3.8 Analysis of Low Energy Proton Capture Cross Section for Light Nuclei

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Proton capture cross sections of D, 6,7Li, 9Be, 10,11B, 12C, 14N and 16O in the incident energy region from 1 keV to 10 MeV were analyzed with direct reaction model for Deuteron and with resonance formula for other nuclides.

1. Introduction
For astrophysical estimation of stellar nucleosynthesis and hydrogen consumption in astrophysical environments, low energy proton capture cross sections for light nuclides are crucially important. In the present study, the experimental cross sections compiled in NACRE file1) and other published data were analyzed for target nuclides D, 6,7Li, 9Be, 10,11B, 12C, 14N and 16O in the incident proton energy region of 1keV to 10 MeV. The calculated cross sections will be used to calculate the astrophysical S factors and reaction rates.

2. Method
For Deuteron, analysis was made with the inverse reaction 3He(γ,p)D analysis formula given by Gunn and Irvng2). They give the cross section formula of the 3T(γ,n)D reaction using an exponential type wave function. The formula was converted to the cross section of the 3He(γ,p)D reaction by replacing the Q-value and Coulomb barrier penetration factors. For the barrier penetration factor calculation, orbital angular momentums of the emitted protons were assumed to be s-wave and p-wave and their mixing ratio was determined to reproduce the experimental cross section comparing with calculated inverse cross section.

For other nuclides, analyses were made with an approximated R-matrix resonance formula3) given by

$$\sigma_{γγ}(E) = \frac{\pi}{k^2} \sum_{Jr} \frac{(2J + 1)}{2(2I + 1)} |U_{Jr}|^2 ,$$

with
\[ U_{jr} = \sum_{\lambda} \frac{i \Gamma_{jr}^{1/2} \Gamma_{jr}^{1/2}}{1 + \sum_{\lambda} \left( \Delta_{\lambda} - i \Gamma_{\lambda} / 2 \right) / (E_{\lambda} - E)} \text{ and } \Gamma_{jr} = 2P_j(E) \gamma_{\lambda}^2, \]

where \( \lambda \) designates a resonance level and includes spin-parity \( J^\pi \) and isospin \( \tau \), and other symbols are same as that of R-matrix theory by Lane and Thomas\(^4\).

The initial resonance parameters were obtained from the compilation "Energy Levels of Light Nuclei"\(^5\) and adjusted to reproduce experimental cross sections.

3. Results

Results of present analysis are shown in Fig.1 to Fig.9, comparing with experimental cross sections. Solid lines show the calculated cross section of the present analysis.

Figure 1 shows the \( ^{12}\text{C}(p,\gamma)^{13}\text{N} \) reaction cross section. Experimental data exist in the energy region of \( E_p(\text{cm}) = 10 \text{keV} \) to \( 22 \text{MeV} \).

Figure 2 shows the \( ^{11}\text{B}(p,\gamma)^{12}\text{C} \) reaction cross section analyzed with 12 resonances. In the energy region below \( E_p(\text{cm}) = 0.3 \text{MeV} \), experimental data would exist, but not available presently, so, in this region, cross section was calculated using resonance parameters given in ref. 5).

Figure 6 shows results of the \( ^{11}\text{B}(p,\gamma)^{12}\text{C} \) reaction analyzed with 12 resonances. The experimental data in the energy region of \( E_p = 1.5-3 \text{MeV} \) are deduced from the differential cross sections of \( (p,\gamma) \) at \( 0^\circ \) and \( 90^\circ \) measured by Rolfs and Azuma\(^6\). And
the data of $E_{p}>9\text{MeV}$ are $(p,\gamma_{0})$ cross section measured by Measday and Hasinoff\textsuperscript{7}), which almost agree with the $(p,\gamma)$ activation cross section measured by Hill et al.\textsuperscript{8}).

Figure 8 shows results of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction analyzed with 22 resonances. There are experimental data of the $(p,\gamma_{0})$ reaction in some energy regions above $E_{p}=1\text{MeV}$. Taking into account the structure of these data, cross sections were reproduced adjusting the resonance parameters given in ref. 5).

Figure 9 shows results of the $^{16}\text{O}(p,\gamma)^{17}\text{F}$ reaction analyzed with 8 resonances including a negative resonance which corresponds to the excited state of $^{17}\text{F}$ ; $E_{x}=0.4956\text{MeV}, J^{\pi} = 1/2^{+}$.

4. Conclusion

Low energy proton capture cross sections were reproduced well with simple formula for Deuteron, and with resonance formula for $^6\text{Li}$, $^9\text{Be}$, $^{10,11}\text{B}$, $^{12}\text{C}$, $^{14}\text{N}$ and $^{16}\text{O}$. In some literatures\textsuperscript{5,9}), smooth parts of cross section were explained to be caused by direct capture reaction, however, there are many cases which show interference with some resonances, and it was found that the smooth parts and the interferences were explained also by tails originated in some distant resonances of broad width, say giant resonance, and/or by negative resonances.

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References
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Fig. 1  Proton capture cross section of $^1$H

Fig. 2  Proton capture cross section of $^6$Li

Fig. 3  Proton capture cross section of $^7$Li

Fig. 4  Proton capture cross section of $^9$Be

Fig. 5  Proton capture cross section of $^{10}$B

Fig. 6  Proton capture cross section of $^{11}$B
Fig. 7  Proton capture cross section of $^{12}$C

Fig. 8  Proton capture cross section of $^{14}$N

Fig. 9  Proton capture cross section of $^{16}$O