Measurement of the Excitation Function of the $^{1}H(^{19}F,\ ^{12}C_{gs})^{8}Be$ Reaction

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In order to see whether the $^{12}C(^{8}Be, p)^{19}F$ reaction can play any significant role for synthesizing ^{19}F in the thermonuclear reaction process of a He-burning star, we measured the excitation function of this reaction through the inverse reaction around the coulomb barrier energy of the $^{12}C+^{8}Be$ channel.

1. Introduction

An ivestigation of the $^{19}F(p, ^{8}Be)^{12}C$ reaction has not been reported previously except a brief note [1] on the observation of resonances. The reason for measuring the excitation function of this rather exotic reaction is to see whether the inverse reaction of this can have any contrilution to necleosynthesis of ^{19}F in a thermonuclear reaction process of a He burning star. In a standard nucleosynthesis calculation elemental abundance of ^{19}F could barely be reproduced by many orders of magnitude less than the solar abundance. Recently a neutrino process in a core-colapse supernova was predicted [2] to be important for transmuting various elements and to modify the elemental abundance of the traditional necleosynthesis. And the solar abundance of ^{19}F was ascribed to this neutrino process. Although the neutrino process is quite interesting, experimental verification of its prediction is extremely difficult and it appears to remain as a hypothetical precess. Thus we looked for an alternative possibility of ^{19}F synthesis.

The ground state of ^{8}Be is unstable against a two-α decay but within the stellar environment of high-temperature He-gas a certain amount of ^{8}Be can exist in chemical equilibrium with ^{4}He through the process $^{4}He+^{4}He \rightleftarrows ^{8}Be$ because the Q-value of the two-α decay is only about 90 keV. Such ^{8}Be further initiate the equilibrium process $^{8}Be+^{4}He \rightleftarrows ^{12}C^{*}$ and is believed to play the key role for synthesizing heavier elements than $A=8$ in stars. Accordingly in a He-burning star a ^{12}C-core grows up gradually. At the interface between the C-core and the outer He-shell it might be possible to synthesize ^{19}F through the $^{12}C(^{8}Be, p)^{19}F$ reaction.

2. Experimental Procedure

The measurement of the excitation function of the $^{1}H(^{19}F, ^{12}C_{gs})^{8}Be$ reaction was done using the tandem accelerator at Kyushu University. Since ^{8}Be detection is not an easy task,

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especially at low energies, we chose to detect the counterpart ^{12}C. Also we adopted inverse kinematics, that is, we used ^{19}F beam and proton target. By doing this outgoing ^{12}C energy is boosted up and particle identification becomes much easier. The excitation functions were measured at energies from $E_{lab}(^{19}\mathrm{F})=40$ to 70 MeV insteps of 0.5 MeV and laboratory angles of $\theta_{lab}=9^\circ$ and 11°. As for proton targets we used mylar sheet (1.5μm thick). Compared to polyethylene sheet, mylar sheet withstood longer time to beam bombardment without breaking. But in order to prevent rapid target deterioration, we have to lower the intensity of ^{19}F-beam less than about $0.5 pnA/mm^2$. Hydrogen content in the target decreased rapidly at the beginning 2～3 μC of accumulated beam bombardment but afterwards the decreasing tendency slowed down. And up to about 20 μC of beam bombardment target surface remained whthout breaking. We moved the target position slightly after each run (10 μC of beam charge was accumulated) and renewed the target surface for the next run.

Reaction products were detected by a gas ΔE-E counter telescope, whose total gas legth was 30cm, out of which 3cm was used as ΔE section. The counter was filled with 300mbar of P-10 gas.

3. Results and Discussion

A typical ΔE-E_{total} scatter plot obtained at $E_{lab}(^{19}\mathrm{F})=70$ MeV and $\theta_{lab}=9^\circ$ is shown in Fig. 1. Localized events seen on the $Z=6$ and 8 lines correspond to the products coming from the ^{1}H(^{19}F, $^{12}C_{gs}$)^{8}Be and ^{1}H(^{19}F, ^{16}O$_{gs}$)^{4}He reactions, respectively, emitted at backward angles in the CM frame. Because of the inverse kinematics employed the corresponding events in the forward CM angles also exist in this plot but they are masked by other contaminant reactions due to carbon and oxygen in the target, such as recoil carbons from elastic and inelastic scatterings. Absolute cross sections of the ^{1}H(^{19}F, $^{12}C_{gs}$)^{8}Be reaction were determined by normalizing to the yields of the ^{1}H(^{19}F, ^{16}O$_{gs}$)^{4}He reaction whose cross sections were well stud-

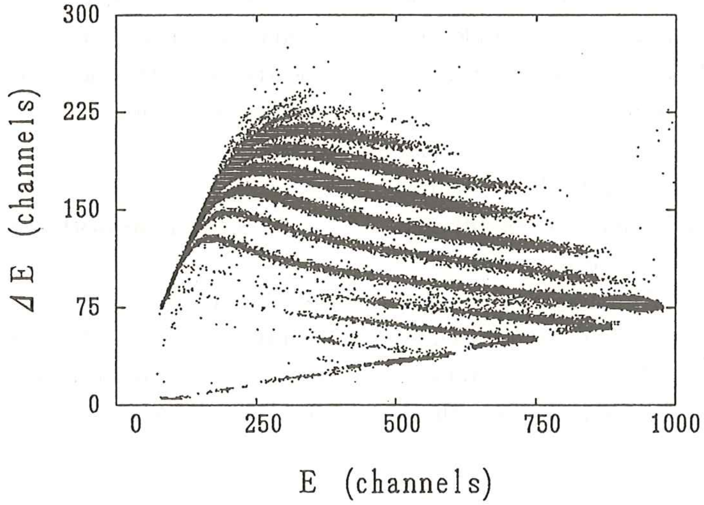

Fig. 1 A typical ΔE-E scatter plot for the reaction ^{19}F+mylar at $E_{lab}(^{19}\mathrm{F})=70$MeV and $\theta_{lab}=9^\circ$ measured by the gas ionigation chamber.

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Fig. 2 shows the resulting excitation function measured at $\theta_{lab}=9°$ and corresponding to backward CM angles, which move with beam energy slightly. Angular range of this variation within the beam energy of the experiment is indicated in the figure. The two laboratory angles adopted (9° and 11°) are 13° apart in average seen from the CM frame. The excitation functions at these two angles were almost parallel. The events corresponding to forward CM angles were simultaneously observed but as described before they were contaminated by large backgrounds and thus their yields could not be determined reliably. Still we tried to estimate the forward CM angle yields, which proved to be nearly the same as the backward yields. Thus angular anisotropy appears not large.

We have compared the observed cross sections with the statistical compound nuclear calculation using the Hauser-Feshbach formula. A solid line in Fig. 2 shows the result of this calculation. This curve is suitably normalized to the experimental data, which are about 1/3 of the calculated values. Although absolute cross sections could not be reproduced by the H-F calculation, average trend of the excitation function looks to be well fitted.

Since angular anisotropy was not very large seeing from the four CM-angle data, we determined angle integrated cross sections simply by multiplying 4π to the observed differential cross sections at $\theta_{lab}=9°$. They were then converted to the cross sections of the inverse reaction using the detailed balance. From the resulting cross sections we calculated the astrophysical S-factors of the $^{12}C(^8Be, p)^{19}F_{g.s.}$ reaction based on the equation

$$S(E)=E\sigma(E)\exp\left(\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right), \tag{1}$$

where $\sigma(E)$ is the angle integrated cross section at relative kinetic energy E of the entrance channel. Z_1 and Z_2 are atomic numbers and v is the relative velocity of the two nuclei in the entrance channel. The result is shown in Fig. 3.

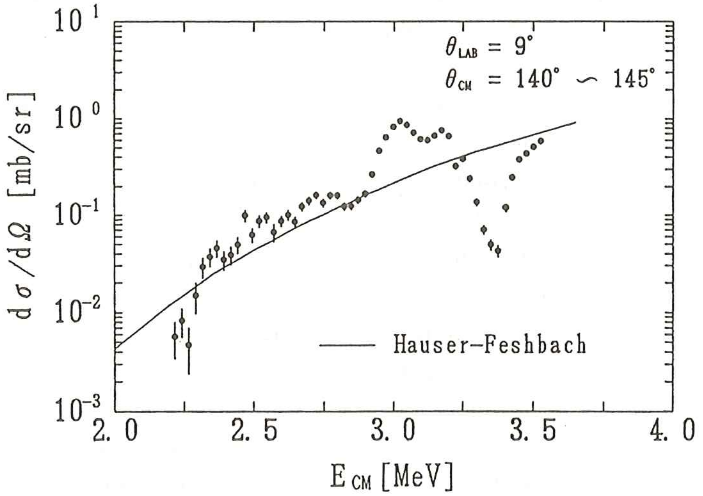

Fig. 2 The measured excitation function of the $^1H(^{19}F, {}^{12}C_{g.s.})^8Be_{g.s.}$ reaction observed at $\theta lab=9°$ and corresponding to backward CM angles. A solid line is the Hauser-Feshbach cross section normalized to the experiment.

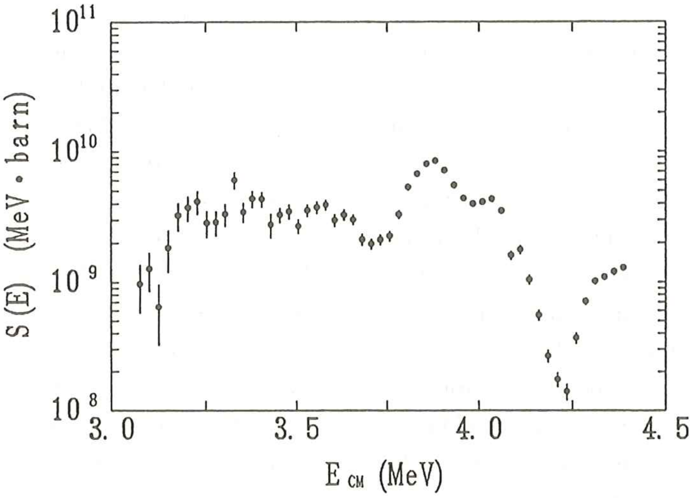

Fig. 3 Astrophysical S-factor of the $^{12}C(^{8}Be, p)^{19}F_{g.s.}$ reaction determined from the experiment.

From the astrophysical point of view, much lower energy data than this figure are needed. For example, at the temperature $T=5\times10^{8}K$ (bottom of burning helium shell is near this temperature [3]), the Gamow peak of the $^{12}C+^{2}Be$ channel is only about 1 MeV. Thus for the calculation of stellar reaction rate, we have to extraporate fairly down the cross secitons towards low energy in some reliable way. We did this extrapolation using the Hauser-Feshbach calculation. Fig. 4 shows the S-factor of the $^{12}C(^{8}Be, p)^{19}F_{g.s.}$ reaction obtained from the Hauser-Feshbach cross sections normalized to the experiment above $E_{CM}=3MeV$. Beacause of the negative Q-value ($Q=-0.86MeV$) of this reaction, the S-factor drops very steeply belew about $E_{CM}=1.5MeV$ and becomes zero at $E_{CM}=0.86MeV$. This is a great demerit of this reaction to be effective in stellar burning process.

Using the S-factor shown in Fig. 4, we further calculated the stellar reaction rate, which is given by σv averaged over the Maxwellian distribution of the relative velocity v of the colliding nuclei. The result is shown in Fig. 5 by a solid line. This reaction rate is only for production of the ground state of ^{19}F. The total reaction rate for ^{19}F must be 2～3 times larger than the ground state value because there are several low-lying excited states. Vertical scale is multiplied by the Avogadro number N_A. In this figure the reaction rate of the $^{12}C(\alpha, \gamma)^{16}O$ reaction obtained from the table given in ref [4] is also shown by a dashed line. Compared to this main He-burning reaction, the $^{12}C(^{8}Be, p)^{19}F$ reaction is very slow especially below $T=0.5\times10^{9}K$ ($T_9=0.5$). For obtaining the production rate of ^{19}F in stellar interier we have to multiply number densities of ^{12}C and ^{8}Be nuclei to the reaction rate. The equilibrium density of ^{8}Be can be estimated by the Saha equation. At $T_9=0.5$ and for helium density of $\rho_{He}=1000g/cm^{3}$, relative number density of ^{8}Be to ^{4}He becomes $n(^{8}Be)/n(^{4}He)\sim10^{-9}$. If we multiply this number density to the above reaction rate, we obtain that the relative production rate of ^{19}F and ^{16}O through the $^{12}C(^{8}Be, p)^{19}F$ reaction and the $^{12}C(\alpha, \gamma)^{16}O$ reaction, respec-

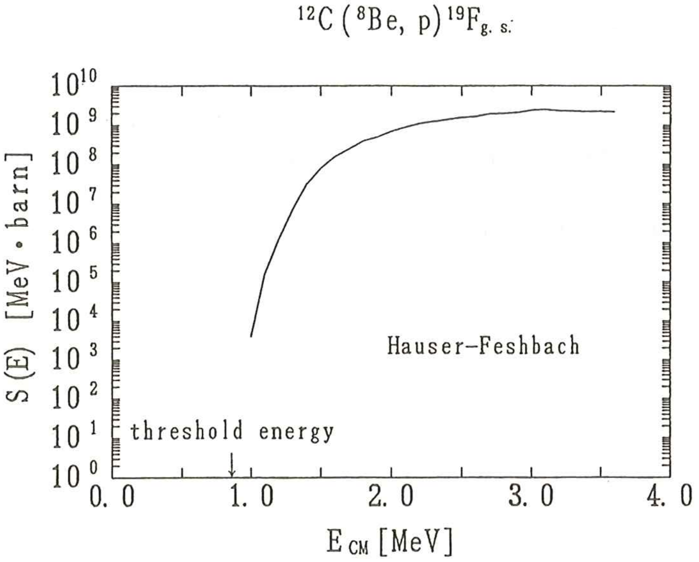

Fig. 4 Astrophysical S-factor of the $^{12}C(^8Be, p)^{19}F_{g.s.}$ reaction obtained by the Hauser-Feshbach calculation normalized to the experimental cross section.

tively, is the order of 10^{-15}. At lower temperatures this ratio becomes even smaller.

4. Conclusion

We calculated the astrophysical S-factor of the $^{12}C(^8Be, p)^{19}F$ reaction at stellar energies by extraporating down the experimental values and then obtained the production rate of ^{19}F through this reaction in stellar interier. It was found to be extremely small compared to the dominating reaction $^{12}C(\alpha, \gamma)^{16}O$ in a He-shell. But the synthesis of ^{19}F by other commonly accepted processes involves more complicated reaction sequences and their production rates are not large enough to explain the solar abundance. Thus it seems worthwhile to include the $^{12}C(^8Be, p)^{19}F$ reaction in a reaction network of the nucleosynthesis calculation and see its effect on ^{19}F production.

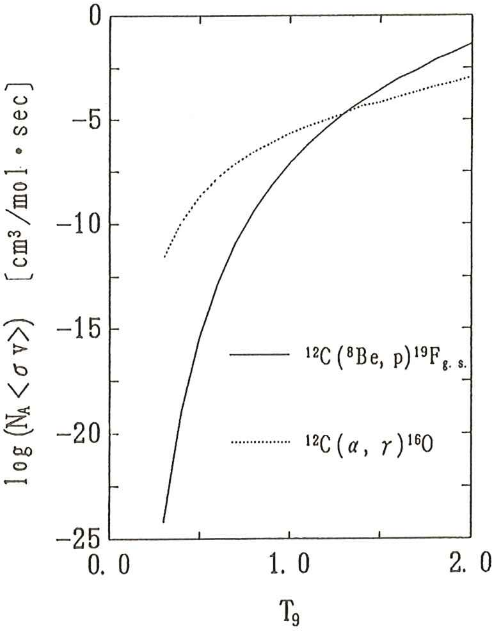

Fig. 5 Astrophysical reaction rate at stellar temperature. A solid line is for the $^{12}C(^8Be, p)^{19}F_{g.s.}$ reaction and a dashed line is for the ^{12}C $(\alpha, \gamma)^{16}O$ reaction.

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