Study of one- and two-neutron removal reactions with core + n + n model

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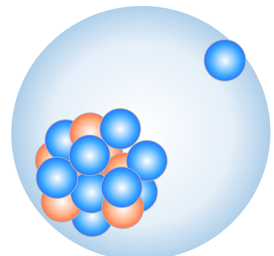
Introduction

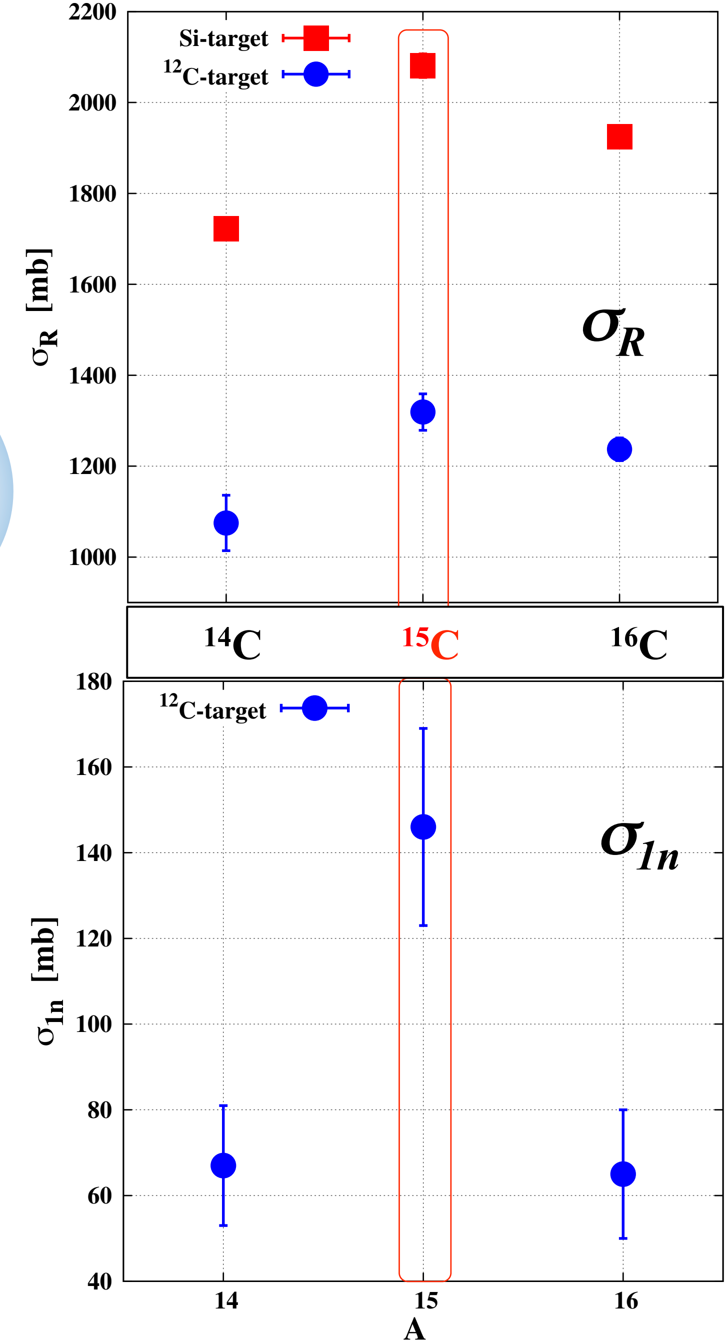
- **Halo nuclei**
  - ✓ *Weakly bound neutron(s)*
  - ✓ *Large radius*



- **Reaction cross section**
  - ✓ *Odd-even deviation of σ_R*
  - ✓ $\sigma_R(^{14}C) < \sigma_R(^{15}C) > \sigma_R(^{16}C)$
- **Neutron removal cross section**
  - ✓ *Enhancement of σ_{1n}*

✧ *Purpose*

✓ *To investigate halo and neighboring nuclei via analyses of σ_R and σ_{1n}.*



[1] Villari et al., PLB268, 345. [2] Fang et al., PRC69.034613.
[3] Yamaguchi et al., NPA724, 3. [4] Zheng et al., NPA709, 103.

Description of ^{14}C, ^{15}C, and ^{16}C

- **^{14}C inert core: HFB calculation with GognyD1S**

- **Two-body model Hamiltonian of ^{15}C**

$$H_{^{15}C} = -\frac{\hbar^2}{2\mu_y}\nabla_y^2 + V_{nc}(y)$$

V_{nc} : central + LS + OCM [1]

$1s_{1/2+}$: -1.215 MeV

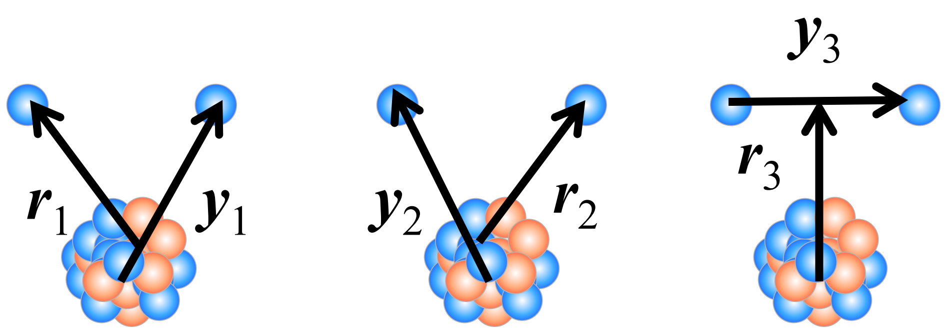
$0d_{5/2+}$: -0.478 MeV

- **Three-body model Hamiltonian of ^{16}C**

$$H_{^{16}C} = -\frac{\hbar^2}{2\mu_r}\nabla_r^2 - \frac{\hbar^2}{2\mu_y}\nabla_y^2 + V_{nc}(y_1) + V_{nc}(y_2) + V_{nn}(y_3) + \boxed{V_{nnc}(r,y)}$$

V_{nn} : BonnA

V_{nnc}: *Phenomenological 3BF*



***Gaussian Expansion Method*[2]**

[1]*Hagino, and Sagawa., PRC75, 021301*

[2]Hiyama et al., Prog. Part. Nucl. Phys. 51, 223

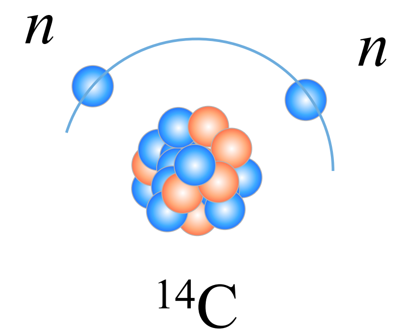
Structure of ^{16}C

^{15}C

$1s_{1/2+}$: -1.215 MeV

$0d_{5/2+}$: -0.478 MeV

Ground state wave function of ^{16}C



$$\Phi(^{16}C) = \alpha\left|\phi(^{14}C)\otimes\left(s_{1/2}\right)^2\right\rangle + \beta\left|\phi(^{14}C)\otimes\left(d_{5/2}\right)^2\right\rangle + \cdots$$

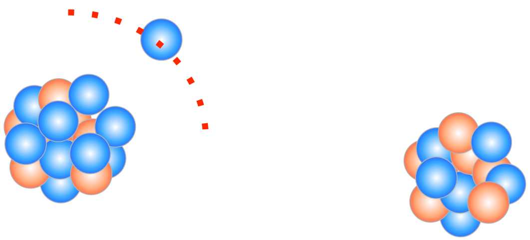
✓ ***Probability of valence neutrons orbit can be changed by V_{nnc}.***

Type I: $\alpha = 0.7, \beta = 0.6 \left(\alpha > \beta\right)$ ***s*-dominant structure**

Type II: $\alpha = 0.4, \beta = 0.8 \left(\alpha < \beta\right)$ ***d*-dominant structure**

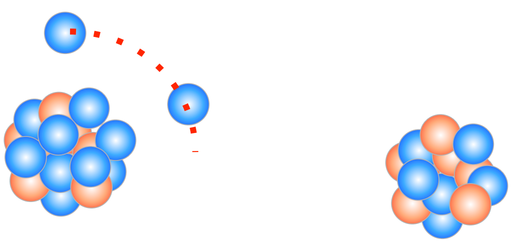
Three- and Four-Body Reactions

Three-body scattering system of ^{15}C



$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + H_{^{15}C} + U_n + U_c - E\right]\Psi = 0$$

Four-body scattering system of ^{16}C



$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + H_{^{16}C} + U_n + U_n + U_c - E\right]\Psi = 0$$

Breakup processes of ^{15}C and ^{16}C are treated by *CDCC*.

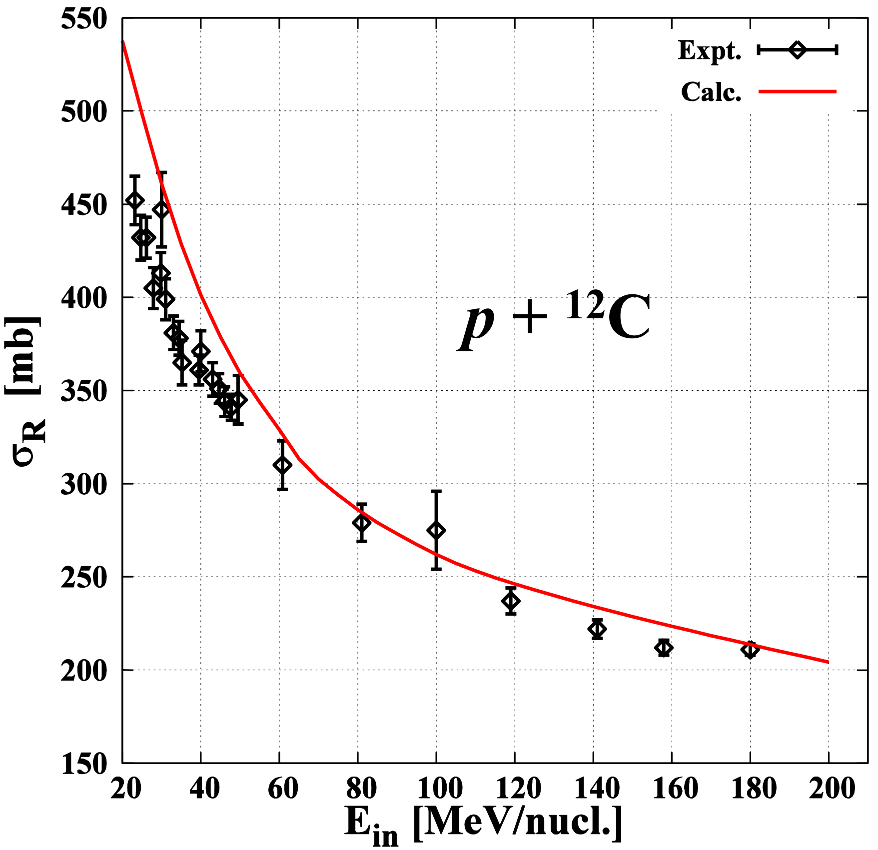
(Review)Yahiro, Ogata, TM, Minomo, PTEP01A206, (2012).

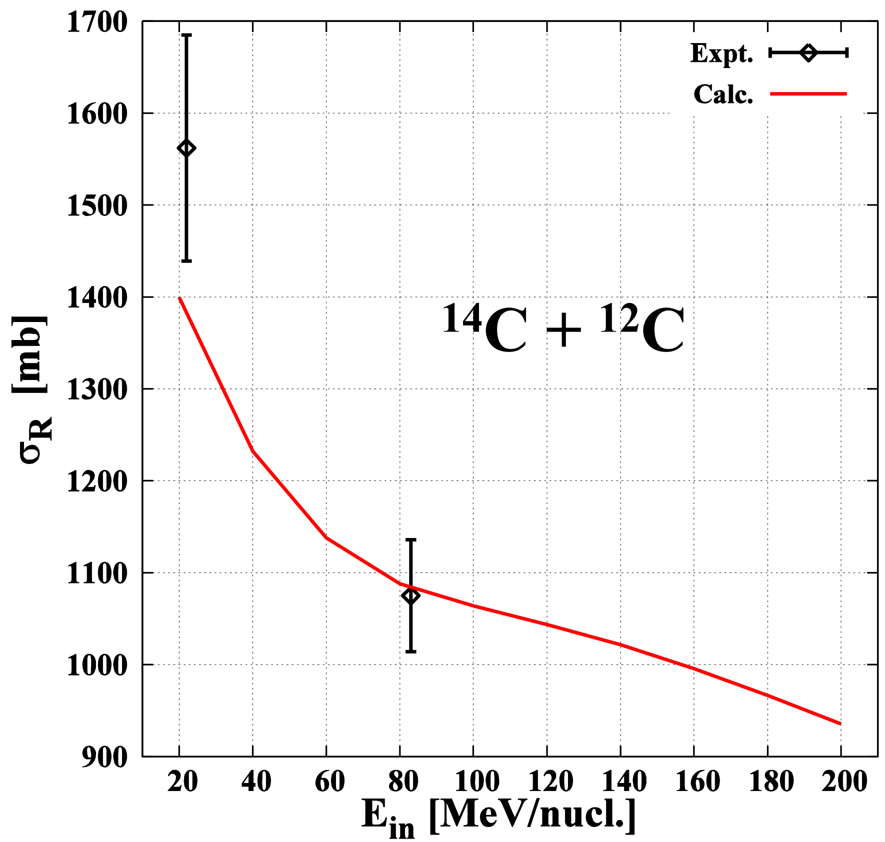
M. Toyokawa et al., PRC92, 024618 (2015)

Optical Potential

Optical potentials of *n*-T and ^{14}C-T are calculated by folding model with *g* matrix based on χ−EFT (N^{3}LO 2BF, N^{2}LO 3BF).

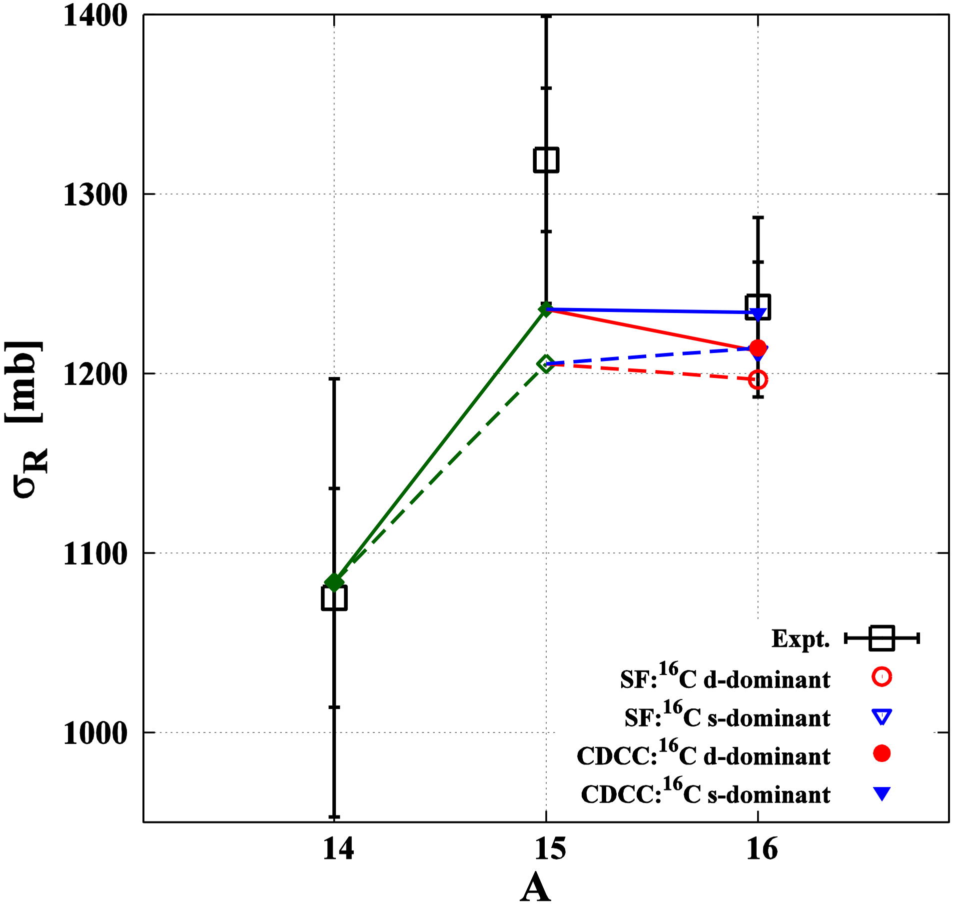
Toyokawa (Poster), Minomo (Thursday)





Reaction Cross Section on ^{12}C

$^{14\text{-}16}C + {}^{12}C$ @83 MeV/nucl

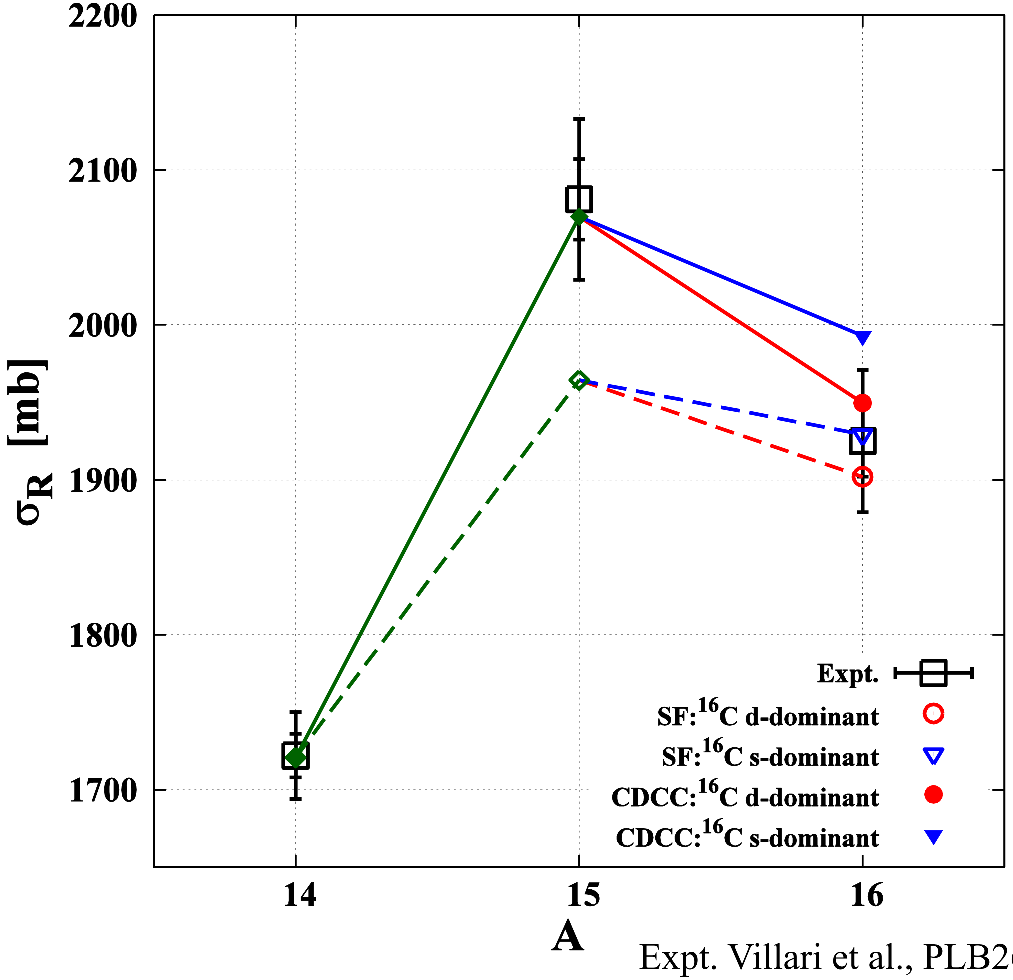


Expt. Fang et al., PRC69.034613.

- **1ch calculation (dashed)**
  - $\sigma_R(^{15}C) < \sigma_R(^{16}C):(s_{1/2})^2$
  - $\sigma_R(^{15}C) > \sigma_R(^{16}C):(d_{5/2})^2$
- **CDCC calculation (solid)**
  - $\sigma_R(^{15}C) \sim \sigma_R(^{16}C):(s_{1/2})^2$
  - $\sigma_R(^{15}C) > \sigma_R(^{16}C):(d_{5/2})^2$

Reaction Cross Section on ^{28}Si

$^{14\text{-}16}$C + ^{28}Si @45-50 MeV/nucl

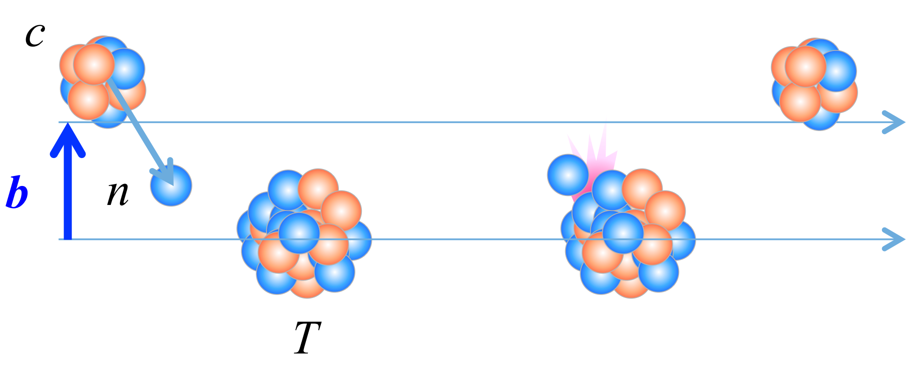


Expt. Villari et al., PLB268, 345.

- ✓ ***In the case of low incident energy, breakup effects are important for ^{15}C, and then odd-even deviation is enhanced.***
- ✓ ***Main configuration of valence two neutrons of ^{16}C is $(0d_{5/2})^2$.***

M. Yahiro, K. Ogata, K. Minomo, PTP126, 167 (2011).

Eikonal Reaction Theory



□ ***S*-matrix in eikonal approximation**

$$S = S_n S_c$$

□ **Stripping cross section (one neutron)**

$$\sigma_n = \int db \langle \phi_0 | |S_c|^2 \left(1 - |S_n|^2\right) | \phi_0 \rangle$$

Hussein and McVoy NPA445, 124 (1985)

□ **Eikonal Reaction Theory (ERT)**

- ***S_c (S_n) is estimated by solving Eikonal-CDCC equation with only U_n (U_c).***

$$\left[-\frac{\hbar^2}{2\mu_R} \nabla_R^2 + h_r + U_n(r, R) \qquad - E \right] \Psi(r, R) = 0 \qquad \textit{for } S_n$$

$$\left[-\frac{\hbar^2}{2\mu_R} \nabla_R^2 + h_r \qquad + U_c(r, R) - E \right] \Psi(r, R) = 0 \qquad \textit{for } S_c$$

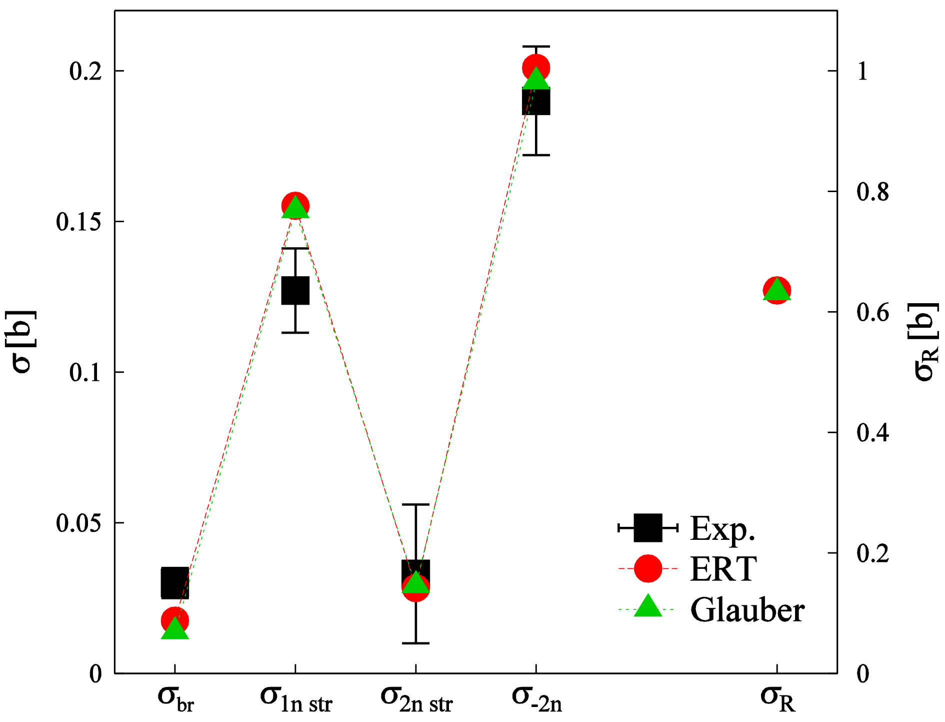
K. Minomo, TM, K. Egashira, K. Ogata, and M.Yahiro, Phys. Rev. C90, 027601.

1- and 2-neutron removal of ^{6}He

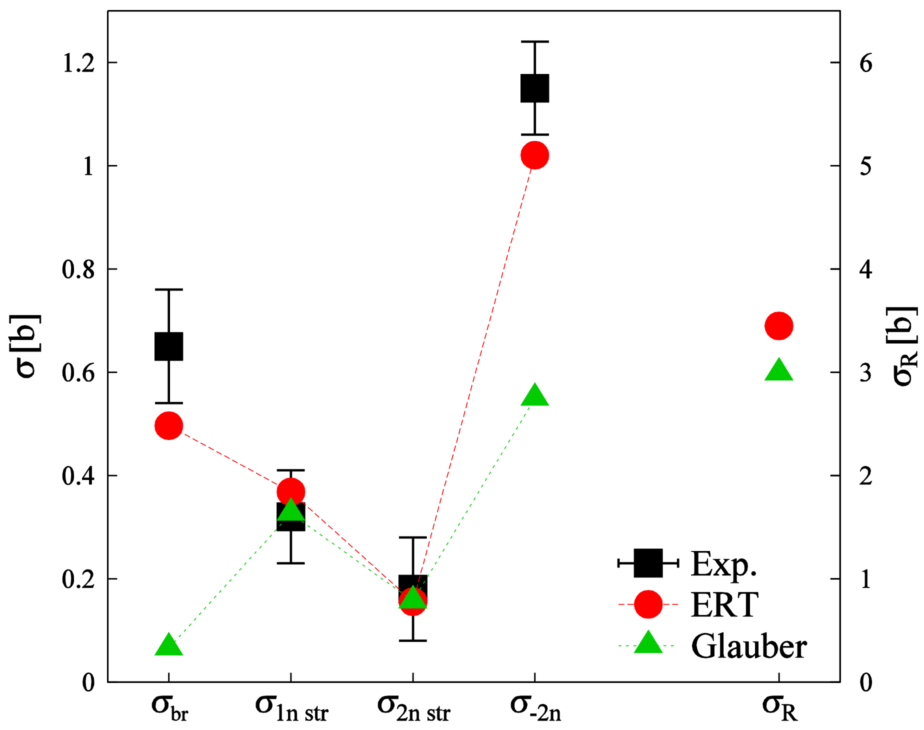
$$\sigma_{2n-str} = \int dB \langle \phi_0 \| S_c |^2 \left(1 - |S_n|^2\right)\left(1 - |S_n|^2\right) | \phi_0 \rangle$$

J. A. Tostevin et al., PRC70, 064602.

^{6}He+^{12}C scattering @ 240MeV/nucl.



^{6}He+^{209}Pb scattering @ 240MeV/nucl.

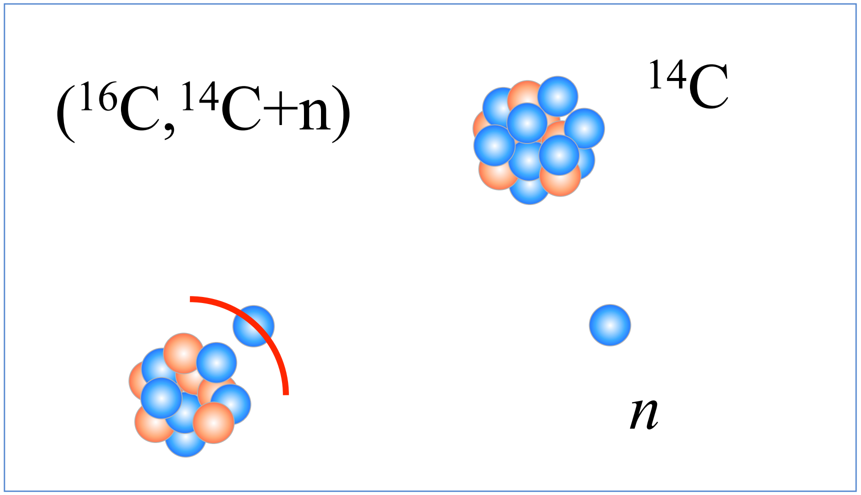


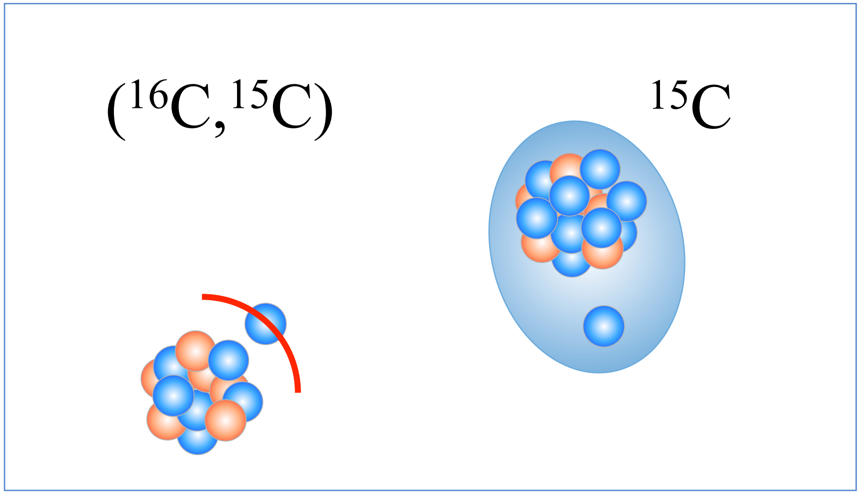
Exp. data from PRC59, 1252 (1999), T. Aumann *et al.*

1-neutron Removal of ^{16}C

$$\sigma_{1n-str} = \int dB \left\langle \phi_0 \left\| S_c \right|^2 \left| S_n \right|^2 \left(1 - \left| S_n \right|^2 \right) \right| \phi_0 \right\rangle$$

J. A. Tostevin and A. Brown, PRC74, 064604.





Simple approximation

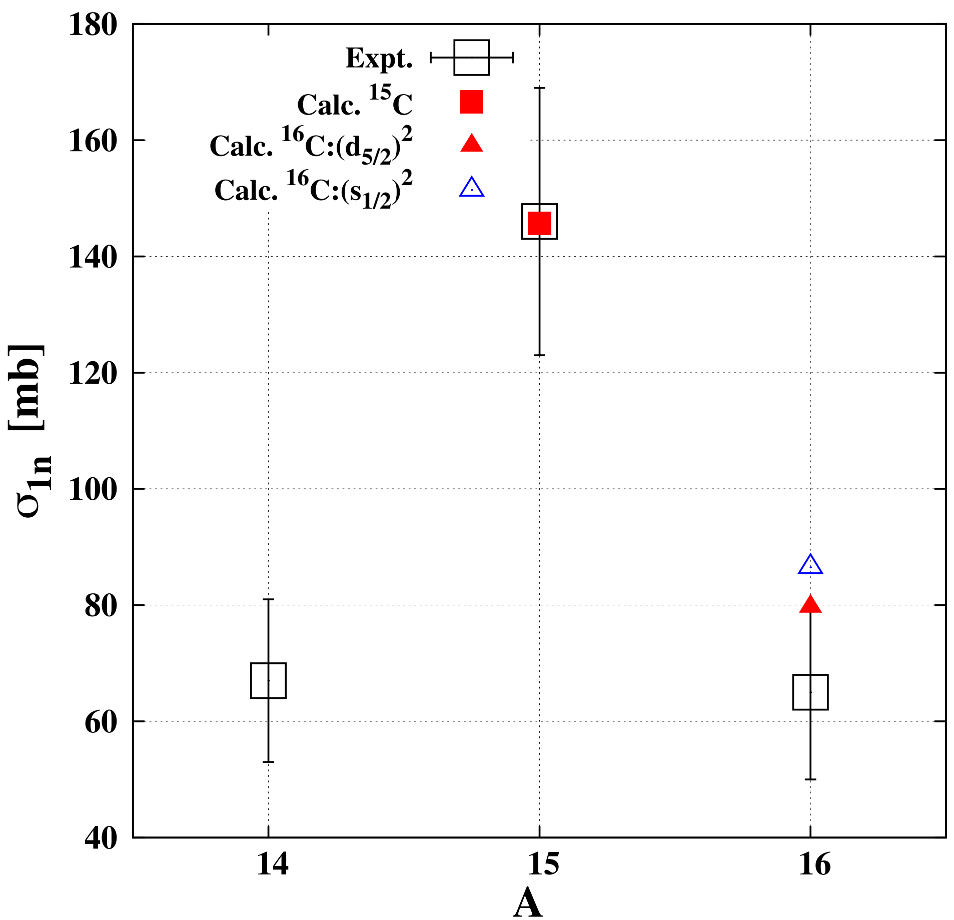
$$\sigma(^{16}C \rightarrow {}^{15}C) = P_{1/2^+}\sigma_{1n-str} + P_{5/2^+}\sigma_{1n-str}$$

Probability of ground and excited states of ^{15}C in ^{16}C

$$P_{1/2^+} = \left| \left\langle \phi_{1/2^+}(^{15}C) \middle| \Phi(^{16}C) \right\rangle \right|^2 = \alpha^2$$

$$P_{5/2^+} = \left| \left\langle \phi_{5/2^+}(^{15}C) \middle| \Phi(^{16}C) \right\rangle \right|^2 = \beta^2$$

1-neutron Removal of ^{15}C & ^{16}C



Expt. Yamaguchi et al., NPA724, 3. Zheng et al., NPA709, 103.

ERT and CDCC well reproduce 1n removal cross sections of ^{15}C and ^{16}C

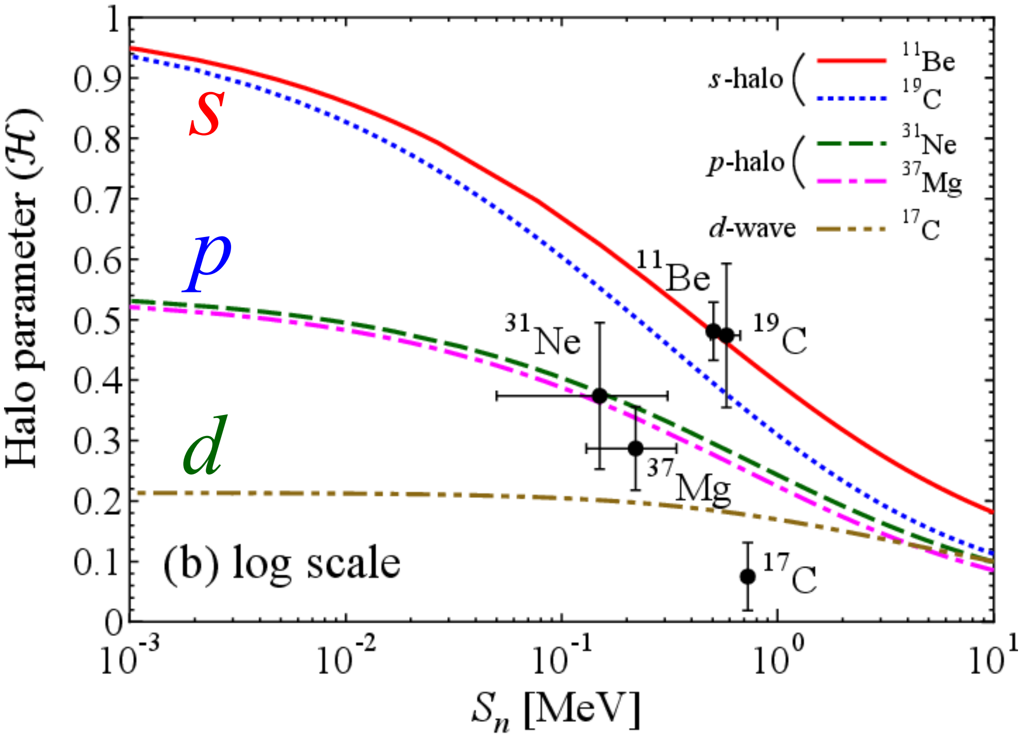
Experimentally, $\sigma_{1n}(^{15}C_{1st})$ is larger than $\sigma_{1n}(^{15}C_{g.s})$.

1. Yamaguchi et al., NPA724,3.
2. Terry et al., PRC69 054306.

$(d_{5/2})^2$ configuration in ^{16}C is preferred.

Yahiro, Watanabe, Toyokawa, TM, PRC93, 064609 (2016)

Halo parameter $\mathcal{H}$



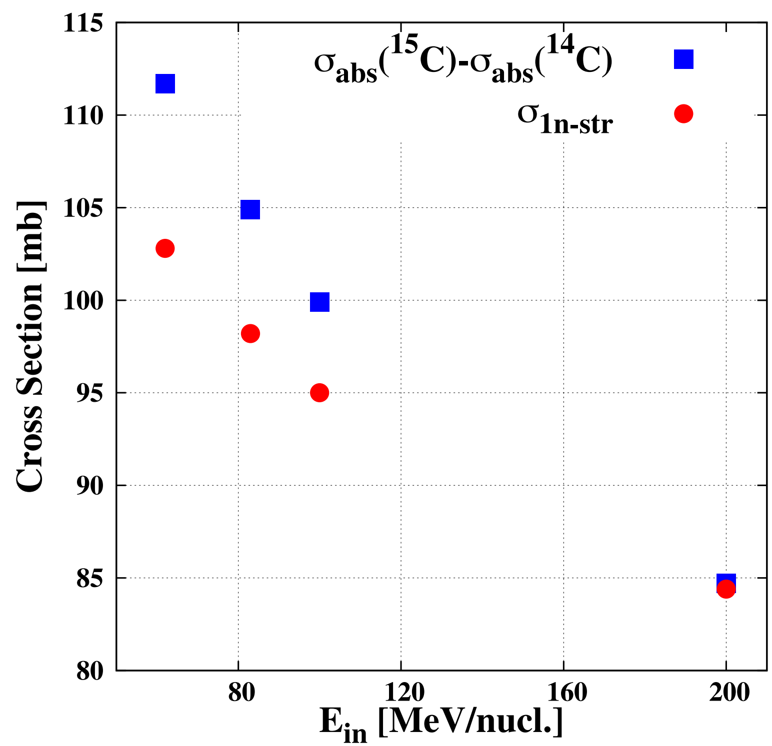
New definition of $\mathcal{H}$ with $\sigma_{1n\text{-}str}$

$$\mathcal{H} \approx \frac{\sigma_{1n-str}}{\sigma_{abs}(n)}$$

Watanabe (Monday)

$$\mathcal{H} = \frac{\sigma_{abs}(^{15}C) - \sigma_{abs}(^{14}C)}{\sigma_{abs}(n)}$$

$$\sigma_{1n-str} \approx \sigma_{abs}(^{15}C) - \sigma_{abs}(^{14}C)$$



Summary

- ***We investigate halo (^{15}C) and neighboring nuclei (^{14}C,^{16}C) with core + neutron(s) model.***

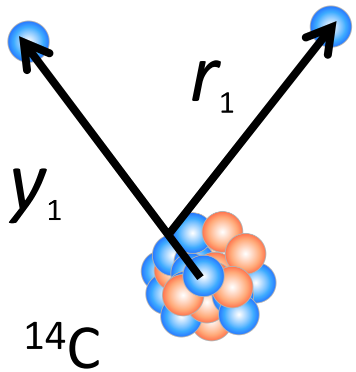
- ***For analyses of σ_R and σ_{1n}, we found main configuration of the ground state of ^{16}C is $(d_{5/2})^2$.***

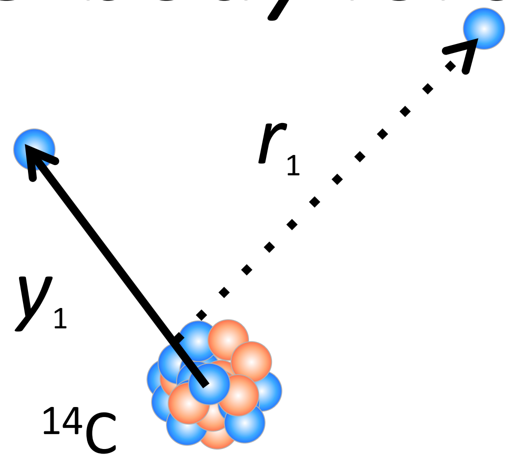
- ***ERT and CDCC calculations well reproduce one-neutron removal cross sections of ^{15}C and ^{16}C.***

- ***Future work***

✓ ***Calculation of two-neutron removal cross section***
✓ ***Other systems ($^{10\text{-}12}Be$, $^{18\text{-}20}C$, $^{30\text{-}32}Ne$)***

Phenomenological 3-body force





$$V_{nnc}(y_1, r_1 \rightarrow \infty) = 0$$

Volume Type Gaussian

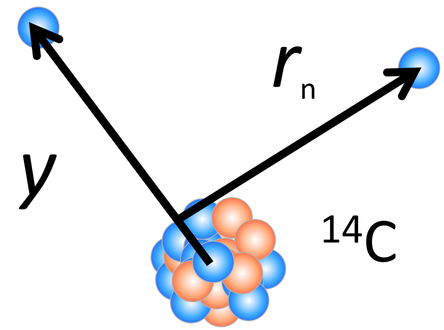
$$V_{nnc}^{(v)}(y_1, r_1) = V_0 e^{-y_1^2/y_0^2} e^{-r_1^2/r_0^2}$$

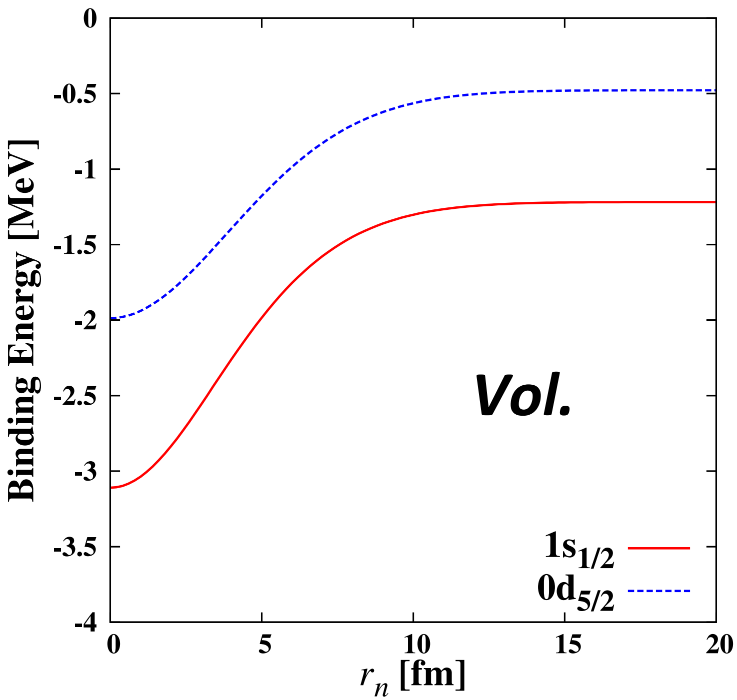
Surface Type Gaussian

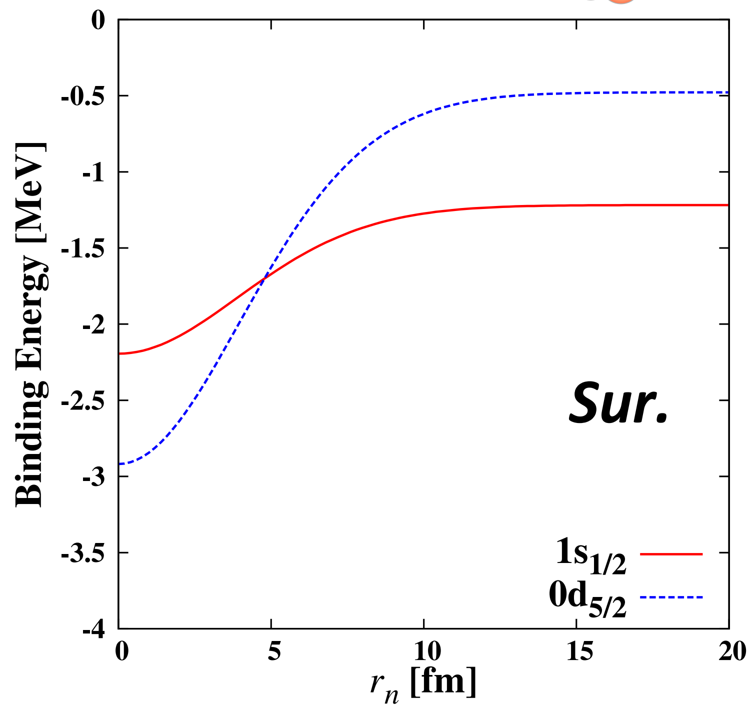
$$V_{nnc}^{(s)}(y_1, r_1) = V_0 y_1^2 e^{-y_1^2/y_0^2} e^{-r_1^2/r_0^2}$$

Effect of 3-body force

$$H_{15C}(r_n) = T_y + V_{nc}(y) + V_{nnc}(y, r_n)$$



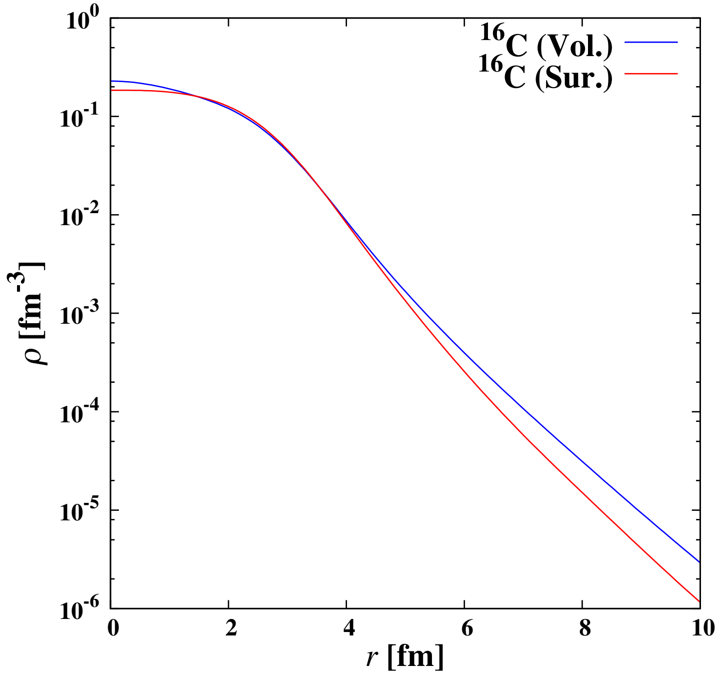




Strong d-wave mixing in ground state of ^{16}C with surface-type

Density of ^{16}C

Density distribution of ^{16}C



Type1: $\langle r_{rms} \rangle^{1/2} = 2.79$ fm

Type2: $\langle r_{rms} \rangle^{1/2} = 2.72$ fm

^{14}C-core : HFB calculation

- ✓ $\langle r_{rms} \rangle^{1/2}(^{14}C) = 2.51$ fm
- ✓ $\langle r_{rms} \rangle^{1/2}(^{15}C) = 2.87$ fm

Valence neutron density of ^{16}C