First Results from the Underground Nuclear Reaction Experiments in JUNA

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The China Jinping Underground Laboratory phase Ⅱ [1] (CJPL-Ⅱ) is the expansion project following the success of CJPL-I. A temporary usage in the year 2020–2021 enabled the Underground Nuclear Astrophysics Experiment in China (JUNA) phase I experiments presented here. Once commissioned in 2023, CJPL-Ⅱ will occupy a much larger underground space (300000 m^3 in volume) for conducting experiments and is planned to house CDEX-Ⅱ, PandaX-Ⅱ, and JUNA. [2] The main progress of JUNA in CJPL-Ⅱ is displayed in Fig. 1.

In December 2020, with the collaboration of JUNA, an accelerator was installed and the first underground beams in CJPL-Ⅱ were obtained before the long-period construction. In the first quarter of 2021, nuclear astrophysics reactions were studied. Some research highlights are presented in the following.

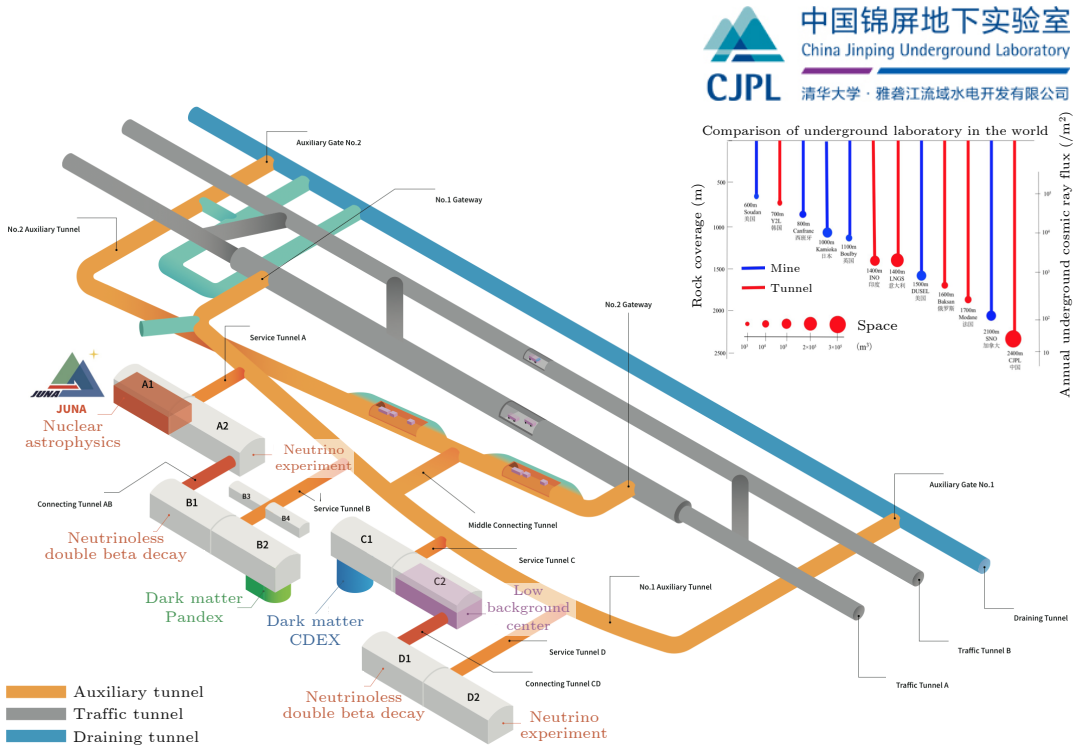

Fig. 1. Summary of JUNA progress in CJPL-Ⅱ.

The $^{12}C(\alpha,\gamma)^{16}O$ reaction is regarded as the holy grail of reactions in nuclear astrophysics. [3] The uncertainty of this reaction affects the nucleosynthesis of elements up to iron and the evolution of massive stars as well as their final fate (black hole, neutron star). The cross section of this reaction must be determined with an uncertainty of $< 10\%$ at helium burning temperatures ($T_9 = 0.2$), corresponding to the Gamow window [4] of approximately $E_{\rm c.m.} = 300$ keV. The reaction cross section (approximately 10^{-17} barn) cannot be determined at such low energies. A direct measurement is conducted close to the Gamow window in JUNA using a high-intensity $^4He^{2+}$ ion beam to provide better constraints for extrapolating models. We used a $^4He^{2+}$ beam with an intensity of 1 emA to achieve the most sensitive upper limit of 10^{-12} barn at $E_{\rm c.m.} = 552$ keV. Moreover, we deduced the cross section and upper limit of this

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reaction near the Gamow window by tuning the accelerator and target-induced background under favorable conditions. The research results are currently being prepared, and further improvements are planned for the upcoming second-stage JUNA run. These improvements will focus on achieving higher beam intensity, target purity, and vacuum levels.

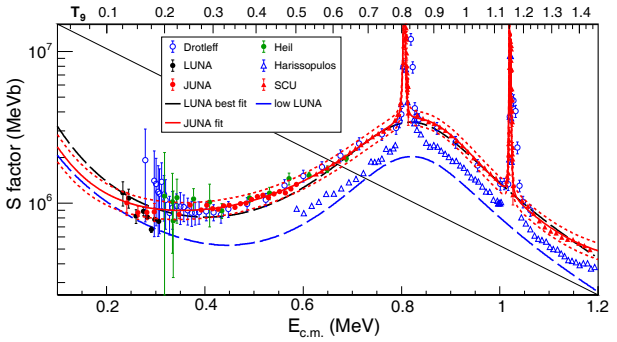

Fig. 2. JUNA results of ^{13}C(α,n)^{16}O reaction.[5]

The ^{13}C(α,n)^{16}O reaction is the key neutron source reaction for stellar *s*- and *i*-process nucleosynthesis. Due to the existence of subthreshold resonances, this crucial reaction rate is associated with a large uncertainty (> 40%), which limits our understanding of the nucleosynthesis of heavy elements. This reaction was studied in the range of $E_{\rm c.m.}$ = 230–600 keV using the ^{4}He^{1+} and ^{4}He^{2+} beams from the JUNA accelerator and in the range of $E_{\rm c.m.}$ = 600–1200 keV using the Tandem accelerator in Sichuan province, see Fig. 2. The beam intensities varied from 0.1 to 2 pmA, and the total underground beam time was fourteen days. The target deterioration problem was resolved by replacing the conventional thin targets with 2-mm-thick ^{13}C targets. We detected neutron events that were considerably higher than the background levels. Our precise results resolved the long-time discrepancy in this crucial neutron source reaction.[5]

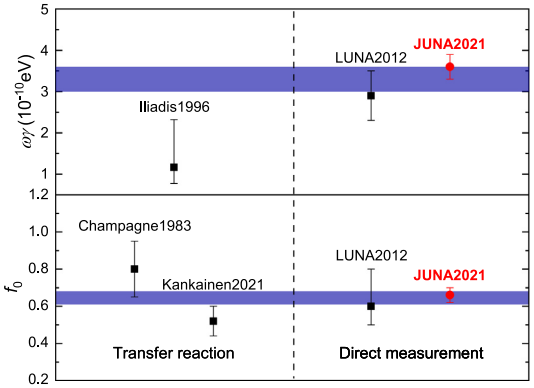

Fig. 3. JUNA results of ^{25}Mg(p,γ)^{26}Al reaction.[6]

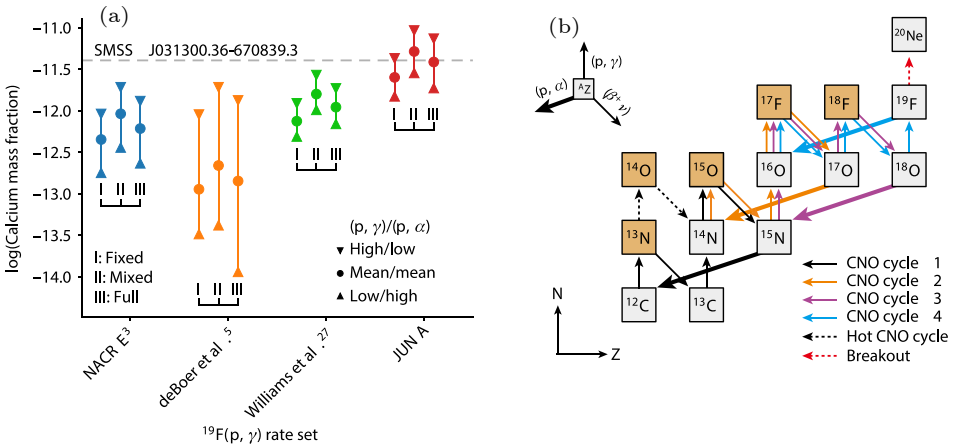

Fig. 4. JUNA results of ^{19}F(p,γ)^{20}Ne reaction.[8]

The ^{25}Mg(p,γ)^{26}Al reaction serves as the primary mechanism in the production of ^{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. Thus, the levels between 50 and 310 keV are crucial in the study of galactic ^{26}Al. The JUNA results reveal that the 58 keV resonance dominates the ^{25}Mg(p,γ)^{26}Al reaction rate at T < 0.06 GK. In addition, we were able to establish the most precise reaction rate for all temperatures owing to our indirect deduction of 58 keV, ground-based experimental results for 304 keV, our underground data for 92 keV (with a more precise ground-state feeding factor), and 189 keV resonances. We published the results,[6] also see Fig. 3.

The ^{19}F(p,α)^{16}O reaction plays a crucial role in the CNO cycles. Currently, the experimental cross sections of this reaction at Gamow energies remain incomplete, and the precision of its thermonuclear reaction rate has yet to satisfy the model requirements. The JUNA experiment aims to conduct direct cross section measurement of the key ^{19}F(p,$\alpha\gamma$)^{16}O reaction, including the Gamow energies ($E_{\rm c.m.}$ = 70–350 keV) with a precision exceeding 10%.[7] Another research highlight is ^{19}F(p,γ)^{20}Ne, in which we extended to the lowest energy point of 188 keV and observed a new resonance at 225 keV, see Fig. 4. This finding resulted in a sevenfold increase in the reaction rate, causing leakage from the CNO cycle.[8] The numerical simulation with the present data achieved a satisfactory agreement regarding Ca abundance in the oldest star, which holds remarkable implications for future JWST activities.

More recently, the ^{18}O(α,γ)^{20}Ne reaction was measured, and its value is critical for AGB star nucleosynthesis

due to its connection to the abundances of several key isotopes such as ^{21}Ne and ^{22}Ne. The ambiguous resonance energy and spin–parity of the dominant 470 keV resonance result in considerable uncertainty in the ^{18}O(α,γ)^{20}Ne reaction rate regarding the temperature of interest. We have measured the resonance energies and strengths of the low-energy resonances in ^{18}O(α,γ)^{20}Ne with enhanced precision. The principal 470 keV resonance energy was measured to be $E_\alpha = 474.0 \pm 1.1$ keV; such a high degree of precision was achieved for the first time. The spin–parity of this resonance state was determined to be 1^-, rectifying discrepancies in the resonance strengths in earlier studies. The results substantially improve the precision of the ^{18}O(α,γ)^{20}Ne reaction rates by up to 10 times compared with the previous data at typical AGB temperatures of 0.1–0.3 GK, see Fig. 5. This improvement facilitates precise ^{21}Ne abundance predictions, impacting the investigation of the origin of meteoritic stardust SiC grains from AGB stars. [9]

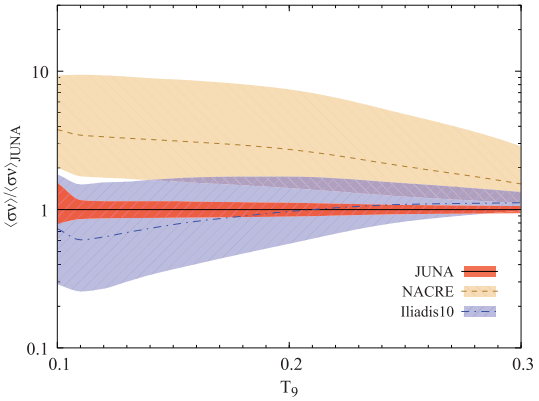

Fig. 5. JUNA results of ^{18}O(α,γ)^{20}Ne reaction. [9]

In summary, JUNA capitalizes on the ultralow background present in CJPL. Employing a high current (mA) 400 kV accelerator with an ECR source and BGO detectors, JUNA directly studies a number of nuclear reactions essential to hydrostatic stellar evolution and heavy-element synthesis at Gamow energies. ^{25}Mg(p,γ)^{26}Al, ^{19}F(p,$\alpha\gamma$)^{16}O, ^{19}F(p,γ)^{20}Ne, ^{13}C(α,n)^{16}O, ^{12}C(α,γ)^{16}O, and ^{18}O(α,γ)^{20}Ne were directly measured with high statistics, precision, and sensitivity. Following the reopening in 2023, we will devote our efforts to enhancing beam intensity, target purity, and improving detectors in the subsequent years. Future upgrading, which will involve constructing an MV level open platform accelerator with high-intensity windowless-target advanced detectors, is under the planning phase (JUNA-Ⅱ). We welcome researchers over the world to join JUNA and to conduct further experiments by taking advantage of the optimal underground conditions in Jinping.

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