Nuclear Instruments and Methods in Physics Research A 735 (2014) 466–470

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A new experimental setup established for low-energy nuclear astrophysics studies

S.Z. Chen [a,b], S.W. Xu [a,b], J.J. He [a,*], J. Hu [a], C.E. Rolfs [a,c], N.T. Zhang [a], S.B. Ma [a,b], L.Y. Zhang [a], S.Q. Hou [a,b], X.Q. Yu [a], X.W. Ma [a]

[a] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Fakultät für Physik und Astronomie, Ruhr-Universität Bochum, Bochum 44780, Germany

ARTICLE INFO

Article history:
Received 8 July 2013
Received in revised form
2 September 2013
Accepted 7 October 2013
Available online 12 October 2013

Keywords:
320 kV platform
Radiative capture
Clover detector
Astrophysical *S*-factors

ABSTRACT

An experimental setup for low-energy nuclear astrophysics studies has been recently established at the Institute of Modern Physics (IMP), Lanzhou, China. The driver machine is a 320 kV high voltage platform, which can provide intense currents of proton, alpha and many heavy ion beams. The energy of a proton beam was calibrated against the nominal platform high voltage by using a well-known resonant reaction of ^{11}B(p,γ)^{12}C and a non-resonant reaction ^{12}C(p,γ)^{13}N. The accuracy was achieved to be better than $\pm$0.5 keV. The detection system consists of a Clover-type high-purity germanium detector, a silicon detector and a plastic scintillator. The performance of the detectors was tested by several experiments. The astrophysical *S*-factors of the ^{7}Li(p,γ)^{8}Be and ^{7}Li(p,α)^{3}He reactions were measured with this new setup, and our data agree with the values found in the literature. In addition, the upgrade of our driver machine and experimental setup has been discussed. As a future goal, a fascinating National Deep Underground Laboratory in China, the deepest underground laboratory all over the world, is prospected.

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 to many areas of basic and applied physics. Perhaps the two most notable areas to which these reactions find application are fusion energy and astrophysics [1]. In the low-temperature astrophysics sites, *e.g.*, our Sun, the Red Giant stars and the nova [1], the 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, sometimes referred to as the 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 $\eta = Z_1 Z_2 e^2/\hbar v$. In numerical units, the exponent is $2\pi\eta = 31.29 Z_1 Z_2 \sqrt{\mu/E}$, 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 factor $S(E)$ is much more useful in extrapolating measured cross-sections at higher energies to Gamow energies. A lot of investigations have been done in the past 60 years (*e.g.*, see compilation [2]). In order to observe the rare events, some crucial reactions have been successfully studied in an ultra-low background deep-underground facility LUNA [3] in Italy. It reveals that the experimental *S*-factors at low energies sometimes show 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. As for the ^{2}H(d,γ)^{4}He reaction involved in both primordial and stellar nucleosynthesis [4,5], its *S*-factors decrease steeply with decreasing energy above

* Corresponding author. Tel.: +86 931 4969312.
E-mail address: jianjunhe@impcas.ac.cn (J.J. He).

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.10.015

$\sim$500 keV. The behavior observed indicates that the reaction mainly proceeds via an $E2$ transition from a $^1D_2$ scattering state to the $^1S_0$ component of the ^{4}He ground state. For a long time, the S-factors of ^{2}H(d,γ)^{4}He had been thought to decrease steeply with decreasing energy even at low energies. However, the later experimental results [6,7] show a significantly higher S-factor (about 32 times) than theoretical expectation in the energy region below $\sim$500 keV. The observed near-constant S factor and isotropy show that the dominant $E2$ radiative capture amplitude is $^5S_2 \rightarrow {}^5D_0$, and demonstrate clearly the existence of a D-state admixture in the ^{4}He ground state whose D-state admixture can be determined from the low-energy cross-section alone. Therefore, the low-energy cross-section measurements are not only important for nuclear astrophysics but also for nuclear structure and reaction studies.

So far, there are still no available experimental S-factor data at the low-energy region for many nuclear reactions of astrophysical importance, and also some existing S-factor data still have very large uncertainties [2,8]. Therefore, it is very important and challenging to directly measure these S-factors (or cross-sections) at low energies.

2. Experiment setup

A low-energy 320 kV high-voltage platform has been under commission for multi-discipline research at IMP since 2008 [9]. The driver machine of this platform is an ECR ion source [10] employing all-permanent magnets, which can typically supply up to about 100 eμA proton, alpha and many heavy ions. Recently, a new experimental setup has been constructed mainly for low-energy nuclear astrophysics studies. A schematic diagram of the setup is shown in Fig. 1. The target chamber, quite similar to that used in Ref. [11], 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^{-7} mbar.

A 4 × 4-fold-segmented Clover-type high-purity germanium detector [12,13], which was placed in close geometry at zero degrees with its front face at a distance of 4 cm from the target, 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 $E_\gamma = 1.3$ MeV). The energy spectrum from four germanium crystals are 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 [12,13]. In this work, the crystal mode was chosen to minimize the summing effect of the cascade γ transitions. An EJ-200 plastic scintillator [14] (length = 100 cm, width = 50 cm, and thickness = 5 cm) was placed 10 cm above the Clover detector acting as a veto to suppress the cosmic-ray background. This veto was switched on for all tests and its performance is described below. An ORTEC ULTRA ion-implanted silicon detector [15] 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.

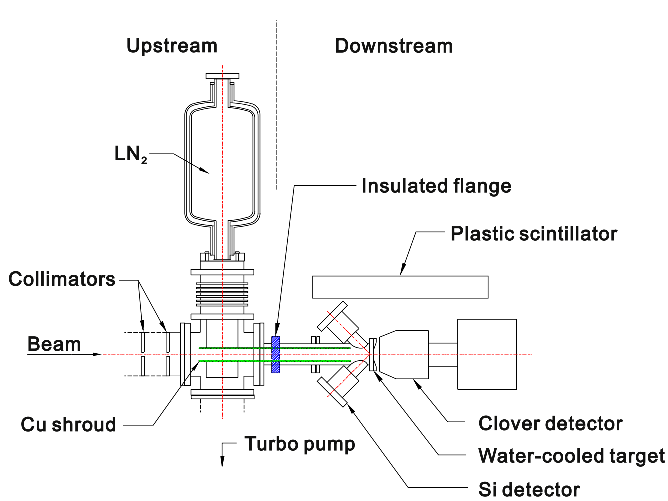

Fig. 1. Schematic view of the experimental setup. One silicon detector was utilized in this work, although two arms were available.

3. Performance tests

3.1. Beam energy calibration

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. In conclusion, an accuracy better than $\pm$0.5 keV has been achieved for the proton beam energy with our platform. The experimental details are described below.

In the former experiment, the proton beam bombarded a 6.3–μg/cm^2–thick natural boron target (80% ^{11}B, 20% ^{10}B) in a high-voltage range of 130–180 kV. The target was made by sputtering natural boron onto a 0.2-mm-thick tantalum backing. The beam current on the target was about 5–15 μA. A sample γ-ray spectrum obtained at an energy of E_p = 167 keV is shown in Fig. 2. The first excited state γ transition (γ_1) and its subsequent decay (γ^*), as well as the ground state transition (γ_0) were observed clearly in the spectrum. The astrophysical S-factors of ^{11}B(p,γ)^{12}C are determined from the measurements on 4.44-MeV γ rays (γ^*) corresponding to the decay of the first excited state of ^{12}C, because there is no angular distribution effect involved for this isotropic γ transition. Here, we assumed that the branching ratio between γ_0/γ_1 transitions is a constant within the small energy range varied in the experiment ($\Delta E \approx 50$ keV). The present data were normalized to the previous S-factor of 100 keV · b [16] at $E_{c.m.} = 179$ keV. The deduced relative S-factors are shown in Fig. 3. The uncertainties are mainly from the normalization. The center-of-mass (c.m.) energies, $E_{c.m.}$, were corrected for the effect of

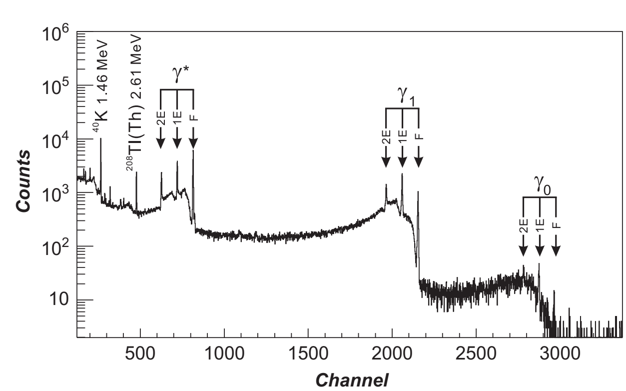

Fig. 2. A sample γ-ray spectrum obtained in the ^{11}B(p,γ)^{12}C experiment at E_p = 167 keV. The capture γ-rays populating the ground (γ_0) and first excited (γ_1) states of ^{12}C, and those decaying from the first excited state to the ground one (γ^*), are labeled in the figure. The labels F, 1E and 2E denote the full photo peak, single-escape peak and double-escape peak, respectively.

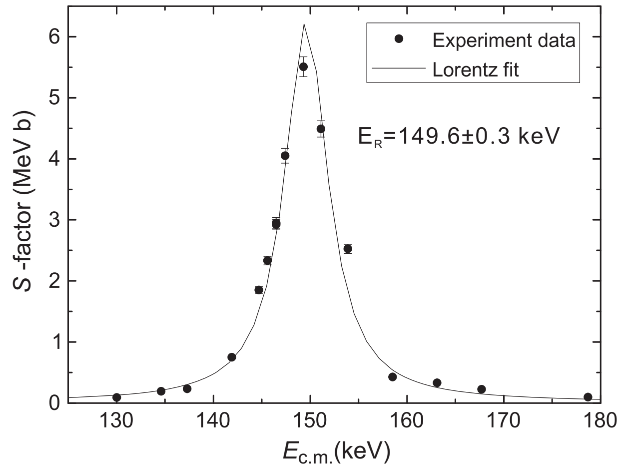

Fig. 3. Relative astrophysical *S*-factors measured for the ^{11}B(p,γ)^{12}C reaction. The present data were normalized to the previous *S*-factor of 100 keV · b [2,16] at $E_{c.m.} = 179$ keV. A Lorentzian-function fit is shown.

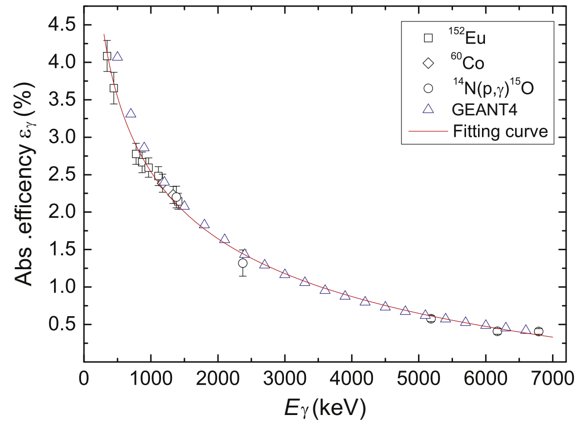

Fig. 5. Absolute efficiencies determined for the Clover detector. The data from the standard sources and ^{14}N(p,γ)^{15}O experiment have been corrected for the dead-time. The error bars of GEANT4 points are negligible. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

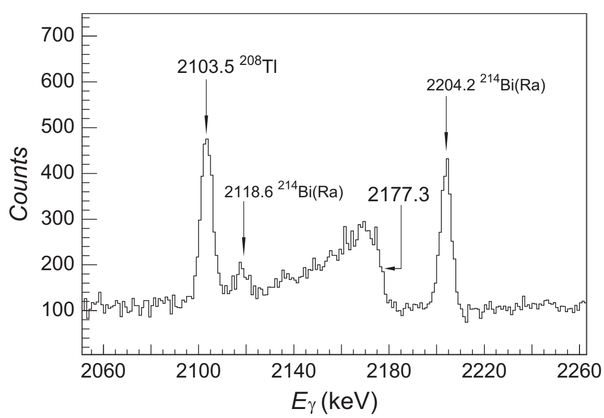

Fig. 4. A sample γ-ray spectrum obtained in the ^{12}C(p,γ)^{13}N experiment at a high-voltage of 250 kV.

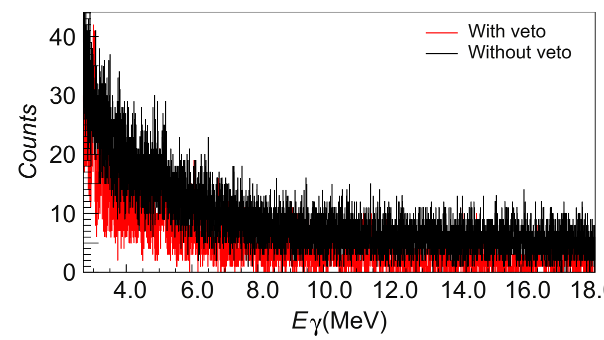

Fig. 6. The normalized background spectra with and without the plastic scintillator veto.

target thickness as described in Ref. [1]. The resonance energy derived from the present work is 149.6 ± 0.3 keV with a Lorentzian-function fit of the experimental data, which is consistent with the literature value of 149.5 ± 0.2 keV [16]. The detailed experimental results will be published elsewhere [17].

The proton beam energy was additionally calibrated by the non-resonant reaction ^{12}C(p,γ)^{13}N, by taking advantage of the high resolution of the Clover detector. The method was described in Ref. [18]. A thick C target (≥ 1 mm) was bombarded by protons at a high-voltage of 250 kV. A sample γ spectrum taken at 0° is shown in Fig. 4. A plateau of the capture transition was observed between two background γ peaks at 2103.5 keV and 2204.2 keV, which were used for the energy calibration. A proton beam energy of $E_p = 250.0 \pm 0.5$ keV was derived from the midpoint (2177.3 keV) on the front edge of the plateau, where the known energy dependence of the capture cross-section [19] and Doppler shift correction were taken into account. The error was mainly from the *Q* value (1943.49 ± 0.27 keV [20]) of ^{12}C (p,γ)^{13}N reaction, as well as that from the midpoint energy (2177.3 keV) determination. It shows that the calibrated proton beam energy agrees very well with the nominal value provided by the high-voltage platform.

3.2. γ-ray efficiency determination

The γ-ray efficiency calibration of the Clover detector has been done carefully in this work. 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 [2]. In our experiment, a 2-mm-thick N_4Si_3 target was bombarded by a 280 keV proton beam. The relative efficiencies of the decay γ rays from ^{15}O at 2373, 5183, 6176, and 6793 keV were normalized to that at 1380 keV, whose absolute efficiency was determined by the standard γ-rays sources mentioned above. The absolute efficiency curve for the Clover detector fitted by the Radware package [21] is shown in Fig. 5, where the (blue) triangles simulated [13] with the GEANT4 toolkit [22] are also shown for comparison. The simulated efficiencies are found to agree very well with the experimental data for the γ rays beyond 1 MeV. Probably due to the random coincidence with the plastic scintillator veto and to a relatively low gain adjusted for the front-end electronics, the simulated efficiencies are slightly larger in the low-energy region.

3.3. Background suppression

The background suppression is important in all γ-ray measurements, especially for low cross-section studies. The background mainly includes the ambient room and cosmic-ray background. Lead bricks can shield the low-energy room background effectively but do not significantly suppress the high-energy background caused by cosmic rays [3]. As mentioned above, a plastic scintillator was utilized as a veto to suppress the high-energy γ-ray background. The normalized spectra with and without the plastic scintillator veto were compared in Fig. 6. The background suppression factors were obtained for different energy regions as

Table 1
Background suppression factors with the plastic scintillator veto.

γ Energies (MeV)	2.6–4.0	4.0–8.0	8.0–12.0	12.0–19.0
Suppression factor	1.4	1.8	2.2	2.8

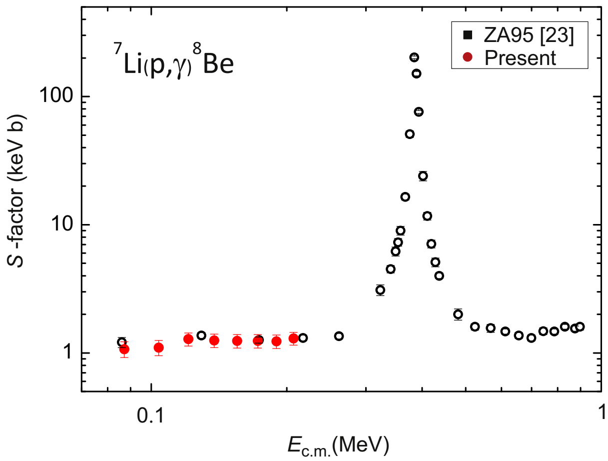

Fig. 7. Astrophysical S-factor data of ^{7}Li(p, γ)^{8}Be as a function of effective energy. The present S factors were normalized to the previous data [23] at energy point of $E_{c.m.} = 217$ keV. The (red) solid data points are from present work, and the (black) hollow circles are from Ref. [23]. The present errors are mainly of statistical and normalization in origin. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

listed in Table 1. It shows that the cosmic-ray background was suppressed by a factor of 2–3 in the high-energy region. The significant amount of background suppression obtained makes the measurement of small reaction cross-section feasible with our setup.

4. *S*-factor measurements

With this new 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 $E_{c.m.} = 80$–210 keV. A 35−μg/cm^2−thick LiF solid target with a tantalum backing was used in the experiment. In this test experiment, 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 [23] at one energy point of $E_{c.m.} = 217$ keV as shown in Fig. 7. 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 [24] at one energy point of $E_{c.m.} = 216$ keV as shown in Fig. 8. Here, energy-dependence on the α-particle angular distribution [25] was taken into account. The large errors in the present data mainly arise from the statistics ($\sim 1\%$), the normalization ($\sim 10\%$), and the energy-dependence on the angular distribution ($\sim 7\%$). For both reaction channels, the $E_{c.m.}$ 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.

The relative S-factors of ^{7}Li(p, γ)^{8}Be and ^{7}Li(p, α)^{3}He were derived in the test. However, it is more compelling to perform the absolute cross-section or S-factor measurements. However, for an accurate absolute measurements, one must handle very well two things below: (i) the chemical composition and thickness of the target should be measured experimentally by the so-called

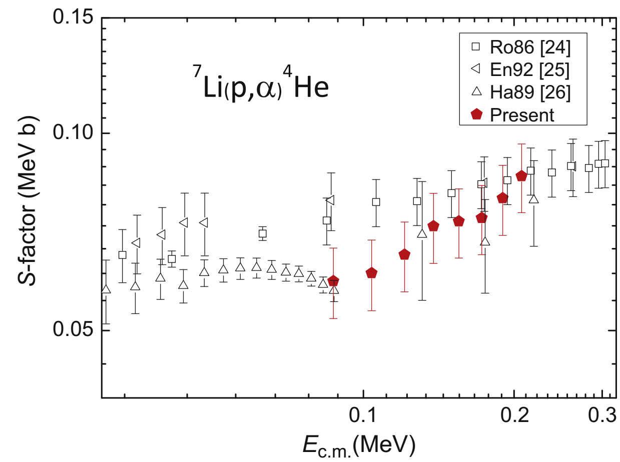

Fig. 8. Astrophysical S-factor data of ^{7}Li(p, α)^{4}He as a function of effective energy. The present S factors were normalized to the previous data [24] at energy point of $E_{c.m.} = 216$ keV. The (red) solid data points are from the present work. The previous data [24–26] are shown for comparison. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Rutherford backscattering (RBS) and elastic recoil detection analysis methods [27,28]; (ii) the angular distribution of the outgoing particles or γ rays sometime need to be measured experimentally, which is really a time-consuming task at very low energies. Inspired by the great astrophysical interest at low energies, the absolute measurements will be accomplished at this 320 kV platform in the near future.

5. Outlook

At present, this new setup is temporarily installed at an experimental terminal for atomic physics research. A new experimental terminal is now being constructed exclusively for low-energy nuclear astrophysics studies. As scheduled, this 320 kV platform will be equipped with a super-conducting ECR source capable of providing much stronger beams, together with a buncher system capable of reducing the background considerably. Thus, active shielding can be achieved with these pulsed beams. In addition, passive shielding for both γ-ray and neutron background sources (*e.g.*, large lead bricks, paraffin blocks, Cd plates) will be installed in the new experimental hall. A new gas target is presently under consideration, employing state-of-the-art plasma windows [29]. In terms of the detection system, many germanium and neutron detectors are available at IMP for constructing large-scale γ and neutron detector arrays [30]. With these advanced features, the studies of low-energy (p,γ), (α,γ) and (α,n) reactions of astrophysical interest become feasible.

Encouraged by the great success of LUNA project, the nuclear astrophysics studies have been integrated into several proposed deep-underground laboratories as one of the most important missions. For example, the Dakota Ion Accelerator for Nuclear Astrophysics (DIANA) facility [31] of the Deep Underground Science and Engineering Laboratory (DUSEL) [32] in U.S., the Boulby mine underground physics facility in U.K. [33], and the Saltmine underground accelerator laboratory [34] in Romania. In addition, a National Deep Underground Laboratory [35] is now being proposed. A 16 km tunnel passing through the Jinping mountain has already been constructed by the Jinping hydropower-station group at Sichuan province, in the southwestern region of China. The laboratory will be constructed along the tunnel, which provides about 2400 meters of overhead shielding from rock. It will become the deepest underground laboratory all over the world. Therefore, the experimental technologies developed at the present 320 kV platform will be extremely helpful for the future deep-underground nuclear astrophysics studies in China.

Acknowledgments

We wish to thank the engineers for operating the 320 kV platform. J.J. would like to express appreciation to D. Kahl (CNS, University of Tokyo) who made helpful comments on the manuscript. This work was financially supported by the National Natural Science Foundation of China (11135005, 11021504), and the Major State Basic Research Development Program of China(2013CB834406). 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).

References

[1] C.E. Rolfs, W.S. Rodney, Cauldrons in the Cosmos, University of Chicago Press, Chicago, 1988.
[2] C. Angulo, et al., Nucl. Phys. A 565 (1999) 3.
[3] C. Broggini, et al., Annu. Rev. Nucl. Part. Sci. 60 (2010) 53.
[4] W.A. Fowler, Rev. Mod. Phys. 56 (1984) 149.
[5] W.D. Arnett, J.W. Truran, Nucleosynthesis - Challenges and New Developments, University of Chicago Press, 1985.
[6] F.J. Wilkinson, F.E. Cecil, Phys. Rev. C 31 (1985) 2036.
[7] C.A. Barnes, et al., Phys. Lett. B 197 (1987) 315.
[8] C. Iliadis, et al., Astrophys. J. Suppl. 134 (2001) 151.
[9] X. Ma, et al., J. Phys.: Conf. Ser. 163 (2009) 012104.
[10] L.T. Sun, et al., Nucl. Instrum. Methods B 263 (2007) 503.
[11] M. Wiescher, et al., Nucl. Phys. A 349 (1980) 165.
[12] N.T. Zhang, et al., Chin. Phys. Lett. 29 (2012) 042901.
[13] N.T. Zhang, et al., J. Phys. G: Nucl. Part. Phys. 40 (2013) 035101.
[14] ELJEN Technology, 〈http://www.eljentechnology.com/〉.
[15] Advance Measurement Technology (AMETEK), 〈http://www.ortec-online.com/〉.
[16] T. Huus, R. Day, Phys. Rev. 91 (1953) 599.
[17] S.W. Xu, et al., in preparation.
[18] T. Freye, et al., Z. Phys. A 281 (1977) 211.
[19] C. Rolfs, R. Azuma, Nucl. Phys. A 227 (1974) 291.
[20] M. Wang, et al., Chin. Phys. C 36 (2012) 1603.
[21] D.C. Radford, Nucl. Instrum. Methods A 361 (1995) 297.
[22] GEANT4, a Toolkit for the Simulation of the Passage of Particles through Matter Developed at CERN, 〈http://geant4.cern.ch/〉.
[23] D. Zahnow, et al., Z. Phys. A 351 (1995) 229.
[24] C. Rolfs, R.W. Kavanagh, Nucl. Phys. A 455 (1986) 179.
[25] S. Engstler, et al., Z. Phys. A 342 (1992) 471.
[26] J.F. Harmon, Nucl. Instrum. Methods B 40/41 (1989) 507.
[27] C. Iliadis, Nuclear Physics of Stars, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2007.
[28] D. Sekiba, et al., J. Appl. Phys. 106 (2009) 114912.
[29] K. Zhu, et al., private communication.
[30] J.J. He, et al., Nucl. Instrum. Methods A 680 (2012) 43.
[31] A. Lemut, et al., Phys. Rev. ST—Accel. Beams 14 (2011) 100101.
[32] K.T. Lesko, J. Phys.: Conf. Ser. 136 (2008) 022022.
[33] M. Aliotta, The Underground Laboratory at Boulby, CANFRANC Workshop, Barcelona, Feb. 2009.
[34] C. Bordeanu, et al., J. Phys. G: Nucl. Part. Phys. 35 (2008) 01401.
[35] Frontiers in Deep Underground Sciences, Xiangshan Conf. Rep. 349 (2009) 1 (in Chinese).