

# Direct measurement of key reaction $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ in stellar evolution

## Abstract

$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  reaction is considered to be the most important reaction in nuclear astrophysics plays an important role in stellar evolution, and is referred to as the "Holy Grail" of Nuclear Astrophysics. The reaction is important for the nucleosynthesis of elements up to iron, and it governs also the stellar evolution of the massive stars and their final fate (black hole, neutron star). The cross section of this reaction has to be known precisely (up to 10%) at helium burning temperatures ( $T_9=0.2$ ), corresponding to a Gamow window around  $E_{\text{c.m.}}=300$  keV. It is extremely difficult to determine the reaction cross section (about  $10^{-17}$  barn) at this energy. Lots of hard work has been done over the past decades, the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  reaction rate, in spite of its importance, is still too uncertain for reliable stellar models. This project aims to carry out the experimental study of the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  reaction in the JinPing deep underground laboratory for nuclear astrophysics. A direct measurement at  $E_{\text{c.m.}}=600$  keV near the Gamow window will be done with the help of ultra-low background level of Jinping laboratory and high-intensity ion beam of the experimental platform for nuclear astrophysics. Undoubtedly, it has the vital significance of solving the century problem in nuclear astrophysics.

## 1 Background

### 1.1 Significance

Nuclear astrophysics is the interdisciplinary research field by combining nuclear physics and astrophysics, the main focus of which is the process and environment of nucleosynthesis and the influence of the nuclear process on the evolution and the ending of galaxy [1]. In the 30's of last century, H. A. Bethe put forward that the energy source of stars mainly comes from nuclear process, which pioneered the subject of astrophysics[2]. William A. Fowler afterwards published the well-known paper called B<sup>2</sup>FH [3] which established the foundation of nuclear astrophysics. As its importance and the nature of interdiscipline, nuclear astrophysics keeps in the frontier of fundamental science all along.

After almost a century of development, nuclear astrophysics has given us a new knowledge of the origin of elements and the complicated evolution of stars, but there are still a lot of open questions to be explored. The precise measurement of the most important reaction in nuclear astrophysics,  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ , is one of the classical challenges [4]. William A. Fowler said during the acceptance speech of 1983's Nobel Prize: "the human body is 65% oxygen by mass and 18% carbon with the remainder mostly hydrogen, but it is little wonder that the determination of the ratio  $^{12}\text{C}/^{16}\text{O}$  produced in helium burning is a problem of paramount importance in nuclear astrophysics."

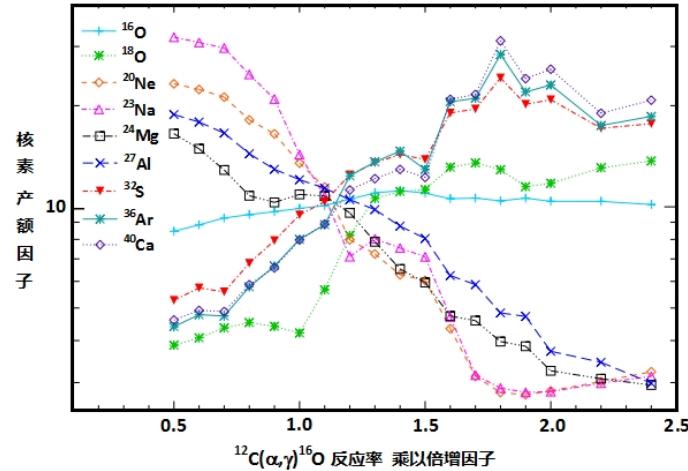


Fig 1 The influence of the reaction rate of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  on the abundance of some of other elements

Indeed,  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  plays an important role in all the reactions in the stars with a mass of  $>0.55\text{M}_\odot$ , the cross section of which has a dominating influence on the nucleosynthesis of the intermediate-mass nuclei and the later evolution of the massive stars. Fig 1 [5] shows that the reaction rate of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  has a dominating influence on the production of other elements, a change by factor of 2 on the reaction rate will cause a drastic change of order of magnitude of the abundance of other elements. Therefore, a precise measurement of the reaction rate of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  is of great importance to the description about the evolution of massive stars. The cosmogony evolutionary model requires a precision of 10% [6] to match the current model uncertainties, which is much higher than the precision of 30% derived by present extrapolation. The precise measurement of this reaction is acknowledged to be the problem of paramount importance in nuclear astrophysics.

After the hydrogen burning stage of the evolution of stars, the helium burning stage is ignited by  $3\alpha \rightarrow ^{12}\text{C}$ .  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  takes place in the environment of  $T_9 \approx 0.2$  ( $T \approx 0.2 \times 10^9$  K) and the center-of-mass energy is 300 keV. Thus  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  dominates in the helium burning stage with the increase in the amount of  $^{12}\text{C}$ .

The cross section of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  in the energy region of the interest of astrophysics ( $E_{\text{c.m.}} = 300 \pm 80$  keV) is quite low ( $\sigma = 10^{-17}$  barn) [7], and the reaction mechanism is very complicated, which causes great difficulties for experiment and theory research. As is shown in Fig 2, the reaction Q-value of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  is 7.16 MeV, and near the  $E_{\text{c.m.}} = 300$  keV, its cross section includes not only the contribution of the direct radioactive capture but also the low-energy tail of the suprathreshold wide-resonance at 9.59 MeV and the high-energy tail of the subthreshold resonance at 7.12 MeV and 6.92 MeV. According to the nuclear reaction theory, the resonance at 9.59 MeV and 7.12 MeV is p-wave (E1) capture, while the direct capture and the resonance at 6.92 MeV is d-wave (E2) capture.

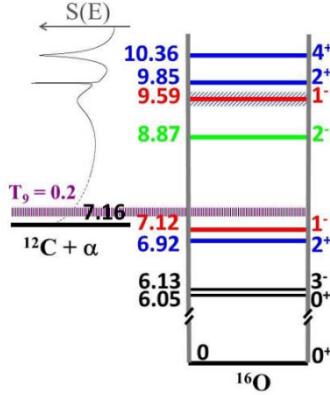


Fig 2 The influence of the resonance level of  $^{16}\text{O}$  on the cross section of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$

The calculation of theory model require the precise data (error~10%) of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  in the energy region of interest in astrophysics ( $E_{\text{c.m.}}=300 \pm 80$  keV), while the present experiment results are far from this energy region and the error of the extrapolation is also large with the amount to be 30%. The underground laboratory can considerably reduce the disturbance of cosmic rays and provide an environment with extremely low background [8]. Especially, the Jinping Underground Laboratory in China is not only the deepest underground laboratory in the world currently, but also has the stratum with extremely low radioactivity, which provides an excellent condition for the measurement of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ .

This subject, which is an important component of the major project “Study of key scientific questions in nuclear astrophysics at Jinping underground laboratory”, will make use of the low-background environment and the beam intensity of Jinping Underground laboratory for Nuclear Astrophysics (JUNA) to measure  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ . This will be the first direct measurement of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  in the energy region of interest in astrophysics in the underground laboratory in the world. The result will be expected to limit the cosmogony model effectively, and be of vast importance to the understanding about the process of the evolution of stars and the paths of element synthesis.

### 1.2 Current status of $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction

Since the 70’s of last century [9], many research groups have tried to measure  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ . However, as was limited to the background of cosmic rays and the extremely low cross section of this reaction, there were still technologies needed to be breakthrough based on experience of the past over 40 years. The lowest current achievable center-of-mass energy measured directly is 891 keV, the error of which is larger than 50% [10]. Figure 3 summarizes up the results of the direct measurement of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ , in which the cross sections are expressed as astrophysics S-factor.

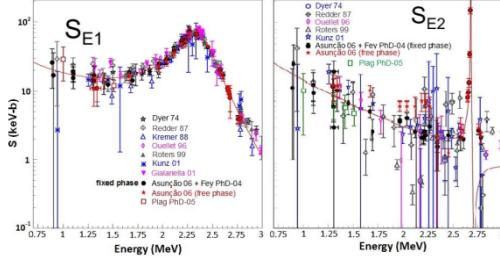


Fig 3 The results of the direct measurement of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$

At present there are two experimental research methods to measure  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ : indirect and direct method. Indirect method can only be used as a reference, while the direct measurement is the most reliable way, with which we can obtain both total cross section data and the angular distribution by using different direct experimental approaches. For example, we can use the forward kinematics, one of the methods of direct measurement, to obtain the angular distribution of  $\gamma$  rays with which the contribution of the captures of E1 and E2 can be derived with R-matrix method, and then extrapolate to the energy region of astrophysics interest. However, as is limited by the cosmic-ray background, the beam energy and the detection efficiency, the error of measurement is large, which results that the value of extrapolation cannot reach the target accuracy (error~10%) required by theory model. The S-factor of derived by R-matrix extrapolation based on the recent results of the forward kinematics measurement is listed in Table 1.

Table 1 The extrapolation S-factor of recent results of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  ( $E_{\text{c.m.}}=300$  keV)

	S-factor (keV b)					
	1999 [11]	2004 [12]	2006 [13]	2006 [14]	2008 [15]	2011 [16]
E1 <sub>0</sub>	79±21	77±17	80±20	~73	70±20	-
E2 <sub>0</sub>	120±60	81±22	53 <sup>+13</sup> <sub>-18</sub>	~82	45 <sup>+15</sup> <sub>-35</sub>	-
6.92+7.12	-	4±4	-		-	-
6.92	-	-	7 <sup>+13</sup> <sub>-4</sub>	~65	10±6	-
6.05	-	-	25 <sup>+16</sup> <sub>-15</sub>		25±16	<1
Total		162±39	165 <sup>+62</sup> <sub>-57</sub>	~210	150 <sup>+57</sup> <sub>-77</sub>	-

Clearly, the direct measurement is basically free of theory analysis, which makes it the most reliable method. In the current experimental condition, the backward kinematics method is limited by the beam intensity of  $^{12}\text{C}$  and the thickness of windowless gas target that it cannot be used in the region near  $E_{\text{c.m.}}=300$  keV, while the total cross section measured also cannot applied in the calculation of R-matrix extrapolation. The underground laboratory can considerably suppress the disturbance of cosmic rays, which provides an excellent environment for the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  measurement. Currently, LUNA (Laboratory for Underground Nuclear Astrophysics) in Italy, the only underground laboratory for astrophysics around the world, proposed the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  measurement in its upgrade work. CJPL in China is the deepest underground laboratory in the world by now [17], in which the background of  $\gamma$  rays is 2 orders of magnitude lower than that in LUNA and the accelerator in the plan will provide a  $\alpha$  beam the intensity of which is 10 times of magnitude higher than that in LUNA currently. All of these enhancements will provide us a great

favorable condition for the measurement of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ .

## 2 Research content and experiment setup

The main content of this research contains: 1) the measurement of angular distribution with high-resolution detectors at  $E_{\text{c.m.}}=600$  keV and the extrapolation to the energy region of interest in astrophysics with the R-matrix theory, 2) optimizing the experiment setup and the condition of environment (including the beam, the background shielding and the high-purity target) according to the results at 600 keV, measuring the total cross section at  $E_{\text{c.m.}}=600$  keV with high-efficiency detection array to derive the accurate cross section data (error~10%), 3) direct measurement in the energy region of interest in astrophysics at  $E_{\text{c.m.}}=380$  keV.

*Angular distribution measurement at  $E_{\text{c.m.}}=600$  keV:* We plan to use  ${}^4\text{He}^{2+}$  beam with an intensity of 5 emA and an energy of 800 keV ( $E_{\text{c.m.}}=600$  keV) to bombard a high-purity  ${}^{12}\text{C}$  target. Four high-resolution segmented clover detectors will be placed in different directions, with which we can obtain the angular distribution of  $\gamma$  rays emitted by  ${}^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ . With the information of angular distribution, the R-matrix method will be used to derive the contribution of the E1 and E2 capture at this energy and extrapolate the cross section and the reaction rate of  ${}^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  in the energy region of interest in astrophysics, which will provide a reliable calibration data for direct measurement. Figure 4 shows the setup of 4 segmented clover detectors and the high-purity  ${}^{12}\text{C}$  target.

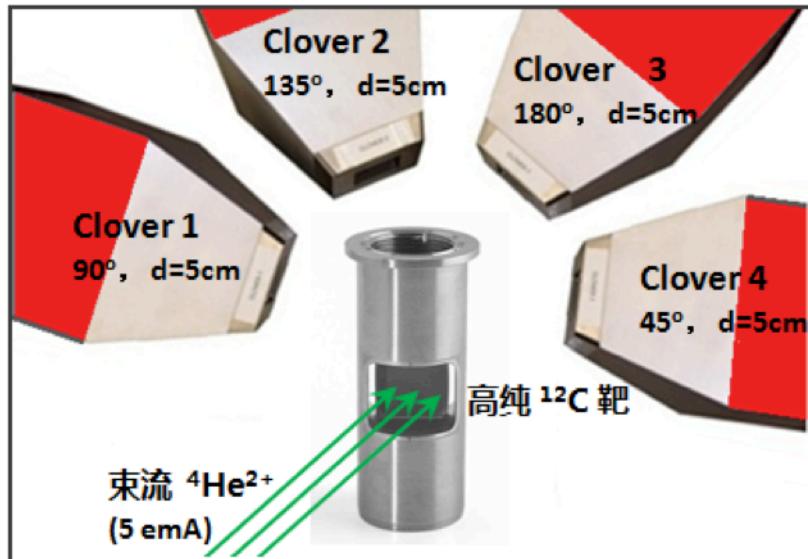


Fig 4 Schematic of  ${}^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  detection setup

*Total cross section measurement at  $E_{\text{c.m.}}=600$  keV:* With the results of angular distribution measurement at  $E_{\text{c.m.}}=600$  keV, we can optimize the experiment condition, 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  ${}^{13}\text{C}$  and improving the implantation condition of  ${}^{12}\text{C}$  implantation target to reduce the disturbance of  ${}^{13}\text{C}$ . The BGO detection array placed around the target chamber can significantly increase the

detection efficiency (with absolute efficiency~75%) of  $\gamma$  rays. With the improvement above, an accurate total cross section will be obtained.

*Total cross section measurement at  $E_{c.m.}=380$  keV:* We will use  ${}^4\text{He}^{2+}$  beam with an intensity of 5 emA and an energy of 507 keV ( $E_{c.m.}=380$  keV) and the high-efficiency BGO detection array (detection efficiency~75%). A direct measurement of the total cross section of  ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$  in the energy region of interest in astrophysics will be performed.

### 3 Key problems to solve

#### 3.1 Background and counting rate estimation

JUNA provides us the environment with the lowest background, which makes the precise measurement of weak signal possible. The lowest center-of-mass energy of  ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$  measured by now is 891 keV with an error larger than 50%. In order to evaluate the possibility of the precise measurement at a lower energy, we should estimate the background of JUNA first.

The  $\gamma$  rays' energy region of interest of  ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$  is 7~8 MeV. In this region, the background signals mainly come from the cosmic rays. Compared with that in LUNA, the flux of the cosmic ray in JUNA is 2 orders of magnitude lower. In CJPL, the amount of the  $\gamma$ -ray background is about  $2 \times 10^{-6}$  per second, that's 0.17 per day. With the beam background considered, the total amount of  $\gamma$ -ray background during the experiment is about 0.25 per day. Figure 5 shows the background comparison between LUNA and the ground laboratory.

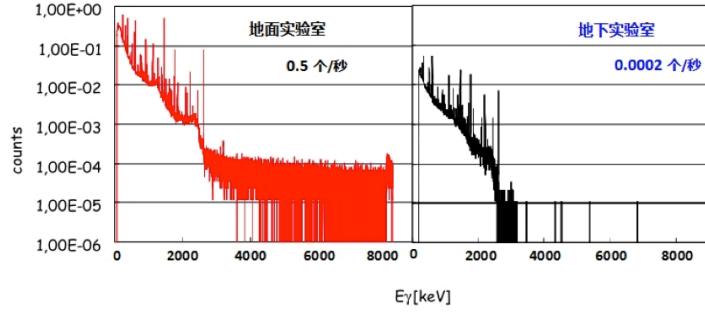


Fig 5 The background comparison between LUNA and the ground laboratory.

The estimation of counting rate during the  ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$  measurement is listed in Table 2. Thereinto, the high-resolution segmented clover detection array is used in the measurement of the angular distribution, while the high-efficiency BGO detection array is used in the measurement of the total cross section. The thickness of target used in estimation is  $10^{18}$  atoms/cm<sup>2</sup>.

Table 2 The estimation of the counting rates in the  ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$  measurement

Beam	Intensity (emA)	$E_{c.m.}$ (keV)	$\sigma^i$ (mb)	Detection efficiency	Counting rate <sup>ii</sup> (d <sup>-1</sup> )	$\gamma$ background <sup>iii</sup> (d <sup>-1</sup> )
${}^4\text{He}^{2+}$	5	600	$2.9 \times 10^{-10}$	2.2%	6.6	
		600	$2.9 \times 10^{-10}$	75%	227.60	0.25
		380	$1.0 \times 10^{-12}$	75%	0.61	

i The cross sections are derived with the results of extrapolation.

ii The counting rates are corrected according to the energy loss of beam in the target

iii The background is estimated with the LUNA data.

According to the estimation above,

- 1) The measurement of angular distribution at  $E_{c.m.}=600$  keV will cost 20 days to reach an error lower than 10%,
- 2) The measurement of total cross section at  $E_{c.m.}=600$  keV will cost about 1 day to reach an error lower than 10%,
- 3) The measurement of total cross section at  $E_{c.m.}=380$  keV will cost about 3 months.

And the preparation of detectors and shielding system will cost 2 months, which means the measurement of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  will cost about half a year.

### 3.2 Suppressing the disturbance of $^{13}\text{C}(\alpha, n)^{16}\text{O}$

In the energy region of experiment, the cross section of  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  is 7 orders of magnitude larger than that of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ . The neutron emitted by  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  will interact with matters around and product  $\gamma$  rays which will disturb the measurement of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ . An efficient way to suppress the disturbance is to apply a high-purity  $^{12}\text{C}$  target and reduce the  $^{13}\text{C}$  in the residual gas in the beam pipeline and the target chamber by increasing the vacuum in them.

Only the implantation of the high-purity of  $^{12}\text{C}$  ions can produce the high-purity  $^{12}\text{C}$  target. In order to avoid other disturbance, we plan to adopt the high-purity gold as the substrate. And  $^{12}\text{C}$  ions with an energy of 100~1000 keV are implanted into the gold substrate in a high vacuum environment. RBS (Rutherford back-scattering spectroscopy) is applied for the analysis of implantation  $^{12}\text{C}$  target. In our experiment, we plan to use a target with a thickness of  $10^{18}\sim 10^{19}$  atoms/cm<sup>2</sup>. Figure 6 shows the distribution of the implantation depth of  $^{12}\text{C}$  ions with an energy of 800 keV simulated with SRIM. JUNA will provide the carbon ions for implantation and the analysis of  $^{12}\text{C}$  ions depth distribution of the implantation will be finished with the 2.5 MeV electrostatic accelerator in Sichuan University.

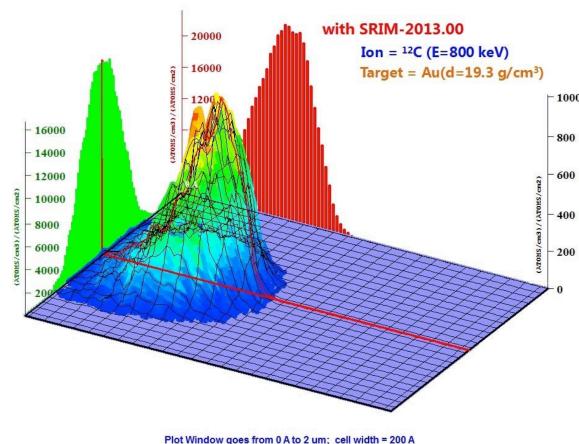


Fig 6 The distribution of implantation depth of  $^{12}\text{C}$  ions with an energy of 800 keV simulated with SRIM code.

### 3.3 Cooling system of large power solid target

As the extremely low cross section of  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ , we have to use high intensity beam to increase

the counting rate, which will certainly deposit a large amount of energy on the target. Thus we should prepare cooling system for target.

Taking the beam in planned experiment for instance, a beam with an  ${}^4\text{He}^{2+}$  intensity of 5 emA, an energy of 800 keV and an beam spot of  $r=0.25$  cm will deposit an energy of about  $10 \text{ kW/cm}^2$ . The designed cooling system contains 10 cooling pipe and cooling water flows in them at high speed (25 m/s) to take heat away. The designed value of the large power solid target system is  $20 \text{ kW/cm}^2$  (the temperature on the target is lower than  $200^\circ\text{C}$ ). According to the simulation of ANSYS, the highest temperature of target is  $103^\circ\text{C}$  when the power on the target is  $12 \text{ kW/cm}^2$ .

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