PROCEEDINGS OF SCIENCE

A surprise in the ^{6}Li(p,γ)^{7}Be reaction at low energies

J.J. He[a,*], **S.Z. Chen**[a,b], **S.W. Xu**[a], **J. Hu**[a], **X.W. Ma**[a], **L.Y. Zhang**[a,b], **S.Q. Hou**[a,b], **X.Q. Yu**[a], **N.T. Zhang**[a], **S.B. Ma**[a,b], **Y.H. Zhang**[a], **X.H. Zhou**[a], **H.S. Xu**[a], **G.Q. Xiao**[a], and **W.L. Zhan**[a]

[a] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*

C.E. Rolfs[c]

[c] *Department of Physics and Astronomy, Ruhr-University Bochum, Bochum 44780, Germany*

M. Wiescher[d], **R.J. deBoer**[d]

[d] *Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

T. Kajino[e,f]

[e] *National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[f] *Department of Astronomy, Graduate School of Science, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

M. Kusakabe[g]

[e] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*

G. Lan[h]

[h] *China Institute of Atomic Energy, P.O. Box 275(1), Beijing 102413, China*

The astrophysical S-factor of ^{6}Li(p,γ)^{7}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. The decline effect might influence the element abundances prediction in the Bing-Bang Nucleosynthesis (BBN) models.

PACS: 25.40.Lw, 26.35.+c, 26.20.+f, 27.20.+n

XII International Symposium on Nuclei in the Cosmos,
August 5-12, 2012
Cairns, Australia

*Email:jianjune@impcas.ac.cn.

PoS(NIC XII)005

The ^{6}Li(p,γ)^{7}Be reaction (Q = 5.606 MeV [1]) has been studied previously over a wide energy range down to about 140 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 work 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]. The proton beam (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 $^6Li_2O$ material evaporated onto a 0.5 mm thick Ta backing, with a ^{6}Li enrichment of 95% and a thickness of 35 μg/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, it constituted the Faraday cup for beam integration. Typical vacuum pressure of target chamber was about 4×10^{-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}B(p,γ)^{12}C and the non-resonant reaction ^{12}C(p,γ)^{13}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}Li(p,γ)^{7}Be. The capture γ-rays have been observed using a Clover detector (relative efficiency of about 200% at E_γ = 1.3 MeV, made by Eurisys), placed in close geometry at zero degree with its front face at a distance of 4 cm from the target. The energy calibration of the detector was obtained using room background lines and a standard ^{152}Eu γ-ray source (E_γ = 0.5 to 2.6 MeV). The efficiency variation of the primary transitions over the small beam energy range (ΔE = 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 charged particles, an Ortec ULTRA lon-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. A gold foil 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}Li radiative capture reaction obtained at an energy of E=94 keV is shown in Fig. 1. The γ transitions to the ground state (γ_0) and to the first excited state (γ_1) in ^{7}Be are clearly observed. It should be noted that the γ-rays from the ^{19}F(p,$\alpha\gamma$)^{16}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 photo-peak γ-ray yields of the ground-state and first-excited captures. Only statistical errors are shown. The ratio is about 1.56 ± 0.10 averaging

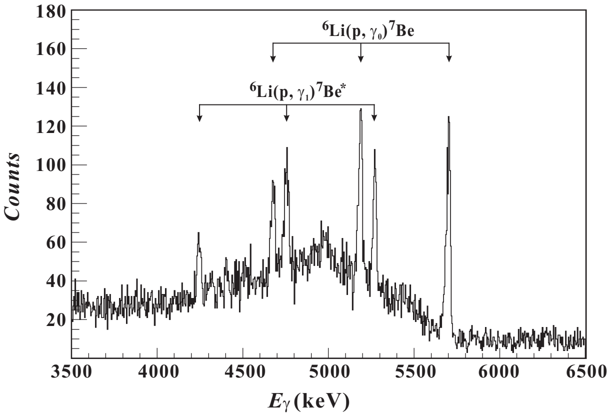

Figure 1: Sample γ-ray spectrum from the p+^{6}Li radiative capture reaction obtained at energy of E=94 keV.

over the measured energy region, consistent with the previous value of 1.56±0.10 [2]. In Fig. 2, the energies shown are the effective ones which are calculated by the method introduced in Ref. [7].

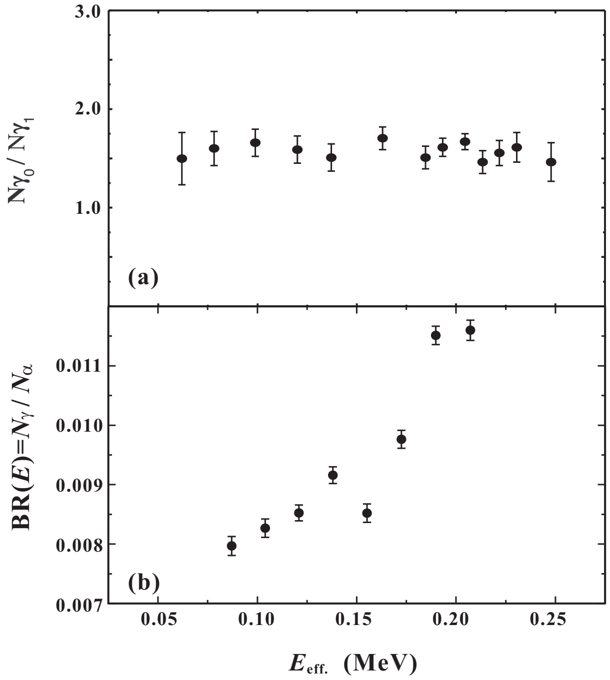

Figure 2: (a) Relative ratio of yields of the ground-state and first-excited captures in the ^{6}Li(p,γ)^{7}Be reaction, and (b) branching ratio BR(E) of the γ-ray-to-α-particle from reactions of ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He. Where all errors are of statistical origin, and x-axis indicates the effective energies [7].

At each energy step the observed yield was corrected for target thickness effects as described in [7]. The present data have been normalized at $E = 214$ keV to previous data using $S = 80$ eV·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

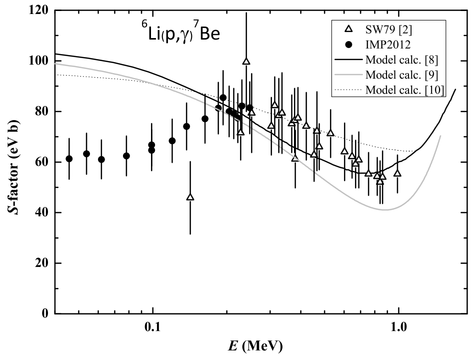

Figure 3: Astrophysical S-factor data of ^{6}Li(p, γ)^{7}Be. The triangle data points are from previous work and the solid points from present work. The solid line represents previous theoretical calculation results [8 – 10].

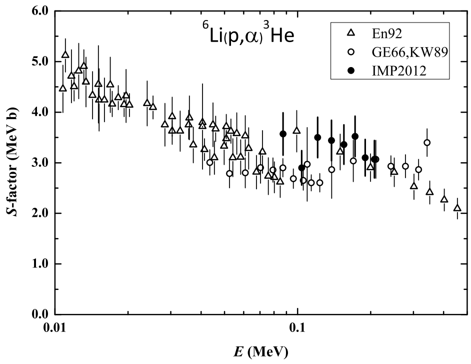

Figure 4: Astrophysical S-factor data of ^{6}Li(p, α)^{3}He. The solid data points are from present work. The previous data are also shown for comparison, where the triangle data points are from [12] and the hollow circles from [15, 16].

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}Li(p,γ)^{8}Be and ^{7}Li(p,α)α 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}Li(p,α)^{3}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 that 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 BR(E) is thus related to the S-factors via the equation [7]

$$\mathrm{BR}(E) = \frac{N_\gamma}{N_\alpha} \simeq \frac{\varepsilon_\alpha}{\varepsilon_\gamma} \times \frac{S_{(p,\gamma)}(E)}{S_{(p,\alpha)}(E)}. \tag{1}$$

Here, N_α, N_γ denote the total counts of α-particle and γ-ray from the respective ^{6}Li(p,α) and ^{6}Li(p,γ) channels 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 BR(E) is shown in Fig. 2(b), where the decline trend with decreasing energy is clearly shown. Where the errors are of statistical origin. It verifies again the sizeable drop in the ^{6}Li(p,γ)^{7}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^π =1/2$^+$. However, there is no known state with this J^π value. Since the low energy ^{6}Li(p,α)^{3}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 cross section is most likely not an effect of the entrance channel. A detailed R-matrix calculation [17] is being attempted by assuming an unexpected broad 1/2$^+$ resonance near E = 200 keV [18]. Usually, increasing behavior of the astrophysical S-factor arises from s-wave, and decreasing behavior is due to d-wave [19]. The major component of the ground state of ^{6}Li(1$^+$) is ^{4}He(0$^+$) plus D(S=1, L=0$^+$) in relative s-wave between ^{4}He and D. However, it is well known that 10% in probability of the ground state of deuteron consists of d-wave, *i.e.*, D(S=1, L=2$^+$) for the tensor interaction. This component can make the ground state of ^{6}Li(1$^+$) as ^{4}He(0$^+$) plus D(S=1, L=2$^+$) in relative d-wave. Thus, the d-wave between ^{6}Li and p might make a decreasing behavior of the S-factor as the energy decreases. The exact nature of the reaction mechanism leading to such an decline effect remains unknown and requires more detailed theoretical characterization, and the novel mechanism of the present data has to await the results of detailed calculations [18, 20, 21].

The decline of cross sections at the energies lower than 0.2 MeV leads to reduction of the reverse rate ^{7}Be(γ,p)^{6}Li in the standard BBN or inhomogeneous BBN. Now, we are evaluating the impact of this drop with a recently developed SUSY assisted BBN model [22]. This case is a good 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.

We wish to thank the engineers for operating the 320 kV platform. This work was financially supported by the National Natural Science Foundation of China (11135005, 11021504), the Major State Basic Research Development Program of China (2013CB834406), and the "100 Persons Project" (BR091104) of Chinese Academy of Sciences. C.R. was supported by the Visiting Professorships Program of CAS and the Joint Institute for Nuclear Astrophysics at the University of Notre Dame (NSF-Phys-0822648). T.K. and M.K. were supported in part by the Grants-in-Aid for Scientific Research of the JSPS (20244035) and Scientific Research on Innovative Area of MEXT (2010544).

References

[1] G. Audi *et al.*, Nucl. Phys. **A729**, 337 (2003).

[2] Z.E. Switkowski *et al.*, Nucl. Phys. **A331**, 50 (1979).

[3] L.T. Sun *et al.*, Nucl. Instr. and Meth. **B263**, 503 (2007).

[4] X. Ma *et al.*, J. of Phys.: Conf. Ser. **163**, 012104 (2009).

[5] M. Wiescher *et al.*, Nucl. Phys. **A349**, 165 (1980).

[6] S.Z. Chen, PhD Thesis, Institute of Modern Physics, Chinese Academy of Sciences (to be published).

[7] C.E. Rolfs and W.S. Rodney, *Cauldrons in the Cosmos*, (University of Chicago Press, Chicago, 1988)

[8] F.C. Barker, Aust. J. Phys. **33**, 159 (1980).

[9] K. Arai *et al.*, Nucl. Phys. **A699**, 963 (2002).

[10] J.T. Huang *et al.*, Atom. Data Nucl. Data Tables **96**, 824 (2010).

[11] D. Zahnow *et al.*, Z. Phys. **A 351**, 229 (1995).

[12] S. Engstler *et al.*, Phys. Lett. **279B**, 20 (1992).

[13] C. Angulo *et al.*, Nucl. Phys. **A565**, 3 (1999).

[14] S. Engstler *et al.*, Z. Phys. **A 342**, 471 (1992).

[15] W. Gemeinhardt *et al.*, Z. Phys. **197**, 58 (1966).

[16] J.U. Kown *et al.*, Nucl. Phys. **A493**, 112 (1989).

[17] R.E. Azuma *et al.*, Phys. Rev. **C 81**, 045805 (2010).

[18] R.J. deBoer, private communication.

[19] T. Kajino *et al.*, Suppl. J. of Phys. Soc. Japan **58**, 639 (1989).

[20] S. Kubono, private communication.

[21] K. Arai, private communication.

[22] M. Kusakabe, T. Kajino, G.J. Mathews, Phys. Rev. D **74**, 023526 (2006).