SESSION 14

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Underground nuclear astrophysics experiment JUNA in China

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Abstract. Underground Nuclear Astrophysics in China (JUNA) will take the advantage of the ultra-low background in Jinping underground lab. High current accelerator with an ECR source and detectors were commissioned. JUNA plans to study directly a number of nuclear reactions important to hydrostatic stellar evolution at their relevant stellar energies. At the first period, JUNA aims at the direct measurements of ^{25}Mg(p,γ)^{26}Al, ^{19}F(p,α)^{16}O, ^{13}C(α,n)^{16}O and ^{12}C(α,γ)^{16}O near the Gamow window. The current progress of JUNA will be given.

Keywords. direct measurement, underground laboratory, ^{25}Mg(p,γ)^{26}Al, ^{19}F(p,α)^{16}O, ^{13}C(α,n)^{16}O and ^{12}C(α,γ)^{16}O reactions, the Gamow window, JUNA

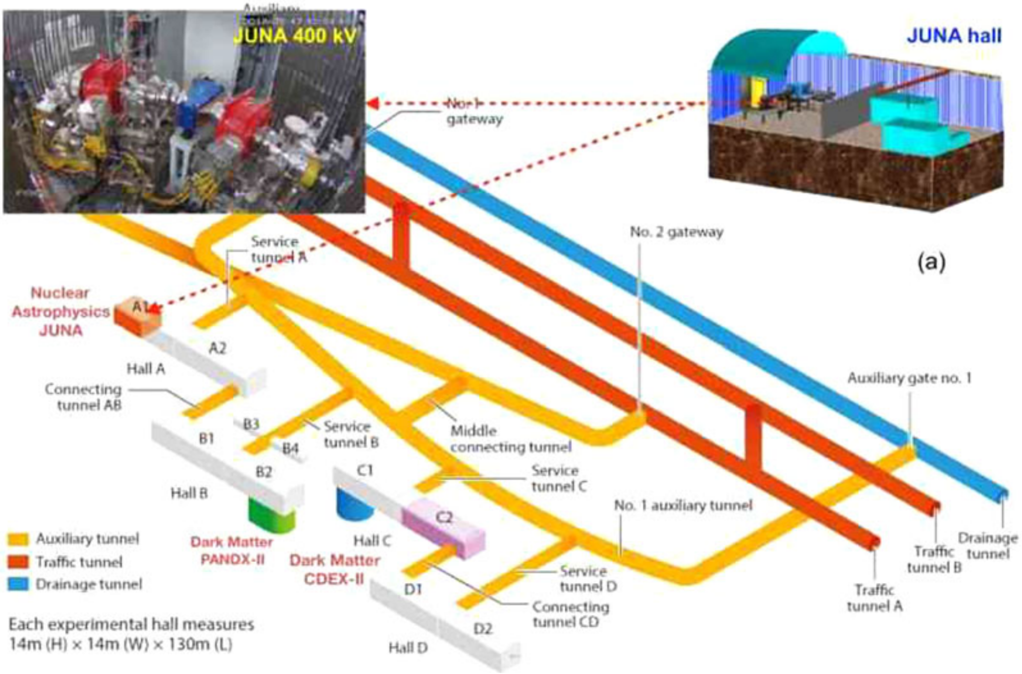

Figure 1. The layout of JUNA in CJPL-II.

1. Underground physics

Direct measurement of the cross sections for the key nuclear reactions crucial to hydrostatic stellar evolution within the Gamow window is important for obtaining benchmark data for stellar models, verifying extrapolation models, constraining theoretical calculations, and solving key scientific questions in nuclear astrophysics Iliadis (2007). The direct measurement of astrophysical reaction rates on stable nuclei that require high-intensity beams and extremely low background represents a major challenge at the frontiers of nuclear astrophysics. The first underground based low-energy accelerator facility, LUNA Formicola *et al.* (2003); Costantini *et al.* (2009) at Gran Sasso underground laboratory has successfully demonstrated the feasibility of meeting these challenges. Encouraged by the LUNA success, underground nuclear astrophysics has became one of the frontiers in the field of nuclear astrophysics. Relevant research programs are proposed in the long range plan in China, US and Europe, with high priorities.

China Jinping underground Laboratory (CJPL) was established on the site of a hydropower plants in the Jinping mountain, Sichuan, China Chen (2010); Cheng *et al.* (2011). The facility is located near the middle of a traffic tunnel. The facility is shielded by 2400 m of mainly marble overburden, with radioactively quiet rock. Its ultra-low cosmic ray background, which is about 2 orders of magnitude lower than that in Gran Sasso, makes it into an ideal environment for low background experiments. CJPL phase I (CJPL-I) is now housing CDEX Zhao *et al.* (2013) and PandaX dark matter experiments. CJPL phase II Normile (2014) (CJPL-II) is expected to be available by the end of 2019 for much larger scale underground experiments (120,000 m^3 volume). Together with CDEX-II and Pandax-II, JUNA will be one of its major research programs in CJPL-II. Liu *et al.* (2016). The layout of JUNA in CJPL-II is shown in Fig. 1

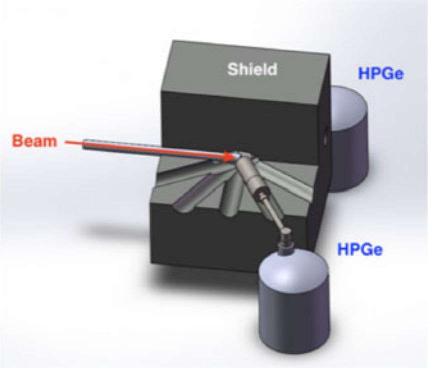

Figure 2. Schematic of ^{12}C(α,γ)^{16}O detection setup.

2. Nuclear astrophysics reactions to be measured

2.1. $^{12}C(\alpha,\gamma)^{16}O$ reaction

The ^{12}C(α,γ)^{16}O reaction is quoted as the holy grail in nuclear astrophysics Rolfs & Rodney (1988). The uncertainty of this reaction affects not only the nucleosynthesis of elements up to iron, but also the evolution of the massive stars and their final fate (black hole, neutron star). The cross section of this reaction needs to be determined with an uncertainty of less than 10% at helium burning temperatures (T_9=0.2), corresponding to the Gamow window around $E_{c.m.}$=300 keV. It is extremely difficult to determine the reaction cross section (about 10^{-17} barn) at such low energy Buchmann (2005). Current ground based technology can only achieve 10^{-14} barn cross section level. A direct measurement at $E_{c.m.}$=600 keV near the Gamow window is planned in JUNA with the high intensity ion beam of the experimental platform to provide better constraints for extrapolating models Liu (2014).

For an angular distribution measurement at $E_{c.m.}$=600 keV, we plan to use ^{4}He^{2+} beam with an intensity of 5 emA and an energy of 800 keV ($E_{c.m.}$=600 keV) to bombard a high-purity ^{12}C target. Two HPGe detectors will be used to obtain the angular distribution of γ-rays emitted by ^{12}C(α,γ)^{16}O reaction. With this information, the R-matrix method will be applied to derive the contribution of the E1 and E2 components and extrapolate the cross section down to the Gamow window. Fig. 2 shows the setup of two HPGe detectors and the high-purity ^{12}C implantation target.

For total cross section measurements at $E_{c.m.}$=600 keV, with the results of angular distribution measurements at $E_{c.m.}$=600, we will optimize the experimental conditions, including: 1) optimizing the beam transmission on the basis of the beam-optics calculation, adjusting the setup of shields to suppress the background coming from the beam, 2) confirming the origin of ^{13}C and improving the implantation condition of ^{12}C implantation target to reduce the disturbance of ^{13}C. The BGO detector array placed around the target chamber can significantly increase the detection efficiency (absolute efficiency 60% at E_γ = 6 MeV) of γ-rays. With the improvement above, an accurate total cross section will be obtained.

For the total cross section test measurement at $E_{c.m.}$=450 keV, we will use ^{4}He^{2+} beam with an intensity of 2 emA and the high-efficiency BGO detection array. A direct measurement of the total cross section of ^{12}C(α,γ)^{126}O in the energy region of near the Gamow window will be tested.

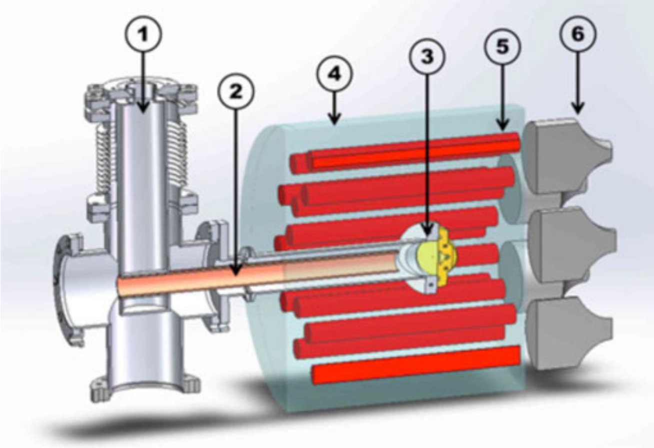

Figure 3. Schematic drawing of low background highly sensitive fast neutron detector. 1) LN_2 cold trap; 2) Copper tube; 3) high power ^{13}C target; 4) Liquid scintillator; 5) ^{3}He detectors; 6) PMTs.

2.2. $^{13}C(\alpha,n)^{16}O$ reaction

The ^{13}C(α,n)^{16}O reaction is the key neutron source reaction for the stellar s-process nucleosynthesis. Due to the existence of sub-threshold resonances, there is a rather large uncertainty (30%) in this important reaction rate which limits our understanding of the nucleosynthesis of heavy elements. We will take the advantage of the ultra low background in Jinping underground lab, the first underground high current accelerator based on an ECR source and high sensitive neutron detector to study directly this important reaction for the first time at energies down to $E_{c.m.}$ ~0.2 MeV, within its relevant stellar energy range Tang (2014).

We are developing a fast neutron detector consisting of 24 ^{3}He proportional counters and a liquid scintillator. The schematic setup of the detector is shown in Fig. 3. The scintillator has a cylindrical shape with a length of 0.4 m and a diameter of 0.4 m. The 24 ^{3}He counters are distributed in the two circles with radii of 0.1 m and 0.15 m, respectively.

The energies of neutrons from the ^{13}C(α,n)^{16}O reaction are in the range of 2 to 3 MeV. The produced neutrons are firstly slowed down by the liquid scintillator. After their thermalization, some neutrons enter ^{3}He counters and are detected. With the coincidence between the fast signal from fast neutron slowing down inside the liquid scintillator and the delayed signal from the thermalized neutrons captured by the ^{3}He counters, we can effectively suppress the backgrounds in liquid scintillator and ^{3}He detectors. The detection efficiency after coincidence is measured to be 20% for neutrons from the ^{13}C(α,n)^{16}O reaction.

2.3. $^{25}Mg(p,\gamma)^{26}Al$ reaction

The ^{25}Mg(p,γ)^{26}Al reaction is the main way to produce ^{26}Al in the galaxy and its cross sections are dominated by the capture process of the isolated resonances in ^{26}Al. The temperature range of astrophysical interest is $T = 0.02$-2 GK, so the levels between 50 keV and 310 keV are more important in the study of galactic ^{26}Al. Many experiments have been performed to study the ^{25}Mg(p,γ)^{26}Al reaction since 1970 (Betts *et al.* (1978); Champagne *et al.* (1983); Endt *et al.* (1986); Champagne *et al.* (1986); Endt & Rolfs (1987); Champagne *et al.* (1989); Rollefson *et al.* (1990); Iliadis *et al.* (1990, 1996); Powell *et al.* (1998); Arazi *et al.* (2006)), but the experiment on the surface of earth ground can

Figure 4. The HPGe, BGO, neutron and charged particle detector arrays for JUNA.

only reach the 190 keV energy level due to the small cross section and large background effects of the cosmic rays. In 2012, the laboratory of underground nuclear astrophysics (LUNA) in Italy successfully measured the resonance strength at 92 keV with the help of high shielding conditions in the underground laboratory Strieder *et al.* (2012); Straniero *et al.* (2013). However, the $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$ cross section of 58 keV resonant capture is inaccessible for direct measurement in the shielding conditions of LUNA experiments. The underground laboratory of Jinping in China covered with a 2400 meter-high marble rock. Benefiting from the ultra low background and the high beam intensity, we will be able to measure the 58 keV resonance strength of $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$ with the newly commissioned 4π BGO γ detectors array, as shown in Fig 4, with energy resolution of 11 % @ -20 deg cooling @ 7 MeV.

In order to optimize the experimental setup for the $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$ reaction at the laboratory of Jinping underground nuclear astrophysics (JUNA), the resonance strength of 58 keV level is estimated by using the shell model calculation. The results show that the 58 keV resonance dominate the $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$ reaction rate at $T < 0.06$ GK Li *et al.* (2015). The thick-target yield of the 58 keV resonance of $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$ with the calculated resonance strength is estimated under the conditions of JUNA with 10 mA proton beams and 4π BGO γ-ray detector.

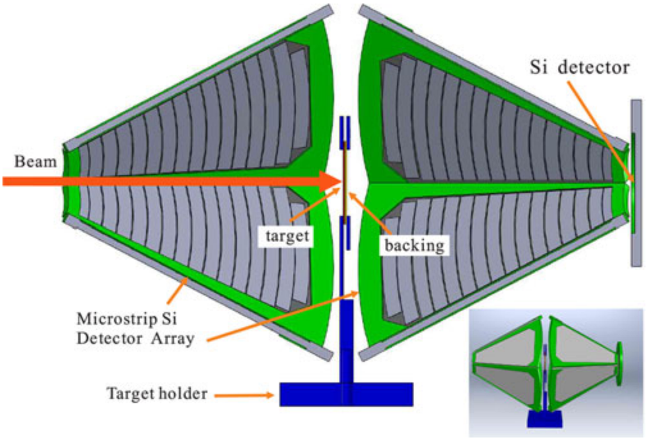

Figure 5. Conceptual silicon detector array designed for measuring the charged particles.

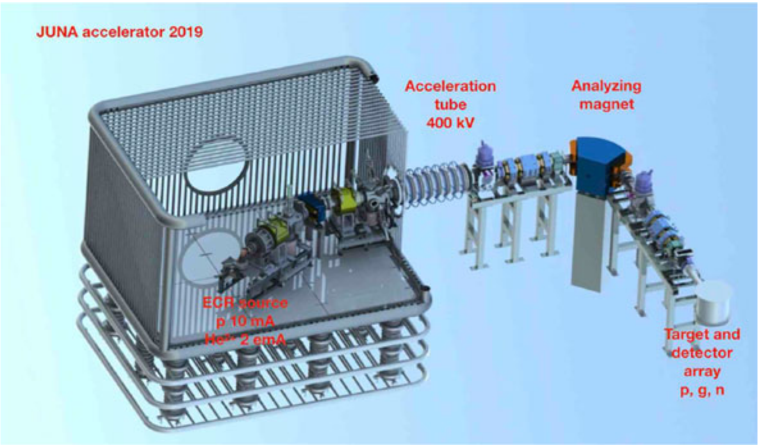

Figure 6. JUNA high current accelerator system.

2.4. $^{19}F(p,\alpha)^{16}O$ reaction

The ^{19}F$(p,\alpha)^{16}$O reaction is considered to be an important reaction in the CNO cycles. Currently, the experimental cross sections of this reaction at Gamow energies are still incomplete, and the precision of its thermonuclear reaction rate does not yet satisfy the model requirement. The proposed experiment is targeting the direct cross section measurement of the key ^{19}F$(p,\alpha)^{16}$O reaction right down to the Gamow energies (70–350 keV in the center-of-mass frame) with a precision better than 10 % (He 2014).

A ‘lamp’-type Micron silicon array is commissioned with energy resolution of 1 % @ −20 deg for the charged particle measurement, which can cover about 4π solid angle. This universal detection array will set the base for studying the charged-particle-induced reactions at JUNA. A conceptual design is shown in Figures 5 & 6. Not only can it measure the total (p,α_0) cross section but also the angular distribution. The experimental angular distribution is very useful for revealing nuclear structure of the low-energy resonances. In this experiment, a thin target of about 4 μg/cm^2 CaF$_2$ will be utilized, which is evaporated on a thin metal backings. Thanks to the high Q value (about 8.11 MeV) for this reaction, the average energy for the emitted α particles is about 6.7 MeV. These relatively high-energy particles can penetrate the backings and be detected easily at the

Table 1. Basic parameters of four reactions planned.

reaction	beam	intensity (emA)	c.m. energy (keV)	cross section	target thickness	efficiency %	CTS (/day)	BKD (/day)
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$	$^{4}\mathrm{He}^{2+}$	2	450	3×10^{-12} mb	10^{18} atoms/cm^2	60	1	1
$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$	$^{4}\mathrm{He}^{1+}$	10	200	10^{-12} mb	10^{21} atoms/cm^2	20	7	1
$^{25}\mathrm{Mg}(\mathrm{p},\gamma)^{26}\mathrm{Al}$	$^{1}\mathrm{H}^{1+}$	10	58	$\omega\ \gamma\ 2\times10^{-13}$ eV	0.6 μg/cm^2	38	2	1
$^{19}\mathrm{F}(p,\alpha_\gamma)^{16}\mathrm{O}$	$^{1}\mathrm{H}^{1+}$	0.1	100	7×10^{-9} mb	4 μg/cm^2	60	24	1

Table 2. Comparison of the goal for four reaction with current status.

reaction	Gamow Energy (keV)	current limit (keV)	precision (%)	ref.	JUNA goal (keV)	precision (%)
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$	220–380	890	60	Hammer *et al.* (2005)	450	test
$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$	140–230	279	60	Drotleff *et al.* (1993)	200	20
$^{25}\mathrm{Mg}(\mathrm{p},\gamma)^{26}\mathrm{Al}$	50–300	92	20	Strieder *et al.* (2012)	58	15
$^{19}\mathrm{F}(p,\alpha_\gamma)^{16}\mathrm{O}$	50–350	189	80	Lombardo *et al.* (2015)	100	10

forward angle. A ground based $^{19}\mathrm{F}(p,\alpha)^{16}\mathrm{O}$ test run was achieved with full detection of α and γ events by using CaF_2 target in Lanzhou 320 kV platform.

2.5. *Summary of the four reactions*

The counting rates and background of four reactions are estimated. The counting rate are estimated according to the updated evaluation and/or the best extrapolation. The counting rate are deduced from the CJPL-I environment and detector γ and neutron measurement data. The results are summarized in Table 1. We also compared our expected precision of data with current experimental results. The results are summarized in Table 2.

3. Accelerator, detector and shielding system

We built a 2.45 GHz ECR source which is developed for the CIADS project. This ion source is achieved to deliver 10 emA proton, 6 emA He^{+} and 2 emA He^{2+} (by a separate ion source). The maximum beam energy out of the ion source is 50 keV/q with emittance less than 0.2 π·mm·mrad. The Low Energy Beam Transport line (LEBT) is installed to minimize the space charge effect and improve the beam transport efficiency. The beam will be accelerated before being focused with two solenoids. To keep the LEBT as short as possible, all the steering magnets are built inside the solenoids. He^{2+} beam is expected to be mixed with a large fraction of the He^{+} beam. A 30 deg magnet will be added between the two solenoids to filter out the intense He^{+} to reduce the burden of the acceleration tube.

For the low energy and high intensity beams, the space-charge effect must be controlled during transmission in order to increase the transport efficiency. The high transport efficiency could not only insure enough beam intensity on target, but also reduce the background brought by the beam itself. We adapted segmental voltage for the accelerating tube and designed an acceleration and deceleration structure for the accelerating tube electrode to reduce the space-charge effect. The machine has delivered 400 hours of user time for ground base test of above 4 experiments.

The effect to background ratio of the nuclear reaction measurement will be significantly enhanced with the ultra-low background of CJPL and high current beam. But at the same time the high current beam will bring new background, which must be shielded. We constructed two shielding system around the target chamber and the detectors, aiming at shielding γ-ray and neutron, respectively.

4. Summary

In summary, a new underground nuclear astrophysics experiment JUNA planned for the expanded space CJPL-II was developed. The plan is to set up a particle accelerator and detectors to replicate the nuclear processes generating energy within stars and the synthesis of heavier elements from hydrogen and helium in the primordial universe. The rock shielding would reduce background noise, making it easier for researchers to detect rare and subtle signals. With a more powerful accelerator and a deeper location than other efforts, JUNA has the potential to occupy a key position among underground nuclear astrophysics laboratories. The accelerator system and detector array will be installed in 2020, the experiments will start in mid 2021 and the first experimental result will be delivered in 2021. This work was performed with the support of the NSFC under Grant No. 11490560, CNNC innovation fund, CAS instrument fund.

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