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Progress of Low-energy Nuclear Astrophysics Studies Based on the 320 kV Platform at Lanzhou

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Abstract: For the hydrostatic stable burning in stars, the Gamow window is well below the Coulomb barriers for the charged-particle-induced nuclear reaction involved. Such nuclear reaction occurs through the quantum-mechanics tunneling effect, and its cross section drops rapidly approaching the Gamow window. An accelerator which can provide intense beam current is thus required to directly measure the reactions at low energies. An experimental setup for low-energy nuclear astrophysics studies has been recently established at a 320 kV high-voltage platform of the Institute of Modern Physics (IMP), Lanzhou, China. The driver machine of this platform is a very strong ECR ion source employing all-permanent magnets, which can typically supply up to about 100 eμA proton, alpha and many other heavy ions, and ultimately about 30 eμA currents can be achieved at the experimental terminal. The experimental setup includes a target chamber, and the charged-particle and γ-ray HPGe detectors. This work describes the setup established, characteristics of detectors, methodologies, and test results of several reactions with known cross sections. Furthermore, some important results published are shown briefly. We believe that the experimental technologies developed and experiences accumulated at this above-ground platform will be extremely helpful for the Jinping Underground Nuclear Astrophysics laboratory (JUNA) project in China.

Key words: reaction cross section; astrophysical S-factor; reaction rate; Gamow window

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1 Introduction

Nuclear astrophysics strives for a comprehensive picture of the nuclear reactions responsible for synthesizing chemical elements and for powering the stellar evolution engine. Thereinto, the measurements of nuclear reaction cross sections at stellar Gamow energies (*i.e.*, effective nuclear-burning energy region) have long been recognized as being of fundamental importance[1]. For the hydrostatic stable nuclear burning in stars, nuclear reactions occur at very low stellar energies. The related Gamow windows are well below the Coulomb barriers for the charged-particle-induced nuclear reactions involved. These nuclear reactions occur through the quantum-mechanics barrier penetration (*i.e.*, tunneling effect) with a small but finite probability. Because of the exponential behavior of the probability for tunneling, the reaction cross section drops rapidly for energies below the Coulomb barrier. Frequently, the reaction cross section is expressed as[1]:

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E)\ . \tag{1}$$

The quantity η is called the Sommerfeld parameter and is defined as $\eta = \dfrac{Z_1Z_2e^2}{\hbar v}$. In numerical units, the exponent is $2\pi\eta$=$31.29Z_1Z_2\sqrt{\mu/E}$, where the center-of-mass energy E is given in units of keV and the reduced mass μ is in amu. In Eq. 1, the function $S(E)$, containing all the strictly nuclear effects, is referred to as the astrophysical S-factor[1]. In contrast to cross section, the S-factor is a smoothly varying function of energy for the non-resonant reactions. With these characteristics, the S-factor is much more useful in extrapolating measured cross sections at higher energies to Gamow

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energies. A lot of investigations have been done in the past sixty years (*e.g.*, see compilation[2]). However, it reveals that the experimental S-factor at low energies sometimes shows quite different behaviors comparing to simple extrapolation from the extensively studied high-energy data. Therefore, extrapolating experimental data over a very large energy range towards stellar energies is sometimes not reliable or dangerous.

So far, there are still no available experimental S-factor data at the low-energy region for many nuclear reactions of astrophysical importance, and some existing S-factor data still have very large uncertainties[2, 3]. Therefore, it is very important and challenging to measure these S-factors (or cross sections) at low energies directly. Recently, we have established an experimental setup for low-energy nuclear astrophysics studies at the Institute of Modern Physics (IMP), CAS, in Lanzhou, China, based on a 320 kV high voltage platform. The present work reports the recent research progress based on this experimental setup.

2 Experimental setup

A low-energy 320 kV high-voltage platform has been under commission for multi-discipline research at IMP since 2008[4]. This platform is driven by a powerful ECR ion source[5] which employs the all-permanent magnets. The ECR source can typically supply up to about 100 eμA proton, alpha, and other less intense heavy ions. Owing to the characteristic of intense beams, an experimental setup has recently been constructed for low-energy nuclear astrophysics studies. A schematic diagram of the setup is shown in Fig. 1. The target chamber is electrically isolated between the upstream and downstream sides of the beam line. Because they are insulated from one another, the downstream side constitutes a Faraday Cup together with a directly water-cooled target for beam integration. There is an inline Cu shroud cooled to LN_2 temperature (a pipe of 4 cm in diameter, 35 cm in length) extended from upstream to downstream (close to the target) for minimizing carbon build-up on the target surface. A negative voltage of 250 V was applied to the pipe to suppress the secondary electrons from the target. Two Cu collimators (each 10 mm in diameter) are located 50 and 100 cm upstream of the target. The typical vacuum pressure of the target chamber was about 4×10^{-5} Pa.

A 4×4-fold-segmented Clover-type high-purity germanium detector[6, 7] placed in close geometry at zero degrees was utilized for the γ-ray detection. The Clover detector has a relative efficiency of about 200% and typical resolution of 2.3 keV (at E_γ=1.3 MeV). The energy spectrum from four germanium crystals were taken simultaneously and then summed up after calibration. The performance of this Clover detector was previously studied in both the crystal (singles) and clover (addback) modes[6, 7]. In the recent experiments, the crystal mode was chosen to minimize the summing effect of the cascade γ transitions. An EJ-200 plastic scintillator[8] (length=100 cm, width=50 cm, thickness=5 cm) was placed 10 cm above the Clover detector acting as a veto to suppress the cosmic-ray background. It shows that the cosmic-ray background was suppressed by a factor of 2–3 in the γ-ray energy region of 4∼19 MeV. An ORTEC ULTRA ion-implanted silicon detector[9] was installed at 135° with respect to the beam direction at a distance of 10 cm from the target. A thin Au foil was placed in front of the Si detector to stop the intense elastically scattered beam ions.

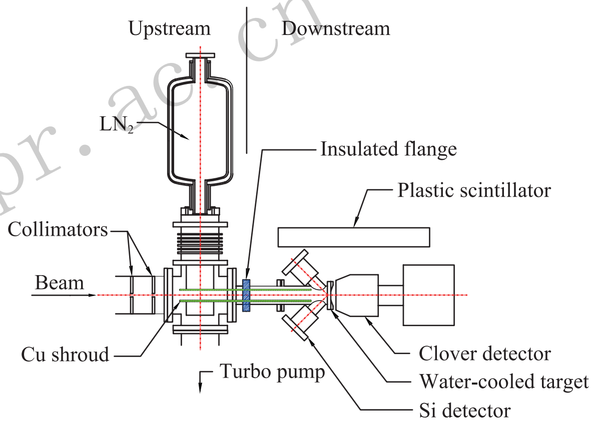

Fig. 1 (color online) Schematic view of the experimental setup. The silicon detector can be installed in two arms at backward angle of 135°.

The energy of a proton beam was calibrated against the nominal platform high voltage by using the well-known resonant reaction of ^{11}B(p,γ)^{12}C and the non-resonant reaction ^{12}C(p,γ)^{13}N. It shows that an accuracy better than ±0.5 keV has been achieved for the proton beam energy with our platform. The γ-ray efficiency was calibrated for the Clover detector: for low energy γ rays, the efficiency was calibrated by two standard ^{152}Eu and ^{60}Co sources with known activities; for high energy ones, the efficiency was determined by a reaction of ^{14}N(p, γ)^{15}O. The GEANT4[10] simulated efficiencies agree very well with the experimental data. For more information about the calibration of beam energy and γ-ray efficiency, the reader may refer to our previous instrumentation paper[11].

3 Test results

With this setup, the astrophysical S-factors of

^{7}Li(p, γ)^{8}Be and ^{7}Li(p, α)^{3}He reactions were measured simultaneously at an energy range of $E_{\rm c.m.}$ = 80∼210 keV. A 35 μg/cm^2-thick LiF solid target with a tantalum backing was used in the experiment. In this test, we have derived the S-factors relative to the previous results. The S-factors of ^{7}Li(p,γ)^{8}Be were normalized to the previous work[12] at one energy point of $E_{\rm c.m.}$=217 keV as shown in Fig. 2. Where the estimated errors are mainly of the statistical and normalization in origin. The S-factors of ^{7}Li(p, α)^{4}He were normalized to the previous work[13] at one energy point of $E_{\rm c.m.}$=216 keV as shown in Fig. 3. Here, energy-dependence on the α-particle angular distribution[14] was taken into account. The large errors in the present data mainly arise from the statistics (∼1%), the normalization (∼10%), and the energy-dependence on the angular distribution (∼7%). For both reaction channels, the $E_{\rm c.m.}$ energies were correct for the effect of target thickness. It shows that our data are consistent with the previous ones within the uncertainties, considering the previous measurements already had differences from one another.

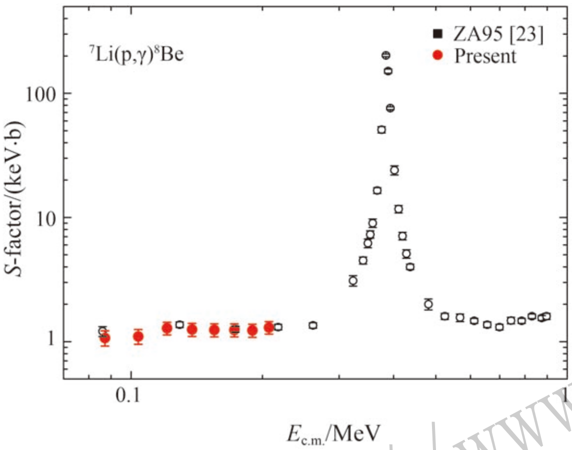

Fig. 2 (color online) Astrophysical S-factor data of ^{7}Li(p, γ)^{8}Be as a function of effective energy. The present S-factors were normalized to the previous data[12] at energy point of $E_{\rm c.m.}$=217 keV. The (red) solid data points are from present work, and the (black) hollow circles are from[12]. The present errors are mainly of statistical and normalization in origin.

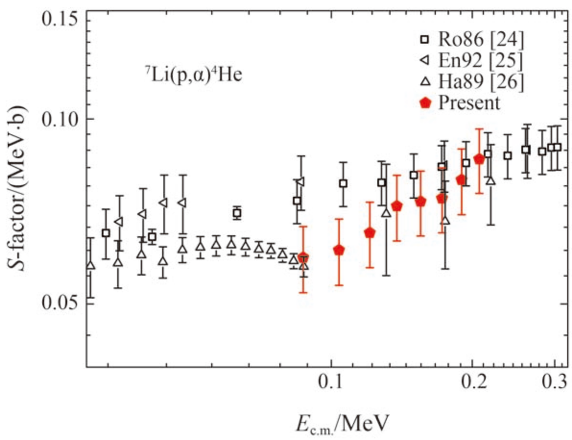

Fig. 3 (color online) Astrophysical S-factor data of ^{7}Li(p, α)^{4}He as a function of effective energy. The present S-factors were normalized to the previous data[13] at energy point of $E_{\rm c.m.}$=216 keV. The (red) solid data points are from the present work. The previous data[13–15] are shown for comparison.

4 Typical examples

We have successfully made the direct cross-section (or astrophysical S-factor) measurements for ^{6}Li(p, γ)^{7}Be and ^{11}B(p, γ)^{12}C reactions based on this experimental setup. Here, we briefly show the results for these two studies, which have been already published elsewhere[16, 17].

4.1 ^{6}Li(p,γ)^{7}Be reaction

The ^{6}Li(p, γ)^{7}Be reaction has been studied previously over a wide energy range down to about center-of-mass (c.m.) energy of $E_{\rm c.m.}$=140 keV[18]. The non-resonant data were well described by the direct capture model except one lowest data point at 140 keV[2]. In addition, an analyzing-power measurement[19] for this reaction indicated that the S-factor had a negative slope towards low energies, while a thick-target measurement with a γ-to-α branching ratio method indicated a positive slope[20]. However, the extrapolated S-factors for both measurements deviated dramatically from those experimental ones[18] around $E_{\rm c.m.}$=200 keV. With regard to the nuclear astrophysical aspect, current models of stellar evolution predicted negligible quantities of ^{6}Li in the hydrogen burning phases of stellar evolution[21]. Primordial, or standard and inhomogeneous big-bang nucleosynthesis (BBN)[22, 23] might have been more generous in its production of this element within an effective temperature region of 1∼0.1 GK. For example, a low quantity of ^{6}Li can survive in the BBN according to Schramm and Wagoner's estimation[24]. Therefore, the measurement of capture cross section of ^{6}Li(p, γ)^{7}Be will permit the production of ^{7}Be in these scenarios to be well evaluated.

We have investigated the low-energy astrophysical S-factors of the ^{6}Li(p, γ)^{7}Be reaction in the proton energy range of 70∼300 keV[16]. The experimental S-factor of this reaction shows an interesting sizable drop contrary to any existing theoretical expectations at energies below 200 keV (see Fig. 4). The appearance of an interesting new positive-parity $1/2^+$ or $3/2^+$ resonance at $E_{\rm c.m.}\approx$195 keV in the compound nucleus ^{7}Be had been discussed under the R-matrix framework[25]. However, for such anomalous behavior, the exact nature of the possible novel reaction mechanism or a new low-energy resonance leading to such a declining effect remains unknown and requires more detailed experimental and theoretical characterization. Furthermore, this study shows the danger of extrapolating experimental data over too large an energy range and demonstrates the need for careful direct experimental studies of reaction cross sections at or near stellar energies.

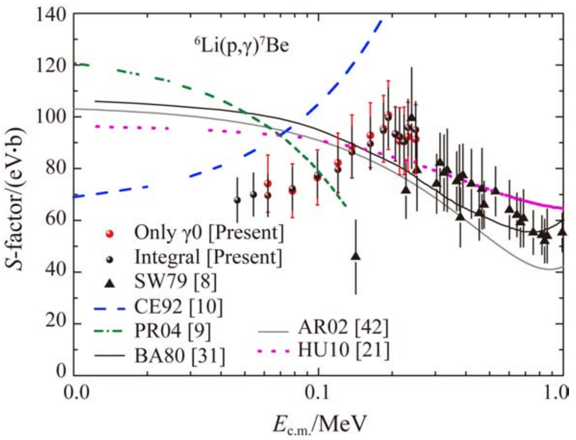

Fig. 4 (color online) Astrophysical S-factors of ^{6}Li(p,γ)^{7}Be as function of energy. The solid circles represent the S-factors determined by the yields only from the photo-peak of γ_0, and the hollow circles represent the ones by the yields from the integration method. The triangular data points are from previous work[18] and the solid points from present work. Three lines represent the previous theoretical results[26–28]. The total S-factor curves of Prior *et al.*[19] and Cecil *et al.*[20] are also shown for comparison.

In the astrophysical aspects, the observed decline in ^{6}Li(p, γ)^{7}Be cross sections at energies below 200 keV also leads to a reduction of the reverse rate ^{7}Be(γ, p)^{6}Li through the detailed balance theory. In our SUSY assisted BBN model[29] calculation, though the fractional reduction rate of ^{7}Be via the reaction ^{7}Be(γ, p)^{6}Li could be as large as the order 0.1~1 at the earlier times t=(2-3)×10^5 s, the final yield of ^{7}Be does not change very much. This is because the threshold energy of ^{7}Be(γ, α)^{3}He (Q=1.587 MeV) is smaller than that of ^{7}Be(γ, p)^{6}Li (Q=5.606 MeV) so that a soft nonthermal photon spectrum generated by the radiative X decay prefers ^{7}Be destruction via the former reaction.

4.2 ^{11}B(p, γ)^{12}C reaction

Theoretical models of stellar evolution predict negligible quantities of ^{6}Li, ^{9}Be, and ^{11}B in the hydrogen burning phases of a star's evolution[21]. The BBN model might be more generous in its production of these elements[24]. The radiative-capture cross section for proton capture on ^{11}B leading to ^{12}C is small at astrophysically interesting energies because of the large Coulomb barrier. For this reason the proton captures on ^{11}B is often neglected in BBN, and ^{12}C creation is assumed to proceed by neutron capture on ^{11}B followed by the subsequent β-decay of ^{12}B. In addition, the ^{4}He density produced in the pp chain is large so that the 3α reaction is responsible for generating most of the ^{12}C nuclei in stellar nucleosynthesis. However proton capture on ^{11}B cannot be entirely neglected in these scenarios. It is thus necessary to measure the ^{11}B(p, γ)^{12}C reaction cross section (or astrophysical S-factor) in the low-energy region of astrophysical interest.

The absolute cross section of the ^{11}B(p, γ)^{12}C reaction was measured in the energy region of $E_{\rm c.m.}$=130~257 keV by using a *thin target* for the first time[17]. The astrophysical S-factors of this reaction were determined for capture to the ground (p,γ_0) and first-excited (p,γ_1) states of ^{12}C. The energy and width derived for the known resonance at ~150 keV agree with the previous results. However, our S-factors are about (15~50)% larger than those adopted values in NACRE II[30] in the energy region of 170~240 keV (see Fig. 5). According to the present results, this reaction rate is enhanced by about (15~50)% compared to the NACRE II rate in the temperature region of 0.32~0.62 GK. This non-negligible correction should be considered in the future nucleosynthesis network calculations.

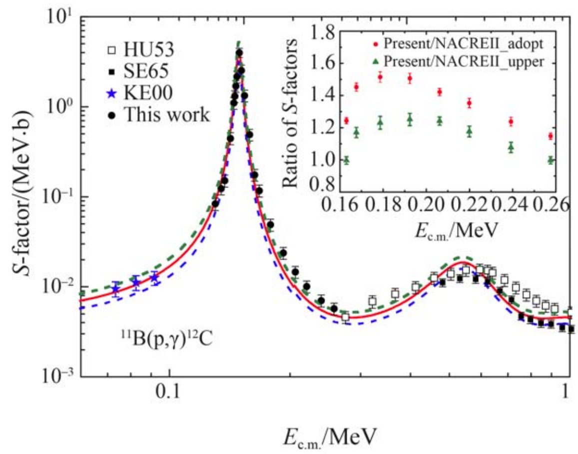

Fig. 5 (color online) Astrophysical S-factors of ^{11}B(p, γ)^{12}C. The previous data, HU53[31], SE65[32] and KE00[33] taken from the NACRE II[30] are shown for comparison. Three lines for the 'Potential Model' (PM) calculations[30] are shown, representing the upper limit, centroid and lower limit, respectively. The S-factor ratios between this work and the NACRE II are shown in the inserted figure, where the solid circles and triangular points represent the ratios between our data and the values of adopted (centroid) and upper limit in the compilation, respectively.

5 Outlook

Recently, the construction of a new experimental hall housing a new beam line and terminal has been completed based on this 320 kV platform. This new terminal is mainly focusing on the low-energy nuclear astrophysics studies. The large-scale γ-ray and neutron detector arrays will be constructed, and hence the studies of low-energy (p, γ), (α, γ) and (α, n) reactions of astrophysical interest become feasible.

It is well-known that for the hydrostatic stable burning in stars the extremely small cross sections result in quite small signal-to-background ratio, which makes the direct measurement in the laboratory at the Earth's surface impossible. In order to observe the rare events, some crucial reactions have been successfully studied in an ultra-low background deep-underground facility LUNA[34] in Italy. Covered by about 2400-meter-thick marbles, China Jinping underground Laboratory (CJPL)[35–37], the deepest underground laboratory in the world, can greatly reduce the muon and neutron fluxes by 6 and 4 orders of magnitudes with respect to those at the Earth's surface. With such unique super-low-background and salient features, the Jinping Underground Nuclear Astrophysics laboratory (JUNA) project[38] was approved by the National Natural Science Foundation of China (NSFC) in 2014 and will be financially supported in period of 2015–2019. It aims at direct measurement of (α, γ) and (α, n) reactions in hydrostatic helium burning, as well as (p, γ) (p, α) reactions in hydrostatic hydrogen burning. We believe that the experimental technologies developed at the above-ground 320 kV platform will be extremely helpful for the deep-underground nuclear astrophysics studies in China.

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兰州 320 kV 高压平台低能核天体物理实验研究进展

何建军[1,2,1)]，许世伟[2]，马少波[2,3]，胡 钧[2]，张立勇[3]，侯素青[2]，于祥庆[2]，贾宝路[2,3]

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摘要: 在低温核天体物理环境下，如静态核稳定燃烧阶段的核反应都发生较低的能区，其伽莫夫窗口内的核反应截面非常小，这就需要加速器提供较强束流才能完成核反应截面的直接测量。最近在中国科学院近代物理的 320 kV 高压平台上建立了低能核天体物理实验室以及相应的研究平台。驱动该平台的是一个 14.5 GHz 的永磁铁型 ECR 离子源，它能够提供非常强的束流离子。对于质子和氦离子，离子源出口的最大流强可以达到 100 eμA，在实验终端上可以获得大约 30 eμA 的流强。基于此强流加速器装置，我们建立了核天体物理实验测量装置，包括靶室以及带电粒子和伽玛射线探测器等设备。利用已知的核反应对探测器性能和实验方法进行了一系列测试。同时，展示了近年来取得的一些主要实验结果。最后，对该平台上开展工作的前景进行了展望，并指出基于该地面装置的低能核反应研究所积累的技术及经验对于我国锦屏深地核天体物理 JUNA 项目的重要意义。

关键词: 核反应；核天体物理 S 因子；反应率；伽莫夫窗口

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