R-matrix analysis of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction

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Abstract

The $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ plays a major role in neutron flux in weak s-process nucleosynthesis path in AGB stars of mass (M $\geq$ 8M$_\odot$). The recent evaluation by Philip et al. of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction rate using updated nuclear data of $^{26}\text{Mg}$ from number of sources shows sizable uncertainty and significant discrepancy with literature at low temperature. Also Philip et al. suggested that R-matrix modeling will required to estimate $^{26}\text{Mg}$ resonance states parameters as well as study the interference patterns between distant levels. Near R-matrix analysis has been performed to study interference effects and constrain spin, parity of resonances by fitting the direct measurement data. The resonance states parameters of Philip et al. are not explain well due to strong interference between same spin, parity states. By changing spin parity of some states, experimental data are nicely explain by present R-matrix calculation for 0.8 to 1.45 MeV energy range.

R-matrix

Keywords: The resonance capture, R-matrix analysis

Almost half of the elements heavier than iron are synthesis via slow (over time scales of thousands of years) neutron capture reaction on stable isotope in s-process nucleosynthesis path. The s-process manly activated in Asymptotic Giant Branch (AGB) stars, seeded by $^{56}\text{Fe}$ iron. The $^{11}\text{C}(\alpha, n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction are main source of neutrons for s-process. For low mass AGB stars with 1M$_\odot$ $\leq$ M $\leq$ 3M$_\odot$ both this two reaction contribute as a neutron source and responsible for synthesis elements of Atomic masses A $\approx$ 90 - 209. But for massive stars (M $\geq$ 8M$_\odot$) only $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction is main source of neutron which synthesize isotopes of mass A $\approx$ 60 - 90 is so call weak s-process nucleosynthesis. Also +ev Q-value reaction $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ is act as a competing reaction that decide neutron release from $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction. So constraining the rate of this two reaction has high sensitive for weak s-process nucleosynthesis.

So many direct [4] and [5-7] indirect experimental measurement has been performed to extracted the spin, parity, partial widths ($\Gamma_\alpha$, $\Gamma_n$, $\Gamma_\gamma$) to constraining the rate of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ and $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ reactions. Recently rate of this two reaction has been re-evaluate [3] based upon updated nuclear data from a number of sources and they suggested that an R-matrix modeling will required due to lack of uncertainty of spin, parity of so many relevant states of $^{26}\text{Mg}$ as well as interference effects same partial waves between two states.

In this context a multilevel R-matrix analysis has been performed on available cross-section data of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction including interference effect in energy range E$_c\approx$ 0.8 to 1.45 MeV range and extrapolate up to 0.57 MeV energy. Main aim is to constraining spin-parity and study interference effect of states of $^{26}\text{Mg}$ in excitation energy E$_x$ $\approx$ 11.319 to 11.828 MeV energy range.

1. R-matrix calculation

The behavior of excitation function for $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction was mainly determined by the resonance capture process through the several resonance states of compound nucleus $^{25}\text{Mg}$. In this work an R-matrix calculation has been performed to describe capture data and constrain the spin, parity and width of the states of $^{26}\text{Mg}$.

R-matrix modeling of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction has been performed using AZURE2 code [8]. This code was developed based on the theory developed of Lane [9] and Thomas [9] and of Vogt [10]. In R-matrix formalism, radial space is divided into two disting regions –an internal region extended up to a
radius \( R_c \approx r_0(A_2^{1/3} + A_3^{1/3}) \) and an external region above \( R_c \). A choice of radius for entrance and exit channels is needed for the model calculation. \( R_c \) of the two channels have been obtained through \( \chi^2 \) minimization. However, as channel radius is not a free parameter in the model, we performed a grid search on the channel radius by changing the value in small steps and varying the parameters to get the fit. The chosen channel radii values are 5.37 fm for the \( ^{22}\text{Ne} + \alpha \) channel and 4.21 fm for the \( ^{25}\text{Mg} + n \) channel. During calculation in AZURE2, the energy resolution (3.38 keV) of the system also accounted.

In this present work, initially \( R \)-matrix calculation has been performed \( ^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \) using the recently updated spin, parity and partial widths of resonance states reported in Ref. [3] for the observed resonances in \( ^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \) reaction. Parameters are listed in Table 1 and result of \( R \)-matrix calculation for \( S \)-factor of \( ^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \) reaction compare with experimental data of Ref [4] shown in Fig. 1. Now to better explain experimental data, we adjust resonance energy and widths of populated states. By adjusting this parameters we reproduced the data form 0.7 to 0.98 MeV energy region but fails to reproduced data 0.98 to 1.2 MeV energy region due to strong destructive interference between same \( J^\pi \) states. For bater explain of the experimental data, spin, parity of \( E_c=11.63 \) and 11.784 MeV resonances are changing form \( 1^- \) to \( 0^+ \) and \( \Gamma_x, \Gamma_n \) left as free parameters. The resultant \( R \)-matrix fit is nicely explain the experimental data in 0.8 to 1.45 MeV energy region. The fitted parameters are listed in Table 2. Also extrapolation has been done up to 0.57 MeV by fixed the resonance parameters in 0.57 to 0.8 energy that are evaluated via indirect measurement. Comparison shown in Fig. 2.

A \( R \)-matrix modeling in \( ^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \) reaction was performed to the description of direct measurement data [4]. The present calculation with recently evaluated resonance parameters

| \( E_x \) (MeV) | \( E_r \) (MeV) | \( J^\pi \) | \( \Gamma_x \) (eV) | \( \Gamma_n \) (keV) |
|----------------|----------------|------------|----------------|----------------|
| 11.828 | 1.214 | 2\(^+\) | 0.18 | 1.1 |
| 11.7847 | 1.169 | 1\(^-\) | 8.0 \times 10^{-3} | 24.5 |
| 11.749 | 1.1456 | 1\(^-\) | 0.02 | 64 |
| 11.63 | 1.016 | 1\(^-\) | 2.4 \times 10^{-4} | 13.5 |
| 11.526 | 0.9112 | 1\(^-\) | 4.3 \times 10^{-4} | 1.8 |
| 11.508 | 0.894 | 1\(^-\) | 1.2 \times 10^{-4} | 1.27 |
| 11.461 | 0.847 | 3\(^-\) | 7.9 \times 10^{-6} | 6.55 |
| 11.441 | 0.827 | 3\(^-\) | 5.5 \times 10^{-6} | 1.47 |
| 11.3196 | 0.7056 | 1\(^-\) | 5.5 \times 10^{-6} | 0.132 |
| 11.272 | 0.65 | 3\(^-\) | 9.2 \times 10^{-8} | 1.81 |
| 11.258 | 0.644 | 2\(^+\) | 1.0 \times 10^{-6} | 0.41 |
| 11.171 | 0.557 | 2\(^+\) | 1.9 \times 10^{-8} | 0.03 |
| 11.169 | 0.552 | 3\(^-\) | 4.4 \times 10^{-10} | 1.94 |
| 11.163 | 0.549 | 2\(^-\) | 2.7 \times 10^{-9} | 5.31 |
| 11.112 | 0.498 | 2\(^-\) | 4.3 \times 10^{-10} | 2.095 |
| 11.084 | 0.470 | 2\(^-\) | 5.7 \times 10^{-11} | - |
| 10.9491 | 0.3351 | 1\(^-\) | 3.0 \times 10^{-14} | 30 |

Table 1: Summary of resonance parameters used in \( R \)-matrix calculation with literature reported values [3] for comparison with direct measurement data.

| \( E_x \) (MeV) | \( E_r \) (MeV) | \( J^\pi \) | \( \Gamma_x \) (eV) | \( \Gamma_n \) (keV) |
|----------------|----------------|------------|----------------|----------------|
| 11.8276 | 1.214 | 2\(^+\) | 0.210657 | 1.144 |
| 11.784 | 1.169 | 0\(^+\) | 23.898285 \times 10^{-3} | 17.226 |
| 11.759 | 1.1456 | 1\(^-\) | 0.0502 | 139.935 |
| 11.63 | 1.016 | 0\(^+\) | 9.106 \times 10^{-3} | 14.341 |
| 11.525 | 0.9112 | 1\(^-\) | 2.529 \times 10^{-4} | 0.5209 |
| 11.506 | 0.894 | 1\(^-\) | 1.399 \times 10^{-4} | 15.346 |
| 11.458 | 0.847 | 3\(^-\) | 9.0014 \times 10^{-6} | 15.588 |
| 11.4401 | 0.827 | 3\(^+\) | 4.59 \times 10^{-6} | 0.700 |
| 11.319 | 0.7056 | 1\(^-\) | 5.1429 \times 10^{-5} | 0.452 |
| 11.272 | 0.65 | 3\(^-\) | 9.2 \times 10^{-9} | 1.81 |
| 11.258 | 0.644 | 2\(^+\) | 1.0 \times 10^{-6} | 0.41 |
| 11.171 | 0.557 | 2\(^+\) | 1.9 \times 10^{-8} | 0.03 |
| 11.169 | 0.552 | 3\(^-\) | 4.4 \times 10^{-10} | 1.94 |
| 11.163 | 0.549 | 2\(^-\) | 2.7 \times 10^{-9} | 5.31 |
| 11.112 | 0.498 | 2\(^-\) | 4.3 \times 10^{-10} | 2.095 |
| 11.084 | 0.470 | 2\(^-\) | 5.7 \times 10^{-11} | - |
| 10.9491 | 0.3351 | 3\(^-\) | 3.0 \times 10^{-14} | 30 |

Table 2: Summary of resonance parameters obtained from \( R \)-matrix fit.
ters [3] for $^{26}$Mg are poorly describe the latest measurement data [4] due to strong destructive interference between consecutive same $J^\pi(1^-)$ states. With changing $J^\pi$ form $1^-$ to $0^+$ experimental data are well describe in 0.8 to 1.45 MeV energy region. The extrapolation with indirectly measured resonance parameters well off with respect to highly uncertain data of Jaeger et. al. [4] in 0.8 to 1.45 MeV energy region. So precise measurement of spin, parity and particle decay width ($\Gamma_n$, $\Gamma_\alpha$) will be required for $E_\alpha \leq 0.8MeV$ to evaluate cross-section with less uncertainty including interference effects.

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