Direct measurement of the $^{19}$F($p, \alpha\gamma$)$^{16}$O reaction in JUNA


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Abstract. The $^{19}$F($p, \alpha\gamma$)$^{16}$O reaction is of crucial importance for Galactic $^{19}$F abundances and CNO cycle loss in first generation Population III stars. Due to its extremely small cross sections, the $^{19}$F($p, \alpha\gamma$)$^{16}$O reaction has not been measured in the low energy part of the Gamow window (70-200 keV). As a day-one campaign, the experiment was performed under the extremely low cosmic-ray-induced background environment of the China Jinping Underground Laboratory (CJPL), one of the deepest underground laboratories in the world. The $\gamma$-ray yields were measured over $E_{\gamma} =$72.4–344 keV, covering the full Gamow window for the first time. The direct experimental data will help people to expound the fluorine over-abundances, energy generation, as well as heavy-element nucleosynthesis scenario in asymptotic giant branch (AGB) stars, with the astrophysical model on the firm ground.

1 Introduction

Fluorine is one of the most interesting elements in nuclear astrophysics, its astrophysical origin is puzzling. $^{19}$F can be produced in the convective zone triggered by a thermal pulse in asymptotic giant branch (AGB) stars [1, 2]. So far, however, the astronomically observed fluorine over-abundances cannot be understood by using current AGB models [3–6]. In AGB
stars, $^{19}\text{F}$ is readily annihilated by hydrogen via the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction [3, 7, 8]. Given its importance, a precise and complete measurement of the total cross section appeared desirable. The $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction occurs via three types of channels, i.e., $(p,\alpha_0)$, $(p,\alpha\pi)$ and $(p,\alpha\gamma)$, as shown in Fig. 1. The total reaction rate is dominated by the $(p,\alpha_0)$ and $(p,\alpha\gamma)$ channel [3]. For the $(p,\alpha\gamma)$ channel, the energy range of $E_{c.m.}>189$ keV has been studied which is much higher than the low energy edge of the Gamow window (70-350 keV) [9, 10]. In this paper, we report on the progress of a direct measurement of the $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$ reaction at Jinping Underground Nuclear Astrophysics experimental facility (JUNA). In the present work, the studies have been extended to $E_{c.m.}=72.4-344$ keV, the lowest to date. The results from present and previous work allow to calculate the reaction rates over a wide range of temperatures.

2 Experiment

The experiment was carried out on the JUNA accelerator at CJPL [11]. The experimental setup is similar to the one described in Ref. [2, 12]. The beam current was 1 mA for the low energy measurements. Two very strong and durable implanted $^{19}\text{F}$ targets were used [10, 12]. A $4\pi$ BGO detector array specially designed for the JUNA project [13] was equipped to detect the $\gamma$-rays, which was already used in previous work [12].

The $\gamma$-ray spectrum taken at a proton beam energy of $E_p=130$ keV with the $4\pi$ BGO array was shown in Fig. 2. Two background peaks at 1460.8 keV (from $^{40}\text{Ar}$) and 2614.5 keV (from $^{208}\text{Ti}$) and the 6130 keV peak from the $^{19}\text{F}(p,\alpha\gamma_2)^{16}\text{O}$ reaction were used for energy calibration [2].

The $\gamma$-ray yield and hence the S Factors of the $^{19}\text{F}(p,\alpha\gamma_2)^{16}\text{O}$ reaction were determined by the integration of the 6130 keV peak of the spectrum (the red region in Fig. 2). The details can be found in Ref [2]. In conclusion, The present S Factors are much larger than the previous predictions. The thermonuclear $^{19}\text{F}(p,\alpha\gamma_2)^{16}\text{O}$ rate has been determined down to 0.05 GK.
and parameterized by the standard format of [14],

\[
N_A(\sigma v)_{(p,\gamma)} = \exp(62.821 - \frac{0.022063}{T_9} - \frac{10.5347}{T_9^{1/3}} - 67.9612 T_9^{1/3} + 50.592 T_9 - 24.327 T_9^{5/3} + 11.0325 \ln T_9) \\
+ \exp(30.5159 - \frac{0.097764}{T_9} + \frac{17.4599}{T_9^{1/3}} + 38.7519 T_9^{1/3} - 134.383 T_9 + 57.3453 T_9^{5/3} + 37.5491 \ln T_9) \\
+ \exp(-18.6175 - \frac{0.349603}{T_9} + \frac{39.0245}{T_9^{1/3}} + 67.2527 T_9^{1/3} - 116.029 T_9 + 39.9547 T_9^{5/3} + 42.7072 \ln T_9) \\
+ \exp(-91.3551 - \frac{0.136527}{T_9} + \frac{0.16144}{T_9^{1/3}} + 21.6386 T_9^{1/3} + 873.979 T_9 - 1709.51 T_9^{5/3} - 7.5102 \ln T_9)
\]

with a fitting error of less than 1% over a temperature region of 0.01–1 GK [2].

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