Study of Halo Nature via Reaction and Neutron Removal Cross Sections

Takuma Matsumoto, Shin Watanabe¹, Masakazu Toyokawa and Yahiro Masanobu
(Kyushu Univ., ¹RIKEN)

International Nuclear Physics Conference
Adelaide Australia, Adelaide Conventional Centre
11-16 September
Introduction

- **Halo nuclei**
  - Weakly bound neutron(s) in s- or p-wave orbit.
  - Large radius

- **Reaction cross section**
  - Enhancement of $\sigma_R$

- **Neutron removal cross section**
  - Enhancement of $\sigma_{1n}$

Villari et al., PLB268, 345, Fang et al., PRC69.034613.

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


Analysis of $^{15}\text{C}$ and $^{16}\text{C}$

Properties of one neutron halo $^{15}\text{C}$ and neighboring nucleus $^{16}\text{C}$ are investigated via analyses of reaction and neutron removal cross sections.

$^{15}\text{C}$: $^{14}\text{C} + n$ two-body model

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

$^{16}\text{C}$: $^{14}\text{C} + n + n$ three-body model

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

$V_{nn}$: BonnA

$V_{nnn}$: Phenomenological 3BF

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

1s$_{1/2}$+: -1.215 MeV
0d$_{5/2}$+: -0.478 MeV

[1] Hagino, and Sagawa., PRC75, 021301
Structure of $^{16}\text{C}$

Ground state wave function of $^{16}\text{C}$

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

✓ Probability of each configuration can be optimized with $V_{nnn}$.

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

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

✓ From analyses of reaction, we discuss which is better structure.
Three- and Four-Body Reactions

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

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

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

\[
\left[-\frac{\hbar^2}{2\mu} \nabla^2 + H^{16}_C + U_n + U_n + U_c - E\right] \Psi = 0
\]
Optical potentials of $n$-$T$ and $^{14}$C-$T$ are calculated by folding model with $g$ matrix based on $\chi$-EFT ($N^3LO$ 2BF, $N^2LO$ 3BF).

Toyokawa (Poster)

M. Toyokawa et al., PRC92, 024618 (2015)
Reaction Cross Section on $^{28}\text{Si}$

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

- For $^{16}\text{C}$, $\sigma_R$ of s-dominant is larger than $\sigma_R$ of d-dominant.
- $\sigma_R$ of d-dominant is well reproduce the odd-even deviation.
- Main configuration of valence two neutrons of $^{16}\text{C}$ is $(0d_{5/2})^2$.

Expt. Villari et al., PLB268, 345.
Eikonal Reaction Theory

- S-matrix in eikonal approximation
  \[ S = S_n S_c \]

- Stripping cross section (one neutron)
  \[ \sigma_n = \int db \langle \phi_0 | S_c |^2 (1 - |S_n|^2) | \phi_0 \rangle \]

- Eikonal Reaction Theory (ERT)

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

\[
\begin{bmatrix}
- \frac{\hbar^2}{2\mu_R} \nabla_R^2 + h_r + U_n(r, R) \\
- \frac{\hbar^2}{2\mu_R} \nabla_R^2 + h_r + U_c(r, R) - E
\end{bmatrix}
\begin{bmatrix}
\Psi(r, R)
\end{bmatrix}
= \begin{bmatrix}
0
0
\end{bmatrix}
\text{ for } S_n
\]

\[
\begin{bmatrix}
- \frac{\hbar^2}{2\mu_R} \nabla_R^2 + h_r + U_n(r, R) \\
- \frac{\hbar^2}{2\mu_R} \nabla_R^2 + h_r + U_c(r, R) - E
\end{bmatrix}
\begin{bmatrix}
\Psi(r, R)
\end{bmatrix}
= \begin{bmatrix}
0
0
\end{bmatrix}
\text{ for } S_c
\]

Hussein and McVoy NPA445, 124 (1985)
**1-neutron Removal of $^{15}$C & $^{16}$C**

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

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

Halo parameter $\mathcal{H}$

$$\mathcal{H} = \frac{\sigma_{\text{abs}}(c+n) - \sigma_{\text{abs}}(c)}{\sigma_{\text{abs}}(n)} \approx \frac{\sigma_R(c+n) - \sigma_R(c)}{\sigma_R(n)}$$

✓ Extrapolation of $\mathcal{H}$ to $S_n = 0$ with Glauber model.
Halo parameter $\mathcal{H}$

$$\mathcal{H} = \frac{\sigma_{abs}(c+n) - \sigma_{abs}(c)}{\sigma_{abs}(n)} \approx \frac{\sigma_R(c+n) - \sigma_R(c)}{\sigma_R(n)}$$

- Extrapolation of $\mathcal{H}$ to $S_n=0$ with Glauber model.
- We can separate neutron orbit at $S_n=0$.
- $\mathcal{H}$ of s-wave halo becomes 1 at $S_n=0$. 
$\mathcal{H}$ defined by $\sigma_{1n-str}$

✓ Glauber model approx.

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

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

$$\mathcal{H} \approx \frac{\sigma_{1n-str}}{\sigma_R(n)}$$
We investigate halo ($^{15}$C) and neighboring nuclei ($^{14}$C,$^{16}$C) with core + neutron(s) model.

For analyses of $\sigma_R$ and $\sigma_{1n}$, 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.

New definition of Halo parameter.

Future work

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