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Charged particle reaction rates from stellar H to C burning

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Abstract. Charged particle reactions determine the stellar burning sequences and timescales of stellar evolution. The low energy cross sections of the reactions carry significant uncertainties mainly due to the lack of experimental data in the stellar energy range and reliable extrapolation techniques for the low energy reaction components. In this paper we discuss the uncertainties of key reactions in stellar hydrogen, helium, and carbon burning. We summarize the results of our recent evaluation of the reaction contributions and parameters for deriving a more reliable prediction of the rates at stellar temperature conditions.

Key words. Stars: abundances – Stars: nucleosynthesis

1. Introduction

Stellar evolution of massive stars is determined by a sequence of subsequent burning phases stabilizing the stellar core against gravitational contraction; hydrogen burning, helium burning, and carbon burning, followed by neon, oxygen, and silicon burning towards the last moments of stellar life. The first three burning phases are characterized by charged particle reactions - proton capture, α capture, and $^{12}C+^{12}C$ fusion - with low cross sections at the typical energy range of stellar burning.

Hydrogen burning in massive stars $M \geq M_{\odot}$ is dominated by the CNO cycles (Wallerstein et al. 2003). The time scale for CNO burning is determined by the slowest reaction in the cycle $^{14}N(p,\gamma)^{15}O$, which has recently been measured towards extremely low energies by Imbriani et al. (2005) and Runkle et al. (2005). The following section of the paper will summarize recent results of extrapolating the existing experimental data towards stellar energies using multi-channel r-matrix techniques.

The ashes of CNO burning are primarily ^4He and ^{14}N; ^4He is the main fuel for the following He burning phase which is driven by the triple alpha process, $^4He(2\alpha,\gamma)^{12}C$ and the subsequent $^{12}C(\alpha,\gamma)^{16}C$ reaction (Buchmann & Barnes 2006). An important reaction sequence in He burning, albeit not in first gen-

Send offprint requests to: M. Wiescher eration stars, is triggered by alpha capture on the CNO ashes ^{14}N leading to the production of ^{22}Ne which has been identified as the most likely neutron source for the weak s-process in stellar core he-burning by Kaeppeler et al. (1994). The present uncertainties in the reaction rate prediction will be analyzed for both reaction channels in terms of experimental data and theoretical estimates for possible low energy reaction contributions.

Carbon burning is driven by the fusion of two ^{12}C nuclei feeding the four competing reaction channels $^{12}C(^{12}C,\alpha)^{20}Ne$, $^{12}C(^{12}C,p)^{23}Na$, $^{12}C(^{12}C,\gamma)^{24}Mg$, and $^{12}C(^{12}C,n)^{23}Mg$. The latter two have small cross sections and the fusion proceeds predominantly through the p and α channels (Buchmann & Barnes 2006). In particular the present uncertainties in the total cross section of the fusion process will be discussed as well as the branching ratio between the two main reaction channels.

2. Reaction Rates in Stellar Hydrogen, Helium, and Carbon Burning

Stellar reaction rates derive from integrating the reaction cross section $\sigma(E)$ over the Maxwell Boltzmann energy distribution of the interacting particles. The reaction rate per particle pair is expressed by

$$N_A < \sigma v > = \sqrt{\frac{8}{\pi \cdot \mu}} \cdot (kT)^{-3/2} \cdot \int_o^{\inf} E \cdot \sigma(E) \cdot exp\left(-\frac{E}{kT}\right) dE \quad (1)$$

with μ the reduced mass, k the Boltzmann constant, and T the stellar temperature. The cross section for charged particle reactions is strongly energy dependent because of the Coulomb barrier and is frequently expressed in terms of the astrophysical S-factor $S(E)$

$$\sigma(E) = \frac{S(E)}{E} \cdot exp(-2\pi\eta) \quad (2)$$

with η as Sommerfeld constant. The exponential term approximates the Coulomb penetrability for ℓ=0 particles. To calculate the reaction rate reliably for stellar burning, the S-factor (or cross section) has to be determined for the energy range of stellar burning, the Gamow window. This is not possible because the associated cross sections are too low to be easily accessible by experiment and the S-factor is mostly determined by extrapolating the available experimental data into the stellar energy range. The reliable extrapolation requires a detailed knowledge about the reaction contributions and the possible interference patterns at low energies. This knowledge is frequently not available, resulting in substantial uncertainties in many of the key reactions of stellar nucleosynthesis.

2.1. The $^{14}N(p,\gamma)^{15}O$ reaction at low energies

The low energy cross section of $^{14}N(p,\gamma)^{15}O$ is characterized by the tails of several high energy resonances, notably the $1/2^+$ resonance at E_{cm}=278 keV and the interference between these resonance contributions, the high energy tails of subthreshold states in the ^{15}O compound nucleus and possible non-resonant direct capture contributions. The reaction cross section is determined by a transition to the ground state in ^{15}O but shows also strong transitions to bound states in the excitation range between 5 and 7 MeV. In particular the transition to the level at 6.79 MeV shows a strong non-resonant direct capture component. At these conditions a reliable extrapolation into the stellar energy range ($\leq$ 50keV) is provided by the application of R-matrix techniques (Angulo & Descouvemont 2001) which are particularly advantageous for this case since several reaction channels in a compound nuclear reaction process are open and compete with each other. The reliability of the R-matrix method is enhanced if all low energy reaction contributions are known and can be implemented, as in the example of the $^{14}N(p,\gamma)^{15}O$ reaction.

Recent measurements by Imbriani et al. (2005) and Runkle et al. (2005) have focused on expanding the experimental data towards lower energies because of the uncertainties in

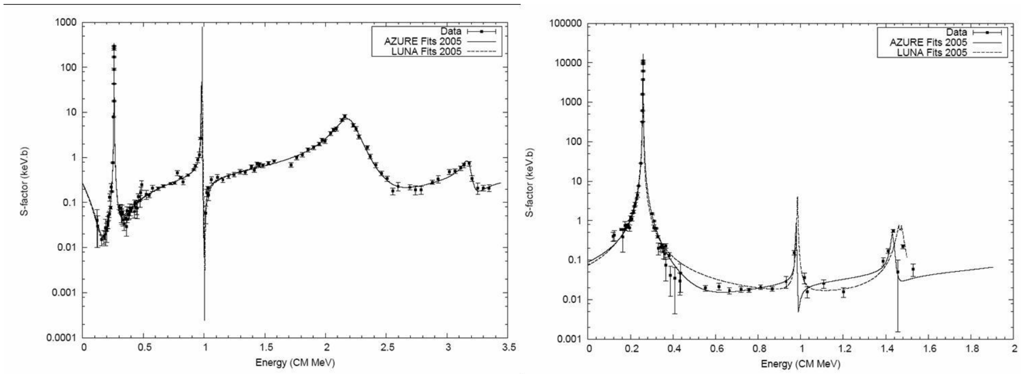

Fig. 1. Excitation curve for the ground state transition (left hand panel) and the transition to the excited state at 6.18 MeV (right hand panel) in $^{14}N(p,\gamma)^{15}O$. The dashed line represents the results of a single R-matrix fit of the data by Imbriani et al. (2005) and the solid line shows the results of the fit with the multi-channel R-matrix code AZURE by Simpson (2006) and Azuma et al. (2006).

the R-matrix analysis highlighted by Angulo & Descouvemont (2001) of previous data by Schröder et al. (1987). We have used the new multi-channel r-matrix code AZURE (Simpson 2006; Azuma et al. 2006) to analyze the old as well as the new data taking also into account the available data for $^{14}N(p,p)^{14}N$ elastic scattering. The code includes all resonant channels as well as the non-resonant direct capture component in the formalism of Barker & Kajino (1991). Figure 1 shows the excitation curve for the ground state ($J^{\pi}=1/2^{-}$) transition and the transition to the $3/2^{-}$ state at 6.18 MeV excitation energy. The results of the present R-matrix analysis are shown in comparison with the results of the single channel analysis by Imbriani et al. (2005). The R-matrix fits to the ground state data show excellent agreement. In the case of the transition to the state at 6.18 MeV excellent agreement is again observed in the low energy range, however at higher energies, above 300 keV significant deviations can be observed between the two R-matrix fits.

Based on these results the reaction rate can be now calculated with significantly higher reliability than before (Wallerstein et al. (2003), as already demonstrated by Imbriani et al. (2005)). We are presently in the process to use AZURE for re-evaluating the cross sections of other critical reactions in the CNO cycles. We focus in particular on reactions of relevance for branchings between the different cycles. The results of our analysis of $^{15}N(p,\alpha)^{12}O$, $^{15}N(p,\gamma)^{16}O$ and $^{17}O(p,\alpha)^{14}N$, $^{17}O(p,\gamma)^{18}F$, $^{17}O(p,p)^{18}F$, as well as $^{19}F(p,\alpha)^{16}O$, $^{19}F(p,\gamma)^{20}Ne$ are being prepared for publication by Azuma et al. (2006).

2.2. The $^{22}Ne(\alpha,n)^{25}Mg$ and $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction branch

In late stellar He burning a large abundance of ^{22}Ne is formed through the reaction sequence $^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne$ (Kaeppeler et al. 1994). While the two reactions $^{14}N(\alpha,\gamma)^{18}F$ and $^{18}O(\alpha,\gamma)^{22}Ne$ have been measured recently towards stellar energies by Görres et al. (2000) and Dababneh et al. (2003), respectively, only limited experimental information is available on the low energy contributions of the subsequent $^{22}Ne(\alpha,n)^{25}Mg$ and $^{22}Ne(\alpha,\gamma)^{26}Mg$ reactions. Low energy experiments have been successful in probing the energy range down to 680 keV center of mass α energy (Jaeger et al. 2001; Wolke et al. 1989). Possible resonances at lower energies where masked by the neutron and γ-ray room background. Alpha transfer studies however, do indicate the existence of α unbound levels with large *alpha* cluster configurations which could contribute to both reaction channels as demonstrated by Giesen et al. (1993). This in-

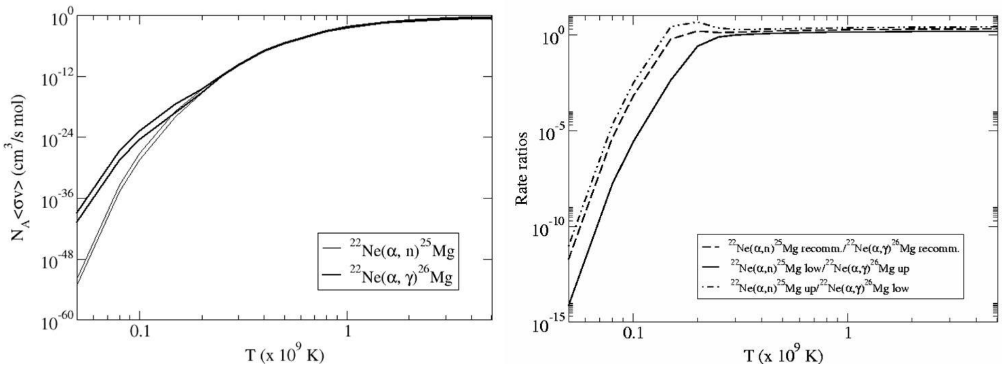

Fig. 2. The left hand panel shows the upper and lower limits of the reaction rate for ^{22}Ne$(\alpha,n)^{25}$Mg (grey line) and ^{22}Ne$(\alpha,\gamma)^{26}$Mg (black line) as a function of temperature. The right hand panel displays the branching ratio between the two reaction channels (dashed lines) as well as the upper (dot-dashed line) and lower limit (solid line) for the ratio based on the available data.

troduces a significant uncertainty for the neutron production in stellar core helium burning and the final abundance distribution for light s-process element as discussed by Kaeppeler et al. (1994),Woosley et al. (2002), and Karakas et al. (2006). Because ^{22}Ne(α,n) has a negative Q-value of -478 keV neutron bound cluster states above the α threshold in ^{26}Mg may enhance the strength of the ^{22}Ne(α,γ) channel significantly. A recent analysis by Koehler et al. (2002) of the earlier data by Jaeger et al. (2001) and Wolke et al. (1989) as well as the results of the ^{25}Mg(n,γ)^{26}Mg reaction by Weigman et al. (1976) demonstrated that the two lowest observed resonances in the ^{22}Ne(α,γ), and ^{22}Ne(α,n) do not correspond to the same level in ^{26}Mg as previously assumed by Angulo et al. (1999). Both resonances have comparable strength; in the absence of reliable low energy data the presently accepted rates of Angulo et al. (1999) are dominated by the contributions of these resonances and are therefore of similar strength at higher temperatures. Possible lower energy n-bound resonance states contribute significantly to the ^{22}Ne(α,γ) channel which becomes dominant at temperatures below 0.2 GK. The level parameters and the resonance strengths of the unobserved low energy resonances rely on the results of the ^{22}Ne$(^6Li,d)^{26}$Mg transfer studies by Giesen et al. (1993) as well as on a preliminary analysis of the α strength distribution in T=1 nuclei by Hess (2006). The details of the analysis are discussed in Karakas et al. (2006) and the results are shown in figure 2. While the rate for ^{22}Ne(α,γ) dominates at lower temperatures, towards higher temperatures of relevance for late core helium burning, both rates are of comparable strength. The branching ratio between the two channels is shown on the right hand side of the figure. The ratio is shown for rate recommended on the basis of the available information as well as for the corresponding upper and lower limits to demonstrate the uncertainty range. The results indicate that both reaction channels are comparable within the Gamow range of stellar He-burning. This reduces the neutron flux and will subsequently influence the nucleosynthesis in the weak s-process.

2.3. ^{12}C+^{12}C in Stellar Carbon Burning

The ^{12}C ashes of stellar He-burning provide the fuel for the subsequent ^{12}C+^{12}C fusion driven phase of stellar carbon burning. The low energy cross section of the fusion process is characterized by pronounced resonance structure as shown in previous experimental work (e.g. Barnes et al. (1985); Kettner et al. (1980); Becker et al. (1981)). These resonances have been interpreted as molecular states on the basis of their small resonance width. The pro-

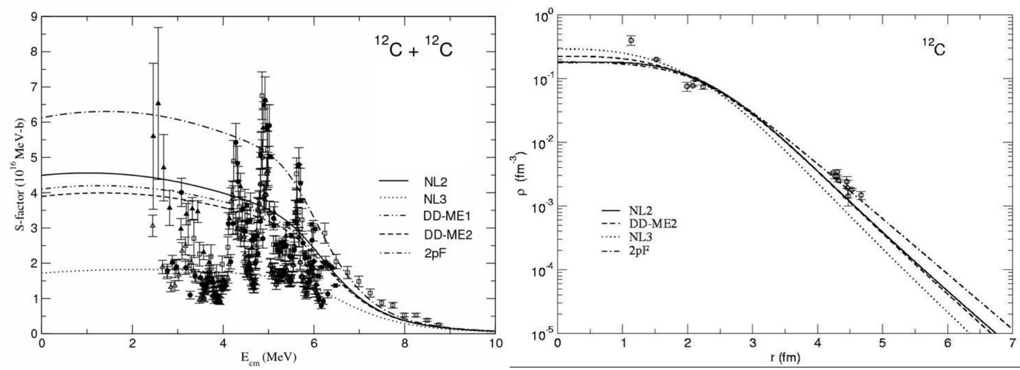

Fig. 3. The left hand panel shows the astrophysical S-factor $S(E)$ for $^{12}C+^{12}C$ as a function of the center-of-mass energy E. The lines show theoretical results obtained within the barrier penetration model for the different model density distributions. The right hand side shows the corresponding density distribution for the ground state of ^{12}C .

nounced resonance structure provides a significant handicap for extrapolating the cross section to lower energies and inhibits a reliable derivation of the reaction rate. The fusion cross section has been calculated within the framework of a folding potential approach described by Gasques et al (2005). The folding potential depends on the density distribution of the nuclei involved in the collision which can be described by different parameter sets (NL2, NL3, DD-ME1, and DD-ME2 (for details see the discussion in Gasques et al (2005)). Figure 3 (left hand side) compares the experimental $^{12}C+^{12}C$ S-factor with the results obtained with the theoretical density distributions. The right hand side shows the corresponding ^{12}C density distribution. The densities obtained with the DD-ME1 and DD-ME2 set of parameters are very similar. The experimental data are taken from Gasques et al. (2002).

These results demonstrate the large uncertainty in the total S-factor and reaction rate for $^{12}C+^{12}C$ fusion at temperature conditions of stellar carbon burning.

Another important aspect is the fusion branching ratio into the two most important reaction channels $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$. This branching ratio influences the subsequent nucleosynthesis through proton or alpha capture on residual light nuclei. Of particular interest is the possibility of neutron production through the reaction sequence $^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)$, as stressed by Arnett & Truran (1969). This primary neutron source may be important for the weak s-process at C-burning conditions. However, this possibility depends strongly on the strength of the $^{12}C(^{12}C,p)$ channel which provides the necessary proton fuel. Previous and recent measurements by Becker et al. (1981) and Aguilera et al. (2006) indicate strong fluctuations in the branching which is directly correlated with the molecular resonance structure of ^{26}Mg in that excitation range. This suggests that the branching ratio might be temperature dependent leading to different nucleosynthesis pattern and neutron production in core carbon and shell carbon burning. The branching ratio depends sensitively on the nuclear structure of ^{24}Mg near the $^{12}C+^{12}C$ threshold; the present experimental results are not conclusive for deciding if single particle structure or α cluster configurations are dominant. More experimental data are clearly needed to come to a conclusion in this question.

3. Conclusions

Its has been demonstrated, that the stellar reaction rates are highly uncertain because of unreliability in the extrapolation of available laboratory cross section data into the stelar energy range (Gamow window). Nuclear reaction theory needs to be applied taking into account the rather complex nuclear structure near the reaction threshold of the compound nucleus. The R-matrix approach works very well for resonance reactions in particular when most or all low energy reaction contributions can be identified.

This approach is handicapped in the case of α capture reactions if low energy cluster resonances cannot be identified. R-matrix simulations need to be coupled with theoretical predictions for the strengths of the low energy resonances to obtain reaction rate which contains both the R-matrix term from higher energy resonance contributions as well as from the resonance levels in the stellar energy range.

The situation is even more complex in the case of low energy heavy ion fusion. The nature of the observed molecular resonance states are not sufficiently known for a reliable R-matrix simulation. Presently potential model are adopted to determine the gross properties of the fusion process far below the Coulomb barrier. Detailed experimental studies of the resonance structure near the threshold is necessary to provide data for an improved reaction theory analysis.

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