Measurement of the low energy ^{25}Mg(p,γ)^{26}Al resonances

Jun Su[1,2*], *Zhihong* Li[2**], *Hao* Zhang[1,2], *Yunju* Li[2], *Ertao* Li[3], *Chen* Chen[2], *Yangping* Shen[2], *Jianjun* He[1], *Liyong* Zhang[1], *Xinyue* Li[1], *Gang* Lian[2], *Bing* Guo[2], *Luohuan* Wang[1], *Yaode* Sheng[1], *Yinji* Chen[1], *Long* Zhang[2], *Fuqiang* Cao[2], and *Weiping* Liu[2]

[1]Key Laboratory of Beam Technology of Ministry of Education, College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China
[2]China Institute of Atomic Energy, P. O. Box 275(10), Beijing 102413, China
[3]College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China

Abstract. The cosmic 1.809 MeV γ-ray emitted by the radioactive nucleus ^{26}Al in the Galaxy is one of the key observation targets of the γ-ray astronomy. The ^{26}Al is mainly produced by the ^{25}Mg(p, γ)^{26}Al reaction in the stellar Mg-Al reaction cycle. At the astrophysical relevant temperatures, the reaction rates of ^{25}Mg(p, γ)^{26}Al are dominated by several narrow resonances at low energy. This work reports a measurement of the low energy ^{25}Mg(p, γ)^{26}Al resonances at Jinping Underground Nuclear Astrophysics experimental facility (JUNA) in the China Jinping Underground Laboratory (CJPL).

1 Introduction

The 1.809 MeV γ-ray emitted from the radioactive decay of ^{26}Al in the interstellar medium of the Galaxy has been observed by several satellites [1–3]. The half-life of ^{26}Al (7.17×10^5 y) is modest for the observation of the γ-ray astronomy. It is long enough that ^{26}Al synthesized in the interior of the star can survive and transfer to the interstellar medium. On the other hand, it is much shorter than the evolution time of the Galaxy so the observation of ^{26}Al decay is direct evidence of the ongoing nucleosynthesis in the Galaxy. Therefore, ^{26}Al is expected to be a tracer for stellar nucleosynthesis and a thermometer for its production site [4].

^{26}Al can be synthesized by Mg-Al reaction cycle in the H burning environments, e.g., asymptotic giant branch (AGB) stars, Wolf-Rayet stars, O-Ne-Mg novae and core collapse supernovae. It is believed that ^{26}Al in the interstellar medium of the Galaxy is mainly from massive stars and partly from AGB stars and novae [4]. In the Mg-Al reaction cycle, ^{26}Al is produced via the ^{25}Mg(p, γ)^{26}Al reaction and destroyed by β-decay or other reactions, e.g., ^{26}Al(p, γ)^{27}Si, ^{26}Al(n, p)^{26}Mg, ^{26}Al(n, α)^{23}Na, depending on the astrophysical sites. Hence, the ^{25}Mg(p, γ)^{26}Al reaction plays an important role in the study of the 1.809 MeV cosmic γ-ray and the origin of ^{26}Al in the Galaxy.

At astrophysical relevant temperatures, the reaction rates of ^{25}Mg(p, γ)^{26}Al are characterized by several narrow resonances at low energy, among which the main contributors are 58, 92, 189, and 304 keV resonances. Due to its extremely low resonance strength, the 58 keV

---

[*] e-mail: sujun@bnu.edu.cn
[**] e-mail: zhli@ciae.ac.cn

resonance has been only investigated by indirect method [5, 6]. The 304 keV resonance has been directly measured in several works [7–9] thus its resonance strength is well determined. Strieder et al. [10] performed the first direct underground measurement of the ^{25}Mg(p, γ)^{26}Al reaction and obtained the 92 and 189 keV resonance strengths. However, the 189 keV resonance strength result of the underground experiment [10] is larger than those obtained by ground measurement [11] and accelerator mass spectrometer(AMS) method [12].

In the present work, we performed a new direct measurement of the low energy resonances of ^{25}Mg(p, γ)^{26}Al at the 400 kV accelerator of Jinping Underground Nuclear Astrophysics experimental facility (JUNA) [13]. Since the result of the 92 keV resonance has already been published elsewhere [14], we present some supplementary results here.

2 Experiment

Figure 1 shows the experimental setup. The proton beam provided by the 400 kV accelerator was collimated by two apertures and then bombarded on the ^{25}Mg enriched isotopic target which was directly cooled by flowing water. In the upstream of the target, a cold trap cooled by liquid nitrogen was used to suppress the carbon deposition on the target. The target and the end of the vacuum tube composed a Faraday cup, which was used to measure the beam current. A ring electrode applied with a voltage of −300 V was installed between the target and cold trap to suppress secondary electrons.

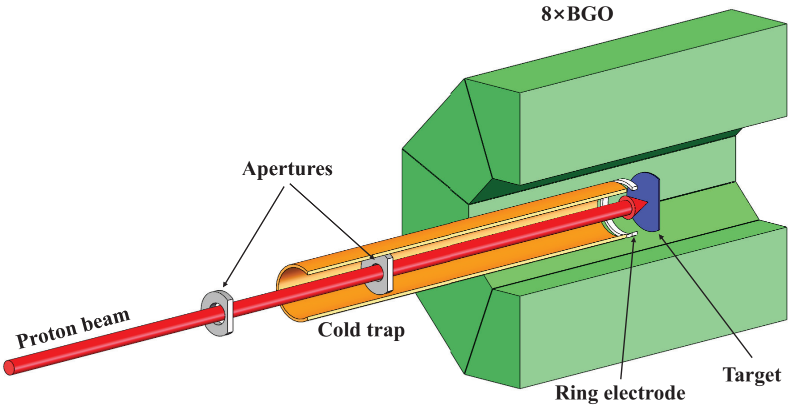

Figure 1: Schematic of the experimental setup.

^{25}Mg isotopic targets made by ^{25}Mg enriched magnesium metal (98.81 ± 0.02% abundance) were used. The thickness of targets was set to be ~60 μg/cm^2. A Cr layer with a thickness of ~40 μg/cm^2 was sputtered on the surface of each target to enhance the radiation resistance of the target. A near 4π BGO detector array was used to detect the γ-rays. The BGO detector array was calibrated by ^{137}Cs and ^{60}Co gamma sources. The single spectrum (sum of the spectra obtained by eight segments) and the sum spectrum (sum of the energies of all eight BGO segments) were obtained. The Monte Carlo simulation based on the GEANT4 software [15] was performed for the BGO detector array, which reproduced the calibration spectra well.

3 Data analysis

The resonance strength $\omega\gamma$ of a narrow resonance can be determined by measuring the maximum yield $Y_{\max}$ of a thick target

$$\omega\gamma = \frac{2\varepsilon_{\mathrm{eff}}(E_{\mathrm{R}})}{\lambda_{\mathrm{R}}^2} Y_{\max}, \tag{1}$$

where λ_{R} is the de Broglie wavelength and $\varepsilon_{\mathrm{eff}}(E_{\mathrm{R}})$ is the effective stopping power of proton in the target. The effective stopping power is related to the concentration of ^{25}Mg in the target, which changed with the bombardment of the proton beam on the target. Therefore, in the measurement with high-intensity beam, such as 92 keV resonance measurement, the effective stopping power was monitored by measuring the maximum yield of the 304 keV resonance regularly. The maximum yield was calculated by $Y_{\max} = A_{\mathrm{sum}}/\eta_{\mathrm{sum}}$, where the A_{sum} is the sum peak count and the η_{sum} is the sum peak efficiency. The sum peak efficiency is related to γ-ray decay scheme as well as the primary γ-ray branching ratios of the resonance.

Figure 2(a) shows the sum spectrum of the 304 keV resonance obtained by BGO detector array, in which the sum peak at $E_{\mathrm{sum}} = 6610$ keV is clearly visible. Figure 2(b) shows the single spectrum obtained by putting a 6400-6800 keV gate on the sum peak shown in Fig. 2(a). In contrast to the sum spectrum, many individual γ peaks, which are closely related to the decay scheme of the resonance, appear in the single spectrum.

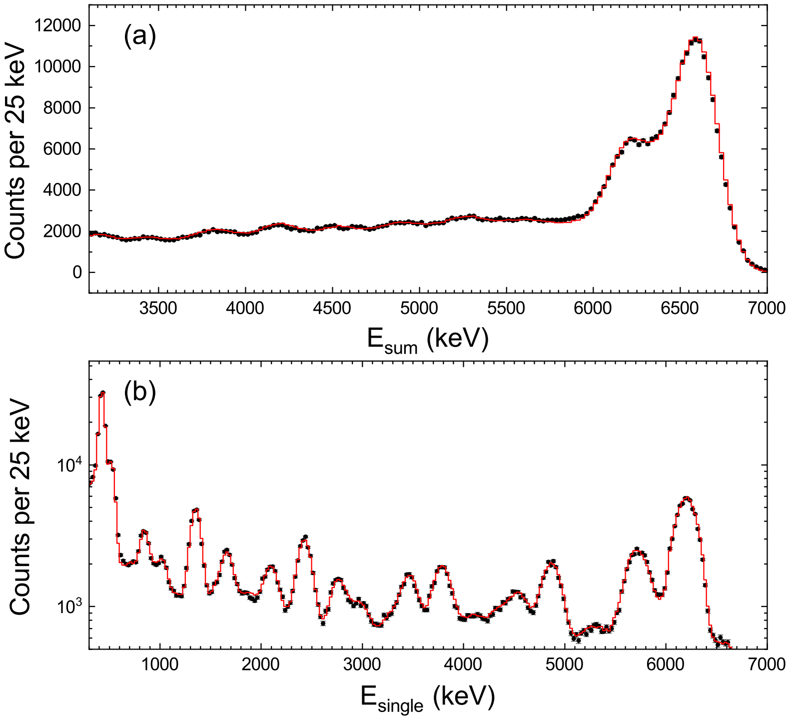

Figure 2: γ-ray spectra of the 304 keV ^{25}Mg(p, γ)^{26}Al resonance (black-filled circle). (a) Sum spectrum, the red line represents the GEANT4 simulation normalized to the experimental data. In the simulation the primary γ-ray branching ratios were extracted from the single spectrum. (b) Single spectrum, the red line represents the fitting results.

A fitting program based on the expectation-maximization method [16] was developed to extract the decay scheme of the resonance from the experimental single spectrum, in which the primary γ-ray branching ratios were set as adjustable input parameters. The fitting process is 1) Initial primary γ-ray branching ratios were fed in the GEANT4 simulation to produce a single spectrum, and 2) The simulation result was compared with the experimental data and the deviations were fed back to adjust the input parameters. After thousands of iterations, the primary γ-ray branching ratios will converge to a final result. By using this program, the primary γ-ray branching ratios of the 304 keV resonance were extracted by fitting the single spectrum shown in Fig. 2(b). The result is in good agreement with those reported by the previous measurements with HPGe detector [8, 9]. The GEANT4 simulation based on primary γ-ray branching ratios reproduced the sum spectrum obtained well, as shown in Fig. 2(a).

The experimental data of the 92 keV resonance were analyzed via the same process as the 304 keV resonance. Figure 3 shows the sum spectrum and single spectrum of the 92 keV resonance. The primary γ-ray branching ratios of the 92 keV resonance were extracted by fitting the single spectrum.

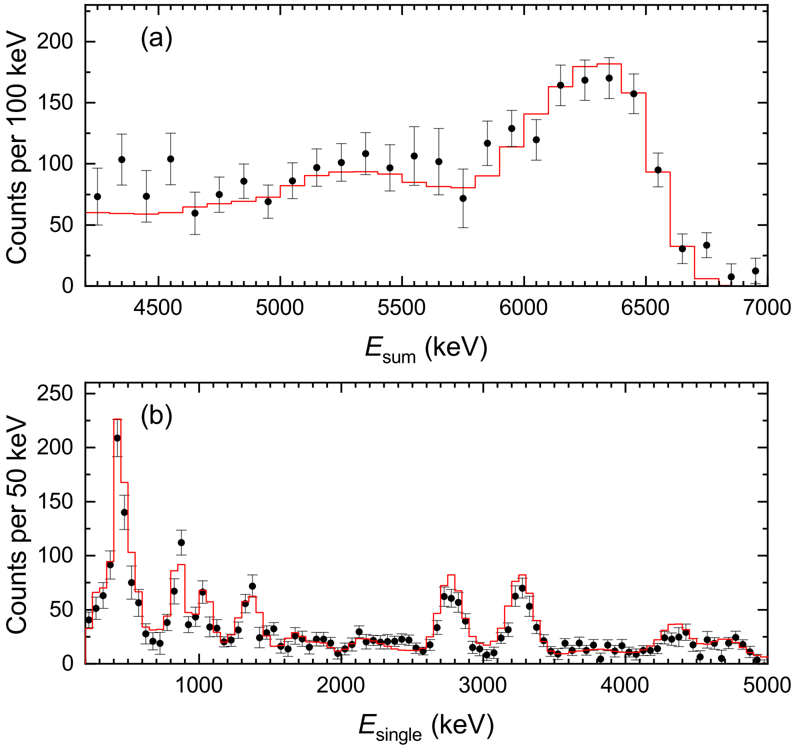

Figure 3: γ-ray spectra of the 92 keV ^{25}Mg(p, γ)^{26}Al resonance (black-filled circle). (a) Sum spectrum after background subtraction, the red line represents the GEANT4 simulation normalized to the experimental data.(b) Single spectrum, the red line represents the fitting results.

The 92 keV resonance strength was determined by a relative method as

$$\omega\gamma_{92} = \frac{\lambda_{\mathrm{R}}^2(304)}{\lambda_{\mathrm{R}}^2(92)} \frac{A_{92}/\eta_{92}}{A_{304}/\eta_{304}} \frac{N_{304}}{N_{92}} \frac{\varepsilon_{\mathrm{eff}}(92)}{\varepsilon_{\mathrm{eff}}(304)} \omega\gamma_{304}, \tag{2}$$

in which A_{R}, η_{R}, and N_{R} are the sum peak count, sum peak efficiency, and proton numbers of the corresponding resonance measurements, respectively. The sum peak efficiency ratio η_{304}/η_{92} is deduced to be 1.3 ± 0.04. The effective stopping power ratio $\varepsilon_{\mathrm{eff}}(92)/\varepsilon_{\mathrm{eff}}(304)$ is calculated to be 1.50 ± 0.01 over a large range of ^{25}Mg content in the target. With the $\omega\gamma_{304}$=(3.1±0.1)×10^{-2} eV value reported in Ref. [9], the resonance strength of 92 keV resonance is determined to be $\omega\gamma_{92}$=(3.8±0.3)×10^{-10} eV [14].

4 Summary

In summary, the $^{25}\mathrm{Mg}(\mathrm{p},\gamma)^{26}\mathrm{Al}$ reaction was directly measured at JUNA in CJPL. The primary γ-ray branching ratios of the 92 and 304 keV resonance were extracted from the single spectrum. The 92 keV resonance strength was determined with improved precision. The data analysis of other low energy resonances including the 189 keV resonance is in process and the results will soon be published.

5 Acknowledgements

The present work is supported by the National Natural Science Foundation of China (Grant Nos. 11490563, U1867211, 12125509, 11961141003, 11775133, and 12175152), and the Continuous Basic Scientific Research Project No. WDJC-2019-13.

References

[1] W.A. Mahoney, J.C. Ling, A.S. Jacobson, R.E. Lingenfelter, Astrophys. J **262**, 742 (1982)

[2] R. Diehl, C. Dupraz, K. Bennett, H. Bloemen, W. Hermsen, J. Knoedlseder, G. Lichti, D. Morris, J. Ryan, V. Schoenfelder et al., Astron. Astrophys. **298**, 445 (1995)

[3] R. Diehl, H. Halloin, K. Kretschmer, G.G. Lichti, V. Schönfelder, A.W. Strong, A. Von Kienlin, W. Wang, P. Jean, J. Knödlseder et al., Nature **439**, 45 (2006)

[4] R. Diehl, M.G. Krause, K. Kretschmer, M. Lang, M.M. Pleintinger, T. Siegert, W. Wang, L. Bouchet, P. Martin, New Astron. Rev. **92**, 101608 (2021)

[5] C. Iliadis, L. Buchmann, P.M. Endt, H. Herndl, M. Wiescher, Phys. Rev. C **53**, 475 (1996)

[6] Y.J. Li, Z.H. Li, E.T. Li, X.Y. Li, T.L. Ma, Y.P. Shen, J.C. Liu, L. Gan, Y. Su, L.H. Qiao et al., Phys. Rev. C **102**, 025804 (2020)

[7] P. Endt, P. De Wit, C. Alderliesten, Nucl. Phys. A **459**, 61 (1986)

[8] B. Limata, F. Strieder, A. Formicola, G. Imbriani, M. Junker, H.W. Becker, D. Bemmerer, A. Best, R. Bonetti, C. Broggini et al., Phys. Rev. C **82**, 015801 (2010)

[9] H. Zhang, Z.H. Li, J. Su, Y.J. Li, C. Chen, L. Zhang, F.Q. Cao, Y.P. Shen, W. Nan, W.K. Nan et al., Chin. Phys. C **45**, 084108 (2021)

[10] F. Strieder, B. Limata, A. Formicola, G. Imbriani, M. Junker, D. Bemmerer, A. Best, C. Broggini, A. Caciolli, P. Corvisiero et al., Phys. Lett. B **707**, 60 (2012)

[11] C. Iliadis, T. Schange, C. Rolfs, U. Schröder, E. Somorjai, H. Trautvetter, K. Wolke, P. Endt, S. Kikstra, A. Champagne et al., Nucl. Phys. A **512**, 509 (1990)

[12] A. Arazi, T. Faestermann, J.F. Niello, K. Knie, G. Korschinek, M. Poutivtsev, E. Richter, G. Rugel, A. Wallner, Phys. Rev. C **74**, 025802 (2006)

[13] W.P. Liu, Z.H. Li, J.J. He, X.D. Tang, G. Lian, Z. An, J.J. Chang, H. Chen, Q.H. Chen, X.J. Chen et al., Sci. China Phys. Mech. Astron. **59**, 642001 (2016)

[14] J. Su, H. Zhang, Z. Li, P. Ventura, Y. Li, E. Li, C. Chen, Y. Shen, G. Lian, B. Guo et al., Science Bulletin **67**, 125 (2021)

[15] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G.. Barrand et al., Nucl. Instr. Meth. A **506**, 250 (2003)

[16] J.L. Taín, D. Cano-Ott, Nucl. Instr. Meth. A **571**, 728 (2007)