Determination of $^8\text{B}(p,\gamma)^9\text{C}$ Reaction Rate from $^9\text{C}$ Breakup

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### Introduction

The process \( ^8\text{B}(p, \gamma)^9\text{C} \) is significant in understanding the nuclear fusion reactions that occur in the Sun's core. This reaction is part of the proton-proton chain, which plays a crucial role in the energy production of stars and is also connected to the CNO cycle.

The CNO cycle involves the following sequence of reactions:

\[
^8\text{B}(p, \gamma)^9\text{C}(\alpha, p)^{12}\text{N}(p, \gamma)^{13}\text{O}(\beta^+ \nu)^{13}\text{N}(p, \gamma)^{14}\text{O}
\]

\[
\text{and } \quad ^{12}\text{C}(^9\text{C}, p^8\text{B})^{12}\text{C}
\]
**Introduction**

Eλ transition cross section

\[ \sigma_{E\lambda} \propto \left| \left\langle I(r) \left| \hat{O}_{E\lambda}(r) \right| \psi_{pB}(r) \right\rangle \right|^2 \]

Overlap function

\[ I(r) \equiv \left\langle \phi_C(r, \xi_p, \xi_B) \left| \phi_p(\xi_p)\phi_B(\xi_B) \right\rangle \right. \quad I(r) \xrightarrow{\ r \gg r_N \ } CW(r) \]

- If \( b_p \) is large, there will be no Breakup because of the short-range property of Nuclear interaction.
- If \( b_B \) is small, there will be no Breakup because of the absorption.

Determine the \( C \) from Breakup reaction:

\[ ^{12}\text{C}(^9\text{C},p^8\text{B})^{12}\text{C} \]

**Peripheral Reaction !!**
Ground state wave function

$$
\phi_{C}^{g.s.}(r) = \sum_{S=3/2,5/2} \frac{\varphi_{g.s.}(r)}{r} \left[ [\eta_{1/2} \otimes \Phi_{2}]_{S} \otimes Y_{1}(\hat{r}) \right]_{3/2,J_z}
$$

Resonance state wave function

$$
\phi_{C}^{\text{res}}(r) = \frac{\varphi_{\text{res}}(r)}{r} \left[ [\eta_{1/2} \otimes \Phi_{2}]_{3/2} \otimes Y_{1}(\hat{r}) \right]_{1/2,J_z}
$$

S conservation

$$
\sigma_{BU} = \sigma_{\text{exp}}^{(3/2)} \sigma_{BU}^{(3/2)} + \sigma_{\text{exp}}^{(5/2)} \sigma_{BU}^{(5/2)}
$$

D.R. Tilley et al.
3-body Schrödinger eq.

\[(H_{3b} - E)\Psi(r, R) = 0\]

\[H_{3b} = T_r + V_{pB} + T_R + U_{pC} + U_{BC}\]

CDCC wave function

\[\Psi(r, R) = \phi_0\chi_0 + \int_0^\infty \phi_k\chi_k dk\]

\[\Psi^{CDCC}(r, R) = \sum_{i}^{i_{\text{max}}} \hat{\phi}_i \hat{\chi}_i\]
\( ^9\text{C} \)

- \( s, p, d, f \) - waves
- \( k_{\text{max}} = 0.6 \text{ [fm}^{-1}] \) (\( E_{\text{rel-max}} \sim 7.7 \text{ [MeV]} \))
- \( \Delta k = 0.05 \text{ [fm}^{-1}] \)

- \( V_{pB} \) : Woods-Saxon pot. reproducing B.E. (-1.3 MeV) & resonance

Distorting pot. : full microscopic folding model

- \( U_{pC} = \int \rho_\text{C}(\mathbf{r}_2) \sum_{i \in \text{C}} g_i d\mathbf{r}_2 \)
- \( U_{BC} = \int \rho_\text{B}(\mathbf{r}_1) \rho_\text{C}(\mathbf{r}_2) \sum_{i \in \text{B}, j \in \text{C}} g_{ij} d\mathbf{r}_1 d\mathbf{r}_2 \)

\[ \begin{pmatrix} \text{NN interaction} & g_{ij} \text{ : Melbourne } g\text{-matrix} \\ \rho_\text{B}, \rho_\text{C} \text{ : Hartree-Fock calc. with Gogny D1S} \end{pmatrix} \]
Result

Nuclear/Coulomb BU Effects

$^{12}\text{(C, }\text{p}^8\text{B)}^{12}\text{C at 65 MeV/A}$

\[ S = \frac{3}{2} \]

\[ S = \frac{5}{2} \]

\[
\begin{align*}
\text{d}E/\text{d}E_{rel} [\text{mb/MeV}] & \quad 0 & \quad 1 & \quad 2 & \quad 3 \\
E_{rel} [\text{MeV}] & \quad 0 & \quad 1 & \quad 2 & \quad 3 \\

\text{d}\sigma/\text{d}\theta_{\text{lab}} [\text{mb/deg}] & \quad 0 & \quad 50 & \quad 100 & \quad 150 \\
\theta_{\text{lab}} [\text{deg}] & \quad 0 & \quad 5 & \quad 10 & \quad 15
\end{align*}
\]
Our CDCC calculation reproduces well the shape of breakup energy spectrum.

ANC: \((C_{3/2})^2 = 0.115 \text{ [fm}^{-1}\text{]}\), \((C_{5/2})^2 = 0.247 \text{ [fm}^{-1}\text{]}\), \(S_{18} = 12 \pm 1 \text{ [eV-b]}\).

There is strong interference between Nuclear & Coulomb breakup.
Result

Double Differential Cross Section

$\frac{d^2\sigma}{dE d\Omega_9}$ [mb/(MeV sr)]

$^{12}\text{C}(^{9}\text{C}, p^{8}\text{B})^{12}\text{C}$ at 65 MeV/A
Result

Coulomb BU Multistep Effects

12C(9C, 8B)12C at 65 MeV/A

E_{rel} [MeV]

\frac{d\sigma}{dE_{rel}} [mb/MeV]

$S = \frac{3}{2}$

\frac{d\sigma}{d\theta_\theta} [mb/deg]

$S = \frac{3}{2}$

$S = \frac{5}{2}$

$S = \frac{5}{2}$
Three “new” aspects of our $S_{17}$ paper

— KO, Hashimoto, Iseri, Kamimura, and Yahiro, PRC73, 024605 (2006).

2) Reduction from 4-body breakup to 3-body breakup

- The triple-differential cross section for $(^8B, ^7Be+p)$ is obtained by $C\rho |T|^2$ with $\mathcal{F} = \langle \chi_1 \chi_7 \phi_7^{(0)} | U_{A3} + U_{A4} + U_{A1} + V_{13} + V_{14} | \Psi_{4\text{-body}} \rangle$

- $^7$Be breakup cross section by $^{208}$Pb turned out to be negligibly small for forward-scattering.

$$
\begin{align*}
U_{A3} + U_{A4} &\approx \langle \phi_7^{(0)} | U_{A3} + U_{A4} | \phi_7^{(0)} \rangle \\
V_{13} + V_{14} &\approx \langle \phi_7^{(0)} | V_{13} + V_{14} | \phi_7^{(0)} \rangle
\end{align*}
$$
$^8$B scattering from $^9$Be at 100 A MeV
$^8$B Energy levels
Structure model

✓ Hartree-Fock method with finite-range Gogny force

It is applicable to obtain the ground-state wave function of all nuclei.

The properties of many stable nuclei such as the binding energy are well reproduced.

We find that this method is reliable.
核半径 $({^6\text{He}}, {^8\text{He}})$