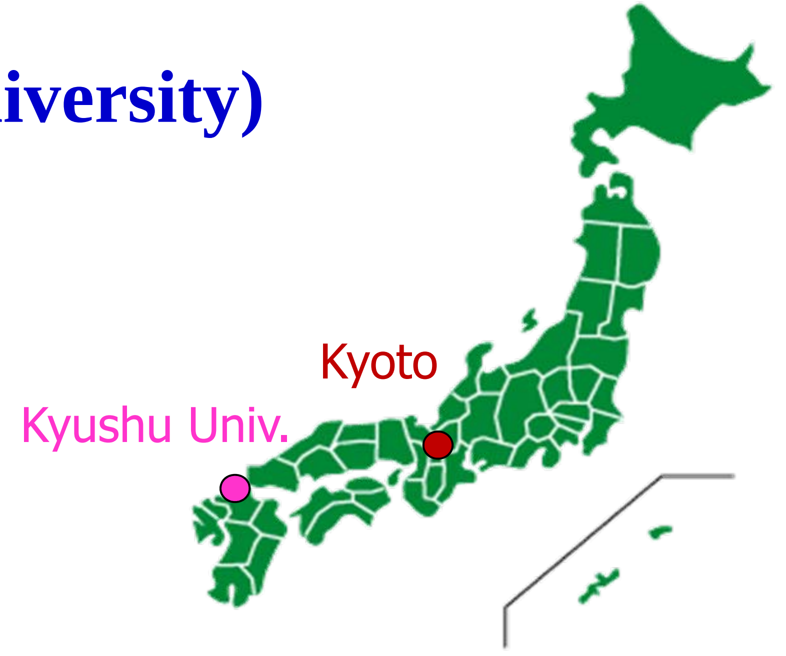
Microscopic reaction theory on reactions of unstable nuclei

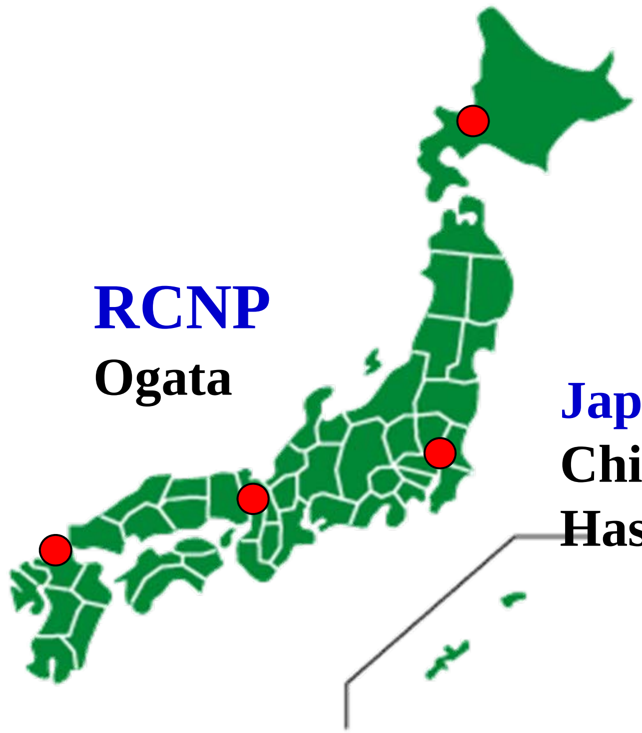
M. Yahiro (Kyushu University)



Collaborators

Kyushu Univ.
Kawai
Shimizu
Sumi
Minomo
Fukui
Watanabe
Ye

RCNP
Ogata



Hokkaido Univ.
Kimura
Matsumoto
Kato

Japan Atomic Energy Agency
Chiba
Hashimoto

Kyushu Dental Coll.
Kohno

Contents

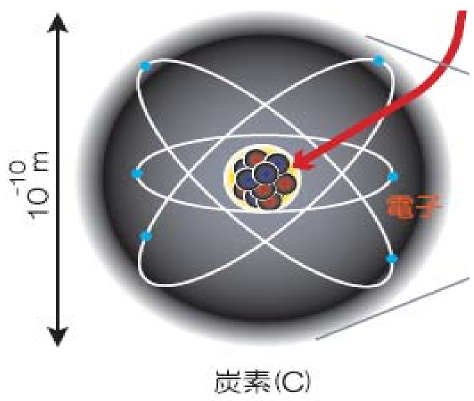
1. Introduction

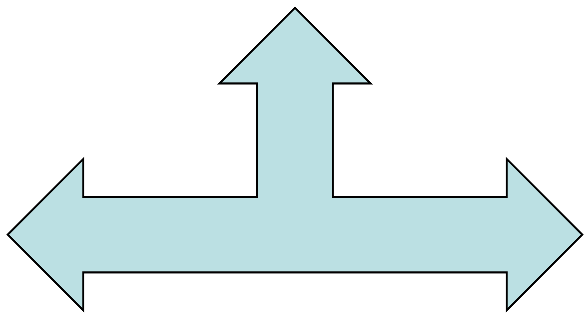
Hegelian dialectic

What is the synthesis?
Effective theory
Effective model

Elementary particles
Fundamental interactions

Nucleus





More is different!
(Antithesis)

P.W. Anderson,
Science 177, 393-396, 1972.

Reductionism
(Thesis)

Hadron physics and Nuclear physics

QCD

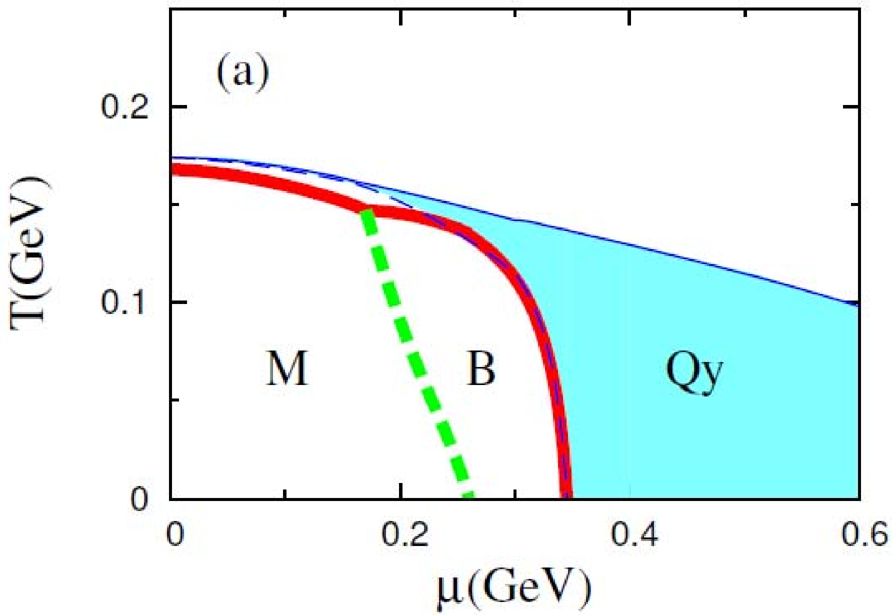
Lattice QCD

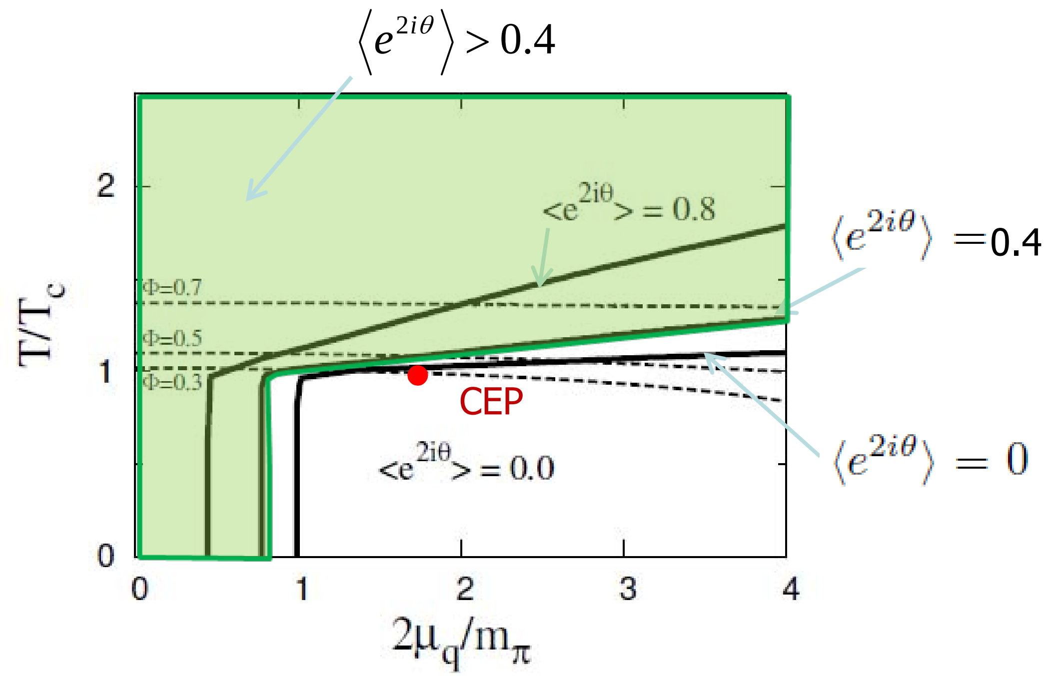
Hadron physics:
Effective theory(CPT)
Effective model(NJL,PNJL)

Nuclear physics:
Effective theory(CPT)
Effective model

QCD phase diagram

Prediction of PNJL model





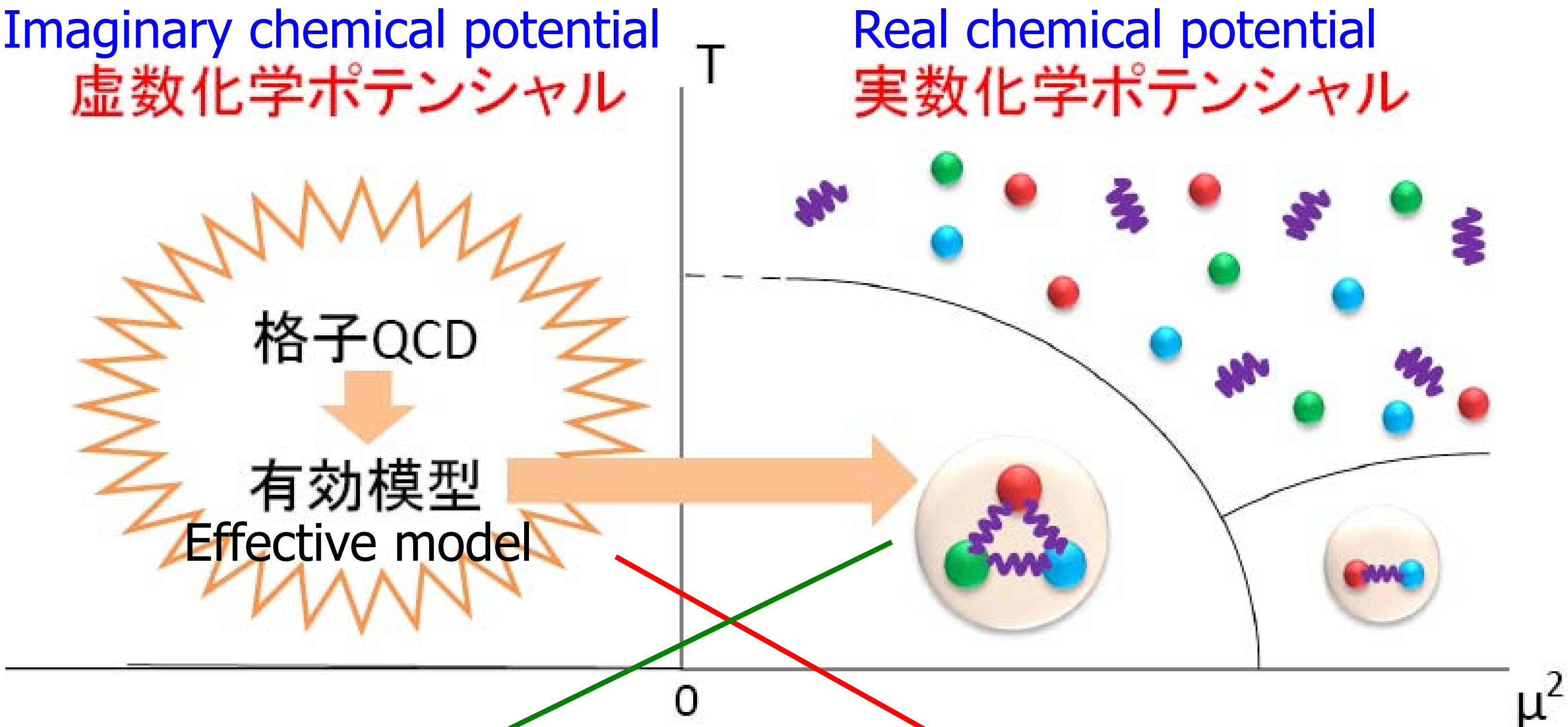
Sakai, Sasaki, Kouno and Yahiro, arXiv:1104.2394 [hep-ph]

Y. Sakai, T. Sasaki, H. Kouno, and M. Yahiro, Phys.Rev.D82:096007,2010.

1.1 Effective model in hadron physics

QCD Phase diagram

Sakai,Kashiwa, Kouno, Matsuzaki, Yahiro
P. R. D 77, 051901 (2008);D78:036001(2008);D78:076007(2008)

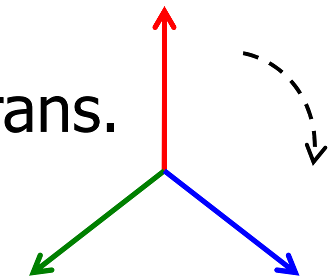


$$\Xi(n) = \frac{1}{2\pi}\int_{-\pi}^{\pi} d\theta e^{-in\theta} Z(\theta), \qquad \mu = iT\theta$$

How to construct an effective model?

Roberger-Weiss periodicity Nucl. Phys. B275, 734 (1986)

Z_3 trans.



$$\mu = iT\theta$$

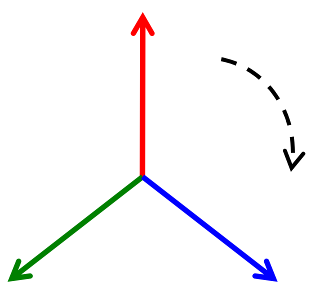
$$Z(\theta) = Z(\theta + 2\pi / 3)$$

色空間

Color space

Extended Z_3 Symmetry

Sakai, Kashiwa, Kouno, Yahiro, P. R. D 77, 051901



$$+ \quad \theta \to \theta - 2\pi / 3$$

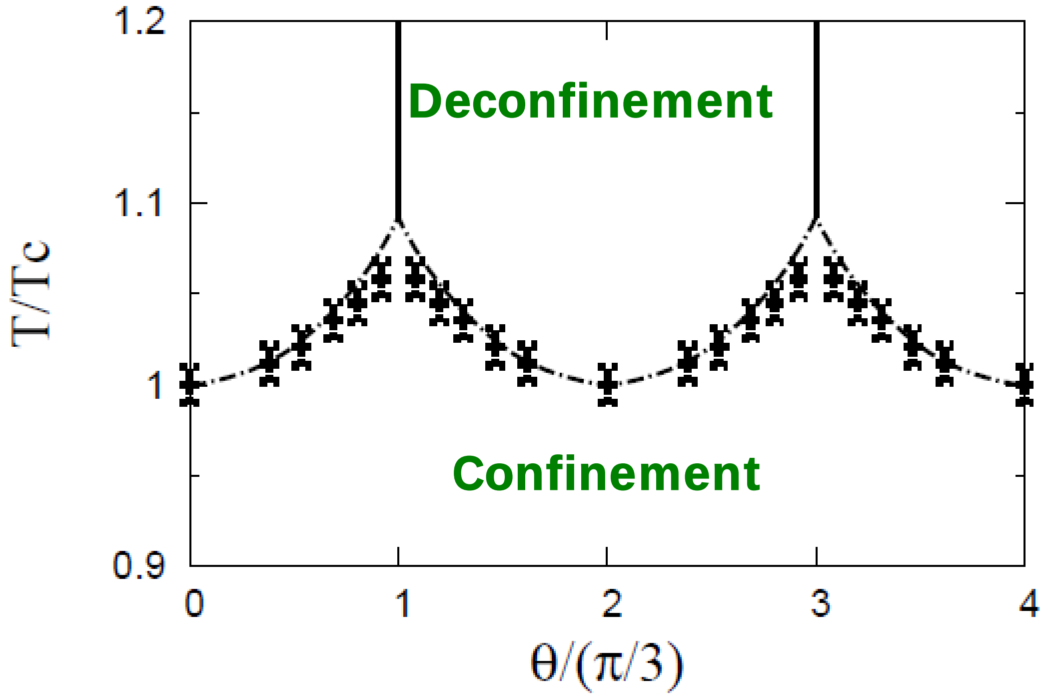
⇨ $Z(\theta)$ invariant

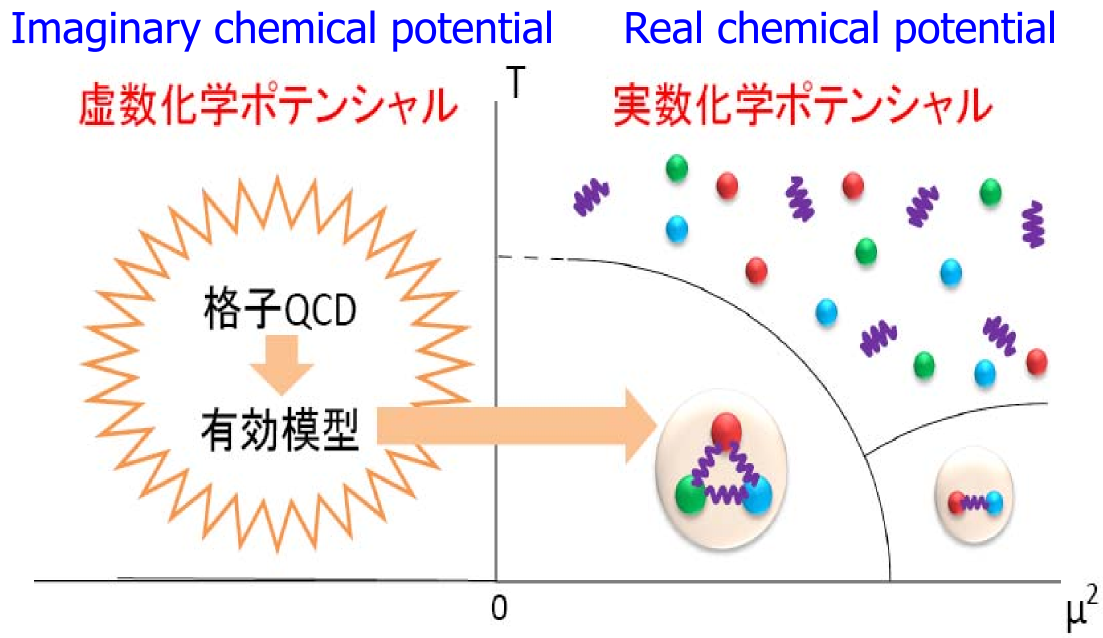
Polyakov-loop exteneded Nambu–Jona-Lasinio（PNJL）model

K. Fukushima, Phys. Lett. B 591, 277 (2004)

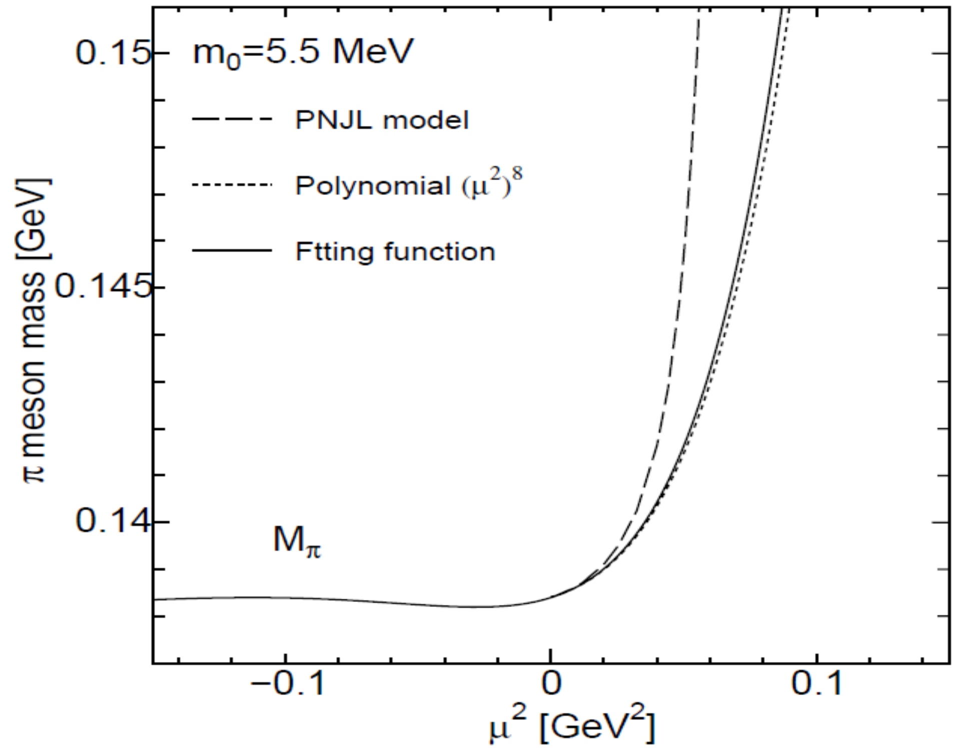
Extended Z_3 symmetry and Chiral symmetry

QCD phase diagram

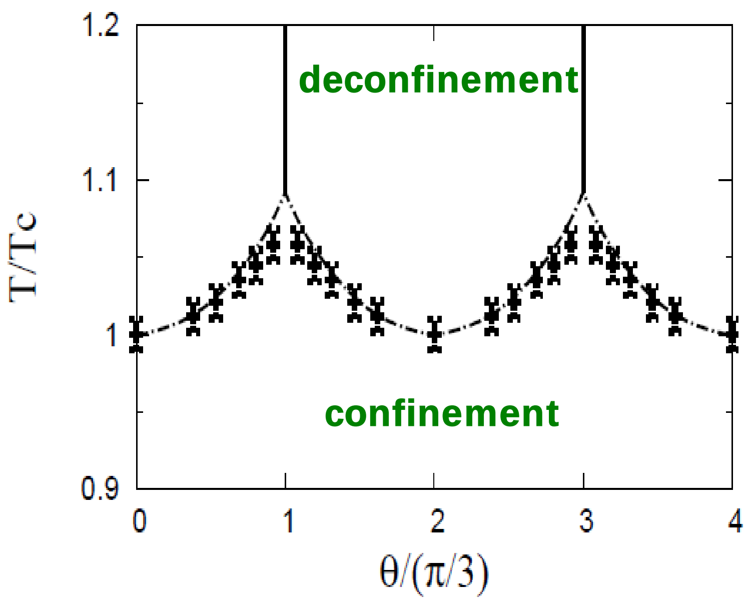




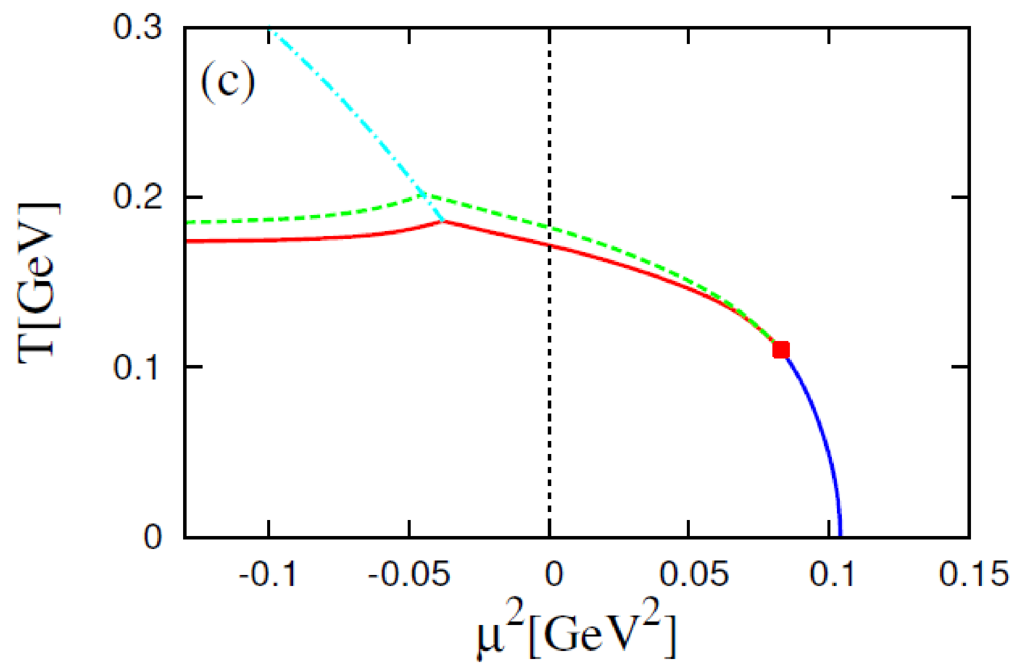
Imaginary chemical potential
Real chemical potential
虚数化学ポテンシャル
実数化学ポテンシャル
T
格子QCD
有効模型
0
μ²



m0=5.5 MeV
PNJL model
Polynomial (μ²)⁸
Ftting function
Mπ
π meson mass [GeV]
0.15
0.145
0.14
−0.1
0
0.1
μ² [GeV²]



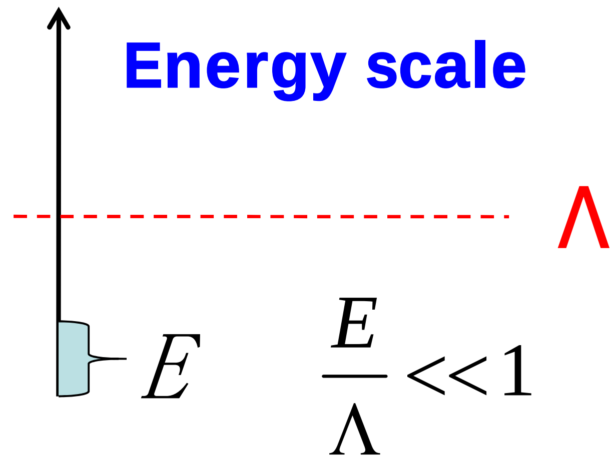
deconfinement
confinement
T/Tc
1.2
1.1
1
0.9
0
1
2
3
4
θ/(π/3)



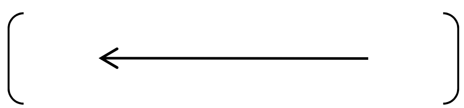
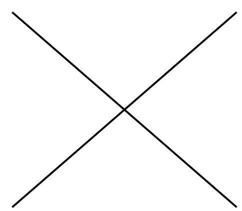
(c)
T[GeV]
0.3
0.2
0.1
0
-0.1
-0.05
0
0.05
0.1
0.15
μ²[GeV²]

Essence of effective model (theory)

QCD→PNJL



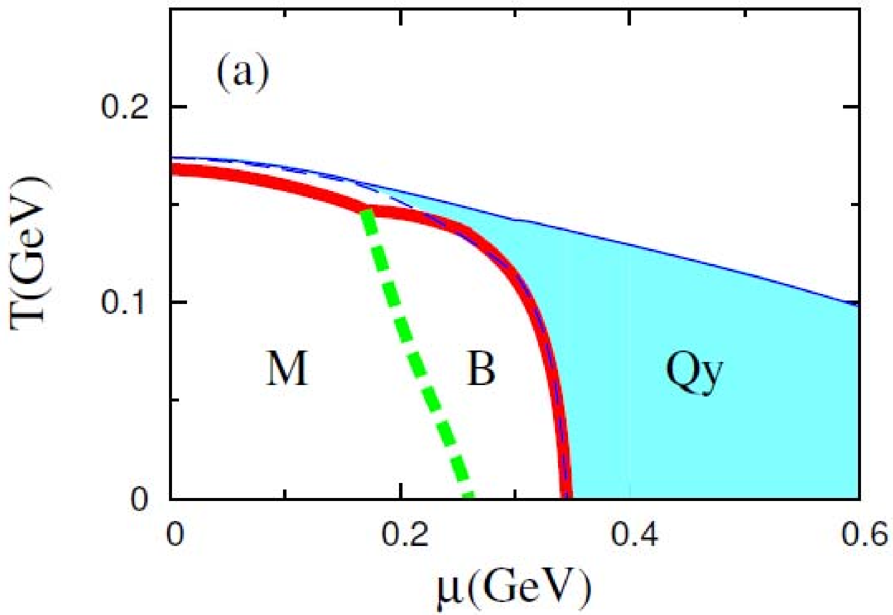
Model space

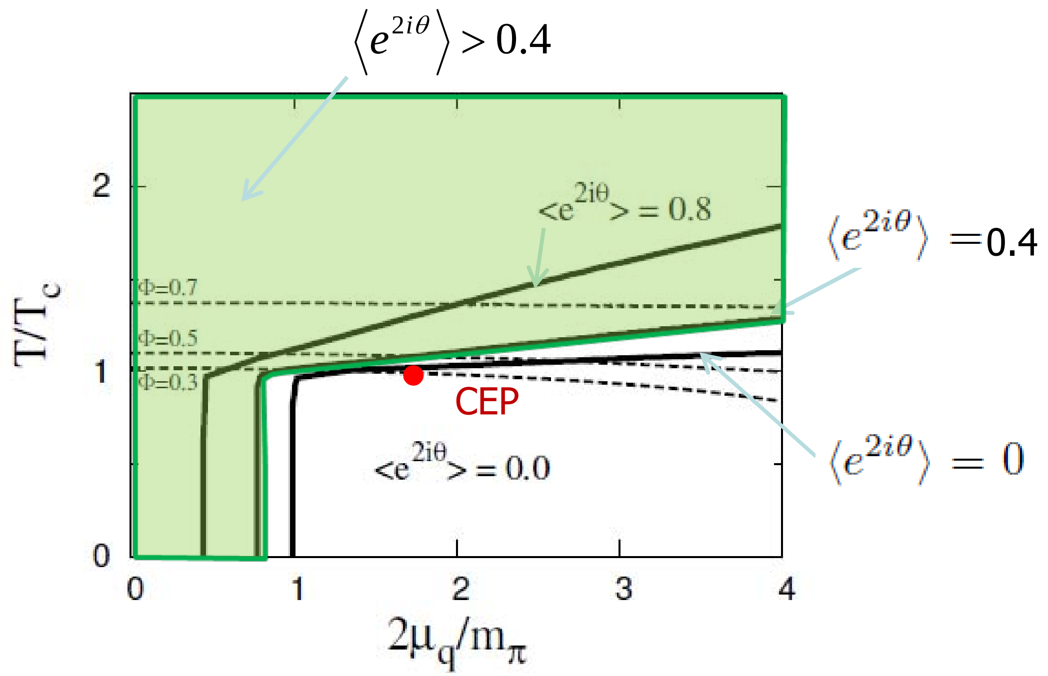
$L_{PNJL} =$  $^{-1}$ +  + Confinement

4-quark interaction

QCD phase diagram

Prediction of PNJL model





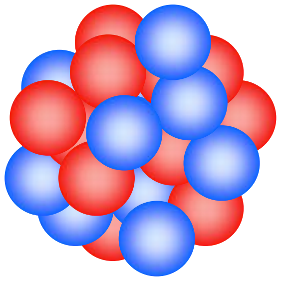
Sakai, Sasaki, Kouno and Yahiro, arXiv:1104.2394 [hep-ph]

Y. Sakai, T. Sasaki, H. Kouno, and M. Yahiro, Phys.Rev.D82:096007,2010.

1.2 Effective model in nuclear physics

Effective model (theory)

$$(K + V - E)\Psi = 0$$

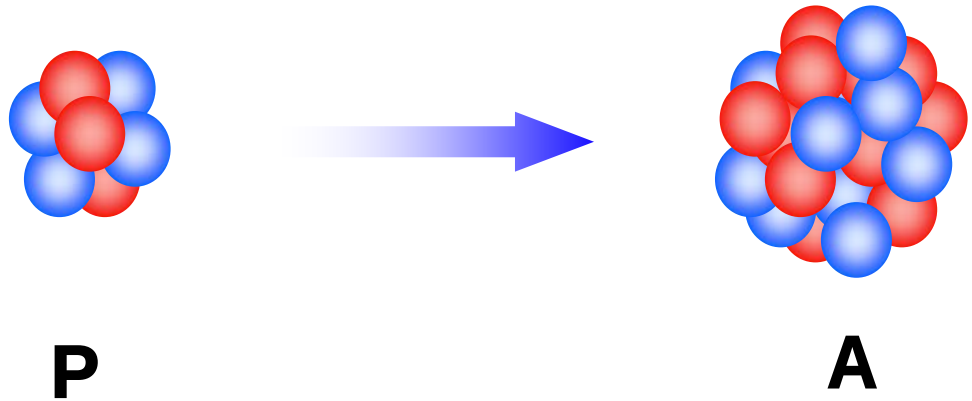


$$V = \sum_{i \in \mathrm{P}, j \in \mathrm{A}} v$$

v_{ij} Phenomenological NN interaction ⇨ Effective model

v_{ij} CPT ⇨ Effective theory

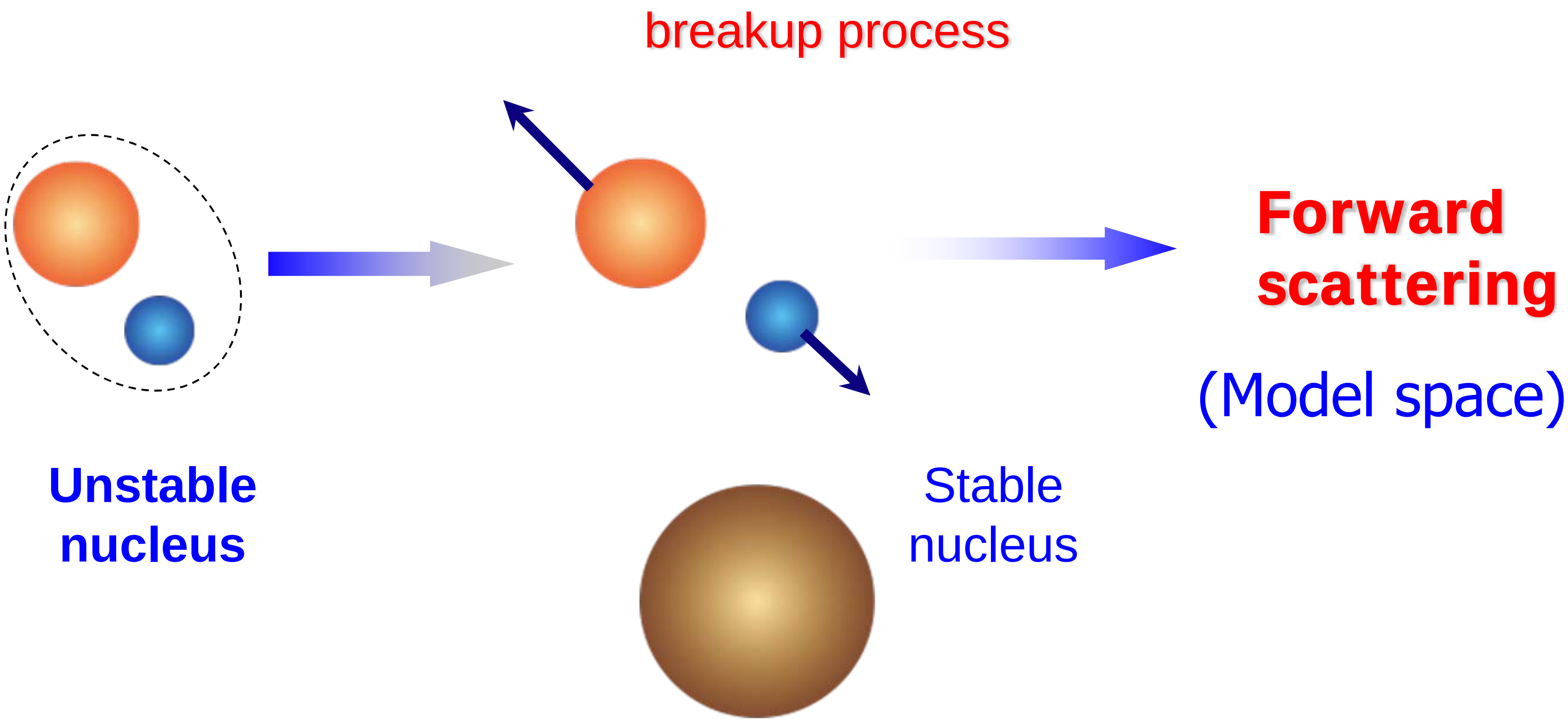
Nucleus-nucleus scattering



$$(K + h_{\mathrm{P}} + h_{\mathrm{A}} + V - \omega)\hat{\Psi}_{\alpha}^{(+)} = 0 \ ,$$

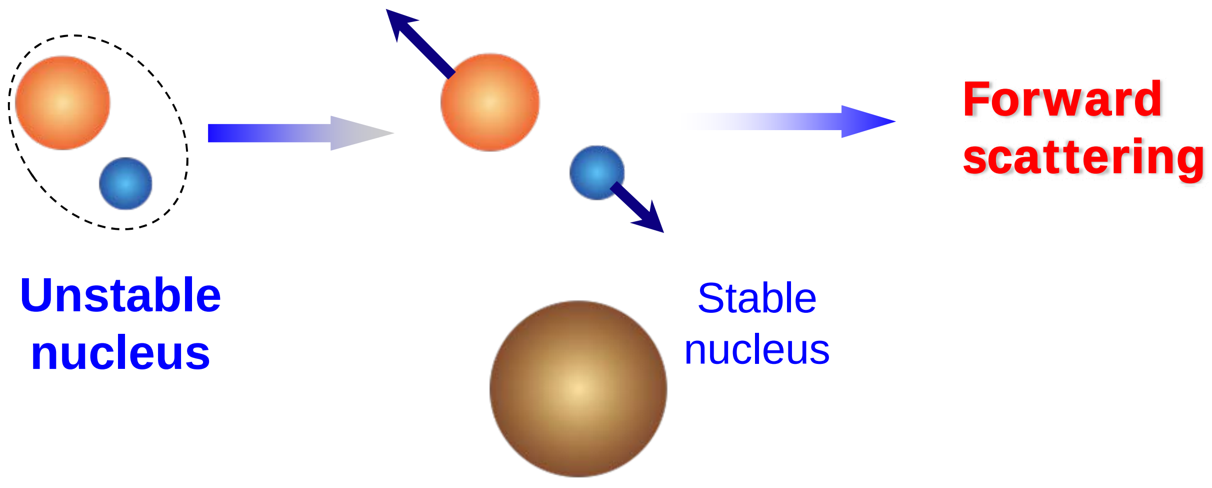
$$V = \sum_{i\in \mathrm{P}, j\in \mathrm{A}} v$$

Scattering of unstable nuclei



Effective model on scattering of unstable nuclei

$$T = \sum_n c_n \left(\frac{q}{\Lambda} \right)^n$$

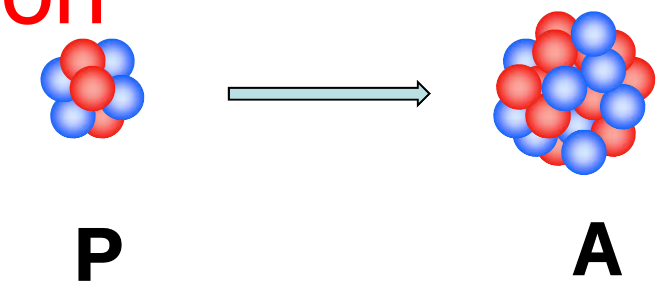


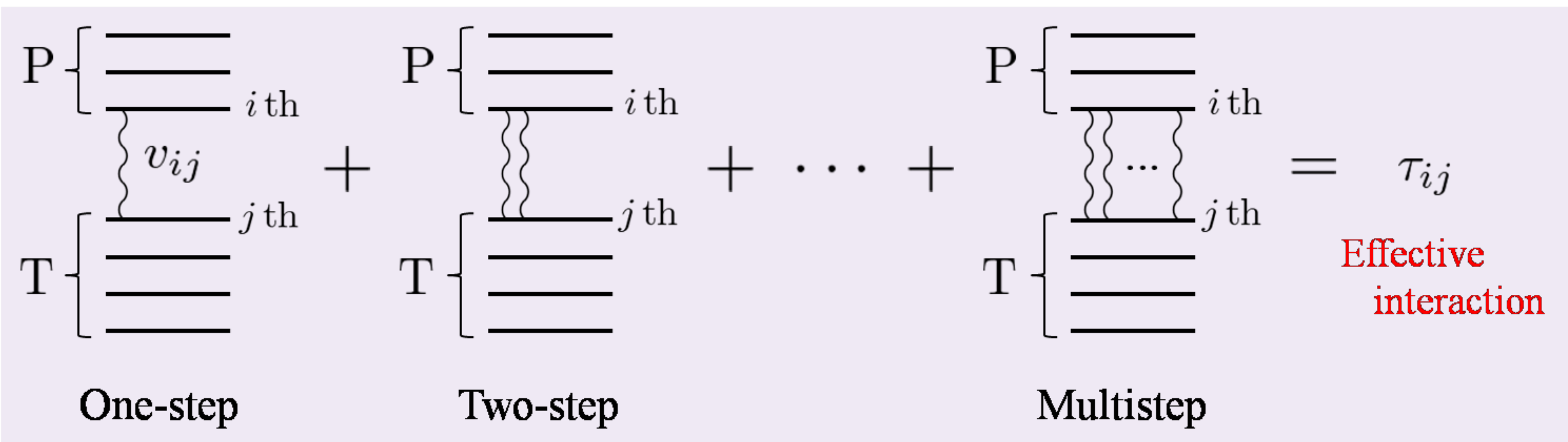
2. Microscopic reaction theory

Many-body Schrödinger equation with realistic NN interaction

Realistic NN interaction

$$\left(K + h_P + h_A + \boxed{\sum_{i\in P,\, j\in A} v_{ij}} - E\right)\Psi = 0$$

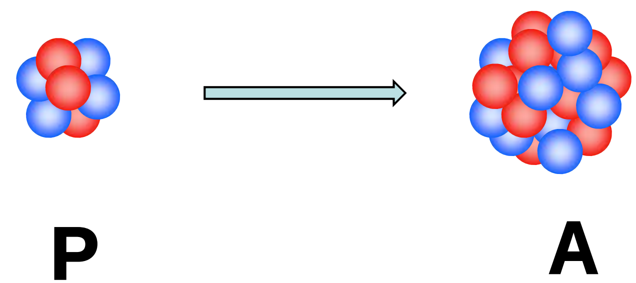




Schrödinger equation with resummation

M. Yahiro, K. Minomo, K. Ogata, M. Kawai, Prog.Theor.Phys.120:767-783,2008

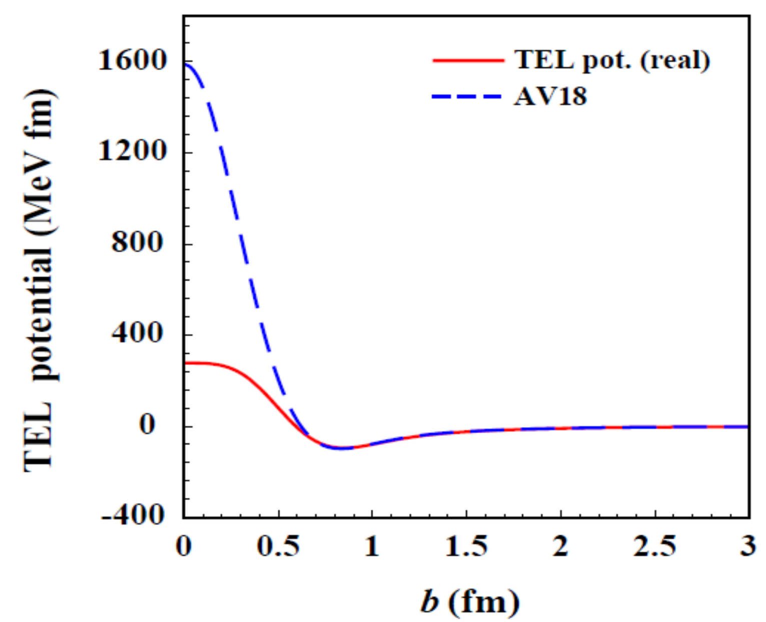
$$(K + h_P + h_A + \frac{A_p A_T - 1}{A_p A_T} \sum_{i \in P, j \in A} \tau_{ij} - \omega)\Psi = 0$$



$$(K + h_P + h_A + \boxed{\sum_{i \in P, j \in A} \tau_{ij}} - E)\Psi = 0$$

Effective NN interaction = G-matrix interaction

$$T = \sum_n c_n \left(\frac{q}{\Lambda} \right)^n$$



How to solve

1. Improved Glauber model

M. Yahiro, K. Minomo, K. Ogata, M. Kawai, Prog. Theor. Phys. 120: 767-783,2008.

2. Double folding model

Minomo, Ogata, Kohno, Shimizu and Yahiro, J.Phys.G37:085011,2010.

Minomo, Sumi, Kimura, Ogata, Shimizu and Yahiro,
to be published in Phys. Rev. C.

3. Cluster folding model

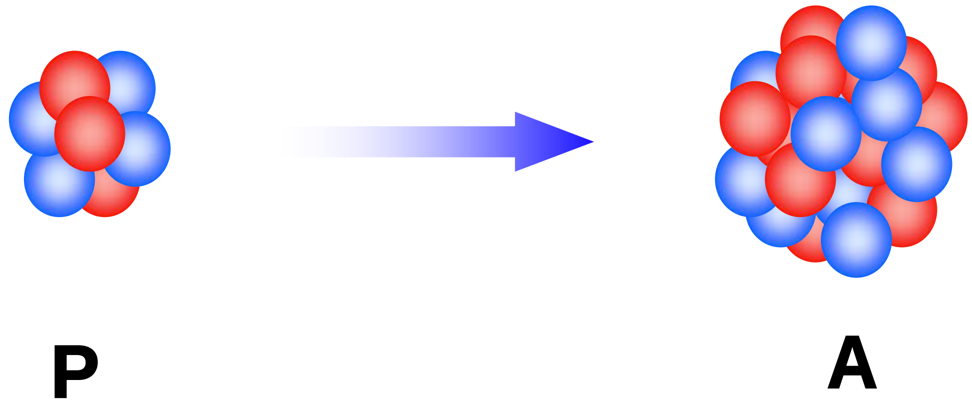
Yahiro, Ogata and Minomo, Prog. Theor. Phys. in press.

Hashimoto, Yahiro, Ogata, Minomo and Chiba, PRC in press.

2.1 Improved Glauber model

M. Yahiro, K. Minomo, K. Ogata, M. Kawai, Prog. Theor. Phys. 120: 767-783,2008.

2.1 Improved Glauber model



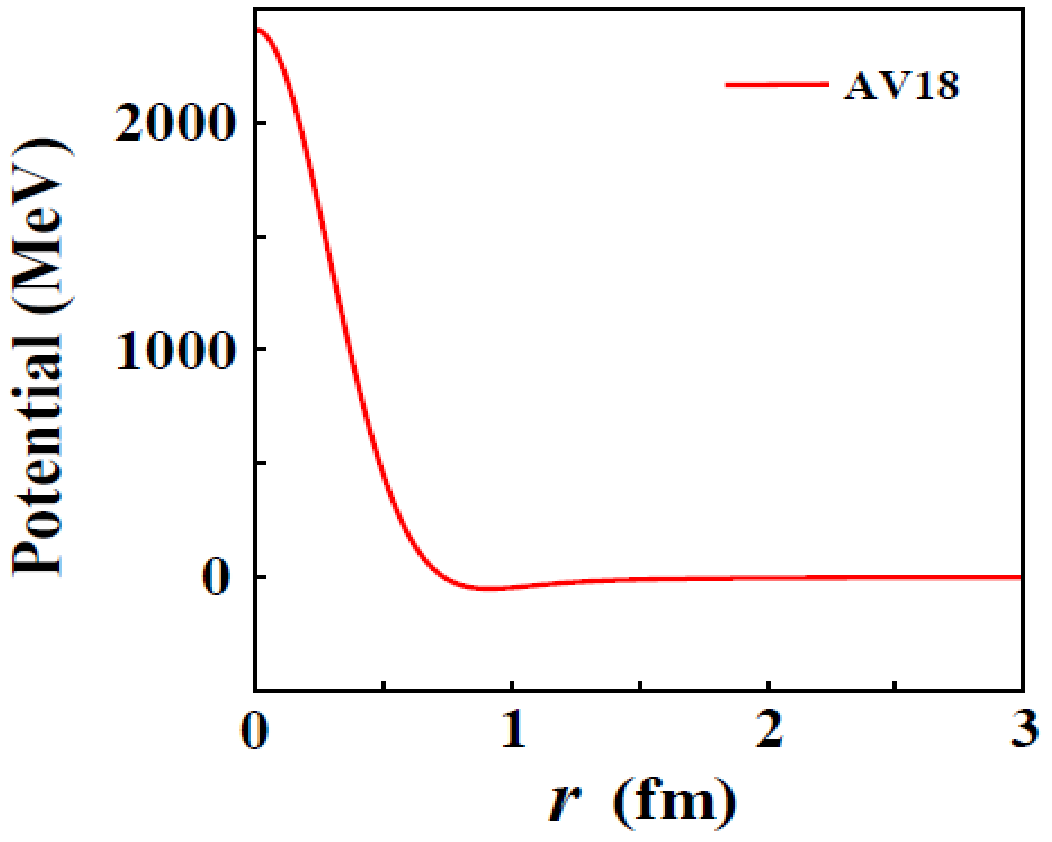
$$(K + h_{\mathrm{P}} + h_{\mathrm{A}} + V - \omega)\hat{\Psi}_{\alpha}^{(+)} = 0 \ ,$$

$$V = \sum_{i\in \mathrm{P}, j \in \mathrm{A}} v$$

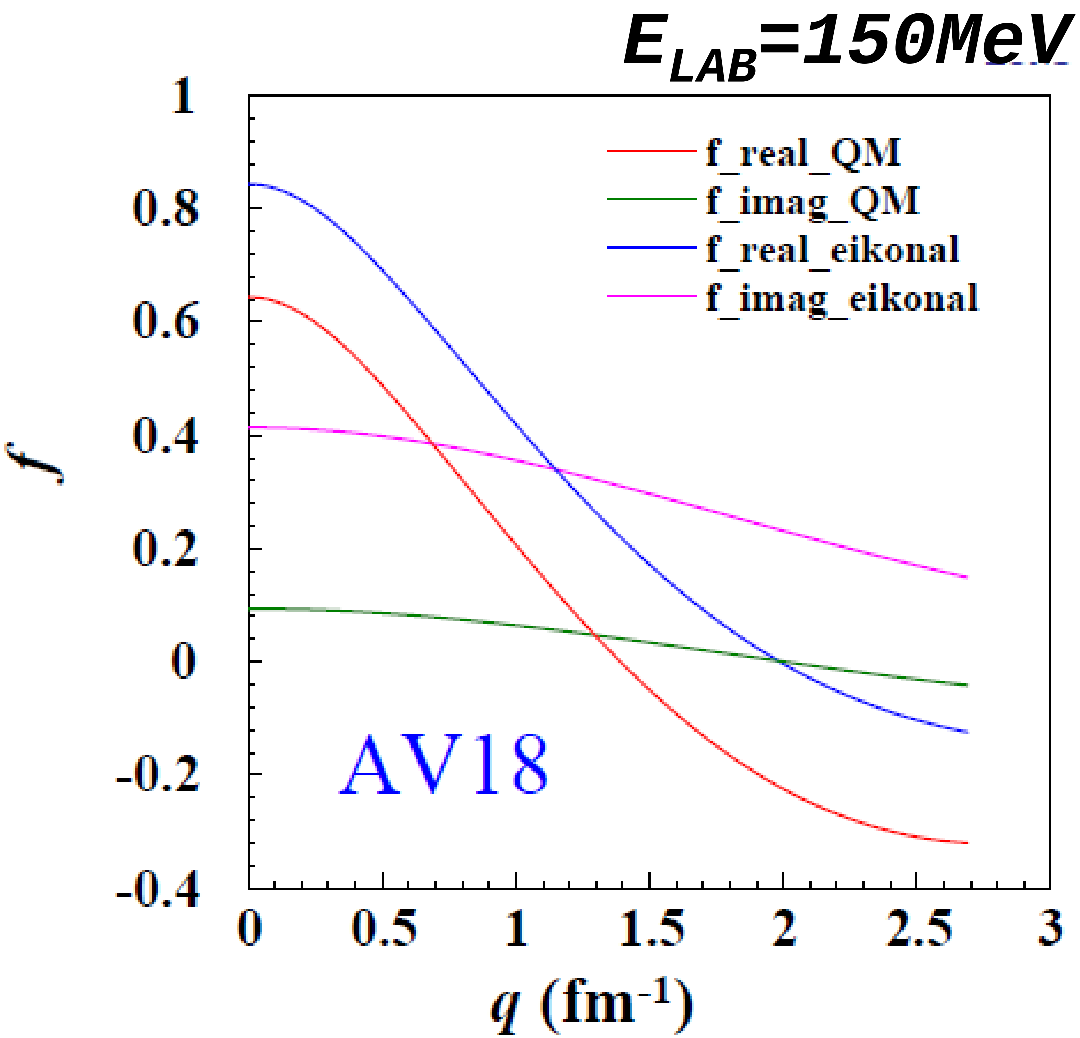
Eikonal approximation + Adiabatic approximation

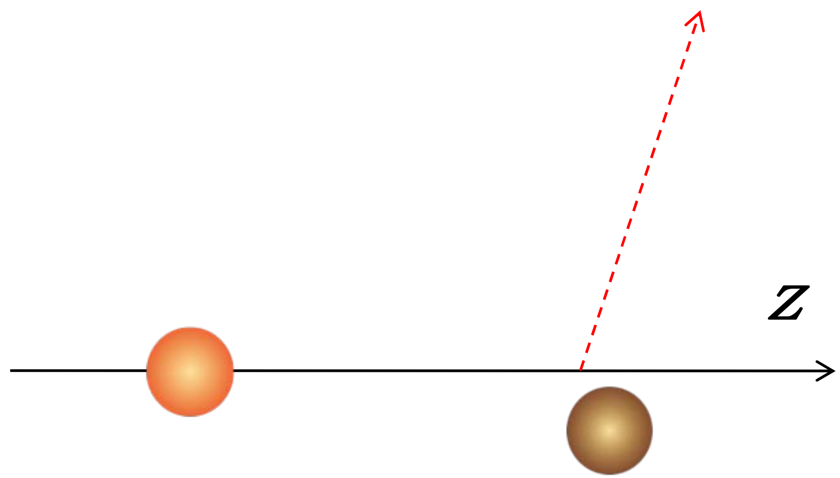
Argonne V18

triplet-even state , central part



N-N scattering amplitude

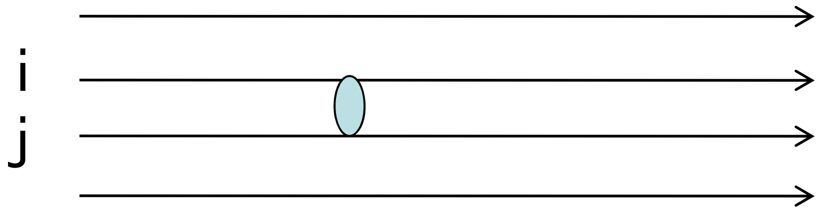




Effective NN interaction

τ

$$\tau = v(\boldsymbol{r}_{ij})(1 + G_0\tau) \qquad G_0 = \frac{\mathcal{P}}{E - K - h_{\mathrm{P}} - h_{\mathrm{A}} + i\epsilon},$$

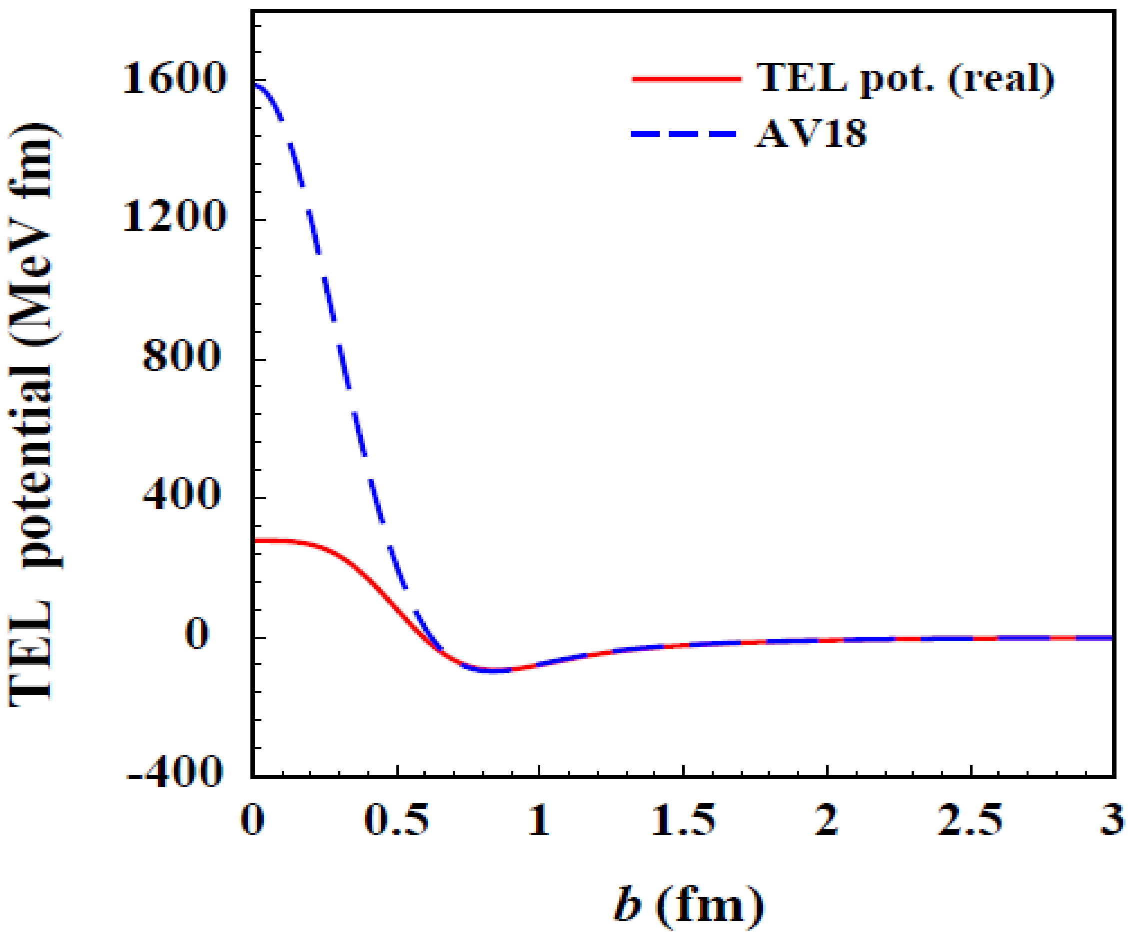


P A

$$v_{ij}\chi_{ij} = \tau_{ij}\phi_{ij}$$

$$(K + h_P + h_A + U - \omega)\Psi_\alpha^{(+)} = 0, \qquad U = \frac{Y-1}{Y}\sum_{ij}\tau_{ij}$$

Comparison of TEL pot. and AV18



The improved Glauber amplitude based on the multiple scattering theory

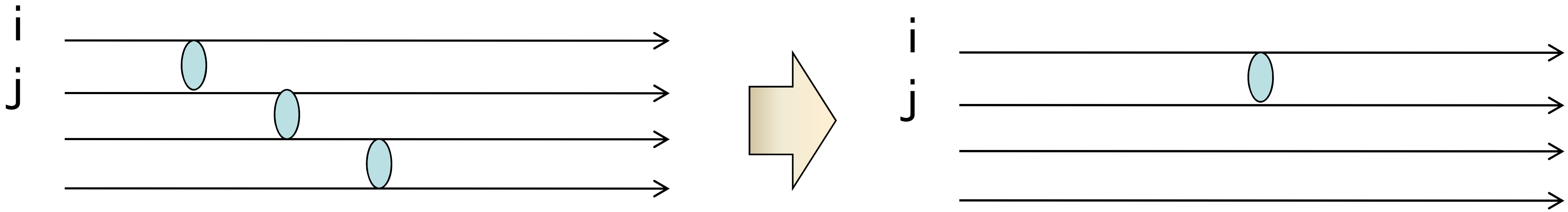
$$T_{\beta\alpha} = -\frac{i\hbar^2 k}{(2\pi)^3 \mu_\alpha} \frac{Y}{Y-1} \int d\boldsymbol{b} \exp[-i\boldsymbol{q}\cdot\boldsymbol{b}] \, \langle \Phi_\beta | \Gamma_U(\boldsymbol{b}) | \Phi_\alpha \rangle \; ,$$

$$\Gamma_U(\boldsymbol{b}) = 1 - \left\{ \prod_{i=1}^{P} \prod_{j=1}^{A} (1 - \Gamma_{NN}^{(\mathrm{eff})}(\boldsymbol{b}_{ij})) \right\}^{(Y-1)/Y} \; ,$$

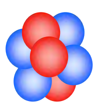
$$\Gamma_{NN}^{(\mathrm{eff})}(\boldsymbol{b}_{ij}) = 1 - \exp[i\chi_{NN}^{(\mathrm{eff})}(\boldsymbol{b}_{ij})] \; .$$

$$\chi_{NN}^{(\mathrm{eff})}(\boldsymbol{b}_{ij}) = -\frac{1}{\hbar v} \int_{-\infty}^{\infty} dz_{ij} \, \tau(z_{ij}, \boldsymbol{b}_{ij})$$

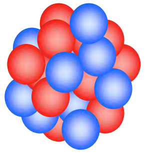
Test of the eikonal approximation



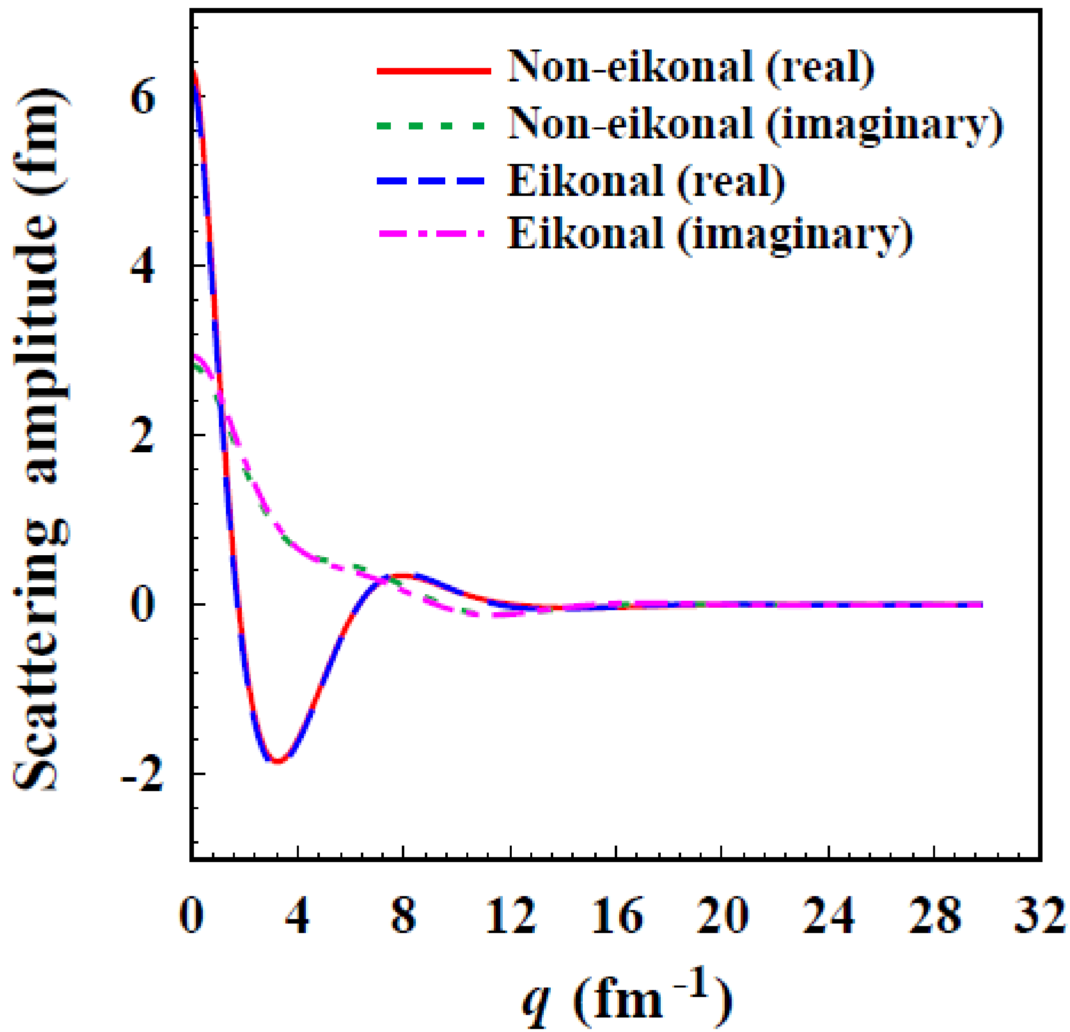
$$\alpha + {}^{208}\mathrm{Pb} \qquad E_{PA} = 300\ \mathrm{MeV/nucleon}$$



P



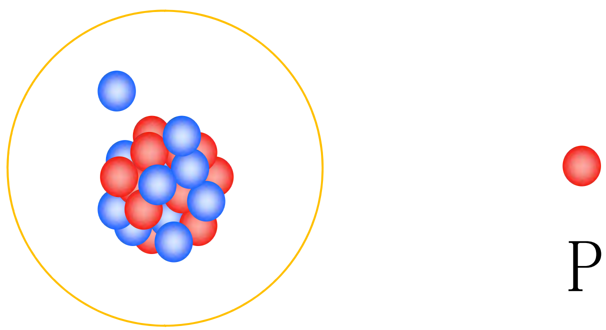
A



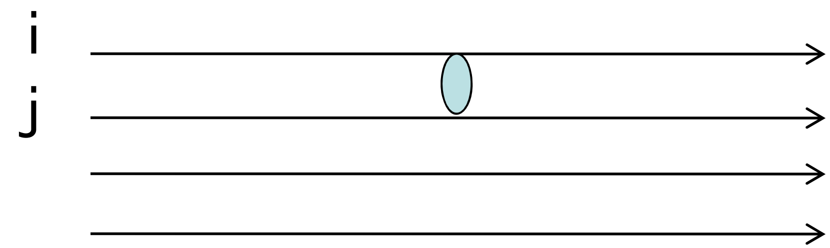
Non-eikonal (real)
Non-eikonal (imaginary)
Eikonal (real)
Eikonal (imaginary)
Scattering amplitude (fm)
6
4
2
0
-2
0
4
8
12
16
20
24
28
32
q (fm^-1)

Test of the adiabatic approximation

$$^{40}\mathrm{Ca} + p \quad (S_n = 15.64\ \mathrm{MeV}) \qquad E_{PA} = 300\ \mathrm{MeV/nucleon}$$



$^{40}\mathrm{Ca}$ P

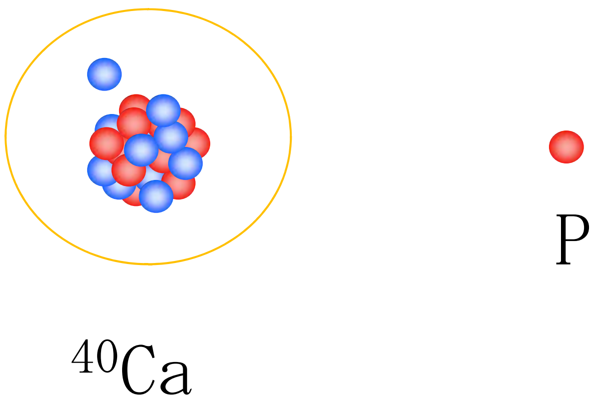


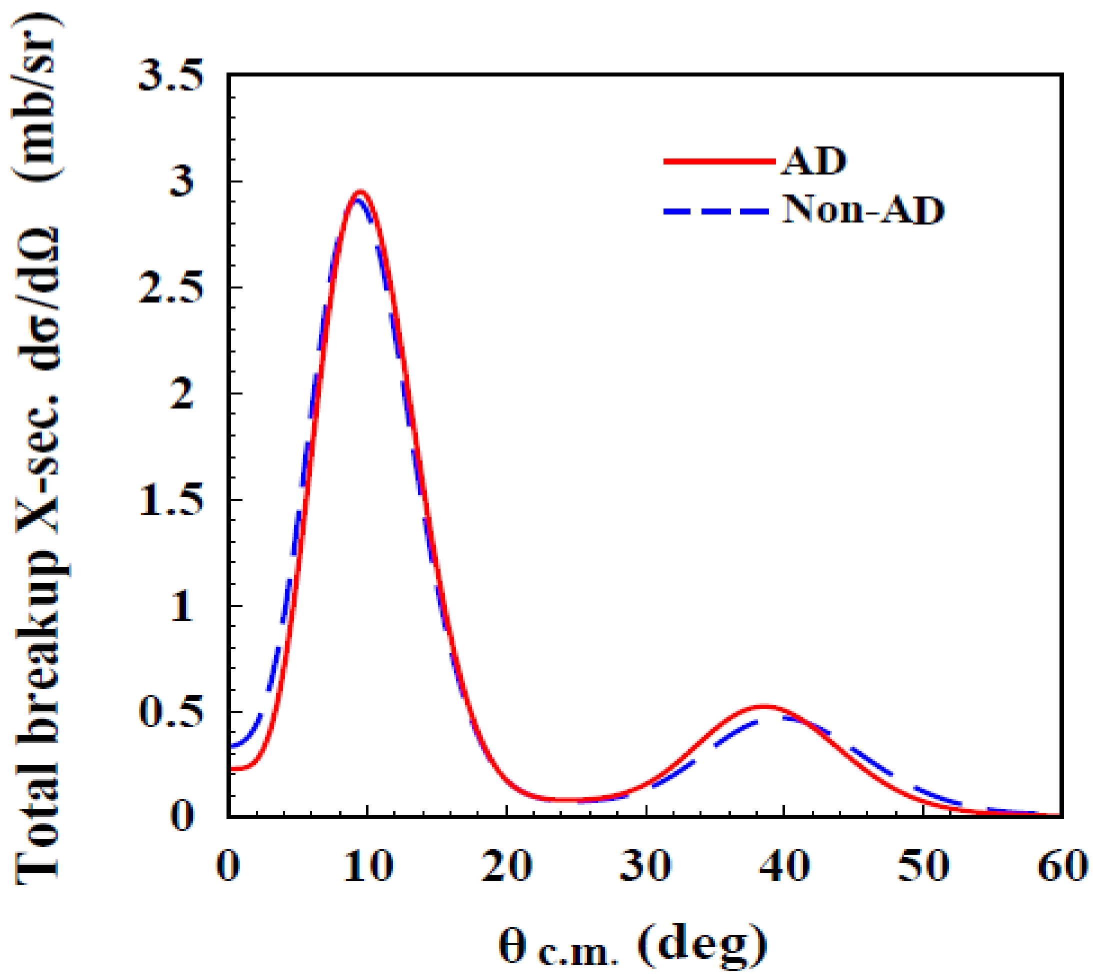
Non-adiabatic : $\left(K + h_P + \tau^{\mathrm{loc}}(\boldsymbol{r}_{ij}) - E\right)\psi = 0$

Adiabatic : $\left(K + \tau^{\mathrm{loc}}(\boldsymbol{r}_{ij}) - E_{PA}\right)\psi = 0$

$^{40}\mathrm{Ca} + p \qquad E_{PA} = 300$ MeV/nucleon

$S_n = 15.64$ MeV





2.2 Double folding model

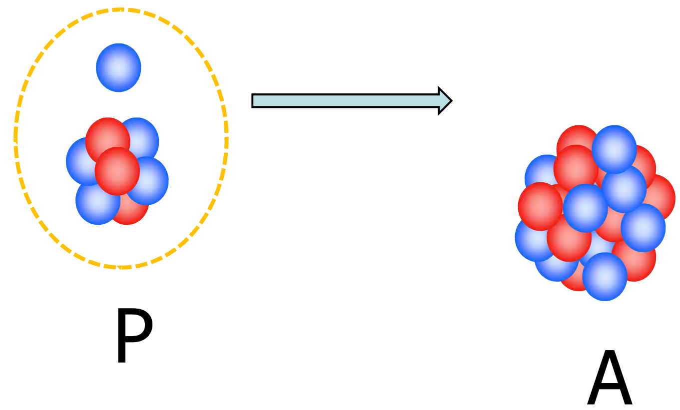
Minomo, Ogata, Kohno, Shimizu and Yahiro, J.Phys.G37:085011,2010.

Minomo, Sumi, Kimura, Ogata, Shimizu and Yahiro,
to be published in Phys. Rev. C.

Double-folding model

Folding potential

$$U_{opt} = < \Phi_P \Phi_A | \sum_{i \in P, j \in A} g_{ij} | \Phi_P \Phi_A >$$



G-matrix: K. Amos et al.,
(Melbourne group)
Adv. Nucl. Phys. Vol.25 (2000) 275

Microscopic calculation
(HF,AMD)

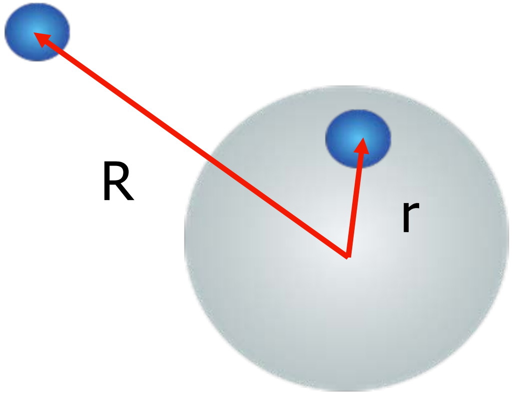
Bonn-B NN interaction
+ phenomenological imaginary potential.

Non-local potential

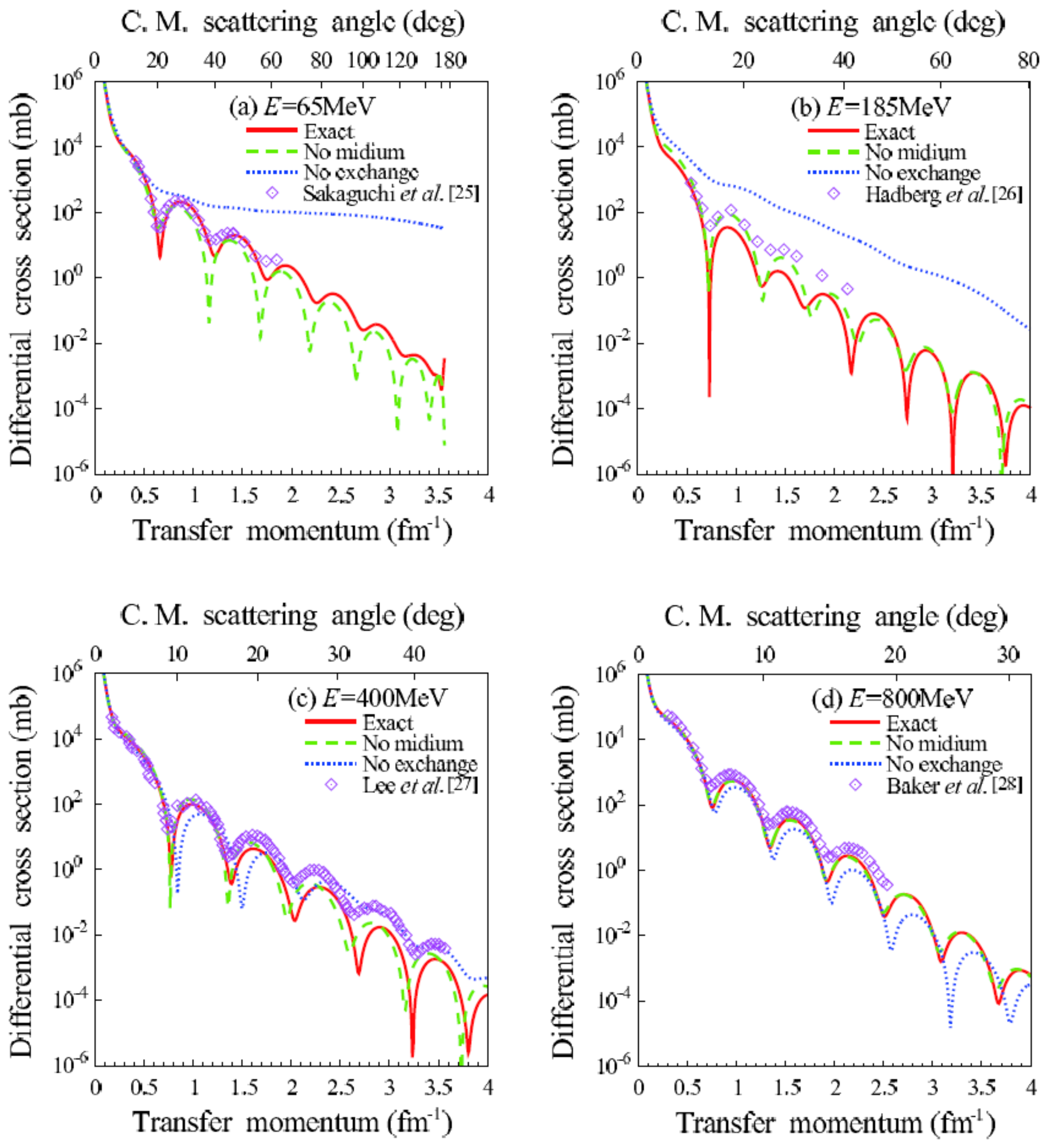
$$g_{0j} = g(r_{0j})(1 + P_{EX})$$

$$\left[-\frac{\hbar^2}{2\mu}\nabla_R^2 + U^{\mathrm{DR}}(\mathbf{R}) + V_{\mathrm{c}}(R)\,\delta_{-1/2}^{\nu_1} - E\right]\chi_{\mathbf{K},\nu_1}(\mathbf{R}) = \int U^{\mathrm{EX}}(\mathbf{R},\mathbf{r})\chi_{\mathbf{K},\nu_1}(\mathbf{r})\,d\mathbf{r}$$

Schroedinger equation for proton scattering



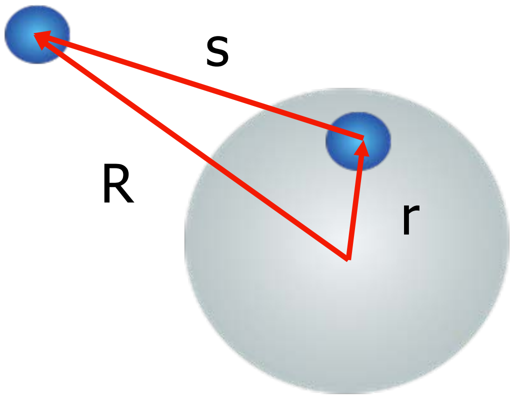
The proton scattering from ^{90}Zr



The Brieva-Rook localization

Nucl. Phys. A291,317

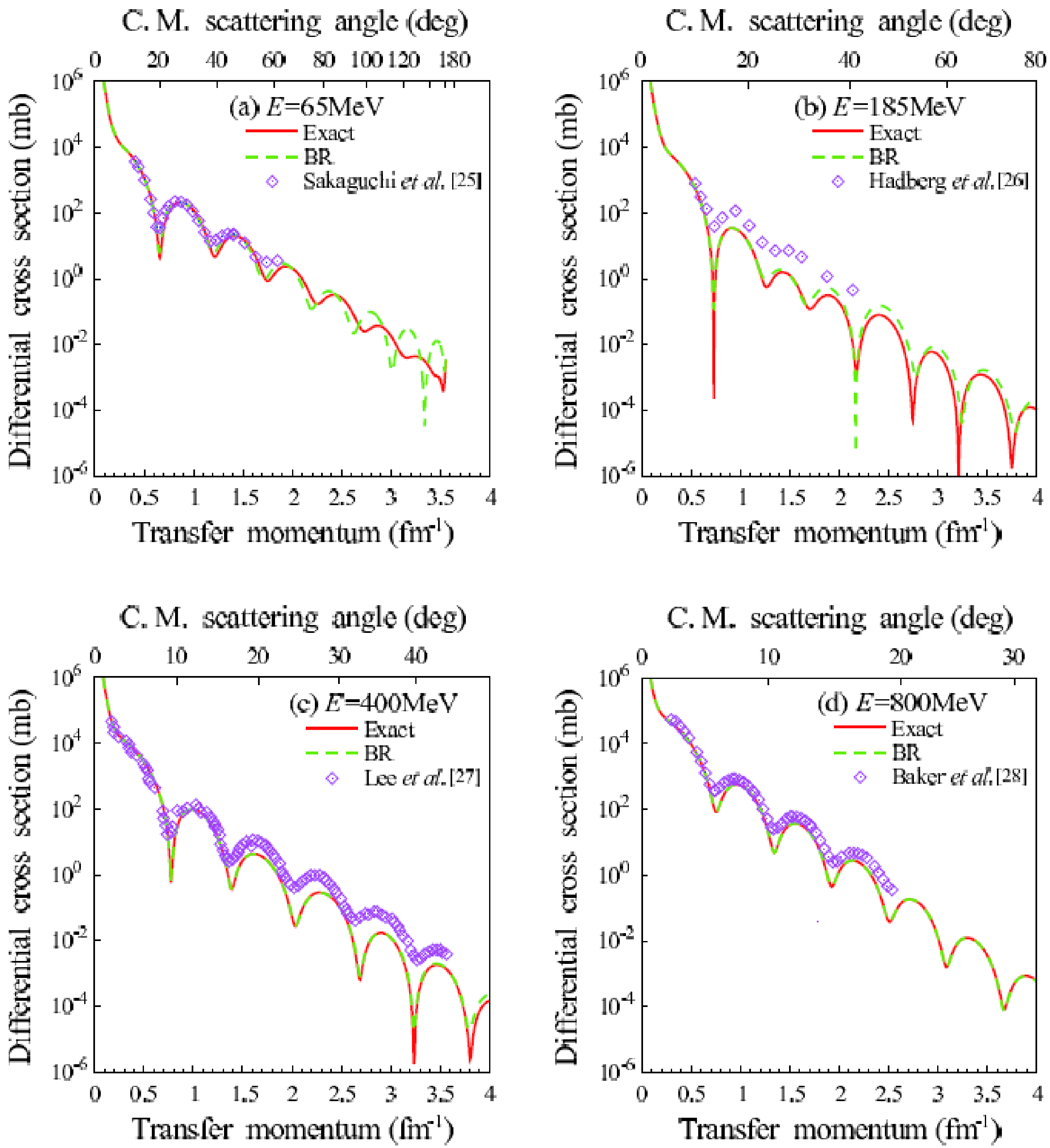
$$U_{\rm BR}^{\rm EX}(R) = \sum_{\nu_2,T_z} \int \rho_{\nu_2}^{\rm LFG}(\mathbf{R},\mathbf{r}) g_{T_z}^{\rm EX}(s;\rho_{\nu_2}(r_g)) j_0(K(R)s) d\mathbf{s}.$$



The mixed density

$$\rho_{\nu_2}(\mathbf{R},\mathbf{r}) = \sum_{nljj_z} \int \varphi^*_{\nu_2;nljj_z}(\mathbf{r},\xi)\, \varphi_{\nu_2;nljj_z}(\mathbf{R},\xi)\, d\xi,$$

K. Minomo, K. Ogata, M. Kohno, Y.R. Shimizu, M. Yahiro, J.Phys.G37:085011,2010.

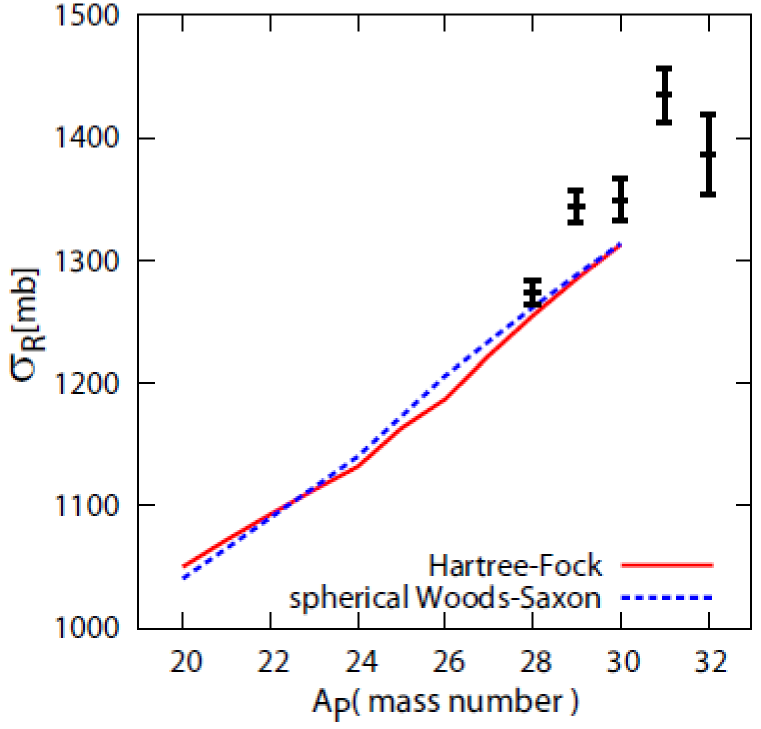


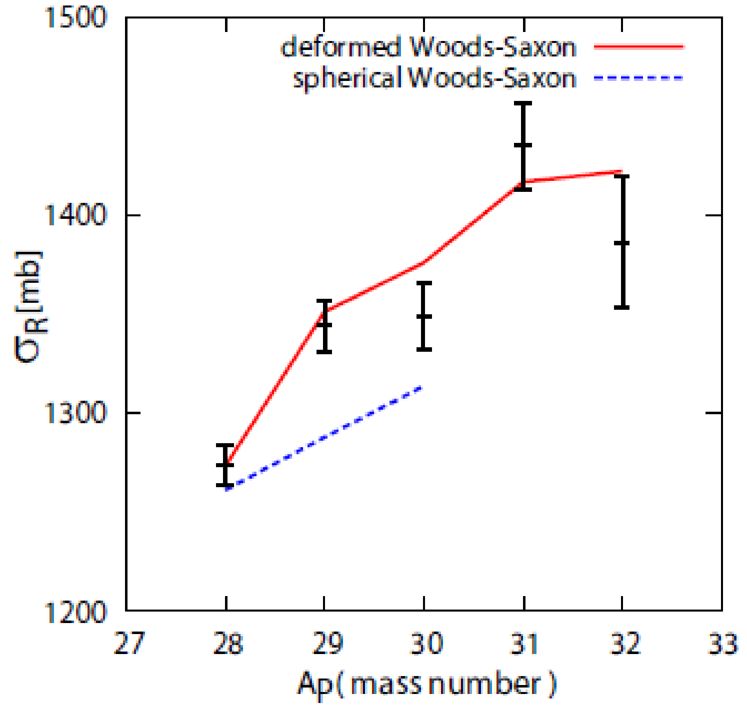
C. M. scattering angle (deg)
Differential cross section (mb)
Transfer momentum (fm-1)
(a) E=65MeV
Exact
BR
Sakaguchi et al. [25]
(b) E=185MeV
Exact
BR
Hadberg et al. [26]
(c) E=400MeV
Exact
BR
Lee et al. [27]
(d) E=800MeV
Exact
BR
Baker et al. [28]

Deformation effect on reaction cross section

Minomo, Sumi, Kimura, Ogata, Shimizu and Yahiro, to be published in Phys. Rev. C.

$^{20\text{-}32}$Ne+^{12}C scattering at 240 MeV/nucleon



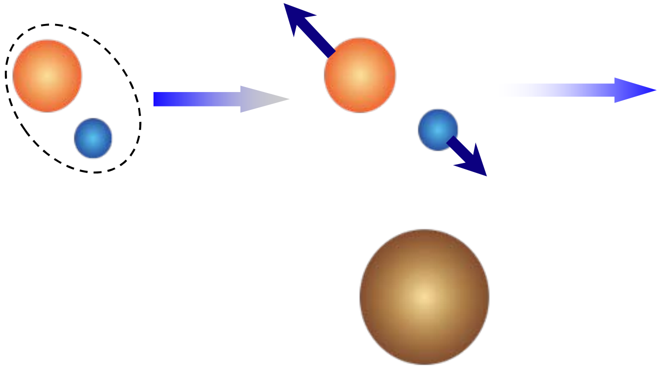


Wyss parametrization

2.3 Cluster folding model

Yahiro, Ogata and Minomo, Prog. Theor. Phys. in press.

Hashimoto, Yahiro, Ogata, Minomo and Chiba, PRC in press.



3. Eikonal Reaction Theory

Yahiro, Ogata and Minomo, Prog. Theor. Phys. in press.

Hashimoto, Yahiro, Ogata, Minomo and Chiba, PRC in press.

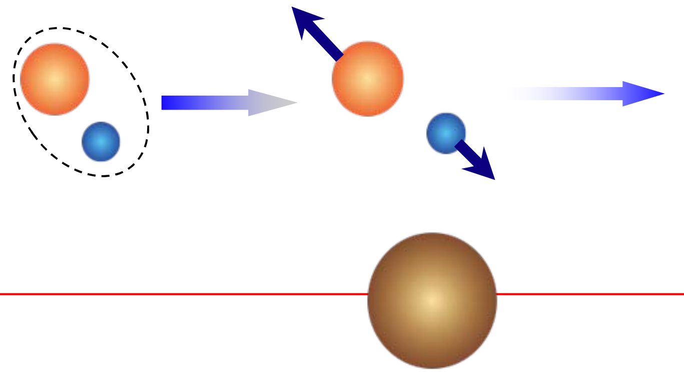
New theory(ERT)

CDCC

Glauber model

Reliable
Theory for exclusive reactions

Less reliable
Theory for inclusive reactions



Numerical results (CDCC)

T. Nakamura, *et al.*, Phys. Rev. Lett. **103** (2009), 262501.

	^{12}C target			^{208}Pb target		
	$p_{3/2}$	$f_{7/2}$	exp	$p_{3/2}$	$f_{7/2}$	exp
$\sigma_{\rm str}$	90	29		244	53	
$\sigma_{\rm bu}$	23.3	3.3		799.5	73.0	(540)
$\sigma_{-\rm n}$	114	32	79 ± 7	1044	126	712 ± 65
$\mathcal{S}$	0.693	2.47		0.682	5.65	

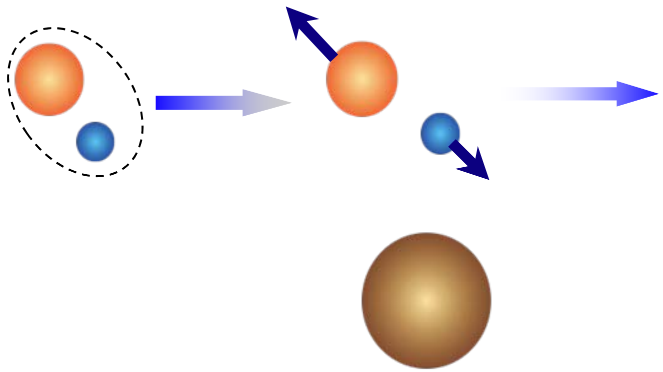
$\mathcal{S}_{\rm AMD} \sim 0.55$ (Preliminary result) by M. Kimura

The Glauber-model calculation with Coulomb corrections

P. Capel, D. Baye, and Y. Suzuki, Phys. Rev. C **78** (2008), 054602.
W. Horiuchi, Y. Suzuki, P. Capel, and D. Baye, Phys. Rev. C **81** (2010), 024606.

$\sigma_{-\rm n} = 96(\rm mb)$ $(\mathcal{S} = 0.823)$ $\sigma_{-\rm n} = 1140(\rm mb)$ $(\mathcal{S} = 0.625)$

Eikonal Reaction Theory



$$(E - \frac{\hbar^2}{2\mu}\Delta - \hat{h} - V_n - V_c)\psi = 0$$

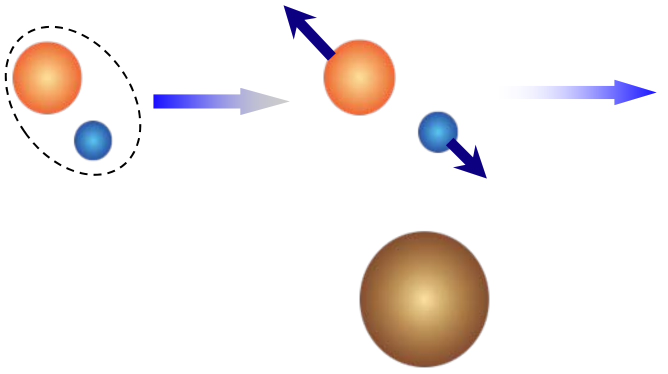
Eikonal assumption

$$\psi = e^{i\hat{k}z}\chi(r) \qquad \hat{k} = \frac{1}{\hbar}\sqrt{2\mu(E-\hat{h})}$$

Formal solution

$$S = \exp\left[-i\frac{1}{\hbar v} P \int_{-\infty}^{\infty} dz O^{-1}(V_n + V_c) O \right]$$

$$O = e^{i\hat{k}z}$$



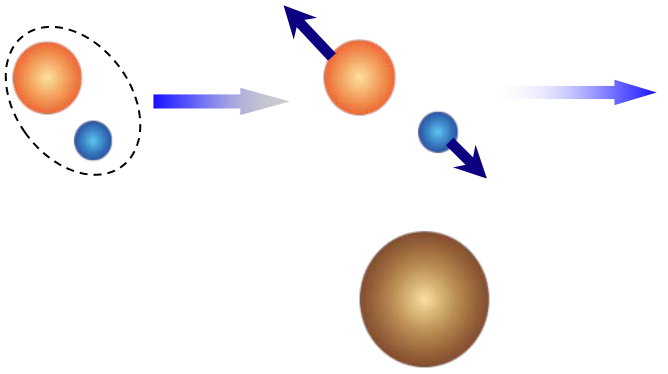
Eikonal decomposition of S

$$S = \exp\left[-i \frac{1}{\hbar v} P \int_{-\infty}^{\infty} dz O^{-1} (V_n + V_c) O \right]$$

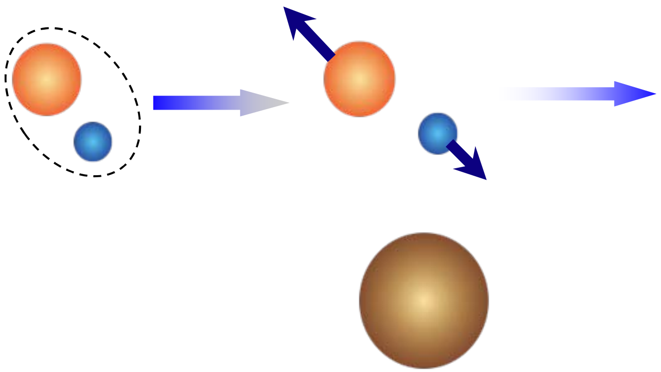
$$\approx \exp\left[-i \frac{1}{\hbar v} \int_{-\infty}^{\infty} dz V_n \right] \exp\left[-i \frac{1}{\hbar v} P \int_{-\infty}^{\infty} dz O^{-1} V_c O \right]$$

$$= S_n S_c$$

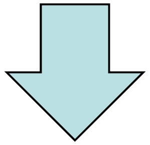
$$O^{-1} V_n O \approx V_n e^{i(k_i - k_f)a}$$



How to get S_c



$$(E - \frac{\hbar^2}{2\mu}\Delta - \hat{h} - V_n - V_c)\psi = 0$$



$$(E - \frac{\hbar^2}{2\mu}\Delta - \hat{h} - V_c)\psi_c = 0$$

Eikonal CDCC

K.Ogata, Hashimoto, Iseri, Kamimura, and Yahiro, PRC<u>73</u>, 024605 (2006).

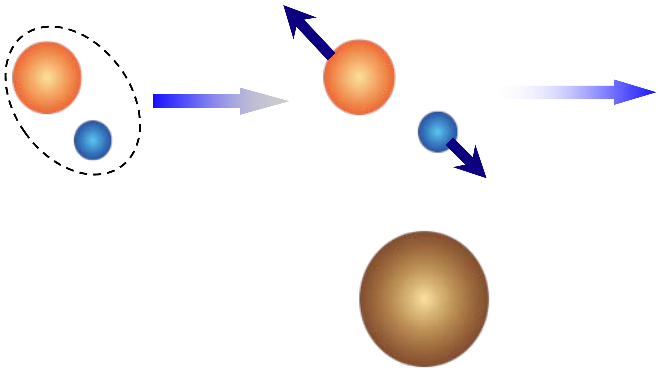
Eikonal decomposition of S

$$S = \exp\left[-i \frac{1}{\hbar v} P \int_{-\infty}^{\infty} dz O^{-1} (V_n + V_c) O \right]$$

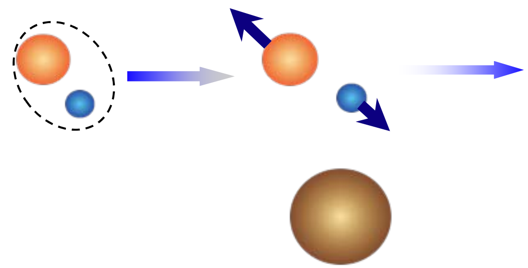
$$\approx \exp\left[-i \frac{1}{\hbar v} \int_{-\infty}^{\infty} dz V_n \right] \exp\left[-i \frac{1}{\hbar v} P \int_{-\infty}^{\infty} dz O^{-1} V_c O \right]$$

$$= S_n S_c$$

$$O^{-1} V_n O \approx V_n e^{i(k_i - k_f) a}$$



One nucleon removal reaction



$$\sigma_{-n} = \sigma_{\rm bu} + \sigma_{\rm str}$$

CDCC ERT

$$\sigma_{\rm str} = \int d^2\boldsymbol{b} \langle \varphi_0 | |S_{\rm c}|^2 (1 - |S_{\rm n}|^2) | \varphi_0 \rangle$$

Numerical results (CDCC)

T. Nakamura, *et al.*, Phys. Rev. Lett. **103** (2009), 262501.

	^{12}C target			^{208}Pb target		
	$p_{3/2}$	$f_{7/2}$	exp	$p_{3/2}$	$f_{7/2}$	exp
$\sigma_{\rm str}$	90	29		244	53	
$\sigma_{\rm bu}$	23.3	3.3		799.5	73.0	(540)
$\sigma_{-\rm n}$	114	32	79 ± 7	1044	126	712 ± 65
$\mathcal{S}$	0.693	2.47		0.682	5.65	

$\mathcal{S}_{\rm AMD} \sim 0.55$ (Preliminary result) by M. Kimura

The Glauber-model calculation with Coulomb corrections

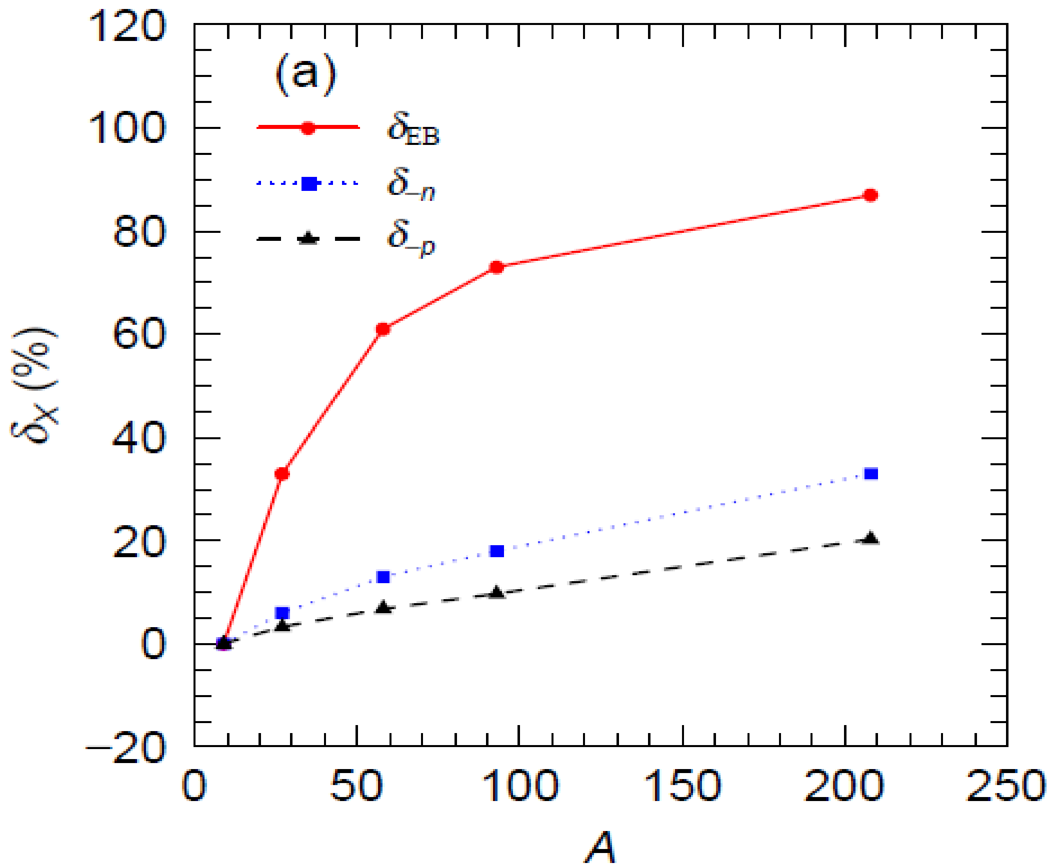
P. Capel, D. Baye, and Y. Suzuki, Phys. Rev. C **78** (2008), 054602.
W. Horiuchi, Y. Suzuki, P. Capel, and D. Baye, Phys. Rev. C **81** (2010), 024606.

$\sigma_{-\rm n} = 96$(mb) $(\mathcal{S} = 0.823)$ $\sigma_{-\rm n} = 1140$(mb) $(\mathcal{S} = 0.625)$

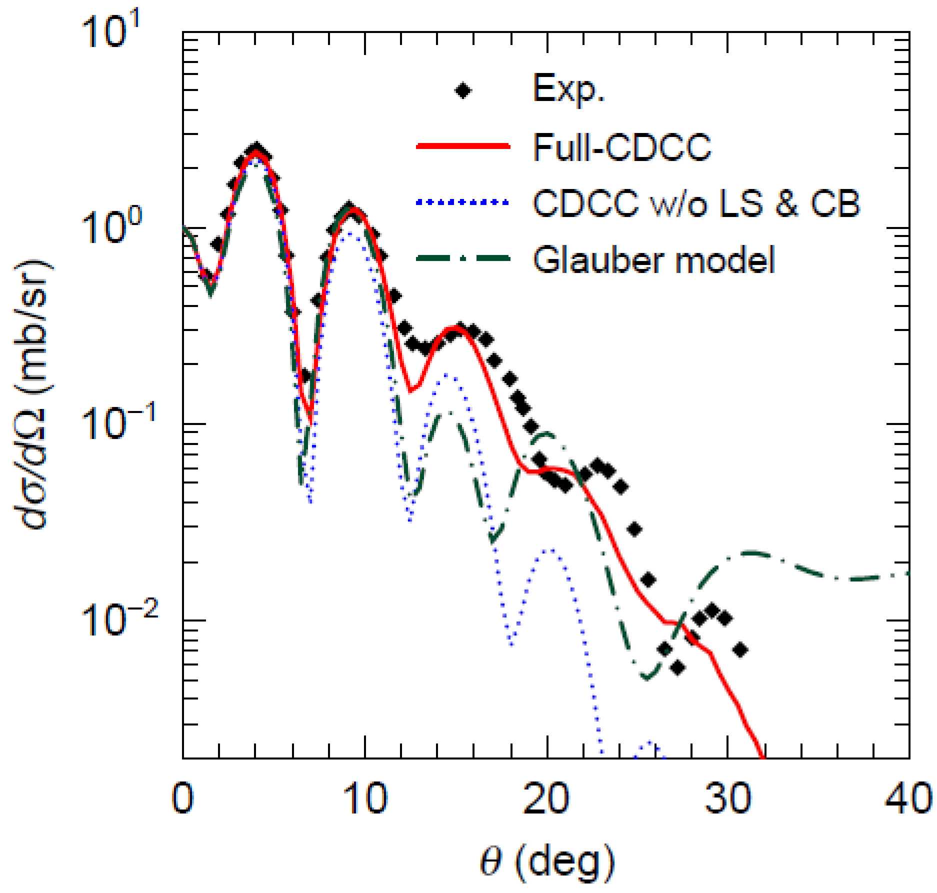
Accuracy of the Glauber model

Hashimoto, Yahiro, Ogata, Minomo and Chiba, PRC in press.

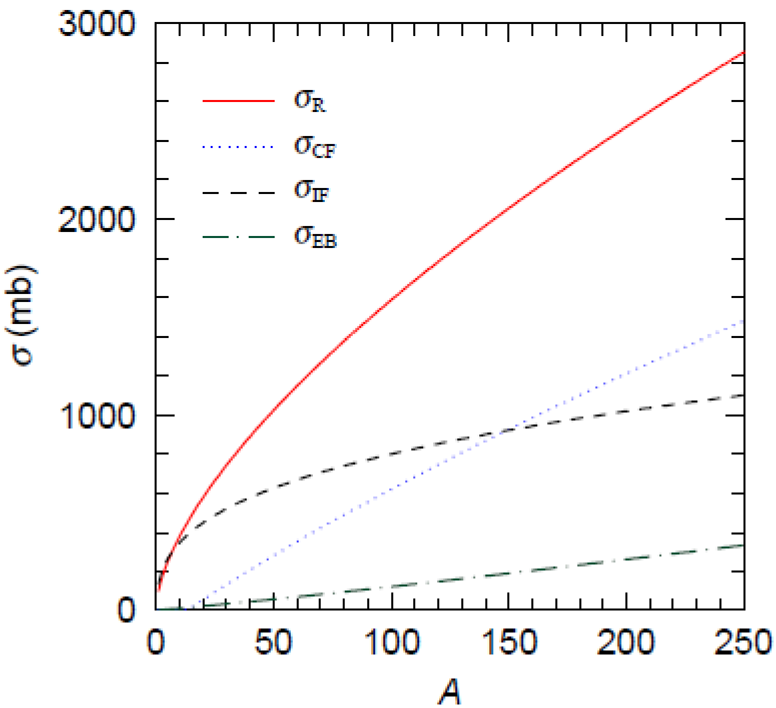
Deuteron scattering from several targets at 200 MeV/nucleon

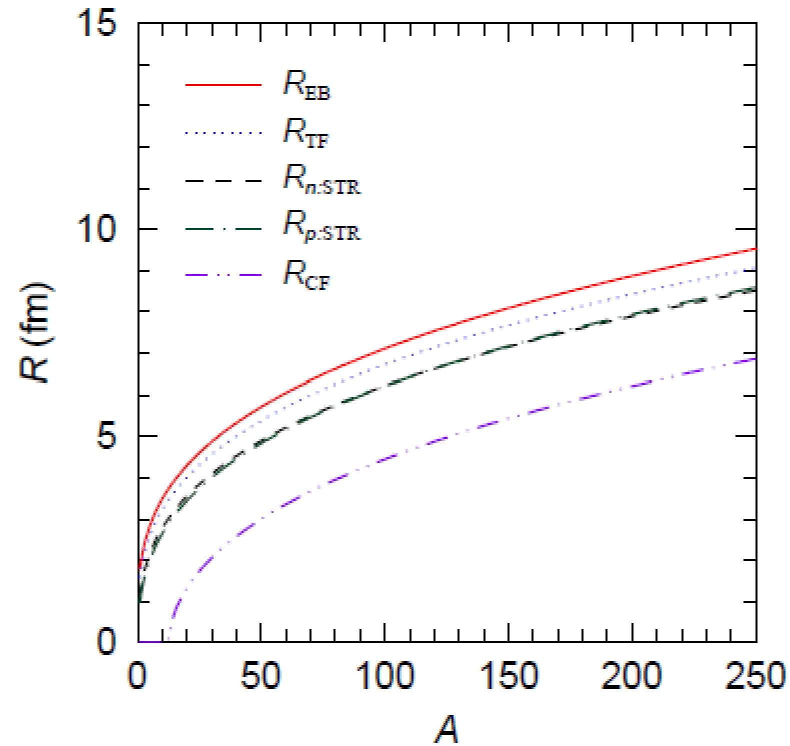


d+^{58}Ni elastic scattering at 400 MeV



Reaction cross sections





4. Summary

Fine spectroscopy in unstable nuclei

↓

1. Fine experiments (RIBF)
2. Fine reaction theory
   (Eikonal reaction theory, Modified Glauber model)
3. Fine structure theory (Shell model, AMD, MF)
4. Fine effective N-N interaction (t-matrix, g-matrix)

↓

The equation of state