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Two measurements of the ^{22}Na+p resonant scattering via thick-target inverse-kinematics method

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Abstract. ^{22}Na is an important isotope for the study of extinct radioactivity, meanwhile its sufficiently long half life provides the possibility to observe live ^{22}Na in nearby nova explosions. The ^{22}Na(p,γ)^{23}Mg is one of the key reactions that influence the ^{22}Na abundance in nova ejecta. To study the proton resonant states in ^{23}Mg relevant to the astrophysical ^{22}Na(p,γ)^{23}Mg reaction rates, two measurements have been carried out at the CRIB separator of University of Tokyo, and the RIBLL secondary beamline in Lanzhou, respectively. The ^{22}Na secondary beam was produced via the ^{1}H(^{22}Ne, ^{22}Na)n charge exchange reaction. Thick-target inverse-kinematics method is applied to obtain the excitation function of ^{22}Na+p elastic scattering. Extended gas target and solid state polyethylene foil were used in the two measurements, respectively, to map the different excitation energy region of the compound nucleus ^{23}Mg. Several new resonant levels are observed and their contribution to the ^{22}Na(p,γ)^{23}Mg reaction rate is evaluated.

1 Introduction

Cosmic γ ray is a powerful tool to trace and locate new cosmic events. Great progress in the field of γ-ray astronomy has been achieved in the past twenty years, brought largely by the Compton Gamma Ray Observatory (CGRO) of NASA [1], and the International Gamma Ray Astrophysics Laboratory(INTEGRAL) of European Space Agency [2]. The main motivation of these missions is to

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observe cosmic γ rays from the decay of relatively long-lived ^{7}Be, ^{18}F, ^{22}Na, ^{26}Al, ^{44}Ti and ^{60}Fe isotopes. ^{22}Na has a half life of 2.6 y, and it decays to the first excited state of ^{22}Ne which emits a 1.275 MeV characteristic γ ray. The stellar sources of radioactive ^{22}Na are primarily created in neon-rich nova [3, 4] and supernova explosions [5, 6]. In neon-rich novae, the ^{22}Na is produced by the so-called high-temperature NeNa-MgAl reaction sequences [7, 8], *i.e.* ^{20}Ne$(p,\gamma)^{21}$Na$(\beta^{+})^{21}$Ne$(p,\gamma)^{22}$Na, or ^{20}Ne$(p,\gamma)^{21}$Na$(p,\gamma)^{22}$Mg$(\beta^{+})^{22}$Na alternatively. In 1972, an extraordinarily large ^{22}Ne/^{20}Ne abundance ratio or nearly pure ^{22}Ne was found in low-density graphite grains separated from carbonaceous meteorites [9], which indicates the extinct radioactivity of ^{22}Na [10]. In 1974, Clayton and Hoyle predicted the possibility to observe live ^{22}Na by the 1.275 MeV γ ray from nearby classical nova explosions [11]. The COMPTEL experiments on board CGRO observed five recent Ne-type novae, which resulted in an upper limit of $3.7 \times 10^{-8} M_{\odot}$ of ^{22}Na ejected by any nova in the Galactic disk [12]. Comparing to its relatively long half life, the main depletion mechanism of ^{22}Na is through the ^{22}Na(p,γ)^{23}Mg reaction, the reaction rate over a large range of temperatures is thus crucial in deriving ranges of ^{22}Na production during nova and supernova outbursts.

Many experimental investigations have been carried out to reduce the uncertainties of the ^{22}Na(p,γ)^{23}Mg reaction rate, including direct measurements of the reaction rate with radioactive ^{22}Na targets [13–16], or indirect measurements for ^{23}Mg resonance properties via the β decay of ^{23}Al [17–20], and various transfer [21–23] or fusion-evaporation [24, 25] reactions. In these studies new ^{23}Mg levels were identified in the energy region of astrophysical interest. However, most of the spectroscopic information is still missing due to the very complicated level structure of odd-mass ^{23}Mg close to the proton threshold. The ^{22}Na+p entrance channel is sensitive to populate the ^{23}Mg proton resonance states relevant to the ^{22}Na(p,γ)^{23}Mg reaction; while thick target inverse kinematics (TTIK) technique [26] facilitates the measurement of the excitation function of ^{22}Na(p,p) elastic scattering. Crucial resonant parameters of ^{23}Mg can then be deduced for the evaluation of the ^{22}Na(p,γ)^{23}Mg reaction rate.

2 Experiment

Two measurements using thick-target inverse kinematics method were carried out with intense radioactive ^{22}Na beams of different energies. Extended gas target and solid state polyethylene foil were used in the two measurements, respectively, to map the different excitation energy region of the compound nucleus ^{23}Mg.

2.1 CRIB experiment

One experiment was carried out at the CNS radioactive ion beam separator (CRIB) [27, 28] of the University of Tokyo located in the RIKEN radioactive ion beam factory (RIBF). CRIB is a low-energy in-flight separator which can deliver intense secondary beams of low- and medium-mass nuclei. In the experiment ^{22}Na was produced via the ^{1}H(^{22}Ne, ^{22}Na)n reaction. The ^{22}Ne primary beam of 6.0 AMeV bombarded in a hydrogen gas cell of 80 mm in length, which was confined by Havar foils of 2.5 μm in thickness and cooled with liquid nitrogen to a temperature of about 90 K. A nearly pure ^{22}Na beam was delivered to the ^{22}Na+p resonant scattering with an intensity of about 2.5×10^{5} pps.

The ^{22}Na beam particles were monitored by two parallel-plate avalanche counters (PPACs) before reaching the secondary hydrogen target. The secondary gas target is semi-cylindrical in shape with a length of 300 mm. The energy of the ^{22}Na secondary beam after the entrance window of the gas target was 37.1±1.0 MeV. During the ^{22}Na + p measurement, the hydrogen gas target was maintained within 310±2 Torr by a gas-flow system; this pressure was chosen to fully stop the ^{22}Na particles in the gas volume. The lighter recoil particles emerging from the exit window were detected by a silicon-detector telescope (ST) centered at $\theta_{\rm lab} = 0°$. The ST consists of ΔE and E layers, where the ΔE layer is a double-sided silicon strip detector (DSSD) with orthogonally oriented 16×16 readout strips on both sides and the E layer is a single-pad silicon detector. All the silicon detectors have an area of 50 mm×50 mm. The thickness of the ΔE detector is 75 μm and that of the E detectors is about 1.5 mm.

2.2 RIBLL experiment

The radioactive ion beam line in Lanzhou (RIBLL) is primarily a double-achromatic anti-symmetry fragment separator [29], which is constructed at the heavy ion research facility of Lanzhou (HIRFL). The operation of RIBLL has been mainly based on the coupling of two cyclotrons together, *i.e.* a K=69 Sector Focus Cyclotron (SFC) for low-energy ions and a K=450 Separate Sector Cyclotron (SSC) for intermediate-energy ions. In order to obtain low-energy intense secondary beams by transfer reaction, a setup similar to CRIB was recently installed including a gas target system at the entrance position of RIBLL [30]. The new setup enables the primary beam from SFC to be transported directly to RIBLL, *i.e.* to bombard the gas target system. The secondary ions are subsequently separated and delivered by the 35 m-long RIBLL separator.

The production condition for ^{22}Na secondary beam is similar to that of the CRIB experiment. The ^{22}Ne primary beam of 7.5 AMeV bombarded in a hydrogen gas cell of 80 mm in length, which was confined by Havar foils of 2.5 μm in thickness and cooled with alcohol to a temperature of about 0 °C. The ^{22}Na secondary beam was monitored by a time-of-flight (TOF) system made of two plastic scintillators, and by two PPACs in the flight path. A schematic layout of the experimental setup for the $^{22}\mathrm{Na} + p$ resonant scattering is shown in Fig. 1. In the target position, a polyethylene foil of 100 μm in thickness served as the reaction target, while a 61 μm thick carbon foil was used to evaluate the background. On the same slide, a single-pad silicon detector was also installed for the beam-tuning runs. Downstream from the target, the detector setup for lighter recoil particles is similar to that of the previous CRIB experiment. For the ΔE layer at $\theta_{lab} = 0°$, a larger DSSD with an area of 70 mm×70 mm was used, which has 32×32 readout strips on both sides. During the experiment, a nearly pure ^{22}Na beam was delivered with an intensity of about 8.5×10^4 pps. The energy of the ^{22}Na secondary beam on the surface of the $(\mathrm{CH_2})_n$ target was 93.3±1.4 MeV.

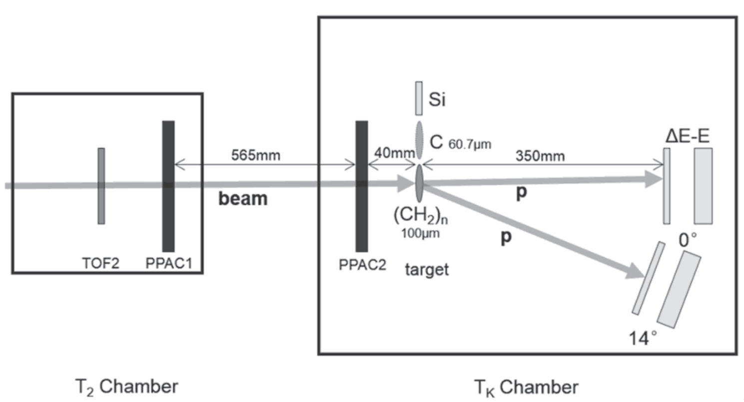

Figure 1. Schematic layout of the experimental setup for the $^{22}\mathrm{Na} + p$ resonant scattering at RIBLL.

3 Results

The complexity in the analysis of a thick-target experimental data lies in the fact that at any individual angle, the proton energy spectrum is continuous over a certain range. By taking the two-body kinematics of ^{1}H(^{22}Na, p)^{22}Na elastic scattering and by considering the energy losses of ^{22}Na and proton along their trajectories, the $E_{\rm c.m.}$ was deduced from the detected proton total energy on an event-by-event basis. After the conversion, the proton yields were added up over different θ_{lab} defined by each pixel of the DSSD. The laboratory averaged differential cross section for the ^{22}Na + p elastic scattering is deduced from the net proton yield according to

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm lab} = \frac{\frac{dN_p}{dE}}{I_{beam}\frac{dN_t}{dE}d\Omega}, \tag{1}$$

where dN_p/dE refers to the net proton yield per $E_{\rm c.m.}$ unit, dN_t/dE is the energy dependent number of hydrogen atoms, I_{beam} is the total number of incident ^{22}Na particles, and $d\Omega$ is the solid angle. The differential cross section in the center-of-mass frame is obtained by

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm c.m.} = \frac{1}{4\cos\theta_0}\left(\frac{d\sigma}{d\Omega}\right)_{\rm lab}, \tag{2}$$

where θ_0 is the averaged laboratory scattering angle.

For the CRIB experiment, the excitation function of the ^{22}Na(p, p) elastic scattering and the R-matrix analysis have been published in Ref. [31]. Due to the stopping power of the gas target, the excitation function for the ^{22}Na(p, p) elastic scattering is obtained over a small range of excitation energies, as shown in Fig. 2. Three peaks have been observed at E_R = 1.030, 1.212 and 1.335 MeV in the excitation function. The best R-matrix fit to the excitation function includes three resonances with $J^\pi = (5/2 \text{ to } 9/2)^-, 7/2^+$ and $5/2^+$, respectively. The proton partial widths of the observed ^{23}Mg states are also deduced from the R-matrix analysis. The explicit assignments of the spin and parity to the 8.793 and 8.916 MeV resonances in ^{23}Mg allow for the shell-model calculation of the proton spectroscopic factors and the γ widths. Based on the resonant parameters obtained in this work, the ^{22}Na(p,γ)^{23}Mg reaction rate is re-evaluated. An enhancement of about 5% over the evaluation by NACRE [32] is found for $T_9 > 2$ owing to the two new s-wave resonant states.

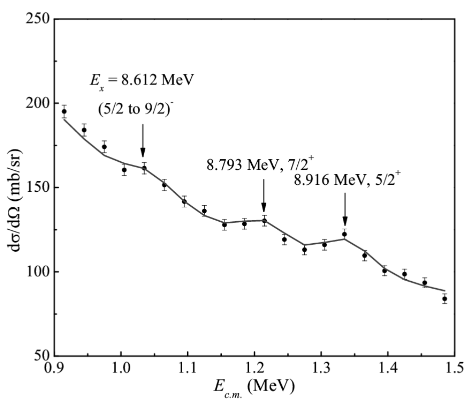

Figure 2. Excitation function for the ^{22}Na(p, p) elastic scattering obtained from the CRIB experiment.

For the RIBLL experiment, a similar data analysis has been performed and a preliminary excitation function for the ^{22}Na(p, p) elastic scattering is shown in Fig. 3. By using a higher-energy ^{22}Na beam and a solid-state $(CH_2)_n$ target, the excitation function for the ^{22}Na(p, p) elastic scattering could be extended up to $E_{c.m.} \approx 4$ MeV, quite complicated resonance structure is observed for further decomposition by R-matrix analysis.

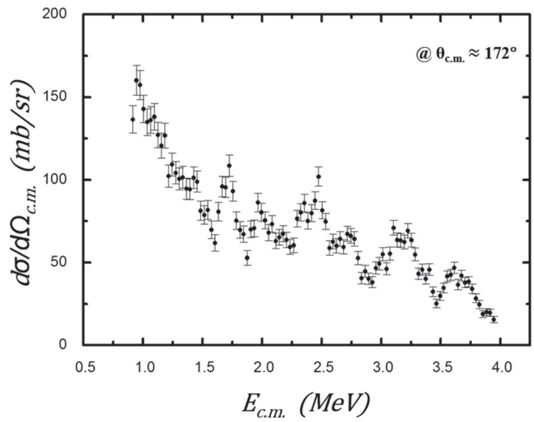

Figure 3. Preliminary excitation function for the ^{22}Na(p, p) elastic scattering obtained from the recent RIBLL experiment.

4 Summary

The ^{22}Na + p resonant scattering has been studied via the thick-target inverse-kinematics method with gas and solid-state targets at different ^{22}Na beam energies. Excitation function for the ^{22}Na(p, p) elastic scattering is extended up to $E_{c.m.} \approx 4$ MeV, corresponding to an excitation energy of about 11.6 MeV in ^{23}Mg. Complicated resonance structure is observed, which indicates the possibility to explore new proton resonance levels in ^{23}Mg relevant to the ^{22}Na(p,γ)^{23}Mg and ^{19}Ne(α,p)^{22}Na reactions. The present work demonstrates that resonance parameters of astrophysical significance can be directly obtained by using the thick-target inverse-kinematics method with secondary beams.

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