EPJ Web of Conferences **66**, 07017 (2014)
DOI: 10.1051/epjconf/20146607017

The ^{6}Li(^{22}Ne,^{26}Mg)d α-transfer experiment for the study of low-energy resonances in ^{22}Ne(α,γ)^{26}Mg

Shuya Ota[1, 2 a], Hiroyuki Makii[1], Tetsuro Ishii[1], Christopher Angell[1], Daniel W. Bardayan[3,5], Satoshi Chiba[4], Ichiro Nishinaka[1], Katsuhisa Nishio[1], Milan Matos[5], Shinichi Mitsuoka[1], and Steven Pain[5]

[1]Japan Atomic Energy Agency, Tokai, Ibaraki, Japan
[2]Rutgers University, NJ, USA
[3]University of Notre Dame, IN, USA
[4]Tokyo Institute of Technology, Tokyo, Japan
[5]Oak Ridge National Laboratory, TN, USA

Abstract. While the reaction ^{22}Ne(α,n)^{25}Mg is considered an important neutron source for the *s* process in massive stars, the competing ^{22}Ne(α,γ)^{26}Mg reaction may be of considerable strength and could significantly suppress the neutron production. For a better understanding of this neutron source, the branching ratio of n and γ partial widths (Γ_n, Γ_γ) and spectroscopic information such as energies and spins of ^{26}Mg resonance states within the Gamow window (E_α = 400-1000 keV) should be experimentally determined with improved accuracy. In the present work, we propose to use the ^{6}Li(^{22}Ne, ^{26}Mg)d α-transfer reaction to investigate those resonance parameters and have tested the feasibility of the experiment.

1 Introduction

In the He-burning phase of massive stars, the ^{22}Ne(α,n)^{25}Mg reaction is considered to be the main neutron source driving the synthesis of nuclides in the A=60-90 mass range during the *s* process [1]. The reaction also acts as a secondary neutron source during the *s* process in low-mass asymptotic giant branch (AGB) stars during which roughly half the abundances of nuclides in the A=90-209 range are thought to be synthesized [2]. A variety of attempts to experimentally determine the rate for this reaction at the Gamow window corresponding to *s* process temperatures (T = 0.2-0.3 GK) have been made either through direct ^{22}Ne(α,n)^{25}Mg measurements [e.g., 3-6] or indirectly via ^{26}Mg(γ,n)^{25}Mg [7], ^{25}Mg(n,γ)^{26}Mg [8], ^{26}Mg(γ,γ')^{26}Mg [9], ^{26}Mg(p,p'γ)^{26}Mg [10], and ^{22}Ne(^{6}Li,d)^{26}Mg reactions [11, 12]. However, direct measurements have been hindered by the small cross section due to the Coulomb barrier and the resonances at E_α < 830 keV have not been identified with this method. The indirect measurements have identified many low-energy resonances, but unambiguous determination of the resonance parameters such as J^π, Γ, Γ_γ, Γ_n and Γ_α in ^{26}Mg produced by α + ^{22}Ne has remained a longstanding problem especially for resonances near the Gamow peak.

Of these uncertainties, the ratio of Γ_n and Γ_γ to determine the branching ratio of n and γ emission channels plays an important role in obtaining the neutron yield for the *s* process. The ^{22}Ne(α,γ)^{26}Mg reaction (Q=10.615 MeV), which competes with the ^{22}Ne(α,n)^{25}Mg reaction (open above the

---

[a] Corresponding author: shuyaota@nuclearemail.org

excitation energy of ^{26}Mg, E_x=11.093 MeV), may be of considerable strength and could significantly suppress neutron production during He burning (E_x=10.9-11.5 MeV). To address this problem, we propose to study the ^{6}Li(^{22}Ne, ^{26}Mg)d α-transfer reaction in this work. Because both the α and ^{22}Ne have ground states with $J^\pi=0^+$, the α-transfer reaction preferentially populates natural parity states in ^{26}Mg. This helps to enable studies of the astrophysically relevant natural parity states in ^{26}Mg. Furthermore, the inverse kinematics approach enables us to determine Γ_n / Γ_γ by direct measurements of the ratio of ^{25}Mg and ^{26}Mg. In this article, we present our preparation for the experiment and results of a preliminary test.

2 Experimental Setup

2.1 Inverse Kinematics

Previous studies of the ^{22}Ne(^{6}Li,d)^{26}Mg reaction (normal kinematics) successfully identified bound and resonance states in ^{26}Mg (E_x=9.4-12.1 MeV) and provided J^π assignments for those states [11, 12]. These studies were hindered however from background due to indirect reactions and the ^{12}C(^{6}Li,d)^{16}O reaction from the C backing foil and some unresolved doublets, thus left some resonance energies uncertain. An inverse kinematics measurement, in which recoils (^{26}Mg, ^{25}Mg) and ejectiles (deuterons) are measured in coincidence, does not suffer from backgrounds [13]. Fig. 1 shows the relationship of scattering angle (in laboratory system, θ_{LAB}) and energy of the ejected deuterons for the reaction in inverse kinematics for the laboratory angular range of 95-160°, corresponding to the Center-of-Mass angles θ_{CM} = 50-10°. This subtends the angular range where the reaction cross sections were measured by a previous experiment in normal kinematics [11]. Kinematic curves corresponding to the twelve resonance states within the range E_x=9.4-12.1 MeV that were observed by [11] are drawn in the figure. While the reaction cross section generally showed peaks around θ_{LAB} = 130-160° (e.g., 10-20 μb/sr for E_x=11.3 MeV which is a particularly important resonance for the *s*-process), the deuteron energies are lower and thus it is harder to separate each state at a given angle. Therefore detectors with good energy-resolution are essential for the present experiment.

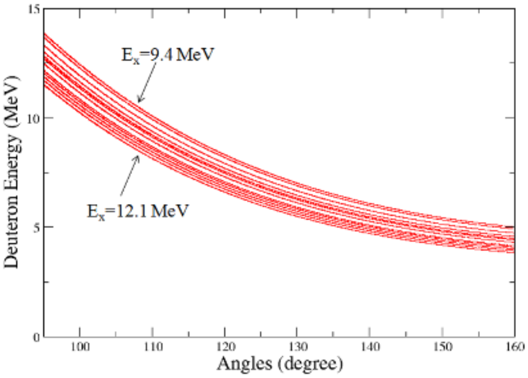

Figure 1. Deuteron energy as a function of scattering angle in laboratory system in the inverse kinematics reaction ^{6}Li(^{22}Ne, ^{26}Mg)d. The twelve resonances within the range E_x=9.4-12.1 MeV observed by [11] are drawn.

2.2 Detectors

Si ΔE-E detectors are used for particle identification for both the recoils and ejectiles. For the detection of Mg ions (downstream of the target), we used 20 μm thick surface-barrier detectors backed by 300 μm thick PIN diode detectors. For the detection of deuterons (upstream of the target), we used

75 μm thick ion-implanted detector backed by 300 μm thick PIN diode detectors. Energy resolutions of ΔE and E detectors for the upstream detectors are 40 keV and 25 keV respectively, measured using ^{241}Am α source. Thus a combined energy resolution of < 50 keV, an improvement over the former experiment in the normal kinematics [12], is expected.

2.3 Preliminary Test

We performed a preliminary beam test using a 110 MeV ^{22}Ne beam from the JAEA (Japan Atomic Energy Agency)-Tokai 20 MV Tandem accelerator. A ^{6}Li-enriched (95%) lithium carbonate (Li_2CO_3) target with a thickness of 20 μg/cm^2 was prepared on a graphite backing foil (20 μg/cm^2) so that the energy loss of the ^{22}Ne beam and deuterons in those materials will be negligibly small. The beam bombarded the target at an intensity of 10 pnA for 12 hours. For both of the upstream and the downstream detectors, four Si ΔE-E telescopes were used, placed at θ_{CM} = 25° ($\theta_{LAB,deuteron}$ = 130°, $\theta_{LAB,Mg}$ = 3°). The angles were chosen as a compromise between enhancing the reaction yield and reducing the contribution from elastic scattering of the ^{22}Ne beam. To limit the scattering angle spread of deuterons, we placed slits with an aperture of ϕ=1.1 mm in front of the downstream detectors and used a tightly focused beam spot (ϕ=1 mm). The energies of deuterons were measured to determine excitation energies of ^{26}Mg and the background events due to other reactions were minimized to become negligibly small in the data by requiring the coincidence detection of Mg ions and deuterons. This was achieved through a clear particle identification of Mg from other elements such as Ne [13].

3 Results and Discussion

Fig. 2 (a) shows the deuteron spectrum obtained by the test experiment. Those deuterons were measured in coincidence with the Mg ions in the forward-angle telescopes. Details of the coincidence detection can be found in [13]. Unfortunately, no clear resonance structure could be confirmed compared to the spectrum obtained in [11] which was measured at almost the same CM angle (θ_{CM} ~ 29°), or to the spectrum simulated on the basis of our experimental conditions, i.e. statistics and energy resolution of telescopes (Fig. 2 (b)). This is mainly because of the insufficient limitation of kinematic broadening given by the slits. In the present test, the slit size was too large, allowing a spread of deuteron angles of about $\delta\theta_{LAB}$ = 2.5° to reach the detectors, resulting in a laboratory energy resolution of the energy about 250 keV. Also, angular uncertainty caused by positional error of the downstream detectors contributes to the broadening of the spectrum. Despite this difficulty, we could still determine whether the expected statistics could be obtained in the limited beam time. Although each resonance peak was not identified, we compared the integrated yields from the region corresponding to E_x=9.4-12.1 MeV to the yield calculated from the cross sections obtained by the normal kinematics experiment [11]. They agreed with each other within 40%. The uncertainty came from ambiguous determination of the energy range E_x=9.4-12.1 MeV in our data due to the unresolved resonance peaks.

In the next experiment, we aim to identify individual resonance states. To improve the problem of kinematic acceptance, we decided to place slits for both sides of upstream and downstream detectors, which will allow us to limit the $\delta\theta_{LAB}$ of deuterons to a small enough (< 0.2°) range. We have completed the construction of the new chamber for this geometry. To get the better statistics, the development of ^{6}LiF and $^{6}Li_2O$ targets is under way, which is expected to produce about 2-3 times more statistics than $^{6}Li_2CO_3$ for the same energy loss. Also, since we have confirmed the insufficient particle identification of ^{26}Mg and ^{25}Mg in the test experiment [13], we try to improve the Mg detectors for the forthcoming experiment.

4 Summary

We studied the ^{6}Li(^{22}Ne,^{26}Mg)d α-transfer experiment to better understand the low-energy resonance states of ^{26}Mg populated by the α + ^{22}Ne reaction. The present measurement in inverse kinematics will be the first experiment for the reaction and is expected to directly investigate Γ_n / Γ_γ and determine the resonance energies which remain ambiguous. The preliminary test results showed successful coincidences of Mg ions and deuterons, insufficient angular resolution prevented us from resolving individual resonances. Simulation indicates that improved energy resolution will result from limiting the angular acceptance of the deuteron detection. A development of the chamber has been completed and the next experiment will be performed shortly.

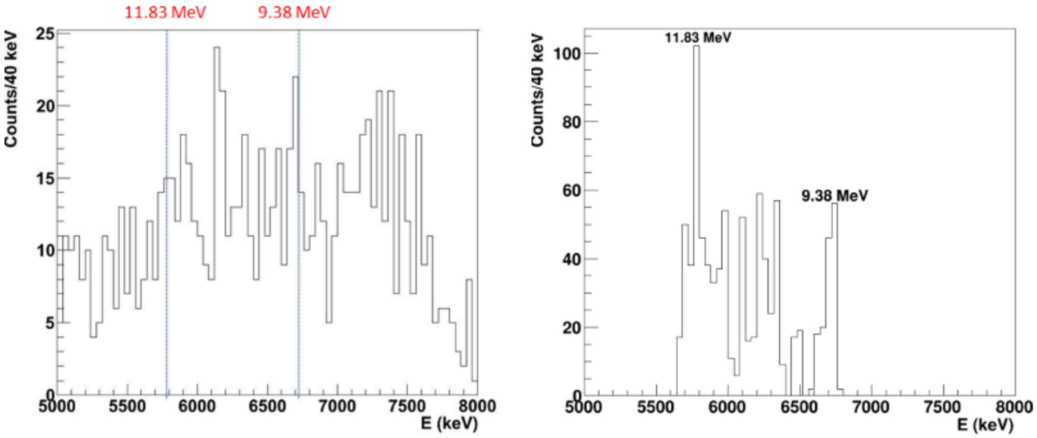

Figure 2. (a) Deuteron spectrum obtained by coincidence detection with Mg in the preliminary test (θ_{CM} = 25°). Two vertical lines indicate the deuteron energies corresponding to the two ^{26}Mg resonance peaks observed in [11]. (b) A simulated spectrum based on our experimental conditions. Yields for individual resonance followed Ref. [11]. Note that states with energy lower than E_x=9.4 MeV or higher than E_x=12.1 MeV were not considered due to the lack of previous data.

Acknowledgement

The authors would like to express our thanks to the staff of the JAEA tandem accelerator for their helpful operation. This work was performed under the support by the JSPS research fellowship.

References

1. F. Kappeler, Prog. Part. Nucl. Phys. **43**, 419 (1999)
2. O. Straniero, R. Gallino, M. Busso, A. Chieffi, R. M. Raiteri, M. Limongi, and M. Salaris, Astrophys. J. Lett. **440**, L85 (1995)
3. K. Wolke, W. Harms, J. W. Becker, J. W. Hammer, K. L. Kratz, C. Rolfs, U. Schroder, H. P. Trautvetter, M. Wiescher, and A. Wohr, Z. Phys. A **334**, 491 (1989)
4. V. Harms, K. L. Kratz, and M. Wiescher, Phys. Rev. C **43**, 2849 (1991)
5. H. W. Drotleff, A. Denker, H. Knee, M. Soine, G. Wolf, J. W. Hammer, U. Greife, C. Rolfs, and H. P. Trautvetter, Astrophys. J. **414**, 735 (1993)
6. M. Jaeger, R. Kunz, A. Mayer, J. W. Hammer, G. Staudt, K. L. Kratz, and B. Pfeiffer, Phys. Rev. Lett. **87**, 202501 (2001)
7. B. L. Berman, R. J. Baglan, and C. D. Bowman, Phys. Rev. Lett. **24**, 319 (1970)
8. C. Massimi et al., Phys. Rev. C **85**, 044615 (2012)
9. R. Longland, C.Iliadis, G. Rusev, A.P. Tonchev, R.J. deBoer, J. Gorres, and M. Wiescher, Phys. Rev. C**80** 055803 (2009)
10. C. E. Moss, Nucl. Phys. A **269**, 429 (1976)
11. U. Giesen, C. P. Browne, J. Gorres, S. Graff, C. Iliadis, W. Harms, K. L. Kratz, B. Pfeiffer, R. E. Azuma, M. Buckby, J. D. King, Nucl. Phys. A **561** (1993)
12. C. Ugalde, A. E. Champagne, S. Daigle, C. Iliadis, R. Longland, J. R. Newton, and E. Osenbaugh-Stewart, J. A. Clark, C. Deibel, A. Parikh, P. D. Parker, C. Wrede, Phys. Rev. C**76**, 025802 (2007)
13. S. Ota, H. Makii, T. Ishii, K. Nishio, S. Mitsuoka, I. Nishinaka, S. Chiba, Proceedings of Science (NIC XII) 221 (2012).