

Glauber-theory calculations for medium- to high-energy nuclear scattering

Intersection of nuclear structure and high-energy nuclear collisions 2026

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YITP, Kyoto, Japan

Wataru Horiuchi (Osaka Metropolitan University; OMU) .

WH, Y. Suzuki, R. B. Wiringa, arXiv: 2512.20095, Phys. Rev. Lett, **accepted on April 21!**

WH, Y. Suzuki, R. B. Wiringa, arXiv: 2512.20100, Phys. Rev. C, in press

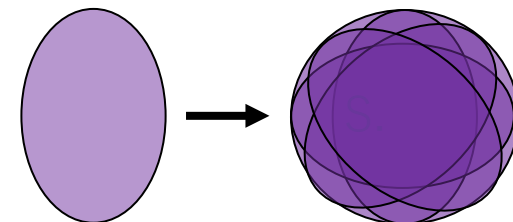
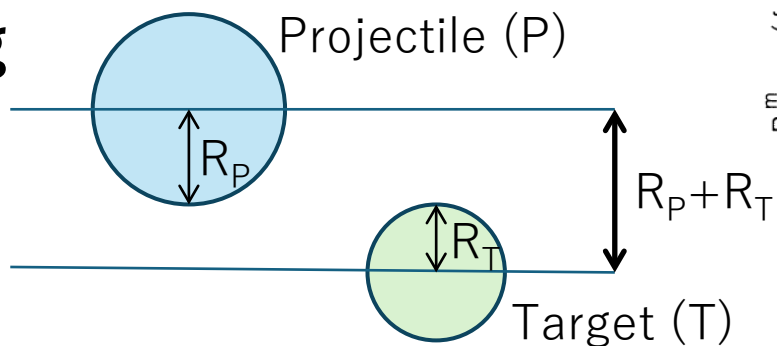
Motivation

I. Tanihata et al., Phys. Rev. Lett. 55, 2676 (1985)
 S. Bagchi et al., Phys. Rev. Lett. 124, 222504 (2020)
 WH, T. Inakura, T. Nakatsukasa, Y. Suzuki, Phys. Rev. C 86, 024614 (2012)
 M. Takechi et al., Phys. Rev. C 90, 061305(R) (2014)

- Medium- to high-energy nucleus-nucleus scattering ($\sim 100-1000$ MeV/nucleon)

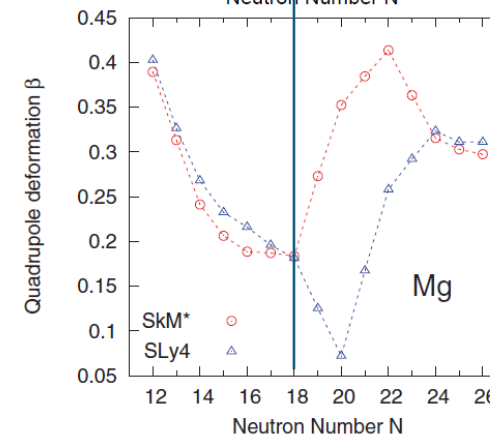
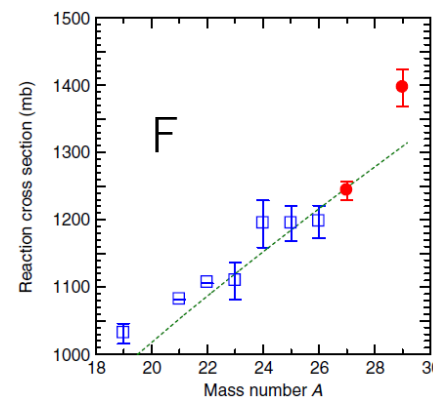
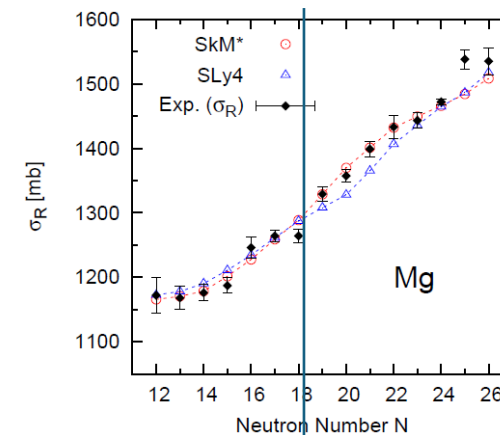
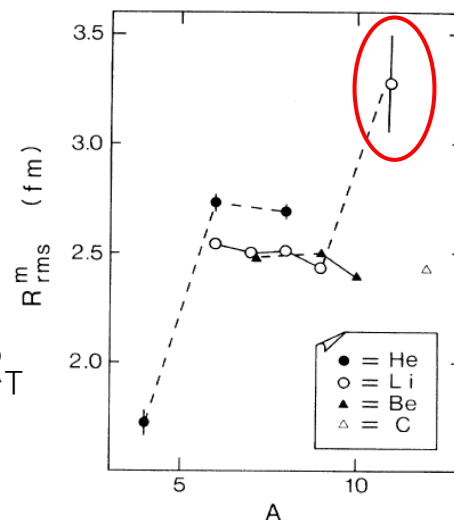
- **Total reaction (interaction) cross section**
- **Elastic scattering**

Total reaction (interaction) cross section $\sim \pi (R_P + R_T)^2$



A probe of nuclear surface properties

- Halo/skin nuclei
 - Spectroscopic information: shell evolution
 - Deformation, core swelling, bubble, etc.
- Bulk properties of nuclear matter



Motivation

- Glauber theory R. J. Glauber, in *Lectures in Theoretical Physics*, (Interscience, New York, 1959), Vol. 1, p. 315.
 - Microscopic high-energy reaction theory
 - Eikonal and adiabatic approximation
 - Starting from NN scattering phase-shift function
 - Direct relationship between many-nucleon wave function and scattering observables
 - “Original” Glauber-theory calculation is involved (e.g., multifold integral)
 - “Approximated” Glauber theory is often applied

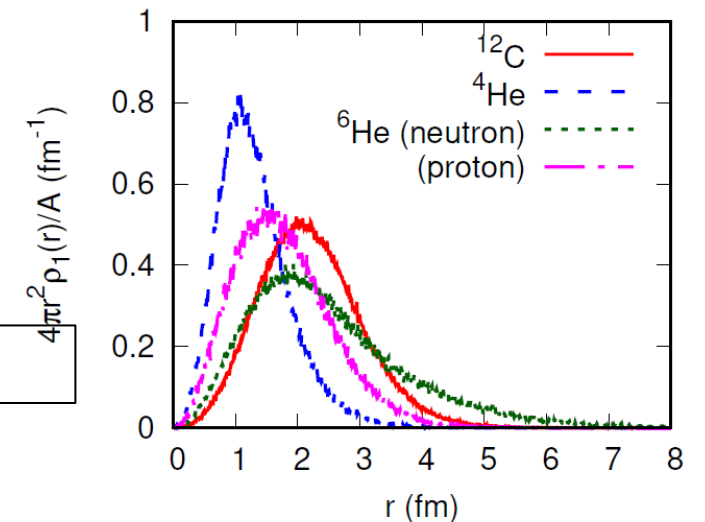
Outline

- Complete evaluation of the Glauber's phase-shift function (psf) involving ^{12}C
 - ^{12}C : Standard target nucleus to extract nuclear size properties
 - **Total reaction and elastic scattering cross sections** can be evaluated **unambiguously**
- Multiple integrals performed by a Monte Carlo integration
- Input: Variational Monte Carlo (VMC) wave function
 - Previous work (^{12}C : cluster model wave function) [K. Varga et al., Phys. Rev. C 66, 034611 \(2002\)](#)
 - Realistic interaction: AV18+UIX [R. B. Wiringa et al., Phys. Rev. C 51, 38 \(1995\)](#)
 - **This work:** ^{12}C , ^4He , ^6He [B. S. Pudliner et al., Phys. Rev. Lett. 74, 4396 \(1995\)](#)
 - 40000 configurations are prepared

Nucleus	r_m	r_n	r_p	r_p (Expt.)
^{12}C	2.35(1)	2.35(1)	2.35(1)	2.326 ± 0.002
^4He	1.44(1)	1.44(1)	1.44(1)	1.455 ± 0.003
^6He	2.54(1)	2.80(1)	1.93(1)	1.92 ± 0.01

The most accurate Glauber theory calculation involving ^{12}C

- Accuracy of the conventional approximations
 - OLA (leading order), 2nd order OLA, NTG



Glauber Theory

R. J. Glauber, in *Lectures in Theoretical Physics*, edited by W. E. Brittin and L. G. Dunham (Interscience, New York, 1959), Vol. 1, p. 315.

- Efficient description of medium to high energy scattering

- Eikonal approximation
- Adiabatic approximation

$$\Psi(\mathbf{R}, \mathbf{r}_1^P, \dots, \mathbf{r}_{A_P}^P, \mathbf{r}_1^T, \dots, \mathbf{r}_{A_T}^T) \equiv e^{iKZ} \hat{\Psi}(\mathbf{R}, \mathbf{r}_1^P, \dots, \mathbf{r}_{A_P}^P, \mathbf{r}_1^T, \dots, \mathbf{r}_{A_T}^T)$$

$$\left[vP_z + \frac{\mathbf{P}^2}{2M_{PT}} + \cancel{(H_P - E_0^P)} + \cancel{(H_T - E_0^T)} + \sum_{i \in P} \sum_{j \in T} V(\mathbf{R} + \mathbf{r}_i^P - \mathbf{r}_j^T) \right] \hat{\Psi}(\mathbf{R}, \mathbf{r}_1^P, \dots, \mathbf{r}_{A_P}^P, \mathbf{r}_1^T, \dots, \mathbf{r}_{A_T}^T) = 0,$$

$$Z \rightarrow \infty \quad \hat{\Psi}(\mathbf{R}, \mathbf{r}_1^P, \dots, \mathbf{r}_{A_P}^P, \mathbf{r}_1^T, \dots, \mathbf{r}_{A_T}^T) = \underline{e^{i\chi(\mathbf{b})}} \Psi_0^P(\mathbf{r}_1^P, \dots, \mathbf{r}_{A_P}^P) \Psi_0^T(\mathbf{r}_1^T, \dots, \mathbf{r}_{A_T}^T).$$

- Essential quantity: **Glauber's phase-shift function (psf)**

$$e^{i\chi(\mathbf{b})} = \langle \Psi_0^P \Psi_0^T | \hat{\Psi} \rangle = \langle \Psi_0^P \Psi_0^T | \prod_{i \in P} \prod_{j \in T} e^{i\chi_{NN}(\mathbf{b} + \mathbf{s}_i^P - \mathbf{s}_j^T)} | \Psi_0^P \Psi_0^T \rangle \quad \mathbf{r}_j = \mathbf{s}_j + z_j \hat{\mathbf{z}}$$

$e^{i\chi_{NN}}$: NN phase-shift function

- “Original” Glauber theory

- Input: A -body densities ($|\Psi_0|^2$) of projectile and target
 $\rightarrow 3 \times (A_T + A_P)$ fold integral for each b **expensive!**
- Optical limit approximation (OLA) often be used
 - Input: one-body density (3+3-fold integral)

Cross sections

Glauber's psf

$$e^{i\chi(\mathbf{b})} = \langle \Psi_0^P \Psi_0^T | \prod_{i \in P}^{A_P} \prod_{j \in T}^{A_T} e^{i\chi_{NN}(\mathbf{b} + \mathbf{s}_i^P - \mathbf{s}_j^T)} | \Psi_0^P \Psi_0^T \rangle$$

$$= \langle \Psi_0^P \Psi_0^T | \prod_{i=1}^{A_P} \prod_{j=1}^{A_T} [1 - \Gamma_{NN}(\mathbf{b} + \mathbf{s}_i^P - \mathbf{s}_j^T)] | \Psi_0^P \Psi_0^T \rangle$$

$$e^{i\chi_{NN}(\mathbf{b})} \equiv 1 - \Gamma_{NN}(\mathbf{b}) \quad \text{Profile function} \quad \Gamma_{NN}(\mathbf{b}) = \frac{1 - i\alpha_{NN}}{4\pi\beta_{NN}} \sigma_{NN}^{\text{tot}} \exp\left(-\frac{b^2}{2\beta_{NN}}\right)$$

B. Abu-Ibrahim, WH, Y. Suzuki, A. Kohama, Phys. Rev. C 77, 034607 (2008).

Consistent with NN scattering properties for $E < \sim 300$ MeV

Contribution of hadron productions at $E > \sim 300$ MeV

NNN contribution negligible in the high-energy reaction processes

Total reaction cross section $\sigma_R = \int d\mathbf{b} \left(1 - \underline{|e^{i\chi(\mathbf{b})}|^2}\right)$

Elastic scattering cross section $\frac{d\sigma}{d\Omega}(\theta) = |F(\theta)|^2$

Scattering amplitude $F(\theta) = F_C(\theta) + \frac{iK}{2\pi} \int d\mathbf{b} e^{-i\mathbf{q} \cdot \mathbf{b} + i\chi_C(\mathbf{b})} (1 - \underline{e^{i\chi(\mathbf{b})}})$

F_C : Rutherford scattering amplitude

$$i\chi_C(\mathbf{b}) = 2i\eta \ln(Kb)$$

$$\eta = Z_P Z_T e^2 / \hbar v$$

Variational Monte Carlo (VMC) method

- Hamiltonian

$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

v_{ij} : Argonne v18 two-nucleon potential

V_{ijk} : Urbana IX three-nucleon potential

- Variational principle $E_V = \frac{\langle \Psi_V | H | \Psi_V \rangle}{\langle \Psi_V | \Psi_V \rangle} \geq E_0$

Trial function

$$|\Psi_V\rangle = \mathcal{S} \prod_{i<j}^A \left[1 + U_{ij} + \sum_{k \neq i,j}^A \tilde{U}_{ijk} \right] |\Psi_J\rangle$$

Jastrow type wave function

$$|\Psi_J\rangle = \prod_{i<j} \underline{f_c(r_{ij})} |\Phi_A(J^\pi; TT_z)\rangle$$

Short-range correlation

Fully antisymmetrized wf (Uncorrelated)

Two-body correlator $U_{ij} = \sum_{p=2,6} u_p(r_{ij}) O_{ij}^p$

Three-body correlator $\tilde{U}_{ijk} = -\epsilon \tilde{V}_{ijk}(\tilde{r}_{ij}, \tilde{r}_{jk}, \tilde{r}_{ki})$

Monte Carlo integration

A type of integration $\int p(x)g(x)dx,$ \mathbf{x} : multiple variable

$\int p(x)dx = 1$ $p(x) \geq 0$ Probability distribution

$\longrightarrow \int p(x)g(x)dx \approx \frac{1}{M} \sum_{i=1}^M g(x_i),$ x_1, x_2, \dots, x_M

generated by Metropolis method
N. Metropolis et al., J. Chem. Phys. 21, 1087 (1953)

Glauber's psf

$$e^{i\chi(\mathbf{b})} = \int \dots \int d\mathbf{r}_1^P \dots d\mathbf{r}_{A_P}^P d\mathbf{r}_1^T \dots d\mathbf{r}_{A_T}^T \rho_{A_P}^P(\mathbf{r}_1^P, \dots, \mathbf{r}_{A_P}^P) \rho_{A_T}^T(\mathbf{r}_1^T, \dots, \mathbf{r}_{A_T}^T) \prod_{i=1}^{A_P} \prod_{j=1}^{A_T} [1 - \Gamma_{NN}(\mathbf{b} + \mathbf{s}_i^P - \mathbf{s}_j^T)],$$

A-body density (Probability distribution)

$$\rho_A(\bar{\mathbf{r}}_1, \dots, \bar{\mathbf{r}}_A) = \langle \Psi | \prod_{i=1}^A \delta(\mathbf{r}_i - \bar{\mathbf{r}}_i) | \Psi \rangle$$

VMC wave function

$\longrightarrow e^{i\chi(\mathbf{b})} = \frac{1}{M^P M^T} \sum_{k=1}^{M^P} \sum_{l=1}^{M^T} \left\{ \prod_{i=1}^{A_P} \prod_{j=1}^{A_T} [1 - \Gamma_{NN}(\mathbf{b} + \mathbf{t}_{i,k}^P - \mathbf{t}_{j,l}^T)] \right\}$

E.g., ¹²C-¹²C (40k*40k)
 1.6 billion configs.
 ~60 days for each E

Coulomb interaction

- Colomb breakup (CBU) contribution

Total Coulomb phase

$$e^{i\chi_C^{\text{tot}}(\mathbf{b}, \{\mathbf{s}^P\}, \{\mathbf{s}^T\})} \equiv \prod_{j=1}^{A_P} \prod_{k=1}^{A_T} e^{i\epsilon_j \epsilon_k \chi_C(\mathbf{b}_{jk})}.$$

Coulomb phase

$$\chi_C(b) = -\eta \int_{-\infty}^{\infty} dz \frac{1}{\sqrt{b^2 + z^2}},$$

Colomb potential between P and T

$$V_C(\mathbf{R}) = \left\langle \sum_{i=1}^{A_P} \sum_{j=1}^{A_T} \frac{\epsilon_i \epsilon_j e^2}{|\mathbf{R} + \mathbf{r}_i^P - \mathbf{r}_j^T|} \right\rangle$$

$$\approx \frac{1}{N_P N_T} \sum_{k=1}^{N_P} \sum_{l=1}^{N_T} \sum_{i=1}^{A_P} \sum_{j=1}^{A_T} \frac{\epsilon_i \epsilon_j e^2}{|\mathbf{R} + \bar{\mathbf{r}}_{i,k}^P - \bar{\mathbf{r}}_{j,l}^T|},$$

$$\Delta\chi_C(\mathbf{b}, \{\mathbf{s}^P\}, \{\mathbf{s}^T\}) = 2\eta \sum_{j=1}^{A_P} \sum_{k=1}^{A_T} \epsilon_j \epsilon_k \ln \frac{|\mathbf{b}_{jk}|}{b}$$

Divergent behavior at $b \rightarrow \infty$

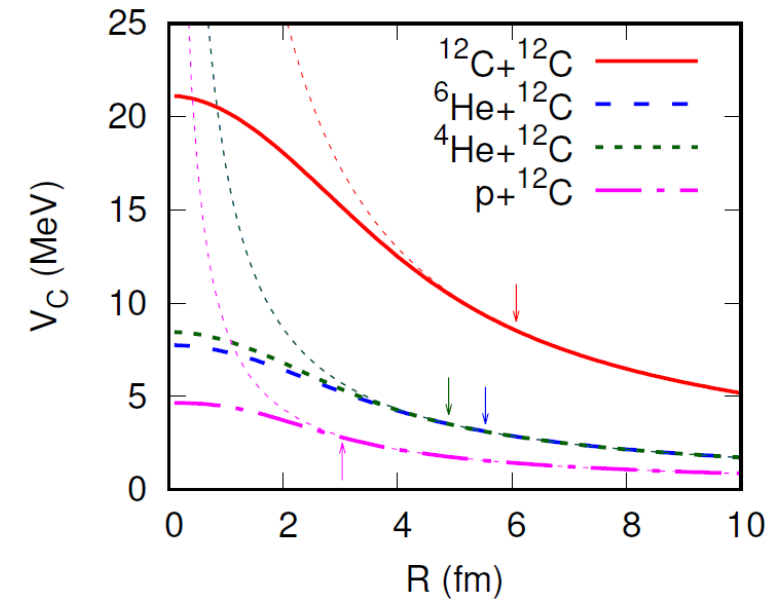
CBU occurs at b less than $b_C \sim R_P + R_T$

$$e^{i\Delta\chi_C(\mathbf{b}, \{\mathbf{s}^P\}, \{\mathbf{s}^T\})} \equiv \prod_{j=1}^{A_P} \prod_{k=1}^{A_T} \left(\frac{|\mathbf{b}_{jk}|}{b} \right)^{2i\eta\epsilon_j\epsilon_k} \Theta(b_C - b) + \Theta(b - b_C).$$

- Coulomb trajectory correction

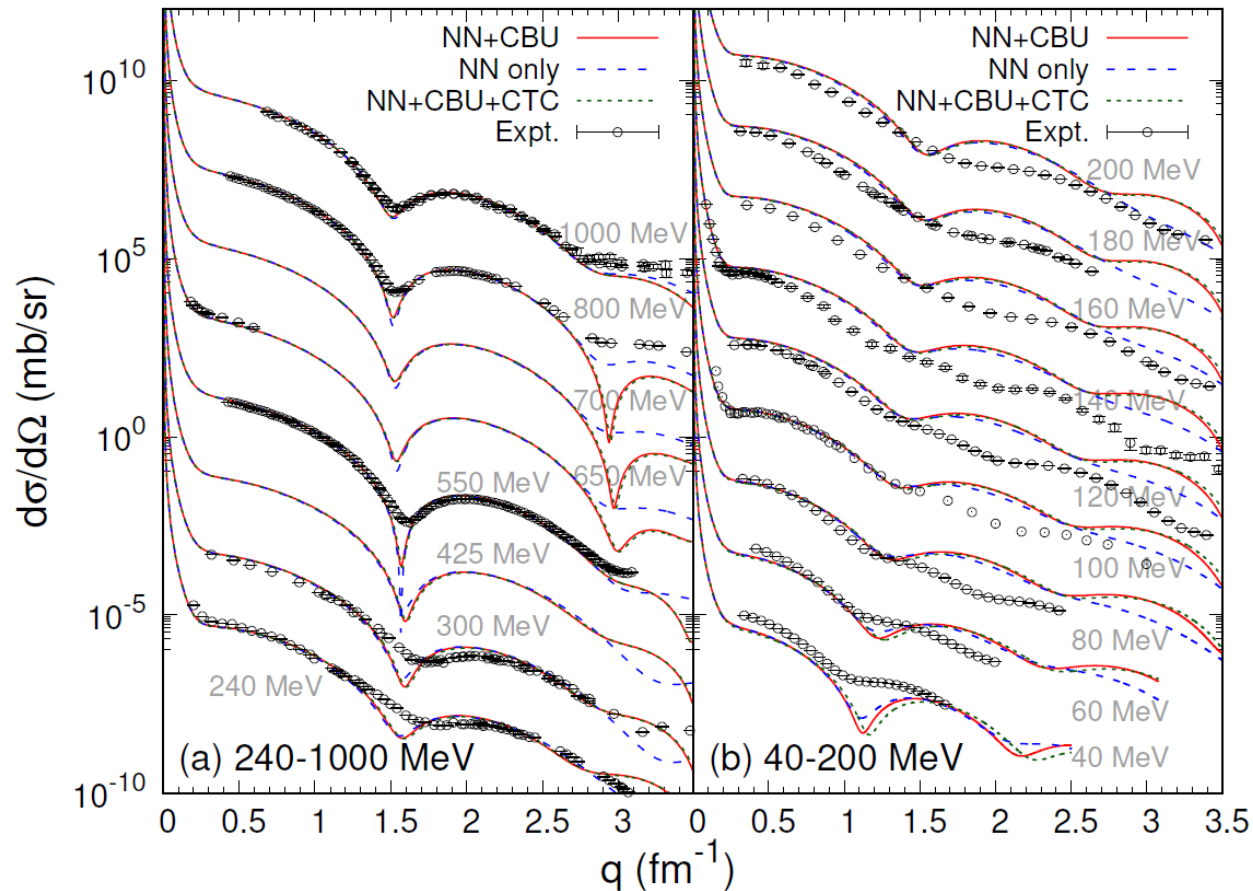
$$Kb \rightarrow \sqrt{(Kb)^2 + \eta_{PT}^2} + \eta_{PT}.$$

A. Vitturi, F. Zardi, Phys. Rev. C 36, 1404 (1987)



Proton-¹²C scattering

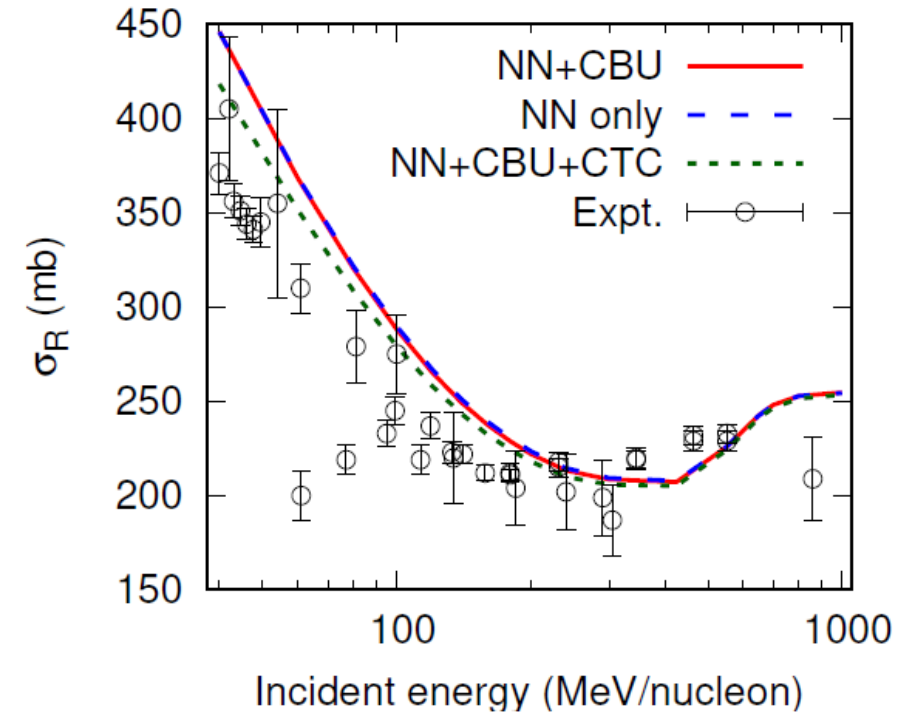
Elastic scattering cross sections



Perfect agreement

Fair agreement

Total reaction cross sections



Eikonal condition: $Ka \gg 1$, $q/K \ll 1$

a : interaction radius

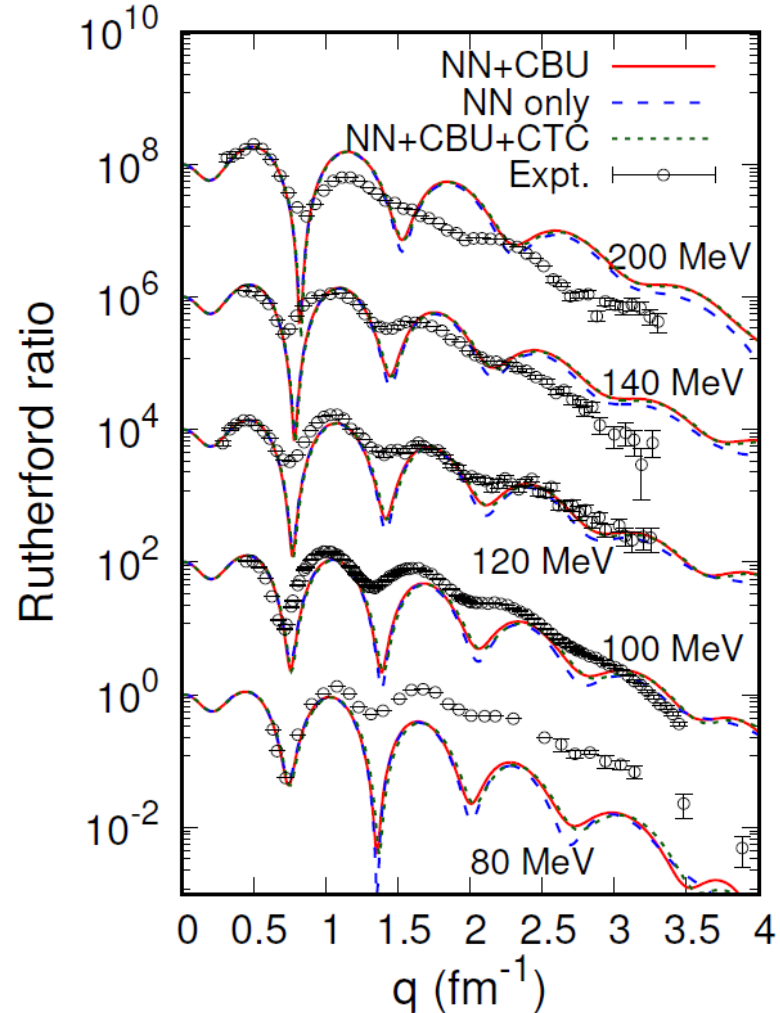
K : Relative wave number

→ Safe for $E/A > 200$ MeV

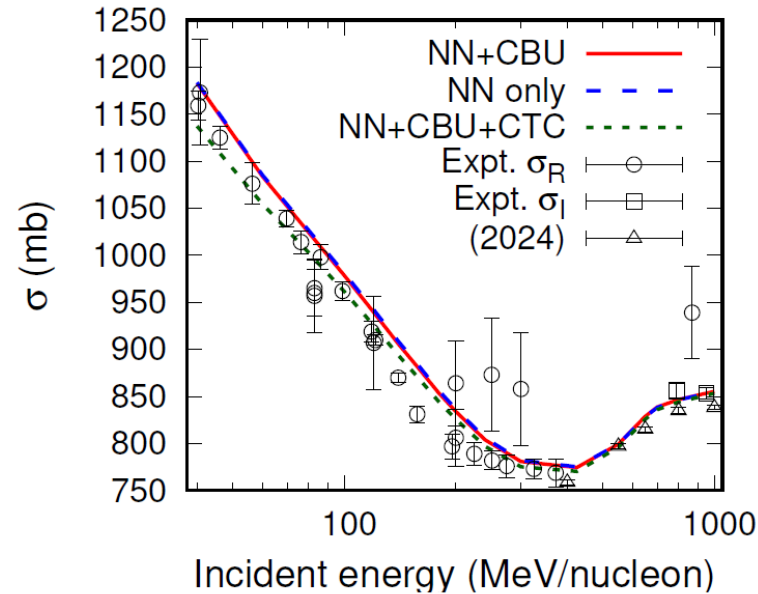
$K \sim 3 \text{ fm}^{-1}$, $a \sim 3 \text{ fm}$

$^{12}\text{C}-^{12}\text{C}$ scattering

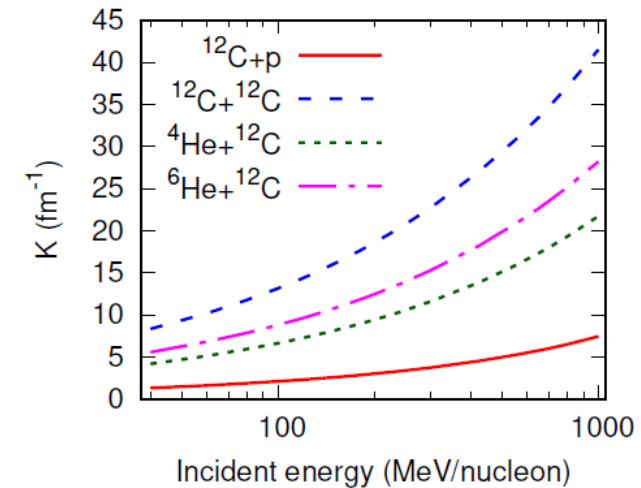
Elastic scattering cross sections



Total reaction cross sections



Relative wave numbers



- **Eikonal conditions always fulfilled**

K : large, $a \sim 6$ fm

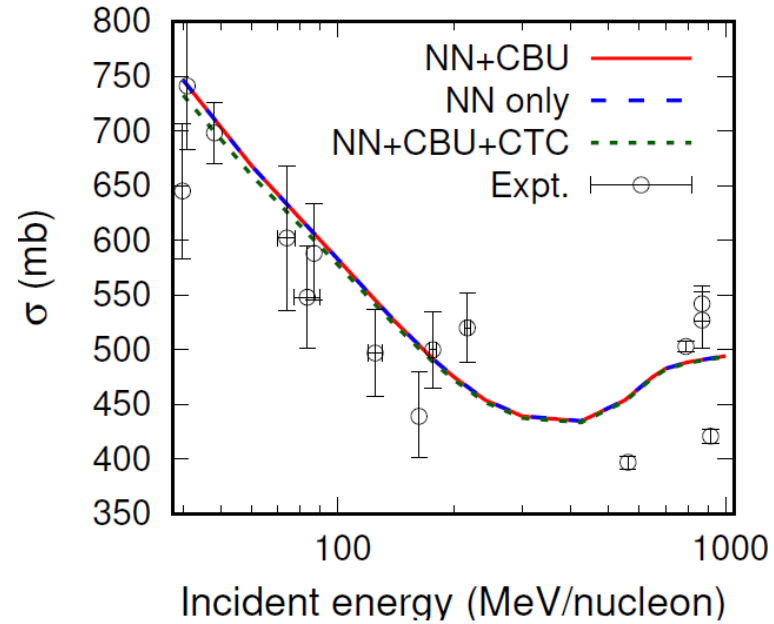
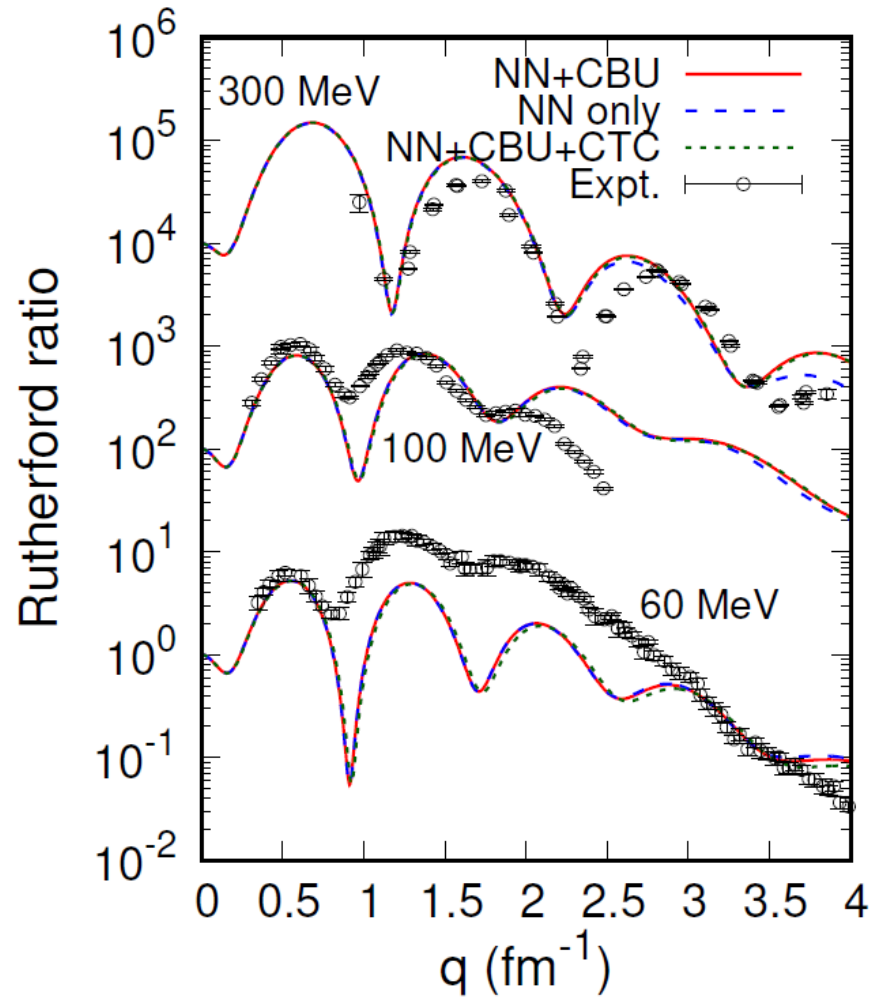
- σ_R : Perfect

- Elastic scattering: Good for $E/A > 100$ MeV

Limited reproduction for $E/A=80$ MeV

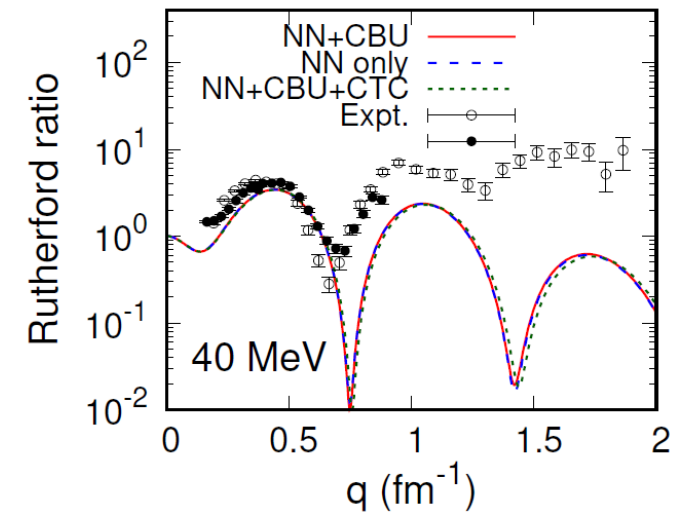
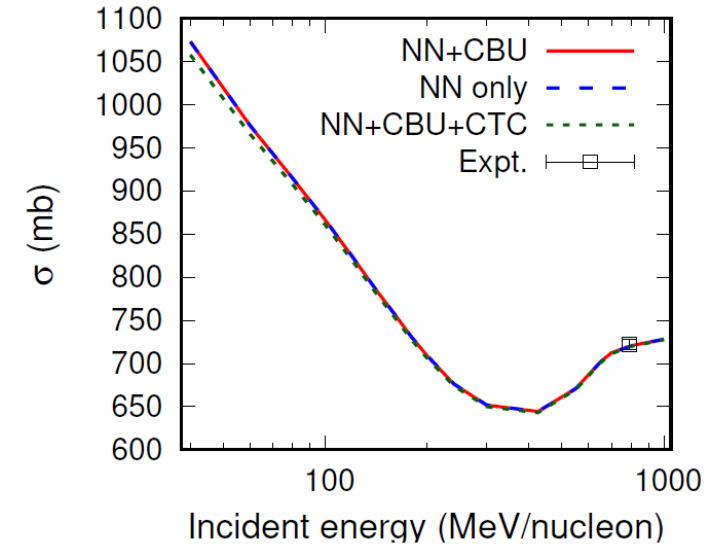
- Fermi energy for two nuclei ~ 60 MeV

$^4\text{He}-^{12}\text{C}$ scattering



- **Eikonal conditions fulfilled**
- σ_R : Good (Expt. scattered)
- Elastic scattering: Good for $E/A > 100$ MeV

$^6\text{He}-^{12}\text{C}$ scattering



Conventional approximations

Glauber's psf

$$e^{\chi(\mathbf{b})} \equiv G(\mathbf{b}; \lambda = 1) = \langle \Psi_0^P \Psi_0^T | \mathcal{O}(\mathbf{b}; \lambda = 1) | \Psi_0^P \Psi_0^T \rangle$$

Multiple scattering operator $\mathcal{O}(\mathbf{b}; \lambda) = \prod_{i=1}^{A_P} \prod_{j=1}^{A_T} [1 - \lambda \Gamma_{NN}(\mathbf{b} + \mathbf{s}_i^P - \mathbf{s}_j^T)]$

Binomial (Moment) expansion \rightarrow **slow convergence** B. Abu-Ibrahim et al., Nucl. Phys. A 657, 391 (1999)

$$G(\mathbf{b}; \lambda) = \sum_{n=0}^{A_P A_T} \lambda^n \mu_n$$

$$\mu_0 = 1, \quad \mu_1 = - \langle \Psi_0^P \Psi_0^T | \sum_{i=1}^{A_P} \sum_{j=1}^{A_T} \Gamma_{NN}(\mathbf{b} + \mathbf{s}_i^P - \mathbf{s}_j^T) | \Psi_0^P \Psi_0^T \rangle,$$

$$\mu_2 = \langle \Psi_0^P \Psi_0^T | \sum_{i=1}^{A_P} \sum_{j=1}^{A_T} \sum_{k=1}^{A_P} \sum_{l=1}^{A_T} \Gamma_{NN}(\mathbf{b} + \mathbf{s}_i^P - \mathbf{s}_j^T) \Gamma_{NN}(\mathbf{b} + \mathbf{s}_k^P - \mathbf{s}_l^T) | \Psi_0^P \Psi_0^T \rangle$$

Cumulant expansion

$$\ln G(\lambda) = \sum_{n=0}^{\infty} \frac{\lambda^n}{n!} \kappa_n$$

$$\kappa_0 = 0, \quad \kappa_1 = \mu_1,$$

$$\kappa_2 = 2\mu_2 - \mu_1^2,$$

Optical Limit Approximation (OLA)

$$\mu_1 = - \iint d\mathbf{r}^P d\mathbf{r}^T [\rho_1^P(\mathbf{r}^P) \rho_1^T(\mathbf{r}^T) \Gamma_{NN}(\mathbf{b} + \mathbf{s}^P - \mathbf{s}^T)]$$

$$G(\lambda = 1) = e^{\ln G(\lambda=1)} = \exp \left(\kappa_1 + \frac{1}{2} \kappa_2 + \dots \right) = \exp \left[\underline{\mu_1} + \left(\underline{\mu_2 - \frac{1}{2} \mu_1^2} \right) + \dots \right]$$

“Average” Conventional OLA

“Variance” 2nd order OLA

Cumulant expansion

- Cumulant expansion

$$\ln G(\mathbf{b}; \lambda) = \sum_{n=1}^{\infty} \frac{\lambda^n}{n!} \kappa_n(\mathbf{b}).$$

$$\kappa_1(\mathbf{b}) = \mu_1(\mathbf{b}), \quad \text{“average”}$$

$$\kappa_2(\mathbf{b}) = 2\mu_2(\mathbf{b}) - \mu_1(\mathbf{b})^2, \quad \text{“variance”}$$

$$\kappa_3(\mathbf{b}) = 6\mu_3(\mathbf{b}) - 6\mu_2(\mathbf{b})\mu_1(\mathbf{b}) + 2\mu_1(\mathbf{b})^3 \quad \text{“kurtosis”}$$

$$\mu_1(\mathbf{b}) = - \left\langle \sum_{i=1}^{A_P} \sum_{j=1}^{A_T} \Gamma_{NN}(\mathbf{b}_{ij}) \right\rangle = - \iint dr dr' \rho_1^P(\mathbf{r}) \rho_1^T(\mathbf{r}') \Gamma_{NN}(\mathbf{b} + \mathbf{s} - \mathbf{s}'), \quad \text{One-body density}$$

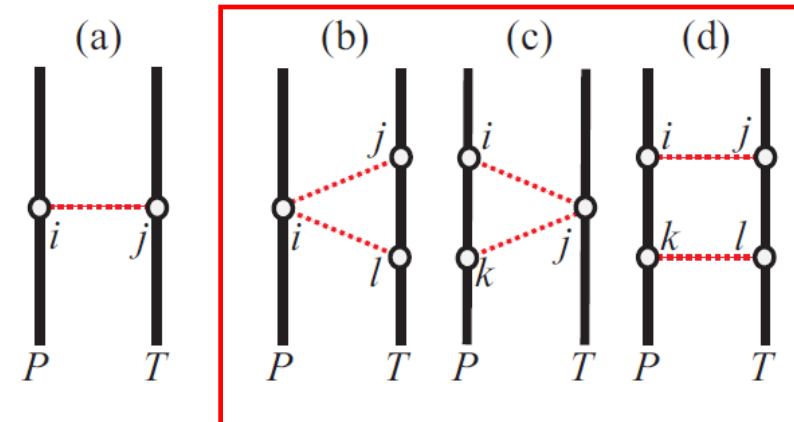
$$\mu_2(\mathbf{b}) = \left\langle \sum_{i=1}^{A_P} \sum_{1 \leq j < l}^{A_T} \Gamma_{NN}(\mathbf{b}_{ij}) \Gamma_{NN}(\mathbf{b}_{il}) \right\rangle + \left\langle \sum_{1 \leq i < k}^{A_P} \sum_{j=1}^{A_T} \Gamma_{NN}(\mathbf{b}_{ij}) \Gamma_{NN}(\mathbf{b}_{kj}) \right\rangle + 2 \left\langle \sum_{1 \leq i < k}^{A_P} \sum_{1 \leq j < l}^{A_T} \Gamma_{NN}(\mathbf{b}_{ij}) \Gamma_{NN}(\mathbf{b}_{kl}) \right\rangle$$

$$= \iiint dr dr' dr'' \rho_1^P(\mathbf{r}) \rho_2^T(\mathbf{r}', \mathbf{r}'') \Gamma_{NN}(\mathbf{b} + \mathbf{s} - \mathbf{s}') \Gamma_{NN}(\mathbf{b} + \mathbf{s} - \mathbf{s}'')$$

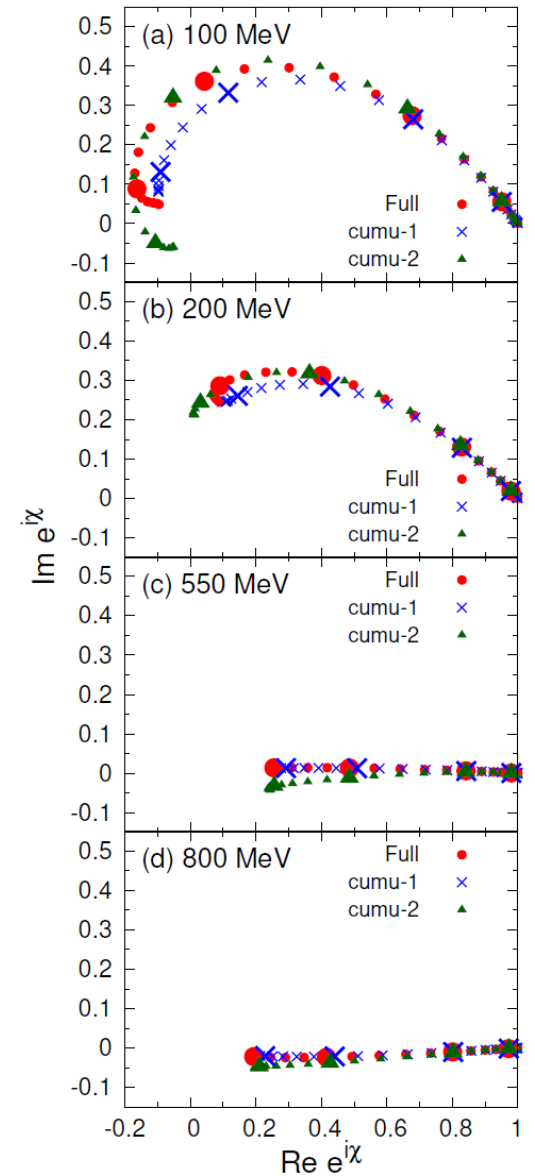
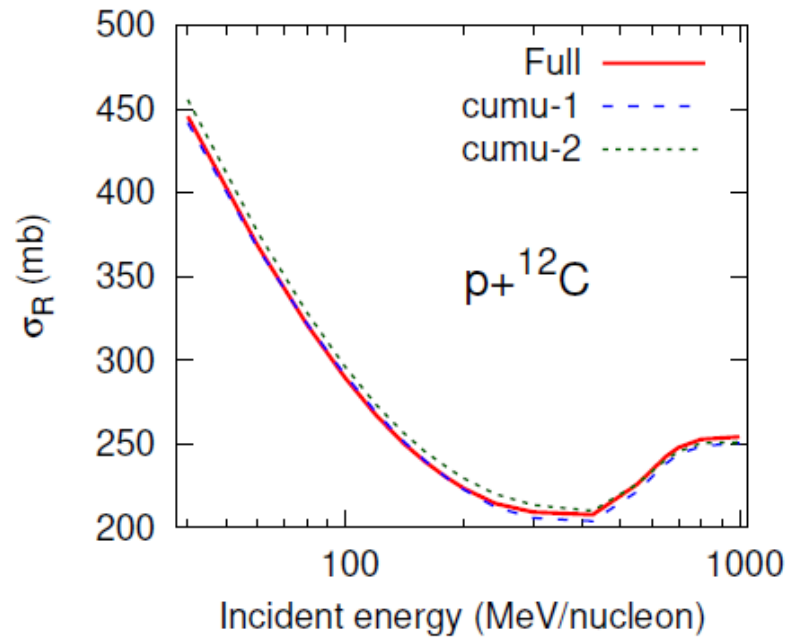
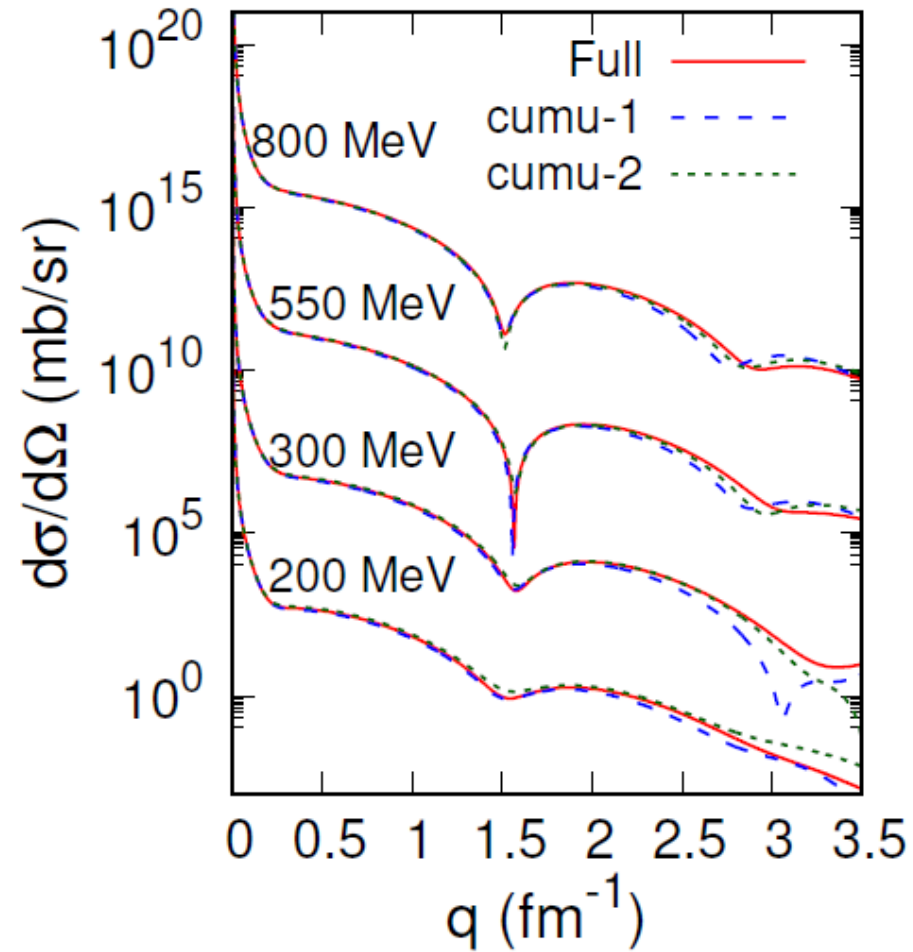
$$+ \iiint dr dr' dr'' \rho_2^P(\mathbf{r}, \mathbf{r}') \rho_1^T(\mathbf{r}'') \Gamma_{NN}(\mathbf{b} + \mathbf{s} - \mathbf{s}'') \Gamma_{NN}(\mathbf{b} + \mathbf{s}' - \mathbf{s}'')$$

$$+ 2 \iiint dr dr' dr'' dr''' \rho_2^P(\mathbf{r}, \mathbf{r}') \rho_2^T(\mathbf{r}'', \mathbf{r}''') \Gamma_{NN}(\mathbf{b} + \mathbf{s} - \mathbf{s}'') \Gamma_{NN}(\mathbf{b} + \mathbf{s}' - \mathbf{s}''').$$

One- and **two**-body densities



Proton- ^{12}C scattering

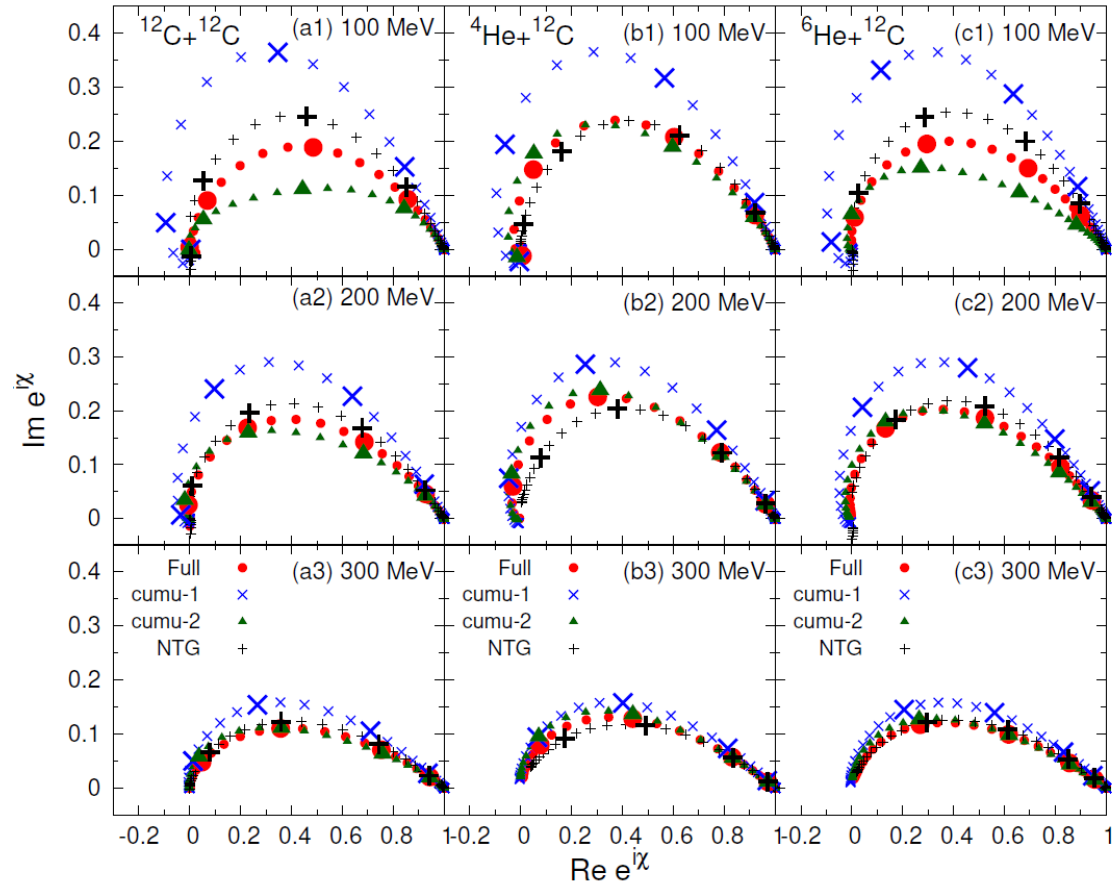
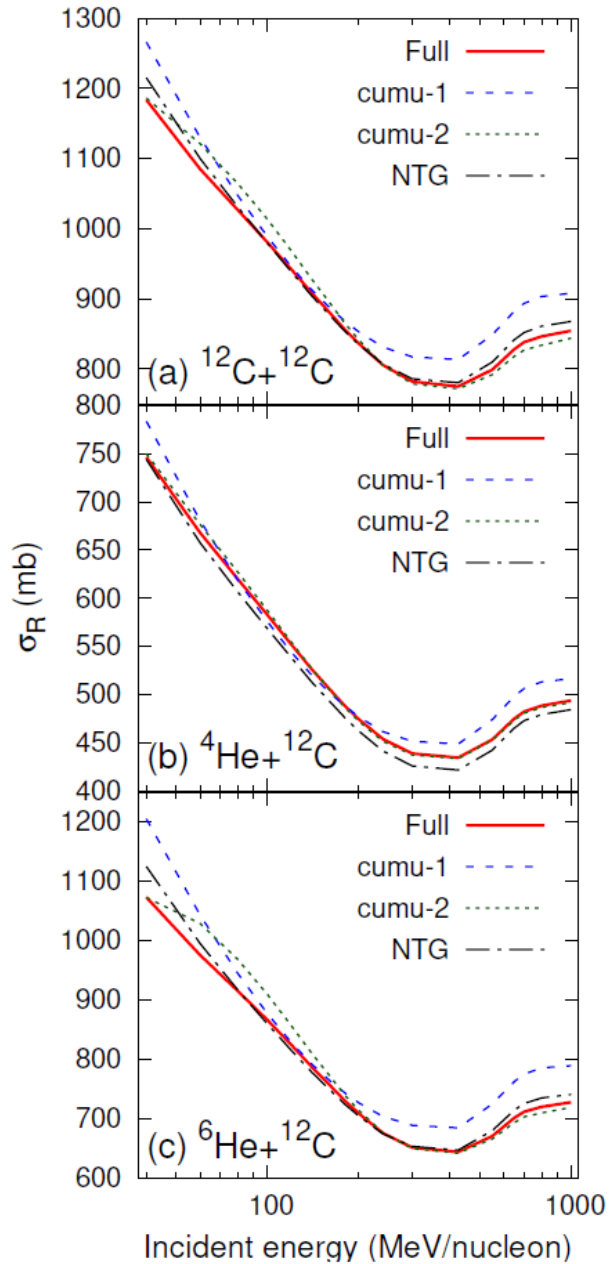


Fluctuation of the psf is not so large

→ Converged already with cumu-1

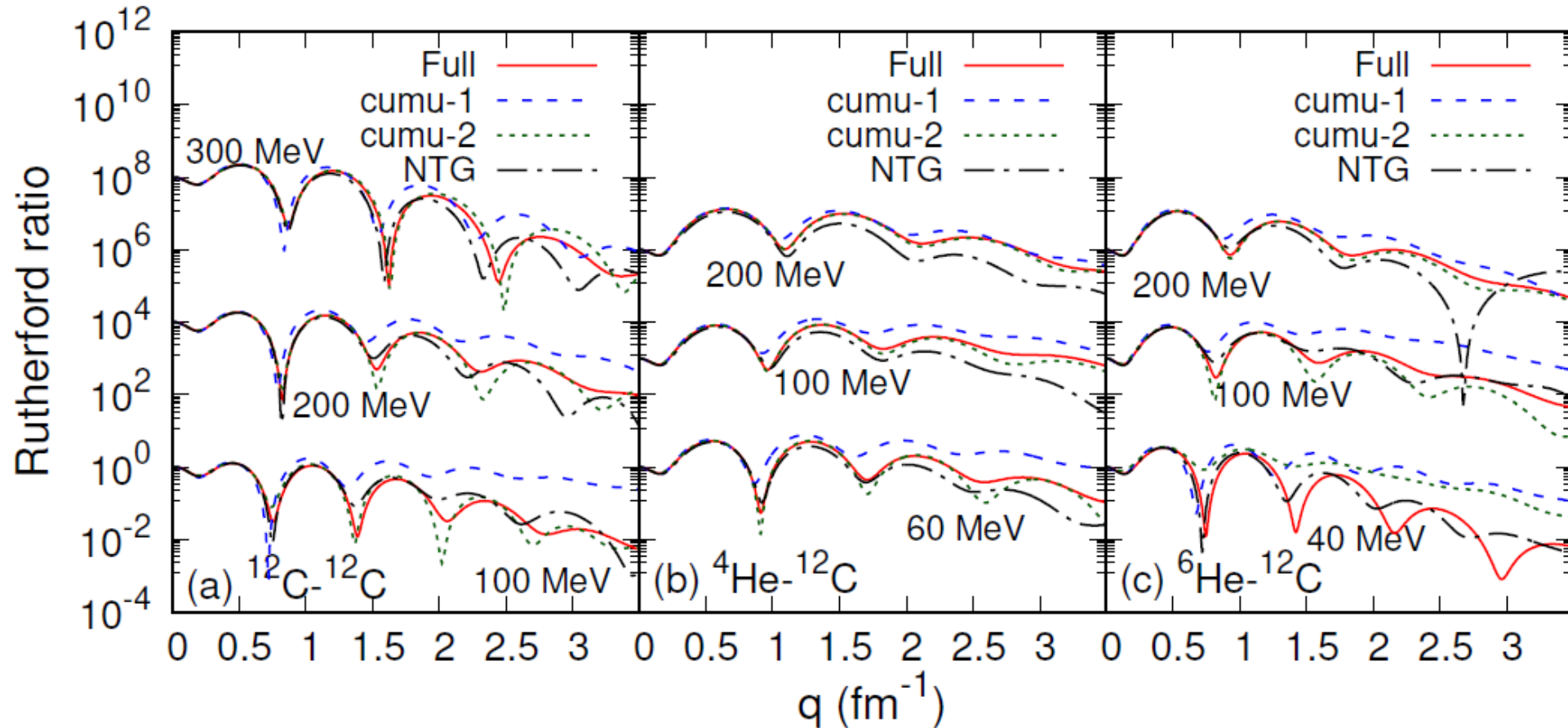
(conventional OLA)

Nucleus-nucleus case: σ_R



- Conventional OLA tends to overestimate the full Glauber results
- 2nd OLA offers converged results for typical nuclear systems

Nucleus-nucleus case: Elastic scattering



- Conventional OLA tends to overestimate the full Glauber results at backward angles
- 2nd OLA offers converged results

Remark on conventional approximation II

- Product ansatz $\rho_A(\mathbf{r}_1, \dots, \mathbf{r}_A) = \prod_{i=1}^A \bar{\rho}(\mathbf{r}_i), \quad \bar{\rho}(\mathbf{r}) = \rho_1(\mathbf{r})/A.$

R. J. Glauber, in *Lectures in Theoretical Physics*, edited by W. E. Brittin and L. G. Dunham (Interscience, New York, 1959), Vol. 1, p. 315.

- Glauber's psf

$$e^{i\chi(\mathbf{b})} = \int \dots \int d\mathbf{r}_1^P \dots d\mathbf{r}_{A_P}^P d\mathbf{r}_1^T \dots d\mathbf{r}_{A_T}^T \rho_{A_P}^P(\mathbf{r}_1^P, \dots, \mathbf{r}_{A_P}^P) \rho_{A_T}^T(\mathbf{r}_1^T, \dots, \mathbf{r}_{A_T}^T) \prod_{i=1}^{A_P} \prod_{j=1}^{A_T} [1 - \Gamma_{NN}(\mathbf{b} + \mathbf{s}_i^P - \mathbf{s}_j^T)],$$

$$e^{i\chi(\mathbf{b})} = \left(1 - \frac{1}{A_P A_T} \iint d\mathbf{r} d\mathbf{r}' \rho_1^P(\mathbf{r}) \rho_1^T(\mathbf{r}') \Gamma_{NN}(\mathbf{b} - \mathbf{s} + \mathbf{s}') \right)^{A_P A_T}$$

$$(A_P A_T \rightarrow \text{Large}) \approx \exp \left(- \iint d\mathbf{r} d\mathbf{r}' \rho_1^P(\mathbf{r}) \rho_1^T(\mathbf{r}') \Gamma_{NN}(\mathbf{b} - \mathbf{s} + \mathbf{s}') \right), \quad \rightarrow \text{OLA}$$

Nothing better than OLA!

Summary

WH, Y. Suzuki, R. B. Wiringa, arXiv: 2512.20095, Phys. Rev. Lett, **accepted on April 21**
WH, Y. Suzuki, R. B. Wiringa, arXiv: 2512.20100, Phys. Rev. C, in press

Complete Glauber-theory cal. using the most accurate wave function of ^{12}C

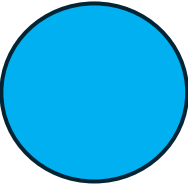
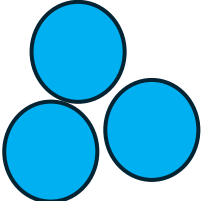
- Solving Glauber's original equation without approximation
 - NN interactions consistent with the NN scattering properties
 - Multiple integration in the Glauber psf is performed by a Monte Carlo technique
- Total reaction and elastic scattering cross sections can be evaluated unambiguously within the Glauber theory
 - Accuracy of the conventional approximations

The Glauber theory works well for $\sim 100\text{-}1000$ MeV/nucleon

Accurate expt. data → **Precise determination of the nuclear size properties**

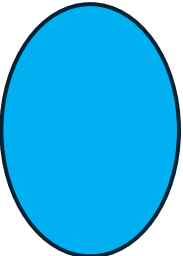
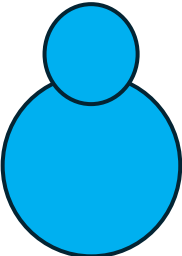
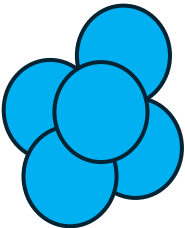
- Conventional OLA can be used for proton scattering (One-body density)
- For nucleus-nucleus scattering, **the second order OLA offers a good approximation (Two-body density)**

Applications: Shell or cluster?

- ^{12}C
 - p3/2 closed? 
 - Triangle? 

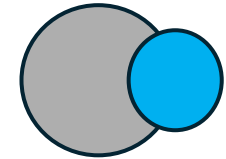
WH and N. Itagaki, Phys. Rev. C 107, L021304 (2023)

- ^{16}O
 - p-shell closed? 
 - Tetrahedron? 

- ^{20}Ne
 - Prolate? 
 - Bi-cluster? 
 - 5 α ? 

- Medium mass nuclei

$^{40,44,48}\text{Ca} + \alpha$?

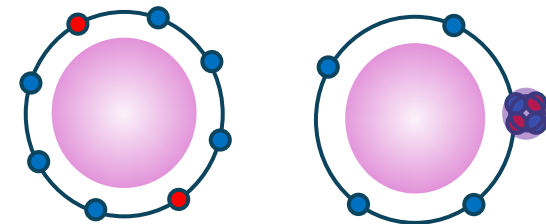


- ^{44}Ti , ^{52}Ti

WH and N. Itagaki, Phys. Rev. C 106, 044330 (2022)

- ^{48}Ti

M. Okada, WH, and N. Itagaki, Phys. Rev. C 109, 054324 (2024)



Y. Yamaguchi, WH, N. Itagaki, , Phys. Rev. C 108, 014322 (2023)

Shell and cluster configurations

Antisymmetrized Quasi-Cluster Model (AQCM) N. Itagaki, H. Matsuno, T. Suhara, Prog. Theor. Exp. Phys. 2016, 093D01.

N α cluster model
$$\Phi(\nu, d, \Lambda) = \mathcal{A} \left\{ \prod_{i=1}^N \Phi_{\alpha}(\nu, R_i, \Lambda) \right\}$$

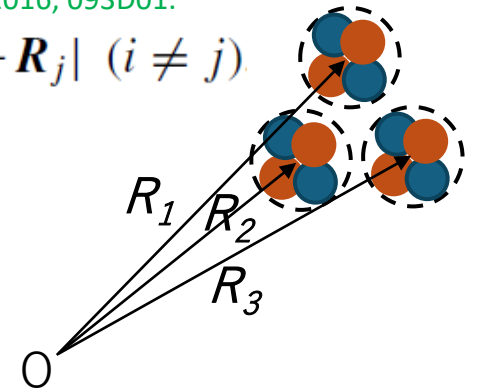
α cluster wf
$$\Phi_{\alpha}(\nu, R_i, \Lambda) = \phi_1^{\nu}(\uparrow, p)\phi_2^{\nu}(\downarrow, p)\phi_3^{\nu}(\uparrow, n)\phi_4^{\nu}(\downarrow, n)$$

Gaussian wave packet
$$\phi_j^{\nu}(s, t) = \left(\frac{2\nu}{\pi}\right)^{3/4} \exp[-\nu(\mathbf{r}_j - \boldsymbol{\zeta}_i)^2] \chi_s \eta_t,$$

$$\boldsymbol{\zeta}_i = \mathbf{R}_i + i\Lambda \mathbf{e}^{\text{spin}} \times \mathbf{R}_i$$

\mathbf{e}^{spin} : unit vector for spin direction

$$d = |\mathbf{R}_i - \mathbf{R}_j| \quad (i \neq j)$$



$\Lambda=0, R \rightarrow 0$ Brink wave function

^{12}C : SU(3) (Harmonic-oscillator wf) $(0s)^4(0p)^8$

$\Lambda=1, R \rightarrow 0$

^{12}C : j-j coupling shell model, p3/2 closed $(0s_{1/2})^4(0p_{3/2})^8$

One-body density
$$\tilde{\rho}(\mathbf{r}) = \langle \Phi | \sum_{i=1}^A \delta(\mathbf{r}_i - \mathbf{r}) | \Phi \rangle / \langle \Phi | \Phi \rangle,$$

Separation of cm wf
$$\int d\mathbf{r} e^{i\mathbf{k}\cdot\mathbf{r}} \rho_{\text{int}}(\mathbf{r}) = \exp\left(\frac{k^2}{8A\nu}\right) \int d\mathbf{r} e^{i\mathbf{k}\cdot\mathbf{r}} \tilde{\rho}(\mathbf{r}).$$

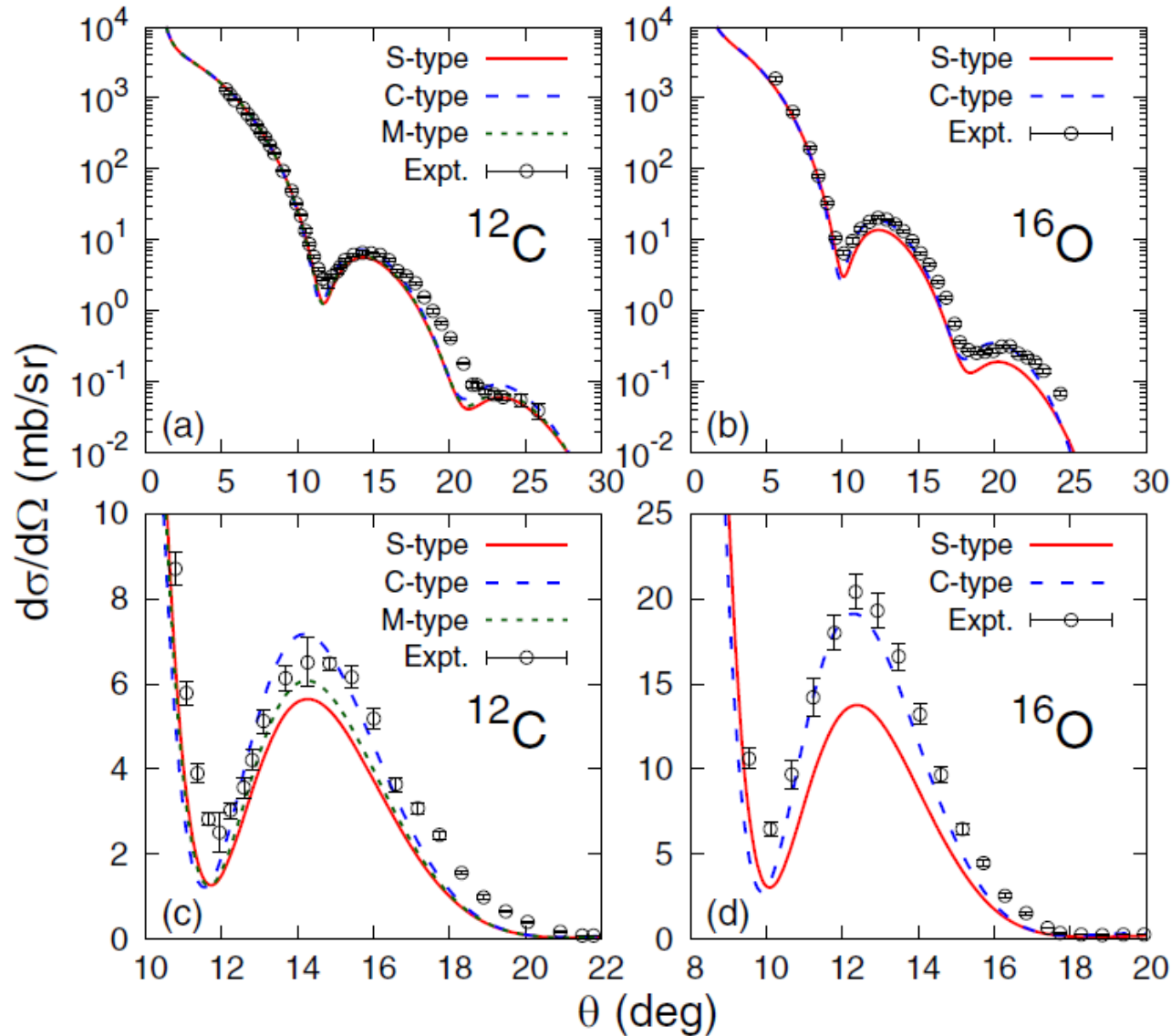
Density in laboratory frame (angle averaged)

$$\rho(r) = \frac{1}{4\pi} \int d\hat{\mathbf{r}} \rho_{\text{int}}(\mathbf{r}).$$

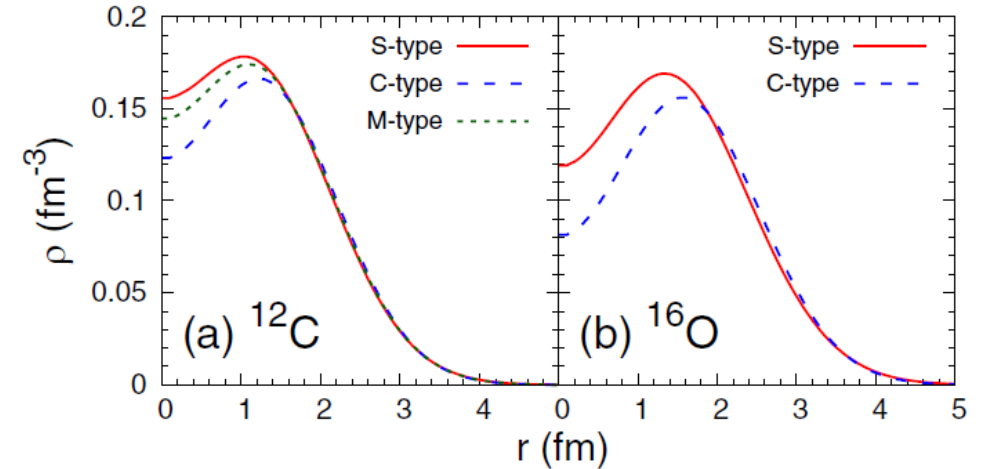
		ν (fm $^{-2}$)	d (fm)	Λ	$\langle Q \rangle$	$\langle LS \rangle$	$\langle P \rangle$
^{12}C	S-type	0.1886	0.010	1	8.0(8)	4.0(4)	-4.0(-4)
	C-type	0.2656	<u>2.636</u>	0	10.6	0.0(0)	-2.0
	M-type	0.2222	2.000	0.2	9.0	1.8	-2.9
^{16}O	S-type	0.1635	0.010	1	12.0(12)	0.0(0)	-8.0(-8)
	C-type	0.2656	<u>3.058</u>	0	18.6	0.0(0)	-2.7

Tetrahedron

^{12}C , ^{16}O : Shell or cluster?



WH and N. Itagaki, Phys. Rev. C 107, L021304 (2023).



Diffuseness fitted by 2-parameter Fermi

^{12}C	S-type 0.432 fm
	C-type 0.401 fm
^{16}O	S-type 0.455 fm
	C-type 0.405 fm

“sharp” $\alpha \rightarrow$ sharp nuclear surface

Comparison tells us dominant configurations

- ^{12}C : Coexistence of shell and cluster conf
- ^{16}O : Large cluster conf (tetrahedron)

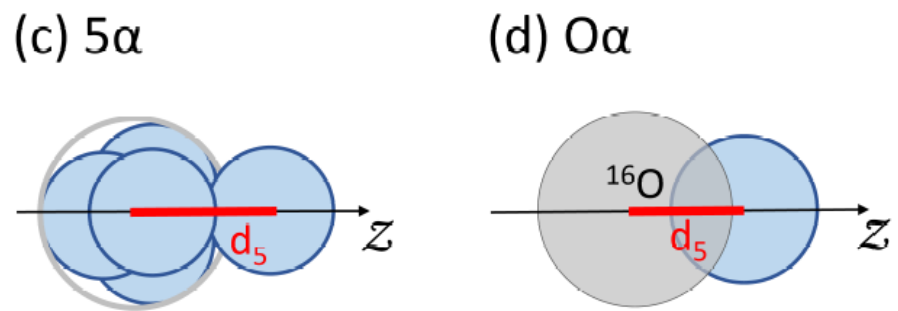
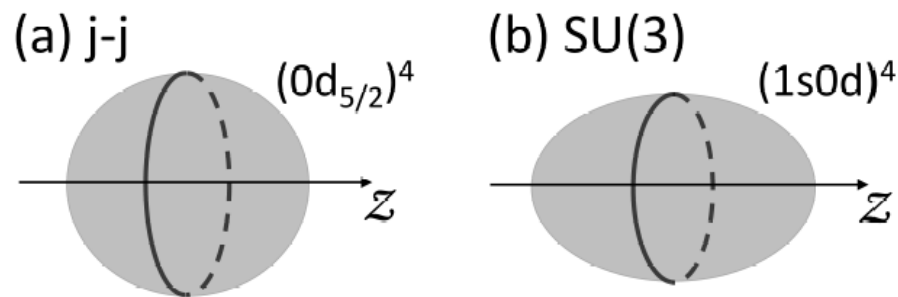
Consistent with recent large-scale computations

E. Epelbaum+, PRL 112, 102501 (2014)

T. Otsuka+, Nature Comm. 12:2234(2022)

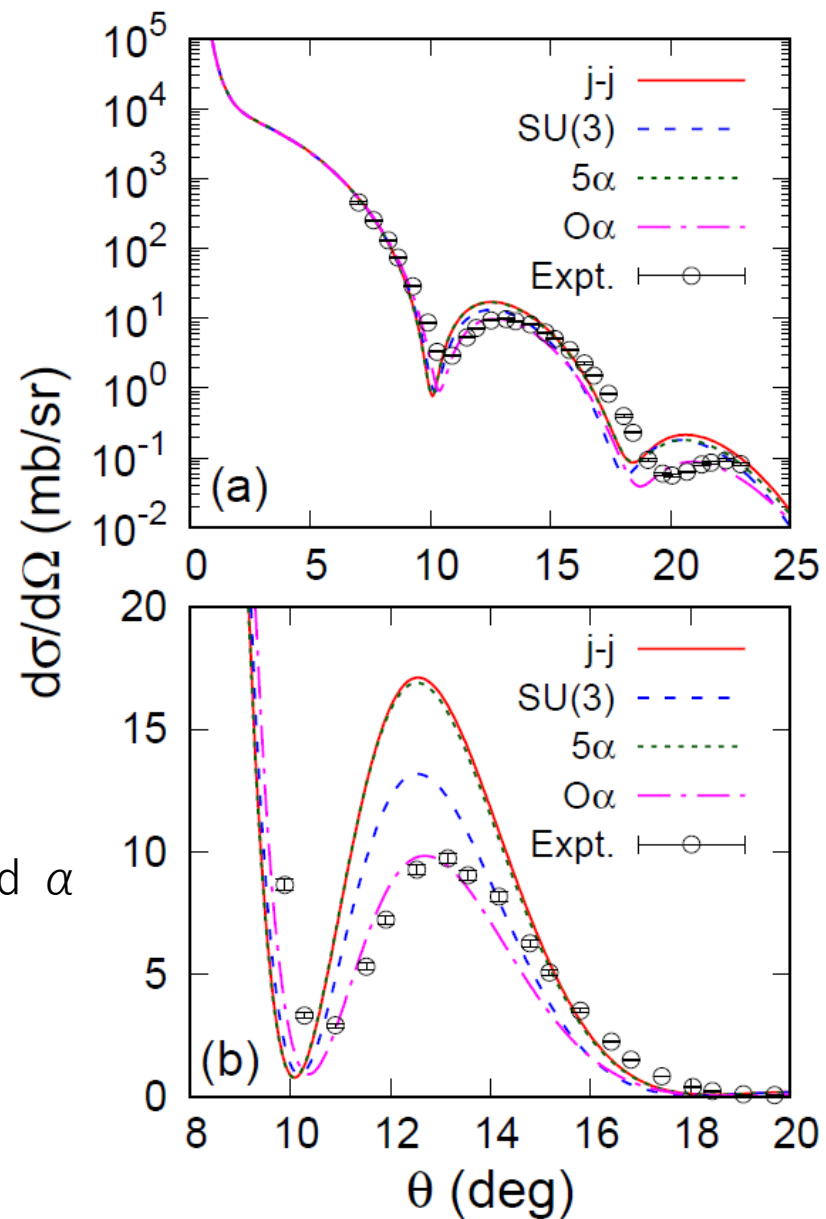
Application to ^{20}Ne

Y. Yamaguchi, WH, and N. Itagaki, Phys. Rev. C 108, 014322 (2023)



d : distance of α in ^{16}O
 d_5 : distance btw ^{16}O and α

	ν (fm^{-2})	d (fm)	d_5 (fm)	Λ	$\langle Q \rangle$	$\langle LS \rangle$	$\langle P \rangle$
$j-j$	0.1453	0.001	0.01	1	20.0(20)	3.99(4)	-4.0(-4)
SU(3)	0.1453	0.001	0.01	0	20.0(20)	0.0(0)	-4.0(-4)
5α	0.2656	<u>3.058</u>	<u>3.895</u>	0	32.3	0.0(0)	-1.5
$O\alpha$	0.1635	0.001	<u>3.012</u>	0	21.3	0.0(0)	-3.7



$^{16}\text{O}(\text{p-shell closed}) + \alpha$ is most probable