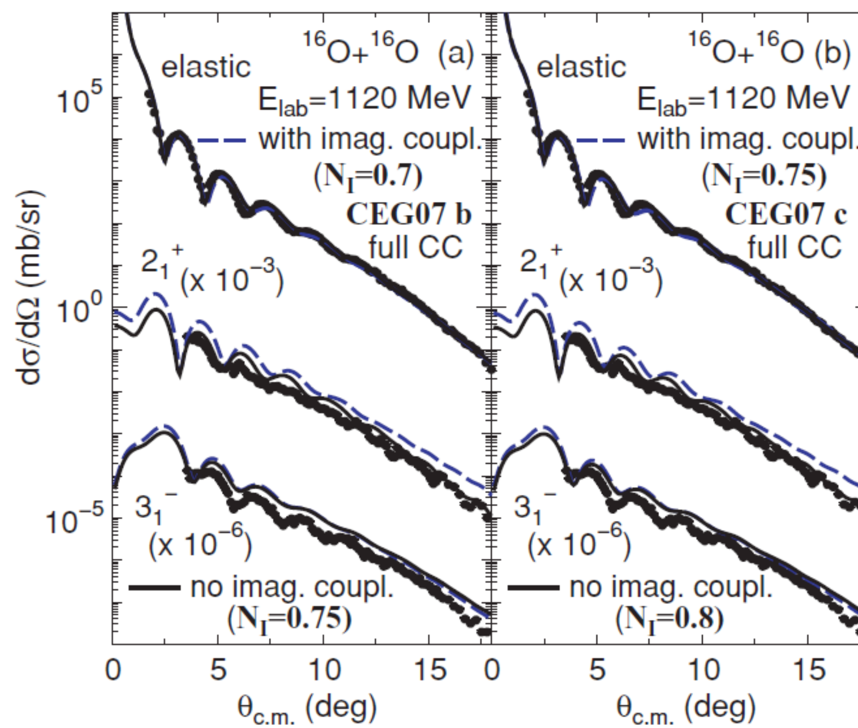
by M.Takashina, T. Furumoto, Y.Sakuragi
PRC **81, 047605 (2010)**





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

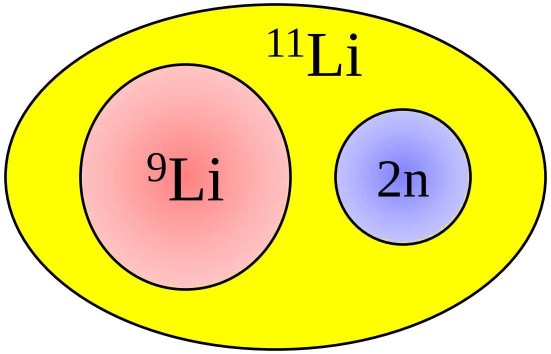
- **^{9}Li density** : proton, neutron ⇒ single Gaussian form

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

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

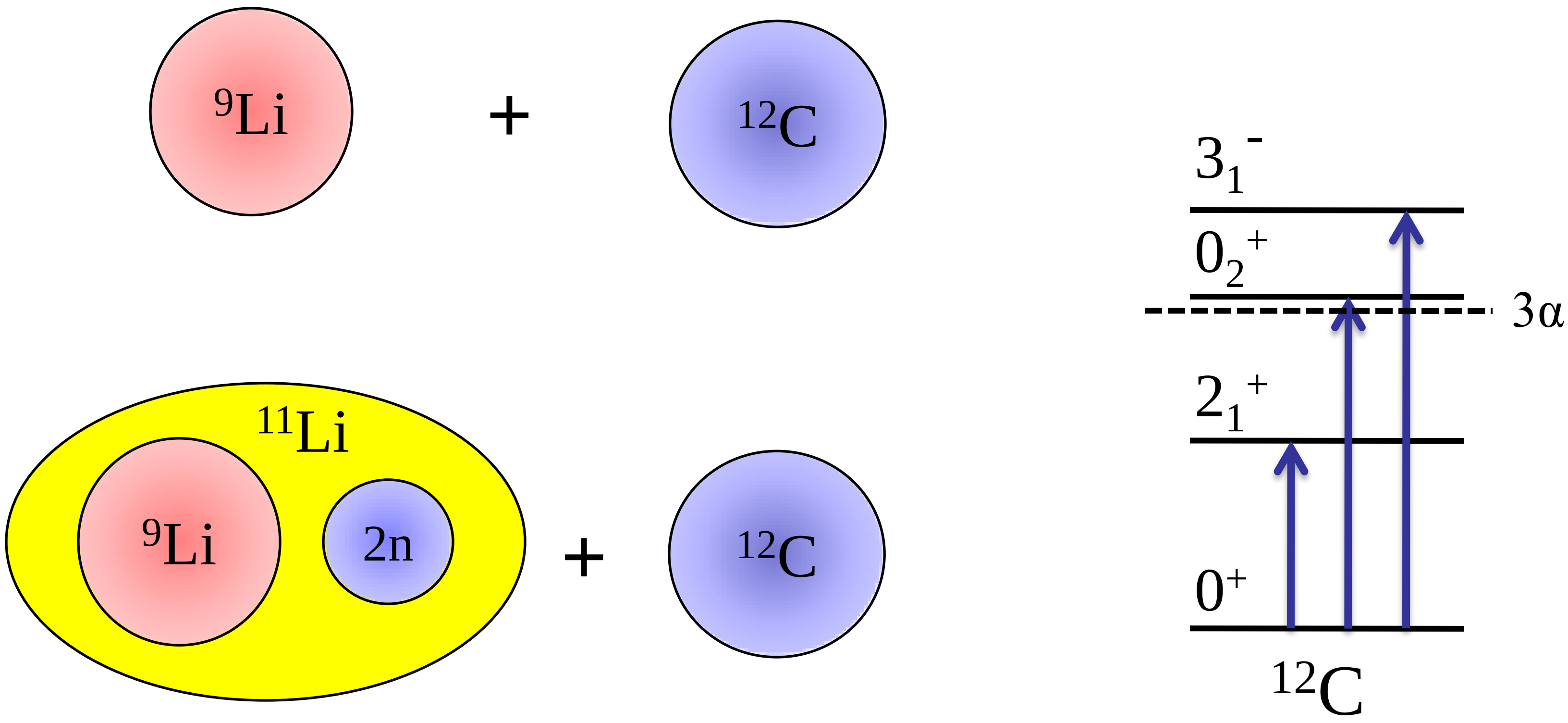
$$\rho^{(^{11}\text{Li})}(r) = \left\langle \psi_0(R) \,\middle|\, \rho^{(^{9}\text{Li})}(\vec{r} - \frac{2}{11}\vec{R}) + \rho^{(2\text{n})}(\vec{r} + \frac{9}{11}\vec{R}) \,\middle|\, \psi_0(R) \right\rangle$$

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



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

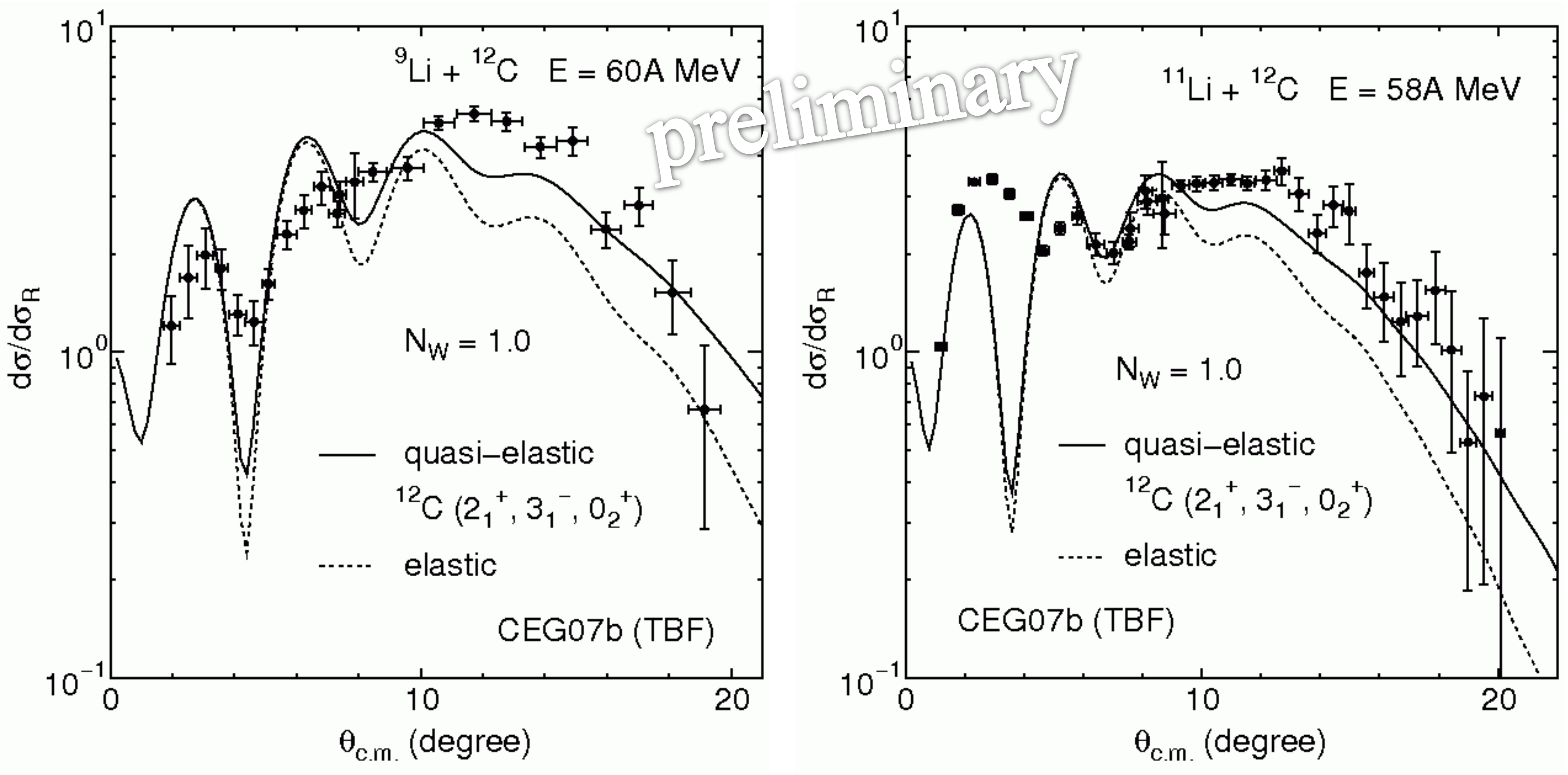


$$U_{ij}^{DFM}(\mathbf{R}) = V_{ij}^{DFM}(\mathbf{R}) + iN_W W_{ij}^{DFM}(\mathbf{R})$$

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

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

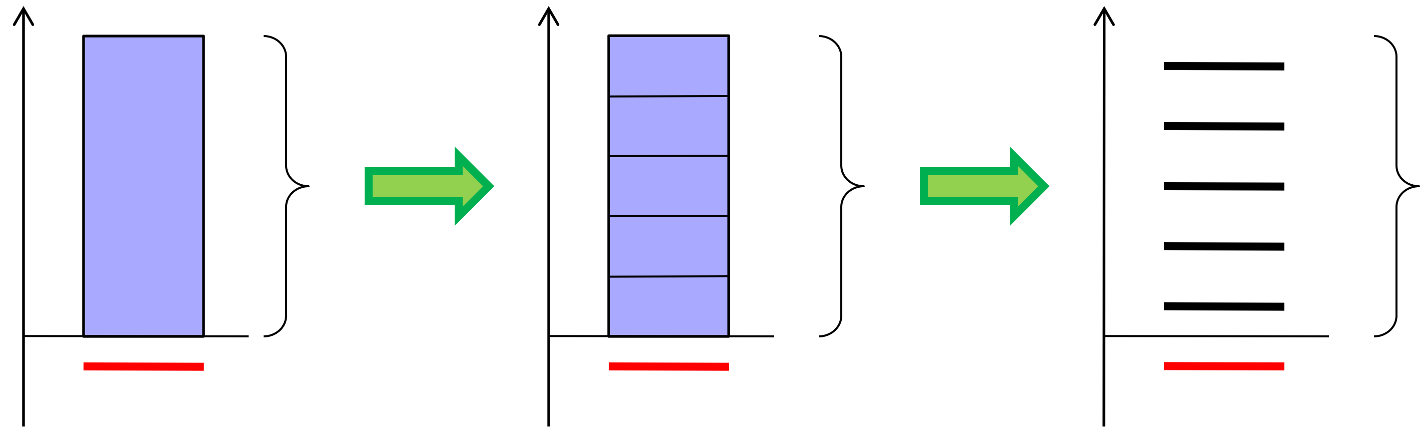
$$U_{DFM}(\mathbf{R}) = V_{DFM}(\mathbf{R}) + iN_W W_{DFM}(\mathbf{R})$$

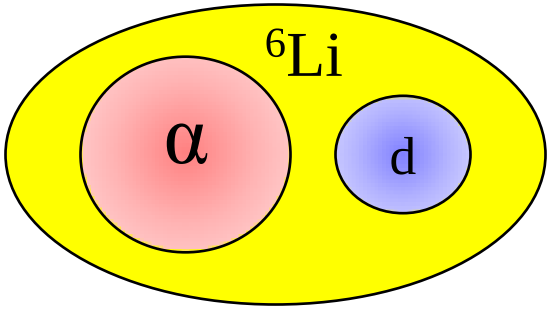


Exp. data : J. J. Kolata et al., (Phys. Rev. Lett. 69 (1993) 2631

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

⇒ Continuum-Discretized Coupled-Channels (CDCC) method





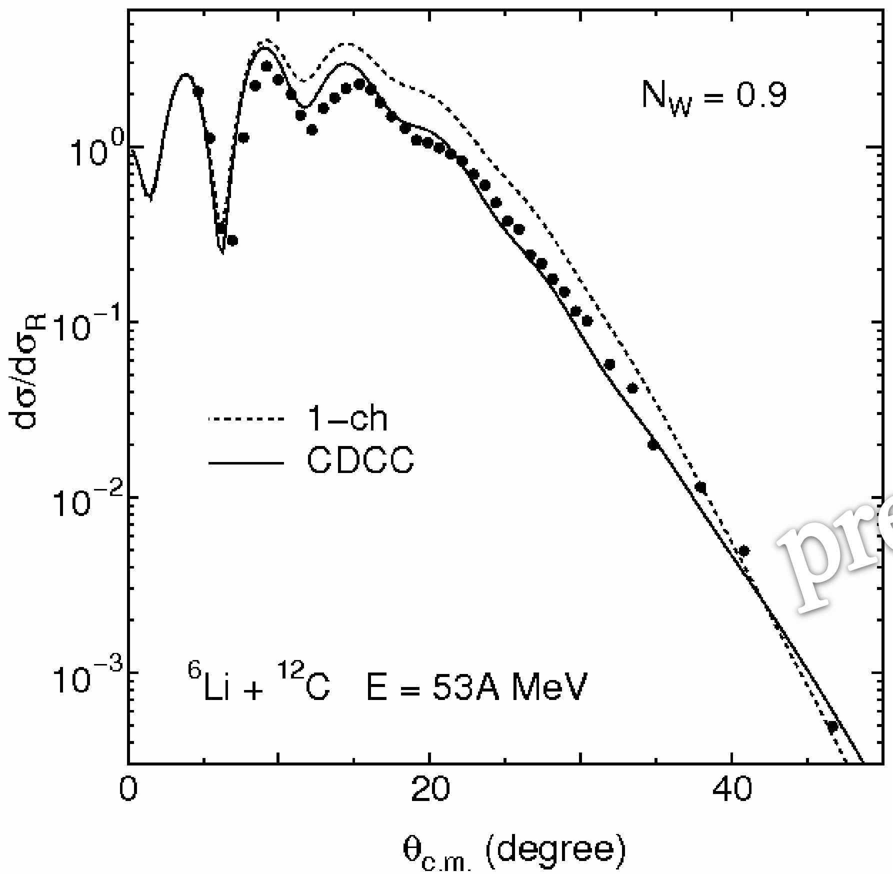
$$U_{ij}^{DFM}(\mathbf{R}) = V_{ij}^{DFM}(\mathbf{R}) + iN_W W_{ij}^{DFM}(\mathbf{R})$$

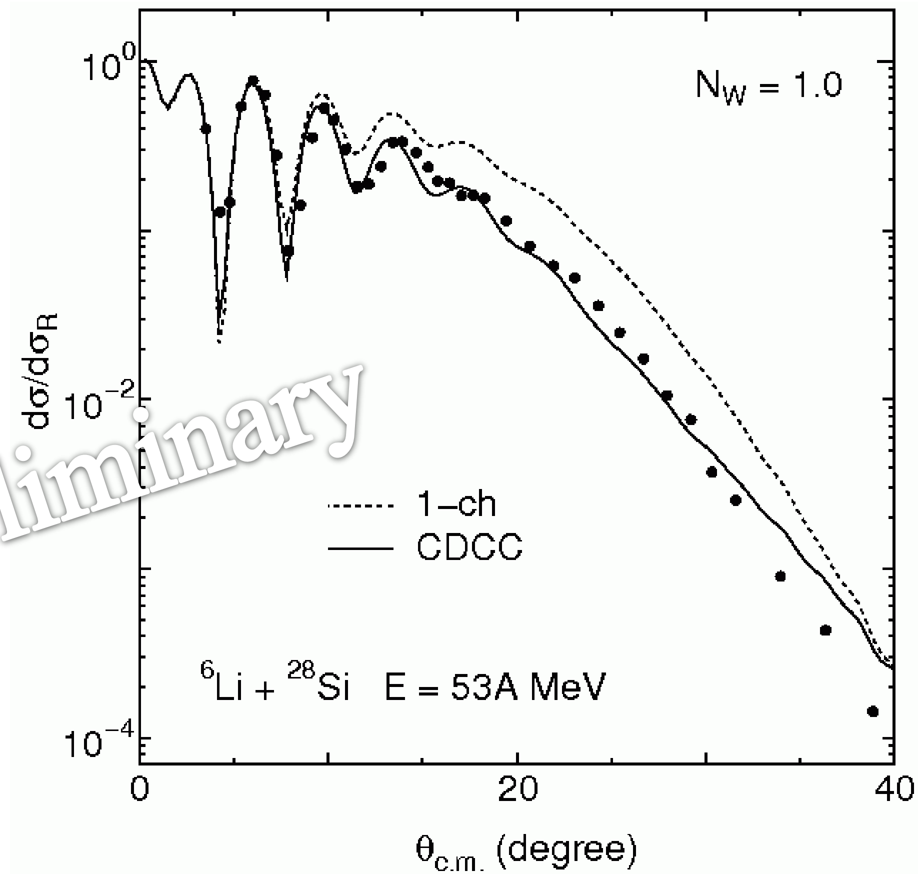
Y. Sakuragi, M, Ito, Y. Hirabayashi , C. Samanta (Prog. Theor. Phys. 98 (1997) 521)

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

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

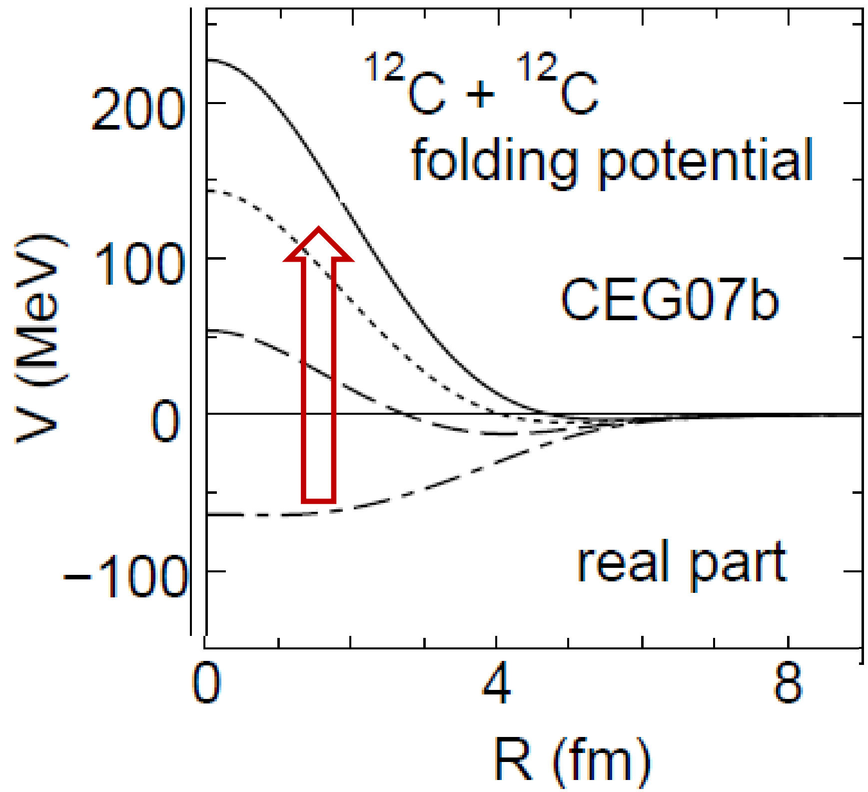
$$U_{ij}^{DFM}(\mathbf{R}) = V_{ij}^{DFM}(\mathbf{R}) + iN_W W_{ij}^{DFM}(\mathbf{R})$$





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

3. *attractive-to-repulsive transition* of the nucleus-nucleus potentials *with the increase of collision energy*



原子核間相互作用が
E/A=100～400 MeVの
間で引力→斥力に転移

丁度、RIBFで多くの核反応実験が行われるエネルギー領域

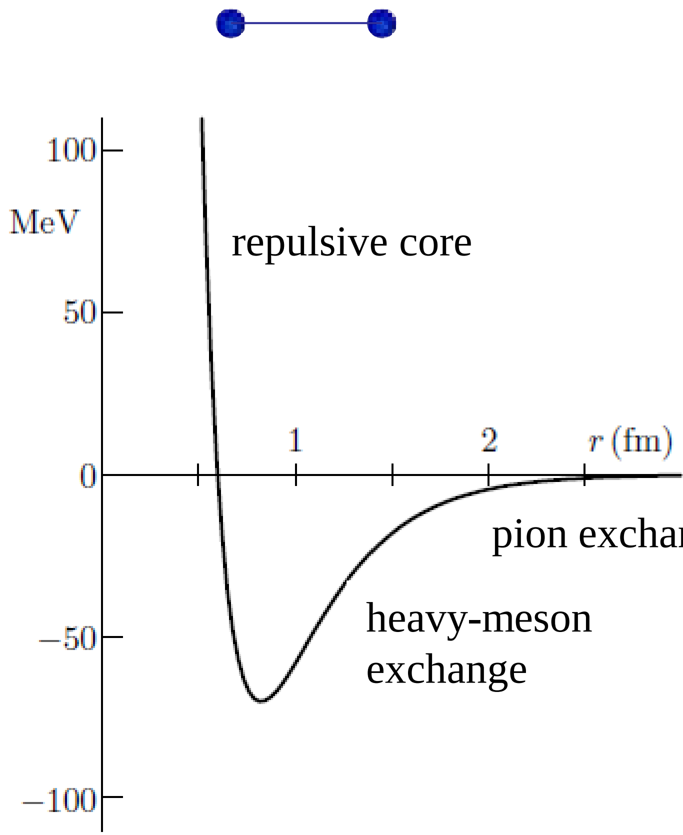
T. Furumoto, Y. Sakuragi, Y. Yamamoto, Phys. Rev. C 82, 044612 (2010)

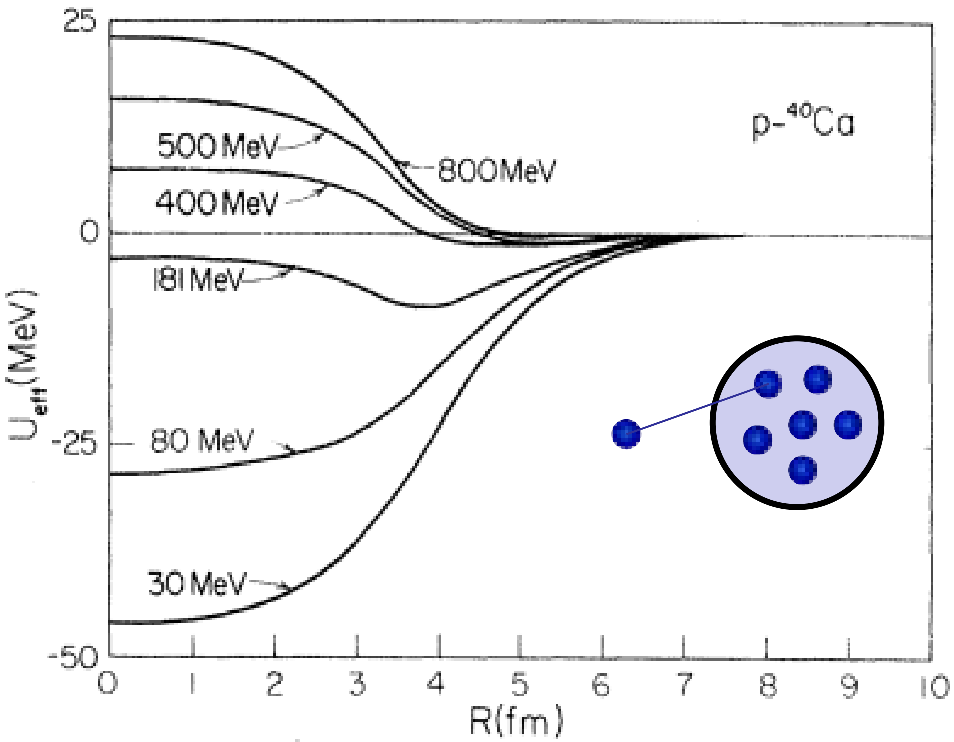
◆ ***NN interaction :***

- *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)*

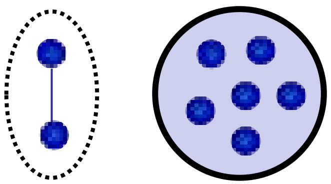




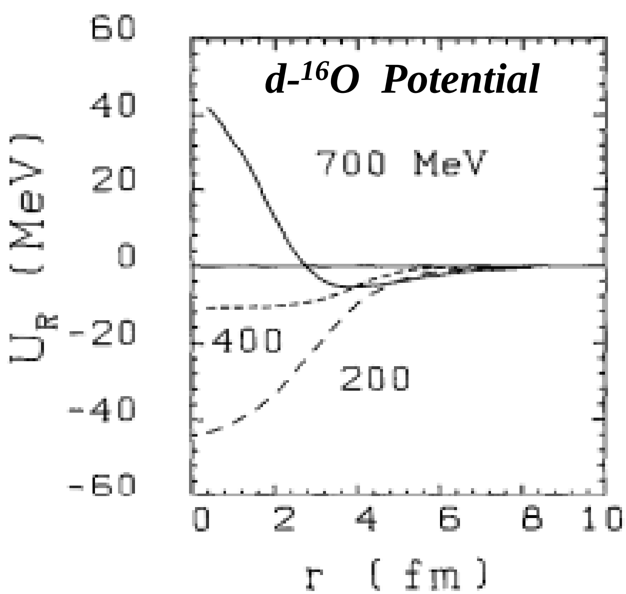
L.G.Arnold, (Phys.Rev.C25(1982)936

◆ *d-A interaction :*

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



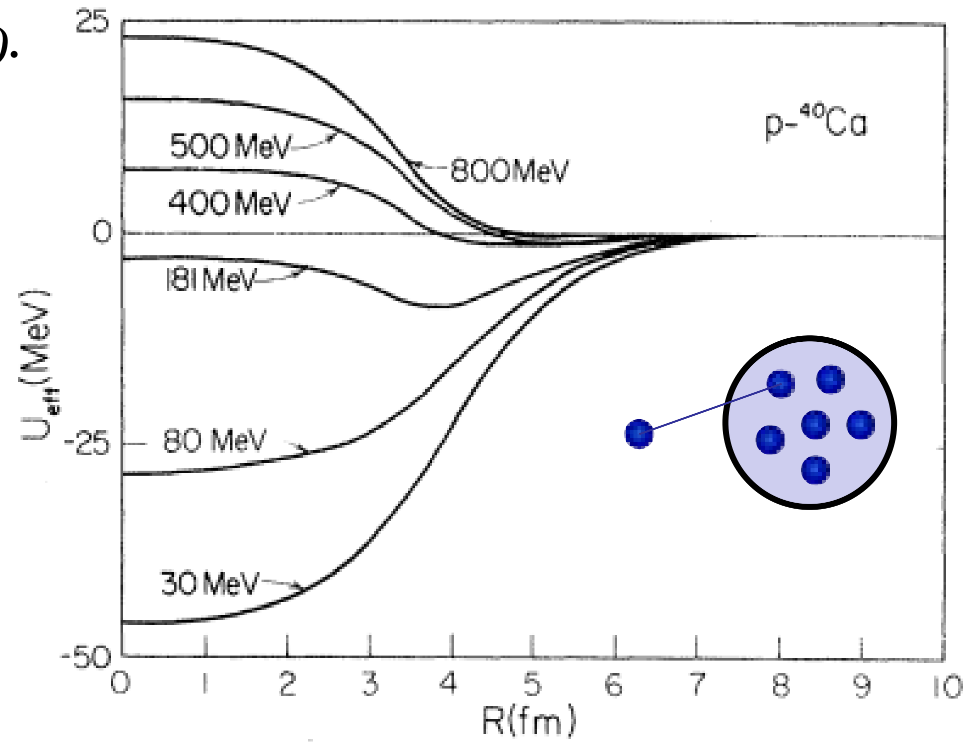
Y. Sakuragi, M. Tanifuji, NPA560, 945(1993).



N.V.Sen, NPA464 (1987) 717

◆ *nucleon-nucleus (NA) interaction :*

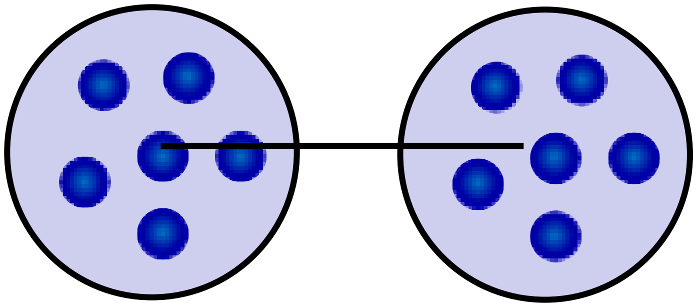
- *attractive at low energies (E<200 MeV)*
- *wine-bottle-bottom (WBB)*
  around transitional energies
- *repulsive at high energies (E>500 MeV)*

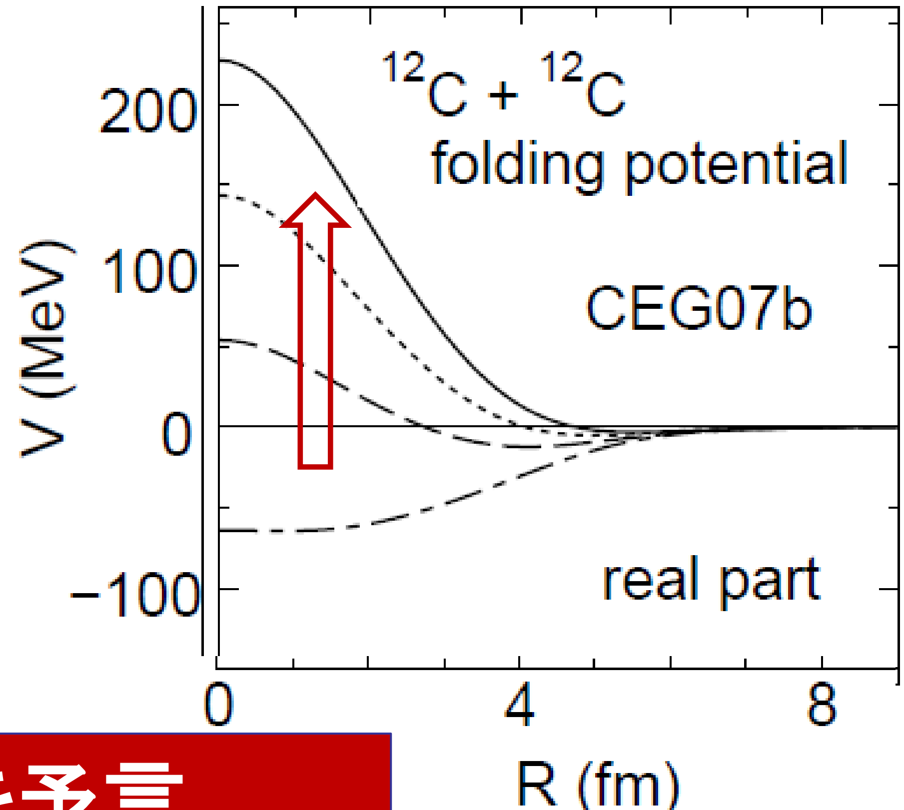


L.G.Arnold, (Phys.Rev.C25(1982)936

Q: How about in **nucleus-nucleus systems?**

E/A=100～400 MeV





引力–斥力転移を予言

T. Furumoto, Y. Sakuragi, Y. Yamamoto, Phys. Rev. C <u>82</u>, 044612 (2010)

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?

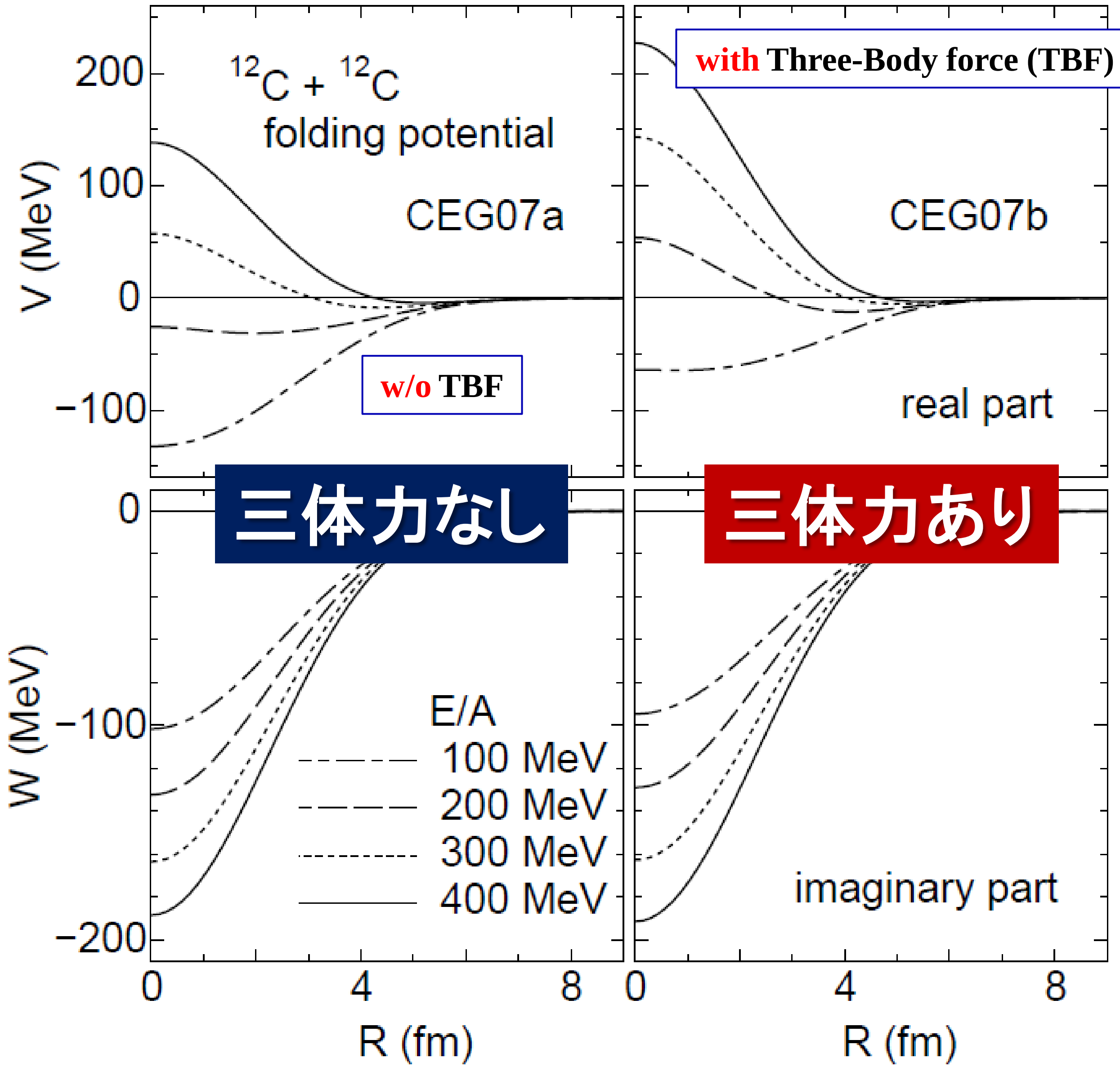
→ *measure the evolution of elastic scattering angular distribution with increasing energy in the energy range of E/A = 200～400 MeV.*

✓ 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.*

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

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

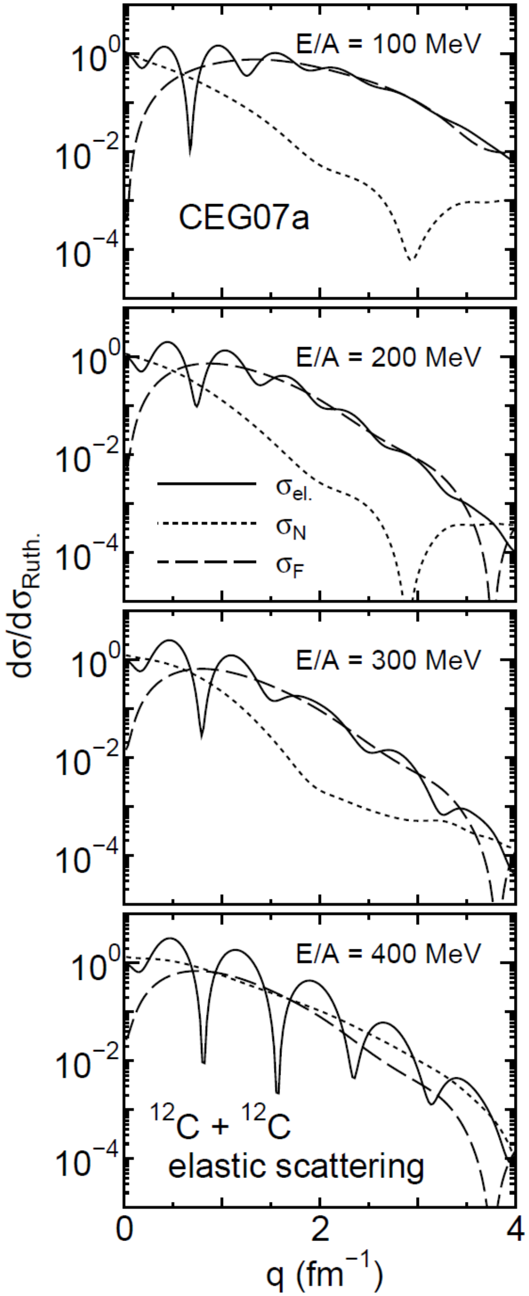


三体力の有無で
引力→斥力転移
のエネルギーが
大きく異なる！

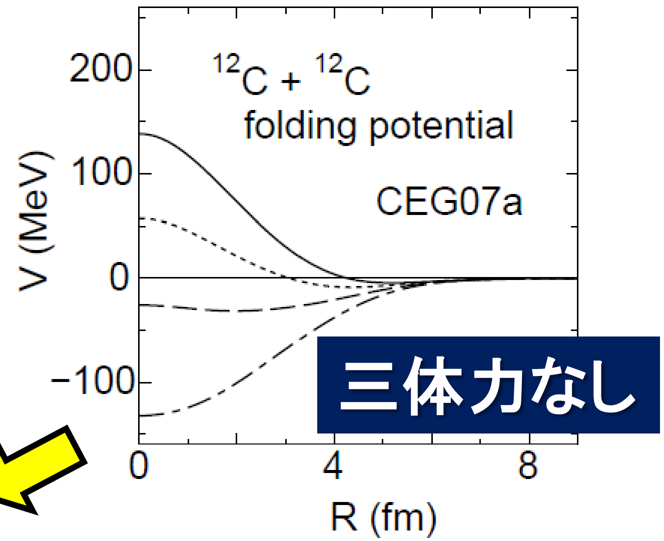
→まだ、誰も
調べたことがない

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

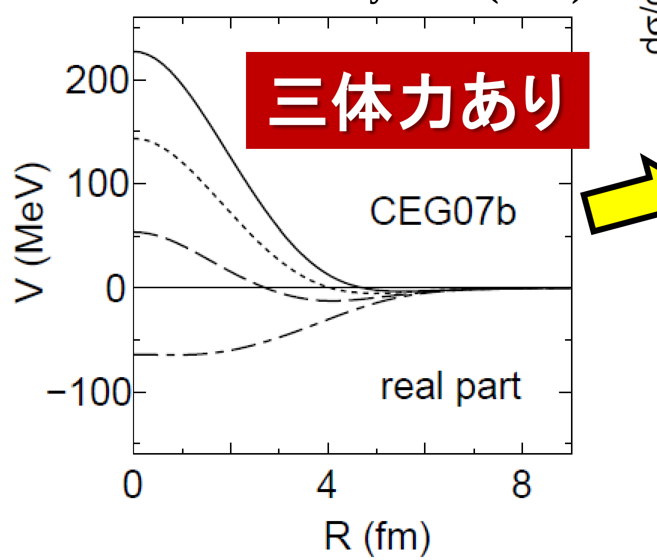
w/o Three-Body force (TBF)



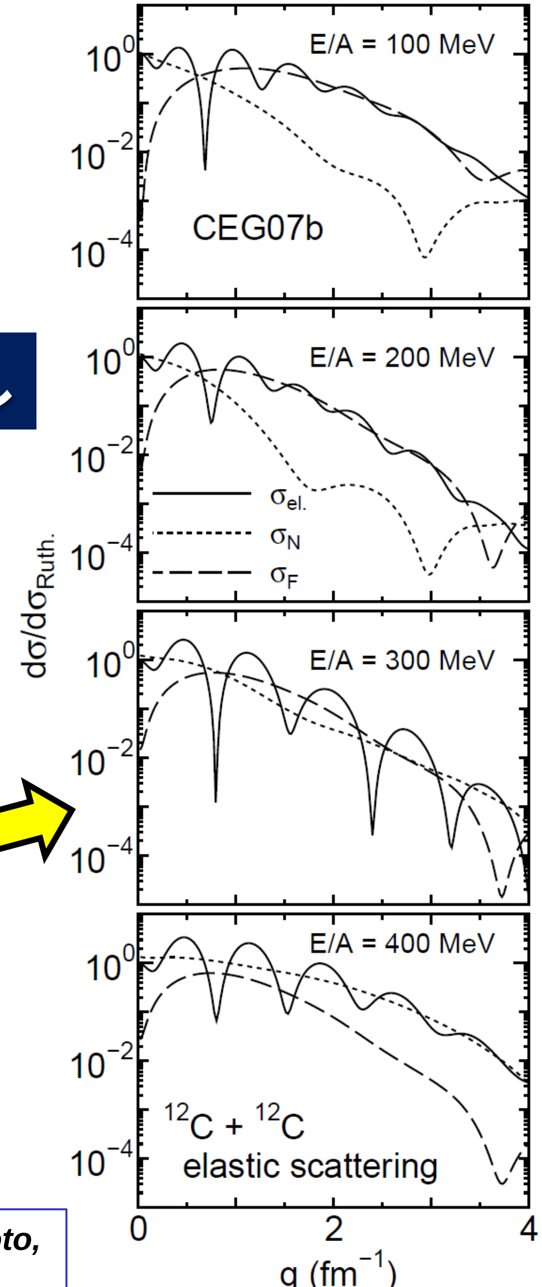
w/o Three-Body force (TBF)



with Three-Body force (TBF)

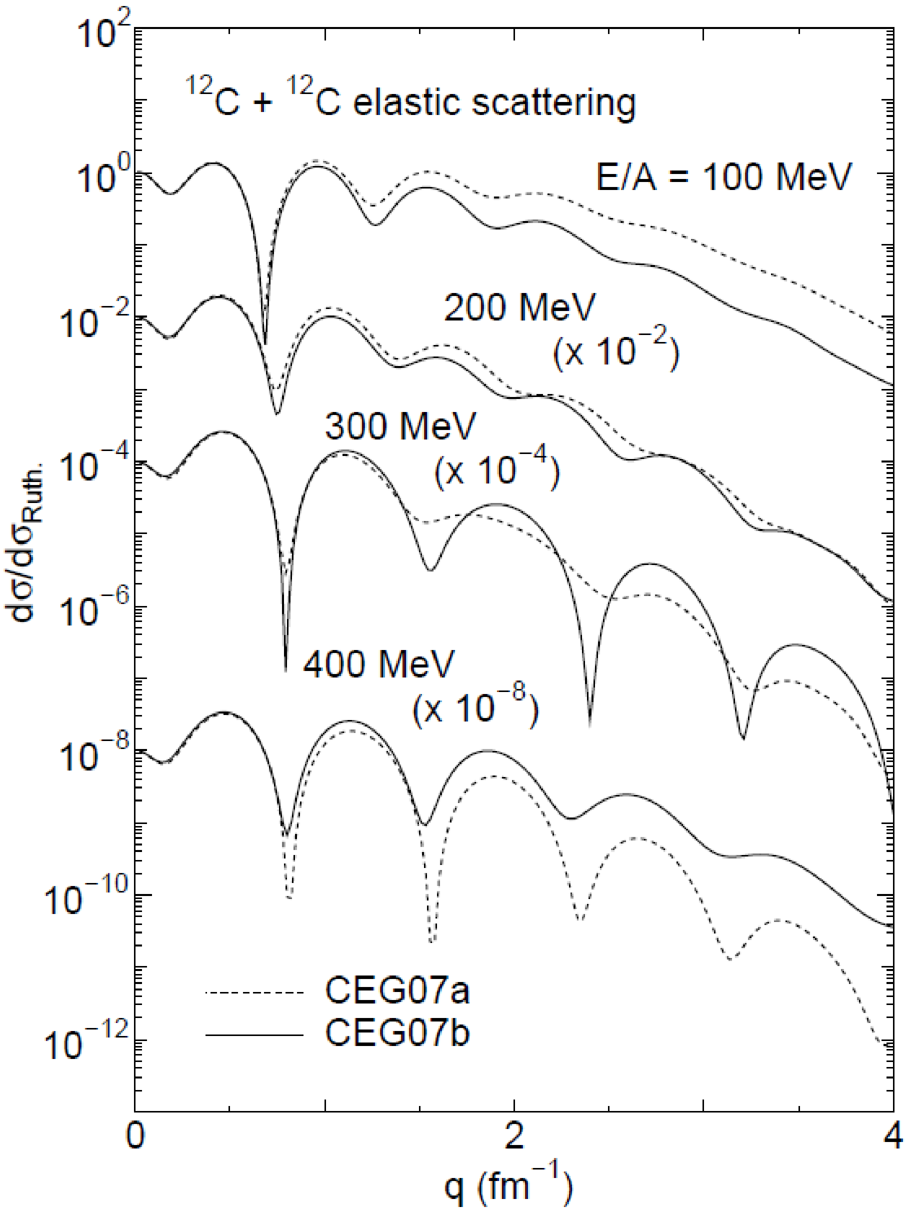


with Three-Body force (TBF)

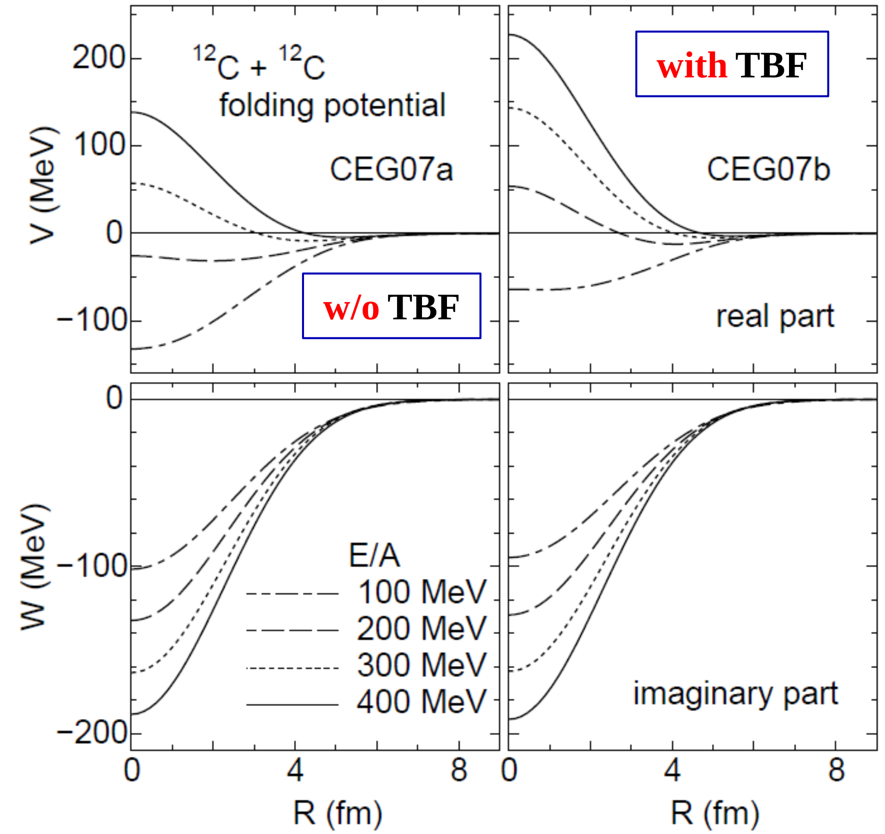


T.Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82, 044612 (2010)

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



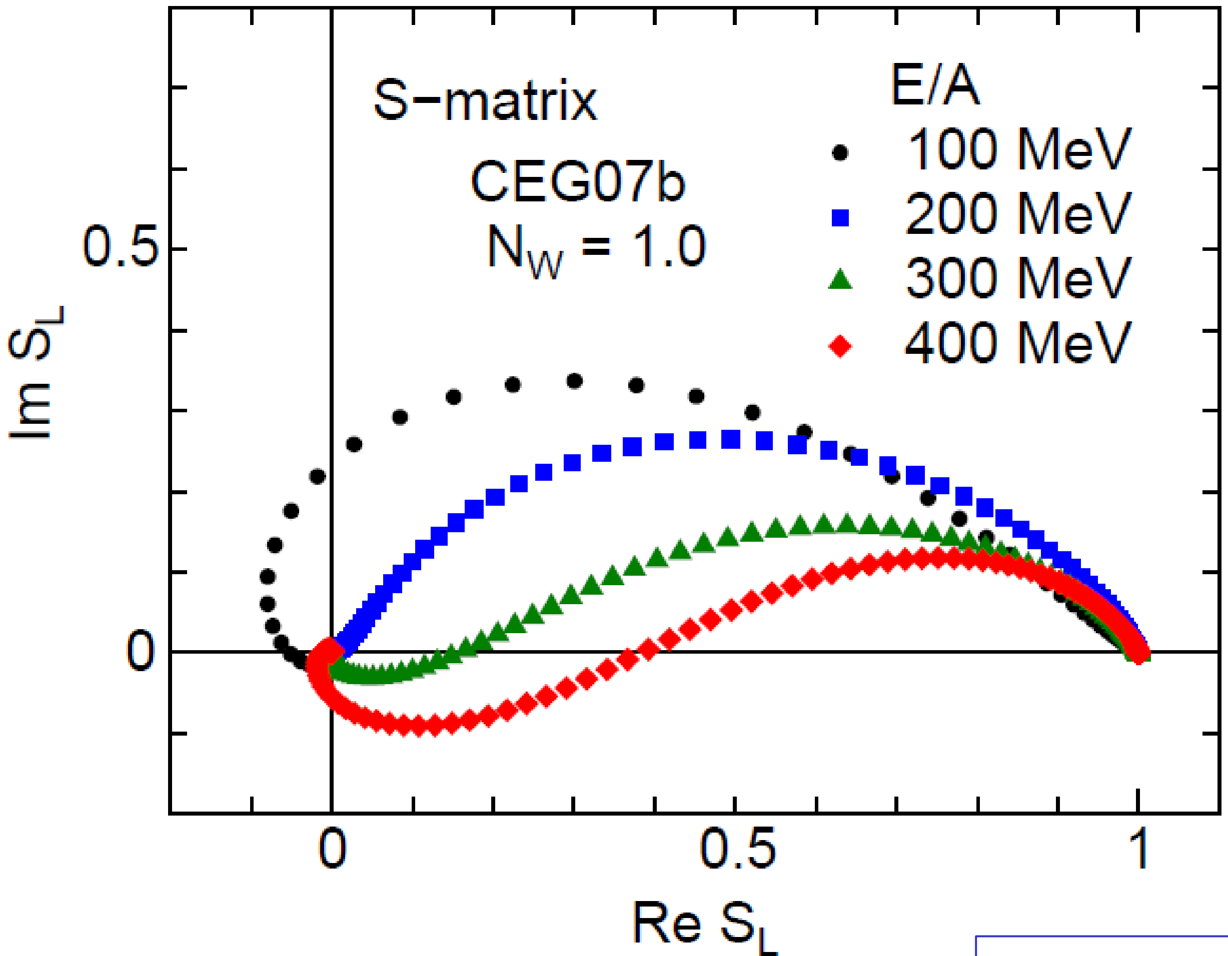
- **real potential : repulsive around *E/A* = 300～400 MeV**

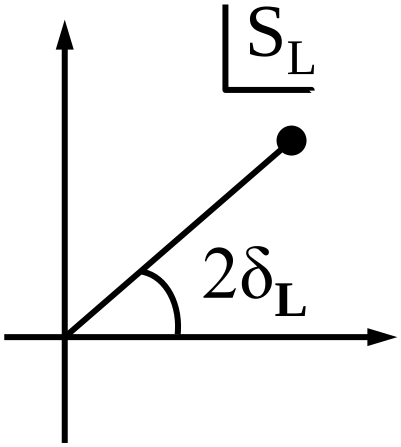


T.Furumoto, Y. Sakuragi, Y. Yamamoto, PRC82 , 044612 (2010)

S-matirx elements of the ^{12}C + ^{12}C elastic scattering

at *E/A* = 100～400 MeV with CEG07b (with TBF effects)





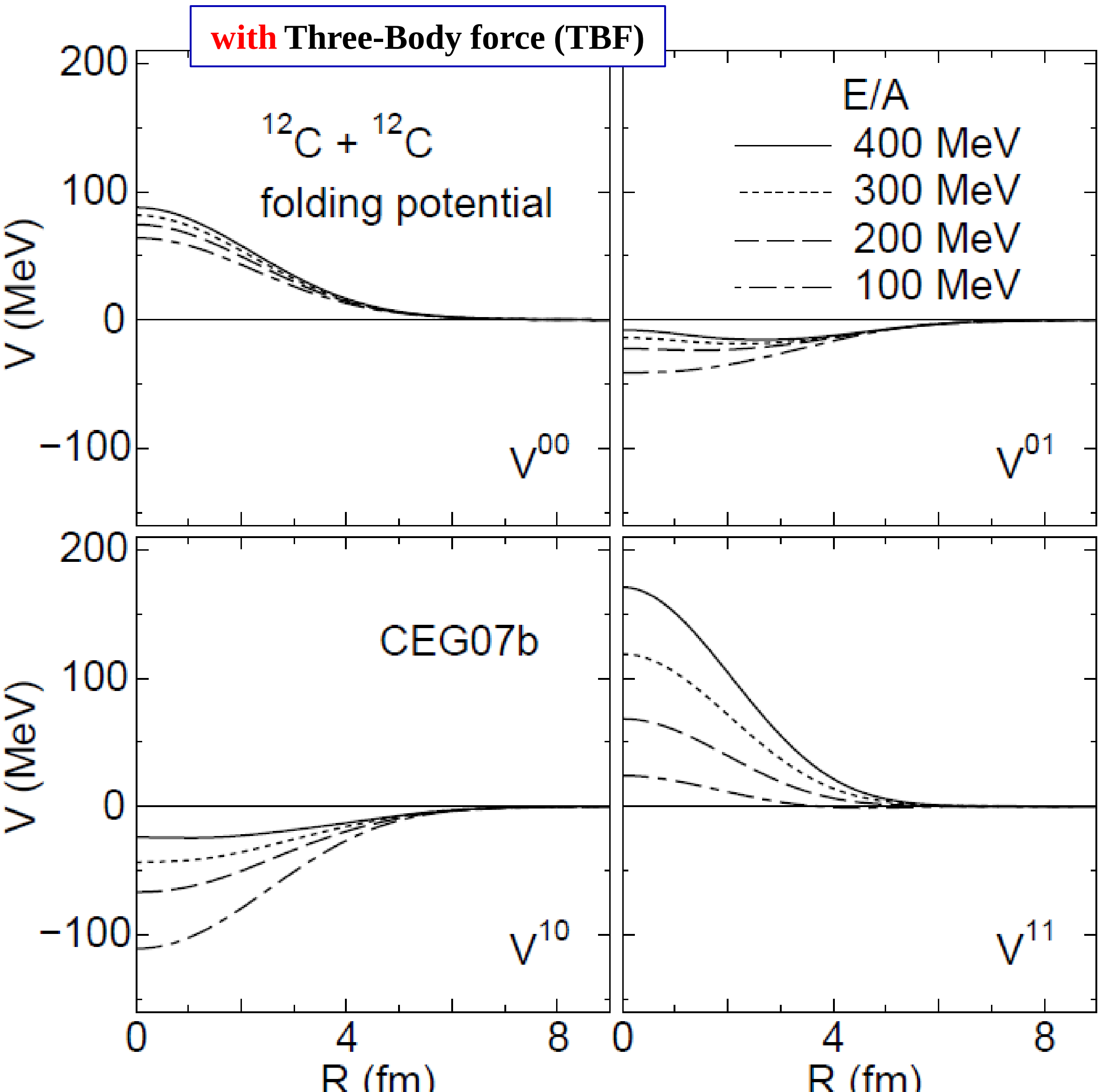
$S_L = \exp(2i\delta_L)$

$\delta_L < 0$: repulsive

$\delta_L > 0$: attractive

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

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



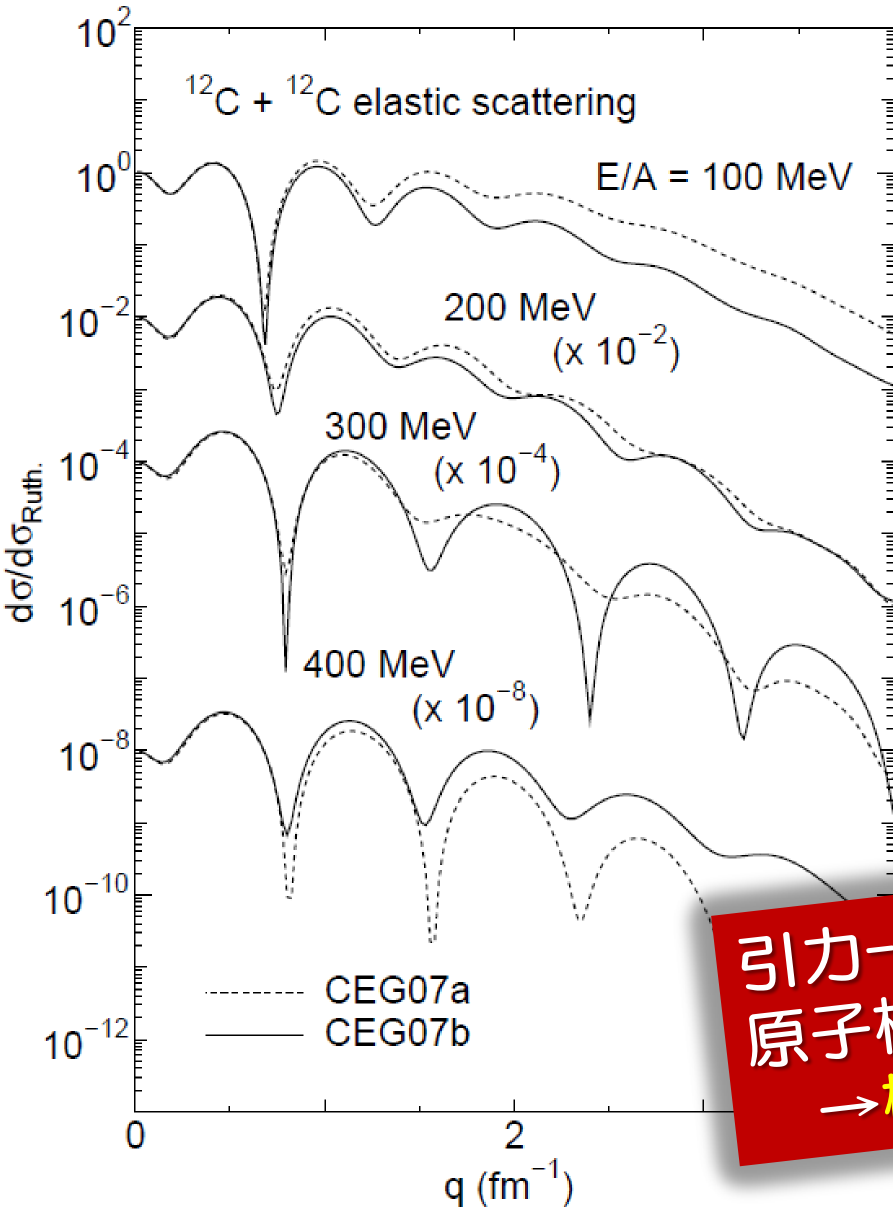
spin(S) and isospin(T) components V^{ST} of folding potential

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

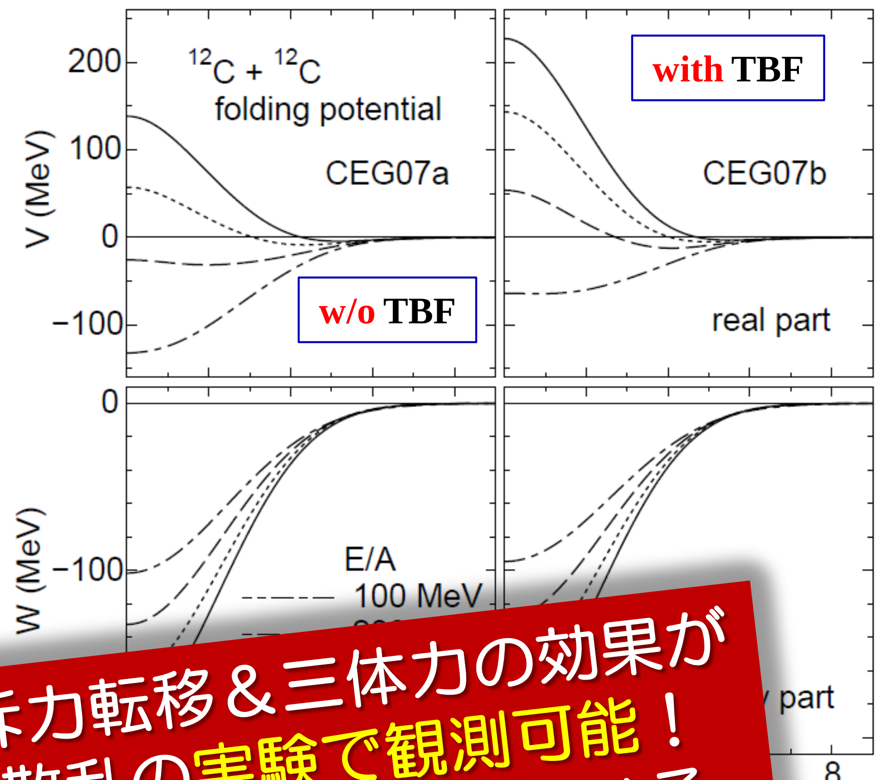
★ **(S,T) = (1,0) and (1,1)** components **include the tensor force**,

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**



引力-斥力転移＆三体力の効果が原子核散乱の実験で観測可能！→検証実験が計画されている

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

Summary & Conclusion of **part 1**

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*

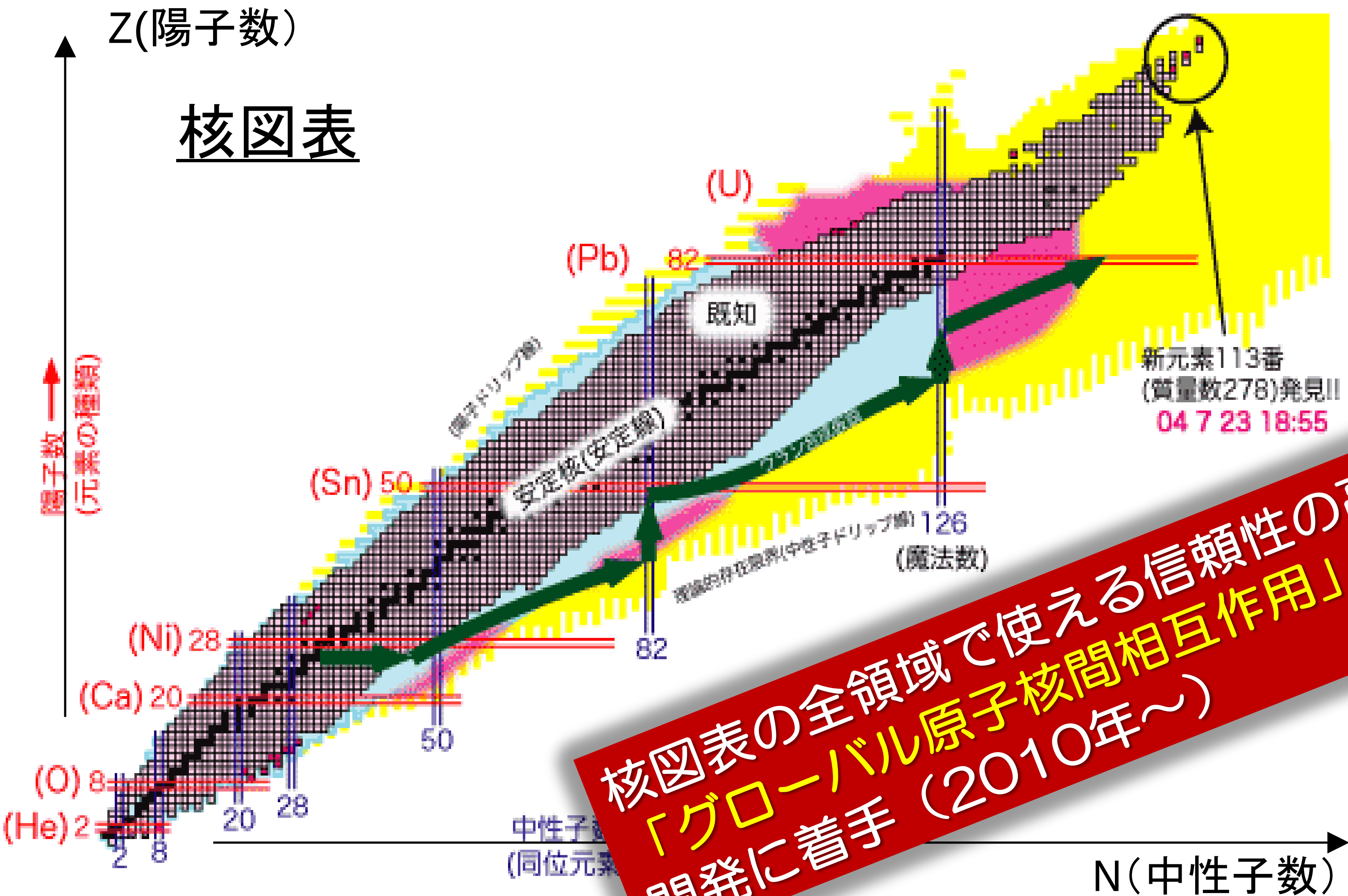
  ② ***tensor force** effects*

4. Global optical potential for heavy ions systems including exotic nuclei

Global potential for projectiles of unstable nuclei up to driplines

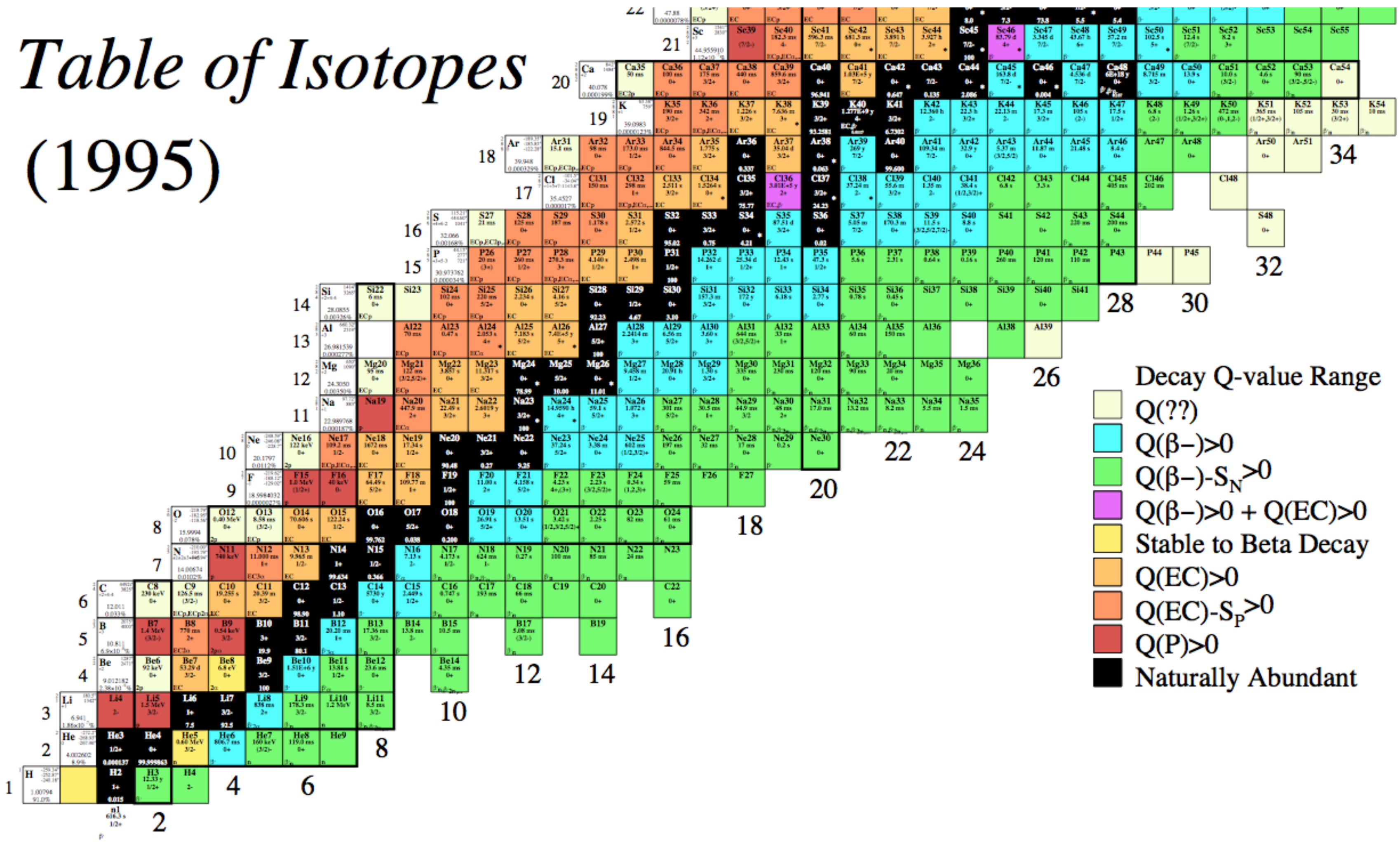
Global optical potential for nucleus-nucleus systems from 50 MeV/u to 400 MeV/u
T. Furumoto, W. Horiuchi, M. Takashina, Y. Yamamoto, Y. Sakuragi
(submitted to PRC, Feb.2012)

核図表



核図表の全領域で使える信頼性の高い
「グローバル原子核間相互作用」の
開発に着手（2010年〜）

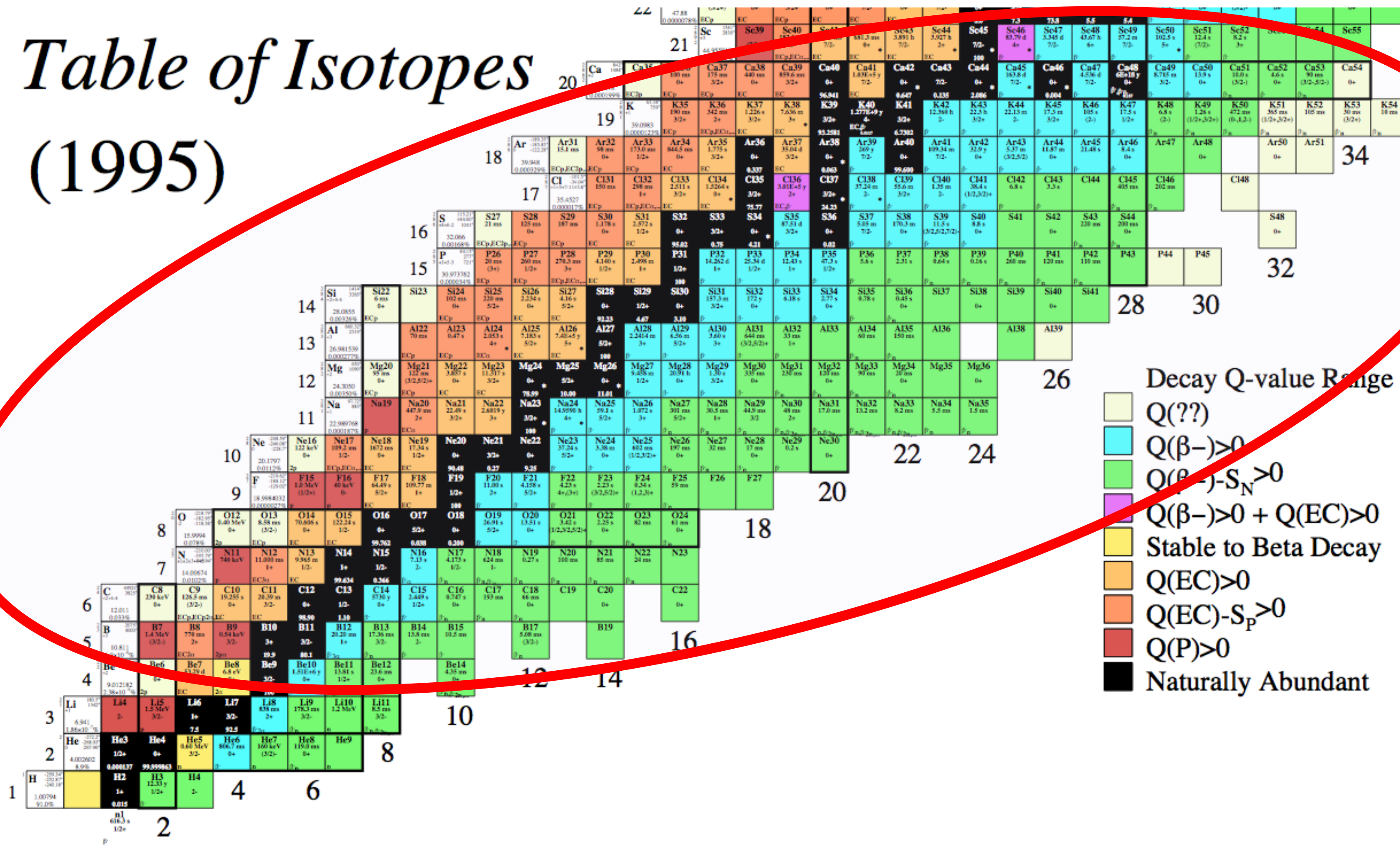
Table of Isotopes (1995)



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

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(submitted to PRC, Feb.2012)

Global optical potential for nucleus-nucleus systems from 50 MeV/u to 400 MeV/u

T. Furumoto, W. Horiuchi, M. Takashina, Y. Yamamoto, Y. Sakuragi
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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

$$\begin{aligned}U_{\mathrm{D}}(R) &= \int \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2)v_{\mathrm{D}}(s;\rho,E/A)d\boldsymbol{r}_1 d\boldsymbol{r}_2 \\ &= \int \{\rho_1^{(\mathrm{p})}(\boldsymbol{r}_1)\rho_2^{(\mathrm{p})}(\boldsymbol{r}_2)v_{\mathrm{D}}^{(\mathrm{pp})}(s;\rho,E/A) + \rho_1^{(\mathrm{p})}(\boldsymbol{r}_1)\rho_2^{(\mathrm{n})}(\boldsymbol{r}_2)v_{\mathrm{D}}^{(\mathrm{pn})}(s;\rho,E/A) \\ &\quad +\rho_1^{(\mathrm{n})}(\boldsymbol{r}_1)\rho_2^{(\mathrm{p})}(\boldsymbol{r}_2)v_{\mathrm{D}}^{(\mathrm{np})}(s;\rho,E/A) + \rho_1^{(\mathrm{n})}(\boldsymbol{r}_1)\rho_2^{(\mathrm{n})}(\boldsymbol{r}_2)v_{\mathrm{D}}^{(\mathrm{nn})}(s;\rho,E/A)\}d\boldsymbol{r}_1 d\boldsymbol{r}_2,\end{aligned}$$

$$\begin{aligned}U_{\mathrm{EX}}(R) &= \int \rho_1(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}(s;\rho,E/A)\exp\left[\frac{i\boldsymbol{k}(R)\cdot\boldsymbol{s}}{M}\right]d\boldsymbol{r}_1 d\boldsymbol{r}_2 \\ &= \int \{\rho_1^{(\mathrm{p})}(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2^{(\mathrm{p})}(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}^{(\mathrm{pp})}(s;\rho,E/A) + \rho_1^{(\mathrm{p})}(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2^{(\mathrm{n})}(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}^{(\mathrm{pn})}(s;\rho,E/A) \\ &\quad +\rho_1^{(\mathrm{n})}(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2^{(\mathrm{p})}(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}^{(\mathrm{np})}(s;\rho,E/A) + \rho_1^{(\mathrm{n})}(\boldsymbol{r}_1,\boldsymbol{r}_1+\boldsymbol{s})\rho_2^{(\mathrm{n})}(\boldsymbol{r}_2,\boldsymbol{r}_2-\boldsymbol{s})v_{\mathrm{EX}}^{(\mathrm{nn})}(s;\rho,E/A)\} \\ &\quad \times\exp\left[\frac{i\boldsymbol{k}(R)\cdot\boldsymbol{s}}{M}\right]d\boldsymbol{r}_1 d\boldsymbol{r}_2,\end{aligned}$$

◆ 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)

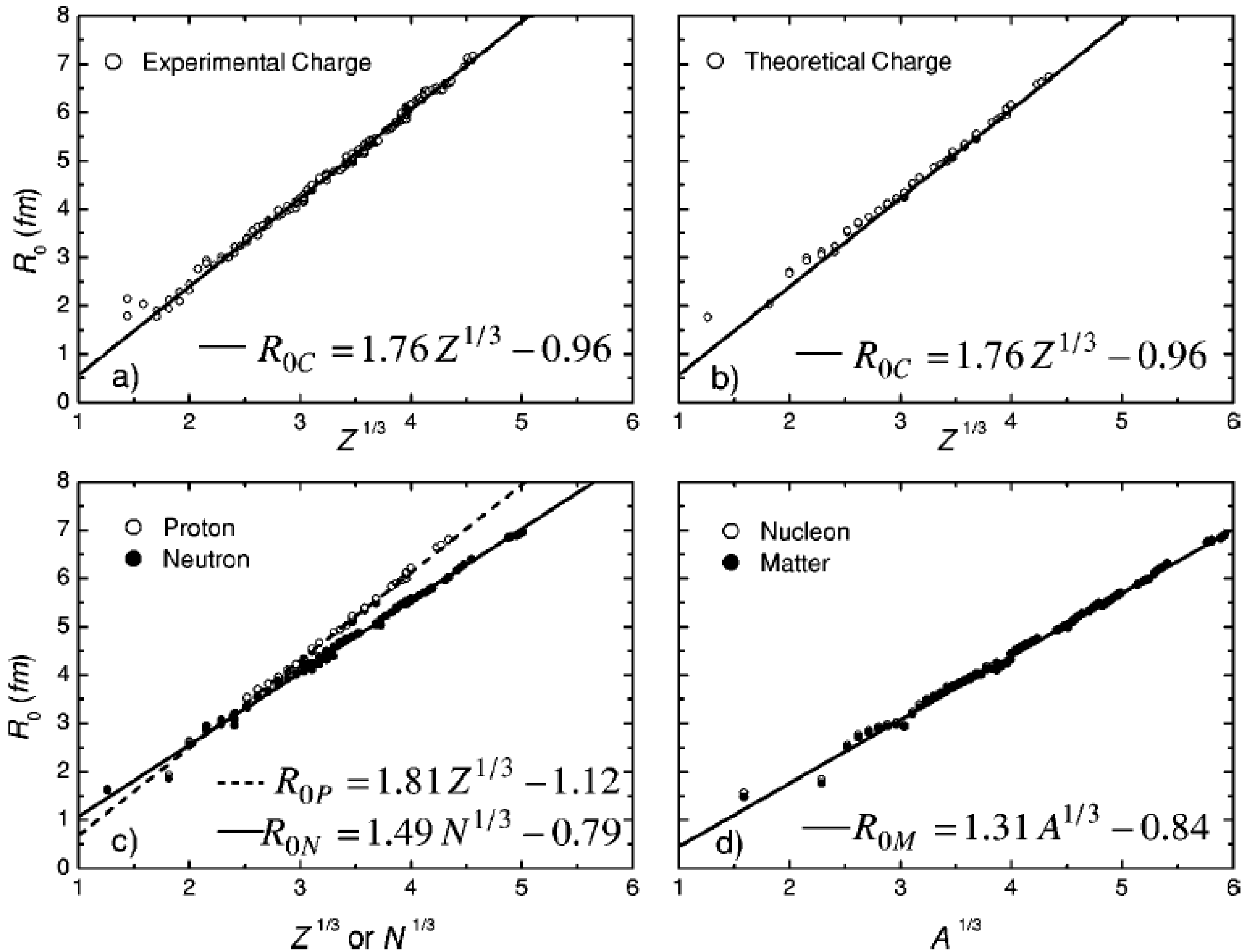

FIG. 3. The R_0 parameter obtained for charge distributions extracted from electron scattering experiments and for theoretical densities obtained from Dirac-Hartree-Bogoliubov calculations.

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

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

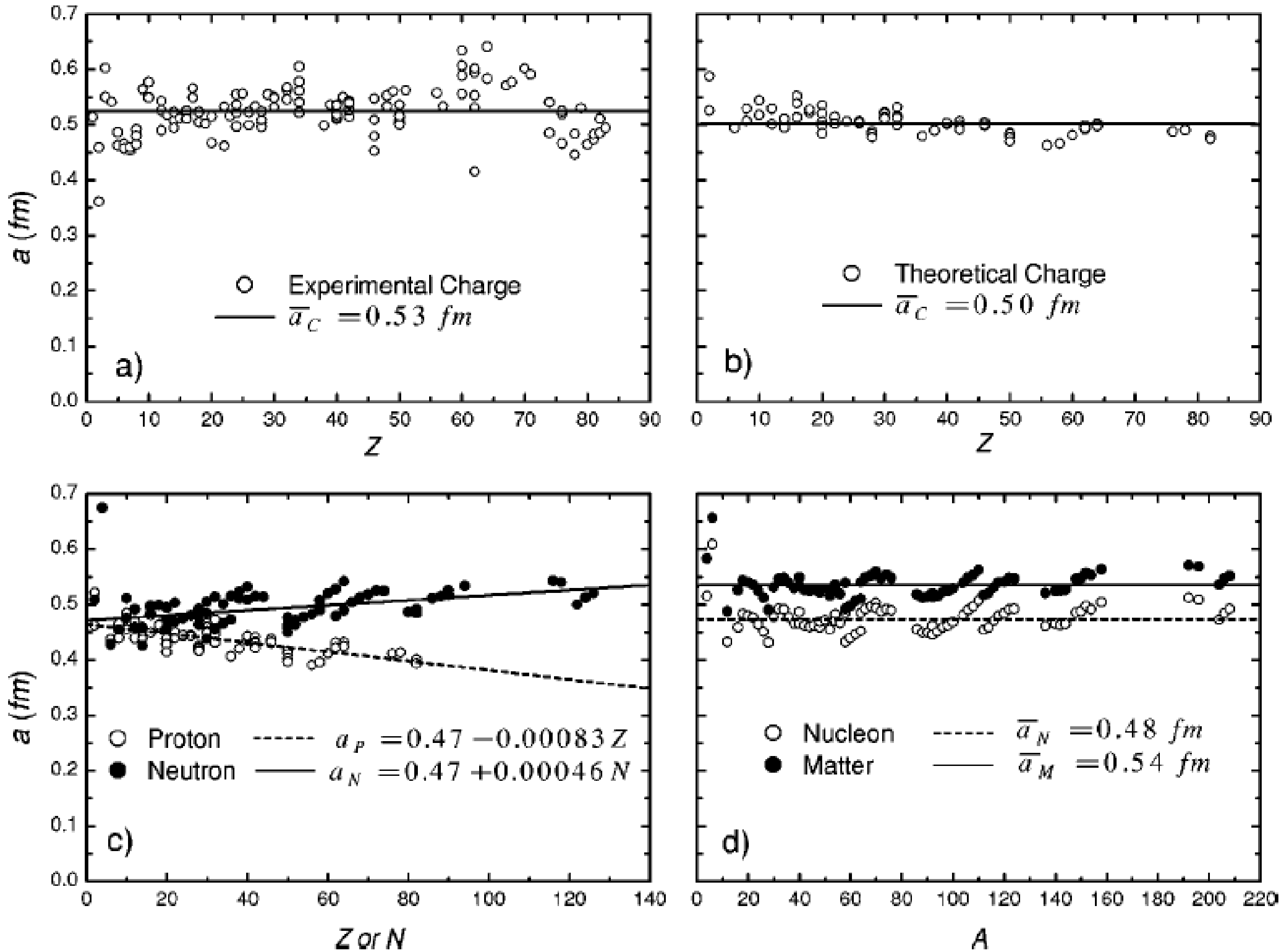

FIG. 2. Equivalent diffuseness values obtained for charge distributions extracted from electron scattering experiments and for theoretical densities obtained from Dirac-Hartree-Bogoliubov calculations.

Global parameterization of the CEG07 folding-model potentials

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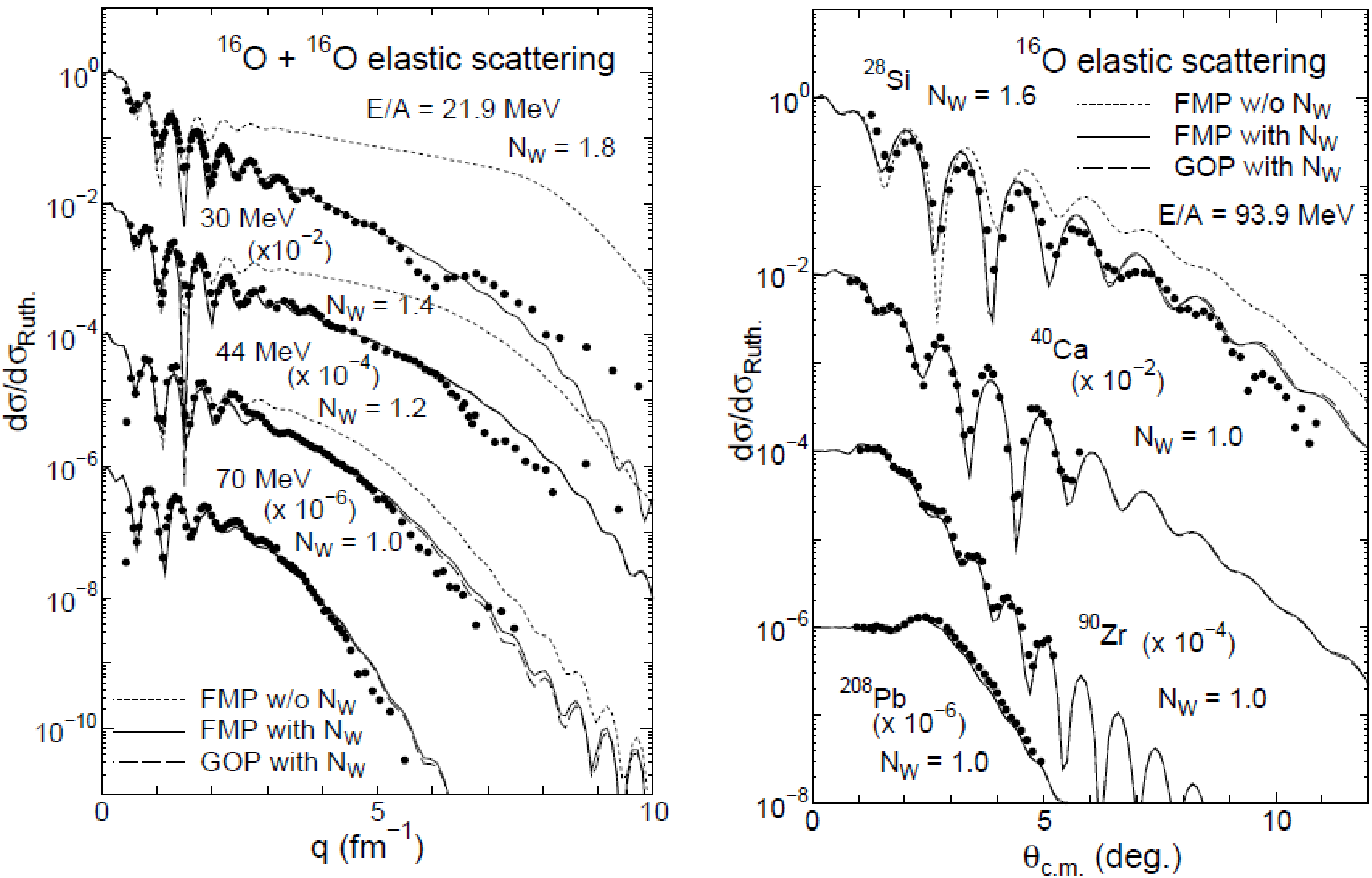
- ✓ **projectiles : Z = 6 (C isotope) ~ 20 (Ca isotope) (even-even)**
- ✓ **targets : ^{12}C ~ ^{208}Pb (closed or sub-closed shell nuclei)**
- ✓ **energy range : E/A = 30 ~ 400 MeV**

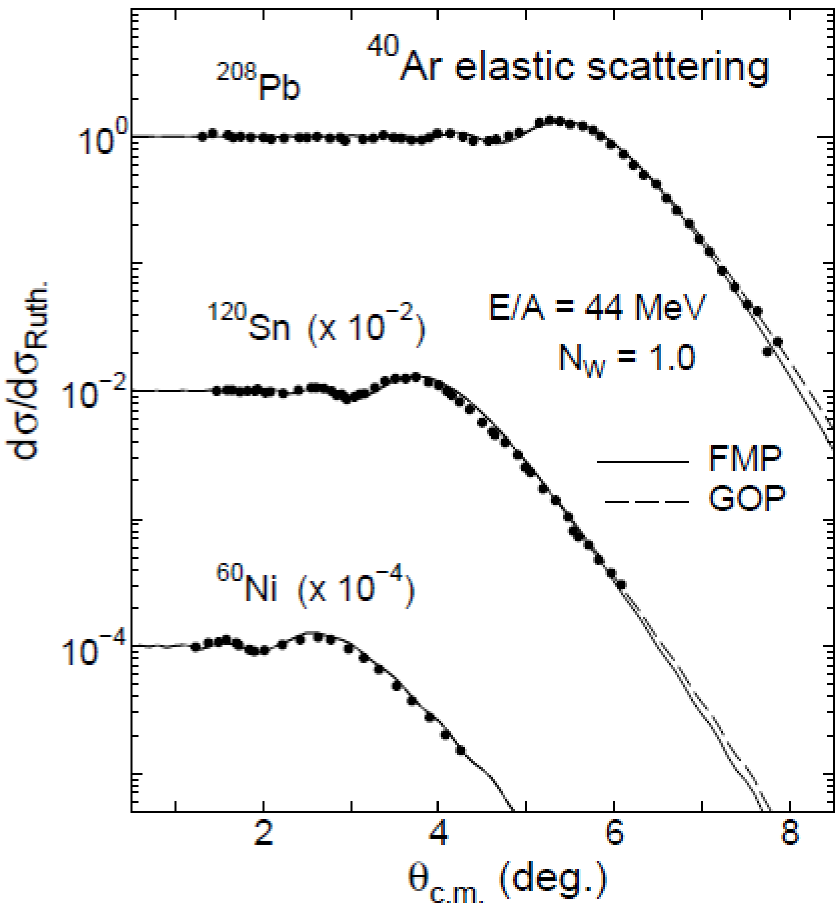
$$V_F(R) = \sum_{n=1}^{10} \left\{ \alpha_n \exp\left(-\frac{R^2}{\gamma_n^2} \right) \right\} ,$$

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

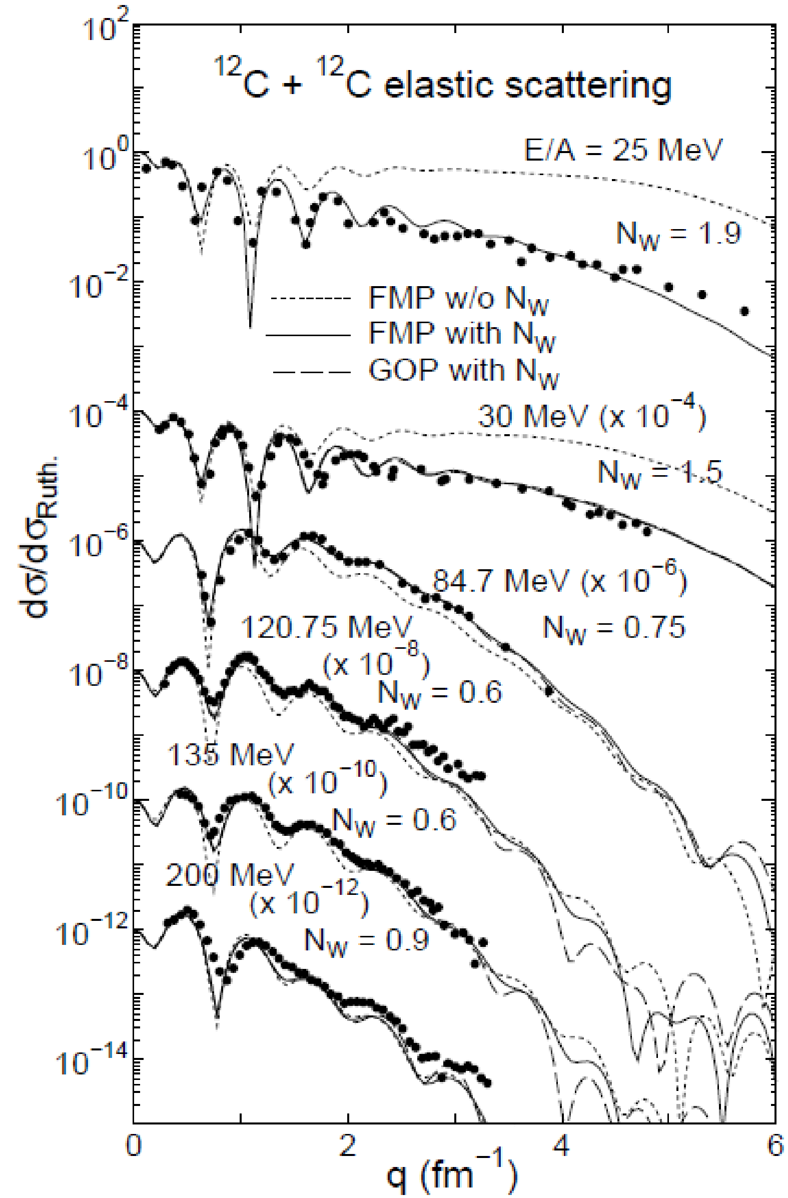
$$\begin{aligned} \alpha_n &= \alpha_n(A_p, Z_p, A_t, E/A) , \\ \beta_n &= \beta_n(A_p, Z_p, A_t, E/A) , \\ \gamma_n &= 0.45 \left(\frac{n+8}{18} \right) (A_p^{1/3} + A_t^{1/3} + 1) \end{aligned}$$



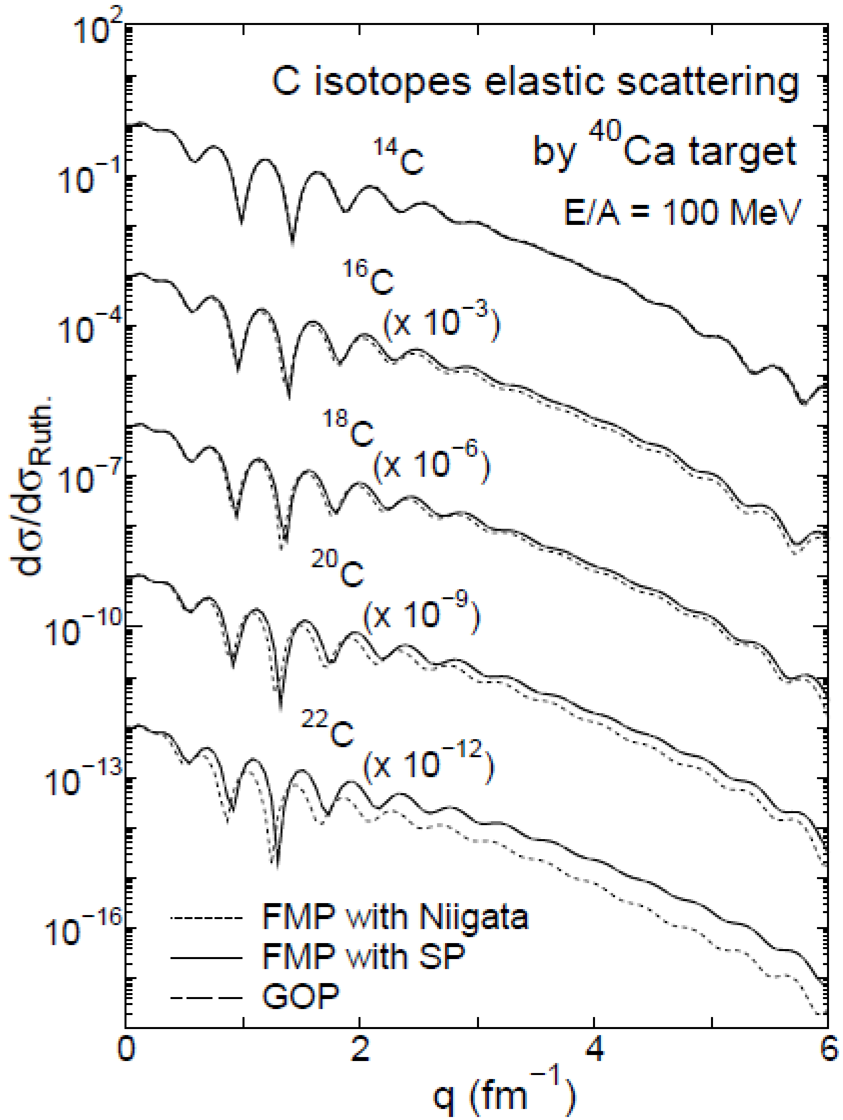
^{16}O + ^{16}O elastic scattering
E/A = 21.9 MeV
N$_W$ = 1.8
30 MeV
(x10^{-2})
N$_W$ = 1.4
44 MeV
(x 10^{-4})
N$_W$ = 1.2
70 MeV
(x 10^{-6})
N$_W$ = 1.0
FMP w/o N$_W$
FMP with N$_W$
GOP with N$_W$
dσ/dσ$_{Ruth.}$
q (fm^{-1})
^{16}O elastic scattering
^{28}Si N$_W$ = 1.6
FMP w/o N$_W$
FMP with N$_W$
GOP with N$_W$
E/A = 93.9 MeV
^{40}Ca
(x 10^{-2})
N$_W$ = 1.0
^{90}Zr (x 10^{-4})
N$_W$ = 1.0
^{208}Pb
(x 10^{-6})
N$_W$ = 1.0
dσ/dσ$_{Ruth.}$
θ$_{c.m.}$ (deg.)

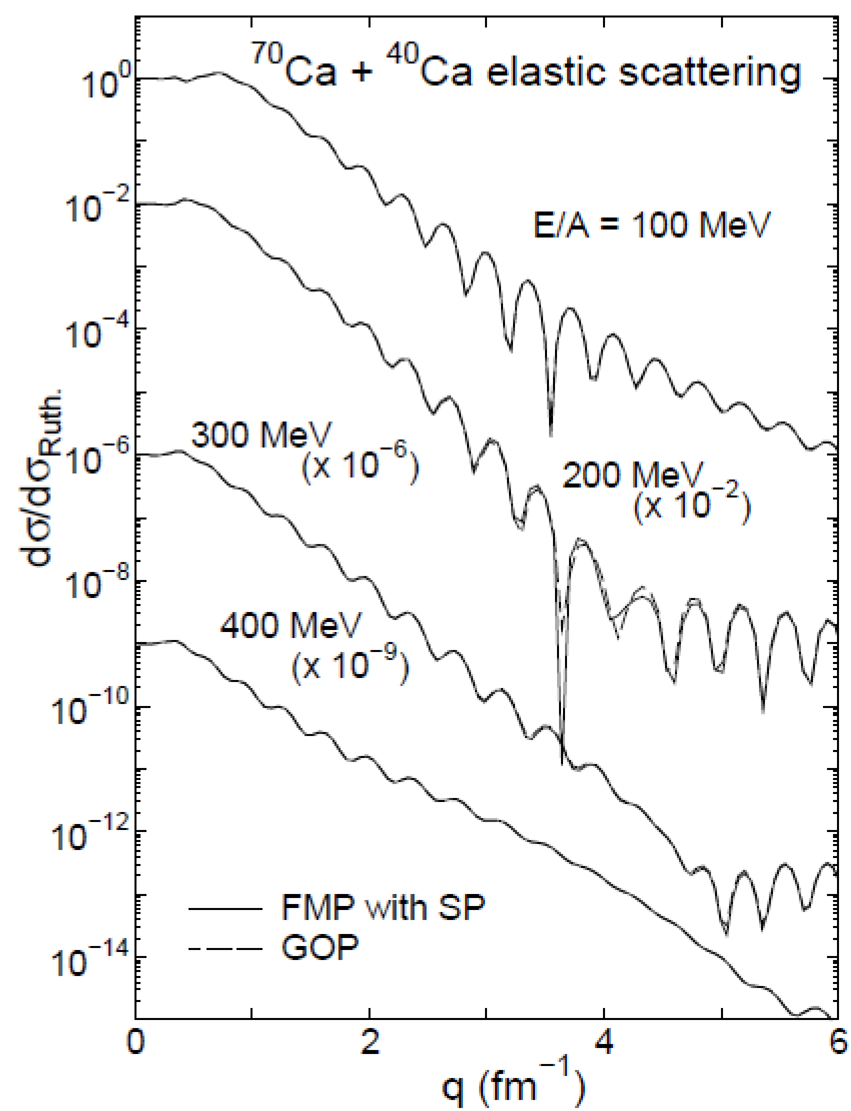


40Ar elastic scattering
208Pb
120Sn (x 10−2)
60Ni (x 10−4)
E/A = 44 MeV
NW = 1.0
FMP
GOP
dσ/dσRuth.
θc.m. (deg.)



12C + 12C elastic scattering
E/A = 25 MeV
NW = 1.9
FMP w/o NW
FMP with NW
GOP with NW
30 MeV (x 10−4)
NW = 1.5
84.7 MeV (x 10−6)
NW = 0.75
120.75 MeV (x 10−8)
NW = 0.6
135 MeV (x 10−10)
NW = 0.6
200 MeV (x 10−12)
NW = 0.9
dσ/dσRuth.
q (fm−1)


C isotopes elastic scattering
by ^{40}Ca target
E/A = 100 MeV
^{14}C
^{16}C (x 10^{-3})
^{18}C (x 10^{-6})
^{20}C (x 10^{-9})
^{22}C (x 10^{-12})
FMP with Niigata
FMP with SP
GOP
$d\sigma/d\sigma_{Ruth.}$
q (fm^{-1})


^{70}Ca + ^{40}Ca elastic scattering
E/A = 100 MeV
300 MeV (x 10^{-6})
200 MeV (x 10^{-2})
400 MeV (x 10^{-9})
FMP with SP
GOP
$d\sigma/d\sigma_{Ruth.}$
q (fm^{-1})

summary

1. Introduction
2. Microscopic theory for nucleus-nucleus interaction with a new complex G-matrix interaction, CEG07
   - I. Application to proton-nucleus scattering
   - II. Application to heavy-ion (HI) scattering/reactions
     - ⇒ Importance of repulsive three-body force effect
3. Attractive-to-repulsive transition of HI optical potential around E/A=200～300 MeV
4. Global optical potential for exotic heavy ions
5. future perspectives

Summary

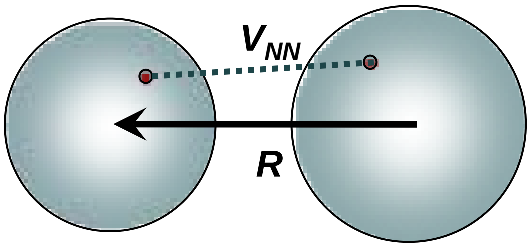
- We have proposed a new complex G-matrix ("CEG07"),
  - ✓ derived from ESC04(extended soft-core) NN force
  - ✓ include three-body force (TBF) effect
  - ✓ calculated up to higher density (about twice the normal density)

- 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.

  ⇒ decisive role of Three-body repulsive force effect
  - ✓We also demonstrated possible applications to nuclear reactions (inelastic/breakup) including unstable nuclei
- The HI optical potential shows attractive-to-repulsive transition around E/A=200～300 MeV
- We constructed Global potentials for projectiles of unstable nuclei up to driplines, based on the microscopic CEG07 folding potentials.

A brief history of the double-folding model (DFM) study of HI optical potentials, before CEG07

- ***Microscopic / semi-microscopic models :***
  - ✓ ***starting from NN interactions (V_{NN})***

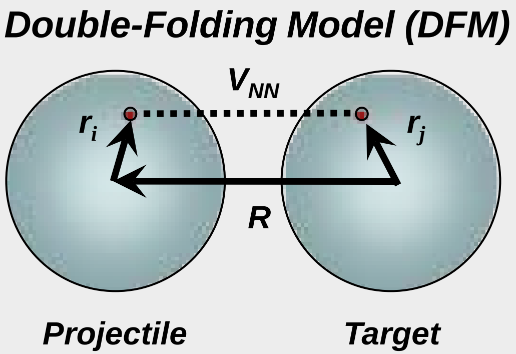


◆ ***G-matrix with scattering b.c.***

- ✓ ***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)

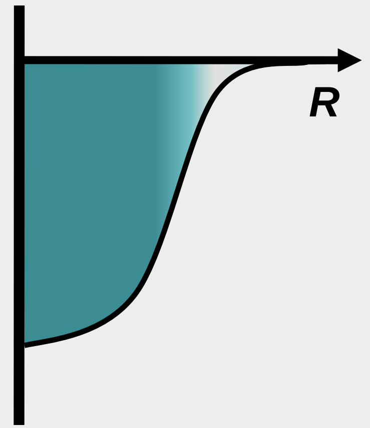


- ✓ ***real part** only (add a phenom. imag. pot)*
- ✓ ***zero-range** exchange term*

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

- ✓ ***no density-dependence***

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



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

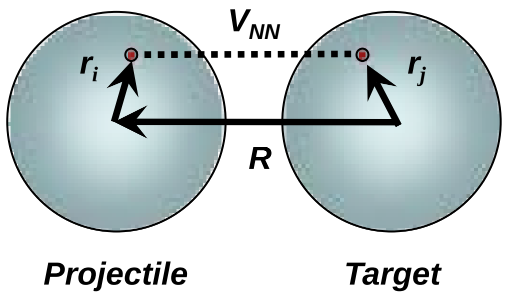
  ⇒ sensitive only to nuclear surface

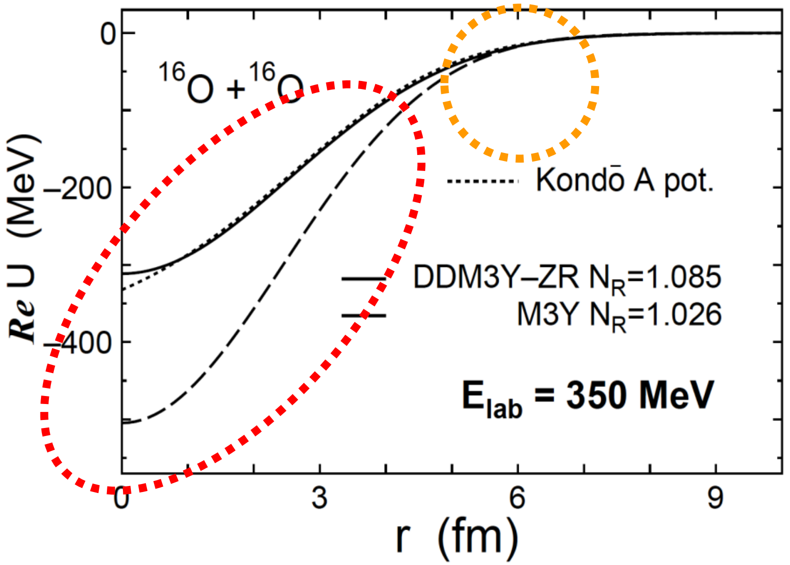
⇒ "Successful" for low-energy (E/A<30 MeV) scattering of heavy-ion (HI) projectiles with A_p<40

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

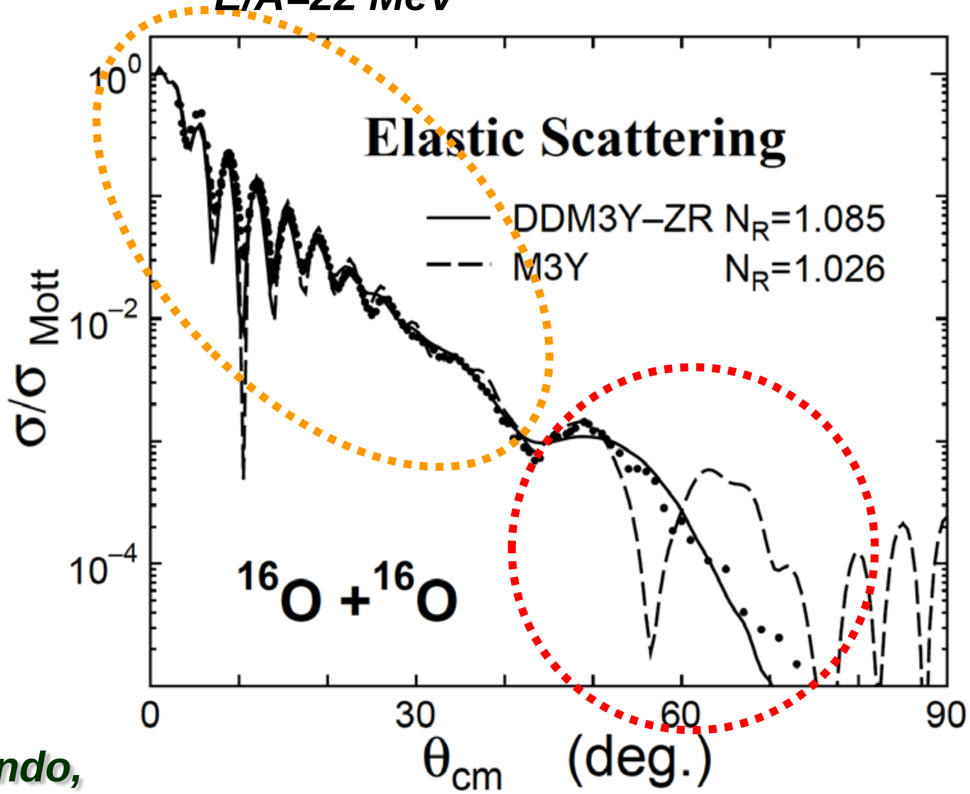
*Double-Folding-model potentials with **M3Y (density-independent)***

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)***

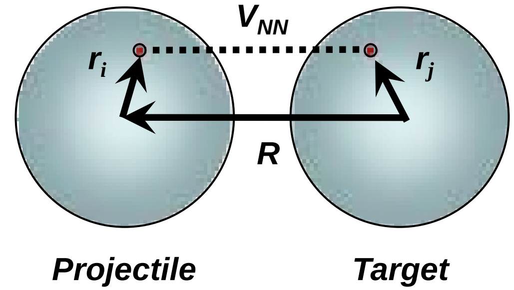
$$v_{NN}(E,\rho;\mathbf{s}) = g(E,\mathbf{s})f(E,\rho)$$

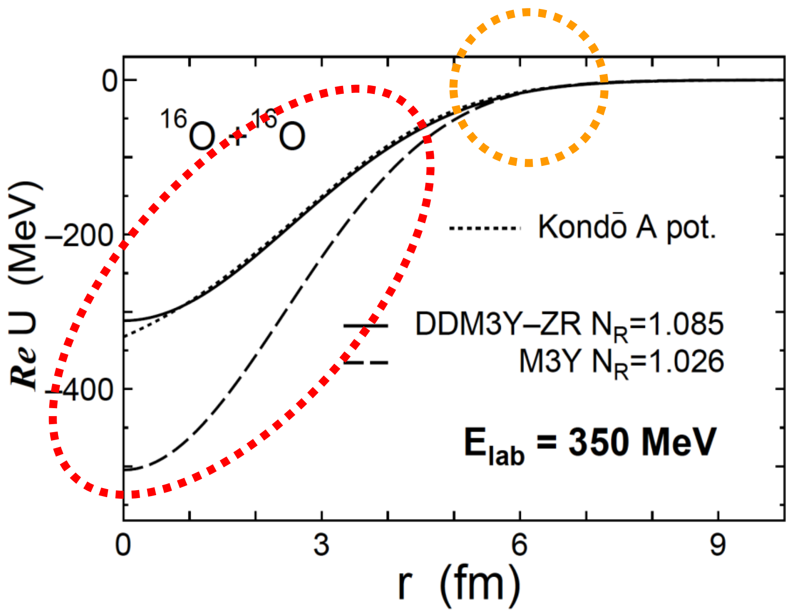
$$f(E,\rho) = C(E)[1+\alpha(E)e^{-\beta(E)\rho}]$$

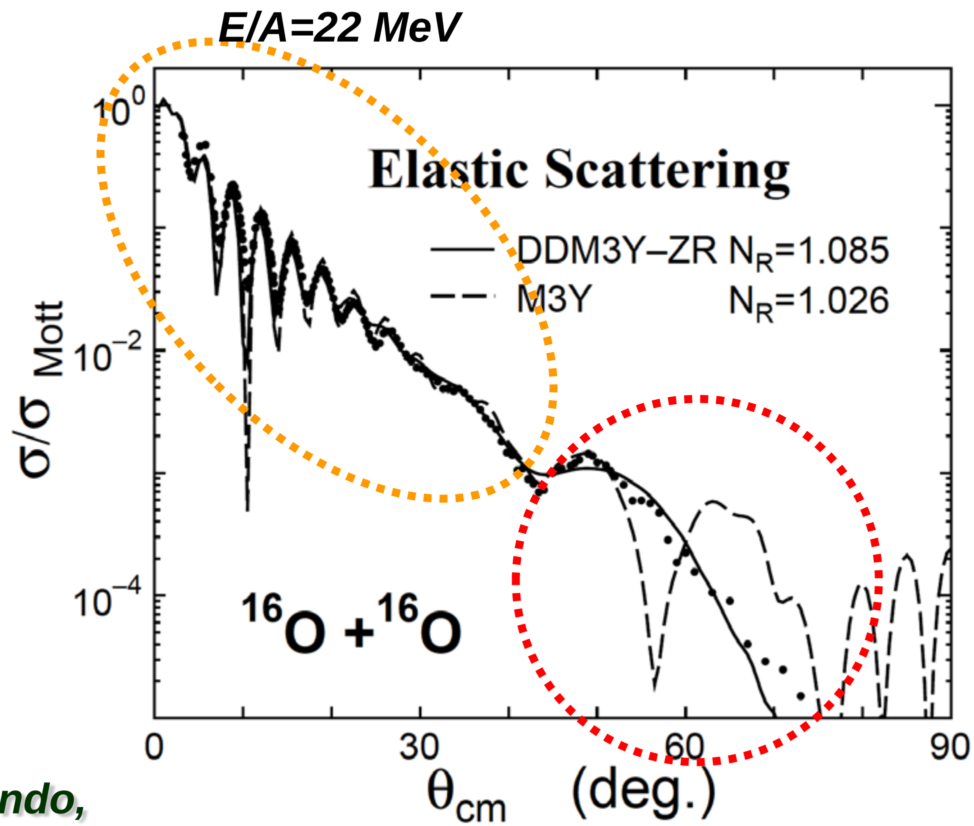
⇒ greatly reduce the potential strength at short distances

⇒ 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)







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