Introduction

Classical novae are violent stellar events at the crossroads of astrophysics, nuclear physics, and cosmochemistry (Figure 1). They are powered by thermonuclear runaways (hereafter, TNR) that take place at the base of an accreted envelope, transferred from a Main Sequence (or a more evolved) stellar companion onto a compact white dwarf in a close binary system. The number of nova explosions expected in our galaxy is $30 \pm 10$ yr$^{-1}$ [1]. Contrary to type Ia supernovae, for which the white dwarf is fully disrupted by the violence of the explosion, all classical novae are expected to recur, with periodicities of the order of $10^4$–$10^5$ years (in contrast, X-ray bursts recur on timescales from hours to days). These cataclysmic events are characterized by a remarkable energy output, of the order of $10^{39}$ ergs (X-ray bursts), $10^{45}$ ergs (classical novae), and $10^{51}$ ergs (supernovae). Another basic difference between these explosive events is the amount of mass ejected (the whole star in a thermonuclear supernova versus $10^{-4}$–$10^{-5}$ $M_\odot$ in a nova) as well as the mean ejection velocity ($>10^4$ km s$^{-1}$ in a supernova, $10^2$–$10^3$ km s$^{-1}$ in a classical nova). In contrast, it is likely that in a typical X-ray burst no mass ejection takes place, because of the extreme escape velocities from a neutron star.

Classical novae are expected to play a role in the enrichment of the interstellar medium through a number of intermediate-mass nuclei as a result of the TNR. The material ejected during the outburst, which is exposed to peak temperatures ranging between $10^8$ and $4 \times 10^8$ K for about several hundred seconds, is expected to show evidences of a significant nuclear activity. Indeed, the identification of these nuclear abundance patterns has been the goal of many nova nucleosynthesis studies, whose story expands for more than three decades already.

Different approaches have been adopted in the modeling of nova nucleosynthesis. A first category includes *parametrized one-zone models* [2–6], in which the overall envelope’s history through the TNR is essentially described by the time evolution of temperature and density as determined in a single point (usually, the envelope’s base, and occasionally adopting T- profiles from 1-D hydro models). This approach, although representing an extreme over-simplification of the physical conditions in nova envelopes, has been widely used in connection with early attempts to include huge nuclear reaction networks (and also for sensitivity studies of the impact of nuclear physics uncertainties on the final yields [7]).

In a somewhat better approach [8], a semi-analytic model [9] is coupled to a detailed nuclear reaction network suited for nova outbursts. However, the model is assumed to be *fully convective* and in *hydrostatic* equilibrium.
Therefore, key aspects of the evolution, such as the onset of accretion or the way convection settles, extends throughout the envelope and retreats from its surface, are completely ignored.

The state-of-the-art in nova nucleosynthesis involves hydrodynamic models, both spherically symmetric or 1-D [10–12] as well as 2- or 3-D [13–14 and references therein]. However, because of computational limitations, only simplified networks to handle approximately the energetic of the explosion rather than a detailed nucleosynthesis have been coupled to the limited efforts in multidimensional calculations to date. Despite the fact that the near future will probably reveal clues on the nature of the nova outburst and its associated nucleosynthesis by means of multidimensional calculations, current numerical limitations force us to rely today on detailed 1-D models to which we will refer hereafter.

One of the topics of interest associated with nova nucleosynthesis is their potential contribution to the Galactic abundances. A number of hydrodynamic simulations have suggested that $^{15}\text{N}$, $^{17}\text{O}$ and, to some extent $^{13}\text{C}$, may be significantly overproduced in nova outbursts [12,15–16], together with a non-negligible contribution (i.e., <20% of the Galactic values) in a number of isotopes of astrophysical relevance, such as $^7\text{Li}$ [17,18], or $^{26}\text{Al}$ [12,15,19].

It is worth noting that this kind of estimate has some associated uncertainty because both the mean ejected mass per nova outburst and the nova rate during the overall galaxy’s lifetime are not well-constrained quantities. The fraction of ONe novae over the total Galactic nova rate, critical to evaluate the contribution of novae to the Galactic $^{26}\text{Al}$, for instance, has been recently revisited, taking into account the effect of binarity (see Ref. [20] for details).

Models of nova nucleosynthesis also suggest a nucleosynthetic endpoint around Ca, in agreement with observations of nova shells. In fact, and despite the problems associated with the modeling of nova outbursts (mainly, the apparent discrepancy in the amount of mass ejected between models and observations [15]), there is, in general, a good agreement between the abundance patterns inferred from observations and those derived from numerical hydro calculations. It is also worth noting that there is a lack of consensus on the nature of the mixing process (that should be able to account for metallicities as high as 0.86 in the ejecta), but the specific properties of the outermost layers of the white dwarf, where the mixing with solar-like accreted material will take place, will have a dramatic influence in the explosion. In fact, one of the most critical quantities at the beginning of the TNR is the amount of $^{12}\text{C}$ present at the base of the envelope. Indeed, the triggering reaction of the TNR is $^{12}\text{C}(p,\gamma)$, which not only determines the amount of mass accreted in the envelope, but also the proper pressure at the envelope’s base, which in turn, determines the strength of the outburst (i.e., peak temperature, mass and velocity of the ejected shells). The existence of two distinct nova classes, hosting CO and ONe white dwarfs, observationally confirmed by the measurement of strong neon lines in some novae (Aql 1982, Cyg 1992 [see Figure 1] etc.) posed interesting questions concerning the previous evolution of the progenitor system. As recently shown [21], the layers of unburnt material from previous evolutionary stages that surround the white dwarf core may have an imprint in the resulting nova nucleosynthesis if accretion settles on top of the white dwarf before these shells are lost. One of the most striking implications from this study is the possibility of misclassification of classical novae, because some explosions hosting ONe cores surrounded by CO “buffer” layers will not show any evidence of neon and may be (wrongly?) identified as non-neon (i.e., CO) novae.

Recent work to improve our nucleosynthesis predictions from 1-D hydro models includes insights into presolar meteoritic grain studies [22] as well as into gamma-ray emission from novae [23]. The recent discovery of five SiC and two graphite grains (Figures 2 and 3), whose isotopic ratios point toward a nova origin [24–25], opens up a very promising tool that may help to constrain models. Indeed, this sample of presolar grains of a likely nova origin is

Figure 2.
characterized by low $^{12}$C/$^{13}$C, and $^{14}$N/$^{15}$N ratios, high $^{30}$Si/$^{28}$Si and close-to or lower-than-solar $^{29}$Si/$^{28}$Si ratios. In addition, some of these grains show $^{26}$Al/$^{27}$Al and $^{22}$Ne/$^{20}$Ne ratios that are compatible with a nova paternity. In an attempt to help the future identification of more nova candidate grains, we have recently performed a detailed analysis [22] of potential nova imprints that may unambiguously characterize the grains condensed in their ejected envelopes, together with preliminary results on equilibrium condensation sequences that predict the mineralogy expected to form in those shells.

**Nuclear Reaction Networks and Nova Nucleosynthesis**

Nucleosynthesis in nova involves approximately 100 nuclei (from H to Ca) linked through a few hundred reactions. Hence, the task of identifying the key reactions that mostly contribute to the uncertainty on calculated isotopic yields is within reach. The normal procedure is to first estimate rate uncertainties, followed by some test calculations (preferably hydrodynamical) to evaluate the corresponding yield uncertainties. In some cases, it is not even necessary to perform such calculations as simple arguments, astrophysical and/or nuclear, are sufficient. For instance, let’s consider several reactions that have been quoted as being important CNO breakout paths to account for the observed heavier species (Ne to Ca) in some nova spectra: $^{15}$O($\alpha$, $\gamma$), $^{14}$O($\alpha$, p), $^{16}$Ne(p,$\gamma$), $^{20}$Na(p,$\gamma$), etc. Theoretical studies of nova outbursts currently invoke mixing episodes between the solar-like accreted material and the CO- (or ONe-rich) outermost layers of the underlying white dwarf cores. In this framework, the nuclear activity in the Ne-Ca mass region is therefore driven by injection of nuclear seeds in the envelope, rather than by CNO-breakout. This is in agreement with the fact that alpha capture reactions are notoriously too slow (Coulomb barrier) to have any significant effect in nova nucleosynthesis. In addition, the main nuclear path toward Ne is severely blocked by the fact that $^{18}$F(p,$\gamma$)$^{19}$Ne is much slower than $^{18}$F(p,e)$^{18}$O (see Figure 4).

Therefore, we can conclude that, at nova temperatures it is unlikely that substantial CNO-breakout takes place. And more significant: CNO-breakout is not at all needed to explain the abundance patterns inferred from observations of nova shells.

Another example concerns $^{22}$Mg(p,$\gamma$)$^{23}$Al, $^{28}$Si(p,$\gamma$)$^{29}$P, and other reactions with small $Q_{\text{pt}}$ values. Whatever their reaction rates, the photodisintegration, readily calculated from the detailed balance theorem, becomes faster than the proton capture one when $kT$~$Q_{\text{pt}}$. This latter is hence blocked (see Figure 5) at nova temperatures.

**$^{18}$F Nucleosynthesis and Gamma-Ray Astronomy**

The $\beta^-$-decay of isotopes produced by proton captures during nova outbursts are a delayed source of positrons that annihilate with the surrounding electrons producing gamma rays. It takes a few hours for the nova envelope to become transparent to gamma rays, so that only sufficiently long-lived isotopes are of importance here. $^{18}$F (and $^{13}$N) is probably the most interesting isotope with its half-life of 108mn. It is responsible for a predicted intense feature at 511 keV plus a continuum at lower energy (down to 20–30keV, $^{20}$Ne.}

![Figure 3.](image1.png)

**Figure 3.**

![Figure 4.](image2.png)

**Figure 4.**
mainly caused by comptonization) [26]. The gamma-ray flux could a priori be large (but of short duration) because \(^{19}\text{F}\) is produced from the seed nuclei \(^{16}\text{O}\) present in large amounts (~10% in mass) in the envelope prior to the outburst. This flux could then be potentially detected by gamma-ray observing satellites like Integral (or by better suited future instruments with large enough field-of-views). However, the prediction of these gamma-ray fluxes associated to \(^{19}\text{F}\)-decay is strongly limited by nuclear uncertainties plaguing \(^{19}\text{F}\) synthesis during nova outbursts. It is interesting to relate here some of the experimental attempts at reducing these uncertainties.

The main nucleosynthetic paths associated with \(^{19}\text{F}\) production (\(^{16}\text{O}(p,\gamma)^{17}\text{F}(B)^{17}\text{O}(p,\gamma)^{19}\text{F}\)) and destruction (\(^{19}\text{F}(p,\alpha)^{15}\text{O}\); the \(^{19}\text{F}(p,\gamma)^{19}\text{Ne}\) reaction rate is approximately 10\(^3\) times lower than the \(^{19}\text{F}(p,\alpha)^{15}\text{O}\) one and hence plays no role in \(^{19}\text{F}\) destruction rate) are displayed in Figure 4. Analysis of available experimental nuclear data, reaction rate uncertainties, and their impact in nova models have shown that at nova temperatures (50–350 MK), the \(^{19}\text{F}(p,\alpha)^{15}\text{O}\) rate was highly uncertain and induced a factor of ~300 uncertainty on the gamma-ray flux [27]. The reason for the lack of experimental data is that, obviously, \(^{19}\text{F}\) is short lived but also because it is a self-conjugate nucleus (\(Z = N\)). Hence no information can be extracted from the conjugate nucleus like for \(^{25}\text{Na}(p,\gamma)^{26}\text{Mg}\) where spectroscopic factors can be obtained from the (d, p) transfer reaction on the stable \(^{25}\text{Mg}\) target. It is worth it to summarize here the experimental efforts still underway for the determination of the rates of production and destruction of \(^{19}\text{F}\).

The first estimate of this rate was published in 1982 [28] but at that time, the spectroscopy of the compound nucleus \(^{35}\text{Ne}\) was very poor compared to its stable analog \(^{19}\text{F}\). Indeed no level was known within the Gamow peak at nova temperatures and the rate was highly uncertain. A first breakthrough occurred with the development of radioactive \(^{19}\text{F}\) beams at the Centre de Recherches du Cyclotron (CRC/UCL, Louvain-la-Neuve), Argonne (ANL), and Oak Ridge National Laboratories (ORNL). The properties of two resonances standing at the edge (330 keV) or above (660 keV) the nova Gamow peak were measured directly [29]. The spectroscopy of \(^{15}\text{Ne}\) was greatly improved through a series of \(^{19}\text{F} + ^{3}\text{He}, ^{16}\text{O} + ^{7}\text{Li}\) and \(^{20}\text{Ne} + \text{d}\) experiments conducted in different North American laboratories [30] leading to the discovery of several new states and the assignment of analog levels in \(^{19}\text{F}\). Two of these new levels, located close to proton threshold, were investigated by a (d, p) transfer reaction with the \(^{19}\text{F}\) beams at CRC and ORNL, and spectroscopic factors were extracted [31]. In spite of these experimental efforts, the important \(^{19}\text{F}(p,\alpha)\) rate remains uncertain at nova temperatures due to possible interference between broad resonances. Hence, several experiments have recently been performed or are planned at SPIRAL (\(^{15}\text{O}\) beam), CRC (\(^{15}\text{O}, ^{19}\text{F},\) and \(^{19}\text{Ne}\) beams) and ORNL.

Although the \(^{19}\text{F}\) destruction rate remains uncertain, its production rate is now comparatively well known due to very recent experiments. The \(^{17}\text{O}(p,\gamma)^{18}\text{F}\) and \(^{17}\text{O}(p,\alpha)^{15}\text{O}\) rates (the former, directly leading to \(^{19}\text{F}\); the later, bypassing \(^{19}\text{F}\) synthesis) were not precisely known at nova temperatures due to a resonance at 180 keV: only upper limits for the \((p,\gamma)\) and \((p,\alpha)\) strengths were known [32]. The energy and lifetime of the corresponding level were measured precisely at the CENBG van de Graaff through the \(^{14}\text{N}(\alpha,\gamma)^{17}\text{O}\) reaction [33] and were found to be in contradiction with earlier measurements. The \(^{17}\text{O}(p,\gamma)^{18}\text{F}\) strength was first measured directly at the LENA van de Graaff (TUNL) [34], whereas the \(^{17}\text{O}(p,\alpha)^{15}\text{O}\) strength was measured directly at the CSNSM, PAPAP electrostatic accelerator. Because of the erroneous lifetime value, this latter measurement was thought to be impossible prior to the CENBG measurement but, on the contrary, the \((p,\alpha)\) strength was found to be large: 1.6 ± 0.2 meV! [33]. Hydrodynamical calculations of the nova outburst, and of the associated gamma-ray emission with these new rates are underway but preliminary results indicate that for a 1.15 Mo ONe nova, the new \(^{17}\text{O} + \text{p}\) rates induce a reduction of a factor of ~8 of the early gamma-ray emission associated with the \(^{19}\text{F}\) decay, as compared with previous estimates (based on the rates published in Ref. [32]). Indeed, the production of the rarest oxygen isotope, \(^{17}\text{O}\), is also significantly reduced.

It is worth noticing here that this astrophysical problem, namely the amount of \(^{19}\text{F}\) produced in nova outbursts, has led to tens of experiments involving a dozen accelerators on both sides of the Atlantic. They ranged from the 200 keV PAPAP electrostatic accelerator to RIB facilities at Louvain la Neuve, ORNL, and Spiral, and included Van de Graaff, Tandems, stable and radioactive beams, and so on. None of these accelerators would have been sufficient to obtain the results briefly summarized earlier. Hence, it is of the utmost importance for nuclear astrophysics that a wide range of facilities remains available in Europe.

**The Importance of \(^{25}\text{Al}(p,\gamma)^{26}\text{Si}\) and \(^{30}\text{P}(p,\gamma)^{31}\text{S}\)**

\(^{30}\text{P}\) is another isotope in the list of N = Z odd-odd nuclei (\(^{19}\text{F}, ^{25}\text{Na}, ^{26}\text{Al},\) and \(^{30}\text{P}\)), which are important for nova
nucleosynthesis. This critical rate governs the path to heavier species, in the mass range S-Ca [35]. Indeed, spectroscopic determinations of nova shells have revealed the presence of elements such as silicon (Nova Aql 1982, QU Vul 1984), sulfur (Nova Aql 1982), chlorine (Nova GQ Mus 1983), argon and calcium (Nova GQ Mus 1983, Nova V2214 Oph 1988, Nova V977 Sco 1989 and Nova V443 Set 1989), but no indication of a significant overproduction with respect to solar abundances has ever been reported for elements above Ca. The $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction (Figure 5) is on the path towards these intermediate-mass elements but its rate come from Hauser-Feshbach estimates, a statistical model notoriously not adapted to such a light isotope [35].

Hydrodynamic calculations have shown that the rate uncertainties have not only a direct influence on the production of these intermediate-mass elements but also on silicon isotopic abundances (specifically in the final amount of $^{30}\text{Si}$, one of the main fingerprints of a nova origin in presolar grain analysis. See Figure 3). This reaction should hence be the focus of future experimental studies. Attempts to reduce the uncertainty associated with this rate are currently in progress at several nuclear physics facilities, including ORNL, ANL, and JYFL (University of Jyväskylä). In particular, a $^{12}\text{C}(^{20}\text{Ne},n)^{31}\text{S}$ experiment to study proton-unbound levels in $^{31}\text{S}$ has been performed in ANL with gammasphere, with the goal to determine their corresponding spins and parities.

The third (and final) major source of uncertainty in nova nucleosynthesis is associated with the $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ rate [8,36]. Its impact on nova nucleosynthesis is primarily associated with the contribution of novae to the Galactic $^{26}\text{Al}$ content. On the basis of the results derived from the COMPTEL/CGRO map of the 1.809 MeV, $^{26}\text{Al}$ emission in the galaxy, young progenitors (i.e., type II supernovae and Wolf–Rayet stars) have been invoked as the main $^{26}\text{Al}$ factories in our galaxy, without excluding a minor contribution from other sources, such as novae. The main source of uncertainty in the $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ rate is due to the unknown location of the analog of the $^{26}\text{Mg}$, $E_x=6.13$ MeV, $3^+$ level. Experiments to improve our knowledge of this rate have been planned at TRIUMF (Vancouver).

We have shown that the main nuclear activity associated with classical nova outbursts is driven by $(p,\gamma)$ and $(p,\alpha)$ reactions, running between the line of stable nuclei and the proton drip line. Most of these rates have been measured at the right energy range in the laboratory because, at the typical temperatures achieved during nova outbursts, measurements of nuclear cross-sections in the region of the Gamow peak are, except for a few exceptions, feasible. In this sense, classical nova are unique stellar explosions, and represent the only explosive site for which the nuclear physics input is (or will be in the near future) primarily based on experimental information.

References