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Measurement of the Proton Beam Characteristics of Low-energy Accelerators

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Abstract: China JinPing underground Laboratory (CJPL) was established inside the tunnels piercing Jinping Mountain in Sichuan Province, China, which can provide an ideal environment for low background experiment. A new 400 kV accelerator, with high current based on an ECR source, will be placed at this underground laboratory for nuclear astrophysics experiment. The beam characteristics of this accelerator, like absolute energy, energy spread, and long-term energy stability, will be determined by several well-known resonance and non-resonance reactions. Due to the new accelerator still being under construction, the resonance reaction of ^{27}Al(p, γ)^{28}Si and non-resonance ^{12}C(p, γ)^{13}N were studied at the 320 kV high-voltage platform in Institute Modern Physics of CAS in Lanzhou. The energy spread of proton beam is about 1.0 keV at proton energy $E_{\rm p} = 224$ keV and the long-term energy stability of proton beam is much better than 200 eV during 4 hours measurement.

Key words: direct measurement; underground laboratory; resonance reaction

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1 Introduction

One of the most important goal of nuclear astrophysics is to measure the cross section of nuclear reactions of interest in astrophysics. At stars temperatures, these cross sections are very low due to the suppression of the Coulomb barrier. Direct measurement of the cross sections of the key nuclear reactions is important to improve current stellar model, but the small cross section and natural background make the measurements challenging. A way to handle the background problem is to go in an underground environment. Laboratory for Underground Nuclear Astrophysics (LUNA) at Gran Sasso underground laboratory of Italy, as the first underground based low-energy accelerator facility, has successfully demonstrated the feasibility of meeting these challenges and opened the way towards ultra low cross section determination[1–3]. China JinPing underground Laboratory (CJPL) is located at the middle portions of the 17.5 km JinPing tunnels in Sichuan province, southwest China, which has approximately 2400 meters of marble and sandstone above it and is currently the world's deepest underground laboratory with horizontal access[4–6]. The cosmic ray muon flux, 2.0±0.4×10^{-10}/(cm^2·s), is about 2 orders of magnitude lower than that in Gran Sasso, which makes it as an ideal environment for low background experiment[7–9].

Jinping Underground experiment for Nuclear Astrophysics project (JUNA), as one of the major research programs in CJPL-II, aims at direct measurement of (α, γ) and (α, n) reactions in hydrostatic helium burning and (p,γ) and (p, α) reactions in hydrostatic hydrogen and helium burning[10]. In the first phase of JUNA, four key reactions, ^{12}C(α, γ)^{16}O, ^{13}C(α, n)^{16}O, ^{25}Mg(p, γ)^{26}Al and ^{19}F(p, α)^{16}O, will be studied for the first time within or near the astrophysical relevant energy regions (Gamow

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window)[10–12]. A new 400 kV accelerator with high stability and high intensity will be placed in CJPL-II, as shown in Fig. 1. The accelerator is now under construction at China Institute of Atomic Energy(CIAE) and Institute of Moden Physics(IMP), CAS, which will be ready to operate on the ground in the beginning of year 2017 and transport to CJPL in the middle of year 2017. To obtain the information about the beam characteristics, like absolute energy, energy spread and long-term energy stability, a series of experiments of several well-known resonance and non-resonance reactions will be performed ahead of the campaign.

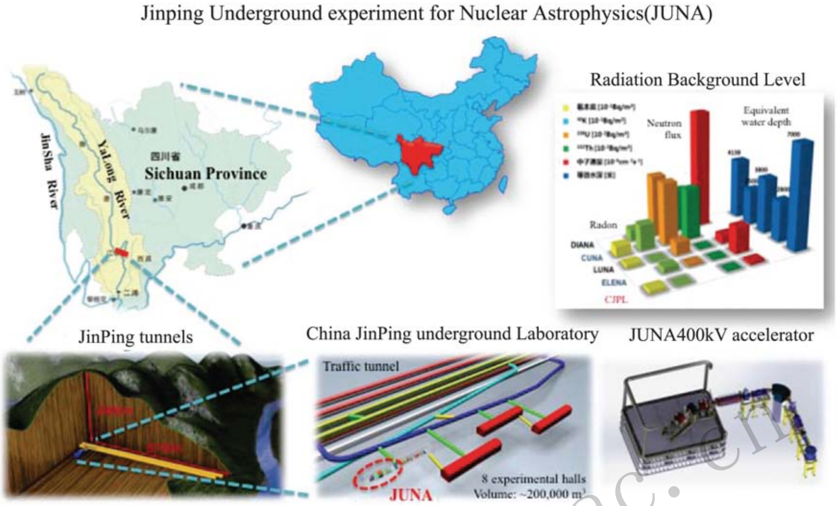

Fig. 1　(color online) Geographical location of JUNA and the radiation background level at CJPL.

The absolute energy can be determined by using the energy of the capture γ-ray transition of $^{12}C(p,\gamma)^{13}N$ as well as resonance energies at $E_p = 163 \sim 389$ keV of $^{11}B(p,\gamma)^{12}C$, $^{23}Na(p,\gamma)^{24}Mg$, $^{25}Mg(p,\gamma)^{26}Al$, $^{26}Mg(p,\gamma)^{27}Al$ and $^{27}Al(p,\gamma)^{28}Si$[2, 13–15]. Study of the resonance reactions may also obtain the value of energy spread and long-term energy stability of beam. A testing experiment for $^{12}C(p,\gamma)^{13}N$ and $^{27}Al(p,\gamma)^{28}Si$ reactions was performed at 320 kV high-voltage platform[16] to determine absolute energy, energy spread and long-term energy stability of proton beam.

2　Experiment setup

The schematic diagram of the experimental setup is shown in Fig. 2. The target chamber is electrically isolated between upstream and downstream sides of the beam line. A $l = 30$ cm long inline Cu shroud

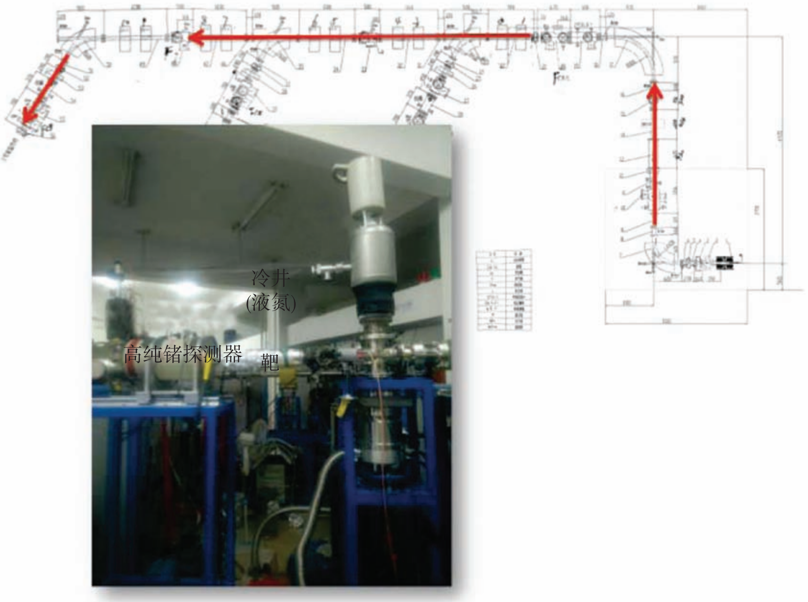

Fig. 2　(color online) Experiment setup at 320 kV high-voltage platform.

(diameter ϕ = 40 mm) cooled to LN_2 temperature was placed from upstream to downstream (close to the target) to minimize carbon build-up on the target surface[13]. A negative voltage of 300 V was applied to Cu shroud to minimize emission of secondary electrons from the target. A High Purity Ge-detector with 70% efficiency (compared to a $3''\times3''$ NaI crystal) was placed at 0° with respect to the beam axis at a distance d=35 mm from the target. The observed energy resolution was ΔE_γ=3.0 keV at E_γ=1.33 MeV.

3 Experimental results

3.1 Study of ^{12}C(p,γ)^{13}N reaction

The ^{12}C(p, γ)^{13}N reaction has been used as an alternative method to determine the absolute proton energy over a wide energy range, due to the smooth cross section of this reaction. The incident energy of proton beam $E_{\rm p}$, which is deduced from high voltage of accelerator, can be precisely determined by the energy of γ-ray from ^{12}C(p, γ)^{13}N reaction:

$$E_\gamma = Q + (12/13)E_{\rm p} + \Delta E_{\rm DC}(0^\circ) - \Delta E_{\rm R} \qquad (1)$$

with Q = 1943.5±0.3 keV[17], $\Delta E_{\rm DC}(0^\circ)$: the Doppler shift at $\theta_\gamma = 0^\circ$, and $\Delta E_{\rm R}$: the nuclear recoil.

A 2-mm thickness graphite target, which can be considered infinitely thick for all proton energies used in the measurement, was bombarded by proton beam at beam energy $E_{\rm p}$ = 250, 260 and 290 keV, and the γ-ray spectra are shown in Fig. 3. A plateau of the capture transition of ^{12}C(p,γ)^{13}N was observed and three background γ-ray peaks were used for the energy calibration. Since the capture cross-section decreases with the proton beam energy, the plateau of γ-ray peak declines towards the low-energy region.

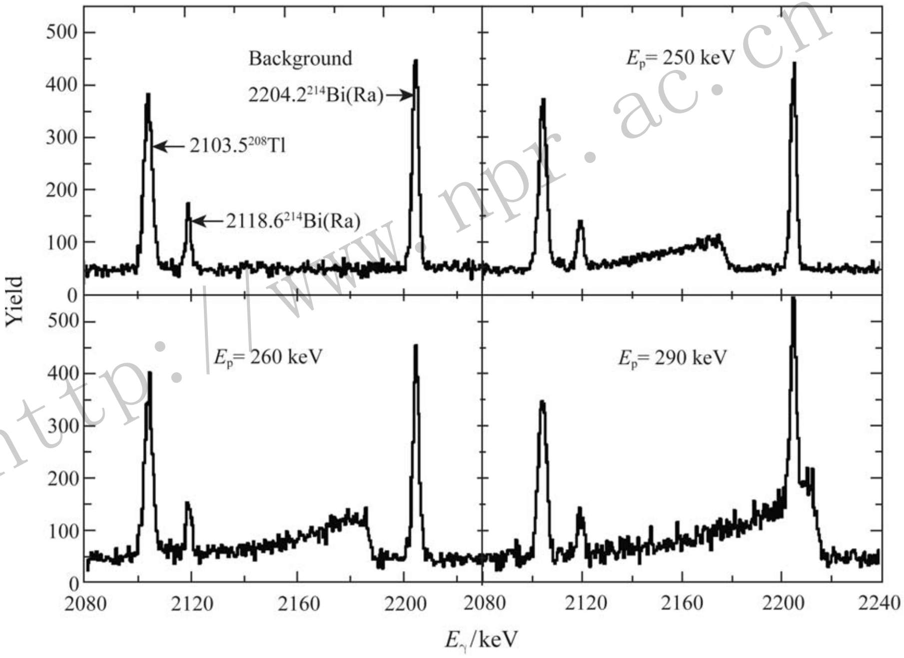

Fig. 3 γ-ray spectra of ^{12}C(p,γ)^{13}N reaction at energy 250, 260, 290 keV and background.

The absolute energy of proton beam is determined by fitting the γ-ray spectra from the observed with GEANT4 simulation, which considered the cross-section decreased with energy loss of the protons in the thick target and the stopping power of the protons in carbon, as shown in Fig. 4. From the fitting results, it suggests that the absolute energy of proton beam is nearly 0.28% lower than that from high voltage of the accelerator.

3.2 Energy spread of proton beam

The energy spread $\Delta E_{\rm B}$ of proton beam has been measured using the 223 keV resonance of ^{27}Al(p,γ)^{28}Si reaction and the upper limit of the resonance width is Γ<34 keV[18]. The yield curve of the 223 keV resonance of ^{27}Al(p,γ)^{28}Si reaction is shown in Fig. 5, where the data points are fitted by an error function. An experimental energy spread of 1.0 keV is deduced from the 25% and 75% points and the resonance energy of 224.4 keV is determined by the 50% point, which has about 1.4 keV shift from the literature[14]. More resonance reactions, like ^{23}Na(p,γ)^{24}Mg, ^{24}Mg(p,γ)^{25}Al, will be studied at 320 kV high voltage platform, thus absolute energy and energy spread of proton beam can be precisely determined.

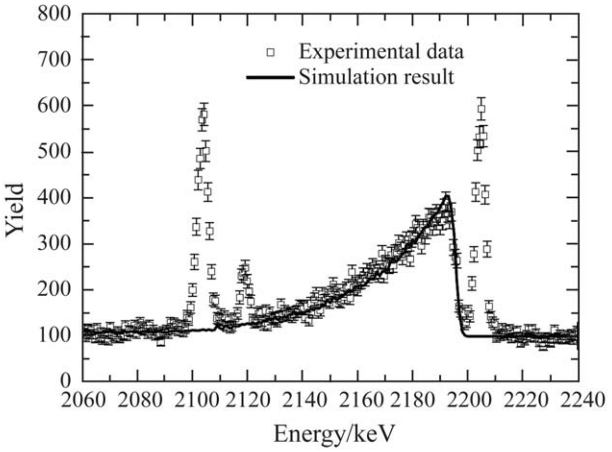

Fig. 4　The γ-ray spectra of ^{12}C(p, γ)^{13}N reaction with E_p = 270 keV is fitted by the simulation result with the incident beam energy of 269.2 keV.

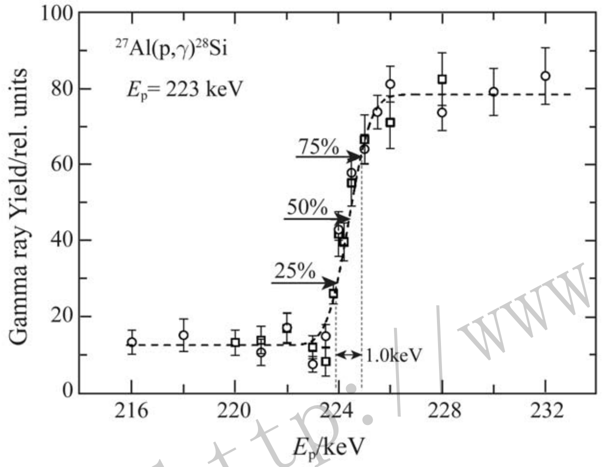

Fig. 5　Thick-target yield curve of the 223 keV resonance of ^{27}Al(p, γ)^{28}Si. The circle and square points show the data at different measurement time. The dashed line through the data points is an error function.

3.3　Long-term energy stability of accelerator

Because the very low cross section of key reaction in astrophysics at star temperature, the long-term energy stability of accelerator is necessary for the experiment. Resonance reaction can also be used to measure it. Due to the steep slope of the yield curve in Fig. 5 near the resonance energy (50% yield point), one can monitor sensitively the long-term energy stability of the accelerator. Fig. 6 shows the energy variation of incident proton beam $\Delta E = \pm 200$ eV, which is deduced from the yield variation at proton energy E_p = 224 keV, during the 4 hours measurement. The variation is mainly from the low statistics during the measurement with low beam current, which indicated that the long-term energy stability of 320 kV accelerator is much better that ±200 eV in 4 hours' measurement.

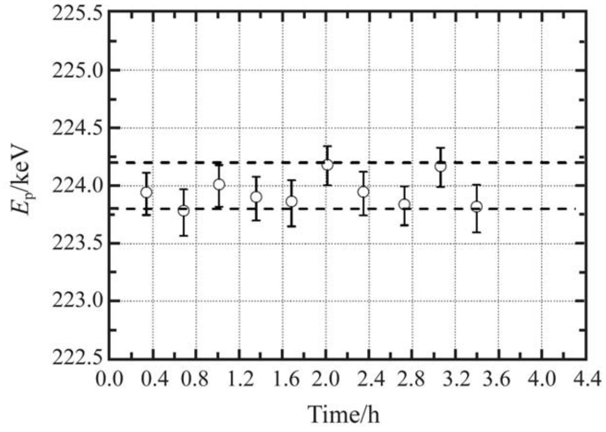

Fig. 6　The result of long-term energy stability measurement. The yield variation at the 50% yield point(in the Fig. 5), which was translated into an energy variation ΔE using the fitting result from Fig. 5, as a function of measurement time. The error bar is from the statistical error.

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低能加速器质子束流性质的测量

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摘要: 中国锦屏地下实验室(CJPL)坐落于四川省锦屏山中，利用水电站修建的隧道建成。由于其本底环境极低，非常适合开展低本底实验测量。一台基于ECR源的400 kV强流加速器将安装在CJPL中，其可以为核天体物理实验提供流强为12 emA的质子束流，6 emA的He^{+}束流和2.5 emA的He^{2+}束流。拟通过非共振反应$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$以及一系列的共振反应$^{27}\mathrm{Al}(\mathrm{p},\gamma)^{28}\mathrm{Si}$等，对加速器的束流能量进行精确刻度，对束流的能量展宽以及长期稳定性进行测量。由于该加速器正在中国原子能科学研究院进行地面调试，我们利用中国科学院近代物理研究所的320 kV研究平台，进行了$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$和$^{27}\mathrm{Al}(\mathrm{p},\gamma)^{28}\mathrm{Si}$反应的测试实验。测量结果表明，在质子束流能量为224 keV时，束流的能量展宽约为1.0 keV，束流能量在连续4小时的测量期间，其晃动幅度远小于± 200 eV。

关键词: 直接测量；深地实验室；共振反应

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