# Study of astrophysically important low-energy resonances in $\alpha$+$^{22}$Ne reaction using $^{6}$Li($^{22}$Ne,$^{26}$Mg)d alpha transfer with TIARA and MDM spectrometer

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In core He burning and C-shell burning of massive stars (> 8 solar mass), the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction is considered to be a dominant neutron source for the weak s-process during which nuclides in the A=60-90 mass range are produced [1]. The reaction also largely contributes to the neutron production for the main s-process in He-low and intermediate mass asymptotic giant branch (AGB) stars during which nuclides in the A~90-209 are produced [1]. Some attempts to experimentally determine the rate for this reaction at the Gamow window corresponding to the *s* process temperatures (T = 0.2-0.3 GK, equivalent to $E_\alpha$ = 400 – 900 keV, where $E_\alpha$ is energy of $\alpha$ particle in the laboratory system, and $E_x$=10.9-11.5 MeV, where $E_x$ is excitation energy of $^{26}$Mg) have been made through direct ($^{22}$Ne+$^{4}$He or $\alpha$+$^{22}$Ne) measurements [e.g., 2]. However, they have been hindered by the small cross section due to the Coulomb barrier and the resonance at $E_\alpha$ ~ 830 keV ($E_x$ ~ 11.32 MeV in $^{26}$Mg excitation energy) is the lowest resonance identified with this method. Although indirect methods such as $^{26}$Mg($\alpha$,$\alpha$')$^{26}$Mg,

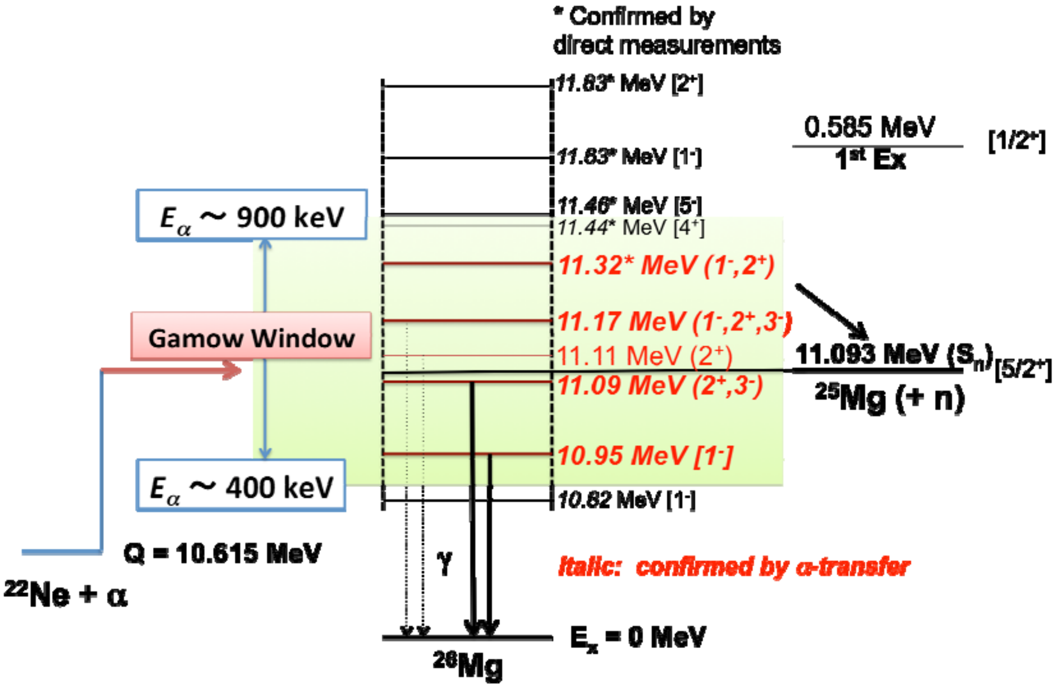

**FIG. 1**. Level scheme of $^{26}$Mg at energy range of our interest. Although the lowest resonance identified by direct measurements is $E_x$=11.32 MeV ($E_\alpha$=832 keV), indirect measurements have identified many lower resonances. Previous ($^{6}$Li,d) measurements in normal kinematics [e.g., 4 and 5] observed four resonances in Gamow window. $E_x$=11.32 MeV and 11.17 MeV are considered the most important contributors to $^{22}$Ne($\alpha$,n) reaction for the s-process [e.g., 5].

$^{22}$Ne($^{6}$Li,*d*)$^{26}$Mg, $^{25}$Mg(n,γ)$^{26}$Mg, $^{26}$Mg(γ,γ')$^{26}$Mg reactions [e.g., 3-6] have been used to identify lower-energy resonances, there remain many uncertainties in spin-parity ($J^{\pi}$), partial wave widths of respective decay channels ($\Gamma_{\gamma}$, $\Gamma_{n}$ and $\Gamma_{\alpha}$) of these resonances. Since past studies identified particularly two resonances, $E_x$=11.32 and 11.17 MeV above neutron separation energy ($S_n$=11.093 MeV), have the largest contribution to the neutron production during the s-process, unambiguously determining $J^{\pi}$, $\Gamma_{\gamma}$, $\Gamma_{n}$ and $\Gamma_{\alpha}$ for these resonances is important. Fig. 1 shows the summary of level scheme in $^{26}$Mg relevant to the present study.

To determine these resonance parameters, we performed an experiment using the $^{6}$Li($^{22}$Ne,$^{26}$Mg)d α-transfer reaction. 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 us to enable studies of the resonance parameters of astrophysically relevant natural parity states in $^{26}$Mg, and $J^{\pi}$ of these resonance states can be determined by measuring the angular distribution of deuterons. Furthermore, the inverse kinematics approach enables us to determine $\Gamma_{n}$ / $\Gamma_{\gamma}$ by direct measurements of the ratio of produced $^{25}$Mg ($^{26}$Mg*$\rightarrow$$^{25}$Mg$_{g.s.}$ + n) and $^{26}$Mg ($^{26}$Mg*$\rightarrow$$^{26}$Mg$_{g.s.}$ + γ) ions at the resonance states. Determining $\Gamma_{n}$ / $\Gamma_{\gamma}$ is important to understand the neutron yield of these resonances. The $^{22}$Ne(α,γ)$^{26}$Mg reaction can be of considerable strength to compete with the $^{22}$Ne(α,n)$^{25}$Mg reaction at $E_x$=11.32 and 11.17 MeV resonances and therefore could significantly suppress neutron production for the s-process.

The experiment was performed at Cave 3 using a 7 MeV/u $^{22}$Ne beam from the K150 cyclotron. $^{6}$Li-enriched (99%) lithium flourite (LiF) targets with the thickness of 30 μg/cm$^{2}$ on a graphite backing foil (10 μg/cm$^{2}$) were prepared so that the effect of the energy loss of the $^{22}$Ne beam and deuterons in those materials on the final energy resolution will be negligibly small. The beam bombarded the target at an intensity of about 3 nA for about 10 days. A large Si detector array, TIARA [8] was used for measuring the energies and angular distribution of light particles (deuterons). The deuteron energies and angles were used to determine excitation energies of $^{26}$Mg. TIARA consists of two types of Si detectors, Hyball and Barrel, which cover 145 – 170° and 40-145° in laboratory frame, respectively (see [8]). TIARA was surrounded by four HPGe clover γ-ray detectors, which were used to confirm the populated states of $^{26}$Mg. Recoil Mg ions were delivered to the Oxford ionization chamber placed at the back of the MDM spectrometer at 0°with ±2°acceptance [9]. The Oxford chamber consists of four proportional wire counters to determine the trajectories of particles and two MicroMegas detectors to measure the deposited energies in the gas (see details in [10]). The chamber was filled with isobutene gas at 35 torr to stop the Mg ions with the energies of our interests in the region of the second MicroMegas detector. The first and the second MicroMegas detectors thus provide ΔE and $E_{res}$ (residual energy), respectively, and the Mg ions are clearly identified from other elements as shown in [11]. Moreover, $^{26,25}$Mg isotopes were identified from each other based on the hit positions on the second wire which is located near the focal plane.

Since the Barrel has insufficient energy resolution to resolve the resonances in $^{26}$Mg, it was mostly used to measure elastic scattering. Data from the Hyball is shown in the following analysis. Fig. 2 shows 2D histograms of $^{26}$Mg excitation energy and hit positions on the second wire in the Oxford chamber, gated on (a) $^{26}$Mg and (b) $^{25}$Mg, respectively. It can be seen a blob (inside the circle) increases the excitation energy with the hit position (rigidity) decreased in the Fig. 2(a). This is because the more highly $^{26}$Mg is excited, the lower rigidity (kinetic energy) it has. The background events (outside the circle) are mostly protons, which was confirmed by the E-ΔE plot obtained by the Barrel. In the Fig. 2 (b), the blob (($^{6}$Li,d+n)) spreads more widely because an evaporating neutron from $^{26}$Mg deposits various momentum to the leftover $^{25}$Mg. In the right side of the ($^{6}$Li,d+n) blob is $^{25}$Mg ions produced by $^{22}$Ne($^{6}$Li,t)$^{25}$Mg reactions. It is worth noting that the $^{26}$Mg (by $^{22}$Ne($^{6}$Li,d+γ)) disappears in Fig. 2 (a) and $^{25}$Mg ($^{22}$Ne($^{6}$Li,d+n)) appears in Fig. 2(b) at nearly $S_n$=11.09 MeV. This proves that our energy determination is reliable.

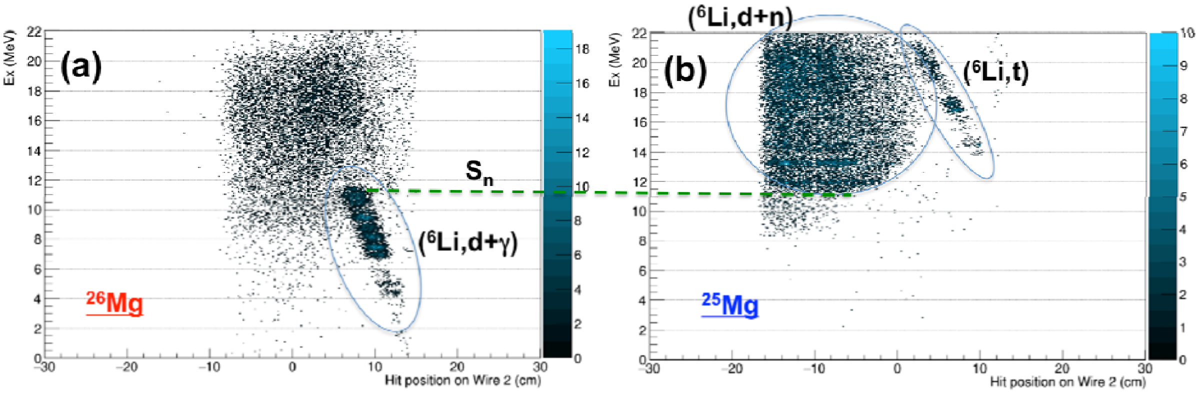

**FIG. 2**. 2D histograms of $E_x$ (determined by Si detectors) and hit positions of Mg ions on the second wire of the Oxford chamber, (a) $^{26}$Mg and (b) $^{25}$Mg.

The excitation energy spectrum of $^{26}$Mg is shown in Fig. 3. The spectrum covered by red shadow is obtained by gating on $^{26}$Mg (the (($^{6}$Li,d+γ) blob) and the total spectrum (blue line) was

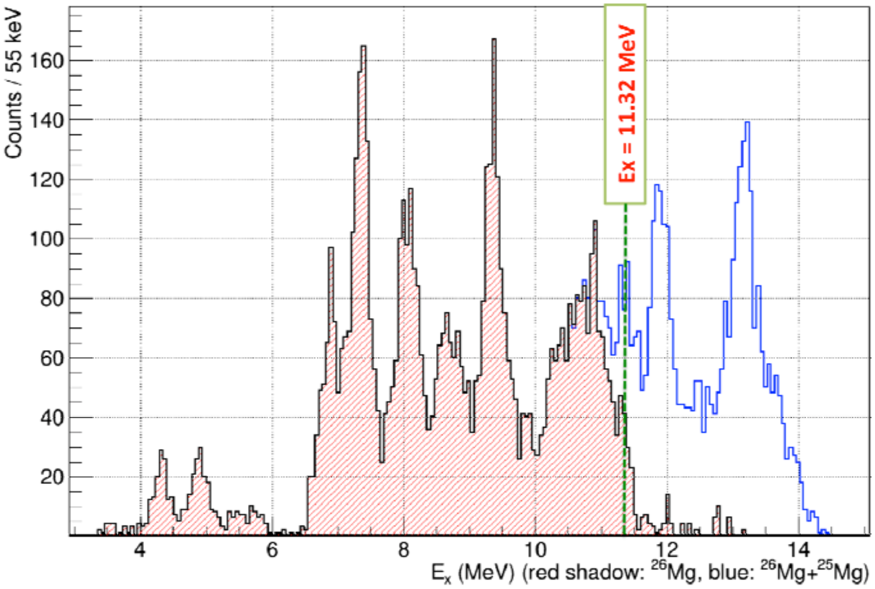

**FIG. 3**. $^{26}$Mg excitation energy spectrum (red shadow: contribution from $^{22}$Ne($^{6}$Li,d)$^{26}$Mg, blue: sum of contributions from $^{22}$Ne($^{6}$Li,d)$^{26}$Mg and $^{22}$Ne($^{6}$Li,d+n)$^{25}$Mg). $E_x$=11.32 MeV resonance peak is distinct in both spectra.

obtained by gating on both $^{26}$Mg and $^{25}$Mg (the ($^{6}$Li,d+n)) blob). It is confirmed that the both spectra ($^{26}$Mg and $^{25}$Mg+$^{26}$Mg) show a distinct peak at Ex=11.32 MeV. On the other hand, no distinct peak was observed at $E_x$=11.17 MeV which was clearly observed by [5]. This may be just because the state is not / very weakly populated as reported in [4]. Currently we are making an effort to extract the numbers of events for these resonances with multiple-Gassian fitting assuming various conditions. This will shortly lead to determining $J^{\pi}$ and $\Gamma_n$ / $\Gamma_\gamma$ and we will study its influence on the s-process nucleosynthesis.

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