

A surprising drop in the ${}^6\text{Li}(p,\gamma){}^7\text{Be}$ reaction cross section at low energies

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The astrophysical S-factor of ${}^6\text{Li}(p,\gamma){}^7\text{Be}$ shows at energies below 200 keV a sizable decline contrary to expectation, a surprise. This corresponds to the energy range, where the reaction is important for both primordial and stellar nucleosynthesis. This drop is not understood and may reflect a novel mechanism.

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The ${}^6\text{Li}(p,\gamma){}^7\text{Be}$ reaction ($Q = 5.606$ MeV [1]) has been studied previously over a wide energy range down to about 200 keV ([2] and references therein). The non-resonant data have been well described by the direct capture model. However, the lowest data point at 140 keV seemed to be significantly lower than the model prediction, a discrepancy that had been ignored in the extrapolation of the experimental data towards stellar energies. This Letter reports on new experimental results covering the reaction cross section for the center-of-mass energy range from 50 to 257 keV, which confirms the previous observation.

The experiment has been carried out at the 320 kV platform [3, 4] for multi-discipline research with highly charged ions at the Institute of Modern Physics. The experimental setup is similar to the one described previously [5]. A proton beam provided by the 320 kV accelerator (current up to 30 μA) passed through 2 collimators (each of 10 mm diameter) and was focused on the target covering a beam spot of 10 mm diameter. The target was located at a distance of 50 and 100 cm from the collimators. The solid targets were prepared from ${}^6\text{Li}_2\text{O}$ material evaporated onto a 0.5 mm thick Ta backing, with a ${}^6\text{Li}$ enrichment of 95% and a thickness of 35 $\mu\text{g}/\text{cm}^2$. The targets were directly water cooled. An inline Cu shroud cooled to LN_2 temperature (a pipe of 4 cm diameter) extended close to the target for minimizing carbon build-up on target surface, together with the target, constituted the Faraday cup for beam integration. Typical vacuum pressure of target chamber was about 7×10^{-7} mbar. A negative voltage of 250 V was applied to the pipe to suppress secondary electrons from the target. No noticeable target deterioration was observed in the experiments by monitoring the yields at $E=214$ keV energy point after

several runs. The energy of the proton beam was tested using the 150 keV resonance in ${}^{11}\text{B}(p,\gamma){}^{12}\text{C}$ and the non-resonant reaction ${}^{12}\text{C}(p,\gamma){}^{13}\text{N}$ and found to be consistent to better than 1 keV [6].

A plastic scintillator (length = 100 cm, width = 50 cm, thickness = 5 cm) was placed 10 cm above the Clover detector and coincidence signals between both detectors have been rejected. This reduced the cosmic-ray background by a factor of 3 in the relevant energy range of the primary capture γ -rays of ${}^6\text{Li}(p,\gamma){}^7\text{Be}$. The capture γ -rays have been observed using a Clover detector (relative efficiency of about 200% at $E_\gamma = 1.3$ MeV, Eurisys), placed with its front face at a distance of 4 cm from the target at zero degree. The energy calibration of the detector was obtained using room background lines and a standard ${}^{152}\text{Eu}$ γ -ray source ($E_\gamma = 0.5$ to 2.6 MeV). The efficiency variation of the primary transitions over the small beam energy range ($\Delta E = 0.18$ MeV) varied by less than 5% [6, 7] and has been neglected. The detector was operated in event-by-event mode and subsequently in a play-back procedure coincidence events have been taken into account. In order to simultaneously detect the reaction particles, an Ortec ULTRA Ion-Implanted Silicon Detector with a 4 mm diameter collimator was installed at angles of 135° to the beam direction at a distance of 10 cm from the target. Gold foils of 1.7 μm thickness was placed in front of the detector to stop the intense elastically scattered protons. The Si detector was insulated electrically from the target chamber.

A sample γ -ray spectrum from the $p+{}^6\text{Li}$ radiative capture reaction obtained at an energy of $E=110$ keV is shown in Fig. 1. It should be noted that the γ -rays from the ${}^{19}\text{F}(p,\alpha\gamma){}^{16}\text{O}$ contamination were not observed at this energy because of its strong Coulomb barrier for emitting α particles. Fig. 2(a) shows the relative ratio of yields of the ground-state and first-excited captures. The ratio is approximately a constant value of about 1.48 over the measured energy region, consistent with pre-

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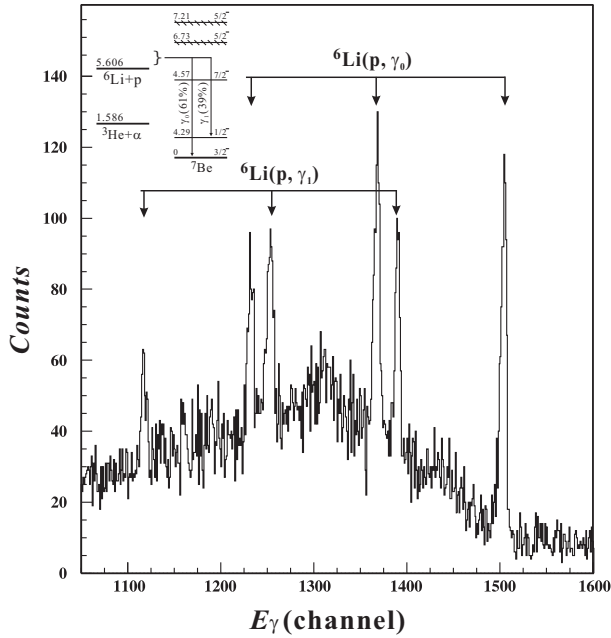


FIG. 1: Sample γ -ray spectrum from the $p+{}^6\text{Li}$ radiative capture reaction obtained at energy of $E=110$ keV.

vious value of 1.56 [2]. Since in astrophysics the total cross section is relevant, summing effects play a negligible role [7]. We have thus taken the integral region of the spectra from the double escape peak of the γ_1 -transition up to the photo peak of the γ_0 -transition [6]. Beyond the 210 keV energy, the contribution of the 6.13 MeV γ -ray from ${}^{19}\text{F}(p,\alpha\gamma){}^{16}\text{O}$ in our region of interest appeared and was determined from the line-shape of this γ -ray using a LiF target [6]. Previous work has shown that the capture γ -rays are isotropic and we assumed this to be the case in our energy range.

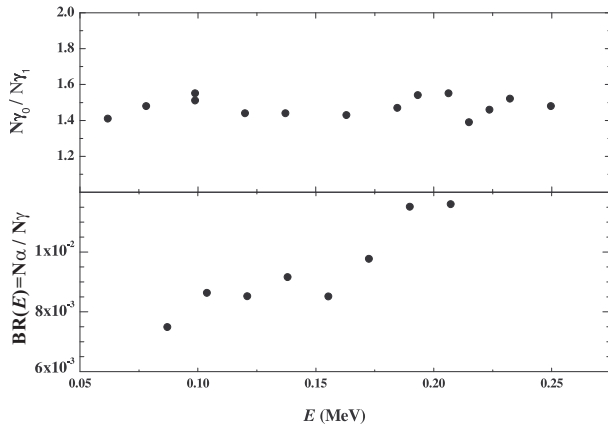


FIG. 2: (a) Relative ratio of yields of the ground-state and first-excited captures in the ${}^6\text{Li}(p,\gamma){}^7\text{Be}$ reaction, and (b) branching ratio $\text{BR}(E)$ of the γ -ray-to- α -particle.

At each energy step the observed yield was corrected for target thickness effects as described in [7]. The

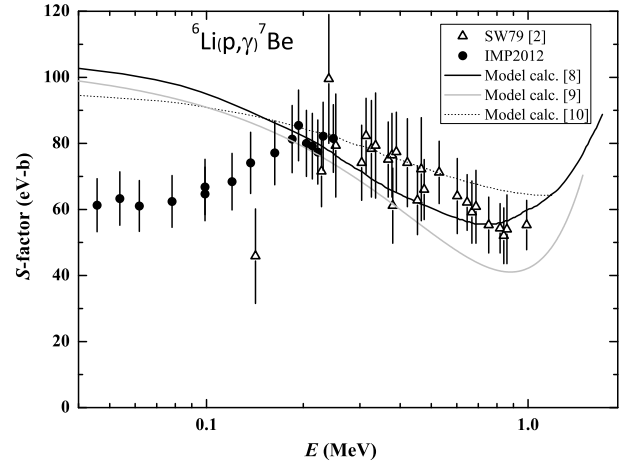


FIG. 3: Astrophysical S -factor data of ${}^6\text{Li}(p,\gamma){}^7\text{Be}$. The triangle data points are from previous work and the solid points from present work. The lines represent previous theoretical calculation results [8–10].

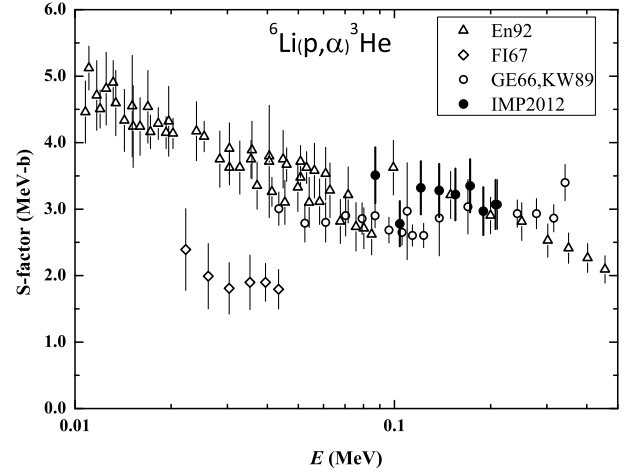


FIG. 4: Astrophysical S -factor data of ${}^6\text{Li}(p,\alpha){}^3\text{He}$. The solid data points are from present work. The previous data are also shown for comparison, where the triangle data points are from [12], the hollow circles from [15, 16] and the rectangular points from [17].

present data have been normalized at $E = 214$ keV to previous data using $S(214 \text{ keV}) = 80 \text{ eV}\cdot\text{b}$ [2]. The results are summarized in Fig. 3, where the errors shown are mainly from those previous ones used for present normalization. The present data are consistent with the data point from previous work obtained beyond $E \sim 200$ keV, but inconsistent, at the lower beam energies, with the direct capture model used in the extrapolation of the available data. In addition, the previous lowest data point at 140 keV is about 1.6 times smaller than the present value. The decline in the S -factor at low energies is a surprise, not predicted by any models [8–10]. We have studied also the ${}^7\text{Li}(p,\gamma){}^8\text{Be}$ and ${}^7\text{Li}(p,\alpha)\alpha$ reactions at $E = 218$ to 96 keV [6] confirming previous observations [11, 12] (see

also compilations [13]), *i.e.*, there is no surprise in the data [6].

For the measurements of ${}^6\text{Li}(p,\alpha){}^3\text{He}$ channel, the present experimental results were normalized to the previous work [12]. The S -factors are shown in Fig. 4, where the solid data points represent the present measurements. It shows our data have similar trend with the previous ones. In this work, the S -factors were assumed energy-independent over the narrow energy interval within a thin target. The γ -ray-to- α -particle branch ratio $\text{BR}(E)$ is thus related to the S -factors via the equation [7]

$$\text{BR}(E) = \frac{N_\alpha}{N_\gamma} \cong \frac{\epsilon_\alpha}{\epsilon_\gamma} \times \frac{S_{(p,\gamma)}(E)}{S_{(p,\alpha)}(E)}. \quad (1)$$

Here, N_α , N_γ denote the total counts of α -particle and γ -ray detected in each energy run. The ϵ_α , ϵ_γ represent the absolute detection efficiency of the Si and Clover detectors, respectively, and their ratio is almost energy insensitive within the energy interval. The corresponding branching ratio $\text{BR}(E)$ is shown in Fig. 2(b), in which the decline trend with decreasing energy is clearly shown. It verifies again the sizeable drop in the ${}^6\text{Li}(p,\gamma){}^7\text{Be}$ cross section at low energies.

At higher beam energies the capture process is dominated by the direct capture amplitude $E1(s \rightarrow p)$, thus possible interference effects need a nearby resonance with $J^\pi = 1/2^+$. However, there exists no known state of this

J^π value. Since the low energy ${}^6\text{Li}(p,\alpha){}^3\text{He}$ S -factor does not exhibits such a sizable decline but is characterized by an S -factor slowly increasing with decreasing energy [14], - as was also confirmed in the present work -, the sizable drop in the capture reaction is most likely not an effect of the entrance channel. The nature of the reaction mechanism leading to such an decline effect remains thus unknown and requires more detailed theoretical characterization, most likely a novel mechanism. This case is an example for the danger of extrapolating experimental data over a too large energy range. It demonstrates again the need for careful direct experimental study of the reaction cross section towards stellar energies to fully investigate all contributions to the specific reaction mechanism governing the cross section at this low energy range. Astrophysical consequences of the present data have to await the results of detailed calculations.

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