NUCLEAR UNCERTAINTIES IN THE NeNa-MgAl CYCLES AND PRODUCTION OF $^{22}$Na AND $^{26}$Al DURING NOVA OUTBURSTS

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ABSTRACT

Classical novae eject significant amounts of nuclear-processed material into the interstellar medium. Among the isotopes synthesized during such explosions, two radioactive nuclei deserve particular attention: $^{22}$Na and $^{26}$Al. In this paper, we investigate the nuclear paths leading to $^{22}$Na and $^{26}$Al production during nova outbursts by means of an implicit hydrodynamic code that follows the course of the thermonuclear runaway from the onset of accretion up to the ejection stage. New evolutionary sequences of ONe novae have been computed, using updated nuclear reaction rates relevant to $^{22}$Na and $^{26}$Al production. Special attention is focused on the role played by nuclear uncertainties within the NeNa and MgAl cycles in the synthesis of such radioactive species. From a series of hydrodynamic models, which assume upper, recommended, or lower estimates of the reaction rates, we derive limits on the production of both $^{22}$Na and $^{26}$Al. We outline a list of nuclear reactions that deserve new experimental investigations in order to reduce the wide dispersion introduced by nuclear uncertainties in the $^{22}$Na and $^{26}$Al yields.

Subject headings: novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

The thermonuclear runaway model has been successful in reproducing the gross features of nova outbursts. According to this widely accepted scenario, classical novae are produced by thermonuclear runaways (TNRs) that take place in the white dwarf component of a close binary system. The large main-sequence companion overfills its Roche lobe, providing matter outflows through the inner Lagrangian point that lead to the formation of an accretion disk around the white dwarf. A fraction of this H-rich matter lost by the companion ultimately ends up on top of the white dwarf, where it is gradually compressed as accretion goes on. The piling up of matter heats the envelope up to the point where ignition conditions necessary to drive a TNR are reached.

An extended set of hydrodynamic computations of classical nova outbursts has been performed during the last 25 yr (see Starrfeld et al. 1972 for the first hydrodynamic study of the TNR model, and the recent papers by Kovetz & Prialnik 1997, Starrfeld et al. 1998, José & Hernanz 1998, and references therein) for a wide range of white dwarf masses and initial luminosities, mass accretion rates, and initial chemical compositions. From the nucleosynthesis viewpoint, these computations have been able to identify two types of nova outbursts, those occurring in CO and in ONe white dwarfs. The latter have provided a framework for the origin of the high concentrations of Ne and more massive isotopes found in the spectra of some well-observed novae, such as V693 CrA 1981, V1370 Aql 1982, QU Vul 1984 2, V838 Her 1991, and V1974 Cyg 1992 (Livio & Truran 1994; Gehrz et al. 1998). Among the isotopes synthesized in these so-called Ne (or ONe) novae, two radioactive species have generated particular astrophysical interest: $^{22}$Na and $^{26}$Al.

The potential role of $^{22}$Na for the diagnosis of nova outbursts was first suggested by Clayton & Hoyle (1974). It decays to a short-lived excited state of $^{22}$Ne (with a lifetime of $\tau = 3.75$ yr), which deexcites to its ground state by emitting a $\gamma$-ray photon of 1.275 MeV. Through this mechanism, nearby ONe novae within a few kiloparsecs from the Sun may provide detectable $\gamma$-ray fluxes. Several experimental verifications of this $\gamma$-ray emission at 1.275 MeV from nearby novae have been attempted in the last 20 yr, using balloon-borne experiments (Leventhal, MacCallum, & Watts 1977) and detectors on board satellites such as HEAO-3 (Mahoney et al. 1982), SMM (Leising et al. 1988), and CGRO (Leising 1993; Iyudin et al. 1995), from which upper limits on the ejected $^{22}$Na have been derived. In particular, the observations performed with the COMPTEL experiment on board CGRO of five recent Ne-type novae (Nova Her 1991, Nova Sgr 1991, Nova Ser 1991, Nova Pup 1991, and Nova Cyg 1992; Iyudin et al. 1995), as well as observations of standard CO novae, have led to an upper limit of $3.7 \times 10^{-8} M_\odot$ for the $^{22}$Na mass ejected by any nova in the Galactic disk. This restrictive limit has placed some constraints on preexisting theoretical models of classical nova explosions.

$^{26}$Al is another unstable nucleus, with a lifetime of $\tau = 1.04 \times 10^6$ yr, that decays from ground state to the first excited level of $^{26}$Mg, which in turn deexcites to its ground state by emitting a $\gamma$-ray photon of 1.809 MeV. This characteristic $\gamma$-ray signature, first detected in the Galactic center
by the HEAO-3 satellite (Mahoney et al. 1982, 1984), has been confirmed by other space missions, such as SMM (Share et al. 1985), and by several balloon-borne experiments. The most recent measurements made with COMPTEL have provided a map of the 1.809 MeV emission in the Galaxy (Diehl et al. 1995, 1997; Prantzos & Diehl 1996). The inferred 1–3 $M_\odot$ of Galactic 26Al are, according to the observed distribution, mainly attributed to young progenitors, such as massive asymptotic giant branch (AGB) stars, Type II supernovae, and Wolf-Rayet stars. More recent analyses of the 1.809 MeV COMPTEL map reveal a correlation between this map and the COBE/DMR maps, tracing free-free emission, thus confirming that the main contributors to the Galactic 26Al are massive stars (Knödlseder 1997). However, a potential contribution from novae or low-mass AGB stars cannot be ruled out (see José, Hernanz, & Coc 1997 for a recent analysis of 26Al production in classical novae).

First estimates of the 22Na and 26Al production in novae were made by different groups using simplified one-zone models with representative temperature and density profiles. Hillebrandt & Thielemann (1982) and Wiescher et al. (1986) suggested that classical novae might produce significant amounts of 26Al, not enough to represent major Galactic sources, but relevant to account for the observed isotopic anomalies found in some meteorites. New parametrized calculations by Weiss & Truran (1990) and Nofar, Shaviv, & Starrfield (1991) revealed that nova envelopes previously ejected during heavy elements (from Ne to Mg) produce large amounts of 22Na and 26Al. Since this metal enrichment is expected to result from a dredge-up of core material, Weiss & Truran suggested that massive ONeMg white dwarfs (the ones attaining the highest peak temperatures, and therefore the most efficient dredge-up) are likely to provide the largest abundances of both 22Na and 26Al in the ejecta. Politano et al. (1995) revisited this scenario using hydrodynamic computations. They reported on a strong anticorrelation between 22Na and 26Al production: novae that produce the largest amounts of 22Na (i.e., massive white dwarfs) are not the same as those accounting for the largest yields of 26Al (i.e., low-mass white dwarfs). The 22Na yields obtained range between $5 \times 10^{-5}$ and $5 \times 10^{-3}$ by mass. Assuming that the whole envelope ($\sim 10^{-4} - 10^{-5} M_\odot$) is ejected during the outburst, they concluded that nearby ONeMg novae with $M_{\text{wd}} \geq 1.25 M_\odot$ should produce detectable 22Na $\gamma$-rays for CGRO, a prediction not confirmed so far (Iyudin et al. 1995). Their results also showed a significant production of 26Al [i.e., $(19.6 - 7.5) \times 10^{-3}$ by mass, corresponding to ONeMg white dwarfs with masses between 1.0 and 1.35 $M_\odot$, respectively], which could account for a major fraction of the Galactic 26Al.

Recent hydrodynamic computations of ONe novae (José et al. 1997; José & Hernanz 1997, 1998) using updated initial compositions and nuclear reaction rates have led to a significant reduction of both 26Al and 22Na ejected during nova outbursts. In particular, a mean mass fraction of $1 \times 10^{-4}$ of 22Na is found in the 1.25 $M_\odot$ ONe model [with $M_{\text{ej}}(22\mathrm{Na}) = 1.3 \times 10^{-6} M_\odot$], whereas a maximum value of 6 $\times 10^{-4}$ results from the 1.35 $M_\odot$ ONe model [with $M_{\text{ej}}(22\mathrm{Na}) = 2.6 \times 10^{-9} M_\odot$]. The corresponding peak fluxes in the 1.275 MeV 22Na line, below $10^{-3}$ photons $s^{-1}$ cm$^{-2}$ for novae at 1 kpc, turn out to be too low to be detected with OSSE or COMPTEL, but represent potential targets for the future International Gamma-Ray Astro-

physical Laboratory (INTEGRAL) mission (Hernanz et al. 1997; Gómez-Gomar et al. 1998). Concerning 26Al, yields ranging from $2 \times 10^{-3}$ to $2 \times 10^{-4}$ by mass have been obtained in a series of ONe nova models with masses between 1.15 and 1.35 $M_\odot$. Contributions from novae to the Galactic 26Al are limited to 0.1–0.4 $M_\odot$ (José et al. 1997). Nevertheless, a larger contribution cannot be ruled out if the (uncertain) lower limit for ONe white dwarfs is reduced to 1.0 $M_\odot$ (José & Hernanz 1998).

Other hydrodynamic computations performed by Starrfield et al. (1997, 1998), also using updated nuclear reaction rates and opacities, have modified their previous estimates (Politano et al. 1995). The expected abundance of 22Na in the ejecta has risen to $(2 - 3) \times 10^{-3}$ by mass, when 1.25 $M_\odot$ ONeMg white dwarfs are adopted, high enough to be detected by CGRO provided that all of the accreted envelope $(3 \times 10^{-5} M_\odot)$ is ejected. On the other hand, the improved input physics translates into a factor of 10 reduction on the synthesis of 26Al, in better agreement with the analysis of the 1.809 MeV emission map provided by COMPTEL, and also with the results previously reported by José et al. (1997).

While the agreement between the different groups on the expected contribution of classical novae to the Galactic 26Al has significantly increased, there remains some discrepancy concerning the amount of 22Na present in the ejecta. Since the synthesis of both 22Na and 26Al is very dependent on the adopted nuclear reaction rates, the large uncertainties present in some key reactions of both NeNa and MgAl cycles (Coc et al. 1995; Prantzos & Diehl 1996) may significantly modify the expected yields. In particular, the study of the influence of a given reaction rate on 22Na production is not trivial because of the two possible modes of formation and their interplay with convection (Coc et al. 1995). Moreover, during a nova outburst, thermodynamic conditions change on a short timescale, so that nuclear reactions are never close to equilibrium. As a result of the obvious experimental difficulties, reaction rates involving short-lived radioactive nuclei of the NeNa-MgAl group are in general poorly known, and the associated uncertainties may reach many orders of magnitude. It is thus important to know how the yields of important isotopes such as 22Na and 26Al are affected by those uncertainties. In this paper, a series of hydrodynamic nova models have been computed assuming upper, recommended, and lower estimates of the reaction rates, from which limits on the production of both 22Na and 26Al have been derived. The present analysis is focused on capture rates on radioactive nuclei, and for a temperature domain in the range $T_\text{e} \approx 0.5–3.5$. We refer the reader to the NACRE compilation (Angulo et al. 1999) for a more general discussion concerning capture rates on stable isotopes and a wider temperature range. For convenience, we use the terms NeNa cycle and MgAl cycle to denote the reactions involved in 22Na and 26Al formation. However, because of the high 23Na($p$, $\gamma$) and 27Al($p$, $\gamma$) rates, they cannot be considered as genuine cycles.

In §2, we outline some details of the method of computation and input physics. A detailed analysis of the synthesis of 22Na and 26Al in classical novae, together with the study of the role played by specific nuclear reactions of the NeNa-MgAl cycles, is given in §§3 and 4. Constraints on the production of 22Na and 26Al assuming lower, recommended, and upper rates for some key reactions are derived in §5.

The most relevant conclusions of this paper are summarized
in § 6. A detailed Appendix focusing on the nuclear physics aspects of the reaction rates within the NeNa and MgAl cycles follows.

2. MODEL AND INPUT PHYSICS

Evolutionary sequences of nova outbursts have been calculated by means of an updated version of the code SHIVA (see José 1996; José & Hernanz 1998), a one-dimensional implicit hydrodynamical code in Lagrangian formulation, which follows the course of the outburst from the onset of accretion up to the expansion and ejection stages. The code solves the standard set of differential equations for hydrodynamical evolution: conservation of mass, momentum and energy, energy transport by radiation and convection, plus the definition of the Lagrangian velocity, including a time-dependent formalism for convective transport whenever the characteristic convective timescale becomes larger than the integration time step (Wood 1974). Partial mixing between adjacent convective shells is treated by means of a diffusion equation (see Prialnik, Shara, & Shaviv 1979 for the formalism). The code is linked to a reaction network, which follows the detailed evolution of 100 nuclei, ranging from \(^1\)H to \(^{40}\)Ca, through 370 nuclear reactions, with updated rates, and screening factors from Graboske et al. (1973) and DeWitt, Graboske, & Cooper (1973). As suggested by Politano et al. (1995), the mass transferred from the companion is assumed to be solar-like and is mixed in a given fraction with the outermost shells of the underlying core by means of an unknown mechanism (either shear mixing, diffusion, or a convective multidimensional process). The composition of the underlying core has been taken from recent detailed evolutionary models in the case of ONe white dwarfs, which are the main contributors to \(^{22}\)Na and \(^{26}\)Al synthesis. These stars are made basically of \(^{16}\)O and \(^{20}\)Ne (Dominguez, Tornambé, & Isern 1993; Ritossa, García-Berro, & Iben 1996), with smaller traces of \(^{23}\)Na, \(^{24}\)Mg, \(^{25}\)Mg, \(^{27}\)Al, and other species. This issue plays a crucial role in the resulting nucleosynthesis, and should be taken into account in comparing results obtained by different groups. In particular, the ONeMg models computed by Starrfield et al. (1998) have an initial composition of the white dwarf core based on old nucleosynthesis calculations of C-burning from Arnett & Truran (1969), which is richer in \(^{24}\)Mg and \(^{20}\)Ne than the one adopted in this paper (see Table 1).

3. SYNTHESIS OF \(^{22}\)Na IN CLASSICAL NOVAE

The high temperatures attained during ONe nova outbursts [with peak values within \((2\text{--}3)\times10^8\) K] allow noticeable nuclear activity in the NeNa and MgAl cycles, which results in a significant production of species of astrophysical interest, such as \(^{22}\)Na and \(^{26}\)Al. In this section, we will describe the main mechanisms of \(^{22}\)Na synthesis through a detailed analysis of a 1.25 \(M_\odot\) ONe white dwarf, which accretes solar-like matter at a rate of \(\dot{M} = 2 \times 10^{-10} M_\odot\) yr\(^{-1}\), assuming a 50% degree of mixing with the ONe core (model ONe5 in José & Hernanz 1998). Snapshots of the evolution of several isotopes relevant to \(^{22}\)Na synthesis (i.e., \(^{20}\)Ne, \(^{21}\)Ne, \(^{22}\)Ne, \(^{21}\)Na, \(^{22}\)Na, \(^{23}\)Na, \(^{22}\)Mg, and \(^{23}\)Mg) are shown in Figure 1.

3.1. Main Nuclear Reactions Involved in \(^{22}\)Na Production

At the onset of accretion, the evolution of \(^{22}\)Na is mainly dominated by the chain of nuclear reactions \(20\text{Ne}(p, \gamma)\ ^{21}\text{Na}(\beta^-)\ ^{21}\text{Ne}(p, \gamma)\ ^{22}\text{Na}(p, \gamma)\ ^{23}\text{Na}\) (i.e., the cold mode of the NeNa cycle; see Fig. 2). When the temperature at the burning shell reaches \(T_{\text{bs}} = 5 \times 10^7\) K (Fig. 1, first panel), the main nuclear reaction of the NeNa cycle is \(^{21}\text{Ne}(p, \gamma)\ ^{22}\text{Ne}\), which significantly reduces the amount of \(^{21}\)Ne. In fact, when \(T_{\text{bs}} = 7 \times 10^7\) K (Fig. 1, second panel), the amount of \(^{21}\)Ne is already too small to maintain the main mechanism for \(^{22}\)Na synthesis. Therefore, \(^{22}\)Na will begin to decrease near the burning shell due to proton captures, following the rise of the temperature toward peak value (Fig. 1, third and fourth panels).

At \(T_{\text{bs}} = 1 \times 10^8\) K (Fig. 1, third panel), the amount of \(^{21}\)Ne has already decreased below \(10^{-6}\) by mass, except at the outer envelope, where some \(^{21}\)Ne is synthesized from the \(\beta^-\)-decay of \(^{21}\)Na [previously built up as \(^{20}\text{Ne}(p, \gamma)\ ^{21}\text{Na}\)]. \(^{21}\)Na and \(^{22}\)Mg increase due to \(^{20}\text{Ne}(p, \gamma)\ ^{21}\text{Na}\) and \(^{22}\text{Na}(p, \gamma)\ ^{23}\text{Mg}\), respectively. Destruction of \(^{22}\)Na through \((p, \gamma)\) reactions continues, but because of convective mixing, \(^{22}\)Na shows a nearly flat profile throughout the envelope.

When \(T_{\text{bs}} = 2 \times 10^8\) K (Fig. 1, fourth panel), there is a dramatic decline in \(^{23}\)Na [due to \((p, \gamma)\) and \((p, x)\) reactions] and in the \(^{22}\)Na abundance [by \(^{22}\text{Na}(p, \gamma)\ ^{23}\text{Mg}\)]. \(^{22}\)Ne has slightly decreased. Also noticeable is the increase of \(^{21}\)Na [since \(^{20}\text{Ne}(p, \gamma)\ ^{21}\text{Na}\) dominates destruction from both \(^{21}\text{Na}(\beta^-)\ ^{21}\text{Ne}\) and \(^{21}\text{Na}(p, \gamma)\ ^{22}\text{Mg}\)], which plays a crucial role in the synthesis of \(^{22}\)Na at the late stages of the outburst. Both \(^{22}\)Mg and \(^{23}\)Mg increase as a result of proton captures on \(^{21}\)Na and \(^{22}\)Na, respectively.

Thirty-three seconds later, the temperature at the burning shell attains its peak value, \(T_{\text{bs,max}} = 2.44 \times 10^8\) K (Fig. 1, fifth panel). The amount of \(^{21}\)Na is maintained by a quasi-equilibrium between \(^{21}\text{Na}(p, \gamma)\ ^{22}\text{Mg}\) and \(^{20}\text{Ne}(p, \gamma)\ ^{21}\text{Na}\). The mean amount of \(^{22}\)Na increases as a result of \(^{22}\text{Mg}(\beta^+)\ ^{22}\text{Na}\), previously transported by convection to the

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**TABLE 1**

**INITIAL COMPOSITION OF THE ENVELOPE**

(UP TO Si), ASSUMING 50% MIXING WITH THE ONe WHITE DWARF CORE

| Nuclei | Mass Fraction |
|--------|---------------|
| \(^1\)H | 3.6E-1        |
| \(^3\)He | 1.5E-5        |
| \(^4\)He | 3.6E-5        |
| \(^6\)Li | 3.2E-10       |
| \(^7\)Li | 4.7E-9        |
| \(^8\)Be | 8.3E-11       |
| \(^10\)B | 5.3E-10       |
| \(^11\)B | 2.4E-9        |
| \(^12\)C | 6.1E-3        |
| \(^13\)C | 1.8E-5        |
| \(^14\)N | 5.5E-4        |
| \(^15\)N | 2.2E-6        |
| \(^16\)O | 2.6E-1        |
| \(^17\)O | 1.9E-6        |
| \(^18\)O | 1.1E-5        |
| \(^19\)F | 2.0E-7        |
| \(^20\)Ne | 1.6E-1        |
| \(^{21}\)Ne | 3.0E-3       |
| \(^{22}\)Ne | 2.2E-3       |
| \(^{23}\)Ne | 3.2E-2        |
| \(^{24}\)Mg | 2.8E-2        |
| \(^{25}\)Mg | 7.9E-3        |
| \(^{26}\)Mg | 5.0E-3        |
| \(^{27}\)Mg | 5.4E-3        |
| \(^{28}\)Si | 3.3E-4        |

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outer, cooler layers of the envelope. The amount of $^{23}\text{Na}$ decreases as a result of both $(p, \gamma)$ and $(p, a)$ reactions, which dominate $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$ as well as $^{23}\text{Mg}(\beta^+)^{23}\text{Na}$. Since the peak temperature achieved in the burning shell is not extremely high, $^{20}\text{Ne}$ remains nearly unchanged (the typical temperature for $^{20}\text{Ne}$ burning exceeds $D_4 \approx 10^8$ K). With respect to the other neon isotopes, $^{21}\text{Ne}$ increases (mainly through the $\beta^-$-decay of $^{21}\text{Na}$ at the outer shells), whereas $^{22}\text{Ne}$ is destroyed by $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$. The two magnesium isotopes $^{22}\text{Mg}$ and $^{23}\text{Mg}$ increase as a result of proton captures onto $^{21}\text{Na}$ and $^{22}\text{Na}$, respectively.

Shortly afterward, as a result of the sudden release of energy from the short-lived $\beta^+$-unstable nuclei $^{13}\text{N}$, $^{14}\text{O}$, $^{15}\text{O}$, and $^{17}\text{F}$, the envelope begins to expand. The role played by $(p, \gamma)$ and $(p, a)$ reactions is therefore reduced following the drop in temperature, while $\beta^-$-decays progressively dominate the evolution. The abundances of $^{21}\text{Na}$, $^{22}\text{Mg}$, and $^{23}\text{Mg}$ decrease as a result of such $\beta^-$-decays, which in turn increase the amount of $^{21}\text{Ne}$, $^{22}\text{Na}$, and $^{23}\text{Na}$ (Fig. 1, sixth and seventh panels).

At the final stages of the outburst (Fig. 1, eighth panel), as the envelope expands and cools down, most of the remaining nuclear activity in the NeNa cycle is due to $\beta^-$-decays such as $^{21}\text{Na}(\beta^-)^{21}\text{Ne}$, $^{22}\text{Mg}(\beta^-)^{22}\text{Na}$, or $^{23}\text{Mg}(\beta^-)^{23}\text{Na}$. The resulting mean abundance of $^{22}\text{Na}$ in the ejected shells of this 1.25 $M_\odot$ ONe model is $X(^{22}\text{Na}) = 9.6 \times 10^{-5}$ by mass, which corresponds to $1.3 \times 10^{-9} M_\odot$ of $^{22}\text{Na}$ ejected into the interstellar medium. Other species of the NeNa cycle present in the ejecta are $^{20}\text{Ne}$ [$X(^{20}\text{Ne}) = 0.18$, a mass fraction slightly higher than its initial value because of the operation of the $^{22}\text{Na}(p, a)^{20}\text{Ne}$ reaction; see Table 1], $^{21}\text{Ne}$ and $^{22}\text{Ne}$ [$X(^{21}\text{Ne}) = 3.5 \times 10^{-3}$, $X(^{22}\text{Ne}) = 1.0 \times 10^{-3}$], and $^{23}\text{Na}$ with $X(^{23}\text{Na}) = 1.4 \times 10^{-3}$.

3.2. Effect of the Reaction Rates on the Synthesis of $^{22}\text{Na}$

From the nuclear physics viewpoint discussed above, the synthesis of $^{22}\text{Na}$ is mainly controlled by four reactions:
of the reduction of the contribution of the MeV uncertainty is of a factor of \( \gamma \) per temperatures considered here, it is well known. The estimated of Caughlan & Fowler (1988; hereafter CF88), which is a factor of \( \gamma \) reaction rates (Angulo et al. 1999), but it is more likely only considered), according to the new compilation of nuclear high and low estimates within the domain of temperature (as well as \( ^{26}\text{Al} \)). The main results for \( ^{22}\text{Na} \) and \( ^{26}\text{Al} \) production, compared with the abundances found in José & Hernanz (1998) using previous prescriptions, are summarized in Table 2.

\( ^{20}\text{Ne}(p, \gamma)^{21}\text{Na} \) is the slowest proton-capture reaction on any stable neon and sodium isotope. According to the adopted composition for the ONe core (Ritossa, García-Berro, & Iben 1996), \( ^{20}\text{Ne} \) is the most abundant Ne-Na isotope. Therefore, \( ^{20}\text{Ne}(p, \gamma)^{21}\text{Na} \) limits \( ^{22}\text{Na} \) production in classical novae. The adopted \( ^{20}\text{Ne}(p, \gamma)^{21}\text{Na} \) rate is that of Caughlan & Fowler (1988; hereafter CF88), which is based on Rolfs et al. (1975) data. In the domain of temperatures considered here, it is well known. The estimated uncertainty is of a factor of \( \approx 3 \) (defined as the ratio between high and low estimates within the domain of temperature considered), according to the new compilation of nuclear reaction rates (Angulo et al. 1999), but it is more likely only a factor of \( \approx 1.5 \), since it is derived from short-range standard extrapolations of experimental data (Rolfs et al. 1975). Therefore, nuclear uncertainties associated with \( ^{20}\text{Ne}(p, \gamma)^{21}\text{Na} \) should play no significant role in \( ^{22}\text{Na} \) production.

Concerning the \( ^{21}\text{Ne}(p, \gamma)^{22}\text{Na} \) rate, no significant effect of the reduction of the contribution of the \( E_x = 6.384 \) MeV level (Górres et al. 1983) with respect to CF88 has been found in \( ^{22}\text{Na} \) production (tested with a 1.25 \( M_\odot \) ONe white dwarf model). According to Angulo et al. (1999), other nuclear uncertainties scarcely affect the \( ^{21}\text{Ne}(p, \gamma)^{22}\text{Na} \) rate at moderate temperatures. On the contrary, much more uncertain is the \( ^{22}\text{Ne}(p, \gamma)^{23}\text{Na} \) rate, which is poorly known in the range of temperatures of interest for nova outbursts (Angulo et al. 1999). Nevertheless, because of the low initial \( ^{22}\text{Ne} \) abundance with respect to \( ^{23}\text{Na} \), and also the negligible \( ^{22}\text{Na} \) decay (\( \tau = 3.75 \) yr) during the TNR, the nuclear uncertainties affecting the \( ^{22}\text{Ne}(p, \gamma)^{23}\text{Na} \) rate are not relevant for \( ^{22}\text{Na} \) production in novae.

Recent experimental investigations of the \( ^{22}\text{Na}(p, \gamma)^{23}\text{Mg} \) reaction (Seuthe et al. 1990; Schmidt et al. 1995; Stegmüller et al. 1996) have provided a firmer basis for the determination of its rate. Since the new rate is lower than the old CF88 analytic fit (i.e., \( 1 \) order of magnitude for \( T_\odot > 1 \)), destruction of \( ^{22}\text{Na} \) by means of \( (p, \gamma) \) reactions is reduced. In a test model consisting of a 1.25 \( M_\odot \) ONe white dwarf (model ONe5; José & Hernanz 1998), the mean abundance of \( ^{22}\text{Na} \) in the ejecta increases by a factor of \( \approx 3 \) when the new \( ^{22}\text{Na}(p, \gamma)^{23}\text{Mg} \) rate (Stegmüller et al. 1996), is adopted instead of the one from CF88 (see Table 2). It is worth noting that significant nuclear uncertainties affect this rate (a factor ranging from 3 to 6 for \( T_\odot > 1 \)), which turns out to be crucial in deriving ranges of \( ^{22}\text{Na} \) production during nova outbursts. According to Stegmüller et al. (1996), this uncertainty is mainly due to the possible effect of a resonance at \( E_p = 225 \) keV. Below \( T_\odot = 1 \), the uncertainty reaches \( 3 \) orders of magnitude, but the rate remains small enough to prevent destruction of \( ^{22}\text{Na} \).

Three test models have been computed to analyze the role played by \( ^{21}\text{Na}(p, \gamma)^{22}\text{Mg} \), in view of the nuclear uncertainties present in this rate, in particular the estimated strength of the first \( E_x = 5.714 \) MeV level above the proton threshold (see Appendix, § A.1). Calculations assume ONe

| Nuclear Reaction | Old Rate | Test Rate | \( X^{(22)\text{Na}}_{\text{old}} \) | \( X^{(22)\text{Na}}_{\text{test}} \) | \( X^{(26)\text{Al}}_{\text{old}} \) | \( X^{(26)\text{Al}}_{\text{test}} \)
|------------------|----------|----------|----------------|----------------|----------------|----------------|
| \( ^{21}\text{Na}(p, \gamma)^{22}\text{Mg} \) | CF88     | CF88/100 | 2.3            | 1.1            |                |                |
| \( ^{23}\text{Al}(p, \gamma)^{24}\text{Si} \) | Wie86    | Coc95, case A | 1             | 1.2            |                |                |
| \( ^{23}\text{Na}(p, \gamma)^{24}\text{Mg} \) | CF88     | CF88 + GWR89 | 1.2           | 1.3            |                |                |
| \( ^{26}\text{Al}(p, \gamma)^{27}\text{Si} \) | Vog89    | Vog89 | 1             | 1.9            |                |                |
| \( ^{26}\text{Si}(p, \gamma)^{27}\text{P} \) | Wie86    | Her95 | 1             | 1              |                |                |
| \( ^{26}\text{Mg}(p, \gamma)^{27}\text{Al} \) | Ili90    | Ili90 + Cha90 | 1             | 1              |                |                |

1.25 \( M_\odot \) ONe

| Nuclear Reaction | Old Rate | Test Rate | \( X^{(22)\text{Na}}_{\text{old}} \) | \( X^{(22)\text{Na}}_{\text{test}} \) | \( X^{(26)\text{Al}}_{\text{old}} \) | \( X^{(26)\text{Al}}_{\text{test}} \)
|------------------|----------|----------|----------------|----------------|----------------|----------------|
| \( ^{21}\text{Na}(p, \gamma)^{22}\text{Mg} \) | CF88     | CF88/100 | 3             | 1.1            |                |                |
| \( ^{23}\text{Na}(p, \gamma)^{23}\text{Mg} \) | CF88     | Ste96 | 3             | 1.2            |                |                |
| \( ^{23}\text{Mg}(p, \gamma)^{24}\text{Al} \) | Wie86    | KKK95 | 1.1           | 1.1            |                |                |

1.35 \( M_\odot \) ONe

| Nuclear Reaction | Old Rate | Test Rate | \( X^{(22)\text{Na}}_{\text{old}} \) | \( X^{(22)\text{Na}}_{\text{test}} \) | \( X^{(26)\text{Al}}_{\text{old}} \) | \( X^{(26)\text{Al}}_{\text{test}} \)
|------------------|----------|----------|----------------|----------------|----------------|----------------|
| \( ^{21}\text{Na}(p, \gamma)^{22}\text{Mg} \) | CF88     | CF88/100 | 1.2           | 1              |                |                |
| \( ^{23}\text{Al}(p, \gamma)^{24}\text{Si} \) | Wor94    | Sch97    | 1             | 1              |                |                |

Sources for the reaction rates: Wie86: Wiescher et al. 1986; CF88: Caughlan & Fowler 1988; GWR89: Górres et al. 1989; Vog89: Vogelaar 1989; Cha90: Champagne et al. 1990; Ili90: Iladis et al. 1990; Wor94: van Wormer et al. 1994; Coc95: Coc et al. 1995; Her95: Hernndi et al. 1995; KKK95: Kubono et al. 1995; Ste96: Stegmüller et al. 1996; Sch97: Schatz et al. 1997.
white dwarfs of masses of 1.15, 1.25, and 1.35 $M_\odot$, and the
same input physics as models ONe3, ONe5, and ONe6 described in José & Hernanz (1998), but reducing the $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ rate given by CF88 by a factor of 100 (similar, for novae, to the lower rate given in the Appendix). This results in a significant increase in the $^{22}\text{Na}$ abundances present in the ejecta (a factor of $\sim 2 - 3$ in the 1.15 and 1.25 $M_\odot$ models, and a factor of $\sim 1.2$ in the 1.35 $M_\odot$ model; see Table 2), as compared with the values found using the standard CF88 rate. This effect can be interpreted as follows: when the $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ rate is reduced by a factor of 100, the alternative path, $^{21}\text{Na}(\beta^+)^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$, is favored. In this case, $^{22}\text{Na}$ production is delayed to a time when the envelope is already expanding and cooling down [contrary to the case when the higher $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ rate is adopted]. As a result, a major fraction of $^{22}\text{Na}$ survives. This, in turn, explains the lower effect found in the 1.35 $M_\odot$ model, caused by the higher temperatures achieved in the envelope (with $T_{\text{max}} = 3.2 \times 10^8 \text{ K}$), which remain high enough at the time when $^{22}\text{Na}$ is synthesized. One should note that this effect [increase in the $^{22}\text{Na}$ yield when the $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ rate is reduced] was not foreseen and highlights the importance of full hydrodynamical calculations.

Other reactions that may be involved in the synthesis of $^{22}\text{Na}$ (and $^{23}\text{Na}$) are $^{22}\text{Mg}(p, \gamma)^{23}\text{Al}$, $^{23}\text{Al}(p, \gamma)^{24}\text{Si}$, or $^{23}\text{Mg}(p, \gamma)^{24}\text{Al}$. However, no significant effect on the $^{22}\text{Na}$ production is found when using updated rates for such reactions (see the Appendix and Table 2), because of the limited nuclear flow they conduct for nova conditions.

According to this analysis, full evolutionary sequences of nova outbursts, from the onset of accretion up to the ejec-

![Fig. 3. Same as Fig. 1, but for the evolution of $^{24}\text{Mg}$, $^{25}\text{Mg}$, $^{26}\text{Mg}$, $^{26}\text{Al}^{\text{p+}}$, $^{25}\text{Al}$, $^{27}\text{Al}$, $^{26}\text{Si}$, and $^{27}\text{Si}$.](image-url)

4. SYNTHESIS OF $^{26}\text{Al}$ IN CLASSICAL NOVAE

In this section, we will analyze the nuclear paths leading to $^{26}\text{Al}$ synthesis. As for $^{22}\text{Na}$ production, we will describe the course of the 1.25 $M_\odot$ ONe nova model (José & Hernanz 1998, model ONe5). Snapshots of the evolution of several isotopes relevant to $^{26}\text{Al}$ synthesis (i.e., $^{24}\text{Mg}$, $^{25}\text{Mg}$, $^{26}\text{Mg}$, $^{25}\text{Al}$, $^{27}\text{Al}$, $^{26}\text{Si}$, $^{27}\text{Si}$, and the ground and isomeric states for $^{26}\text{Al}$, hereafter $^{26}\text{Al}^g$ and $^{26}\text{Al}^i$) are shown in Figure 3.

4.1. Main Nuclear Reactions Involved in $^{26}\text{Al}$ Production

Nucleosynthesis of $^{26}\text{Al}$ is complicated by the presence of a short-lived ($T_{1/2} = 6.3 \text{ s}$) spin isomer. At low temperatures ($T_e \lesssim 4$), the $^{26}\text{Al}$ ground and isomeric states do not reach thermal equilibrium and must be treated as two separate isotopes (Ward & Fowler 1980; see also Coc & Porquet 1998).

The nuclear activity in the MgAl cycle at the early phases of the TNR, when the temperature at the burning shell is $T_{\text{in}} = 5 \times 10^7 \text{ K}$, is dominated by $^{25}\text{Mg}(p, \gamma)$, which leads to both $^{26}\text{Al}$ ground and isomeric states. A significant amount of $^{26}\text{Al}^i$ is already synthesized at such temperatures (Fig. 3, first panel). Another aluminum isotope, $^{27}\text{Al}$, is slightly
enhanced with respect to its initial abundance by means of $^{26}\text{Al}(p, \gamma)^{27}\text{Al}$. A similar trend is found when $T_{\text{bs}} = 7 \times 10^7$ K (Fig. 3, second panel): both $^{26}\text{Al}$ and $^{27}\text{Al}$ continue to rise (especially the first, which increases by nearly a factor of 10 from the abundance shown in Fig. 3, first panel).

At $T_{\text{bs}} = 10^8$ K (Fig. 3, third panel), the evolution in the MgAl cycle is dominated by $^{24}\text{Mg}(p, \gamma)^{25}\text{Al}$ and $^{26}\text{Mg}$, which in turn accounts for a noticeable production of the $^\beta^-$-unstable nuclei $^{25}\text{Al}$, and also for the increase in the mean $^{26}\text{Al}$ abundance [by means of $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$]. A nearly flat profile of $^{26}\text{Al}$ results from convective mixing, which already extends throughout the whole envelope.

A major change in the dominant nuclear path is found when $T_{\text{bs}} = 2 \times 10^8$ K (Fig. 3, fourth panel). The temperature attained near the burning shell is high enough to allow $(p, \gamma)$ reactions to proceed efficiently. In particular, the abundance of $^{24}\text{Mg}$ is reduced by a factor of $\sim 1000$. The isomer $^{26}\text{Al}$ already exceeds $10^{-3}$ by mass for most of the envelope. A significant fraction of $^{25}\text{Al}$ is transformed through proton captures into $^{25}\text{Si}$, which will increase the abundance of $^{26}\text{Al}$ and in turn that of $^{27}\text{Al}$ in the late phases of the TNR. The final $^{27}\text{Al}/^{26}\text{Al}$ ratio will reflect a competition between two different paths: $^{26}\text{Mg}$ [fed by $^{25}\text{Na}(p, \gamma)^{26}\text{Al}$] is transformed by proton captures into $^{25}\text{Al}$, which can either decay into $^{24}\text{Mg}$ or capture another proton, leading to $^{26}\text{Si}$. Only the first channel accounts for $^{26}\text{Al}$ synthesis, whereas $^{24}\text{Mg}$ can be produced by both paths, following $^{24}\text{Mg}(p, \gamma)^{25}\text{Al}$, $^{25}\text{Al}(p, \gamma)^{26}\text{Si}$ or $^{26}\text{Si}(p, \gamma)^{27}\text{Al}$ or $^{26}\text{Si}(p, \gamma)^{27}\text{Al}$ or $^{24}\text{Al}(p, \gamma)^{25}\text{Si}$. $^{25}\text{Al}$ becomes the major source of $^{26}\text{Al}$. Some leakage from the MgAl cycle as a result of $^{24}\text{Al}(p, \gamma)^{25}\text{Si}$ is also obtained at this stage of the outburst.

When the burning shell attains its peak temperature ($T_{\text{bs, max}} = 2.44 \times 10^8$ K; Fig. 3, fifth panel), most of the MgAl isotopes show a significant reduction near the burning shell as a result of $(p, \gamma)$ reactions. The dominant paths at this stage are $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}(p, \gamma)^{27}\text{Si}$ and $^{24}\text{Al}(p, \gamma)^{25}\text{Si}$, which also account for a significant leakage from the cycle [moreover, $^{25}\text{Si}(p, \gamma)$ and $^{25}\text{Si}(p, \gamma)$ are much faster than the corresponding $^\beta^+$-decays]. Following the course of the outburst (Fig. 3, sixth, seventh, and eighth panels), the envelope expands and cools down, proton-capture reactions are progressively reduced. Therefore, the late-time evolution is mainly dominated by $^\beta^+$-decays, such as $^{26}\text{Si}(^\beta^+)^{26}\text{Al}$, $^{27}\text{Si}(^\beta^+)^{27}\text{Al}$, $^{25}\text{Al}(^\beta^+)^{25}\text{Mg}$, and $^{26}\text{Al}(^\beta^+)^{26}\text{Mg}$, which in turn increase the final amounts of $^{25}\text{Mg}$, $^{26}\text{Mg}$, and $^{27}\text{Al}$. The mean abundance of $^{26}\text{Al}$ in the ejecta of this 1.25 $M_\odot$ ONe white dwarf model is $X(^{26}\text{Al}) = 5.4 \times 10^{-4}$ by mass, which translates into $7.6 \times 10^{-9}$ $M_\odot$ of $^{26}\text{Al}$ ejected into the interstellar medium. Other isotopes of the MgAl group present in the ejecta are $^{27}\text{Al}$ [$X(^{27}\text{Al}) = 2 \times 10^{-3}$, half the initial abundance; see Table 1], $^{25}\text{Mg}$ ($2.4 \times 10^{-3}$), $^{26}\text{Mg}$ ($2.0 \times 10^{-4}$), and $^{24}\text{Mg}$ ($2 \times 10^{-4}$).

4.2. Effect of the Reaction Rates on the Synthesis of $^{26}\text{Al}$

The previous analysis has revealed that several isotopes should be considered as potential seeds for $^{26}\text{Al}$ synthesis: $^{24}\text{Mg}$, $^{25}\text{Mg}$ and, to some extent, $^{23}\text{Na}$ and $^{22}\text{Ne}$. In this case, the number of nuclear reactions involved in the synthesis of $^{26}\text{Al}$ is rather large (see Fig. 2). Several test models of nova outbursts have been computed in order to analyze the role played by each of the most relevant reactions. The main results are summarized in Table 2.

The $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$ rate [in contrast to $^{23}\text{Na}(p, \alpha)^{20}\text{Ne}$] has been strongly modified by the introduction of the upper limit for the $E_{\text{cm}} = 0.138$ MeV resonance strength obtained by Görres, Wiescher, & Rolfs (1989). When taking this upper limit, the rate is significantly increased, up to $T_\odot \approx 2$ (Görres et al. 1989). Its effect has been tested by recomputing a 1.15 $M_\odot$ ONe white dwarf model (i.e., model ONe3 of José & Hernanz 1998); an increase by a factor of $\sim 3$ of the final $^{24}\text{Mg}$ yields results, which in turn lead to slightly larger mass fractions of both $^{25}\text{Mg}$ (by a factor of 1.4) and $^{26}\text{Al}$ (by a factor of 1.3). Some $^{27}\text{Al}$ is also overproduced (by a factor of 1.4) when this resonance is taken into account. These effects are expected to be stronger for more massive white dwarfs.

At the temperatures attained in nova outbursts, $^{24}\text{Mg}(p, \gamma)^{25}\text{Al}$ may become even faster than $^{12}\text{C}(p, \gamma)^{13}\text{N}$. The $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$ rate is dominated by the presence of the $E_{\text{cm}} = 0.214$ MeV, $J^\pi = 1/2^+$ resonance and suffers little uncertainty.

$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$ is also of great importance, since it is the only channel that leads to $^{26}\text{Al}$ in its ground state. One might expect that its potential uncertainties are directly reflected in the $^{26}\text{Al}$ yields. The new rate is significantly smaller, by a factor of $\approx 7$ (Iliadis et al. 1996), than the CF88 one below $T_\odot \approx 1$, but this has no consequences in the nova domain. Iliadis et al. (1996) reanalyzed available transfer reaction data for the lower lying resonances and concluded that the associated uncertainties are relatively small (i.e., a factor of 1.5–2). For $T_\odot > 1.5$, available direct measurements also lead to very small uncertainties (a factor of 1.5, according to Iliadis et al. 1996) and should not significantly influence $^{26}\text{Al}$ production. Moreover, since $^{25}\text{Mg}(p, \gamma)$ can lead to either $^{26}\text{Al}$ or $^{26}\text{Al}$, with a known branching ratio (Endt & Rolfs 1987; Iliadis et al. 1996), the $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$ rate is known with a similar precision as that of $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$.

In nova nucleosynthesis, the most important resonance in $^{25}\text{Al}(p, \gamma)^{26}\text{Si}$ is the $E_{\text{cm}} = 0.188$ MeV, while uncertainties on the lower lying resonances have no influence (Coc et al. 1995). In our calculations, we use the only single direct measurement available (Vogel et al. 1989) for this crucial resonance strength. Recently, the results of the proton transfer reaction that motivated this subsequent direct measurement have been published (Vogel et al. 1996), but the resonance strength deduced from this indirect measurement is strongly dependent on the adopted transferred angular momentum. Accordingly, we have checked the influence of such resonance on the resulting $^{26}\text{Al}$ yields by reducing its strength by a factor of $\frac{1}{2}$, well within the range of values adopted by Angulo et al. (1999). We obtain a significant increase by a factor of $\sim 2$ in the final amount of $^{26}\text{Al}$ (for a 1.15 $M_\odot$ ONe white dwarf model; see Table 2), which strongly stresses the need for additional direct measurements to confirm the results found by Vogel et al. (1989).

$^{25}\text{Al}(p, \gamma)^{26}\text{Si}$ plays an important role in $^{26}\text{Al}$ synthesis, since it leads to the formation of the short-lived isomer [through $^{25}\text{Si}(^\beta^+)^{26}\text{Al}$], instead of the long-lived ground state. We have checked the role played by the $^{25}\text{Al}(p, \gamma)^{26}\text{Si}$ rate, adopting the upper and lower estimates (see Appendix) provided by Coc et al. (1995). Results are compared with those obtained with the $^{25}\text{Al}(p, \gamma)^{26}\text{Si}$ rate given by Wiescher et al. (1986). While the final amounts of $^{26}\text{Al}$ and $^{27}\text{Al}$
are very slightly enhanced when the lower rate is adopted (i.e., case A; Coc et al. 1995), a significant reduction of $^{26}$Al, by a factor of $\sim 2$, is obtained for the upper rate (case C). In the first case, $^{25}$Al($\beta^+$)$^{26}$Mg becomes faster than $^{25}$Al($p$, $\gamma$)$^{26}$Si, and therefore the final amount of $^{25}$Mg (and in turn $^{26}$Al) increases (Table 2).

Large uncertainties affect the $^{26}$Al($p$, $\gamma$)$^{27}$Si rate. The existing CF88 prescription for this rate results from a Hauser-Feschbach calculation, a statistical approach that is not reliable at low temperatures, where the contribution of isolated resonances dominates. Hence, the rate may differ by several orders of magnitude from the theoretical one at the temperatures achieved during nova outbursts. However, no noticeable effect on $^{26}$Al production is found when the $^{26}$Al($p$, $\gamma$)$^{27}$Si rate, as given by CF88, is multiplied arbitrarily by a factor of 100, with the exception of a net reduction (by a factor of $\sim 2$) in the final amount of $^{26}$Mg.

Nuclear uncertainties significantly affect the $^{26}$Mg($p$, $\gamma$)$^{27}$Al rate. Since the initial amount of $^{26}$Mg is of the same order of magnitude as that of $^{27}$Al, and it is also fed continuously by $^{26}$Al($\beta^+$)$^{26}$Mg ($t = 9.15$ s), these uncertainties cannot be ignored as for $^{22}$Ne($p$, $\gamma$)$^{23}$Na (see § 3.2). They are especially important around $T_8 = 0.5$, where the rate remains uncertain by a factor of $\sim 100$ (Champagne et al. 1990), due to the unknown strength of a hypothetical resonance at $E_{\gamma}^p = 90$ keV. No influence on the final $^{26}$Al and $^{27}$Al yields results from the inclusion of the $^{26}$Mg($p$, $\gamma$)$^{27}$Al recommended rate given by Champagne et al. (1990) (tested with a $1.15 M_{\odot}$ ONe white dwarf model).

With respect to CF88, the $^{27}$Al($p$, $\gamma$)$^{28}$Si rate has not changed; above $T_8 = 1$, uncertainties are limited to a factor of $\sim 2$ (Angulo et al. 1999). On the other hand, new experimental data for the $^{27}$Al($p$, $\alpha$)$^{24}$Mg rate appeared shortly after the CF88 compilation: a direct measurement by Timmermann et al. (1988) and a study of proton and alpha emission from $^{28}$Si levels performed by Champagne et al. (1988). As a result, the rate is strongly reduced with respect to the CF88 one, by up to 4 orders of magnitude in the region of interest. As a consequence, the calculated $^{26}$Al yields were strongly reduced (José et al. 1997).

The new rates available for $^{23}$Al($p$, $\gamma$)$^{24}$Si (Schatz et al. 1997), $^{26}$Si($p$, $\gamma$)$^{27}$P (Hrndl et al. 1995), and $^{23}$Mg($p$, $\gamma$)$^{24}$Al (Kubono, Kajino, & Kato 1995; Hrndl et al. 1998) have no significant effect on the resulting $^{26}$Al and $^{27}$Al yields, as compared with the results obtained by José & Hernanz (1998) with a $1.25 M_{\odot}$ ONe white dwarfs, using earlier prescriptions for these rates (i.e., van Wormer et al. 1994, Wiescher et al. 1986, and Wiescher et al. 1986, respectively).

### TABLE 3

**Reaction Rates Adopted for the Calculation of Maximum (A), Recommended (B), and Minimum (C) $^{22}$Na-$^{26}$Al Production Compared with Those Adopted in José & Hernanz (1998)**

| Reaction | JH98 | Maximum (A) | Recommended (B) | Minimum (C) |
|----------|------|-------------|-----------------|-------------|
| $^{21}$Na($p$, $\gamma$)$^{22}$Mg ...... | CF88 | This work | This work | This work |
| $^{21}$Ne($p$, $\gamma$)$^{22}$Na ...... | CF88 | $f = 0.1$ | CF88 | CF88 |
| $^{25}$Al($p$, $\gamma$)$^{26}$Si ...... | Wie86 | Lower limit | Case A (Lower) | Case B (Recommended) |
| $^{25}$Al($p$, $\gamma$)$^{26}$Mg ...... | CF88 | $f = 1$ | CF88 + GWR89 | CF88 + GWR89 |
| $^{23}$Mg($p$, $\gamma$)$^{24}$Al ...... | Wie86 | $f = 1$ | KKK95 | KKK95 |
| $^{23}$Al($p$, $\gamma$)$^{24}$Si ...... | CF88 | $f = 1$ | CF88 | CF88 |
| $^{23}$Al($p$, $\gamma$)$^{24}$Mg ...... | WW80 | Lower limit | Schw97 | Schw97 |

**NOTE.** $f$, $f_1$, and $f_2$ represent uncertainty factors in the analytic rates. Sources for the reaction rates: WW80: Wallace & Woosley 1980; Wie86: Wiescher et al. 1986; CF88: Caughlan & Fowler 1988; Cha88: Champagne et al. 1988; Tim88: Timmermann et al. 1988; GWR89: Görres et al. 1989; Voc89: Vogelaar 1989; Cha90: Champagne et al. 1990; Il90: Ililias et al. 1990; Coc95: Coc et al. 1995; Her95: Hernnd et al. 1995; KKK95: Kubono et al. 1995; Ste96: Stegmüller et al. 1996; Schw97: Schatz et al. 1997; NACRE: Angulo et al. 1999.
obtained with the different nuclear reaction networks, which are summarized in Tables 4, 5, and 6, allow us to derive error bars for the synthesis of $^{22}$Na and $^{26}$Al. Since we have not included other sources of uncertainty (convective, modeling of the explosion, etc.), these error bars are only of nuclear physics origin.

5.1. Characteristics of the Explosion

The early stages of the outburst are mainly dominated by the CNO cycle (José & Hernanz 1998). Therefore, the updating of the nuclear reaction rates of the NeNa-MgAl cycles has no influence on the characteristics of the accretion phase (for instance, the duration of the accretion phase, $t_{\text{acc}}$, or the mass of the accreted envelope, $\Delta M_{\text{env}}$).

Differences in the time evolution appear when the temperature near the burning shell reaches $T_{\text{sh}} \approx 10^{8}$ K. At this stage, energy generation by nuclear reactions involves a relevant contribution from the NeNa-MgAl cycles, together with the hot and cold modes of the CNO cycle. The use of updated rates modifies several properties of the TNR, such as the time required for a temperature rise from 3 x $10^7$ K up to $10^8$ K (hereafter $t_{\text{rise}}$). For instance, a value of $t_{\text{rise}} = 6.8 \times 10^5$ s was found for model ONe5 (José & Hernanz 1998), whereas a shorter time, $t_{\text{rise}} = 4.3 \times 10^5$ s, has been obtained in model ONe125B, computed with updated (recommended) rates.

The role played by the NeNa-MgAl cycles increases when the temperature at the location of the burning shell exceeds $2 \times 10^8$ K. This has an important effect on the energy production as well as on the resulting peak temperature achieved during the TNR. For instance, peak values for the nuclear energy generation rate and temperature achieved in model ONe5, $\epsilon_{\text{nuc,max}} = 2.1 \times 10^{16}$ ergs g$^{-1}$ s$^{-1}$ and $T_{\text{max}} = 2.44 \times 10^8$ K, translate into $\epsilon_{\text{nuc,max}} = 3.0 \times 10^{16}$ ergs g$^{-1}$ s$^{-1}$ and $T_{\text{max}} = 2.51 \times 10^8$ K for model ONe125B. A similar trend was also pointed out by Starrfield et al. (1998), using updated nuclear reaction rates with respect to the CF88 ones.

Such differences also have some influence on the last phases of the evolution, when the envelope expands, cools

| Parameter          | ONe3 | ONe115A | ONe115B | ONe115C |
|--------------------|------|---------|---------|---------|
| Reaction network   | Old  | A       | B       | C       |
| $\Delta M_{\text{env}}$ (10$^{-3}$ $M_\odot$) | 3.2  | 3.2     | 3.2     | 3.2     |
| $T_{\text{max}}$ (10$^8$ K) | 2.19 | 2.33    | 2.31    | 2.30    |
| $\Delta M_{\text{rise}}$ (10$^{-5}$ $M_\odot$) | 1.9  | 2.6     | 2.6     | 2.6     |
| $K$ (10$^{45}$ ergs) | 1.2  | 1.5     | 1.5     | 1.5     |

| Parameter          | ONe5  | ONe125A | ONe125B | ONe125C |
|--------------------|-------|---------|---------|---------|
| Reaction network   | Old   | A       | B       | C       |
| $\Delta M_{\text{env}}$ (10$^{-3}$ $M_\odot$) | 2.2  | 2.2     | 2.2     | 2.2     |
| $T_{\text{max}}$ (10$^8$ K) | 2.44 | 2.54    | 2.51    | 2.51    |
| $\Delta M_{\text{rise}}$ (10$^{-5}$ $M_\odot$) | 1.4  | 1.4     | 1.4     | 1.4     |
| $K$ (10$^{45}$ ergs) | 1.4  | 1.5     | 1.5     | 1.5     |

| Parameter          | ONe6  | ONe135A | ONe135B | ONe135C |
|--------------------|-------|---------|---------|---------|
| Reaction network   | Old   | A       | B       | C       |
| $\Delta M_{\text{env}}$ (10$^{-3}$ $M_\odot$) | 0.54 | 0.54    | 0.54    | 0.54    |
| $T_{\text{max}}$ (10$^8$ K) | 3.24 | 3.22    | 3.31    | 3.23    |
| $\Delta M_{\text{rise}}$ (10$^{-5}$ $M_\odot$) | 0.44 | 0.44    | 0.44    | 0.44    |
| $K$ (10$^{45}$ ergs) | 0.9  | 1.0     | 1.0     | 1.0     |
down, and eventually a fraction of the formerly accreted shells is ejected. In general, we find that models computed with updated rates lead to slightly larger ejected masses with larger mean kinetic energies (see Tables 4–6), as a result of the larger $e_{\text{nuc,max}}$ attained. It is worth noting that these differences in the properties of the TNRs will be reflected in the accompanying nucleosynthesis. The reason is twofold: first, the update of the reaction rates implies a certain modification of the nuclear paths. Second, the differences found in the time evolution as well as in the peak temperatures achieved modify the role played by $(p, \gamma)$ and $(p, \alpha)$ reactions.

5.2. Nucleosynthesis in the NeNa-MgAl Cycles

Because of the higher peak temperatures achieved in the models computed with the updated network (recommended rates; see Tables 4–6), $^{20}$Ne is slightly reduced in the ejecta with respect to previous results obtained with older rates (José & Hernanz 1998). The differences are rather small (i.e., a mean mass fraction of 0.17 by mass, instead of 0.18, is obtained for the 1.15 and 1.25 $M_\odot$ models), but they turn out to be important in determining the synthesis of less abundant species within the NeNa cycle. For instance, the abundance of $^{21}$Ne increases by a factor of between ~3 and 5 [the higher temperatures as well as the lower rate adopted for $^{21}$Na$(p, \gamma)$22Mg favor the chain $^{20}$Ne$(p, \gamma)$21Na($\beta^+$)$^{21}$Ne]; however, no significant change is found for $^{22}$Ne [which is essentially reduced by $(p, \gamma)$ reactions from its initial amount]. It is also worth noting the net increase in the final amount of $^{22}$Na in the ejecta: a factor of ~4–5 for the 1.15 and 1.25 $M_\odot$ models [resulting from the lower rates adopted for $^{21}$Na$(p, \gamma)$22Mg and $^{22}$Na$(p, \gamma)$23Mg]. This may have important consequences for $\gamma$-ray astronomy, since it translates into a change by a factor of ~2 in the maximum expected distance at which the 1275 keV 22Na line emitted by an exploding ONe nova would eventually be detected. Other isotopes, such as $^{23}$Na and $^{25}$Mg, are also overproduced (except for the 1.35 $M_\odot$ model), but less efficiently. As a result, the isotopic ratios $^{23}$Na/$^{20}$Na decrease by nearly a factor of ~2–3. The abundances of the other magnesium isotopes, $^{24}$Mg and $^{26}$Mg, are slightly enhanced (in some cases even by a factor of ~2–4). Another interesting feature is that $^{26}$Al remains essentially unaffected by the update of the network when the recommended rates are used. Therefore, the conclusions regarding the small contribution of classical nova outbursts to the synthesis of the Galactic $^{26}$Al (see José et al. 1997) still hold. Since the amount of $^{27}$Al (and of $^{28}$Si) in the ejecta remains essentially unchanged, no variation in the isotopic ratio $^{26}$Al/$^{27}$Al is found.

Another relevant outcome from the nucleosynthetic point of view is the dispersion in the mean ejected abundances obtained when the uncertainties associated with the nuclear reaction rates are taken into account. In the following discussion, we will analyze the impact of such uncertainties in the resulting mean abundances in the ejecta. For that purpose, we will compare the yields obtained when the two extreme networks listed in Table 3 (i.e., A and C, leading to maximum and minimum $^{22}$Na-$^{26}$Al production, respectively) are adopted. We define the dispersion factor, $F$, as the ratio between the mean ejected abundances of a given nuclear species obtained when network A and C are adopted. All models computed (i.e., involving 1.15, 1.25, or 1.35 $M_\odot$ white dwarfs) show a very small dispersion in the $^{20}$Ne yields, which results essentially from the different peak temperatures attained at the envelope rather than from uncertainties in the nuclear reactions [such as $^{20}$Ne$(p, \gamma)$21Na]. We also found no relevant dispersion for $^{22}$Ne, $^{22}$Na, $^{27}$Al, and $^{28}$Si. On the other hand, the $^{21}$Ne yields show a rather wide dispersion, a factor of $F \sim 25$ in the 1.35 $M_\odot$ models. For $^{22}$Na, differences of $F \sim 2$–4 are found. Similar degrees of dispersion are also obtained for the magnesium isotopes, with $F$ ranging from 3 to 5 in the case of $^{25}$Mg and from 2 to 3 for $^{24}$Mg. Dispersion factors between 0.3 and 0.7 are found for $^{26}$Mg. The variation in the ejected amounts of $^{26}$Al is particularly worth noting, with a dispersion factor ranging from $F \sim 4$ to 7 [not considering the possible uncertainty associated with the 188 keV resonance in $^{26}$Al$(p, \gamma)^{27}$Si]. Also interesting to note is the fact that the $^{26}$Al/$^{27}$Al ratio remains in the range of 0.5–0.1 (see Tables 4–6).

In view of this analysis, the nuclear uncertainties accompanying the reaction rates within the NeNa-MgAl cycles introduce a relatively wide dispersion in the yields resulting from classical nova outbursts. Therefore, predictions of $^{22}$Na and $^{26}$Al yields would benefit from new nuclear physics experiments aimed at reducing the uncertainties associated with some key reactions of the NeNa-MgAl cycles, in particular $^{21}$Na$(p, \gamma)^{22}$Mg and $^{25}$Al$(p, \gamma)^{26}$Si, the rates of which are uncertain by several orders of magnitude, but also $^{23}$Na$(p, \gamma)^{24}$Mg and $^{22}$Na$(p, \gamma)^{23}$Mg. In addition, a verification of the as-yet-unpublished values corresponding to the 0.188 MeV resonance of $^{25}$Al$(p, \gamma)^{25}$Si, as measured by Vogelaar (1989), is also recommended, on account of its crucial role in the synthesis of $^{26}$Al. These experiments should be focused on the measurement of a few key parameters (level energies, spectroscopic factors, etc.). Many of these measurements involve short-lived radioactive species and should benefit from the current development of radioactive ion beam facilities.

On the other hand, our calculations have shown that the remaining uncertainties on $^{23}$Mg$(p, \gamma)^{24}$Al, $^{23}$Al$(p, \gamma)^{24}$Si, $^{25}$Mg$(p, \gamma)^{26}$Al, $^{25}$Al$(p, \gamma)^{26}$Si, $^{26}$Al$(p, \gamma)^{27}$P, $^{28}$Si$(p, \gamma)^{29}$P, $^{27}$Al$(p, \gamma)^{28}$Al, $^{28}$P$(p, \gamma)^{29}$S, and $^{28}$Si$(p, \gamma)^{29}$P have no effect on $^{21}$Ne and $^{26}$Al production.

6. CONCLUSIONS

We have computed a series of hydrodynamic models of nova outbursts, from the onset of accretion up to the ejection stage, for a range of ONe white dwarfs with masses between 1.15 and 1.35 $M_\odot$, with the aim of analyzing in detail the main nuclear paths leading to the synthesis of $^{22}$Na and $^{26}$Al. The roles played by several key reactions within the NeNa-MgAl cycles have been tested by a series of models, which have been compared with previous results obtained by José & Hernanz (1998) with different prescriptions for the reaction rates. Limits on the production of both $^{22}$Na and $^{26}$Al have been derived from a series of computations assuming upper, recommended, or lower estimates of the reaction rates. The most relevant conclusions extracted from this work can be summarized as follows:

1. The update of the nuclear reaction network results in a net increase in the final amount of $^{22}$Na ejected into the interstellar medium during classical nova outbursts. This translates into an increase (by a factor of ~2) of the expected maximum distance at which an exploding ONe nova would be eventually detected through its emission at 1275 keV ($^{22}$Na decay $\gamma$-ray line).
2. The final amount of $^{26}$Al remains essentially unaffected by the update of the network, confirming that classical novae scarcely contribute to the Galactic $^{26}$Al, as pointed out earlier by José et al. (1997).

3. Large nuclear uncertainties affect some key reactions of the NeNa-MgAl cycles, with a significant effect on the production of both $^{22}$Na and $^{26}$Al. When a combination of reaction rates, leading to maximum or minimum $^{22}$Na-$^{26}$Al synthesis, is adopted, a large dispersion in the final abundances is found. We stress that the derived ranges for $^{22}$Na-$^{26}$Al production can be interpreted as error bars on sodium and aluminum production posed by nuclear physics uncertainties.

4. In order to reduce the impact of the nuclear uncertainties in the production of $^{22}$Na and $^{26}$Al, we point out some nuclear reactions that deserve new experiments, in particular, $^{21}$Na$(p, \gamma)^{22}$Mg, $^{22}$Na$(p, \gamma)^{23}$Mg, and $^{25}$Al$(p, \gamma)^{26}$Si. A confirmation of the values corresponding to the 0.188 MeV resonance of $^{26}$Al$(p, \gamma)^{27}$Si, as measured by Vogelaar (1989), would also be of great importance.

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APPENDIX A

NUCLEAR REACTIONS

Here we discuss the reaction rates corresponding to proton-capture reactions on short-lived nuclei. Other reactions within the NeNa and MgAl cycles are analyzed in the text (see §3.2 and 4.2) and more extensively in the forthcoming “Compilation of Charged-Particle-Induced Thermonuclear Reaction Rates” (Angulo et al. 1999). First, we introduce some standard nuclear physics quantities and notations. We also briefly summarize several indirect methods that are generally used to extract or estimate unavailable direct data for the calculation of thermonuclear rates.

For an $A(x, y)B$ reaction, resonance strengths (at $E = E_r$) are given by $\omega_r$, where $\omega = (2J + 1/2)(2J + 3/2)\Gamma_s h/\pi$. The total width, $\Gamma(E)$, corresponds to the sum of partial widths, $\Gamma(J):$ $\Gamma = \sum_{J=x, y, ...} \Gamma_j$. The spectroscopic factor, $C^2 S$, relates single-particle widths ($\Gamma_j^r$) to actual ones: $\Gamma_j = C^2 S \Gamma_j^r$. These single-particle widths are calculated by solving the Schrödinger equation for a particle in a realistic nuclear potential. An approximation for the upper limit of single-particle widths is given by the Wigner limit: $\Gamma^W_s = 3h/\mu^2 \cdot \Gamma_j(E = E_r, s)$, where $s$ is the channel radius, $\mu$ is the reduced mass, $P_j(E, s)$ is the penetration factor, and $\ell_j$ is the orbital angular momentum transferred by particle $x$. We introduce the reduced width, $\theta_j^2$, defined by $\Gamma_j = \theta_j^2 \Gamma_j^W$, because it is sometimes used to derive estimates of reaction rates (see Illiads 1997 for a discussion of the relationship between $\theta_j^2$ and $C^2 S$).

Experimental spectroscopic factors can be extracted from transfer reactions [e.g., the proton-transfer reaction $X(\alpha, d)Y$] will lead to the one-proton spectroscopic factor used to calculate proton widths entering into the calculation of the $X(p, \gamma)Y$ rate]. Spectroscopic factors for conjugate reactions (obtained by the $p = n$ exchange) are assumed to be approximately equal. For instance, neutron spectroscopic factors for $^{24}$Ne can be extracted from the one-neutron $^{21}$Ne$(d, p)^{22}$Ne transfer reaction. According to the above approximation, these neutron spectroscopic factors can be used to determine proton widths for the calculation of the $^{21}$Na$(p, \gamma)^{22}$Mg rate, for instance. Radiative widths ($\Gamma_j^r$) correspond to transitions of the magnetic ($M\lambda$) or electric type ($E\lambda$) of order $\lambda$ are often ordered in Weiskopf’s units (W.u.) to remove the effect of their dependence on $E_{2^{+} \rightarrow 1}$ dependence and strong variation with $\lambda$ (e.g., Firestone et al. 1996). Combinations of $\Gamma_j^r$ expressed in these units are available (Endt 1979) and can be used to estimate unknown radiative widths. They can also be obtained from the conjugate nuclei after correction for the $E_{2^{+} \rightarrow 1}$ dependence. If particle emission is energetically forbidden in the conjugate level, the radiative width equals the total width. If the lifetime of this level is known, the radiative width is easily obtained.

A1. THE $^{21}$Na$(p, \gamma)^{22}$Mg REACTION

Estimates of the $^{21}$Na$(p, \gamma)^{22}$Mg reaction rate (CF88) have been provided by Wiescher et al. (1986) and Wiescher & Langanke (1986), considering the first three levels (Endt 1990) above the proton threshold. With the exception of the first level, the proton widths are much larger than the $\gamma$-widths, so that $\omega r \approx \omega L^r$. Only the first two levels ($E_x = 5.714$ and 5.837 MeV) contribute to the rate in the temperature domain considered. The $E_x = 5.837$ MeV level is assumed to be the conjugate of the $E_x = 5.910$ level in $^{22}$Ne (Endt 1990). If this assignment is correct, the corresponding $\gamma$-width can be reliably deduced (Wiescher & Langanke 1986). On the other hand, the strength of the first $E_x = 5.714$ MeV, $J^P = 2^+$ level suffers from a significant uncertainty. For this level, the total width is known experimentally to be $\Gamma = 16.5 \pm 4.4$ MeV. To calculate the corresponding resonance strength, Wiescher & Langanke (1986) and Wiescher et al. (1986) estimated the proton width, $\Gamma_p$, and deduced the radiative width, $\Gamma_j^r$, from the relation $\Gamma = \Gamma_j^r + \Gamma_j$, to estimate the proton width, two hypotheses were considered: Wiescher et al. (1986) assumed $\ell_j^r = 0$ and $\theta_j^2 = 0.01$, but later Wiescher & Langanke (1986) took $\ell_j^r = 2$ and $\theta_j^2 = 0.5$. Nevertheless, because of the $\Gamma_j^r + \Gamma_j = 16.5 \pm 4.4$ MeV constraint, the corresponding width ratios, $\gamma$, are not very different: 3.4 or 3.8 MeV, very close to the maximum value ($\Gamma/4$), obtained when $\gamma = 1/4$. There are two reasons to think that, on the contrary, $\Gamma_j < \Gamma_j^r$ and that the corresponding strength is much smaller than the estimates provided by Wiescher et al. (1986). First, this level has a known counterpart in $^{22}$Ne at $E_x = 6.120$ MeV (Endt 1998) with a measured, purely radiative, total width of $\Gamma = 29 \pm 9$ MeV, which enables us to calculate the radiative width of the $E_x = 5.714$ MeV.
$^{22}$Mg level to be $\Gamma_\gamma \approx 23$ meV. Since it is found to be greater than the measured total width (16.5 ± 4.4 meV), it is likely that $\Gamma_\gamma < \Gamma$ for this level. The second indication comes from experimental data on the $^{22}$Ne($d, p$)$^{22}$Ne reaction, which provides information on neutron capture on $^{21}$Ne (i.e., the mirror counterpart of proton capture on $^{21}$Na). Neutron spectroscopic factors were obtained by Neogy, Middleton, & Scholtz (1972) for many $^{22}$Ne levels, from $E_x = 0$ to 9.07 MeV, but not for the $E_x = 6.120$ MeV level because of its very low population and flat angular distribution. Indeed, the direct comparison of peak heights in the experimental spectrum (Fig. 1 of Neogy et al. 1972) shows that, within levels of the same spin and transferred angular momentum, the cross section for the production of the $E_x = 6.120$ MeV level is very small. In addition, the corresponding angular distribution (Fig. 5 of Neogy et al. 1972) is very flat, presenting no evidence for a direct component and hence a very small neutron spectroscopic factor. This conclusion can be extended to the proton spectroscopic factor in the $^{22}$Na mirror level. The 6.551 MeV $^{22}$Na level is assumed (Endt 1990, 1998) to belong to the same isospin triplet as the 6.120 MeV $^{22}$Ne level. Its proton spectroscopic factor has been measured by Garrett, Middleton, & Fortune (1971) to be $\approx 0.1$. This value is not consistent with the Neogy et al. (1972) data and would result, for the 5.714 MeV $^{22}$Mg level, in a proton width in excess of the measured 16.5 meV total width. Hence, one may question the isospin triplet assignment made by Endt (1990, 1998). Moreover, the 5.714 MeV $^{22}$Mg level is withdrawn from the triplet in the last paper by Endt (1998). Accordingly, we consider the Wiescher et al. (1986) estimate for this resonance strength as an upper limit and adopt $\omega \gamma = 2.5, 0.25$, and 0.0 meV for the upper limit ($\Gamma_\gamma = \Gamma_p = \Gamma/2$), recommended value (with the usual 0.1 reduction factor), and lower limit, respectively. Below we provide an updated formula for the rate, including the uncertainty factors and the direct-capture contribution from CF88:

$$1.41 \times 10^5 T_\gamma^{-2/3} \exp \left[ -20.739/T_\gamma^{1/3} - (T_\gamma/366)^2 \right]$$

$$\times (1. + 0.02 T_\gamma^{1/3} + 4.741 T_\gamma^{2/3} + 0.667 T_\gamma + 16.38 T_\gamma^{4/3} + 5.858 T_\gamma^{5/3})$$

DC(CF88)

$$+ (0 \to 10) 40.8 T_\gamma^{-3/2} \exp (-2.52/T_\gamma) \quad (E_x = 5.714)$$

$$+ 1857. T_\gamma^{-3/2} \exp (-3.95/T_\gamma) \quad (E_x = 5.837)$$

$$+ (0.1 \to 10) 408. T_\gamma^{-3/2} \exp (-5.49/T_\gamma) \quad (E_x = 5.965).$$

The third term corresponds to the 5.837 MeV level, assuming that the analog assignment made by Endt (1990) is correct. This is, however, not assured, since it is no longer present in Endt (1998). The last term corresponds to the $E_x = 5.965$ MeV, $J^\pi = 0^+$ level. Since its widths are unknown (apart from that $\Gamma_\gamma \ll \Gamma \approx \Gamma_p$), Wiescher et al. (1986) assumed a typical value for $\Gamma_\gamma$ based on the statistics of Endt (1979). We introduce a factor of 10 uncertainty to account for the dispersion of the $\gamma$-strengths within this statistics, but it has a little effect on the rate. The corresponding rates, relative to CF88 (i.e., Wiescher et al. 1986) are shown in Figure 4: the maximum effect occurs between $T_\gamma = 0.5$ and 3, well within the nova temperature range. Experimental data for the $E_x = 5.714$ MeV, $J^\pi = 2^+$ level are clearly needed to improve the reliability of this rate.

**A2. THE $^{22}$Mg($p, \gamma$)$^{23}$Al AND $^{23}$Al($p, \gamma$)$^{24}$Si REACTIONS**

Since $^{22}$Mg plays a crucial role on the synthesis of $^{22}$Na through its beta decay, its destruction by $^{22}$Mg($p, \gamma$)$^{23}$Al must be considered. The contribution of the direct capture to the ground state for the $^{22}$Mg($p, \gamma$)$^{23}$Al reaction has been calculated by Wiescher et al. (1986). Later, Wiescher et al. (1988) measured the location of the first resonance and also calculated its strength (shell model and mirror level). But because of the very low Q-value (0.125 MeV), rapid photodisintegration of $^{23}$Al prevents $^{22}$Mg destruction. Another destruction channel has also been proposed: this takes place via two proton captures on $^{22}$Mg [i.e., proton capture on the small population of $^{23}$Al through $^{23}$Al($p, \gamma$)$^{24}$Si; Görges, Wiescher, & Thielemann 1995], and a new rate was proposed by Herndl et al. (1995), based on shell-model calculations. The location of the first two $^{24}$Si levels has recently been determined experimentally (Schatz et al. 1997), leading to a higher rate than given in Herndl et al. (1995) because...
of the lower location of the first resonance \((E_{cm}^{25} = 0.141 \pm 0.031 \text{ MeV})\) instead of 320 keV. In our nova models, we have adopted the new limits for the \(^{25}\text{Al}(p, \gamma)^{26}\text{Si}\) rate given by Schatz et al. (1997).

A3. THE \(^{23}\text{Mg}(p, \gamma)^{24}\text{Al}\) AND \(^{24}\text{Al}(p, \gamma)^{25}\text{Si}\) REACTIONS

An estimate of the \(^{23}\text{Mg}(p, \gamma)^{24}\text{Al}\) rate has been provided by Wiescher et al. (1986), based on direct capture and three resonances. Since then, Kubono et al. (1995), Endt (1998), and Herndl et al. (1998) have discussed analog level assignments, in particular with the help of shell-model calculations and the isobaric multiplet mass equation (Herndl et al. 1998). For nova nucleosynthesis, only the two first resonances need to be considered. They correspond to the \(E_x = 2.349\) and 2.534 MeV levels and are assumed to be the analogs of the 2.514 MeV, \(3^+\) and 2.563 MeV, \(4^+(2^+\) levels in \(^{24}\text{Na}\) (Endt 1998; Herndl et al. 1998). In addition to the estimate provided by Wiescher et al. (1986), the strength of the second resonance has been calculated (via shell model) by Herndl et al. (1998). However, combining statistics of reduced radiative widths (Endt 1979) with the spectroscopic factor reported in Endt & Van Der Leun (1978) show that its contribution is, in any case, negligible with respect to the first one in the domain of temperature considered here. The strength of the first resonance is deduced from the analog level \((\Gamma_\gamma \ll \Gamma_p)\) and hence suffers only small uncertainty, similar to the direct-capture contribution (see Wiescher et al. 1986). In the domain of nova nucleosynthesis, the main uncertainty comes from the determination of the energy of the first level: taking \(E_{cm}^{25} = 0.458\) (Kubono et al. 1995), 0.478 (Endt 1998; Herndl et al. 1998), or 0.51 MeV (Wiescher et al. 1986) results in a variation of the rate of less than a factor of \(\sim 10\) around \(T_8 = 2.5\). To check the importance of this reaction, we adopted the highest rate (Kubono et al. 1995) in our test calculations.

For \(^{24}\text{Al}(p, \gamma)^{25}\text{Si}\), we use the rate proposed by Herndl et al. (1995), based on shell-model calculations. It remains very uncertain, because of the limited experimental spectroscopic information on \(^{25}\text{Si}\). However, it should have very little effect on Ne-Na leaks, since either \(^{24}\text{Al}(\beta^+)^{25}\text{Mg}(p, \gamma)^{26}\text{Al}\) or \(^{24}\text{Al}(p, \gamma)^{25}\text{Si}(\beta^+)^{26}\text{Al}\) lead to \(^{26}\text{Al}\) in the MgAl cycle.

A4. THE \(^{24}\text{Al}(p, \gamma)^{25}\text{Si}\) REACTION

\(^{25}\text{Al}(p, \gamma)^{26}\text{Si}\) is important, since it leads to the formation of the short-lived isomer \(^{25}\text{Al}^m\) instead of the long-lived ground state \(^{25}\text{Al}^g\). Its rate suffers from large uncertainties in the domain of nova nucleosynthesis, mainly because of the unknown location of the analog of the \(^{24}\text{Mg}\) \(E_x = 6.13\) MeV, \(3^+\) level. A level shift similar to that of its immediate neighbor \((E_x = 6.26\) MeV; \(0^+\) in \(^{26}\text{Mg}\)) would bring the \(3^+\) level within the Gamow peak, with a dramatic influence on the rate. The maximum effect on \(^{26}\text{Al}\) production is found when \(E_{cm}^{25}(3^+) = 0.2 \pm 0.1\) MeV (Coc et al. 1995). New Coulomb displacement energy calculations (Iliadis et al. 1996) give \(E_{cm}^{25}(3^+) = 0.45 \pm 0.1\) MeV. However, discrepancies between calculated and experimentally known \(^{26}\text{Si}\) level energies can exceed \(\pm 0.1\) MeV, so the case of \(E_x(3^+) = 0.2\) cannot be ruled out [see, e.g., the \(^{23}\text{Al}(p, \gamma)^{24}\text{Si}\) case above, in which the location of the first resonance is found \(\sim 180\) keV below the calculated one]. Accordingly, for this rate we used the recommended limit, \(E_x = 0.141\) MeV; the upper limit provided by Coc et al. (1995; cases A, B, and C, respectively).

A5. THE \(^{26}\text{Si}(p, \gamma)^{27}\text{P}\) REACTION

The \(^{26}\text{Si}(p, \gamma)^{27}\text{P}\) reaction rate has been discussed by Wiescher et al. (1986) and more recently by Herndl et al. (1995). Only two excited states are known in \(^{27}\text{P}\), and only one \((E_x = 1.660\) MeV, \(J^x = 5/2^+\)) is low enough to be of astrophysical interest. From the comparison with the spectrum of the mirror nucleus, another level, \(J^x = 3/2^+\), located at \(E_x = 0.985\) MeV in \(^{27}\text{Mg}\), is expected below the \(5/2^+\) level. Wiescher et al. (1986) assumed a small shift, while shell-model calculations (Herndl et al. 1995) led to a much larger shift, which resulted in a dramatic increase of the rate, by almost 4 orders of magnitude. The calculated strength (Herndl et al. 1995) is in good agreement with the \(\Gamma_\gamma, \text{value (0.8 MeV)}\) inferred from the lifetime of the \(E_x = 0.985\) \(^{27}\text{Mg}\) conjugate level and with the \(\Gamma_\gamma\) obtained from the neutron spectroscopic factor in the conjugate \(^{27}\text{Mg}\) level reported in Endt & Van Der Leun (1978). In consequence, the uncertainty results from the unknown position of the resonance. However, it does not strongly affect the rate (a factor of 10 at most) for \(1.5 < T_8 < 4\) down to \(E_{cm}^{25} \leq 0.2\) MeV, because of the compensating effect of the evolution of the penetrability \(P_L(E_x, s)\) and \(|-E_x/kT|\) factors with \(E_x\) small variations. The strength of the \(5/2^+\) resonance is known from the Wiescher et al. (1986) estimates, from \(^{25}\text{Mg}\) spectroscopy, and from the Herndl et al. (1995) calculations. However, its location \((E_x = 0.76\) MeV) makes its contribution negligible compared to that of direct capture at nova temperatures. The latter provides the lower limit for the rate, reflecting the possibility that the \(J^x = 3/2^+\) resonance energy is lower than \(E_{cm}^{25} \approx 0.2\) MeV, as considered by Wiescher et al. (1986), while the upper limit is given by the Herndl et al. (1995) rate. One should note that this effect could be enhanced if the uncertain \(^{25}\text{Al}(p, \gamma)^{26}\text{Si}\) rate is close to its maximum value (see above).

A6. THE \(^{27}\text{P}(p, \gamma)^{28}\text{Si}\) AND \(^{27}\text{Si}(p, \gamma)^{28}\text{P}\) REACTIONS

Only the ground state of \(^{28}\text{Si}\) is known, but from the level scheme of the conjugate nucleus, \(^{28}\text{Mg}\), one can infer that no resonance is expected for \(E_{cm}^{28} \leq 1.4\) MeV. Hence, at the temperatures considered in the text, the \(^{27}\text{P}(p, \gamma)^{28}\text{Si}\) reaction proceeds only through direct capture. The corresponding rate has been obtained by Herndl et al. (1995) from shell-model calculations. It is about a factor of 10 higher than the CF88 rate and can be considered as reliable enough (i.e., within an order of magnitude), due to the expected absence of resonances.

The \(^{27}\text{Si}(p, \gamma)^{28}\text{P}\) reaction rate given in CF88 comes from the analysis of Wiescher et al. (1986). They considered five resonances corresponding to the \(^{28}\text{P}\) levels between \(E_x = 2.143\) and 2.628 MeV, out of which, for three levels, the spins are uncertain. From the assumed conjugate levels in \(^{28}\text{Al}\), they extracted radiative widths and proton widths using spectroscopic
factors obtained by neutron transfer on $^{27}$Al. More recently, the good agreement between calculated (Endt & Booten 1993) and experimental (Endt 1990) level schemes, spectroscopic factors, and radiative widths for $A = 28$ nuclei gives confidence to the $^{28}$Al and $^{28}$P conjugate level assignment (see also Iliadis et al. 1999). The first level above the proton threshold, $E_p = 2.104$ MeV, $J^p = 2^-$, was not considered by Wiescher et al. (1986), but its estimated proton width is too small ($\Gamma_p \approx 10^{-20}$ eV) to contribute to the rate for $T_9 \geq 0.3$. The uncertainty remains limited to transposition of $^{28}$Al data to $^{28}$P.

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