Few-Body Syst (2022) 63:43
https://doi.org/10.1007/s00601-022-01735-3

**W. P. Liu · Z. H. Li · J. J. He · X. D. Tang · G. Lian ·
J. Su · Y. P. Shen · Z. An · F. Q. Chao · J. J. Chang ·
L. H. Chen · H. Chen · X. J. Chen · Y. H. Chen · Z. J. Chen ·
B. Q. Cui · X. C. Du · X. Fang · C. B. Fu · L. Gan · B. Guo ·
Z. Y. Han · X. Y. Guo · G. Z. He · J. R. He · A. Heger ·
S. Q. Hou · H. X. Huang · N. Huang · B. L. Jia · L. Y. Jiang ·
S. Kubono · J. M. Li · M. C. Li · K. A. Li · E. T. Li · T. Li ·
Y. J. Li · M. Lugaro · X. B. Luo · H. Y. Ma · S. B. Ma ·
D. M. Mei · W. Nan · W. K. Nan · N. C. Qi · Y. Z. Qian ·
J. C. Qin · J. Ren · C. S. Shang · L. T. Sun · W. L. Sun ·
W. P. Tan · I. Tanihata · S. Wang · P. Wang · Y. B. Wang ·
Q. Wu · S. W. Xu · S. Q. Yan · L. T. Yang · Y. Yang ·
X. Q. Yu · Q. Yue · S. Zeng · L. Zhang · H. Zhang ·
H. Y. Zhang · L. Y. Zhang · N. T. Zhang · P. Zhang ·
Q. W. Zhang · T. Zhang · X. P. Zhang · X. Z. Zhang ·
W. Zhao · J. F. Zhou · Y. Zhou**

Progress of Underground Nuclear Astrophysics Experiment JUNA in China

Received: 18 October 2021 / Accepted: 14 February 2022 / Published online: 13 April 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Austria, part of Springer Nature 2022

Abstract Underground Nuclear Astrophysics Experiment in China (JUNA) takes the advantage of the ultra-low background in Jinping underground lab. High current mA level 400 KV accelerator with an ECR source, BGO and neutron detectors were commissioned. JUNA studies directly a number of nuclear reactions important

---

This work was supported by NSFC under Grant No. 11490560, CNNC innovation fund, CAS instrument fund.

W. P. Liu (✉)· Z. H. Li · G. Lian · Y. P. Shen · F. Q. Cao · L. H. Chen · X. J. Chen · B. Q. Cui · B. Guo · Z. Y. Han · G. Z. He · H. X. Huang · L. Y. Jiang · Y. J. Li · W. Nan · W. K. Nan · J. C. Qin · J. Ren · Y. B. Wang · S. Q. Yan · S. Zeng · L. Zhang · H. Zhang · W. Zhao
China Institute of Atomic Energy, Beijing, China
E-mail: wpliu@ciae.ac.cn

X. D. Tang · J. J. Chang · H. Chen · Z. J. Chen · S. Q. Hou · B. L. Jia · K. A. Li · T. Li · Y. H. Ma · S. B. Ma · L. T. Sun · Q. Wu · S. W. Xu · Y. Yang · X. Q. Yu · N. T. Zhang · X. Z. Zhang · Z. M. Zhang
Institute of Modern Physics, Lanzhou, China

Q. H. Chen · J. M. Li · Q. Yue· L. Y. Yang · H. Zhang · W. Zhao
Tsinghua University, Beijing, China

Z. An
Sichuan University, Chengdu, China

C. B. Fu
Shanghai Jiaotong University, Shanghai, China

to hydrostatic stellar evolution at their relevant stellar energies. In the first quarter of 2021, JUNA performed the direct measurements of $^{25}\text{Mg}(\text{p}, \gamma)^{26}\text{Al}$, $^{19}\text{F}(\text{p}, \alpha)^{16}\text{O}$, $^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$ and $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ near the Gamow window. The experimental results reflect the potential of JUNA with higher statistics, precision and sensitivity of the data. The preliminary results of JUNA experiment and future plan are given.

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 calculation, verifying extrapolation method, constraining theoretical calculations, explaining the abundance observations and solving key scientific questions in nuclear astrophysics [1].

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 due to the cosmic ray background and extremely low cross section, thus the combination of underground laboratory and high exposure accelerator/detector complex is the only solution.The first underground based low-energy accelerator facility, LUNA [2,3] at Gran Sasso underground laboratory has successfully demonstrated the feasibility of meeting these challenges. Encouraged by the LUNA success, underground nuclear astrophysics has become 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, such as JUNA, LUNA and CASPER.

A. Heger
Monash University, Melbourne, VIC, Australia

S. Kubono
RIKEN, Institute of Physical and Chemical Research, Wako, Japan

M. Lugaro
Konkoly Observatory of the Hungarian Academy of sciences, Budapest, Hungary

D. M. Mei
South Dakota State University, Brookings, SD, USA

Y. Z. Qian
Minnesota University, Minneapolis, Saint Paul, MN, USA

W. P. Tan
University of Notre Dame, Notre Dame, IN, USA

I. Tanihata
Osaka University, Suita, Osaka, Japan

S. Wang
Shandong University, Weihai Campus, Weihai, China

L. Gan · R. T. Li
Shenzhen University, Shenzhen, China

X. Fang
Zhongshan University, Guangzhou, China

J. J. He · J. Su · L. Y. Zhang
Beijing Normal University, Beijing, China

Y. H. Chen · X. Y. Guo · J. R. He · M. C. Li · N. C. Qi · C. S. Shang · W. L. Sun · P. Zhang · J. F. Zhou · Y. Zhou
Yalong River Hydro-Electronic Power Limited, Sichuan, China

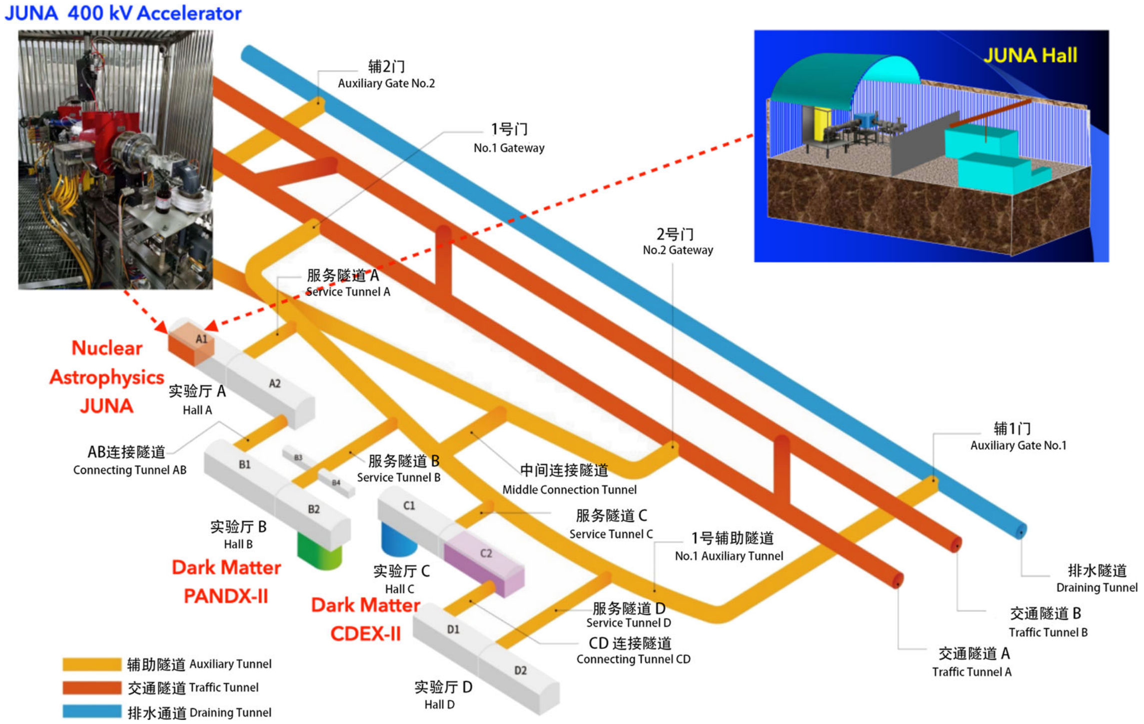


Fig. 1 The layout of JUNA in CJPL-II

China Jinping Underground Laboratory (CJPL) was established on the site of a hydro-power plants in the Jinping mountain, Sichuan, China [4,5]. The facility is located near the middle of a traffic tunnel. The facility is shielded by 2400 m of mainly marble overburden (6720 m.w.e.), with radioactively quiet rock. Its ultra-low cosmic ray background makes it into an ideal environment for low background experiments. CJPL phase I (CJPL-I) is now housing CDEX [6] and PandaX dark matter experiments.

CJPL phase II [7] (CJPL-II) is the expansion followed by the success of CJPL-I, it currently available for temporary usage in year 2020–2021. It has much larger scale underground experiments space (300,000 m^3 volume), planned to house CDEX-II, PandaX-II, and JUNA [8]. The layout of JUNA in CJPL-II is shown in Fig. 1. The complete commissioning of CJPL-II is scheduled in March 2023, when all the three experiments can be restarted in a well equipped condition. In December of 2020, the JUNA collaboration installed the accelerator in CJPL-II before the long-period construction. Four reactions had been studied in the first quarter of 2021. Some preliminary results are presented in the following section.

2 Nuclear Astrophysics Reactions Measured

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

The $^{12}C(\alpha, \gamma)^{16}O$ reaction is quoted as the holy grail reaction in nuclear astrophysics [9]. 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 [10,19]. A direct measurement near the Gamow window is planned in JUNA with high intensity $^4He^{2+}$ ion beam to provide better constraints for extrapolating models [11].

We established the experimental conditions, including: (1) optimizing the beam transmission on the basis of the beam-optics calculation and collimator, adjusting the setup of shields to suppress the background coming from the beam and rock decay, (2) confirming the origin of ^{13}C and improving the depositing condition of isotope pure ^{12}C implantation target to reduce the disturbance of ^{13}C (with the ratio of less than 10^{-5}), (3) suppressing the neutron-induced background with the fired number of BGO array. The BGO and LaBr detector array placed around the target can significantly increase the detection efficiency (absolute efficiency 30% at $E_\gamma = 8$ MeV for BGO with fired number selected) of γ-rays. With the improvement above, an accurate total cross section can be obtained with the flexibility of cross anti-coincidence to decrease the beam induced background.

We used $^4He^{2+}$ beam with an intensity near 1 emA to achieve the most sensitive upper limit of 10^{-12} barn at $E_{c.m.} = 538$ keV. At the moment, we only deduced upper limit of this reaction near Gamow window, since the accelerator and target induced background [23] is higher than we expected. Further effects need to be done, for higher intensity beam, higher purity target and higher vacuum, planned for the coming second stage JUNA run.

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

The $^{13}C(\alpha, n)^{16}O$ reaction is the key neutron source reaction for the stellar s-and i-process nucleosynthesis [20]. Due to the existence of sub-threshold resonances, there is a rather large uncertainty ($> 40\%$) in this important reaction rate which limits our understanding of the nucleosynthesis of heavy elements. We are planning for the first time at energies close to $E_{c.m.} \sim 200$ keV, within its relevant stellar energy range [12].

A neutron detector array with two different configurations has been developed to detect the neutrons from the $^{13}C(\alpha, n)^{16}O$ reaction in the range of 2.3–2.6 MeV. The first configuration of the array consists of 24 ^3He proportional counters and a large plastic scintillator. The scintillator has a cylindrical shape with a length of 0.4 m and a diameter of 0.4 m. The 24 ^3He counters are distributed in the two circles with radii of 0.1 and 0.15 m, respectively. The alpha background can be effectively suppressed by using the coincidence of plastic scintillator and the ^3He counters. The second configuration of the array is similar to the first one except that the plastic scintillator is replaced with a plastic moderator shielded by borated polyethylene.

The second configuration of the array was used in the measurement in the underground lab. After underground experiment, the detector was shipped to Tandem accelerator laboratory in Sichuan University where its efficiency was calibrated with the $^{51}V(p, n)^{51}Cr$ reaction.

The $^{13}C(\alpha, n)^{16}O$ reaction was studied in the range of $E_{c.m.} = 240$–600 keV using the $^4He^{1+}$ and $^4He^{2+}$ beams from the JUNA accelerator. The beam intensities varied from 0.1 to 2 pmA. The total beam time was 14 days. The problem of target deterioration was solved by replacing the conventional thin targets with 2-mm thick ^{13}C targets. Well above background neutron events were detected. The final result will be available in the near future.

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

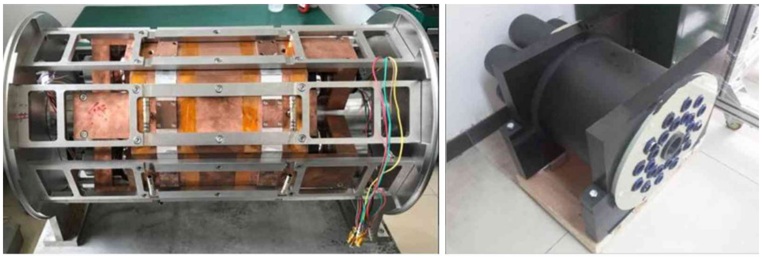
The $^{25}Mg(p, \gamma)^{26}Al$ reaction is the main way to produce ^{26}Al in the galaxy and its cross sections are dominated by the capture process of the isolated resonances in ^{26}Al. The temperature range of astrophysical interest is $T = 0.02$–2 GK, so the levels between 50 and 310 keV are more important in the study of galactic ^{26}Al. Many experiments have been performed to study the $^{25}Mg(p, \gamma)^{26}Al$ reaction since 1970 [13,14], but the experiment on the surface of earth ground can only reach the 189 keV energy level due to the small cross section and large background effects of the cosmic rays. In 2012, LUNA successfully measured the resonance strength at 92 keV with the help of high shielding conditions underground [15,16].

However, the uncertainty of $^{25}Mg(p, \gamma)^{26}Al$ cross section of 92 keV resonant capture is still needed for more direct measurement. Benefiting from the ultra low background and the high beam intensity, we measured the above resonance strength [17] with the newly commissioned 4π BGO γ detectors array, as shown in Fig. 2, with energy resolution of 11% @ −20 degree cooling.

At the moment, we measured the resonance width of 92 and 189 keV with higher precision, which provide a cross check for LUNA results.

The thick-target yields of the 92 and 189 keV resonances of $^{25}Mg(p, \gamma)^{26}Al$ were measured with 2 pmA proton beams and 4π BGO γ-ray detector. The event rate of the $^{25}Mg(p, \gamma)^{26}Al$ reaction at $E_{\mathrm{c.m.}} = 92$ keV is about 200 events per day. The background counting rate is measured to be less than 5 events per day. Thus we accumulated around 1200 reaction events in two weeks, and the statistic uncertainty is about 3% with total exposure of 1225 coulomb proton beam.

The resonance strength of 58 keV level is estimated by using the shell model calculation and the in-direct measurement by $^{25}Mg(^7Li, ^6He)^{26}Al$ one nucleon transfer reaction [17]. The results show that the 58 keV



BGO array
ΔE/E = 13%@662 keV;
ε = 60%@7 MeV

He & LS
ε = 25%@2 MeV

Fig. 2 The BGO and neutron detector arrays for JUNA

resonance dominate the ^{25}Mg$(p,\gamma)^{26}$Al reaction rate at $T < 0.06$ GK [17]. Thanks for our indirect deduction of 58 keV, and our ground based experimental results for 304 keV, based on our underground data for 92 and 189 keV resonances, we are able to build up most precise reaction rate for all temperatures, together with that of LUNA data, the results is published [25].

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 [21]. 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 on the direct cross section measurement of the key ^{19}F$(p,\alpha)^{16}$O reaction right down to the Gamow energies ($E_{c.m.} = 70$–350 keV) with a precision better than 10% [18].

A ground based ^{19}F$(p,\alpha)^{16}$O test run was achieved with full detection of α and γ events by using CaF$_2$ target in Lanzhou 320 kV platform.

For the ^{19}F$(p,\alpha_\gamma)^{16}$O channel, the energies of emitted γ rays are about 6–7 MeV. With the 4π BGO array as introduced above, absolute efficiency is about 60%, but with moderate resolution. Here, the HPGe array will be utilized in $E_{c.m.} > 140$ keV energy region, while the BGO array will be used below this energy region. With the excellent resolution of the HPGe detector for ground experiments, the possible contaminations were resolved and identified clearly, which makes the BGO γ-ray identification reliable at lower-energy region.

The ground based studies were mainly done on the 320 kV platform at IMP Lanzhou. In the period of 2015–2016, several tests for the proposed experiment were carried out, in order to check: (1) the stability of the thin CaF$_2$ target against the high current, about several tens of μA of proton; (2) the contaminants in the forward angle; (3) the chemical compositions of the target. In the period of 2017–2020, many tests were done on the JUNA accelerator which located aboveground at CIAE, to optimize the durable and strong implanted fluorine targets. And finally, an optimum target scheme was selected: first, implanting fluorine ions into the pure Fe backings with an implantation energy of 40 keV, and then sputtering a 50 nm thick Cr layer to further prevent the fluorine material loss.

Up to now, the underground ^{19}F run provide us two data, one is planned ^{19}F$(p,\alpha_\gamma)^{16}$O, in which we extend to a lowest energy point of $E_{c.m.} = 72$ keV, [24] the other is ^{19}F$(p,\gamma)^{20}$Ne, in which we extended to a lowest energy point of 188 keV and observed a new resonance at 225 keV. It is interesting to mention the later data reveal that the reaction rate is about 4 times higher than previous evaluation, and such larger leakage from CNO cycle may shed the light to explain the Ca abundance in the first generation Pop III stars, the simulation of astrophysics implications is in progress.

The parameters of four reactions are summarized in Table 1.

We built a 2.45 GHz ECR source which is developed for the China ADS project (CIADS). This ion source is achieved to deliver up to 10 emA proton, 6 emA ^{4}He$^+$ and 2 emA ^{4}He^{2+} (by a separate ion source) [22]. The maximum beam energy out of the ion source is 50 keV/q with emittance less than 0.2 $\pi\cdot$mm$\cdot$mrad. The Low Energy Beam Transport line (LEBT) is installed to minimize the space charge effect and improve the beam transport efficiency. The beam is accelerated before being focused with two solenoids. To keep the LEBT as short as possible, all the steering magnets are built inside the solenoids. Since ^{4}He^{2+} beam is expected to be

Table 1 Basic parameters of four reactions studied

Reaction	Beam	Intensity (emA)	$E_{c.m.}$ (keV)	Target thickness	Efficiency %	Counts (/day)	BKD (/day)
$^{12}C(\alpha,\gamma)^{16}O$	$^{4}He^{2+}$	1	538	10^{18} atoms/cm^2	60	–	1.2
$^{13}C(\alpha,n)^{16}O$	$^{4}He^{1+,2+}$	2	230–600	2 mm	26	97 ± 24	113 ± 5
$^{25}Mg(p,\gamma)^{26}Al$	$^{1}H^{1+}$	2	$E_x = 92$	60 μg/cm^2	38	200	10
$^{19}F(p,\alpha_\gamma)^{16}O$	$^{1}H^{1+}$	0.5–1.0	72–344	4 μg/cm^2	60	24	1

mixed with a large fraction of the $^{4}He^{1+}$ beam. A 30 deg magnet will be added between the two solenoids to filter out the intense $^{4}He^{1+}$ to reduce the burden of the acceleration tube and to purify the beam.

3 Summary

In summary, a new underground nuclear astrophysics experiment JUNA planned for the expanded space CJPL-II was developed. With a more powerful accelerator and a deeper location, JUNA has the potential to join the research among underground nuclear astrophysics laboratories. The accelerator system and detector array was installed by the end of 2020, the experiments started in the beginning 2021 and the first four experimental data accumulated in the first quarter of 2021. The astrophysical implications base on those data is going on, with the published result hopefully available in the middle and end of 2021.

In the coming years before the re-opening in 2023, we will put more efforts to enhance beam intensity, target purity, as well as improving detectors. Future upgrading is planned (JUNA-II), by considering to build a MV level Van de Graaff for ^{12}C and ^{16}O beam in inverse kinematics and window-less targets as well as recoil spectrometers. We welcome the researchers world wide to join JUNA to perform more experiments by using the most favorable underground condition in Jinping.

References

1. C. Iliadis, *Nuclear Physics of Stars* (Wiley-VCH Verlag GmbH, 2007)
2. A. Formicola, G. Imbriani, M. Junker et al., Nucl. Instrum. Methods Phys. Res. **507**, 609–616 (2003)
3. H. Costantini, A. Formicola, G. Imbriani et al., Rep. Prog. Phys. **972**, 086301 (2009)
4. H.S. Chen, Science **62**, 4 (2010). (**in Chinese**)
5. J.P. Cheng, S.Y. Wu, Q. Yue et al., Physics **03**, 149–154 (2011). (**in Chinese**)
6. W. Zhao, Q. Yue, K.J. Kang et al., Phys. Rev. D **88**, 1201–1205 (2013)
7. D. Normile, Science **346**, 1041–1041 (2014)
8. W.P. Liu et al., Sci. China Phys. Mech. Astron. **59**, 642001-1–640001-7 (2016)
9. C. Rolfs, W. S. Rodney, *Cauldrons in the Cosmos* (The University Chicago Press, 1988)
10. L. Buchmann, Nucl. Phys. A **758**, 335c–362c (2005)
11. W.P. Liu, The $^{12}C(\alpha,\gamma)^{16}O$ reaction proposal (in Chinese) (2014). Unpublished
12. X.D. Tang, The $^{13}C(\alpha,n)^{16}O$ reaction proposal (in Chinese) (2014). Unpublished
13. R.R. Betts, H.T. Fortune, D.J. Pullen, Nucl. Phys. A **299**, 412–428 (1978)
14. A. Arazi, T. Faestermann, J.O.F. Niello et al., Phys. Rev. C **74**, 025802 (2006)
15. F. Strieder, B. Limata, A. Formicola et al., Phys. Lett. B **707**, 60–65 (2012)
16. O. Straniero, G. Imbriani, F. Strieder et al., Astrophys. J. **763** (2013)
17. Z.H. Li, J. Su, Y.J. Li et al., Sci. China Phys. Mech. Astron. **58** (2015)
18. J.J. He, Sci. China Phys. Mech. Astron. **59**, 652001 (2016)
19. J.W. Hammer, M. Fey, R. Kunz et al., Nucl. Phys. A **758**, 363–366 (2005)
20. H.W. Drotleff, A. Denker, H. Knee et al., Astrophys. J. **414**, 735–739 (1993)
21. I. Lombardo, D. Dell'Aquila, A.D. Leva et al., Phys. Lett. B 178–182 (2015)
22. G. Lian, The JUNA platform proposal (in Chinese) (2014). Unpublished
23. Y.P. Chen et al., Sci. China Phys. Mech. Astron. **60**, 102022 (2015)
24. L.Y. Zhang, et al., Phys. Rev. Lett. **12**, 152702 (2021)
25. J. Su et al., Science Bulletin **67**, 2 (2022)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.