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*@Center for Computational Sciences (CCS), University of Tsukuba*

# Systematic analysis of light heavy-ion scatterings based on microscopic structure and reaction models

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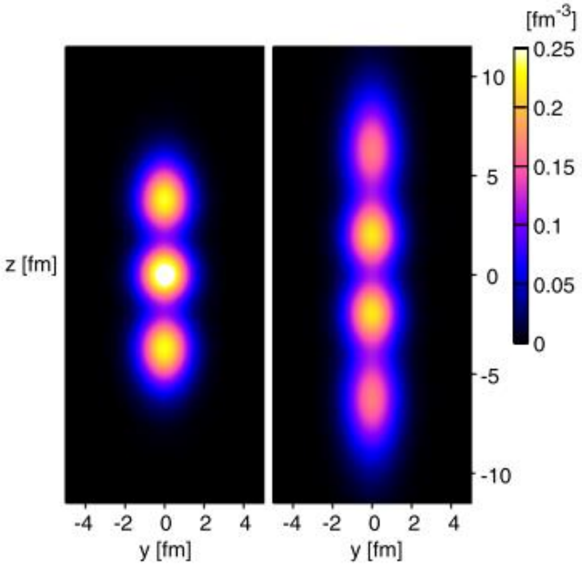
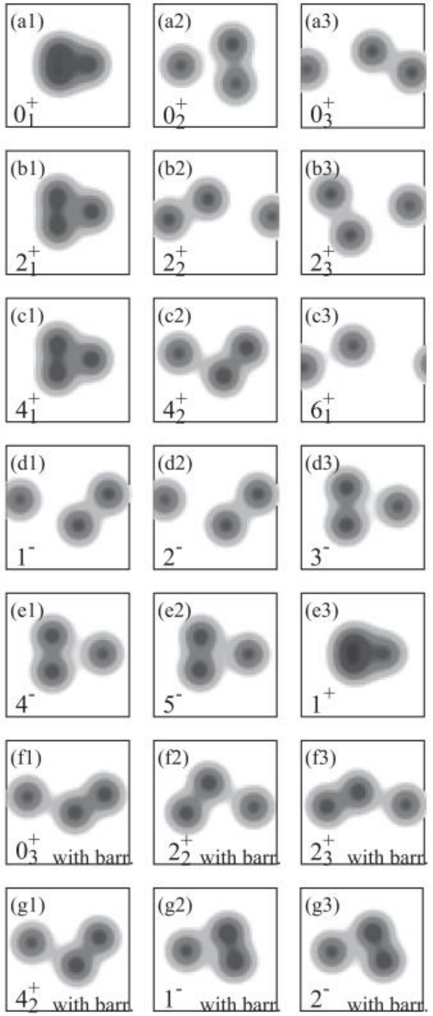
# Introduction ~Exotic structures in stable light heavy-ions~

⇨ The cluster structure is one of hot topics in the light heavy-ions

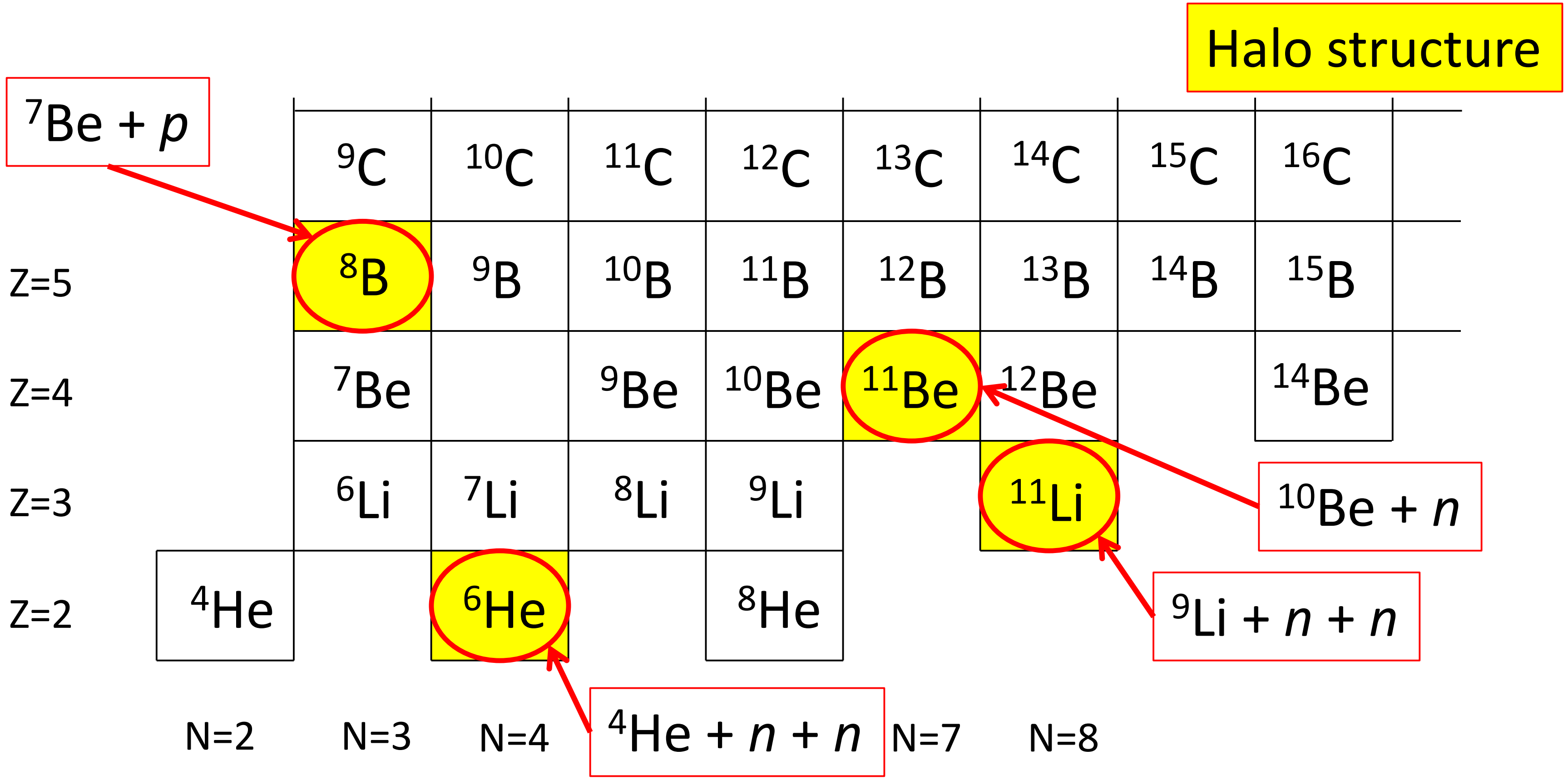



T. Suhara et al., PRL112, 062501 (2014)




Y. Kanada-En'yo, PTP117, 655 (2007)

# Introduction ~Exotic structures in unstable light heavy-ions~

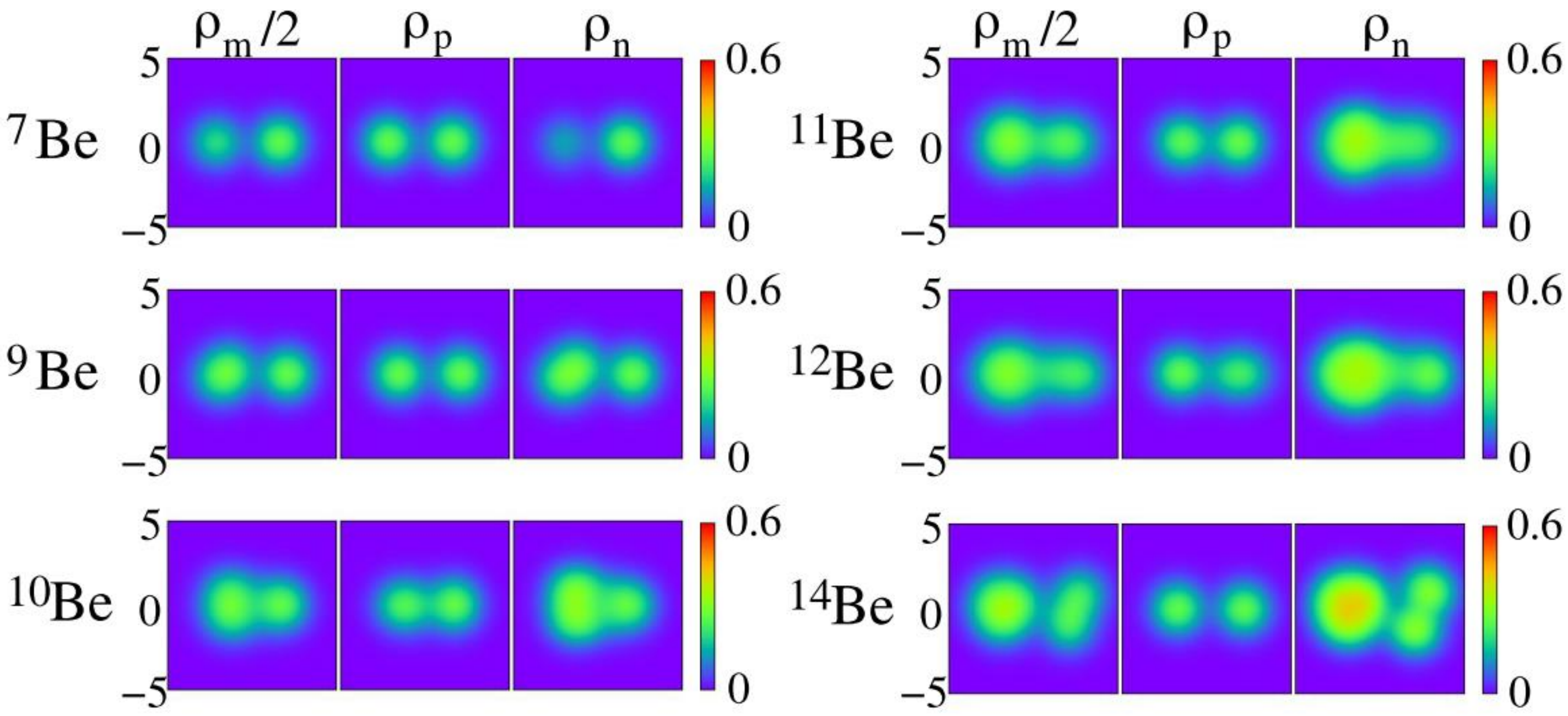



Experiment

*I. Tanihata et. al., (Phys. Rev. Lett. 55 (1985) 2676)*
*T. Minamisono et. al., (Phys. Rev. Lett. 69 (1992) 2058)*
*I. Tanihata, (J. Phys. G: Nucl. Part. Phys. 22 (1996) 157)*

# Introduction ~Exotic structures in unstable light heavy-ions~

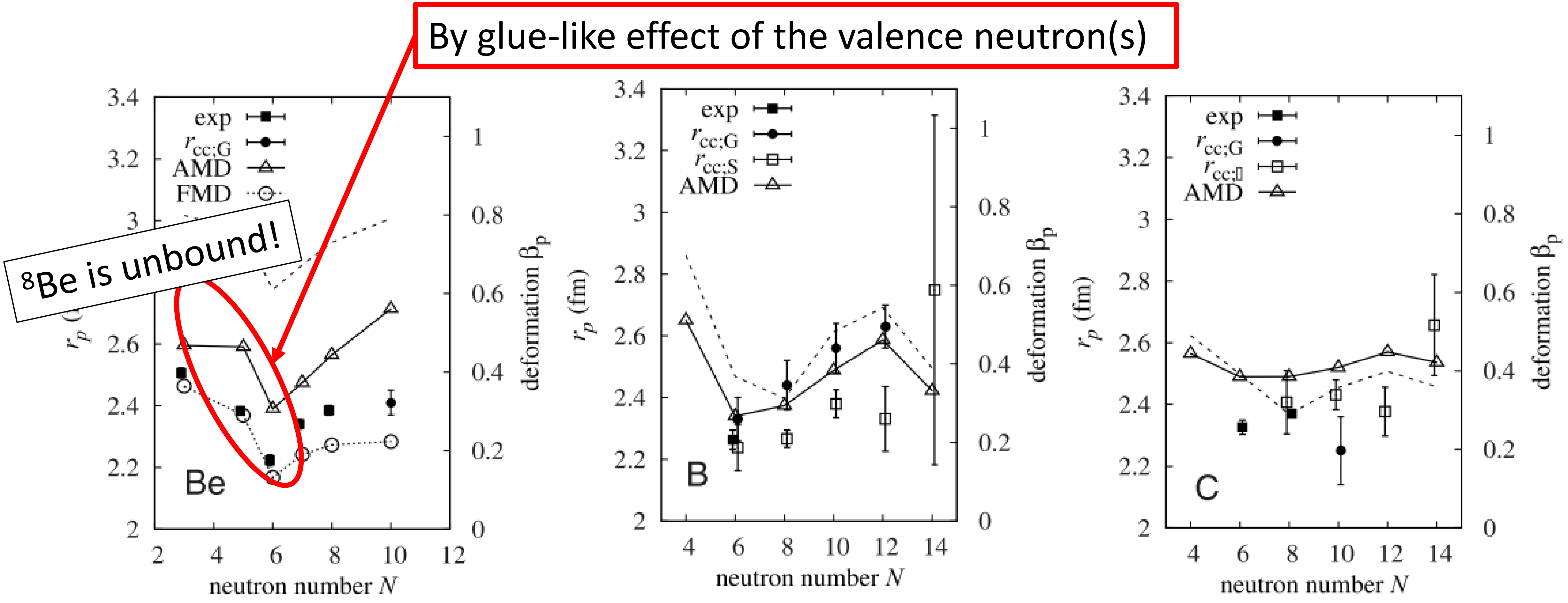
⇨ The cluster feature **in unstable nuclei** is also hot topics!




*M. Kimura, T. Suhara and Y. Kanada-En'yo, EPJA52, 373 (2016)*

# Introduction ~*Exotic structures in unstable light heavy-ions*~

By glue-like effect of the valence neutron(s)

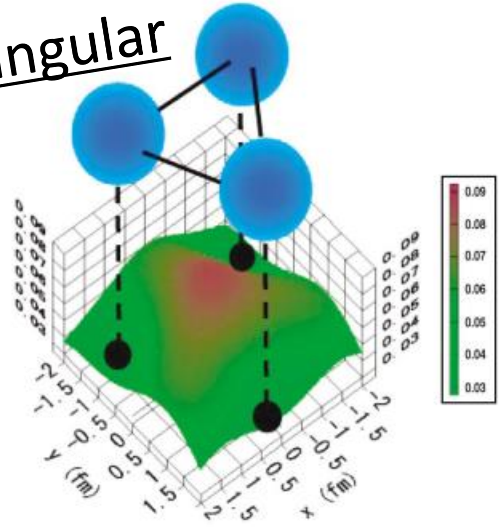



*M. Kimura, T. Suhara and Y. Kanada-En'yo, EPJA52, 373 (2016)*

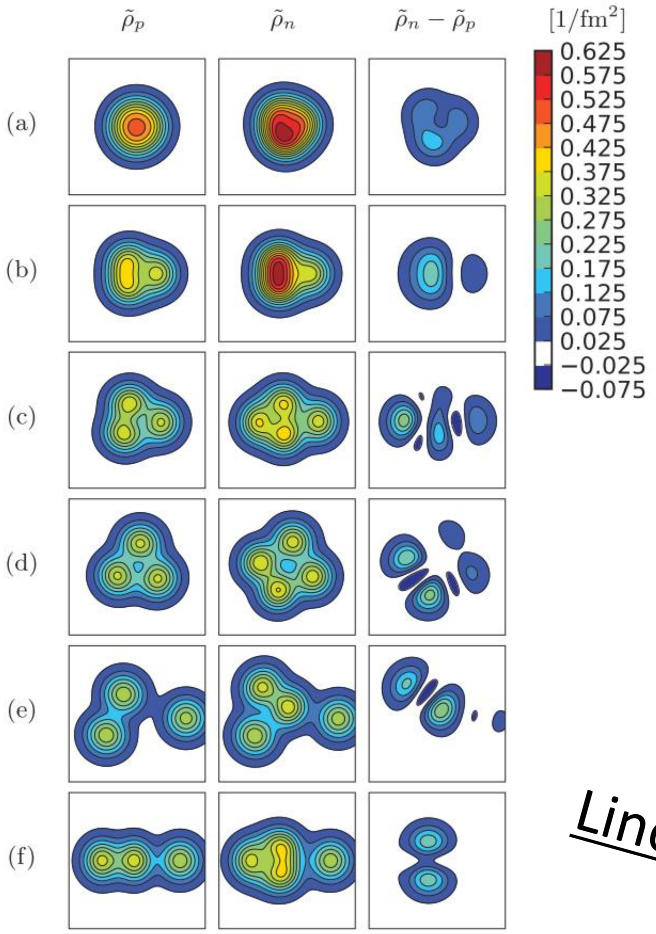
# Introduction ~Exotic structures in unstable light heavy-ions~

⇨ The excess neutrons play a glue-like role between alpha-clusters in $^{14}$C.

Equilateral-Triangular



*N. Itagaki et al., PRL92, 142501 (2004)*




Linear-chain

*T. Suhara and Y. Kanada-En'yo, PRC82, 044301 (2010)*

# *Formalism (Outline)*

To investigate such exotic features in light heavy-ions, we have combined the microscopic structure and reaction models.

**"Structure"**

**Cluster model + Stochastic multi-configuration mixing**

→ Biding energy
→ Radius
→ Transition strength

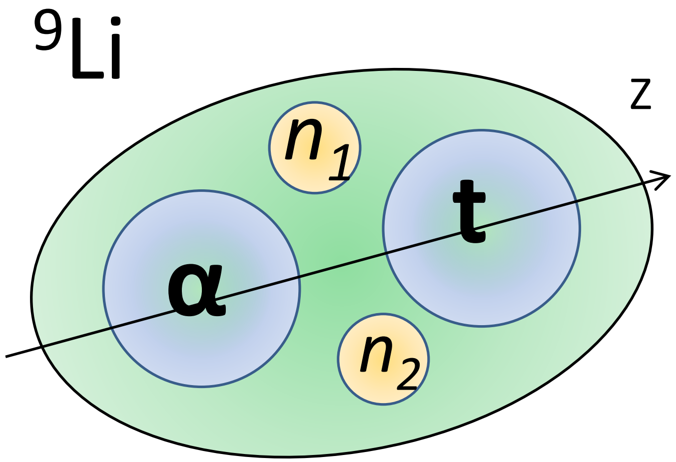
**Transition density**

**"Reaction"**

**Microscopic Coupled Channel (MCC)**

→ Cross section

# Structure part ($^9$Li case)




**Cluster model + Stochastic multi-configuration mixing**

$$\Phi^{J^\pi M} = \sum_K \sum_i c_{i,K} \Psi_i^{J^\pi MK}$$

Randomly fixed

$$\Psi_i^{J^\pi MK} = P^\pi P^{JMK}[A\{\phi_\alpha(\mathbf{r}_1\mathbf{r}_2\mathbf{r}_3\mathbf{r}_4,\mathbf{R}_1)\phi_t(\mathbf{r}_5\mathbf{r}_6\mathbf{r}_7,\mathbf{R}_2)\phi_{n_1}(\mathbf{r}_8,\mathbf{R}_3)\phi_{n_2}(\mathbf{r}_9,\mathbf{R}_4)\}]$$

$$\phi(\mathbf{r}_j,\mathbf{R}_k) = \exp\left[-\nu\left(\mathbf{r}_j - \frac{\mathbf{R}_k}{\sqrt{\nu}}\right)^2\right]\chi_j$$

$\chi_j$ : spin and isospin parts

**Hamiltonian**

$$\hat{H} = \sum_{i=1}^{A} \hat{t}_i - \hat{T}_{c.m.} + \sum_{i>j}^{A} \hat{v}_{ij}$$

$\nu = 0.235$

$M = 0.60$

$B = H = 0.08$

**Effective *NN* interaction**

Central : Volkov No.2 (W=1-M)

LS : G3RS ($V_{LS}$=2000MeV)

# Reaction part (Heavy-ion scattering)

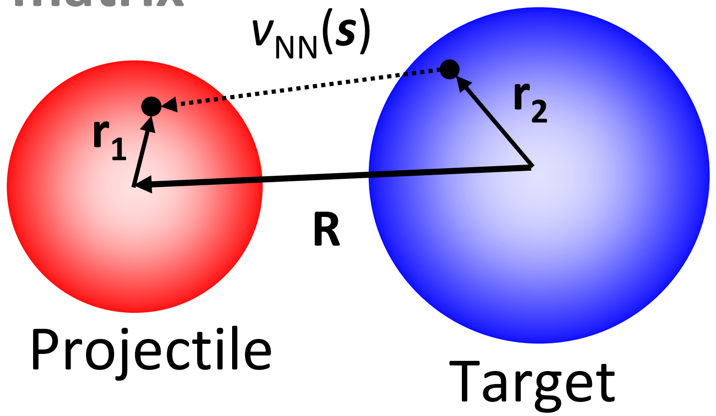
**Microscopic Coupled Channel (MCC)**

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

**The diagonal and coupling potentials are derived from microscopic view point.**

$$U_{\alpha\beta}(\mathbf{R}) = \int \rho_{ik}^{(P)}(\mathbf{r}_1)\rho_{jl}^{(T)}(\mathbf{r}_2)\, v_{NN}(\mathbf{s};\rho,E)\, d\mathbf{r}_1 d\mathbf{r}_2$$

transition density Complex G-matrix

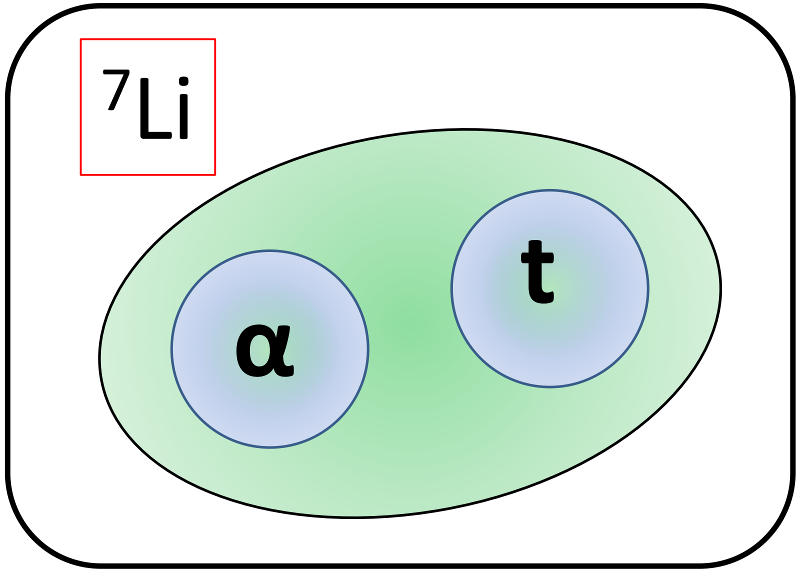


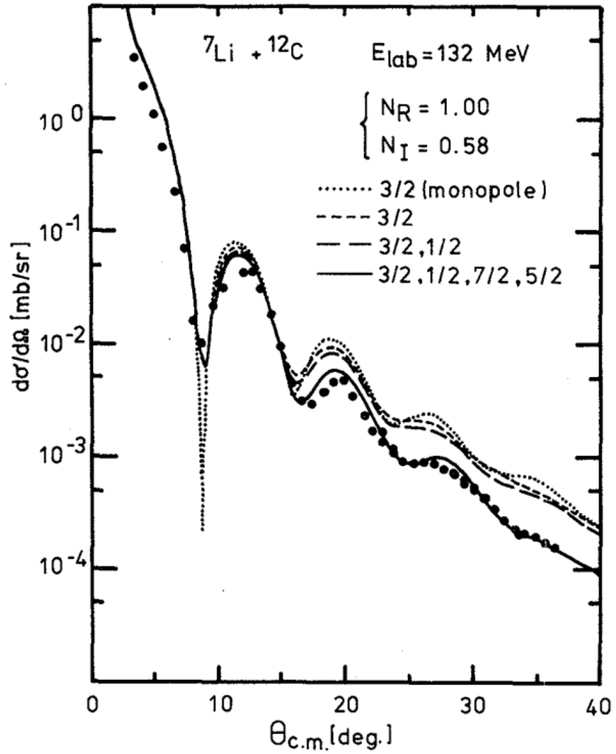

**Transition density**

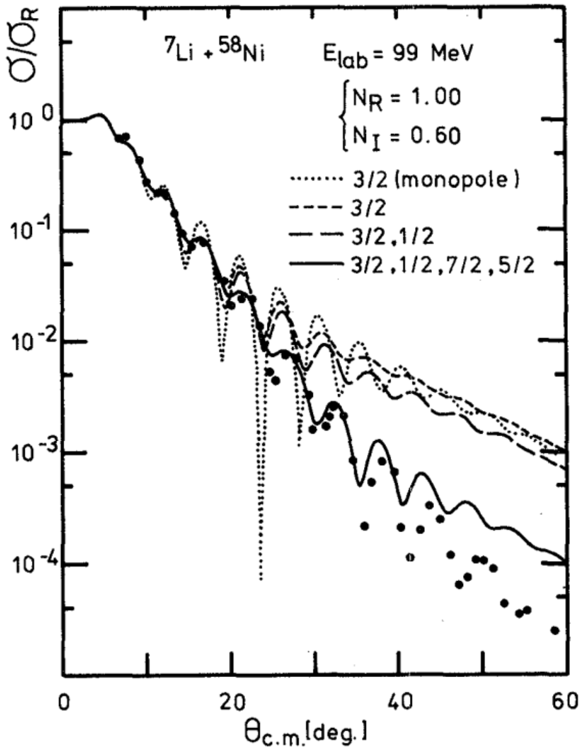
$$\rho_{ik}(\mathbf{r}) = \langle \varphi_i(\xi) | \sum_i \delta(\mathbf{r}_i - \mathbf{r}) | \varphi_k(\xi) \rangle$$

# *Results* ~Li isotopes~

Glue like role of neutron in Li isotopes

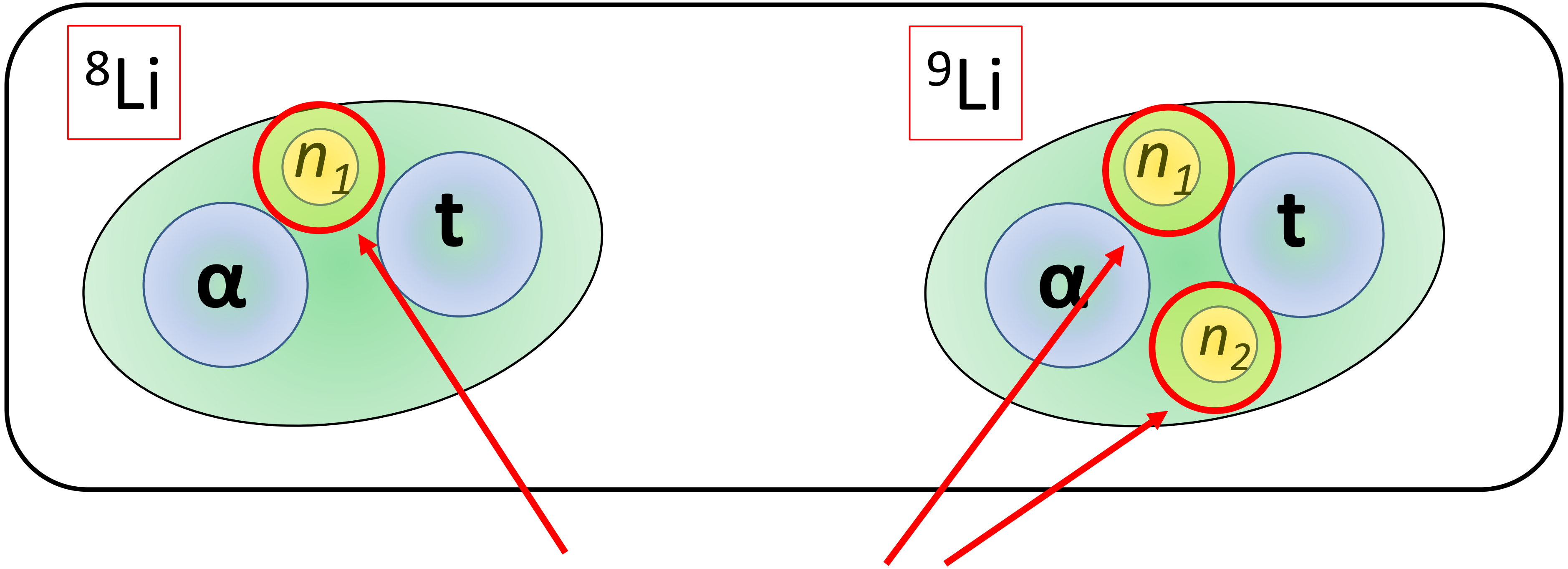



*Y. Sakuragi, M. Yahiro and M. Kamimura, PTP89, 136 (1986)*

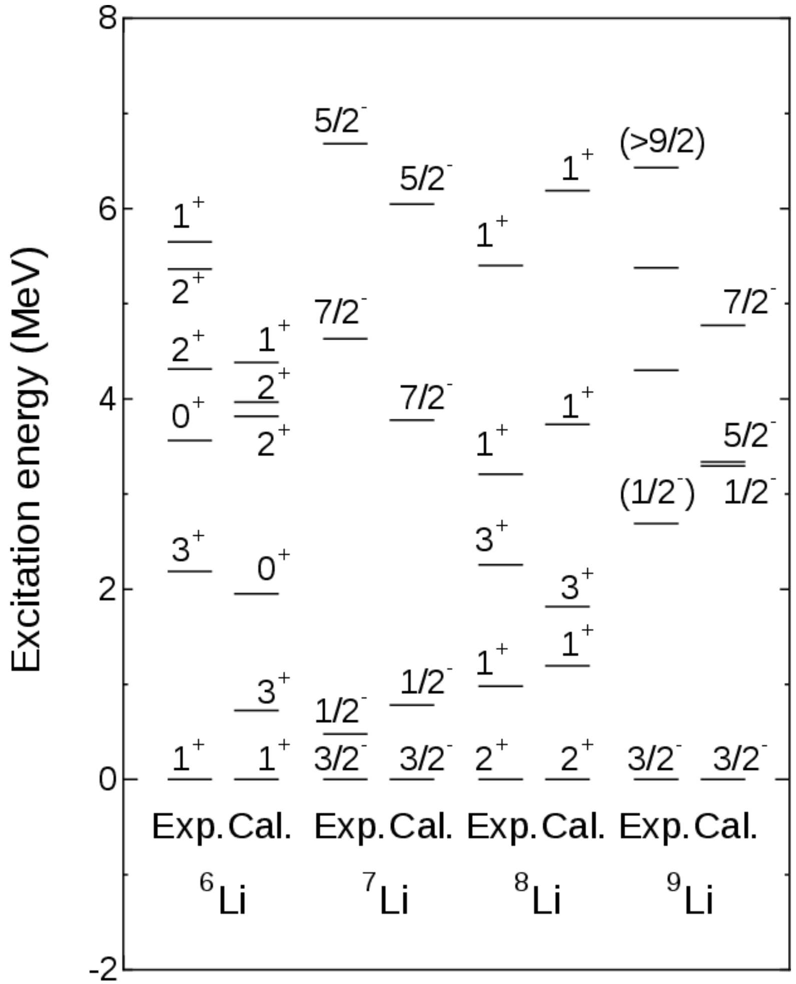
# Results ~Li isotopes~




It is anticipated that **the excess neutron(s)** plays **a glue-like role** to attract α and *t* clusters in the $^8$Li & $^9$Li nuclei.

# Comparison with data for excitation energy &

Proton radius becomes smaller and smaller.




| | | (fm) | Point neutron (fm) | Point matter (fm) |
|---|---|---|---|---|
| | | 2.54(3) | 2.54(3) | 2.54(3) |
| | $^{7}$Li | 2.43(3) | 2.54(3) | 2.50(3) |
| | $^{8}$Li | 2.41(3) | 2.57(3) | 2.51(3) |
| | $^{9}$Li | 2.30(2) | 2.50(2) | 2.43(3) |
| Ref. [52] | $^{6}$Li | 2.517(30) | | |
| | $^{8}$Li | 2.299(32) | | |
| | $^{9}$Li | 2.217(35) | | |
| Calc. | $^{6}$Li | 2.662 [2.523] | 2.556 | 2.539 |
| | $^{7}$Li | 2.636 [2.495] | 2.604 | 2.558 |
| | $^{8}$Li | 2.530 [2.379] | 2.615 | 2.529 |
| | $^{9}$Li | 2.393 [2.237] | 2.562 | 2.445 |


*[1] I. Tanihata et al., PRL55, 2676 (1985)*
*[52] R. Sanchez et al., PRL96, 033002 (2006)*

*T. Furumoto, T. Suhara, and N. Itagaki, PRC97, 044602 (2018)*

# Transition strength (B(IS2)) of Li isotope

**6Li**

| | | |
|---|---|---|
| B(IS2) | (g.s. → $3_1$) | 57.13 $fm^4$ |
| | (g.s. → $2_1$) | 54.78 $fm^4$ |
| | (g.s. → $1_2$) | 33.56 $fm^4$ |

**7Li**

| | | |
|---|---|---|
| B(IS2) | (g.s. → $1/2_1$) | 54.47 $fm^4$ |
| | (g.s. → $5/2_1$) | 22.06 $fm^4$ |
| | (g.s. → $7/2_1$) | 96.78 $fm^4$ |

**8Li**

| | | |
|---|---|---|
| B(IS2) | (g.s. → $1_1$) | 16.24 $fm^4$ |
| | (g.s. → $3_1$) | 47.96 $fm^4$ |
| | (g.s. → $2_1$) | 7.384 $fm^4$ |
| | (g.s. → $2_2$) | 15.68 $fm^4$ |

**9Li**

| | | |
|---|---|---|
| B(IS2) | (g.s. → $1/2_1$) | 19.26 $fm^4$ |
| | (g.s. → $5/2_1$) | 19.19 $fm^4$ |
| | (g.s. → $7/2_1$) | 31.55 $fm^4$ |

By shrinking the density,
the transition strength becomes small.

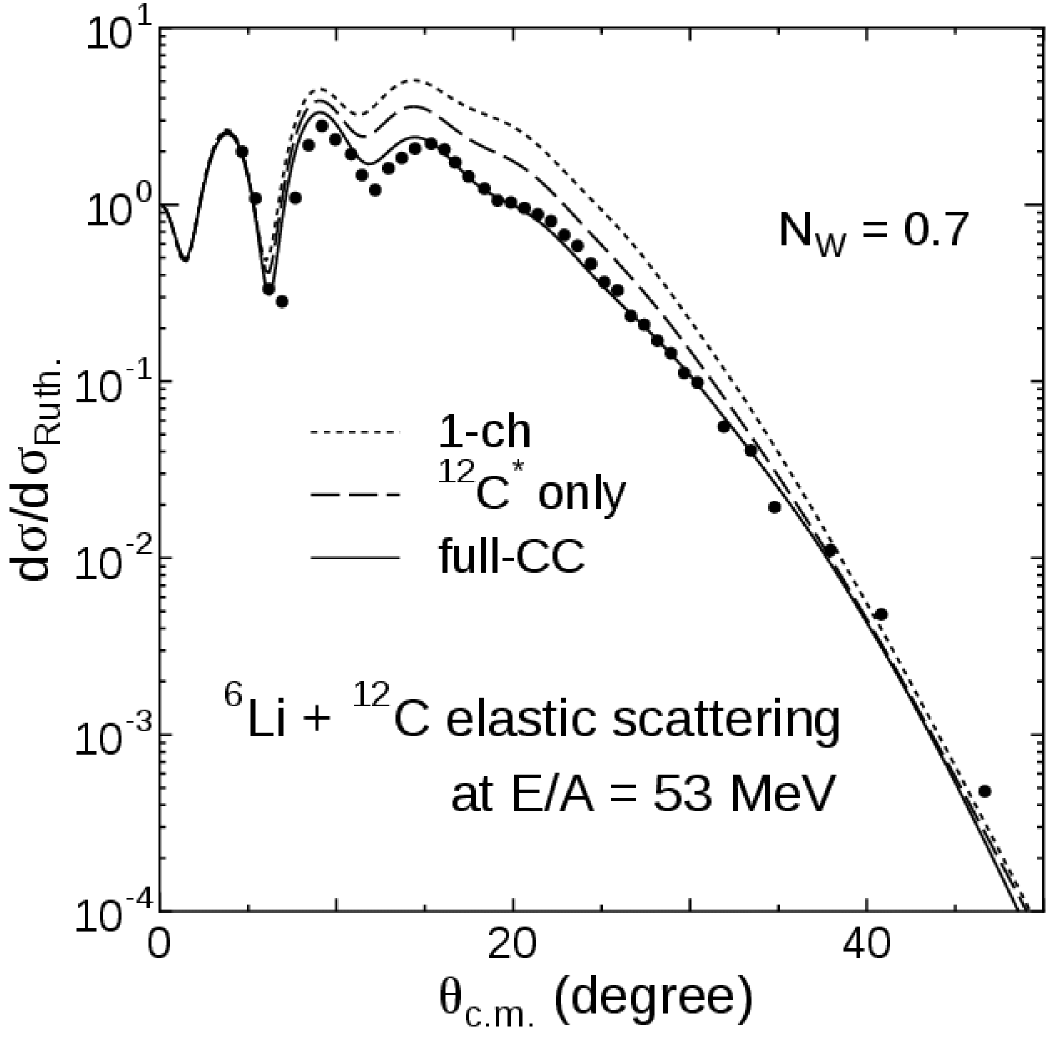
Large

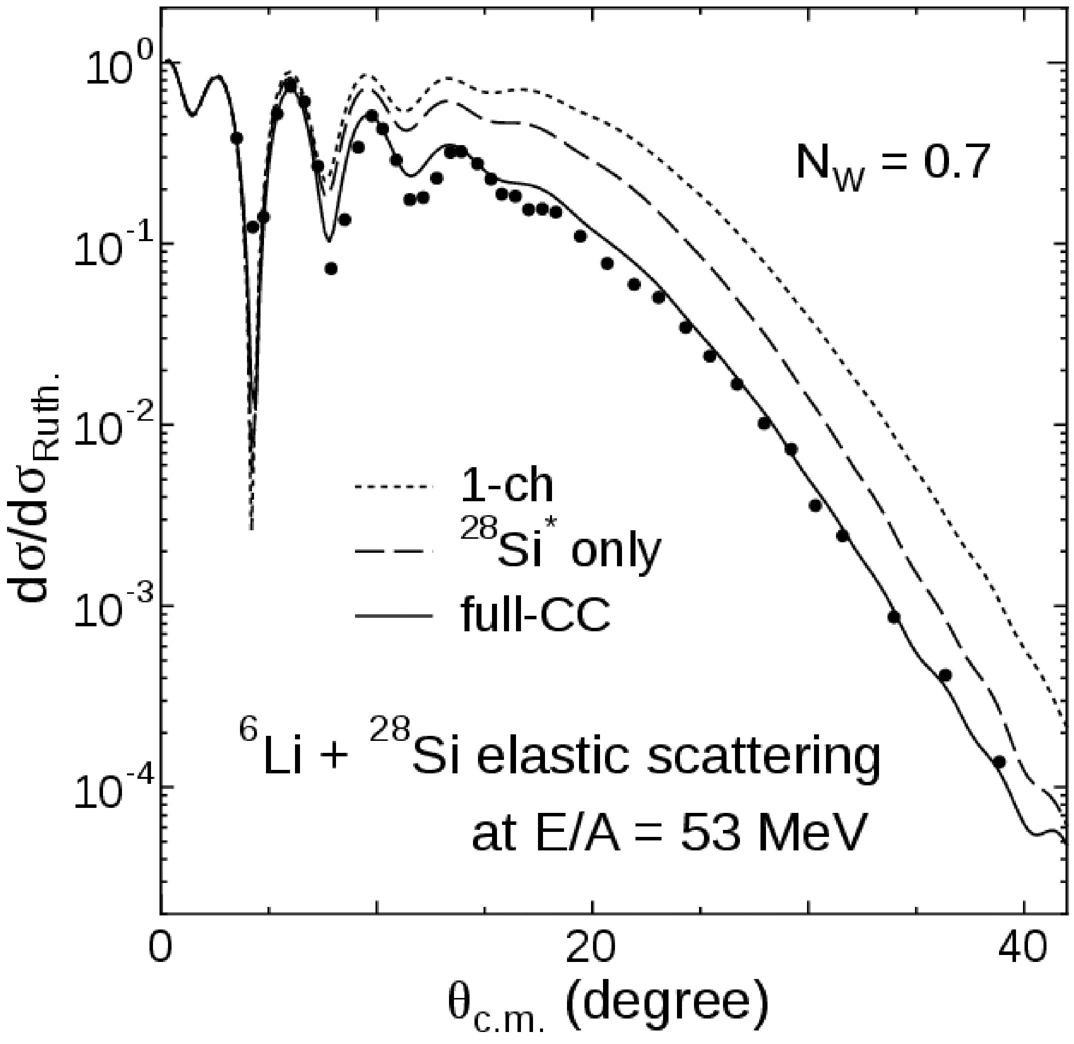
Small

⇨ glue-like role by valence neutrons

*T. Furumoto, T. Suhara, and N. Itagaki, PRC97, 044602 (2018)*

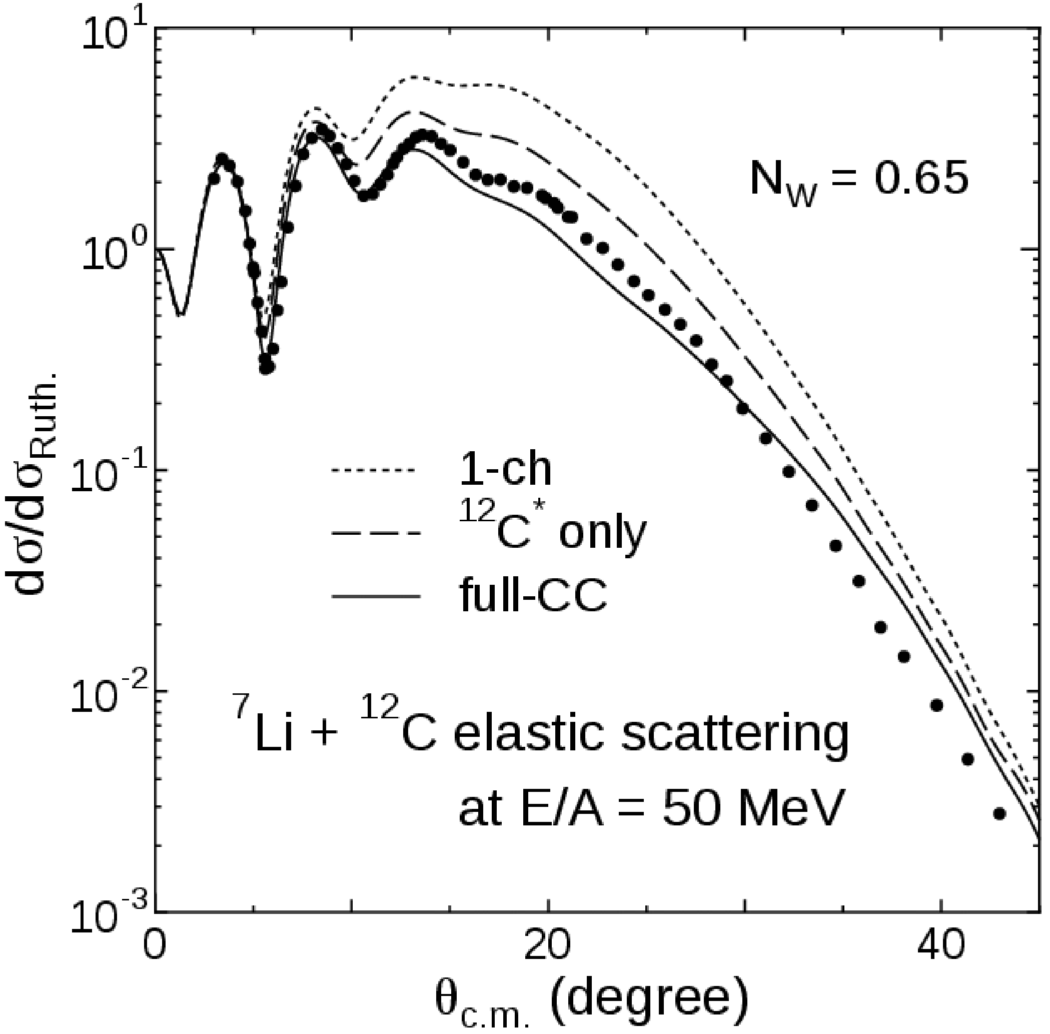
# $^{6}$Li elastic scattering by $^{12}$C and $^{28}$Si at E/A = 53 MeV

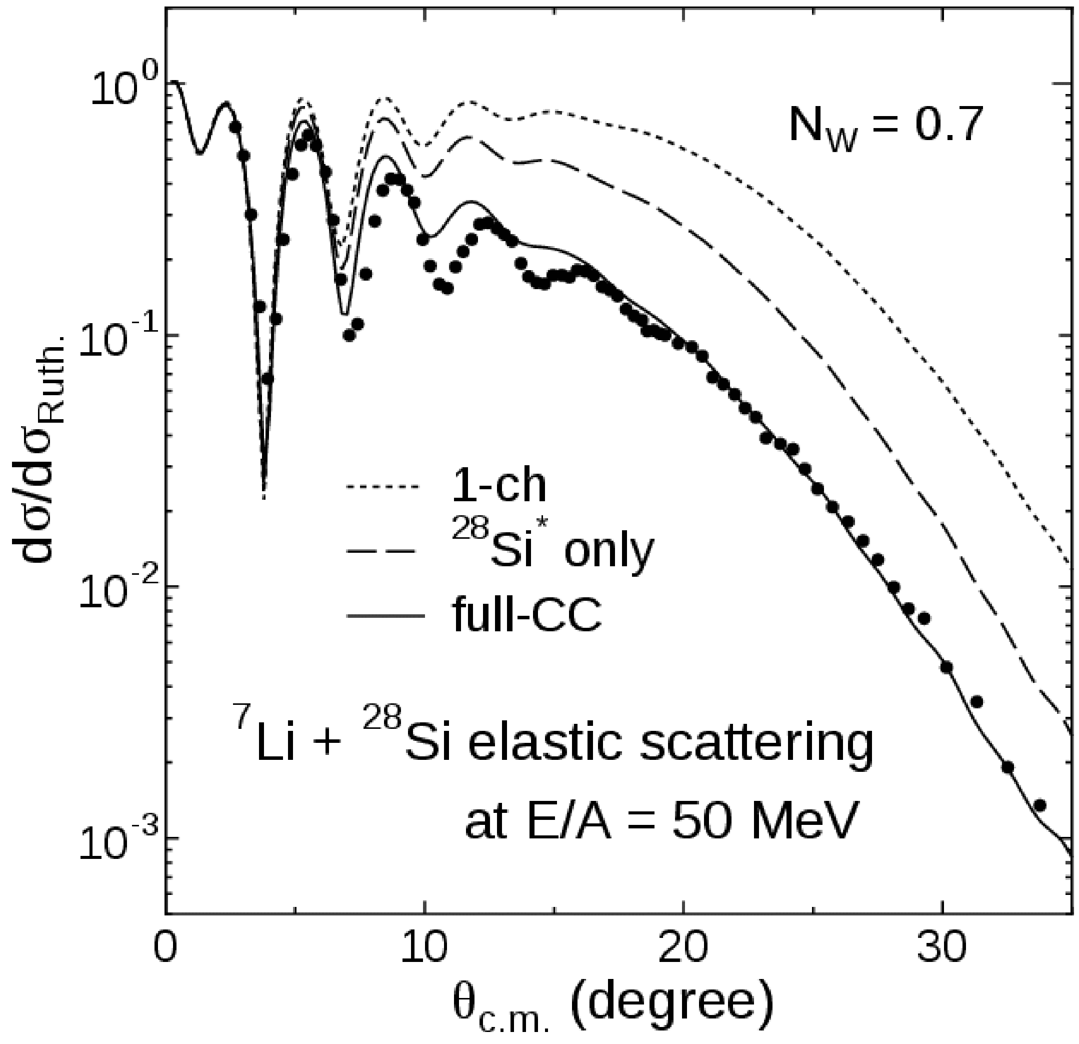



*T. Furumoto, T. Suhara, and N. Itagaki, PRC97, 044602 (2018)*

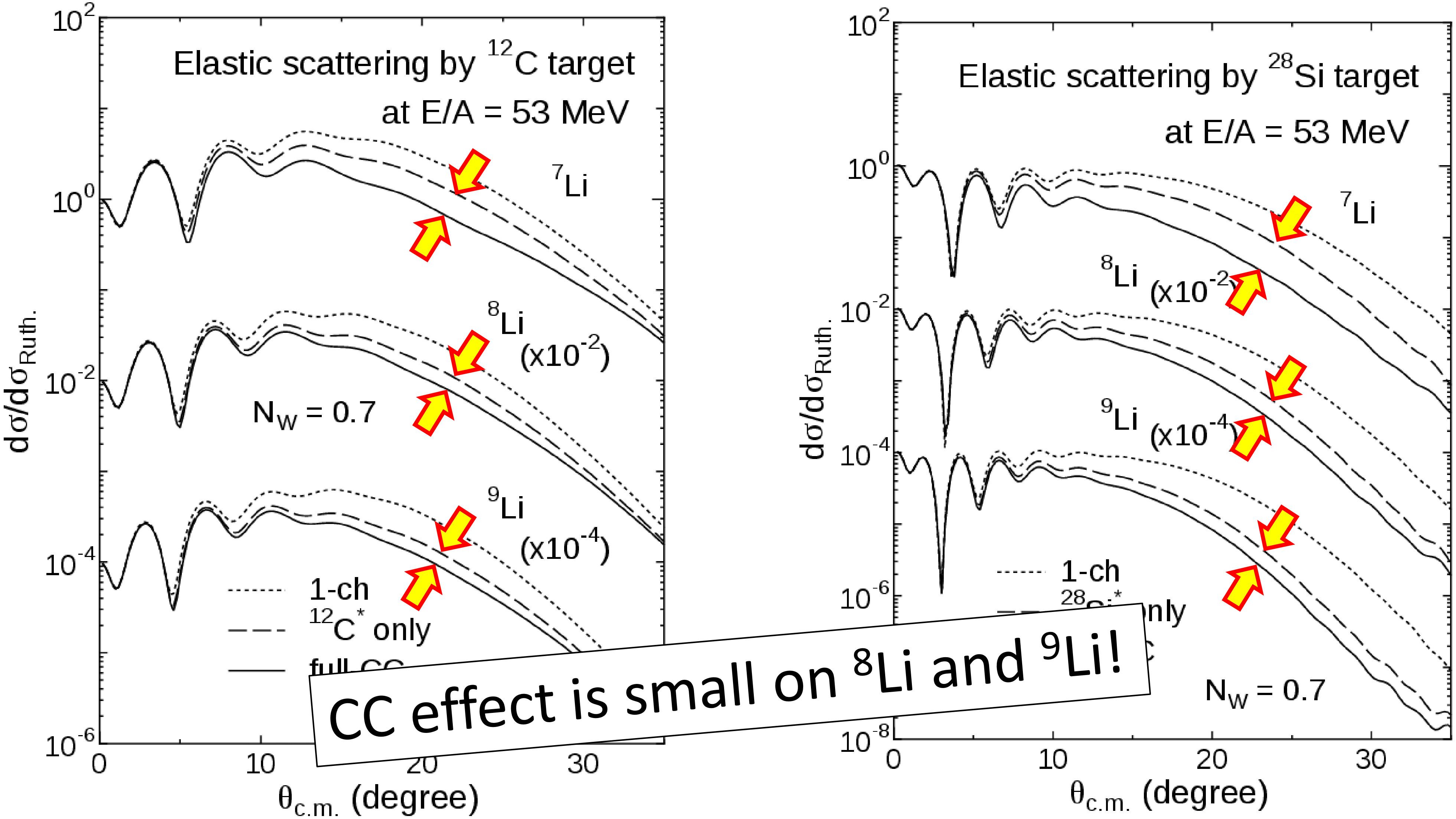
# $^{7}$Li elastic scattering by $^{12}$C and $^{28}$Si at E/A = 50 MeV




*T. Furumoto, T. Suhara, and N. Itagaki, PRC97, 044602 (2018)*

# $^{7\text{-}9}$Li elastic scatterings by $^{12}$C and $^{28}$Si at E/A = 53 MeV



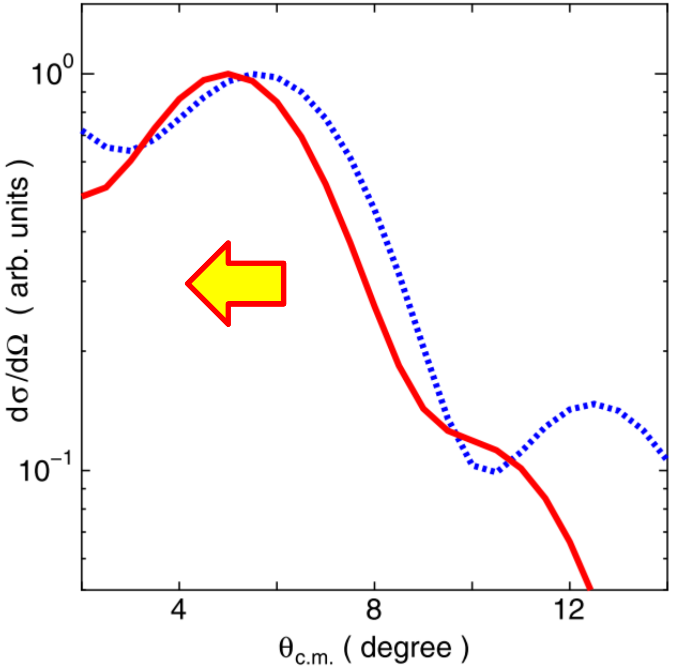

CC effect is small on $^{8}$Li and $^{9}$Li!

*T. Furumoto, T. Suhara, and N. Itagaki, PRC97, 044602 (2018)*

# Is it true that the inelastic cross section tells the radius of the excited state?

**M. Ito (Phys. Rev. C 97 (2018) 044608)**

having an extended radius. Thus, I conclude that the shrinkage in the $2_2^+$ cross section originates from the spatially extended structure of the Hoyle rotational $2_2^+$ state if the difference in the excitation energies, that is, $E_x = 4.44$ MeV for $2_1^+$ and $E_x = 10.3$ MeV for $2_2^+$, can be safely neglected.




To compare the two excited states

TABLE I. Difference in spatial size of the $2_{1,2}^+$ states. $\Delta R_m$ represents the difference in the nuclear radius $\Delta R_m = R_m(2_2^+) - R_m(2_1^+)$ with root mean squared radius $R_m$, while $\Delta R_{trd}$ represents the difference in the peak position of the transition density, that is, $\Delta R_{trd} = R_{trd}(2_2^+) - R_{trd}(2_1^+)$. $\Delta a$ shows the difference in the diffraction radius, which is derived from the differential cross section at $E_\alpha = 386$ MeV. See text for details.

| $\Delta R_m$ | $\Delta R_{trd}$ | $\Delta a$ |
|---|---|---|
| 1.6 fm | 1.0 fm | 0.6 fm |

a is inelastic black-sphere radius.

# Is it true that the inelastic cross section tells the radius of the excited state?

⇨ We apply our models to investigate such mechanisms and systematics.

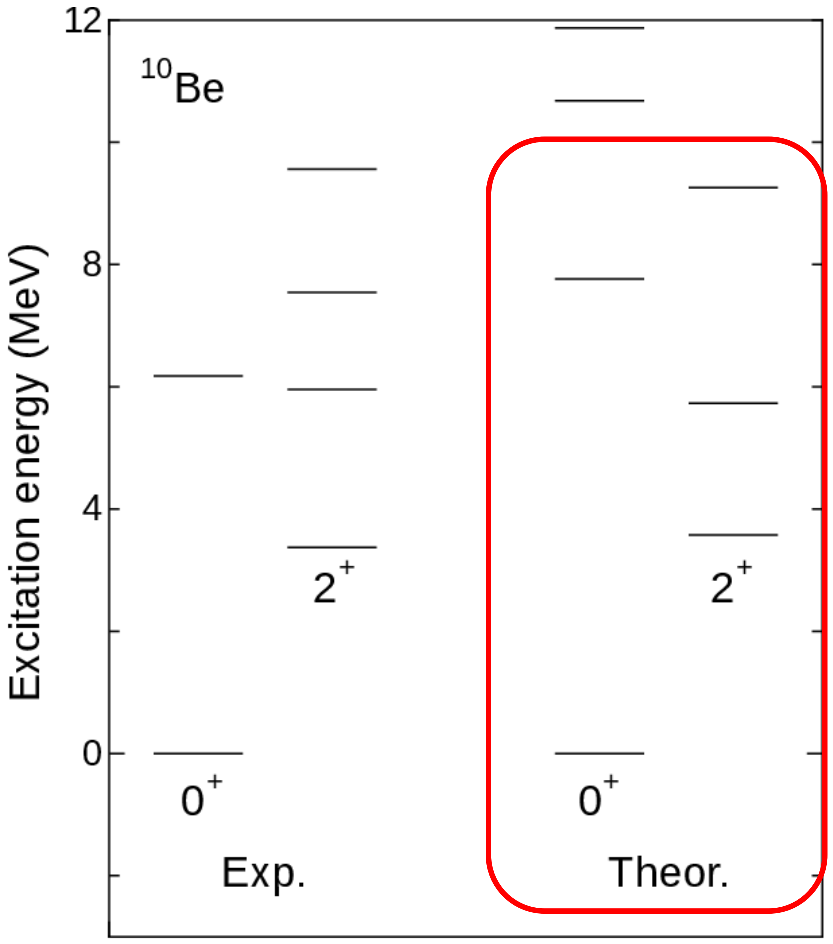
In this test, we choose the well-known nucleus.

→ $^{10}$Be nucleus.

- 2α + 2n clusters system
- Two neutrons occupy the $\pi$ orbit in the ground state
  but the $\sigma$ orbit in the 2nd $0^+$ state
- Low lying $2^+$ states are rotational band members of the $0^+$ states

# Results ~$A = 10$ nuclei~

Excitation energy and r.m.s. radius




$^{10}$Be

$1^{st}$ 0+ : 2.526 fm
$2^{nd}$ 0+ : 3.137 fm

$1^{st}$ 2+ : 2.558 fm
$2^{nd}$ 2+ : 2.672 fm
$3^{rd}$ 2+ : 3.158 fm

# *$^{10}$Be elastic & inelastic scatterings by $^{12}$C target at E/A = 59.4 MeV*

➡ We test radii of the excited states for the $^{10}$Be nucleus.

**$^{10}$Be**

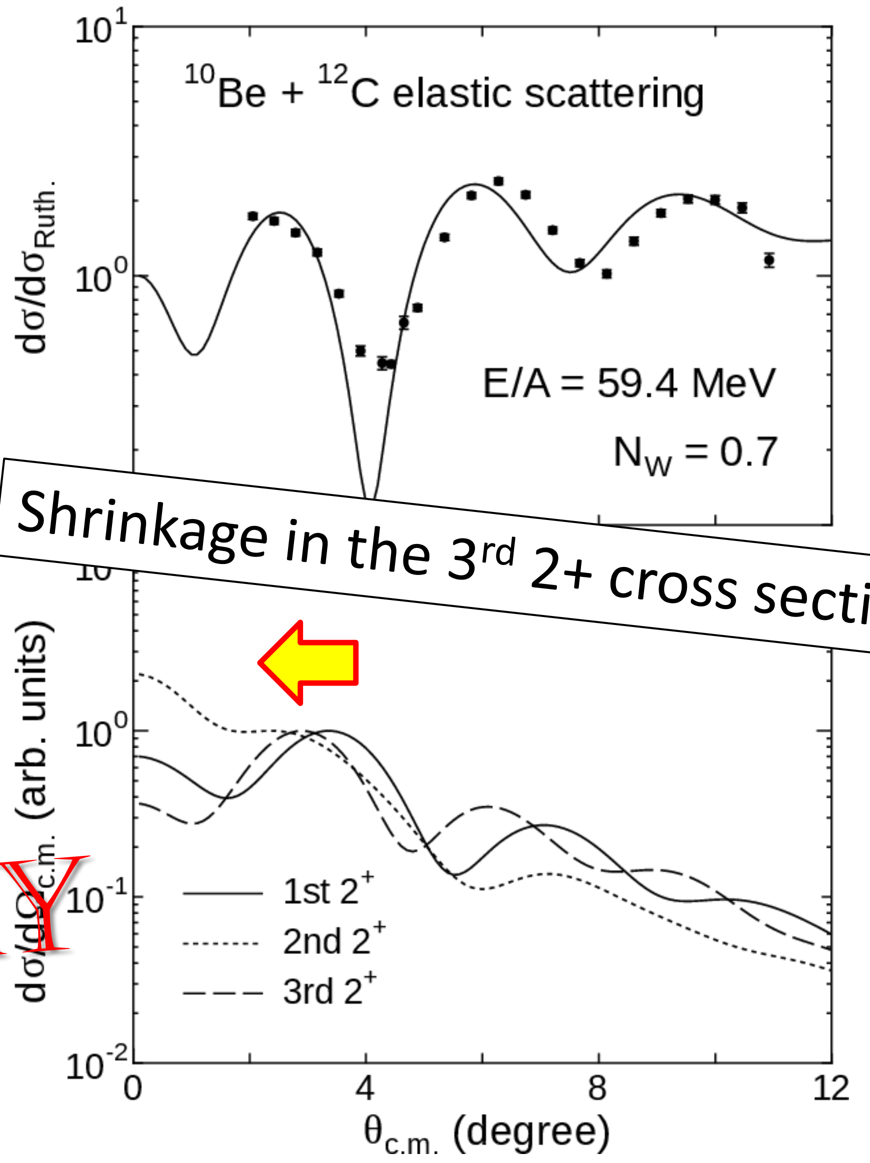
$1^{st}$ 0+ : 2.526 fm

$2^{nd}$ 0+ : 3.137 fm

$1^{st}$ 2+ : 2.558 fm

$2^{nd}$ 2+ : 2.672 fm

$3^{rd}$ 2+ : 3.158 fm




Shrinkage in the $3^{rd}$ 2+ cross section

VERY PRELIMINARY

# *Summary*

- **We have combined microscopic structure and reaction models**

⇨ the structure and reaction parts
are based on the cluster and folding models, respectively.

- **Application to Li isotope scatterings**

⇨ give the feature of glue-like role in Li isotopes
from the structure and reaction viewpoints.

- **Application to $^{10}$Be nucleus**

⇨ The size of the excited states for $^{10}$Be is investigated based on the previous study.