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A proposed direct measurement of cross section at Gamow window for key reaction $^{19}{\rm F}(p,\alpha)^{16}{\rm O}$ in Asymptotic Giant Branch stars with a planned accelerator in CJPL

HE Jianjun^{1*}, XU Shiwei^{1,2}, MA Shaobo^{1,2}, HU Jun¹, ZHANG Liyong¹, FU Changbo³, ZHANG Ningtao¹, LIAN Gang⁴, SU Jun⁴, LI Yunju⁴, YAN Shengquan⁴, SHEN Yangping⁴, HOU Suqing¹, JIA Baolu^{1,2}, ZHANG Tao³, ZHANG Xiaopeng³, GUO Bing⁴, KUBONO Shigeru^{1,5} & LIU Weiping⁴

¹Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China;

²University of Chinese Academy of Sciences, Beijing 100049, China;

³Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, Peoples Republic of China;

⁴China Institute of Atomic Energy, P. O. Box 275(10), Beijing 102413, China;

⁵RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

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In 2014, the National Natural Science Foundation of China (NSFC) approved the Jinping Underground Nuclear Astrophysics laboratory (JUNA) project, which aims at direct cross-section measurements of four key stellar nuclear reactions right down to the Gamow windows. In order to solve the observed fluorine overabundances in Asymptotic Giant Branch (AGB) stars, measuring the key 19 F(p,α) 16 O reaction at effective burning energies (i.e., at Gamow window) is established as one of the scientific research sub-projects. The present paper describes this sub-project in details, including motivation, status, experimental setup, yield and background estimation, aboveground test, as well as other relevant reactions.

Jinping Underground Nuclear Astrophysics laboratory (JUNA), direct measurement, Gamow window, cross section, AGB star, nucleosynthesis

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Introduction

Nuclear processes play an extremely important role in the evolution of our Universe after the Big Bang [1, 2]. Thereinto, nuclear reactions not only provide the energy for stars to resist the gravitation, but also power the astrophysical explosion, such as x-ray bursts, novae and supernovae. Astrophysical models that address the quiescent stellar evolutions and explosive astrophysical events require a huge amount of nuclear physics information as inputs. Thermonuclear reac-

tion cross section (or reaction rate) is one of the crucial quantities from nuclear physics aspect for modeling stellar phenomena. For hydrostatic stable buring in stars, nuclear reactions occur at very low stellar energies. At the effective Gamow window, the extremely small cross sections result in quite small signal-to-background ratio, which makes impossible the direct measurement in the laboratory at the Earth's surface. Covered by about 7000-mwe-thick marbles, China Jinping underground Laboratory (CJPL) [3–5], the deepest underground laboratory in the world, can greatly reduce the

^{*}Corresponding author (email: jianjunhe@impcas.ac.cn)

muon and neutron fluxes by 6 and 4 orders of magnitudes with respect to those at the Earth's surface. With such unique super-low-background and salient features, the Jinping Underground Nuclear Astrophysics laboratory (JUNA) project was approved by the National Natural Science Foundation of China (NSFC) in 2014 and will be financially supported in period of 2015–2019. The JUNA project* aims at direct measurement of (α, γ) and (α, n) reactions in hydrostatic helium burning, as well as (p, γ) (p, α) reactions in hydrostatic hydrogen burning. In the first stage, four key reactions, i.e., $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$, $^{13}\text{C}(\alpha, n)^{17}\text{O}$, $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$ and $^{19}\text{F}(p, \alpha)^{16}\text{O}$, will be directly measured at individual Gamow window [6].

This paper describes details of the sub-project for $^{19}F(p,\alpha)^{16}O$ reaction study. The proposed experiment aims at direct cross section measurement of this key stellar reaction right down to the Gamow window ($E_{c.m.}$ =70–350 keV in the center-of-mass frame), with sufficient accuracy required by the stellar model calculations. The direct experimental data will help people to expound the element abundances, especially the fluorine overabundances observed in Asymptotic Giant Branch (AGB) stars, energy generation, as well as heavy-element nuclosynthesis scenario, with the astrophysical model on the firm ground.

2 Scientific motivation

Fluorine is one of the most important elements for nuclear astrophysics. As the unique stable fluorine isotope, the ¹⁹F abundance is very sensitive to the physical conditions within stars. Therefore, it is often used to probe the nucleosynthesis scenarios [7] of violent controversy. Most likely, fluorine can be produced: 1) during core collapse of Type II supernovae [8], 2) in Wolf-Rayet stars [9], and 3) in the convective zone triggered by a thermal pulse in Asymptotic Giant Branch (AGB) stars [10]. Recently, fluorine overabundances by factors of 800–8000 [11] have been observed in R-Coronae-Borealis stars, providing evidence for the fluorine synthesis in such hydrogen-deficient supergiants. However, a detailed description of fluorine nucleosynthesis is still missing in despite of its crucial importance.

The major contributors to the Galactic fluorine [12] are the AGB stars. The observed fluorine overabundances cannot be explained with standard AGB models, and additional mixing is still required [13]. For example, deep mixing phenomena in AGB stars can alter the stellar outer-layer isotopic composition due to proton capture at low temperatures ($T_9 \le 0.04$), and affect the transported material [14–16]. In this environment (corresponding to Gamow window around $E_{c.m.}$ =27–94 keV), the main fluorine destruction reaction of $^{19}F(p,\alpha)^{16}O$ possibly modifies the fluorine surface abundances [7, 17]. As for the hydrogen-deficient post-AGB stars, hydrogen admixture plays a key role to reverse the effect of excessive He

burning and yields elemental abundances in better agreement with observations [18]. Here, the $^{19}F(p,\alpha)^{16}O$ reaction might bear a great importance as it would remove both protons and fluorine nuclei from the nucleosynthesis scenario. Therefore, the $^{19}F(p,\alpha)^{16}O$ cross section should be well determined at $E_{c.m.}{\sim}50{-}300$ keV for accurate modeling because of the temperature at the base of the accreted material approaching $T_9{\sim}0.2$ [11].

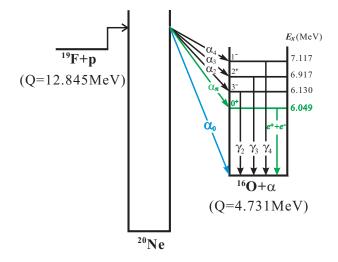


Figure 1 Reaction scheme of 19 F $(p,\alpha)^{16}$ O.

3 Status and Goal

The reaction scheme for $^{19}F(p,\alpha)^{16}O$ is shown in Fig. 1. It shows that this reaction occurs through three different types of channels: (p,α_0) , (p,α_π) and (p,α_γ) . Here, the combination of (p,α_2) , (p,α_3) and (p,α_4) with the subsequent transitions of γ_2 , γ_3 and γ_4 , is referred to as the (p,α_γ) channel. The research status for these reaction channels are described in the following three subsections, and the final goal for the proposed experiment is summarized in the last subsection.

3.1 (p,α_0) channel

The recommended 19 F(p, α_0) 16 O astrophysical S(E)-factor was determined from several works [19–27] in the NACRE compilation [28], with the lowest energy direct data at $E_{c.m.}$ =461 keV [20]. The Gamow window is only partially covered by the unpublished data of Lorentz-Wirzba [29], which were utilized [30, 31] later to evaluate the astrophysical factor in the zero and finite-range Distorted Wave Born Approximation (DWBA) approaches. These data support a strong suppression of compound 20 Ne decay to the ground state of 16 O at E_{cm} ~0.14–0.6 MeV. However, these results were not included in the NACRE compilation as possible systematic errors affecting the absolute normalization might lead

^{*} Refer to five proposals submitted to NSFC in 2014, W.P. Liu et al., The 12 C(α,γ) 16 O reaction; X.D. Tang et al., The 13 C(α,n) 16 O reaction; Z. Li et al., The 25 Mg(p,γ) 26 Al reaction; J.J. He et al., The 19 F(p,α_{γ}) 16 O reaction; L. Gang et al., The JUNA common platform. Please visit http://www.juna.ac.cn/pub/proposals for details.

to an underestimate of S(E) by a factor of two [28]. The astrophysical factor was then extrapolated to low energies assuming a dominant contribution of the non-resonant part [28]. This conclusion disagrees with the older measurement [20], where the existence of two resonances with $J^{\pi}=1^{-}$ and 0^{+} had been reported at E_{cm} \sim 0.4 MeV. Actually, additional resonances might be populated in ²⁰Ne [32]. A recent experiment [33] measured the ${}^{19}F(p,\alpha_0){}^{16}O$ astrophysical S(E)factor by indirect means of the Trojan Horse method, and found that the largest rate difference, about 70%, occurs at temperatures relevant for post-AGB stars (~0.1 GK), exceeding the upper limit set by the previous uncertainties [28]. Such difference is clearly due to the presence of the 113 keV resonance (E_x =12.957 MeV, 2^+). However, the energy resolution was not enough for achieving a good separation between resonances, thus preventing an accurate estimate of the their total widths as well as the reaction rate. Most recently, Lombardo et al. reported new direct measurement data [34,35] on the 19 F $(p,\alpha_0)^{16}$ O reaction at the energy region of $E_{c.m.}$ =0.18-1 MeV, and found the deduced astrophysical S-factor $\approx 1.5-2$ times larger than currently recommended one. However, their uncertainties are still too large below 0.2 MeV, which need to be well constrained. The available experimental and theoretical data for this reaction channel are shown in Fig. 2.

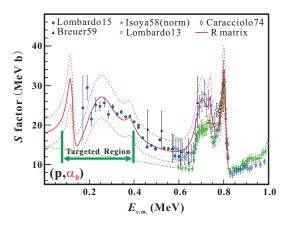


Figure 2 Available experimental data and *R*-matrix calculations for the (p,α_0) channel [20, 22, 25, 28, 34, 35]. The green arrows indicate the energy regions targeted for the JUNA experiment. (The figure is credited to I. Lombardo et al.)

3.2 (p,α_{γ}) channel

The recommended 19 F $(p,\alpha_{\gamma})^{16}$ O astrophysical S(E)-factor in the NACRE compilation [28] had been derived from the ear-

lier works [36–43] down to $E_{c.m.}$ =957 keV. Later on, Spyrou et al. [44] measured this channel down to ~189 keV with a 4π NaI summing spectrometer. In this work, the strengths of all resonances at E_p =200–800 keV, including a new one at E_R =237 keV, have been extracted. Furthermore, the width of the important 1+ resonance at E_R =11 keV was estimated, which affects the S-factor dramatically within the Gamow region owing to the inference effects with the strong 1+ resonance at E_R =340 keV. Therefore, this width needs to be determined experimentally. The available experimental and theoretical data for this reaction channel are shown in Fig. 3.

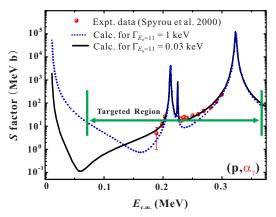


Figure 3 Available experimental data and theoretical calculations for the (p, α_{γ}) channel [28, 44]. The green arrows indicate the energy regions targeted for the JUNA experiment. (The figure is credited to K. Spyrou et al.)

3.3 Roles of different channels

Based on the work of Spyrou et al. [44] and the NACRE compilation [28], the roles of three reaction channels are compared as shown in Fig. 4. It shows that the (p,α_0) channel dominates the total rate below ~ 0.1 GK; the (p,α_γ) channel dominates above ~ 0.15 GK; both two channels dominates over 0.1-0.15 GK. Here, contribution from the (p,α_γ) channel is negligible based on our current knowledge about this reaction. Therefore, we will focus on the measurements of (p,α_0) and (p,α_γ) channels in the proposed experiment.

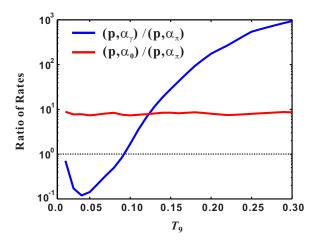


Figure 4 The role of three reaction channels contributing to the total reaction rate of 19 F(p,α) 16 O.

3.4 Final goal

In a summary, there are currently no direct experimental data below $E_{c.m.}$ =180 keV for the (p,α_0) channel (note: the uncertainty of the datum point at 180 keV is quite large in Ref. [35]), and below $E_{c.m.}$ =189 keV for the (p,α_γ) channel (note: the uncertainties of the data points below 200 keV are quite large in Ref. [44]). In the proposed experiment, we will target on measuring the cross sections of these two reaction channels at the targeted energy regions indicated in Figs. 2 & 3 in JUNA. As a final goal, we may obtain the reliable direct experimental data with a precision about 10% at lower energies or even better at higher energies (see Tabs. 1 & 2), and implement them into the nucleosynthesis model to achieve a better understanding of the fluorine overabundances in AGB stars.

4 Experimental setup

In the proposed $^{19}\text{F}(p,\alpha)^{16}\text{O}$ experiment, two reaction channels of (p,α) and (α,p) will be measured separately. The details for these two measurements will be described as below.

A 'lamp'-type Micron silicon array will be constructed for the charged-particle measurement, which can cover about 4π solid angle. This universal detection array will set the base for other (p,α) and (α,p) reaction studies at JUNA. A conceptual design is shown in Fig. 5. It can not only measure the total (p,α_0) cross section but also the angular distribution. The angular distribution measured is much useful for determining the nuclear structure of the 1^+ resonance at $E_R=11$ keV as discussed above. In this experiment, a very thin about $4 \mu g/cm^2 CaF_2$ target will be utilized, which is evaporated on a thin backings. Thanks to the very 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 α s can penetrate the backings and can be detected easily at the forward angle. The detectors at the forward angle do not face the Rutherford-scattered strong proton beam which is stopped in the backings. However, those detectors at the backward angle should be shielded by a thin foil, e.g., a mylar foil, to stop the scattered protons. The target backing will be connected to a cooling device to release the heat during the experiment.

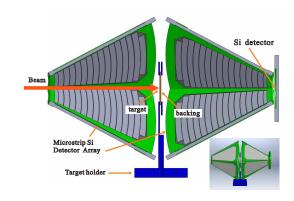


Figure 5 Conceptual silicon detector array designed for measuring the charged particles.

As for the $^{19}\text{F}(p,\alpha_{\gamma})^{16}\text{O}$ channel, the energies of emitted γ rays are about 6–7 MeV, where the background mainly originates from the cosmic rays. Covered with about 2400 km marbles, such background can be greatly reduce, which makes the low-energy measurements feasible. In this project, two gamma detection arrays will be constructed for the γ -ray measurements. One is the High-Purity Germanium (HPGe) Clover array whose absolute detection efficiency is about 1% [45] for the γ rays of interest, but with excellent energy resolution; another is the 4π BGO array whose absolute efficiency is estimated to be about 75%, but with relatively worse resolution. Now, this BGO array is under construction. Here, the Clover array will be utilized in the $E_{c.m.}>140$ keV energy region, while the BGO array will be used below this energy region. With the excellent resolution of the Clover detector, the possible contaminations can be resolved and identified clearly, which makes the BGO γ -ray summing reliable at lower-energy region. A conceptual design for the Clover array is shown in Fig. 6.

Table 1 α yields estimated for the (p,α_0) channel. The S-factor data are estimated from the (red) solid line in Fig. 2, please refer to Ref. [35].

$E_{c.m.}$ (keV)	S-factor (MeV b) [35]	Cross section (b)	Current (µA)	Counting rate
70	21.0	$1.70 \times 10^{-12} \text{ (pb)}$	100	47/week
80	22.0	1.29×10^{-11}	100	360/week
90	23.5	7.10×10^{-11}	100	280/day
100	26.5	3.18×10^{-10}	100	1270/day
130	20.0	5.40×10^{-9} (nb)	10	2160/day
160	16.0	3.77×10^{-8}	1	1500/day
180	18.5	1.34×10^{-7}	1	220/hour
200	22.0	4.10×10^{-7}	1	680/hour
250	27.0	3.12×10^{-6}	1	5200/hour
350	21.5	2.61×10^{-5}	0.1	4350/hour

Table 2 γ yields estimated for the (p,α_{γ}) channel. The S-factor data are estimated from the solid line in Fig. 3, please refer to Ref. [44].

$E_{c.m.}$ (keV)	S-factor (MeV b) [44]	Cross section (b)	Current (µA)	Counting rate	Detector (ϵ_{γ})
100	0.6	$7.21 \times 10^{-12} \text{ (pb)}$	100	27/day	BGO (75%)
110	0.8	3.13×10^{-11}	100	118/day	BGO (75%)
120	1.0	1.09×10^{-10}	100	410/day	BGO (75%)
140	1.8	$1.08 \times 10^{-9} \text{ (nb)}$	100	54/day	HpGe (1%)
160	3.5	8.24×10^{-9}	50	206/day	HpGe (1%)
200	12	2.23×10^{-7}	20	93/hour	HpGe (1%)
250	29	3.35×10^{-6}	5	350/hour	HpGe (1%)
300	235	1.03×10^{-4}	1	2140/hour	HpGe (1%)

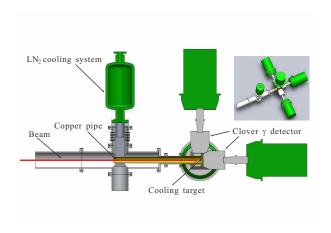


Figure 6 Conceptual Clover detector array designed for measuring the γ rays.

Yield estimated for the (p,α_{γ}) *channel:* Based on the theoretically calculated cross section in Ref. [44], the γ -ray yields from the (p,α_{γ}) channel have been estimated as listed in Table 2. This reaction becomes dominant above 0.12 GK (see Fig. 4), and the corresponding lower limit of the Gamow energy is ~100 keV. Similarly, the target thickness is also assumed to be 4 μ g/cm² in the calculation. It can be seen from Table 2 that even at the lowest 100 keV (cross section at the order of pb), 380 counts can be expected in two weeks, with

5 Yield estimation

Yield estimated for the (p,α_0) *channel:*

Based on the theoretically calculated cross section in Ref. [35], the alpha yields from the (p,α_0) channel have been estimated in Table 1. In the calculations, we propose to use a $4~\mu g/cm^2$ thickness CaF₂ target in which the energy loss of a 70-keV proton is only about 1.6 keV. The detection efficiency of the 'lamp'-type silicon array is estimated to be about 80%. It can be seen from Table 1 that measurements below 90 keV energy region become increasingly difficult because of the much smaller cross section. As a conservative estimation, the highest current utilized in the present calculation is 100 μ A. The experiment becomes easier with the higher current, but the target must be cooled accordingly. Based on the experience of LUNA experiments, the directly water cooled target can fully endure the supposed $100~\mu$ A current.

a statistical error of $\sim 5\%$.

It should be noted that the JUNA 400 kV accelerator can provide beam current in the order of mA. This strong beam will mainly apply to those those reactions with extremely low cross section reactions (e.g., $^{12}\text{C}(\alpha,\gamma)^{16}\text{O})$ and targets with very high melting point (such as the melting point is about 3500 °C for the C target). As for the CaF₂ target, the melting point is only about 1400 °C. Here, we only assumed a 100 μA beam current. The practical highest current which the target

Table 3 Comparison of the radioactivity background for the surrounding rocks in JUNA, LUNA and earth surface. The data of LUNA are taken from Ref. [50].

Location	$^{40}\mathrm{K}$	²²² Rn (Bq/m ³)	²²⁶ Ra (Bq/kg)	²³² Th (Bq/kg)
JUNA	< 0.1 [48]	10–20 [49]	1.8±0.2 [48]	< 0.27 [48]
LUNA	224	20–90	-	8.8
Beijing ground level	600 [49]	200–400	25 [49]	50 [49]

Table 4 Comparison of the γ -ray background levels for laboratories of JUNA, LUNA and earth surface.

Laboratory	Depth (km)	Cosmic-ray flux (cm ⁻² s ⁻¹)	Counting rate of 3–8 MeV γ rays
JUNA	2400	2×10^{-10} [51]	2×10^{-6} /s (estimated)
LUNA	1400	3×10^{-8} [50]	$2 \times 10^{-4} / s$ [50]
Earth surface	~0	2×10^{-2} [52]	0.5/s [50]

can stand will be tested experimentally.

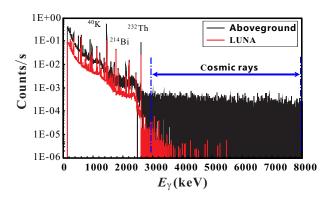


Figure 7 Comparison of γ -ray background levels at LUNA and earth surface [50].

6 Background estimation

Charged-particle background: In the deep underground laboratory, the environmental and material background become dominant in the charged-particle detection. All of the material used in the experiment, such as target chambers, targets and the holders, detectors and even the radiation of the shielding material can disturb the charged-particle detection [46]. For instance, the α activity of the stainless steel is one order

 γ -ray background: JUNA will provide an unique ultra-low background level in the world, which makes the rare-event detection possible. The 3–8 MeV γ -ray background in LUNA is about 2×10^{-4} event/s [50], \sim 2000 times lower than that aboveground, which is mainly caused by the cosmic rays (see Fig. 7). Owing to the depth advantage, the cosmic-ray induced background at JUNA is expected to be about 100 times lower than that in LUNA [51] (see also Table 4). Thus, the 3–8 MeV γ -ray background at JUNA is estimated to be 2×10^{-6} event/s, i.e., 0.17 event/day. By taking the beam-

of magnitude lower than that of the commercial aluminum material. Moreover, cosmic-ray induced γ rays, neutrons and charged particles can also affect the rare event detection. (1) In the ${}^{3}\text{He}({}^{3}\text{He},2p){}^{4}\text{He}$ experiment at LUNA, the cosmicray induced background in the silicon detectors is as less as 3.5×10^{-4} event/s, which is about 200 times lower than that achieved aboveground [47]. The JUNA background is expected to be better than that of LUNA because of the depth. (2) The neutron background in LUNA is about 3 orders of magnitude lower than that aboveground, and additionally the JUNA background is about 10 times [53] lower than that of LUNA. Therefore, the influence of neutron background on Si detectors at JUNA is about 4 orders of magnitude lower than that aboveground. (3) It was measured that the radioactivities of the surrounding rocks in JUNA is much lower than the earth surface level (see Table 3). These natural α radioactivities (together with γ radiation) will produce background in Si detectors. Furthermore, the Si detectors in the target chamber should be shielded by the *old lead* or oxygenfree copper with extremely low background. Moreover, the μ particles in cosmic ray can only deposit less than 0.5 MeV energy in the detectors, while the targeted α particles have energy loss more than 6 MeV, and therefore, the extremely low charged-particle background in JUNA makes the present measurement around 70 keV feasible.

induced background into account, the γ background is expected to be about 0.25 event/day. Based on the above estimation, the targeted γ -ray yield at 100 keV is 27 events/day, far greater than the background level. In aboveground lab., the background level is 0.5 event/s, i.e. 4.3×10^5 events/day, which indicates only the measurements above 200 keV can be performed [44]. Consequently, JUNA can provide us an excellent condition to extend the $^{19}F(p,\alpha_{\gamma})^{16}O$ cross section measurement down to the Gamow window. For comparison, the background levels in LUNA, JUNA and earth-surface lab.

are listed in Table 4. Recently, the realistic γ -ray background has been measured by both a HPGe and a BGO crystal at JUNA, and the data analysis is still in progress.

Comparing to the radioactivity background for the surrounding rocks in JUNA, the cosmic-ray induced γ background can be entirely neglected because of the extremely reduced muon fluxes at JUNA (see Table 4). Therefore, a good shielding for the background originated from the surround rocks, concrete wall, as well as accelerator is quite important for the underground experiments. In addition, the radioactive decay products from the radon (existing in the air and rocks) can pollute the surface of the detector (in the order of about 1 event/month), and hence the γ -ray detectors should be assembled, disassembled and operated in the radon free environment. Furthermore, the decaying radon and its daughters produce α and β particles that produce again secondary γ radiation by bremsstrahlung and nuclear reactions. A popular solution of this problem is to house the detector in a box with a small overpressure of flushing nitrogen: i.e., by substituting normal air containing Radon with Nitrogen inside the box [53].

Further studies

In nuclear-physics input aspect, it is necessary to well study other three keys reactions in order to solve the observed fluorine overabundances in AGB stars, except the $^{19}F(p,\alpha)^{16}O$ reaction proposed above. These are the α -induced reactions of ${}^{13}\text{C}(\alpha,n){}^{17}\text{O}$ [28, 54, 55], ${}^{14}\text{C}(\alpha,\gamma){}^{18}\text{O}$ [56] and 19 F $(\alpha,p)^{22}$ Ne [57]. As one of the experimental goals in the JUNA project, the details of the first (α,n) reaction is described elsewhere [?]. We will target on studying the remaining two important reactions following the proposed $^{19}\text{F}(p,\alpha)^{16}\text{O}$ experiment, with the γ -ray and chargedparticle detector arrays constructed. Certainly, such universal charged-particle array can play a very important role in JUNA, to study other key reactions (emitting charged particles) of astrophysical importance.

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- 1 M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci. 51, 91 (2001).
- Ulf-G Meißner, Science Bulletin 60(1), 43 (2015).
- D. Normile, Science 324, 1246 (2009).
- 4 T. Feder, Physics Today, 63, 25 (2010).
- 5 D. Normile, Science 346, 1041 (2014).
- C. Rolfs and W.S. Rodney, Cauldrons in the Cosmos, Chicago: Univ. Chicago Press, 1988
- S. Lucatello, T. Masseron, J.A. Johnson, M. Pignatari, and F. Herwi, Astrophys. J. 729, 40 (2011).
- 8 S.E. Woosley and W.C. Haxton, Nature 334, 45 (1988).
- 9 G. Meynet and M. Arnould, Astron. Astrophy. 355, 176 (2000).
- 10 S. Cristallo, O. Straniero, R. Gallino, L. Piersanti, I. Domínguez, and M.T. Lederer, Astrophys. J. 696, 797 (2009).

- 11 G. Pandey, D.L. Lambert, and R.N. Kameswara, Astrophys. J. 674, 1068 (2008).
- A. Jorissen, V.V. Smith, and D.L. Lambert, Astron. Astrophys. 261, 164 (1992).
- 13 M. Lugaro, C. Ugalde, A.I. Karakas, J. Görres, M. Wischer, J.C. Lattanzio, and R.C. Cannon, Astrophys. J. 615, 934 (2004).
- K.M. Nollett, M. Busso, and G.J. Wasserburg, Astrophys. J. 582, 1036
- 15 M.L. Sergi, C. Spitaleri, M. La Cognata, A. Coc, A. Mukhamedzhanov, S.V. Burjan, S. Cherubini, V. Crucillá, M. Gulino, F. Hammache, Z. Hons, B. Irgaziev, G.G. Kiss, V. Kroha, L. Lamia, R.G. Pizzone, S.M.R. Puglia, G.G. Rapisarda, S. Romano, N. de Séréville, E. Somorjai, S. Tudisco, and A. Tumino, Phys. Rev. C. 82, 032801R (2010).
- 16 M. Busso, S. Palmerini, E. Maiorca, S. Cristallo, O. Straniero, C. Abia, R. Gallino, and M. La Cognata, Astrophys. J. 717, L47 (2010).
- C. Abia, K. Cunha, S. Cristallo, P. de Laverny, I. Domínguez, A. Recio-Blanco, V.V. Smith, and O. Straniero, Astrophys. J. 737, L8 (2011).
- G.C. Clayton, T.R. Geballe, F. Herwig, C. Fryer, and M. Asplund, Astrophys. J. 662, 1220 (2007).
- R.L. Clarke and E.B. Paul, Can. J. Phys. 35, 155 (1957).
- 20 G. Breuer, Z. Phys. 154, 339 (1959).
- K.L. Warsh, G.M. Temmer, and H.R. Blieden, Phys. Rev. 13, 1690
- 22 R. Caracciolo, P. Cuzzocrea, A. De Rosa, G. Inglima, E. Perillo, M. Sandoli, and G. Spadaccini, Lett. Nuovo Cim. 11, 33 (1974).
- P. Cuzzocrea, A. De Rosa, G. Inglima, F. Perillo, E. Rosato, M. Sandoli, and G. Spadaccini, Lett. Nuovo Cim. 28, 515 (1980).
- A. Isoya, K. Goto, and T. Momota, J. Phys. Soc. Japan 11, 899 (1956).
- 25 A. Isoya, H. Ohmura, and T. Momota, Nucl. Phys. 7, 116 (1958).
- 26 A. Isoya, Nucl. Phys. 7, 126 (1958).
- 27 S. Morita, T. Nakagawa, H. Chu-Chung, and L. Sang-Mu, J. Phys. Soc. Japan 21, 2435 (1966).
- 28 C. Angulo, M. Arnould, M. Rayet, P. Descouvemont, D. Baye, C. Lecercq-Willain, A. Coc, S. Barhoumi, P. Aguer, C. Rolfs, R. Kunz, J.W. Hammer, A. Mayer, T. Paradellis, S. Kossionides, C. Chronidou, K. Spyrou, S. Degl'Innocenti, G. Fiorentini, B. Ricci, S. Zavatarelli, C. Providencia, H. Wolters, J. Soares, C. Grama, J. Rahighi, A. Shotter, M.L. Rachti, Nucl. Phys. A 656, 3 (1999).
- 29 H. Lorentz-Wirzba, PhD thesis, Univ. Müster, 1978
- H. Herndl, H. Abele, G. Staudt, B. Bach, K. Griin, H. Scsribany, H. Oberhummer, and G. Raimann, Phys. Rev. C 44, 952R (1991).
- 31 Y. Yamashita and Y. Kudo, Prog. Theor. Phys. 90, 1303 (1993).
- D.R. Tilley, C.M. Cheves, J.H. Kelley, S. Raman, and H.R. Weller, Nucl. Phys. A 636, 249 (1998).
- 33 M. La Cognata, A.M. Mukhamedzhanov, C. Spitaleri, I. Indelicato, M. Aliotta, V. Burjan, S. Cherubini, A. Coc, M. Gulino, Z. Hons, G.G. Kiss, V. Kroha, L. Lamia, J. Mrázek, S. Palmerini, Š. Piskoř, R.G. Pizzone, S.M.R. Puglia, G.G. Rapisarda, S. Romano, M.L. Sergi, and A. Tumino, Astrophys. J. 739, L54 (2011).
- I. Lombardo, D. Dell'Aquila, L. Campajola, E. Rosato, G. Spadaccini, and M. Vigilante, J. Phys. G: Nucl. Part. Phys. 40, 125102 (2013).
- 35 I. Lombardo, D. DellAquila, A. DiLeva, I. Indelicato, M. La Cognata, M. La Commara, A. Ordine, V. Rigato, M. Romoli, E. Rosato, G. Spadaccini, C. Spitaleri, A. Tumino, M. Vigilante, Phys. Lett. B 748, 178 (2015).
- 36 T.W. Bonner and J.E. Evans, Phys. Rev. 73, 666 (1948).
- C.Y. Chao, A.V. Tollestrup, W.A. Fowler, and C.C. Lauritsen, Phys. Rev. 79, 108 (1950).
- 38 L. Ask, Ark. Phys. 29, 196 (1965).
- H.W. Becker, W.E. Kieser, C. Rolfs, H.P. Trautvetter, and M. Wiescher, Z. Phys. A 305, 319 (1982).
- 40 D. Grambole, C. Bauer, P. Gippner, C. Heiser, W. Rudolph, and H.-J.

- Thomas, J. Radioanal. Nucl. Chem. 83, 107 (1984).
- 41 S. Croft, Nucl. Instr. Meth. A 307, 353 (1991).
- 42 D. Zahnow, C. Angulo, C. Rolfs, S. Schmidt, W.H. Schulte, and E. Somorjai, Z. Phys. A 351, 229 (1995).
- K. Spyrou, C. Chronidou, S. Harissopulos, S. Kossionides, T. Paradellis, Z. Phys. A 357, 283 (1997).
- 44 K. Spyrou, C. Chronidou, S. Harissopulos, S. Kossionides, T. Paradellis, C. Rolfs, W.H. Schulte, L. Borucki, Eur. Phys. J. A 7, 79 (2000).
- 45 S.Z. Chen, S.W. Xu, J.J. He, J. Hu, C.E. Rolfs, N.T. Zhang, S.B. Ma, L.Y. Zhang, S.Q. Hou, X.Q. Yu, X.W. Ma, Nucl. Instr. Meth. A 735, 466 (2014).
- 46 C. Iliadis, Nuclear Physics of Star, New York: Wiley-VCH, 2007
- 47 U. Greife, C. Arpesella, C.A. Barnes, F. Bartolucci, E. Bellotti, C. Broggini, P. Corvisiero, G. Fiorentini, A. Fubini, G. Gervino, F. Gorris, C. Gustavino, M. Junker, R.W. Kavanagh, A. Lanza, G. Mezzorani, P. Prati, P. Quarati, W.S. Rodney, C. Rolfs, W.H. Schulte, H.P. Tryutvetter, D. Zahnow, Nucl. Instr. Meth. A 350, 327 (1994).
- 48 K.J. Kang, et al. CDEX Collaboration, Front. Phys. 8, 412 (2013).
- 49 X.G. Cao, et al. PandaX Collaboration, Sci. China-Phys. Mech. Astron. 57, 1476 (2014).

- 50 G. Imbriani, Int. Workshop on Nucl. Phys. 28th Course, Italy, 16-24th
- 51 Y.C. Wu, X.Q. Hao, Q. Yue, Y.J. Li, J.P. Chen, K.J. Kang, Y.H. Chen, J. Li, J.M. Li, Y.L. Li, S.K. Liu, H. Ma, J.B. Ren, M.B. Shen, J.M. Wang, S.Y. Wu, T. Xue, N. Yi, X.H. Zeng, Z. Zeng, Z.H. Zhu, Chin. Phys. C 37, 086001 (2013).
- 52 G. Heusser, Nucl. Instr. Meth. B 83, 223 (1993).
- 53 A. Caciolli, et al. LUNA Collaboration, Eur. Phys. J. A 39, 179 (2009).
- 54 B. Guo, Z.H. Li, M. Lugaro, J. Buntain, D.Y. Pang, Y.J. Li, J. Su, S.Q. Yan, X.X. Bai, Y.S. Chen, Q.W. Fan, S.J. Jin, A.I. Karakas, E.T. Li, Z.C. Li, G. Lian, J.C. Liu, X. Liu, J.R. Shi, N.C. Shu, B.X. Wang, Y.B. Wang, S. Zeng, and W.P. Liu, Astrophys. J. 756, 193 (2012).
- 55 M. La Cognata, C. Spitaleri, O. Trippella, G.G. Kiss, G.V. Rogachev, A.M. Mukhamedzhanov, M. Avila, G.L. Guardo, E. Koshchiy, A. Kuchera, L. Lamia, S.M.R. Puglia, S. Romano, D. Santiago, and R. Spartà, Phys. Rev. Lett. 109, 232701 (2012).
- 56 E.D. Johnson, G.V. Rogachev, J. Mitchell, L. Miller, and K.W. Kemper, Phys. Rev. C 80, 045805 (2009).
- 57 C. Ugalde, R.E. Azuma, A. Couture,? J. Görres, H.Y. Lee, E. Stech, E. Strandberg, W. Tan, and M. Wiescher, Phys. Rev. C 77, 035801