Measurements of $^{13}\text{C} + ^{12}\text{C}$ and $^4\text{He} + ^{64}\text{Zn}$ fusion cross section at deep sub-barrier energies in IFIN-HH

D. Tudor

Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, Bucharest, Romania

12.09.2018 - 14.09.2018 @ Atomki, Debrecen
Nuclear physics in stellar explosions Workshop '18
Outline

➢ Introduction

➢ Motivation

➢ $^{12}C(^{13}C, p)^{24}Na, and ^{64}Zn(\alpha, p)^{64}Ga$ reactions

➢ Results

➢ Conclusions
Introduction

The origin of chemical elements in the Universe:
➢ Big Bang Nucleosynthesis
➢ Stellar Nucleosynthesis

Nuclear Physics for Astrophysics (NPA) - to determine reaction rates in the stars

\[
\langle \sigma v \rangle = \left( \frac{8}{\pi \mu} \right)^{1/2} \left( \frac{1}{(kT)^{3/2}} \right) S(E_0) \int_0^\infty e^{-\frac{E}{kT} - \frac{b}{E^{1/2}}} dE
\]

\( E_0 \) is the Gamow energy

\( E_0 = \left( \frac{bkT}{2} \right)^{2/3} = 1.22(Z_1^2Z_2^2\mu T_6^2)^{1/3} \text{ keV} \)

\( \Delta \) is the energy window width

\[
\Delta = \frac{4}{3^{1/2}} (E_0 kT)^{1/2} = 0.749(Z_1^2Z_2^2\mu T_6^5)^{1/6} \text{ keV}
\]

Figure 1. Gamow peak, the region where reactions relevant for nuclear astrophysics occur. Claus E. Rolfs and William S. Rodney [1].
Motivation

Possibility for direct nuclear astrophysics measurements induced by light ions at IFIN-HH, with:
- high currents
- 3 MV Tandetron accelerator!
- stability of beam energies
- appropriate energy range

Main problems in direct measurements are:
- low reaction cross sections
- high radiation background

Despite this, we benefit of an Ultra low background at µBq laboratory placed in Unirea salt mine!

- Low background laboratory: GammaSpec
- NAG (Nuclear Astrophysics Group) laboratory in IFIN-HH
The $^{13}\text{C} + ^{12}\text{C}$ Experiment

- **Important reaction in nuclear astrophysics:** $^{12}\text{C} + ^{12}\text{C}$ (carbon burning scenario)

- Very difficult to measure, cross section fluctuating due to resonances!

No resonances observed in $^{13}\text{C} + ^{12}\text{C}$!

Obs: for most energies, the $^{12}\text{C} + ^{12}\text{C}$ cross sections are suppressed!

- Only at resonant energies, the $^{12}\text{C} + ^{12}\text{C}$ cross sections match with those of $^{12}\text{C} + ^{13}\text{C}$ and $^{13}\text{C} + ^{13}\text{C}$!

- Proposed tests using $^{13}\text{C} + ^{12}\text{C}$, measured in the Gamow window.

Therefore, the study of $^{13}\text{C} + ^{12}\text{C}$ in the Gamow energy region would be useful to understand the reaction dynamics at such low energies

---

**Figure 2. Modified astrophysical S factor**

NPSE Workshop Atomki, Debrecen
The $^{13}$C+$^{12}$C Experiment

- $^{13}$C beam energy 11 – 4.6 MeV ($E_{cm}=5.3 – 2.2$ MeV), in steps of 0.2 MeV

<table>
<thead>
<tr>
<th>Canalul de iese</th>
<th>$E_{\gamma}$ [keV]</th>
<th>$\epsilon_{\gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{21}$Ne + $\alpha$</td>
<td>350.7</td>
<td>0.182%</td>
</tr>
<tr>
<td>$^{23}$Na + $p\alpha$</td>
<td>439.9</td>
<td>0.199%</td>
</tr>
<tr>
<td>$^{24}$Na + $p$</td>
<td>472.2</td>
<td>0.205%</td>
</tr>
<tr>
<td>$^{24}$Mg + $n$</td>
<td>1368.63</td>
<td>0.287%</td>
</tr>
</tbody>
</table>

$^{12}$C ($^{13}$C, $p$) $^{24}$Na

NPSE Workshop Atomki, Debrecen
µBq laboratory

NPSE Workshop Atomki, Debrecen
Cross section determination

The cross sections were determined starting from the experimental yields:

\[
Y(E) = \int_{0}^{E} \sigma(E) \frac{dx}{dE} \frac{N_A}{A_t} dE
\]

\[
\Lambda = \frac{N_{ydet}}{\epsilon_y I_y} \frac{\lambda e^{-\lambda \Delta t}}{(1 - e^{-\lambda t_{max}})}
\]

\[
Y(E) = \frac{\Lambda}{I_{t*\Delta t}}
\]

\[
I = \sum_{t_0}^{t_f} I(t) e^{-\lambda (t_f - t)} \Delta t
\]

Last step was the determination of experimental cross section:

\[
\sigma(\tilde{E}) = \frac{Y(E + \Delta E) - Y(E)}{n_t} \cdot 10^{24} b
\]

NPSE Workshop Atomki, Debrecen
Cross section determination

\[ \sigma (13C, p)^{24}Na \]

NPSE Workshop Atomki, Debrecen
The $^{64}\text{Zn}(\alpha,p)^{67}\text{Ga}$ reaction

- Natural zinc targets
- $E_{lab}$ between 5.4 – 8 MeV in steps of 0.2 and 0.25 MeV
- Beam current: 0.5 – 0.65 µA

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Product isotope</th>
<th>Half-life</th>
<th>$E_\gamma$ [keV]</th>
<th>Relative Intensity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{64}\text{Zn}(\alpha,p)$</td>
<td>$^{67}\text{Ga}$</td>
<td>3.26 d</td>
<td>184.6</td>
<td>21.41 ± 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>209.0</td>
<td>2.46 ± 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300.2</td>
<td>16.64 ± 0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>393.5</td>
<td>4.56 ± 0.24</td>
</tr>
</tbody>
</table>
Activation measurements. Preliminary results

\[ S(E) = \sigma(E) \ast E \ast \exp(2\mu\eta) \]

The astrophysical S(E) factor of experimental data obtained from \(^{64}\text{Zn} \, (\alpha, \text{p}) \, ^{67}\text{Ga}\), \(^{64}\text{Zn} \, (\alpha, \text{n}) \, ^{67}\text{Ge}\), \(^{64}\text{Zn} \, (\alpha, \gamma) \, ^{68}\text{Ge}\) reaction channels in comparison with theoretical results [9, 10].
Conclusions

- We studied the $^{12}$C($^{13}$C,p)$^{24}$Na and $^{64}$Zn(α,p)$^{67}$Ga fusion reactions in the energy range $E=4.6-11$ MeV and $E=5.4-8$ MeV respectively.

- Measurements in different setups: NAG, GammaSpec and μBq are consistent.

- Activities of the irradiated targets measured both in the underground and surface laboratory allowed to determine the lowest cross sections of the order of 100 pb for $^{12}$C($^{13}$C,p)$^{24}$Na and 30 nb for $^{64}$Zn(α,p)$^{67}$Ga.

- We extended the range of measurements down into the Gamow windows, with the important conclusion that the Hindrance model does not work for 13C+12C.
Many thanks to:


and

N.T. Zhang, X. Tang, H. Chen (IMP - Lanzhou, China)

Acknowledgements

- PNIII Grant NUCASTRO2
- The ChETEC Cost Action (CA16117) for support at this meeting.
References

Thank you!