Current Status of the $^{22}\text{Ne}+\alpha$ s-Process Neutron Source

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Abstract. The reaction rates of the s-process neutron producing $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction and its competing $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ reaction are needed to accurately predict nucleosynthesis in massive stars and Asymptotic Giant Branch stars. Here, we present a re-evaluation of the reaction rates by incorporating recent data and by using a Monte Carlo uncertainty propagation method. The effect of those results on nucleosynthesis in massive stars is studied. We show that our new rates lead to similar final abundances, but with significantly reduced uncertainties in comparison to literature rates.

1. Introduction
Neutron capture reactions are the main producer of nuclei heavier than iron in our solar system; slow neutron captures (the s-process) being responsible for a large fraction of them. The $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction is a key source of neutrons in both the main and weak components of the s-process. For the main component, where the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction produces the majority of neutrons, the $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction affects mainly branchings in the s-process path. For the weak component, the $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction is the main source of neutrons. Knowing the $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction rates in these environments as well as those of its competing $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ reaction are therefore essential to fully understand s-process nucleosynthesis.

Recent experimental results motivate a complete re-evaluation of the available nuclear physics data for the $^{22}\text{Ne}+\alpha$ reactions. Here we present the results of that evaluation using a Monte Carlo method for propagation of uncertainties. The impact of these results on nucleosynthesis in massive stars will also be discussed.

2. $^{22}\text{Ne}+\alpha$ Reaction Rates
Rates for the $^{22}\text{Ne}+\alpha$ reactions based on experimental results were published in Refs. [1] and [2] for the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reactions respectively. Since those publications, a number of improvements have been made in the available experimental data concerning properties of states in the $^{26}\text{Mg}$ compound nucleus. Most notable are the $^{25}\text{Mg}(n,\gamma)^{26}\text{Mg}$ analysis by Ref. [3] and the $^{26}\text{Mg}(\gamma,\gamma')^{26}\text{Mg}$ results published in Refs. [4, 5]. The former experiment used an R-matrix fit to assign quantum numbers and spins to important states, as well as determining partial widths that allow us to reliably integrate wide resonances numerically in reaction rate calculations. The $^{26}\text{Mg}(\gamma,\gamma')^{26}\text{Mg}$ experiment resolved definite spin-parities of several states above and below the neutron threshold. Most significantly, they found that a state corresponding to a $\alpha$-particle resonance energy of $E_{r}\text{lab} = 630$ keV...
Figure 1. Comparison of our new rates for (a) the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ reaction in comparison to those presented in Ref. [1] and (b) the $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction in comparison to those presented in Ref. [2]. The thick solid line represents our recommended rate while the thinner lines represent our 68% uncertainties. The red regions indicate the temperatures most important for helium (‘He’) and carbon (‘C’) burning.

has an unnatural parity of $J^P = 1^-$. It therefore cannot contribute to the reaction rate, contrary to previous assumptions.

The calculation of reaction rates is well understood, and is presented in detail elsewhere (see, for example, Ref. [6]). However, it is important to also calculate statistically meaningful uncertainties on the rates for them to be useful in determining the reliability of nucleosynthesis predictions. To calculate the rates for the $^{22}\text{Ne}+\alpha$ reactions, we have employed a Monte Carlo method, which takes into account the probability density functions of every nuclear physics input [7].

The reaction rates are compared with the literature results of Refs. [1] and [2] in Fig. 1. Although our $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ rates do not differ significantly from those of Ref. [2] (they are slightly lower because the $E_{\text{lab}}=630$ keV resonance is now removed), the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ rates are significantly lower, which should lead to a new increase in the neutron flux. The reason for this discrepancy is mostly because the contribution of wide resonances did not include experimental values for the resonance widths in the literature rates. The measured widths from Refs. [2] and [3] are found to be significantly smaller than those assumed in Ref. [1] and hence the rate at low temperatures is dramatically reduced.

3. Impact on Nucleosynthesis

The effect of our new rates for the $^{22}\text{Ne}+\alpha$ reactions have been calculated for nucleosynthesis during convective core helium burning in massive stars. We have utilised a single zone temperature-density profile for the core helium burning stage of $25M_\odot$ star from Ref. [8]. The impact on nucleosynthesis yields is shown in Fig. 2.

The most significant change is in the production of $^{26}\text{Mg}$, whose abundance at the end of core helium burning is about 5 times less than with the previous rates. The p-process nuclides: $^{74}\text{Se}$, $^{78}\text{Kr}$, and $^{84}\text{Sr}$ are also present in lower quantities by greater destruction through neutron capture. The uncertainties in p-nuclide abundances is, however, still quite large. With our new rates, the increased neutron flux does not extend the reach of the weak s-process component, but rather increases production of nuclei situated around the iron peak by a small amount. One reason for this insensitivity of nucleosynthesis to neutron flux could be that the neutron poison, $^{14}\text{N}(n,\gamma)^{15}\text{N}$, dilutes the effect. In addition to modified yields, the uncertainties in nucleosynthesis have been significantly reduced by roughly an order of magnitude with the new reaction rates.
Figure 2. Change in isotopic abundances produced at the end of core helium burning in comparison to those obtained using the literature rates. Points above unity represent an increase in production when using the new rates.

4. Conclusions
The $^{22}\text{Ne}+\alpha$ reactions are an important source of neutrons for the s-process in massive stars and AGB stars. Uncertainties in their rates can therefore give rise to large uncertainties in s-process nucleosynthesis of nuclei heavier than iron. Here, we have presented the reaction rates that arise from a full re-evaluation of the rates using up-to-date nuclear data and a Monte Carlo uncertainty propagation method.

We have shown that our new rates affect the production of nuclei around the iron peak, but most significantly affect the production of $^{26}\text{Mg}$, which is reduced by a factor of five at the end of core helium burning for our massive star model. The uncertainties in nucleosynthesis are also reduced significantly with our new rates. However, we must emphasise that further studies should be performed to resolve ambiguities in the nuclear physics data, particularly for low energy resonances below $\alpha$-particle bombarding energies of $E_{\text{lab}} = 1000$ keV.

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