



Uncertainties in the $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ reaction rate in classical novae

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ABSTRACT

Context. Direct observation of γ -ray emission from the decay of ^{18}F ejected in classical nova outbursts remains a major focus of the nuclear astrophysics community. However, modeling the abundance of ejected ^{18}F , and thus the predicted detectability distance of a γ -ray signal near 511 keV emitted from these transient thermonuclear episodes, is hampered by significant uncertainties in our knowledge of the key $^{18}\text{F}(\text{p}, \alpha)$ reaction rate.

Aims. We analyze uncertainties in the most recent nuclear physics experimental results employed to calculate the $^{18}\text{F}(\text{p}, \alpha)$ reaction rate. Our goal is to determine which uncertainties have the most profound influence on the predicted abundance of ^{18}F ejected from novae in order to guide future experimental works.

Methods. We calculated a wide range of $^{18}\text{F}(\text{p}, \alpha)$ reaction rates using the R -Matrix formalism, which allowed us to take all interference effects into account. Using a selection of 16 evenly spaced rates over the full range, we performed 16 new hydrodynamic nova simulations.

Results. We have performed one of the most thorough theoretical studies of the impact of the $^{18}\text{F}(\text{p}, \alpha)$ reaction in classical novae to date. The $^{18}\text{F}(\text{p}, \alpha)$ rate remains highly uncertain at nova temperatures, resulting in a factor of ~ 10 uncertainty in the predicted abundance of ^{18}F ejected from nova explosions. We also found that the abundance of ^{18}F may be strongly correlated with that of ^{19}F .

Conclusions. Despite numerous nuclear physics uncertainties affecting the determination of the $^{18}\text{F}(\text{p}, \alpha)$ reaction rate, dominated by unknown interference signs between $1/2^+$ and $3/2^+$ resonances, future experimental work should focus on firmly and precisely determining the directly measurable quantum properties of the subthreshold states in the compound nucleus ^{19}Ne near 6.13 and 6.29 MeV.

Key words. novae, cataclysmic variables – gamma rays: stars – stars: abundances – white dwarfs

1. Introduction

Classical novae are thermonuclear explosions that take place in the envelopes of accreting white dwarfs in stellar, short orbital period, binary systems (see Starrfield et al. 2008; José et al. 2008, and José 2016 for reviews). They have been systematically observed in all wavelengths, ranging from radio to γ rays. However, while novae have been predicted to emit γ rays of specific energies around 1 MeV, associated with electron-positron annihilation (e.g., from $^{18}\text{F}(\beta^+\gamma)$) and with nuclear decay (e.g., ^{22}Na at 1.275 MeV and ^{26}Al at 1.809 MeV), they have only been detected in γ rays for energies exceeding 100 MeV. In symbiotic binary systems, such as V407 Cyg, this high-energy emission has been attributed to shock acceleration in the ejected shells after interaction with the dense wind of the red giant companion. The emission reported from several classical novae involving less evolved stellar companions (e.g., V1324 Sco, V959 Mon, V339 Del, and V1369 Cen; Ackermann et al. 2014) has been attributed to internal shocks in the ejecta. In this scenario, γ rays are produced either through a hadronic process, in which accelerated protons collide with matter to create neutral pions that decay into γ -ray photons, or through a leptonic process, in which visible or infrared photons reach high energies in the interaction with high-energy electrons. While the hadronic process seems to be favored, the exact nature of the mechanism responsible for γ -ray production remains unknown.

The most intense γ -ray signal predicted for classical novae corresponds to the 511-keV line that is due to electron-positron annihilation in the expanding ejecta, together with a lower-energy continuum (powered both by positronium decay and by Comptonization of 511-keV photons) with a cutoff at ~ 20 – 30 keV due to photoelectric absorption (Clayton & Hoyle 1974; Leising & Clayton 1987; Gomez-Gomar et al. 1998; Hernanz et al. 1999). As the expanding envelope begins to become transparent to γ radiation after around ~ 2 hr, the main contributor to the bulk of positrons is ^{18}F , which decays with a characteristic half-life, $t_{1/2}$, of about 110 min. Therefore, all nuclear processes involved in the synthesis and destruction of ^{18}F are of paramount importance for predicting the expected amount of ^{18}F that survives the explosion and powers the predicted prompt 511-keV line and the lower-energy continuum. Synthesis of ^{18}F in novae is driven by the CNO-cycle reaction $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}$, which is either followed by $^{17}\text{F}(\text{p}, \gamma)^{18}\text{Ne}(\beta^+)^{18}\text{F}$ or by $^{17}\text{F}(\beta^+)^{17}\text{O}(\text{p}, \gamma)^{18}\text{F}$. Because of the relatively long half-life of ^{18}F , its dominant destruction channel is mainly $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$, with a minor contribution from $^{18}\text{F}(\text{p}, \gamma)^{19}\text{Ne}$. The most uncertain nuclear process involved in the creation and destruction of ^{18}F for nova conditions is $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ (José et al. 2006; José 2016, and references therein).

We begin in Sect. 2 with a review and analysis of the present nuclear physics uncertainties affecting the $^{18}\text{F}(\text{p}, \alpha)$ reaction, including the latest experimental results. Using these evaluated

experimental nuclear uncertainties, in Sect. 3 we calculate a range of reaction rates and vary these within new hydrodynamic nova simulations. Subsequently, in Sect. 4 we discuss and interpret all observed differences in our model outputs. In Sect. 5 we conclude by providing a road map to guide future nuclear experiments.

2. Nuclear physics uncertainties

The $^{18}\text{F}(p, \alpha)^{15}\text{O}$ reaction plays a critical role in nova explosions, yet insufficient experimental information is available to calculate a reliable, precise rate for this reaction. A quarter of a century ago, the first pioneering direct measurements were performed using ^{18}F radioactive beams (Coszach et al. 1995; Rehm et al. 1995). However, the cross section at the lowest temperatures achieved in novae ($T_8 \approx 1$, where T_8 is in units of 10^8 K) remains highly uncertain because it is too small for direct measurement, even with presently available radioactive beam intensities. Consequently, the structure of the ^{19}Ne compound nucleus has also been extensively studied in order to indirectly estimate the $^{18}\text{F}(p, \alpha)$ stellar reaction rate (for previous evaluations of the $^{18}\text{F}(p, \alpha)$ rate, see, e.g., Nesaraja et al. 2007; Iliadis et al. 2010b; La Cognata et al. 2017; Kahl et al. 2019; Hall et al. 2019, 2020). As our understanding of excited states near the proton threshold in ^{19}Ne continues to progress, it is necessary to address the latest findings and any discrepancies. Several new experimental works have recently been published (Kahl et al. 2019; Hall et al. 2019; La Cognata et al. 2019), and it is timely to review the status of nuclear physics uncertainties to examine which ones most strongly influence the $^{18}\text{F}(p, \alpha)$ rate in classical novae. Here we provide the first self-consistent evaluation of the $^{18}\text{F}(p, \alpha)$ reaction rate, combining all these latest results in a hydrodynamic nova model.

The $^{18}\text{F}(p, \alpha)$ reaction rate at the highest nova temperatures ($T_8 \approx 4$) is dominated by a $J^\pi = 3/2^-$ (orbital angular momentum $\ell = 1$) state at a resonance energy $E_r = 332$ keV and a broad $3/2^+$ ($\ell = 0$) resonance at 665 keV (Bardayan et al. 2002, 2001); we adopt the precisely measured properties of these states in the present work. At lower nova temperatures ($T_8 \lesssim 3$), $1/2^+$ and $3/2^+$ ($\ell = 0$) states predicted near the proton threshold in ^{19}Ne , including subthreshold resonances, can significantly influence the reaction rate by interfering with higher-lying, broad $1/2^+$ and $3/2^+$ states (Dalouzy et al. 2009; Chae et al. 2006). A broad $1/2^+$ state has been reported, but not resolved, near $E_r \approx 1.5$ MeV in several works (Dalouzy et al. 2009; Adekola et al. 2012; Mountford et al. 2012). Most recently, an $\ell = 0$ state with a total width of $\Gamma = 130(10)$ keV was firmly observed at 1.38(3) MeV by Kahl et al. (2019).

To explore the magnitude of quantum interference effects on the $^{18}\text{F}(p, \alpha)$ cross section, we carefully evaluated uncertainties in our knowledge of s-wave states in ^{19}Ne close to the proton separation energy $S_p = 6.4100(5)$ MeV (Wang et al. 2017). Because ^{19}F (the mirror nucleus of ^{19}Ne) is stable, its excitation structure has been comparatively well understood (see, e.g., Tilley et al. 1995), and a comprehensive, high-resolution experimental and theoretical investigation of electron inelastic scattering has been conducted (Brown et al. 1985). Near the proton threshold energy in ^{19}Ne , there is one $1/2^+$ state and two $3/2^+$ states known in ^{19}F , located at 6.255, 6.497, and 6.528 MeV, respectively. We therefore focus our attention on the location and properties of three such s-wave states in ^{19}Ne . The values adopted in the present work are shown in Fig. 1 and Table 1 and discussed presently.

$1/2^+$	7.79
$3/2^+$	7.0747
$3/2^-$	6.742
$(3/2^+)$	6.42
$S_p = 6.4100$	
$3/2^+, 1/2^+$	6.29
$1/2^+, 3/2^+$	6.13

^{19}Ne

Fig. 1. Partial level scheme of ^{19}Ne , with an emphasis on s-wave states affecting the $^{18}\text{F}(p, \alpha)$ reaction rate. See Table 1 for details.

Most recently, Hall et al. (2019, 2020) considered the astrophysical impact of uncertainties in the resonance properties on the $^{18}\text{F}(p, \alpha)$ reaction rate by deriving attributes of multiple resonances in ^{19}Ne from the same analog state in ^{19}F . Unfortunately, such an approach can lead to unphysical results. In the present work, all calculations are self-consistent, that is, they are in agreement with the overall known structure and properties of ^{19}F . For example, we only pair the properties of the known 6.528 MeV state in ^{19}F with just one candidate analog state in ^{19}Ne for each calculation, whereas these properties are applied simultaneously to four resonances in ^{19}Ne by Hall et al. (2020). This, for example, impacts the potential importance of the recently observed $\ell = 0$ subthreshold resonance at 6.13 MeV in ^{19}Ne by Kahl et al. (2019).

Despite tabulated mirror pairings¹, Hall et al. (2020) clearly obtained the alpha partial width, Γ_α , for both their suggested ($3/2^+$) states in ^{19}Ne from the broader 6.528 MeV state in ^{19}F . They further adopted a ($5/2^-$) resonance with Γ_α and the proton partial width, Γ_p , derived from the same 6.528 MeV state in ^{19}F (see Appendix A and Laird et al. 2013). Hall et al. (2020) then evaluated that the subsequent “inclusion” of the 6.13 MeV state in ^{19}Ne (with its properties derived from the same 6.528-MeV state in ^{19}F) has a less than $\pm 7.5\%$ influence on their reaction rate limits over nova temperatures. Those authors justified not “including” this $\ell = 0$ state because γ -ray transitions have not been observed for this unbound state, and no significant strength was seen in a measurement of the $^{18}\text{F}(d, n)$ reaction (Adekola et al. 2011a), yet they adopted other states that do not satisfy the same criteria. We demonstrate in Fig. A.1 that the sum of four $\ell > 0$ resonances included by Hall et al. (2019, 2020) exhibits an influence smaller than 7.5% near peak nova temperatures, resulting in an inconsistent methodology.

In the present work, for the neighboring $3/2^+$ states at 6.497 and 6.528 MeV in ^{19}F , one of which has a measured alpha strength and one just an upper limit from experiments, we only allow one of these values per candidate analog state in ^{19}Ne . For near-threshold and subthreshold resonances in the $^{18}\text{F}(p, \alpha)$ reaction, Γ is dominated by Γ_α . We find that the values of Γ_α

¹ Hall et al. (2020) show a firm value for Γ_α of the ^{19}F state at 6.497 MeV in their Table 1, where there is only an upper limit (see Nesaraja et al. 2007, cited therein). They also did not consider the recent value of $\Gamma_\alpha = 13.9$ keV for the 6.528-MeV state in ^{19}F (La Cognata et al. 2019).

Table 1. Resonance parameters and uncertainties used in the $^{18}\text{F}(\text{p}, \alpha)$ reaction rate calculations.

E_{ex} (MeV)	$E_{\text{c.m.}}$ (keV)	J^π	ANC or Γ_{p} ($\text{fm}^{-1/2}$ or keV)	Γ_{α} (keV)
6.132(5) ^(a)	-278(5)	1/2 ⁺ , 3/2 ⁺	≤ 8 ^(b) , ≤ 6 ^(b)	8.6 ^(c) \sim 16 ^(d) , 0.74 ^(c) \sim 8.5 ^(e)
6.286(4) ^{(f),(g)}	-124(4)	3/2 ⁺ , 1/2 ⁺	59 ^(h) , 83.5 ^(h)	1.00 ^(c) \sim 11.6 ^(e) , 11.7 ^(c) \sim 16 ^(d)
6.416 ^(b) , 6.423 ^(g)	6, 13	(3/2 ⁺)	$\leq 4.2 \times 10^{-45}$ ^{(b),(h)} , $\leq 3.9 \times 10^{-29}$ ^{(g),(h)}	≤ 0.5 ^(c)
6.742 ⁽ⁱ⁾	332	3/2 ⁻	2.22×10^{-3} ⁽ⁱ⁾	5.2 ^(c)
7.0747 ^(j)	664.7	3/2 ⁺	15.2 ^(j)	23.8 ^(j)
7.79(3) ^(b)	1380(30)	1/2 ⁺	83^{+56}_{-82} ^{(b),(k)}	47^{+46}_{-92} ^{(b),(k)}

Notes. The asymptotic normalization coefficient (ANC) is used for subthreshold states ($E_{\text{c.m.}} < 0$), and the proton partial width, Γ_{p} , is used otherwise. Firmly tabulated values were not varied in the present work. In the case of values separated by a comma, corresponding quantities are tabulated in the same order throughout a row. For the $E_{\text{ex}} = 7.79$ MeV state, we fixed the total width to 130(10) keV, allowing Γ_{p} and Γ_{α} to vary up and down, with a minimum of 1 keV each when the other absorbs the rest of the width. See the text and Fig. 1.

References. ^(a)Laird et al. (2013); ^(b)Kahl et al. (2019); ^(c)Bardayan et al. (2005), Nesaraja et al. (2007); ^(d)Torresi et al. (2017); ^(e)La Cognata et al. (2019); ^(f)Parikh et al. (2015); ^(g)Hall et al. (2019); ^(h)Adekola et al. (2011a,b); ⁽ⁱ⁾Bardayan et al. (2002); ^(j)Bardayan et al. (2001); ^(k)Adekola et al. (2012).

chosen for a given state strongly affect the magnitude of interference with higher-lying, broad resonances and thus can significantly influence the $^{18}\text{F}(\text{p}, \alpha)$ reaction rate. In contrast, Hall et al. (2019, 2020) find Γ_{α} to be negligible by application of the isolated, narrow-resonance condition for the reaction $A(i,j)B$ as

$$\gamma \equiv \frac{\prod_i \Gamma_i}{\sum_i \Gamma_i} \approx \Gamma_j \iff \Gamma_j \ll \Gamma_{i \neq j}, \quad (1)$$

where γ is the reduced width (Rolfs & Rodney 1988). However, the simplification of Eq. (1) is inapplicable to the case of interference with a broad resonance of the same J^π .

Kahl et al. (2019) unambiguously identified an $\ell = 0$ state at 6.130(5) MeV in ^{19}Ne using a model-independent approach and, based on the systematics of Coulomb energy differences, strongly favored pairing this state with the 1/2⁺ 6.255-MeV state in ^{19}F . This conclusion is supported by the significant strength from a 1/2⁺ resonance in ^{19}Ne observed near ~ 6.1 MeV (Laird 2000; Laird et al. 2002) with a magnitude comparable to the population of the 1/2⁺ 6.225-MeV state in analogous studies of ^{19}F (Green et al. 1970; Schmidt & Duhm 1970). Torresi et al. (2017) observed the signature of a 1/2 state of ambiguous parity in ^{19}Ne at 6.197(8)(50) [statistical and systematic uncertainties] with a large Γ_{α} of 16 keV. In the present work, we adopted the excitation energy of 6.132(5) MeV from the highest-resolution studies to observe this low-spin state (Laird et al. 2013; Parikh et al. 2015). As a possible 3/2⁺ assignment for this state cannot be definitively ruled out, we compared and contrasted the implications of the J assignment of the 6.132-MeV state. Table 1 shows that the resulting uncertainty in Γ_{α} of the 6.132-MeV state spans considerably different ranges depending upon the assumed J .

A strong $\ell = 0$ component was observed by Adekola et al. (2011a,b) at 6.289 MeV, but subsequent studies led to the conflicting conclusions that the state was not low spin (Laird et al. 2013) and that it was 1/2⁺ (Bardayan et al. 2015). There is now compelling evidence of a doublet in this region. Parikh et al. (2015) observed a structure broader than their experimental resolution ($\Gamma \approx 16$ keV) and identified the possibility of a doublet with peaks at 6.282 and 6.294 MeV. Subsequently, Kahl et al. (2019) demonstrated that the structure at 6.288(5) MeV cannot be attributed to a single, pure $\ell = 0$ resonance. Finally, Hall et al. (2019) observed a state at 6291.6(9) keV that they suggested to be (11/2⁺). Although such a high-spin subthreshold state would

not contribute to the astrophysical reaction rate, its presence near a subthreshold $\ell = 0$ state continues to be challenging to simultaneously and unambiguously resolve experimentally.

The mirror partner of the remaining $\ell = 0$ state in ^{19}F is likely located above the proton threshold in ^{19}Ne , but the situation is complicated as half a dozen states may exist within just 50 keV (see, e.g., Nesaraja et al. 2007 and Laird et al. 2013). Hall et al. (2019) tentatively suggest (3/2⁺) assignments for two states above the proton threshold: a newly proposed state at 6.423(3) MeV and a previously identified state at 6.441(3) MeV. Clearly, three $\ell = 0$ states in ^{19}F cannot be paired with four states in ^{19}Ne , and one of these tentative (3/2⁺) pairings should be rejected. Kahl et al. (2019) observed a peak at 6.421(10) MeV, which could include an $\ell = 0$ component near the centroid, but an $\ell = 0$ state at higher excitations is incompatible with that study and Laird et al. (2013). The 3/2⁺ state at 6.528 MeV in ^{19}F has the larger Γ_{α} , with values of 4, 1.2, and 13.9 keV reported (Smotrlich et al. 1961; Bardayan et al. 2005; La Cognata et al. 2019); its mirror partner in ^{19}Ne is thus unlikely to be observed in the low-statistics γ -ray spectroscopy experiment of Hall et al. (2019). We therefore assumed the mirror partner of the 3/2⁺ state at 6.497 MeV in ^{19}F to be near 6.42 MeV in ^{19}Ne , which is supported by perfect consistency in the observed γ transitions (Tilley et al. 1995; Hall et al. 2019).

As for the possible contribution of $\ell > 0$ resonances near the proton threshold, none have firm values for all their properties – besides many J^π ambiguities, at least one of the partial widths for each resonance is an experimental upper limit (see, e.g., Nesaraja et al. 2007 and Laird et al. 2013). Nonetheless, we consider the possible impact of such $\ell > 0$ states on the $^{18}\text{F}(\text{p}, \alpha)$ reaction rate in novae (see Table A.2).

3. Reaction rate and stellar model

We calculated a wide range of $^{18}\text{F}(\text{p}, \alpha)$ stellar reaction rates with the R -Matrix code AZURE2 (Azuma et al. 2010; Mountford et al. 2014) based on the nuclear physics uncertainties presented in Table 1. Our goal was to assess which specific nuclear quantities have the largest impact on nova observables in our model to guide future experimental measurements. Based on our evaluation in Sect. 2, we focused on, but did not limit ourselves to, variation in the following ten parameters within their uncertainties: (i) the interference sign between the two 1/2⁺ states; (ii)

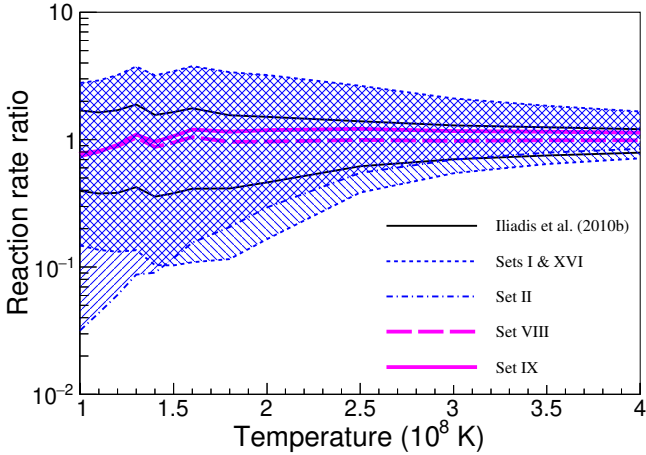


Fig. 2. Range of reaction rates explored in the present work (see Tables 1 and B.1) normalized to the median rate of Iliadis et al. (2010b); the low and high rates of Iliadis et al. (2010b) are also shown. The recommended (median) rates from the present work are shown in magenta for Sets VIII and IX, where the subthreshold spin ordering is $3/2^+$, $1/2^+$ and $1/2^+$, $3/2^+$, respectively. The highest rate (Set XVI) represents a case of maximally constructive interference, while the lowest rates (Sets I and II) are obtained via maximally destructive interference.

interference signs between up to three $3/2^+$ states; (iii) the J of the $\ell = 0$ state at 6.13 MeV; (iv) the unknown proton asymptotic normalization coefficient (ANC) of the 6.13 MeV state; (v) the J and E_{ex} of the $\ell = 0$ state near 6.29 MeV; (vi) the Γ_{α} for the mirror of the $3/2^+$, 6.528-MeV state in ^{19}F ; (vii) the Γ_{α} of the $1/2^+$ subthreshold state; (viii) the E_{ex} of a narrow ($3/2^+$) state just above S_p ; (ix) the influence of $\ell > 0$ states near S_p ; and (x) the Γ as well as the Γ_p/Γ_{α} ratio of the $1/2^+$ state near 7.8 MeV.

We found variation in other properties to be implausible or inconsequential. Further details of the R -Matrix calculations are provided in Appendix A.

Considering this large set of codependent parameters, a Monte Carlo approach, such as that employed in RatesMC (Longland et al. 2010; Iliadis et al. 2010b,a), is quite attractive. However, the case of $^{18}\text{F}(p, \alpha)$ presents a particular challenge owing to the possible influence of the interference between up to three resonances of the same J^{π} , namely the $3/2^+$ states. For this reason, the previous evaluation of Iliadis et al. (2010b) considered only the interference between a pair of $3/2^+$ states, and RatesMC uses the simple Lane and Thomas analytic formula (Longland, priv. comm., Lane & Thomas 1958, and Longland et al. 2010). Here we aim to improve upon the previous works by fully considering the latest experimental results using an R -matrix approach to handle multiple interference effects over a large and internally consistent parameter space. A comparison of the range of the present rates against those of Iliadis et al. (2010b) is shown in Fig. 2; the corresponding rates from the present work are listed in Table B.1. We recommend the median rates (Sets XIII and IX) obtained in the present work (see Fig. A.2). After a careful evaluation of the impact of each noted uncertainty on the stellar reaction rate, we selected a representative sample of 16 possible rates over the full range for a further analysis.

We assessed the astrophysical impact of these new $^{18}\text{F}(p, \alpha)$ rates through a series of 16 new hydrodynamic models of nova explosions. The simulations were performed with the hydrodynamic, Lagrangian, finite-difference, time-implicit code SHIVA (José & Hernanz 1998; José 2016). SHIVA relies on the stan-

Table 2. Mean, mass-averaged abundances of $^{18,19}\text{F}$ in the nova ejecta.

Set	Abundance		Rate (T_8)		
	$^{18}\text{F}^{(a)}$	^{19}F	1	2.5	4
I	1.1×10^{-5}	1.8×10^{-7}	1.22×10^{-5}	0.466	96.5
II	9.3×10^{-6}	1.2×10^{-7}	2.63×10^{-6}	0.664	115
III	8.6×10^{-6}	1.1×10^{-7}	3.69×10^{-6}	0.685	116
IV	7.9×10^{-6}	1.4×10^{-7}	2.31×10^{-5}	0.493	95.7
V	7.8×10^{-6}	9.9×10^{-8}	6.57×10^{-6}	0.702	116
VI	7.0×10^{-6}	8.9×10^{-8}	8.83×10^{-6}	0.740	118
VII	2.9×10^{-6}	4.0×10^{-8}	6.05×10^{-5}	1.16	132
VIII	2.8×10^{-6}	3.8×10^{-8}	6.46×10^{-5}	1.21	134
IX	2.6×10^{-6}	3.1×10^{-8}	6.15×10^{-5}	1.48	154
X	2.4×10^{-6}	2.9×10^{-8}	7.03×10^{-5}	1.55	157
XI	1.9×10^{-6}	2.3×10^{-8}	1.10×10^{-4}	1.82	162
XII	1.8×10^{-6}	2.2×10^{-8}	1.17×10^{-4}	1.89	165
XIII	1.6×10^{-6}	2.0×10^{-8}	1.36×10^{-4}	2.05	170
XIV	1.4×10^{-6}	1.6×10^{-8}	1.58×10^{-4}	2.51	198
XV	1.3×10^{-6}	1.6×10^{-8}	1.77×10^{-4}	2.53	193
XVI	1.1×10^{-6}	1.2×10^{-8}	2.30×10^{-4}	3.20	225

Notes. Calculated for each set of ^{19}Ne resonance parameters considered for the $^{18}\text{F}(p, \alpha)$ reaction rate, $N_A \langle \sigma v \rangle$, in $\text{cm}^3 \text{mol}^{-1} \text{s}^{-1}$. Samples of the rates are provided at the representative temperatures of $T_8 = 1, 2.5,$ and 4 . The sets are enumerated according to the ^{18}F abundance for convenience. ^(a)1 hour after T_{peak} .

dard set of differential equations of stellar evolution and has been extensively used in the characterization of nova outbursts, Type-I X-ray bursts, and sub-Chandrasekhar supernova explosions for more than 20 years. SHIVA uses a general equation of state that includes contributions from the degenerate electron gas, the ion plasma, and radiation. Coulomb corrections to the electron pressure are taken into account, and both radiative and conductive opacities are considered in the energy transport. Nuclear energy generation is obtained by means of a reaction network that contains 120 species (from ^1H to ^{48}Ti), linked through 630 nuclear processes, with updated rates from the STARLIB database (Sallaska et al. 2013 and Iliadis, priv. comm.). The accreted matter from the stellar companion, at a typical rate of $2 \times 10^{-10} M_{\odot} \text{yr}^{-1}$, is assumed to mix with material from the outer layers of the underlying white dwarf to a characteristic level of 50%. In all the hydrodynamic simulations performed in this work, the mass of the (ONe) white dwarf hosting the explosion was assumed to be 1.25 solar masses (and its initial luminosity 10^{-2} solar luminosities); all these simulations were identical, differing only in the specific prescription adopted for the $^{18}\text{F}(p, \alpha)$ rate.

4. Results

The main difference in our output nova model parameters is centered, as expected, around ^{18}F . As the energetics of the explosion are not affected by variations in the $^{18}\text{F}(p, \alpha)$ reaction rate within current uncertainties, the results for other model quantities are identical, such as the total ejected mass, the peak temperature, T_{peak} , achieved, etc. The values shown in Table 2 correspond to mass-averaged (mean value) abundances of $^{18,19}\text{F}$ in mass fractions, X , in the ejecta and representative temperature samples of the employed reaction rate. The ejected abundances of all the other isotopes examined varied between the models by at most a relative shift of $\pm 1\%$, which we adopted as the precision of

sensitivity achieved in the present work. While classical novae are thought to be a major source of ^{15}N , ^{17}O , and, to some, extent ^{13}C (José et al. 2006 and José 2016, and references therein), we observed no significant variation in the abundances of any of these isotopes in the present study. For example, the contribution of radiogenic ^{15}N from the $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ reaction is negligible as our model consistently ejected ^{15}N with an abundance of 3.39×10^{-2} , about four orders of magnitude larger than our predicted $\pm 5 \times 10^{-6}$ abundance shift in ^{18}F . It can be seen in Table 2 that the ejected abundances of ^{18}F (1 hour after T_{peak}) and ^{19}F covary by about an order of magnitude and are inversely correlated with the respective $^{18}\text{F}(\text{p}, \alpha)$ reaction rate. Since the observational detectability distance is taken as the square root of the ejected mass fraction, our results indicate a factor of ~ 3 uncertainty in the detectability distance of γ rays from ^{18}F decay in classical novae from the $^{18}\text{F}(\text{p}, \alpha)$ reaction rate alone.

The strong correlation of ^{18}F and ^{19}F abundances over a wide range of $^{18}\text{F}(\text{p}, \alpha)$ reaction rates is consistent with this reaction's predominance over the $^{18}\text{F}(\text{p}, \gamma)^{19}\text{Ne}$ reaction in novae. ^{19}Ne is very short lived ($t_{1/2} \approx 18$ s) and decays to the only stable isotope of fluorine, ^{19}F , which was indeed identified in the spectra of Nova Mon 2012 (Shore et al. 2013). The abundance shifts in ^{19}F are understandable since the $^{18}\text{F}(\text{p}, \alpha)$ rate limits the available ^{18}F by flushing away material faster than the $^{18}\text{F}(\text{p}, \gamma)^{19}\text{Ne}(\beta^+)^{19}\text{F}$ sequence can occur. We emphasize that the true $^{18}\text{F}(\text{p}, \alpha)$ rate remains quite uncertain.

Snapshots of the evolution of a number of representative isotopes of the O-Ne group, relevant in the synthesis and destruction of ^{18}F (i.e., $^{16,17,18}\text{O}$, $^{17,18,19}\text{F}$, and $^{18,19}\text{Ne}$) are depicted in Fig. 3. The initial mass fractions of these species throughout the envelope at the onset of the accretion stage are as follows: $X(^{16}\text{O}) = 0.13$, $X(^{17}\text{O}) = 2.1 \times 10^{-6}$, $X(^{18}\text{O}) = 1.2 \times 10^{-5}$, and $X(^{19}\text{F}) = 3.1 \times 10^{-7}$. As matter transferred from the secondary star piles up on the surface of the white dwarf star, compressional heating and nuclear reactions increase the temperature (and pressure) of the accreted envelope. When the temperature at the base of the envelope achieves $T_{\text{base}} \sim 5 \times 10^7$ K (Fig. 3, panel 1), the main nuclear activity in the O-Ne mass region is dominated by the chain $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}(\beta^+)^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$. The main effect, at this stage, is the increase in ^{17}O , whose abundance rises by two orders of magnitude at the base of the envelope with respect to its initial value. However, since the temperature achieved is not high enough to fuse a significant fraction of ^{16}O , changes on most of the species are moderate. This mostly affects the buildup of $^{17,18}\text{F}$, whose mass fractions reach $\sim 10^{-7}$. Proton capture reactions onto $^{17,18}\text{F}$ also result in a very modest increase in both $^{18,19}\text{Ne}$ ($< 10^{-10}$, by mass). Convective transport is scarcely present at this stage, which explains the inhomogeneous chemical abundance pattern of the envelope (see, for instance, the larger abundance of ^{18}F near the core-envelope interface in panel 1).

A similar behavior is observed when $T_{\text{base}} \sim 7 \times 10^7$ K (Fig. 3, panel 2), with the same chain of reactions as described in panel 1 still dominating the nuclear activity in the envelope. Convection has already extended throughout larger areas of the envelope, which translates into smoother chemical profiles across the envelope for species such as ^{18}F , which is synthesized close to the base of the envelope and is efficiently carried away to the outer, cooler layers of the envelope. At this stage, $^{18}\text{F} \sim 10^{-6}$ ($^{17}\text{F} \sim 10^{-5}$) at the base of the envelope. After ^{16}O , the second most abundant isotope of the O-Ne group at this stage is still ^{17}O .

When T_{base} reaches 10^8 K (Fig. 3, panel 3), most of the accreted envelope becomes convective. This tends to homoge-

nize the envelope, as shown by the nearly flat profiles of most species, particularly $^{16,17}\text{O}$ and $^{17,18,19}\text{F}$. The abundance of ^{16}O is being reduced by (p, γ) reactions. An increase in ^{17}O is seen, with a mass fraction ranging from 6.3×10^{-4} (inner envelope) to 8.7×10^{-4} (outer envelope). Here, the chain $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}(\beta^+)^{17}\text{O}$ dominates the destruction channel $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$. Both $^{17,18}\text{F}$ have notoriously increased with respect to the previous panel, through $^{16,17}\text{O}(\text{p}, \gamma)^{17,18}\text{F}$ reactions, while ^{19}F has been severely depleted, mostly through $^{19}\text{F}(\text{p}, \alpha)^{16}\text{O}$. The mean, mass-averaged abundances of the isotopes of $^{18,19}\text{Ne}$ continue to rise in the innermost layers of the envelope by means of proton captures onto $^{17,18}\text{F}$.

When T_{base} reaches 2×10^8 K (Fig. 3, panel 4), ^{16}O experiences a significant decrease via proton-capture reactions, which reduce its abundance by nearly a factor of two in the innermost layers of the envelope. This, in turn, induces a reduction in ^{17}O (with $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ reactions dominating over $^{17}\text{F}(\beta^+)^{17}\text{O}$). With regard to ^{18}F , its abundance is mostly dominated by the destruction channel $^{18}\text{F}(\text{p}, \alpha)^{15}\text{O}$ at the hotter, inner regions of the envelope, while $^{17}\text{O}(\text{p}, \gamma)^{18}\text{F}$ and $^{18}\text{Ne}(\beta^+)^{18}\text{F}$ contribute to raising its mass fraction in the outer, cooler regions. As a result, ^{18}F begins to show a steeper profile, which, except for the outermost layers of the envelope, increases outward. At this stage, ^{18}O and ^{19}F have been severely reduced by proton captures, while a remarkable increase in $^{18,19}\text{Ne}$ by several orders of magnitude is mainly driven by proton-capture reactions onto $^{17,18}\text{F}$, which, at these temperatures, become faster than the corresponding β^+ decays.

Shortly thereafter, the base of the envelope achieves a maximum temperature of 2.38×10^8 K (Fig. 3, panel 5). At this stage, the entire envelope has become fully convective. The ^{16}O abundance continues to decrease via proton captures, and, for the first time, a different species, ^{17}F , becomes the most abundant O-Ne group element in most of the envelope. The nuclear path is still dominated by the $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}(\beta^+)^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ chain. At this stage, the abundances of the different species reflect a competition between different destruction and creation modes, which are mostly governed by (p, γ) and (p, α) reactions in the inner regions of the envelope and by β^+ decays in the outer regions. With the exception of ^{16}O , the O-Ne group isotopes shown in panel 5 experience a net increase.

A few minutes after the envelope attains peak temperature, the sudden release of energy from the very abundant, short-lived species ^{13}N , $^{14,15}\text{O}$, and ^{17}F forces the envelope to expand. Hereafter, proton-capture reactions become confined to the innermost regions of the envelope following a dramatic temperature decrease in the outer layers (Fig. 3, panels 6 and 7). Simultaneously, convection begins to recede from the outer envelope shells.

The final stages of the outburst (Fig. 3, panel 8), when a significant fraction of the envelope has already achieved escape velocity, are dominated by the release of nuclear energy by the β^+ -decay processes $^{17,18}\text{F}(\beta^+)^{17,18}\text{O}$. The mean ^{18}F abundance in the ejecta for this model (Set IX), one hour after peak temperature, is $X(^{18}\text{F}) = 2.6 \times 10^{-6}$. The most abundant isotopes of the O-Ne group in the ejecta are, however, $X(^{16}\text{O}) = 9.2 \times 10^{-3}$ and $X(^{17}\text{O}) = 7.9 \times 10^{-3}$. In addition, some amounts of ^{18}O (1.1×10^{-6} , by mass) and ^{19}F (3.1×10^{-8} , by mass), have been found for this model (Set IX), assuming that all radioactive isotopes have already decayed into the corresponding daughter nuclei.

We confirmed that the largest variation among the $^{18}\text{F}(\text{p}, \alpha)$ reaction rates, and thus the ejected ^{18}F , arises from the unknown interference signs between the $\ell = 0$ resonances. As for directly measurable quantum properties, we found that the Γ_α of a broad $3/2^+$ subthreshold state has the most profound influence on

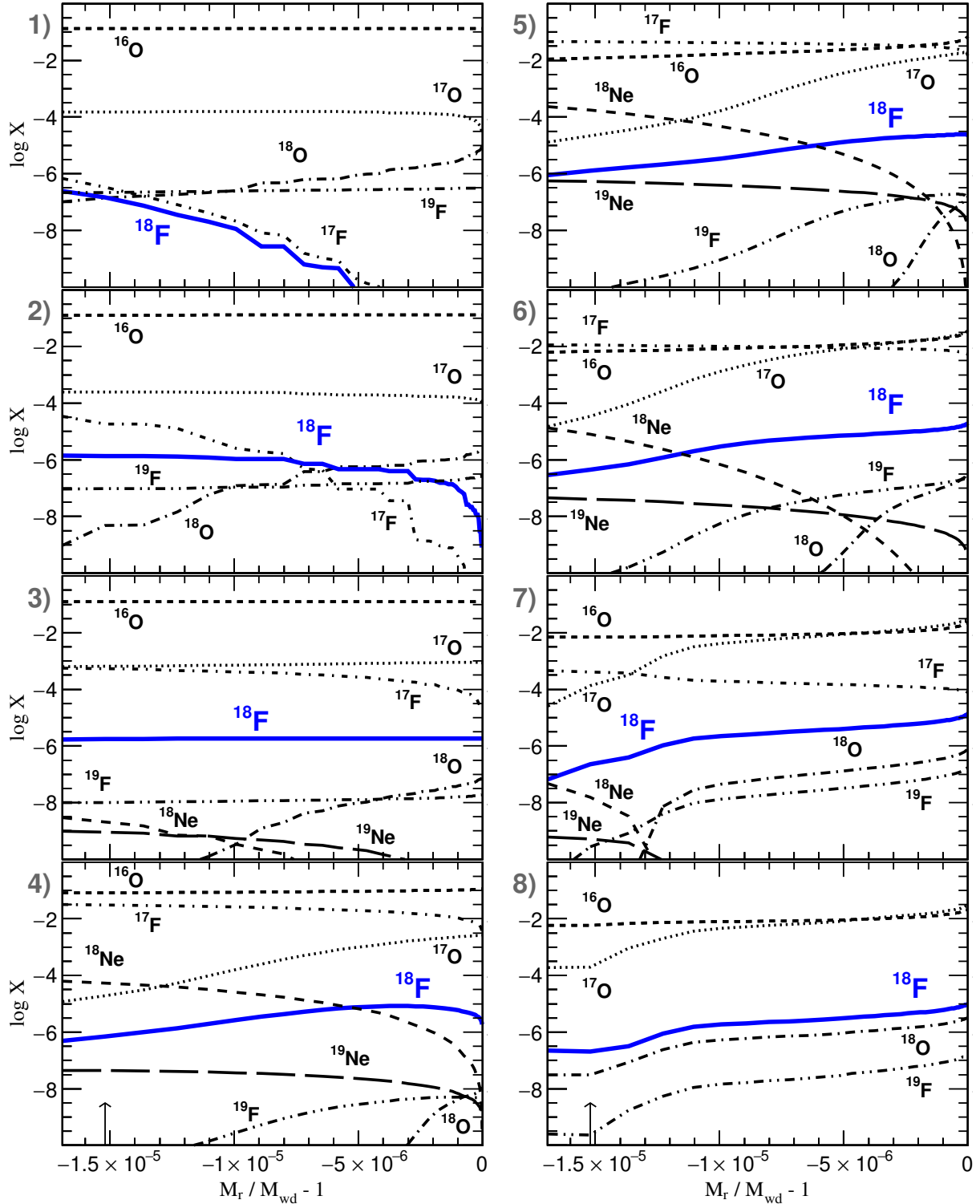


Fig. 3. Mass fractions of selected isotopes within the expanding envelope at various stages of the explosion using our newly recommended $^{18}\text{F}(p, \alpha)$ reaction rate, Set IX. The horizontal axes correspond to a relative mass coordinate where the origin is set at the surface of the envelope and where the arrows show the limit of the ejected material. The different panels correspond to temperatures at the base of the accreted envelope of approximately 5×10^7 (panel 1), 7×10^7 (panel 2), 1×10^8 (panel 3), 2×10^8 (panel 4), and $T_{\text{max}} = 2.4 \times 10^8$ K (panel 5) and to the last phases of the evolution, when the nova envelope has already expanded to a size of $R_{\text{wd}} \sim 10^9$ (panel 6), 10^{10} (panel 7), and 10^{12} cm (panel 8). We plot our results in a manner almost identical to Fig. 2 in Coc et al. (2000) to facilitate comparison.

both the maximum and minimum reaction rates. In the case of maximally destructive interferences, the lowest rates are always obtained when the 6.13 MeV state is assumed to be $1/2^+$. Conversely, the maximum rates are similar for either spin ordering

for the $\ell = 0$ subthreshold states, depending on the other assumptions. Our minimum rate is sensitive to the proton ANC of the 6.13 MeV state when it is $1/2^+$; here, a lower (but nonzero) value of $4 \text{ fm}^{-1/2}$ compared with the presumed experimental

upper limit of $8\text{ fm}^{-1/2}$ surprisingly leads to the largest effects, by shifting the dip of the destructive interference into the center of the astrophysical energy region. Although the broad $1/2^+$ state near 7.8 MeV is found to strongly affect the reaction rate by interference, we found that the rate is not sensitive to the adopted Γ_p/Γ_α ratio nor to the uncertainty in E_{ex} for this state. Finally, a $3/2^+$ state above the proton threshold can have a modest impact on the rate, depending on its exact energy and if Γ_α , Γ_p , and E_{ex} are simultaneously taken to be near the maximal values consistent with experimental measurements, although we consider such a scenario to be unlikely.

We found that the possible impact of $\ell > 0$ states (e.g., the ones assumed in Hall et al. 2019) near S_p to the maximum $^{18}\text{F}(p, \alpha)$ rate is in general trivial in relation to other nuclear uncertainties, the magnitude of their effect on the reaction rate being comparable to the least influential uncertainties of $\ell = 0$ resonances we considered (see Appendix A). For the minimum rate, setting a given partial width with only an upper limit to an arbitrarily small value is compatible with experimental results.

5. Conclusions

We performed a thorough analysis of the impact of the presumed $^{18}\text{F}(p, \alpha)$ reaction rate on the predicted abundance of the astronomical observable ^{18}F produced in classical novae. The reaction rates were obtained using the *R*-Matrix method, where the uncertainties in the nuclear input parameters were derived from a self-consistent evaluation of all available nuclear physics data, including the latest experimental results. An advantage of our approach is the ability to include all quantum interference effects on the reaction rate. The range of reaction rates we explored turned out to be quite large, and we selected 16 evenly spaced rates over our full range for further analysis. Using these new rates, we performed 16 (otherwise identical) hydrodynamic nova simulations, and we have presented and analyzed the only differences in model results we observed. The uncertainty in the observational distance arising from the decay of ejected ^{18}F from novae is about a factor of three. We conclude by emphasizing the extant nuclear physics quantities that need to be known more precisely to significantly reduce this astronomical uncertainty:

- interference effects between $\ell = 0$ states;
- precise knowledge of the properties of the $\ell = 0$ states near 6.13 and 6.29, the lack of which dominates the uncertainties;
- the proton ANC of the 6.13 MeV state;
- more definitive spin assignments on the $\ell = 0$ states near 6.13 and 6.29 MeV, ideally with $<5\text{ keV}$ resolution;
- a stronger upper limit on the Γ_α , and thus on the Γ , of the putative $3/2^+$ state near 6.42 MeV.

In the future, it will be interesting to investigate the uncertainties in other nuclear reactions that affect ^{19}F abundances in novae to determine if ^{19}F can be used as an observational tracer for the $^{18}\text{F}(p, \alpha)$ reaction.

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Appendix A: Details of R -Matrix calculations

We calculated the $^{18}\text{F}(p, \alpha)$ stellar reaction rate using the R -Matrix formalism with AZURE2 (Azuma et al. 2010; Mountford et al. 2014). We fixed the channel radius $a = 5.25$ fm, similar to the values adopted in previous works of 5.5, 5.0, and 5.2 fm (in de Séréville et al. 2009, Beer et al. 2011, and Hall et al. 2019, respectively). The sensitivity of the R -Matrix calculations on the assumed channel radius was previously explored over the range 4.5–6.5 fm (see Fig. 6 of de Séréville et al. 2009), where a larger channel radius was seen to push a destructive interference dip to lower energies, and vice versa, all other parameters being equal. We separate our employed ^{19}Ne resonance parameters into the following three categories: (i) strongly influential resonances used in all calculations where variation in their properties within experimental uncertainties has a negligible influence on the reaction rate (shown in Table A.1); (ii) $\ell > 0$ resonances with poorly known properties that nevertheless exhibit a minimal influence on the present uncertainty in the reaction rate (shown in Table A.2); and (iii) $\ell = 0$ resonances that dominate the present uncertainty in the reaction rate (shown in Table A.3).

The possible contribution of the $\ell > 0$ resonances in Table A.2 is shown in Fig. A.1. We compare the sum of these four resonances against the maximum rate (Set XVI), as well as the case when the 6.13 MeV state is $1/2^+$ and has $\Gamma_\alpha = 16$ keV (Torresi et al. 2017) rather than 8.6 keV (as assumed in Set XVI). Our analysis showed that the largest resonant contribution in Table A.2 is from the 6.459 MeV state in ^{19}Ne ; this was tentatively assigned as $(5/2^-)$ by Laird et al. (2013), who did not observe any $3/2^+$ states in ^{19}Ne in this region. As there seemed to be no corresponding $5/2^-$ state in ^{19}F near this energy, Laird et al. (2013) scaled the properties of the 6.528 MeV $3/2^+$ state in ^{19}F given by Nesaraja et al. (2007). As our calculations already assign a mirror partner to the 6.528 MeV state in ^{19}F , we infer that the maximum contribution of the 6.459 MeV state in ^{19}Ne is significantly less than what Fig. A.1 suggests.

For the $(3/2)^-$ state at 6.416 MeV, Hall et al. (2019) have the value of Γ_p shown in Table A.2, while Hall et al. (2020) claim $\Gamma_p = 2.8 \times 10^{-27}$ keV for a 1 keV resonance energy shift (inconsistent with Bardayan et al. 2015). We instead found $\Gamma_p = 2.3 \times 10^{-45}$ keV for such a $(3/2)^-$ resonance at $E_{c.m.} = 6$ keV. We tested all of these values for Γ_p , and, even with an erroneous increase of 10^{18} in Γ_p , the contribution of this state to the maximum reaction rate of Set XVI remains negligible. We explore the energies near 6.416 versus 6.423 MeV for a $(3/2^+)$ state in Table A.3, with appropriate shifts in Γ_p and consistent use of Γ_α so that readers can evaluate the impact of the state newly suggested by Hall et al. (2019); this is not the same as considering a 6.416-MeV, negative parity state to be the same as the mirror pair of a $3/2^+$ state, but rather as a previously unresolved doublet.

The astrophysical S factor, $S(E)$, is shown and compared with experimental results in Fig. A.2. We show the exact $S(E)$ without taking into account the individual experimental target thicknesses, which differ from one another by more than a factor of two. Considering the scatter in the experimental data, the agreement is reasonably good, except at 250 keV, where only two events (and no background) were observed by Beer et al. (2011),

Table A.1. Resonance parameters used in all of the $^{18}\text{F}(p, \alpha)$ astrophysical calculations.

E_{ex} (MeV)	$E_{c.m.}$ (keV)	$2J^\pi$	Γ_p (keV)	Γ_α (keV)
6.742 ^(a)	332	3^-	2.22×10^{-3}	5.2
7.0747 ^(b)	664.7	3^+	15.2	23.8
7.79(3) ^(c)	1380	1^+	83^{+56}_{-82}	47^{+46}_{+92}

Notes. For the $E_{\text{ex}} = 7.79$ MeV state, we fixed the total width to 130(10) keV, allowing Γ_p and Γ_α to vary up and down, with a minimum of 1 keV each when the other absorbs the rest of the width. ^(a)All level parameters taken from Bardayan et al. (2002). ^(b)All level parameters taken from Bardayan et al. (2001). ^(c)All level parameters taken from Kahl et al. (2019).

Table A.2. Resonance parameters added to the maximum rate (Set XVI) that exhibits minimal influence.

E_{ex} (MeV)	$E_{c.m.}$ (keV)	$2J^\pi$	Γ_p (keV)	Γ_α (keV)
6.416(4)	6	$(3)^-$	4.7×10^{-50} ^(a)	<0.5
6.439(3)	29	1^-	$\leq 3.8 \times 10^{-19}$	220
6.459(5)	49	$(5)^-$	8.4×10^{-14} ^(b)	5.5 ^(b)
6.669(3)	289	$(5)^+$	$<2.4 \times 10^{-5}$	1.2

Notes. All level parameters are taken from Hall et al. (2019), modified here to show limit signs and tentative assignment notation provided in the original references therein. ^(a)Differs from Hall et al. (2020). See the text. ^(b)Laird et al. (2013), shifted from the $3/2^+$ 6.528-MeV state in ^{19}F . Provided for illustrative purposes only. See the text.

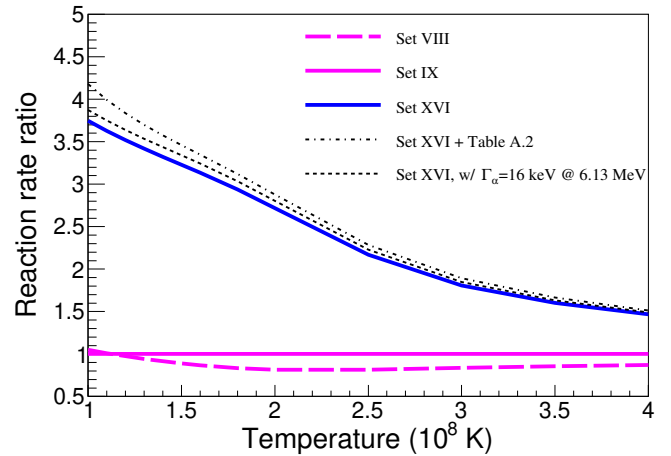


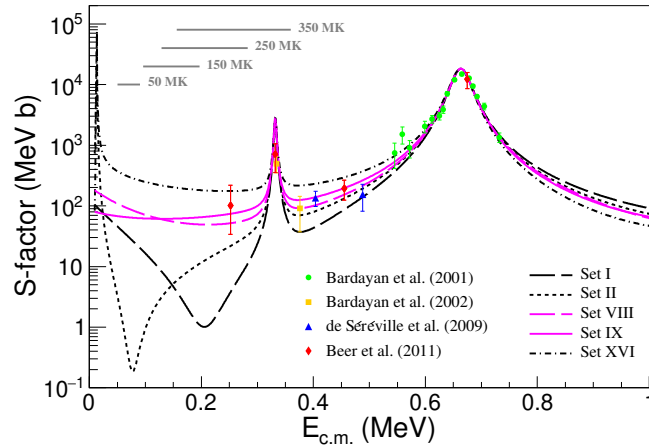
Fig. A.1. Comparison of the potential contribution of $\ell > 0$ resonances in Table A.2 to the $^{18}\text{F}(p, \alpha)$ rates utilized in the astrophysical calculations in the present work (normalized to our Set IX). We demonstrate that the potential influence of the sum of those four resonances is not much more than, e.g., the uncertainty in Γ_α of the 6.13 MeV state observed by Kahl et al. (2019).

allowing for the possibility that the true $S(E)$ could be significantly smaller, as explored in the present work.

Table A.3. Resonance parameters varied in the calculation of the $^{18}\text{F}(p, \alpha)$ reaction rate and $S(E)$.

Set	Interference Signs		Properties of $\ell = 0$ state				Properties of $\ell = 0$ state				Properties of $(\ell = 0)$ state			
	J^π 1/2 ⁺	J^π 3/2 ⁺	E_{ex} (MeV)	J^π	ANC_p (fm ^{-1/2})	Γ_α (keV)	E_{ex} (MeV)	J^π	ANC_p (fm ^{-1/2})	Γ_α (keV)	E_{ex} (MeV)	J^π	Γ_p (keV)	Γ_α (keV)
I	(++)	(++)	6.132	1/2 ⁺	4	8.6	6.289	3/2 ⁺	59	11.6	–	–	–	–
II	(++)	(+++)	6.132	1/2 ⁺	2.5	8.6	6.289	3/2 ⁺	59	1	6.423	3/2 ⁺	$<3.9 \times 10^{-29}$	<0.5
III	(++)	(+++)	6.132	1/2 ⁺	2.5	8.6	6.289	3/2 ⁺	59	1	6.416	3/2 ⁺	$<4.2 \times 10^{-45}$	<0.5
IV	(++)	(+++)	6.132	1/2 ⁺	8	8.6	6.289	3/2 ⁺	59	11.6	6.423	3/2 ⁺	$<3.9 \times 10^{-29}$	<0.5
V	(++)	(+++)	6.132	1/2 ⁺	8	8.6	6.289	3/2 ⁺	59	1	6.416	3/2 ⁺	$<4.2 \times 10^{-45}$	<0.5
VI	(++)	(++)	6.132	1/2 ⁺	8	8.6	6.289	3/2 ⁺	59	1	–	–	–	–
VII	(++)	(+++)	6.132	3/2 ⁺	6	0.74	6.289	1/2 ⁺	83.5	11.7	6.416	3/2 ⁺	$<4.2 \times 10^{-45}$	<0.5
VIII	(++)	(++)	6.132	3/2 ⁺	6	0.74	6.289	1/2 ⁺	83.5	11.7	–	–	–	–
IX	(-+)	(-+)	6.132	1/2 ⁺	8	8.6	6.289	3/2 ⁺	59	1	–	–	–	–
X	(-+)	(--+)	6.132	1/2 ⁺	8	8.6	6.289	3/2 ⁺	59	1	6.416	3/2 ⁺	$<4.2 \times 10^{-45}$	<0.5
XI	(-+)	(-+)	6.132	3/2 ⁺	6	0.74	6.289	1/2 ⁺	83.5	11.7	–	–	–	–
XII	(-+)	(--+)	6.132	3/2 ⁺	6	0.74	6.289	1/2 ⁺	83.5	11.7	6.416	3/2 ⁺	$<4.2 \times 10^{-45}$	<0.5
XIII	(-+)	(-+)	6.132	3/2 ⁺	6	0.74	6.289	1/2 ⁺	83.5	16	–	–	–	–
XIV	–	(-+)	–	–	–	–	6.289	3/2 ⁺	59	11.6	–	–	–	–
XV	(-+)	(--+)	6.132	3/2 ⁺	6	8.5	6.289	1/2 ⁺	83.5	16	6.423	3/2 ⁺	$<3.9 \times 10^{-29}$	<0.5
XVI	(-+)	(--+)	6.132	1/2 ⁺	8	8.6	6.282	3/2 ⁺	59	11.6	6.423	3/2 ⁺	$<3.9 \times 10^{-29}$	<0.5

Notes. See Table 1.


Fig. A.2. Astrophysical $S(E)$ for the $^{18}\text{F}(p, \alpha)$ reaction. See Tables 1, A.1, and A.3 for details. Experimental works are from Bardayan et al. (2001, 2002), de Sérville et al. (2009), and Beer et al. (2011).

Appendix B: Reaction rate table

Table B.1. Thermonuclear reaction rates for the $^{18}\text{F}(p, \alpha)$ sets shown in Fig. 2.

T_8	Set I Minima	Set II	Set VIII	Set IX ^(†) Medians	Set XVI Maximum
0.010	7.336×10^{-65}	9.379×10^{-65}	1.228×10^{-64}	5.253×10^{-65}	4.664×10^{-65}
0.020	6.493×10^{-49}	3.201×10^{-48}	1.108×10^{-48}	4.881×10^{-49}	4.984×10^{-49}
0.030	3.459×10^{-41}	3.938×10^{-39}	6.006×10^{-41}	2.710×10^{-41}	3.522×10^{-39}
0.040	2.546×10^{-36}	6.399×10^{-34}	4.490×10^{-36}	2.069×10^{-36}	6.504×10^{-34}
0.050	7.290×10^{-33}	9.337×10^{-31}	1.305×10^{-32}	6.129×10^{-33}	1.048×10^{-30}
0.060	3.132×10^{-30}	1.295×10^{-28}	5.683×10^{-30}	2.718×10^{-30}	1.758×10^{-28}
0.070	3.940×10^{-28}	5.091×10^{-27}	7.245×10^{-28}	3.524×10^{-28}	9.911×10^{-27}
0.080	2.115×10^{-26}	1.025×10^{-25}	3.939×10^{-26}	1.947×10^{-26}	3.253×10^{-25}
0.090	6.098×10^{-25}	1.445×10^{-24}	1.150×10^{-24}	5.773×10^{-25}	7.250×10^{-24}
0.100	1.099×10^{-23}	1.589×10^{-23}	2.098×10^{-23}	1.068×10^{-23}	1.136×10^{-22}
0.110	1.371×10^{-22}	1.395×10^{-22}	2.651×10^{-22}	1.369×10^{-22}	1.304×10^{-21}
0.120	1.277×10^{-21}	9.915×10^{-22}	2.498×10^{-21}	1.307×10^{-21}	1.149×10^{-20}
0.130	9.359×10^{-21}	5.825×10^{-21}	1.853×10^{-20}	9.821×10^{-21}	8.107×10^{-20}
0.140	5.630×10^{-20}	2.897×10^{-20}	1.128×10^{-19}	6.052×10^{-20}	4.744×10^{-19}
0.150	2.868×10^{-19}	1.248×10^{-19}	5.810×10^{-19}	3.156×10^{-19}	2.369×10^{-18}
0.160	1.268×10^{-18}	4.741×10^{-19}	2.599×10^{-18}	1.429×10^{-18}	1.032×10^{-17}
0.180	1.751×10^{-17}	5.007×10^{-18}	3.669×10^{-17}	2.063×10^{-17}	1.402×10^{-16}
0.200	1.669×10^{-16}	3.775×10^{-17}	3.575×10^{-16}	2.054×10^{-16}	1.328×10^{-15}
0.250	1.494×10^{-14}	2.055×10^{-15}	3.381×10^{-14}	2.043×10^{-14}	1.203×10^{-13}
0.300	4.493×10^{-13}	4.032×10^{-14}	1.073×10^{-12}	6.783×10^{-13}	3.737×10^{-12}
0.400	6.080×10^{-11}	2.643×10^{-12}	1.616×10^{-10}	1.107×10^{-10}	5.542×10^{-10}
0.500	1.892×10^{-09}	5.287×10^{-11}	5.603×10^{-09}	4.119×10^{-09}	1.922×10^{-08}
0.600	2.502×10^{-08}	7.703×10^{-10}	8.268×10^{-08}	6.471×10^{-08}	2.853×10^{-07}
0.700	1.901×10^{-07}	9.381×10^{-09}	7.032×10^{-07}	5.822×10^{-07}	2.447×10^{-06}
0.800	9.848×10^{-07}	8.302×10^{-08}	4.088×10^{-06}	3.562×10^{-06}	1.435×10^{-05}
0.900	3.858×10^{-06}	5.333×10^{-07}	1.803×10^{-05}	1.646×10^{-05}	6.385×10^{-05}
1.000	1.224×10^{-05}	2.633×10^{-06}	6.457×10^{-05}	6.152×10^{-05}	2.305×10^{-04}
1.100	3.297×10^{-05}	1.056×10^{-05}	1.967×10^{-04}	1.949×10^{-04}	7.069×10^{-04}
1.200	7.806×10^{-05}	3.593×10^{-05}	5.270×10^{-04}	5.412×10^{-04}	1.904×10^{-03}
1.300	1.672×10^{-04}	1.073×10^{-04}	1.273×10^{-03}	1.351×10^{-03}	4.617×10^{-03}
1.400	3.325×10^{-04}	2.896×10^{-04}	2.823×10^{-03}	3.088×10^{-03}	1.026×10^{-02}
1.500	6.329×10^{-04}	7.223×10^{-04}	5.840×10^{-03}	6.566×10^{-03}	2.121×10^{-02}
1.600	1.193×10^{-03}	1.696×10^{-03}	1.141×10^{-02}	1.315×10^{-02}	4.125×10^{-02}
1.800	4.578×10^{-03}	8.207×10^{-03}	3.826×10^{-02}	4.582×10^{-02}	1.346×10^{-01}
2.000	1.940×10^{-02}	3.443×10^{-02}	1.135×10^{-01}	1.391×10^{-01}	3.779×10^{-01}
2.500	4.658×10^{-01}	6.639×10^{-01}	$1.205 \times 10^{+00}$	$1.476 \times 10^{+00}$	$3.201 \times 10^{+00}$
3.000	$4.512 \times 10^{+00}$	$5.784 \times 10^{+00}$	$8.103 \times 10^{+00}$	$9.673 \times 10^{+00}$	$1.747 \times 10^{+01}$
3.500	$2.429 \times 10^{+01}$	$2.976 \times 10^{+01}$	$3.714 \times 10^{+01}$	$4.345 \times 10^{+01}$	$6.961 \times 10^{+01}$
4.000	$9.646 \times 10^{+01}$	$1.146 \times 10^{+02}$	$1.338 \times 10^{+02}$	$1.536 \times 10^{+02}$	$2.253 \times 10^{+02}$
4.500	$3.308 \times 10^{+02}$	$3.804 \times 10^{+02}$	$4.237 \times 10^{+02}$	$4.761 \times 10^{+02}$	$6.457 \times 10^{+02}$
5.000	$1.023 \times 10^{+03}$	$1.140 \times 10^{+03}$	$1.227 \times 10^{+03}$	$1.348 \times 10^{+03}$	$1.706 \times 10^{+03}$
6.000	$6.938 \times 10^{+03}$	$7.399 \times 10^{+03}$	$7.675 \times 10^{+03}$	$8.136 \times 10^{+03}$	$9.358 \times 10^{+03}$
7.000	$3.006 \times 10^{+04}$	$3.133 \times 10^{+04}$	$3.199 \times 10^{+04}$	$3.326 \times 10^{+04}$	$3.638 \times 10^{+04}$
8.000	$9.187 \times 10^{+04}$	$9.454 \times 10^{+04}$	$9.583 \times 10^{+04}$	$9.856 \times 10^{+04}$	$1.050 \times 10^{+05}$
9.000	$2.184 \times 10^{+05}$	$2.230 \times 10^{+05}$	$2.251 \times 10^{+05}$	$2.300 \times 10^{+05}$	$2.410 \times 10^{+05}$
10.000	$4.333 \times 10^{+05}$	$4.401 \times 10^{+05}$	$4.431 \times 10^{+05}$	$4.508 \times 10^{+05}$	$4.673 \times 10^{+05}$
12.500	$1.440 \times 10^{+06}$	$1.450 \times 10^{+06}$	$1.454 \times 10^{+06}$	$1.470 \times 10^{+06}$	$1.499 \times 10^{+06}$
15.000	$3.093 \times 10^{+06}$	$3.097 \times 10^{+06}$	$3.097 \times 10^{+06}$	$3.122 \times 10^{+06}$	$3.154 \times 10^{+06}$
17.500	$5.206 \times 10^{+06}$	$5.191 \times 10^{+06}$	$5.179 \times 10^{+06}$	$5.213 \times 10^{+06}$	$5.229 \times 10^{+06}$
20.000	$7.558 \times 10^{+06}$	$7.509 \times 10^{+06}$	$7.479 \times 10^{+06}$	$7.518 \times 10^{+06}$	$7.500 \times 10^{+06}$
25.000	$1.233 \times 10^{+07}$	$1.218 \times 10^{+07}$	$1.209 \times 10^{+07}$	$1.213 \times 10^{+07}$	$1.200 \times 10^{+07}$
30.000	$1.664 \times 10^{+07}$	$1.635 \times 10^{+07}$	$1.621 \times 10^{+07}$	$1.622 \times 10^{+07}$	$1.594 \times 10^{+07}$
35.000	$2.025 \times 10^{+07}$	$1.981 \times 10^{+07}$	$1.962 \times 10^{+07}$	$1.957 \times 10^{+07}$	$1.914 \times 10^{+07}$
40.000	$2.316 \times 10^{+07}$	$2.256 \times 10^{+07}$	$2.235 \times 10^{+07}$	$2.220 \times 10^{+07}$	$2.161 \times 10^{+07}$
50.000	$2.719 \times 10^{+07}$	$2.630 \times 10^{+07}$	$2.609 \times 10^{+07}$	$2.566 \times 10^{+07}$	$2.480 \times 10^{+07}$
60.000	$2.945 \times 10^{+07}$	$2.829 \times 10^{+07}$	$2.815 \times 10^{+07}$	$2.737 \times 10^{+07}$	$2.630 \times 10^{+07}$
70.000	$3.051 \times 10^{+07}$	$2.913 \times 10^{+07}$	$2.910 \times 10^{+07}$	$2.796 \times 10^{+07}$	$2.673 \times 10^{+07}$
80.000	$3.082 \times 10^{+07}$	$2.925 \times 10^{+07}$	$2.934 \times 10^{+07}$	$2.785 \times 10^{+07}$	$2.650 \times 10^{+07}$
90.000	$3.063 \times 10^{+07}$	$2.891 \times 10^{+07}$	$2.912 \times 10^{+07}$	$2.732 \times 10^{+07}$	$2.588 \times 10^{+07}$
100.000	$3.014 \times 10^{+07}$	$2.830 \times 10^{+07}$	$2.862 \times 10^{+07}$	$2.655 \times 10^{+07}$	$2.505 \times 10^{+07}$

Notes. ^(†)Set IX is adopted for the results presented in Fig. 3.