

Measurement of the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ astrophysical factor at threshold energies

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Proton-induced reactions on ^{19}F can lead to different branches of the CNO cycles, possibly resulting in the synthesis of heavier nuclei. For instance, CNO breakout is considered to be a viable path to the production of calcium in the most metal-poor stars. Present-day observational studies indicate that ^{19}F is mostly produced in the asymptotic giant branch phase of low- and intermediate-mass stars, and its synthesis and surface abundance are strictly intertwined with the production of heavy elements through slow neutron captures (s-process). Therefore, ^{19}F can act as a probe of nucleosynthesis scenarios and stars inner structure. In recent years, new experimental data on ^{19}F destruction reactions have been published, highlighting the occurrence of several resonances at astrophysical energies close to the proton threshold. While direct measurements relied on extrapolation from higher energies, indirect measurements made it possible to cover the astrophysical energies. In this work we will focus on the threshold region, which has been studied by means of the Trojan Horse method (THM) in the framework of the modified R -matrix approach. Thanks to this novel measurement, we could derive the asymptotic normalization coefficient (ANC) of the -448 keV subthreshold resonance and the strength of the 11 keV one, which turned out to be significantly lower than previously extrapolated. To evaluate the astrophysical impact, we calculated the astrophysical reaction rates using a modern Monte Carlo approach, constraining them with the ANC and threshold resonance strengths measured via the THM.

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I. ASTROPHYSICAL MOTIVATION

The abundance of fluorine, represented by its single stable isotope ^{19}F , is a sensitive indicator of the physical conditions and mixing processes operating within stellar interiors. Acting as a bridge between light- and intermediate-mass elements, from neon up to calcium, fluorine is synthesized in distinct stellar sites, including the asymptotic giant branch (AGB) phase of low- and intermediate-mass stars, as well as in (rotating) massive stars [1–6]. However, ^{19}F is fragile and destroyed in proton-rich environments via the $^{19}\text{F} + p$ reactions, even at temperatures of a few tens of million kelvin ($\leq 4 \times 10^7$ K). This destruction process is particularly relevant in low- and intermediate-mass AGB stars undergoing hot bottom burning (HBB), where the internal temperatures approach the region where low-energy resonances can significantly influence the reaction rate [7].

Historically, due to the lack of low-energy experimental data, standard evaluations of the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction, such as the NACRE compilation, relied on nonresonant extrapolations. This landscape was challenged by Ref. [8], who suggested that a strong low-energy resonance at 11 keV enhances the $^{19}\text{F} + p$ destruction rate by orders of magnitude at astrophysical energies. This increase was proposed to trigger a CNO breakout capable of explaining the anomalous calcium production observed in primordial, ultra-metal-poor stars, such as the Keller star (SMSS 0313-6708) [9,10]. However, in Ref. [11] a more recent indirect measurement of the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ astrophysical factor is reported at threshold energies, in which it is shown that the Ca enhancement in Population III (Pop III) stars cannot be attributed to ^{19}F destruction, and in particular, not to this reaction. If Pop III progenitor stars undergo explosive events, the synthesis of calcium is an expected outcome. Calcium is classified as a primary element, whose nucleosynthetic production proceeds independently of the progenitor star's initial metallicity [12]. The hypothesis of chemical enrichment from Pop III star explosions is supported by the observation of Fe (albeit in trace amounts) in stars like SMSS 0313-6708, and at that stage of the evolution of the Universe, such Fe could only be produced by core-collapse supernovae. An alternative pathway for a CNO breakout involves hydrogen ingestion episodes in Pop III stars. However, these events are driven by temperatures exceeding 100 MK and do not produce fluorine. In this H-ingestion scenario, Ca is instead produced via the intermediate neutron-capture process (i-process), which predominantly populates ^{42}Ca and ^{48}Ca [13].

This work focuses on a data-driven constraint of the threshold and subthreshold regions of the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction. By applying the Trojan Horse method (THM) within a modified R -matrix framework, we accessed these low-energy regions without suppression from the Coulomb barrier or electron screening effects. This approach allowed us to determine the asymptotic normalization coefficient (ANC) of the -448 keV subthreshold resonance and extract the strength of the 11 keV resonance. Utilizing these empirical parameters, we performed a Monte Carlo reaction rate calculation for future astrophysical impact studies of the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ and $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$ channels.

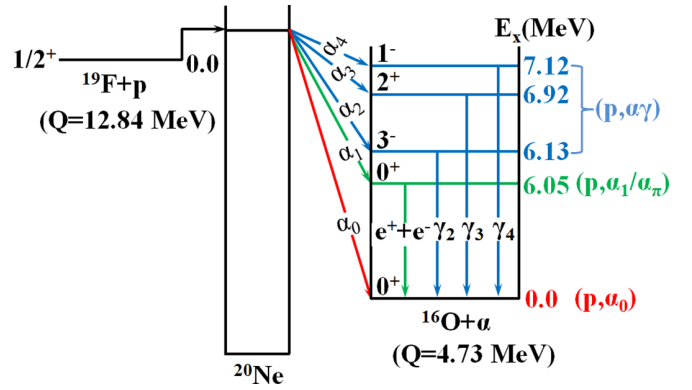


FIG. 1. Scheme of the channels populated in the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction, corresponding to different ^{16}O excited states.

II. STATE OF THE ART OF THE $^{19}\text{F}(p, \alpha)^{16}\text{O}$ REACTION STUDIES

A recent exhaustive review of the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction is given in Ref. [14] (hereafter, Solar Fusion III). In this section we discuss the aspects more relevant to our study. Solar Fusion III reported a large uncertainty affecting the recommended reaction rate due to the need of establishing a sound contribution from the 11 keV resonance, playing a very important role at low energies, below about 50 keV. Indeed, before the works of Refs. [8,15] it was commonly assumed a dominant contribution of the $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ channel (leading to the population of ^{16}O ground state, see Fig. 1), to the total $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction rate, following the recommendation by NACRE [16] and the direct and indirect measurements of the $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ astrophysical factor. Such studies [17–20], covering the astrophysical energies down to about 5 keV, contradicted the assumed nonresonant trend in NACRE evaluation below about 600 keV, pointing out the occurrence of many resonances with energies as low as about 100 keV, in agreement with the resonant trend shown by the $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ S factor above 600 keV, where measurements were available.

The work of Refs. [8,15] focused instead on the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ channel, populating the second ^{16}O excited state and above (see Fig. 1). Thanks to the reduced background of the underground JUNA facility, the authors of that work could reach energies as low as ~ 72 keV in the center of mass, still larger than the energies of interest for quiescent H burning. The R -matrix analysis reported in Refs. [8,15] indicated the occurrence of an extremely strong resonance at a center-of-mass energy of ~ 11 keV, corresponding to a ^{20}Ne excitation energy of 12.855 MeV. As a result, at solar fusion temperatures (1.5×10^7 K), the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction rate in Ref. [15] is six times larger than the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction rate in NACRE [16], including also the α_0 and the α_π (populating ^{16}O first excited state, see Fig. 1) channels.

Even taking into account the electron screening effect [21], for which JUNA data [8,15] were not corrected, the only contribution that could explain such an enhancement is the contribution of the 11 keV resonance, though its determination was merely based upon extrapolation in

Refs. [8,15]. Other resonances, such as the one at 213 keV, would contribute only at much higher temperatures, about 2.7×10^8 K, as a simple calculation of the Gamow energy would entail [22]. Therefore, as pointed out in Solar Fusion III, while the contributions of the α_0 and the α_π channels to the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ total reaction rate are well constrained by direct and indirect measurements or spectroscopic studies covering the center of mass energies of interest, at present the largest contribution to the uncertainty is attributed to the unconstrained contribution of the 11 keV resonance.

Given the large impact of such a resonance over a broad temperature region (see Ref. [11] and Supplemental Material therewith), and its likely impact on several astrophysical scenarios not well constrained yet, a novel measurement based on the THM was carried out. Preliminary results were published in Ref. [11], using the narrow-resonance approximation. In the present work, we will reanalyze the experimental results focusing on the low-energy regions of astrophysical interest, using a modified *R*-matrix approach [23–25], with the aim of cross checking the results in Ref. [11] and extend the analysis to the subthreshold region, following the approach of Refs. [26–28]. Indeed, as pointed out in Ref. [15], an accurate reproduction of the experimental data could be achieved only by including a 1^+ subthreshold resonance at a center-of-mass energy of -448 keV, corresponding to a ^{20}Ne state at 12.396 MeV [15]. This resonance has been reported in the unpublished Ph.D. thesis in Ref. [29], and its relevance due to possible interference effects in the low-energy cross section has been pointed out already in Ref. [30]. For the first time, the THM will make it possible to experimentally access the subthreshold energy region to prove the occurrence of the -448 keV resonance and extract resonance parameters with no need of extrapolation, to be used in the calculation of a data-driven reaction rate.

III. THE THM EXPERIMENT AND DATA REDUCTION

The THM is an indirect method used to access low-energy astrophysical factors, well below the Coulomb barrier, with no need of extrapolation and devoid of electron screening enhancement (see Ref. [31] for a recent review of indirect methods and related topics). In the THM framework, the *S* factor of an $A(x, c)C$ reaction is determined by isolating the quasifree (QF) component of an appropriate $A(a, cC)s$ reaction. Under QF kinematic conditions, particle *a*, which exhibits a well-defined $(x \oplus s)$ cluster configuration, serves to deliver the participant cluster *x* and populate the excited states of the $F = c + C$ system. In contrast, the remaining constituent cluster *s* is emitted without interacting with the *F* system, thereby acting as a spectator in the $A(x, c)C$ subreaction. A schematic representation of the QF reaction mechanism is provided in Fig. 2 for the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ subreaction, using deuteron to transfer a proton and populate ^{20}Ne excited states, while the neutron is emitted without influencing the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction of astrophysical interest.

The experiment was conducted at the INFN Laboratori Nazionali del Sud in Catania, Italy, employing a 55 MeV ^{19}F beam (1 mm beam spot diameter, relative energy spread of 10^{-4}) produced by the SMP Tandem accelerator and directed

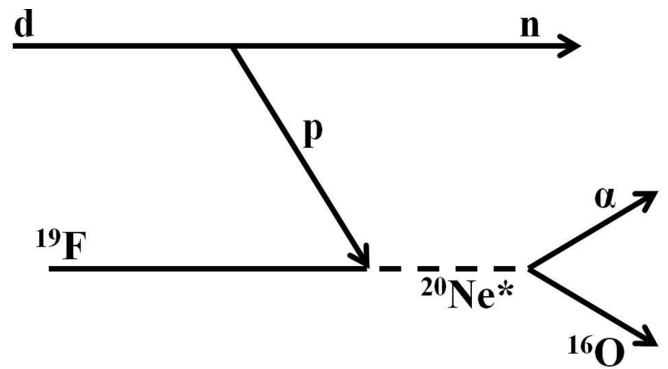


FIG. 2. Sketch of the $^2\text{H}(^{19}\text{F}, \alpha^{16}\text{O})n$ QF reaction. In the upper vertex, the deuteron breaks up into a spectator neutron and a proton, which is the participant in the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ reaction proceeding through the population of ^{20}Ne excited states (lower vertex).

onto a self-supporting CD_2 target (where ‘D’ denotes ‘ ^2H ’) with a thickness of $105 \mu\text{g}/\text{cm}^2$, isotopically enriched to 99% in ^2H . The detection setup, described in detail in Ref. [11] and shown in Fig. 3, consisted of four position-sensitive detectors (PSDs), arranged almost symmetrically with respect to the beam axis, spanning the laboratory angular ranges A: 5.6° – 12.4° , B: 5.6° – 12.4° , C: 15.7° – 31.6° , and D: 16.5° – 32.4° . Detectors A and B, whose angular positions were optimized to detect ^{16}O ejectiles emitted at QF angles, were equipped with ionization chambers to single out the $Z = 8$ locus in standard ΔE -*E* spectra [32]. The remaining two PSDs (C and D) were devoted to α -particle detection under QF conditions. Details on the data analysis are given in Ref. [11].

This latter work showed a clear separation of the $^{19}\text{F}(p, \alpha)^{16}\text{O}$ channel from other reactions occurring in the target, once the $Z = 8$ locus and the A-C and B-D coincidences were imposed in data reduction. Background-free *Q*-value and energy-momentum spectra [32] were deduced, demonstrating the population of the ^{16}O states at 6.049 MeV, 6.130 MeV, 6.917 MeV, and 7.117 MeV (Figs. 1 and S5 of Ref. [11]). In the following analysis we will focus on the channel populating the 6.130 MeV ^{16}O state (referred to as α_2 channel hereafter), constituting the dominant contribution to the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ channel [30]. Next, to apply the modified

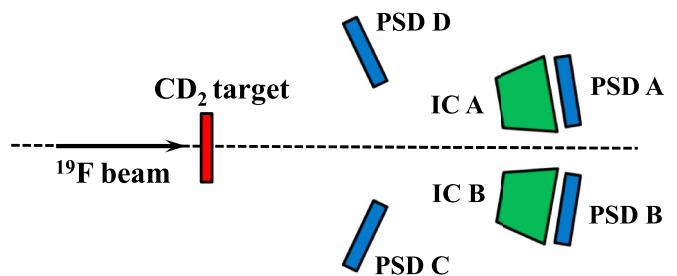


FIG. 3. Drawing of the experimental setup [11]. A ^{19}F beam was incident on a CD_2 target, and the charged reaction products were detected by silicon position-sensitive detectors (PSDs), two of which were coupled to ionization chambers (ICs) for particle identification using the ΔE -*E* technique [32].

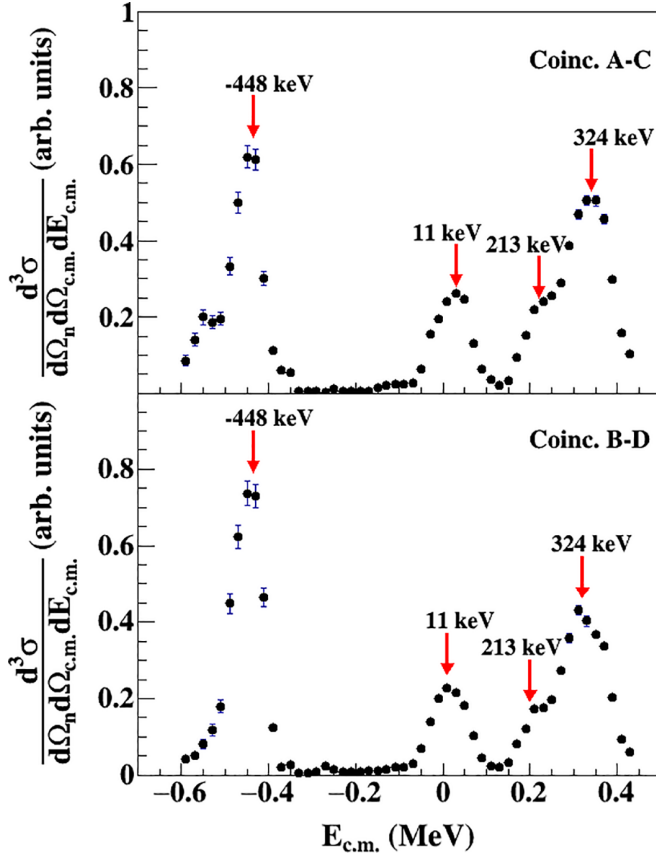


FIG. 4. The experimental ${}^2\text{H}({}^{19}\text{F}, \alpha {}^{16}\text{O})n$ QF cross sections for the two couples of detectors A-C (upper panel) and B-D (lower panel) as displayed in Fig. S4 of Ref. [11] are shown as full circles. Error bars represent standard 1σ uncertainties. Arrows mark the resonances of astrophysical interest.

R -matrix analysis framework to the ${}^2\text{H}({}^{19}\text{F}, \alpha {}^{16}\text{O})n$ cross section, the occurrence of the QF reaction mechanism was tested by comparing the experimental neutron momentum distribution with the theoretical one, given by the Hulthén function in momentum space [33]. The data agree very well with the theoretical trend, and the shape of the distribution excludes the presence of background processes, making us confident of the fulfillment of the requisite for the application of the THM (Fig. S7 in Ref. [11]).

Figure 4 displays the ${}^2\text{H}({}^{19}\text{F}, \alpha {}^{16}\text{O})n$ QF cross sections for the two coincidence pairs. The data analysis for the two detector couples, A-C and B-D, was performed separately in order to provide an internal consistency check of the results, as clearly evidenced by the comparison between the upper and lower panels. The extracted cross sections exhibit a pronounced resonance structure that spans the entire energy range under investigation, including the 324 keV resonance that will be used for normalization and the subthreshold energy region (negative energies in the $E_{\text{c.m.}}$ center of mass energy spectra). The reason why it is possible to explore the negative energy region in the application of the THM is apparent from the inspection, for instance, of Eq. (3) in Ref. [27], adapted here for the ${}^2\text{H}({}^{19}\text{F}, \alpha {}^{16}\text{O})n$ case (where m_i , E_i , and $\mathbf{p}_i$ are the

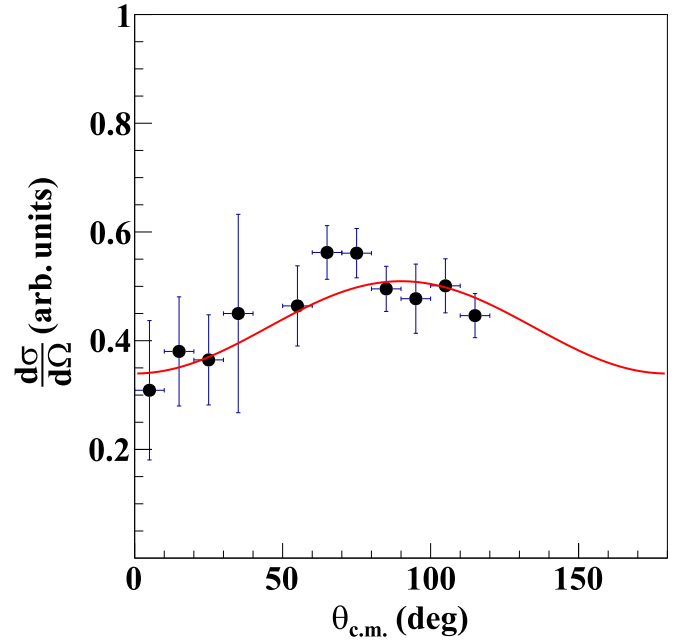


FIG. 5. The experimental angular distribution for the ${}^{19}\text{F}(p, \alpha) {}^{16}\text{O}$ reaction populating ${}^{16}\text{O}$ second excited state is shown as black circles. The $E_{p, {}^{19}\text{F}}$ energy range for resonance selection is $-0.46 - 0.43$ MeV. The red line is the theoretical angular distribution calculated as detailed in the text.

mass, energy, and momentum of the i th nucleus, and μ_{ij} the reduced mass of the i - j system):

$$E_{p, {}^{19}\text{F}} = \frac{m_p}{m_p + m_{{}^{19}\text{F}}} E_{{}^{19}\text{F}} - \frac{p_n^2}{2\mu_{n, {}^{20}\text{Ne}}} + \frac{\mathbf{p}_n \cdot \mathbf{p}_{{}^{19}\text{F}}}{m_p + m_{{}^{19}\text{F}}} - \varepsilon_d. \quad (1)$$

Since it is necessary to supply energy to break the bound Trojan Horse nucleus (deuteron in the present case, with binding energy ε_d) and thanks to the participant-spectator intercluster motion within it, negative p - ${}^{19}\text{F}$ relative energies $E_{p, {}^{19}\text{F}}$ can be attained and subthreshold resonances are experimentally achievable. This is apparent for the hypothesized -448 keV resonance introduced in the Ref. [15] R -matrix analysis, based on the unpublished results of Ref. [29], which is clearly seen in the ${}^2\text{H}({}^{19}\text{F}, \alpha {}^{16}\text{O})n$ QF cross section spectra in Fig. 4, as marked by the arrow. To apply the modified R -matrix analysis, these cross sections have to be integrated over the angular distributions and summed together.

Figure 5 reports the ${}^{19}\text{F}(p, \alpha) {}^{16}\text{O}$ experimental angular distribution for the subthreshold resonance (black circles). Angular distributions were deduced for detector couples A-C and B-D and averaged out in the overlapping center-of-mass angular range. The red line is the theoretical angular distribution calculated for a 1^+ resonance spin-parity using the general expression for the case of an isolated resonance of Ref. [34], given also in Ref. [27] for the THM case [Eq. (20)]. A normalization factor was fitted to the experimental data to fix the overall normalization. A very good agreement is apparent in the overlapping center-of-mass angular interval, which has allowed us to assess the spin-parity 1^+ of the subthreshold resonance. The fitting approach additionally

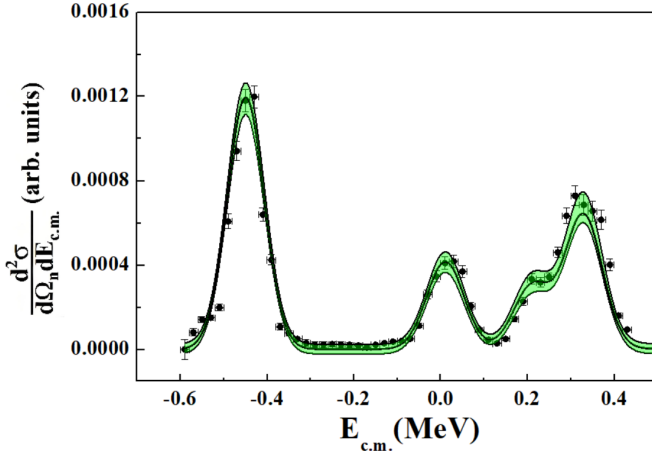


FIG. 6. Experimental cross section of the $^{19}\text{F}(p, \alpha_2)^{16}\text{O}$ reaction (see Fig. 1) and best-fit curve. The former is given as full circles and error bars represent the total uncertainty. The middle solid line is the best-fit curve in the modified R -matrix framework (see text for details) and the green band highlights the 1σ uncertainty range. At these energies, the α_2 channel essentially corresponds to the $\alpha\gamma$ one [30].

enabled the evaluation of the experimental uncertainty associated with the integration of the angular distributions, which is necessary for the application of the modified R -matrix analysis, as these distributions had to be extrapolated into angular regions not covered by the experimental setup. By integrating the angular distributions and summing together the cross sections for the A-C and B-D coincidence detectors in Fig. 4 we obtained the $d^2\sigma/d\Omega_n dE_{c.m.}$ cross section in Fig. 6 (black circles), that is the starting point for the extraction of the resonance strengths. Error bars in the figure include statistical and systematic errors, the latter accounting for the uncertainty in the extrapolation of angular distributions in the region not covered by experimental data. This is done by assuming different trends for the angular distribution still allowed for by the uncertainties affecting experimental data [11].

IV. THE MODIFIED R -MATRIX ANALYSIS

In Refs. [26–28], a specialized version of the modified R -matrix approach already used in the analysis of the $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ reaction [17,18,20] has been introduced, to deduce resonance parameters for subthreshold resonances and, in particular, the asymptotic normalization coefficient (ANC). While an exhaustive discussion of the THM framework for resonant reactions can be found, for instance, in Ref. [35] and references therein, we will give here the details relevant to our analysis.

The general THM reaction amplitude describing the $A(a, cC)s$ three-body process [27,35], acting through the transfer of the cluster x off a and populating resonances in the $F = c + C = x + A$ compound system, is expressed in post form as

$$M(P, \mathbf{k}_{aA}) = \langle \chi_{\mathbf{k}_{sF}}^{(-)} \Phi_F^{(-)} | \Delta V_{sF} | \Psi_i^{(+)} \rangle, \quad (2)$$

where $\Psi_i^{(+)}$ is the exact $a + A$ scattering wave function, $\Phi_F^{(-)}$ is the final-state wave function of the F nucleus, and $\chi_{\mathbf{k}_{sF}}^{(-)}$ describes the distorted motion of the spectator s relative to F . To treat resonant contributions in the F subsystem, the exact amplitude is recast using a spectral decomposition of $\Phi_F^{(-)}$ [36], leading to a shell-model-based R -matrix representation,

$$\Phi_{F\alpha}^{(-)} \approx \sum_{\nu, \tau=1}^N \tilde{V}_{\nu\alpha}(E_\alpha) [\mathbf{D}^{-1}]_{\nu\tau} \Phi_\tau, \quad (3)$$

where Φ_τ denotes the compound nuclear levels, $\mathbf{D}$ is the R -matrix level matrix, and $\tilde{V}_{\nu\alpha}$ is the resonant form factor describing the decay into channel α [24]. The corresponding formal partial width is

$$\tilde{\Gamma}_{\nu\alpha}(E_\alpha) = 2\pi |\tilde{V}_{\nu\alpha}(E_\alpha)|^2, \quad (4)$$

which is related to the reduced width $\gamma_{\nu\alpha}$ through the penetrability factor P_l in standard R -matrix theory [37]. Observable widths are obtained via the Thomas approximation [38]. The resulting TH resonant amplitude takes the form

$$M^{(R)} \approx \sum_{\nu, \tau=1}^N \tilde{V}_{\nu\alpha}(E_{cC}) [\mathbf{D}^{-1}]_{\nu\tau} M_\tau(\mathbf{k}_{sF}, \mathbf{k}_{aA}), \quad (5)$$

where M_τ is the transfer amplitude populating the compound state τ . This expression generalizes the multilevel R -matrix formalism to THM reactions [23,24,39], with the crucial difference that the entrance-channel Coulomb penetrability is replaced by the transfer amplitude, reflecting the half-off-energy-shell (HOES) nature of the method.

In practical applications, the exact transfer amplitude is replaced by its DWBA approximation, which serves as a form factor in the THM reaction amplitude. The corresponding triple differential cross section explicitly connects the measured three-body yield to the reduced widths governing the binary reaction. Under simplifying assumptions, such as isolated resonance and plane waves, the THM cross section of the $A(x, c)C$ reaction reduces to a compact R -matrix-like expression [17,26,39]

$$\frac{d^2\sigma}{dE_{xA} d\Omega_s} \propto \left| \frac{\sqrt{2P_l} M_i(p_{xA} R_{xA}) \gamma_{cC} \gamma_{xA}}{D(E_{xA})} \right|^2, \quad (6)$$

where the same reduced widths appear as in the on-energy-shell (OES) astrophysical $S(E)$ factor, but without Coulomb suppression in the entrance channel. This enables the extraction of low-energy reaction rates free from electron screening and experimental resolution effects from the fitting of the THM $\frac{d^2\sigma}{dE_{xA} d\Omega_s}$ QF cross section. The formalism can be extended to sub-threshold states by redefining the shift function [27] and exploiting the connection between reduced widths and ANCs [40–42]. In this case,

$$\gamma^2 = \frac{\hbar^2}{2\mu a} \frac{C^2 W(a)^2}{1 - C^2 \int_a^\infty |W(r)|^2 dr}, \quad (7)$$

where a is the channel radius and W the Whittaker function, highlighting the deep relationship between THM and ANC methods [26].

TABLE I. Comparison of the resonance strengths and the resonance parameters in the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction, as determined in this work and in the literature. For the subthreshold resonance, the ANC is given instead of the partial width Γ_p .

$E_{\text{c.m.}}^R$ (MeV)	J^π	$\omega\gamma$ (eV)			Γ_{p_0} or ANC (eV or $\text{fm}^{-1/2}$)		Γ_{α_2} (eV)	
		Ref. [11]	This work	NACRE [16]	This work	Refs. [8,15]	This work	Refs. [8,15]
-0.448	1^+				$(9.30^{+0.18}_{-0.22}) \times 10^{-1}$	15	$62.10^{+0.86}_{-0.57}$	62^{+41}_{-30}
0.011	1^+	$1.30 \pm 0.16 \times 10^{-29}$	$1.13 \pm 0.06 \times 10^{-29}$	$7.5 \pm 3.0 \times 10^{-29}$	$1.50 \pm 0.08 \times 10^{-29}$	1.14×10^{-28}	$162.8^{+10.3}_{-6.3}$	600^{+230}_{-280}
0.213	2^-	$2.30 \pm 0.27 \times 10^{-2}$	$9.8 \pm 1.1 \times 10^{-3}$	$2.2 \pm 0.4 \times 10^{-2}$	$7.80^{+0.91}_{-0.88} \times 10^{-3}$	0.012	1069^{+193}_{-69}	1100
0.324	1^+	24.5 ± 1.8	$27.0^{+3.9}_{-1.5}$	23.1 ± 0.9	$36.7^{+5.6}_{-2.1}$	35.8	2206^{+99}_{-301}	2200

We have applied the modified R -matrix formalism briefly illustrated so far to the analysis of the $d^2\sigma/d\Omega_n dE_{\text{c.m.}}$ THM cross section. The experimental data in Fig. 6 were fitted using a modified R -matrix formula including all resonances marked in Fig. 4 and the effect of energy resolution (~ 100 keV full width at half-maximum). In the fitting procedure, the centroids were set to the energies reported in the literature [43] and, for normalization to direct data, the resonance parameters of the 324 keV resonance were adjusted to the ones in Ref. [15]. The best-fit curve is given by the middle black line in Fig. 6 with a χ^2 per number of degrees of freedom equal to 5.8 including the uncertainty on the evaluation of the nonresonant contribution, while the green band highlights the uncertainty range in the fitting parameters as constrained by the experimental error bars. The resonance parameters deduced by the fitting of the THM cross sections are listed in Table I, in particular, the partial widths Γ_p and Γ_{α_2} for the resonances above threshold, the ANC for the subthreshold resonance (along with the corresponding Γ_{α_2}), and the resonance strengths.

The THM parameters are compared with the partial widths and strengths in the literature, in particular, in Refs. [15,16]. Focusing on the results above the threshold, we have a very good agreement between the Γ_{p_0} and the Γ_{α_2} partial widths of the 324 keV resonance, both with the R -matrix analysis of Refs. [8,15] and the resonance strength in NACRE [16]. Regarding the 213 keV resonance, the use of the modified R -matrix analysis leads to partial widths in agreement with those in Refs. [8,15,30] and a resonance strength comparable to the one in Refs. [30,44]. This is due to the application of the more advanced modified R -matrix approach in the present work, which closely resembles the R -matrix analysis adopted in the direct data analysis, and which is much more accurate in the present case as the 213 keV resonance partly overlaps with the more intense 324 keV resonance due to the energy resolution. For the isolated 11 keV case we get a strength in very good agreement with the one in Ref. [11], supporting the accuracy of our result that has been confirmed by a completely different analysis approach, and confirming the reduction with respect to JUNA extrapolation (the strength calculated from the resonance parameters in Table II of Ref. [15] equals about 0.9×10^{-28} eV). Also the uncertainty on the 11 keV strength has been reduced thanks to the application of the modified R -matrix approach, giving evidence of the better accuracy this method makes it possible to achieve. Finally, using the formalism illustrated in the previous section, we have been able to

measure the ANC of the subthreshold -448 keV resonance; while the Γ_{α} perfectly agrees with the one in Table II of Ref. [15], the experimentally determined ANC equals about $0.9 \text{ fm}^{-1/2}$, to be compared with $15 \text{ fm}^{-1/2}$, about 15 times larger than our result even taking into account the $\sim 2\%$ uncertainty affecting the THM result. In the next section we will compare the THM based R -matrix calculation with the one from Ref. [15] to evaluate the possible consequences of our results.

V. THE $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ S FACTOR

To compare the present-work results with the extrapolation based on the underground measurement of Zhang *et al.* [8,15], the astrophysical S factor [22] for the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction was calculated using the multilevel, multichannel R -matrix code AZURE2 [45,46], which employs the alternative parametrization of Brune [47]. This parametrization allows the model parameters to be directly identified with the physically observable level properties, removing the need for explicit boundary condition specifications. The channel radii were fixed at $a_{p+^{19}\text{F}} = 5.136 \text{ fm}$ and $a_{\alpha_2+^{16}\text{O}} = 5.75 \text{ fm}$, consistent with Ref. [30].

The ^{20}Ne intermediate system was described by including all resonance levels relevant at astrophysical energies. The resonance parameters and the respective uncertainty range for the levels indicated in Table I are those obtained by the fitting of the THM cross sections, as described in the previous sections. For all other resonances within the energy region of interest, the partial widths were adopted from the direct measurements reported in Zhang *et al.* [15], and from the evaluation of deBoer *et al.* [30] for the remaining levels.

In order to propagate the uncertainties arising from resonance parameters onto the final S factor and reaction rate, a dedicated Monte Carlo code was developed, which uses AZURE2 to perform the actual R -matrix calculations. Each uncertain nuclear input quantity is described by a user-defined probability density function (PDF), and at each Monte Carlo iteration a random value is independently sampled from its respective PDF.

The sampled parameters are then injected directly into the AZURE2 input files, and AZURE2 is executed to compute the R -matrix cross section for that particular realization of the parameter space. All other model parameters are held fixed throughout. After $N_{\text{MC}} = 5000$ iterations, the resulting ensemble of cross sections is used to construct the uncertainty band on the S factor as a function of energy. In this scheme,

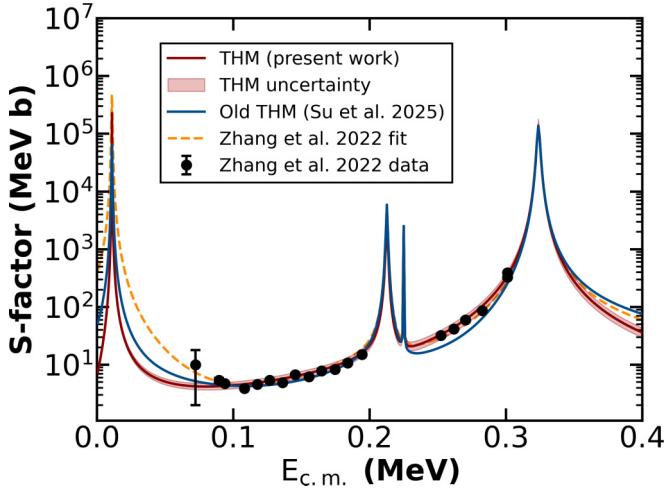


FIG. 7. Astrophysical S factor of the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction as a function of the center-of-mass energy $E_{\text{c.m.}}$. The present-work R -matrix calculation (AZURE2), using the resonance parameters deduced from the new modified R -matrix analysis, is shown as the solid red line, with the red band giving the associated uncertainty from the Monte Carlo propagation. It is compared with the previous THM-based R -matrix calculation of Su *et al.* [11] (blue line), the direct data of Zhang *et al.* [8] (black circles) and the corresponding R -matrix fit [15] (orange dashed line).

the Monte Carlo code is solely responsible for the statistical sampling, while AZURE2 acts exclusively as the physics engine for each forward calculation.

Figure 7 shows the comparison of the present-work R -matrix calculation (red solid line), including the resonance parameters deduced from the THM data, with the experimental data in Ref. [8] (black solid circles), the corresponding R -matrix fit [15] (orange dashed line), and the THM based R -matrix calculation in Ref. [11] (blue solid line). The latter was based on the resonance strengths deduced from the application of the simplified THM approach modified to analyze cross sections characterized by narrow resonances, without considering the contribution of the -448 keV subthreshold resonance in that preliminary work. The present-work R -matrix calculation based on the more advanced modified R -matrix approach shows a very good agreement with the direct data by Zhang *et al.* [8], while it is significantly lower than the corresponding R -matrix fitting below about 100 keV. This is a consequence of the present-work resonance parameters as measured through the application of the THM down to the astrophysical energies and in the subthreshold energy region, a feature unique to the THM [26]. The present-work results are also lower than the R -matrix calculation in Ref. [11] due to the inclusion of the interfering subthreshold resonance.

VI. THERMONUCLEAR REACTION RATES FOR $^{19}\text{F}+p$

The experimental data from the current measurement (see Table I) along with literature values from other resonances in both the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ and $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$ channels were used to calculate the thermonuclear reaction rates $N_A\langle\sigma v\rangle$,

which can be given using the following:

$$N_A\langle\sigma v\rangle = \frac{1.5399 \times 10^{11}}{T_9^{3/2}} \left(\frac{M_0 + M_1}{M_0 M_1} \right)^{3/2} \times \sum_i (\omega\gamma)_i e^{-11.605 E_i^R / T_9}, \quad (8)$$

where the masses $M_0 = M_{^{19}\text{F}}$ and $M_1 = M_p$, $\omega\gamma$ are the resonance strengths, T_9 is the temperature in GK, and E_i^R the resonance energy in MeV [48].

For broad resonances, we explicitly integrate the reaction rate, using a one-level Breit-Wigner formula for the cross section $\sigma(E)$:

$$N_A\langle\sigma v\rangle_{01} = \frac{3.7318 \times 10^{10}}{T_9^{3/2}} \sqrt{\frac{M_0 + M_1}{M_0 M_1}} \times \int_0^\infty E \sigma(E) e^{-11.605 E / T_9} dE. \quad (9)$$

For the purposes of the present work, we expanded the capabilities of the code RATESMC [49] to include the contribution of the three 1^+ interfering resonances ($E_{\text{c.m.}}^R = -0.448, 0.011, 0.324$ MeV).

The interference cross section for multiple resonances with the same spin-parity is given by

$$\sigma(E) = \sum_i \sigma_i(E) + 2 \sum_{i < j} \sqrt{\sigma_i(E) \sigma_j(E)} \cos(\delta_i(E) - \delta_j(E)) \quad (10)$$

with resonance phase shifts

$$\delta_i(E) = \arctan \left[\frac{\Gamma_i(E)}{2(E - E_i^R)} \right]. \quad (11)$$

RATESMC calculates both the constructive and destructive interference between the three resonances and propagates the uncertainties appropriately.

For both $^{19}\text{F}+p$ reactions we used the partial widths from the present study ($E_{\text{c.m.}}^R = -0.448, 0.011, 0.213, 0.324$ MeV). We also used the (p, α_2) resonance strengths for $E_{\text{c.m.}}^R = 0.791, 0.831$, and 0.886 MeV from Su *et al.* [11]. For the resonances at $E_{\text{c.m.}}^R = 0.225, 1.044$, and 1.068 MeV we used the data from Zhang *et al.* [8], and Angulo *et al.* [16]. To calculate the direct capture (DC) component of the rate, we used the prescription described in Williams *et al.* [50] using the value reported in Wiescher *et al.* [51] [$S(0) = 5.6$ keV b].

For the calculation of the rate at high temperatures, we are using the same matching technique with statistical (Hauser-Feshbach) model of nuclear reactions, as described in Refs. [48,52]. We find the matching temperatures at $T = 3.47$ and 3.59 GK for the (p, α) and (p, γ) reactions, respectively.

RATESMC is very well suited to properly propagate the uncertainties of the experimental results, and provide a statistically meaningful thermonuclear reaction rate. The code samples the experimental data using a Monte Carlo method according to their uncertainties and produces a lognormal distribution for the thermonuclear reaction rate, from which we can extract the associated uncertainty (f.u. = e^σ), where σ is the lognormal shape parameter.

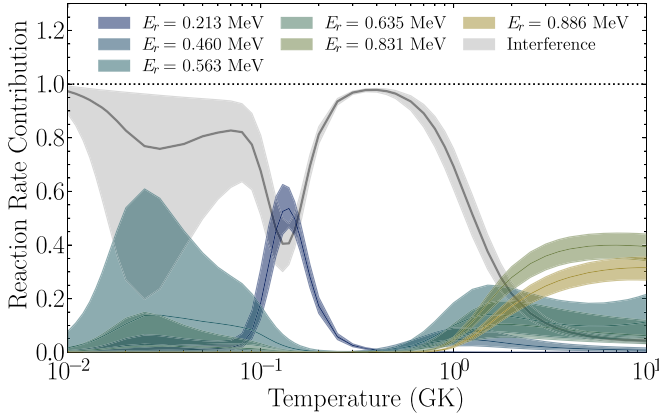


FIG. 8. Fractional contributions to the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ thermonuclear rate. “Interference” labels the combined contribution of the three interfering $J = 1^+$ resonances at $E_{\text{c.m.}}^R = -0.448, 0.011$, and 0.324 MeV.

In Fig. 8 we present the fractional contribution of each resonance to the total reaction rate of the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction. The interference between the three 1^+ resonances dominates the rate at temperatures $T < 1$ GK, with a smaller contribution from the resonance at $E_{\text{c.m.}}^R = 0.213$ MeV.

The uncertainty of our rate compared to the literature [16,43] is shown in Fig. 9. We find a lower rate compared to Zhang *et al.* [43] for $T < 0.1$ GK, and we agree with NACRE [16] within uncertainties.

We also calculated the ratio between the (p, γ) and $(p, \alpha\gamma)$ channels and compared it to three different datasets, namely [16] (NACRE), deBoer *et al.* [30], and [8,10] (JUNA). The results are shown in Fig. 10. All datasets agree within uncertainty at most temperatures $T < 1$ GK, except in the range $T = 0.1$ – 0.2 GK, where our rate and the one from

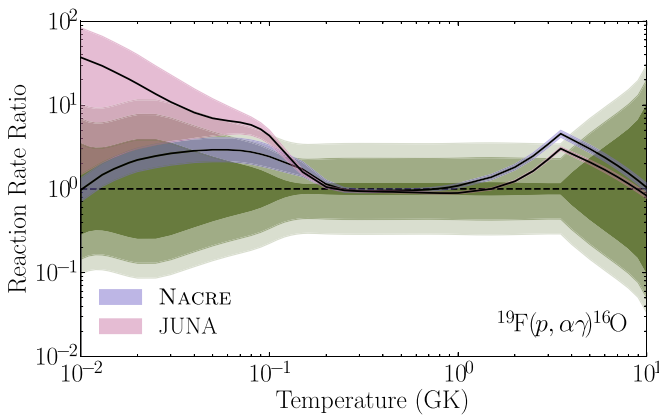


FIG. 9. Reaction rate uncertainties versus temperature derived in the present work (green shaded area). The three different shades refer to coverage probabilities of 68%, 90%, and 98%. The rates of Angulo *et al.* [16] (NACRE) and Zhang *et al.* [43] (JUNA) are also compared with the present work.

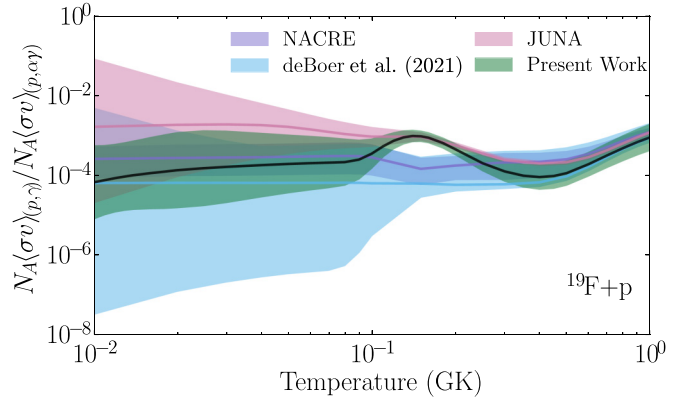


FIG. 10. Reaction rate ratio between $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$ and $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$. The rates of Angulo *et al.* [16] (NACRE), deBoer *et al.* [30], and Zhang *et al.* [10,8] (JUNA) are also compared with the present work.

JUNA disagree compared to NACRE and deBoer *et al.* [30]. This is caused by the inclusion of the newly discovered $E_{\text{c.m.}}^R = 0.225$ MeV resonance in the (p, γ) channel [10]. Both rates are presented in tabulated format in Tables II and III.

VII. CONCLUSION AND DISCUSSION

In this work, we re-evaluated the astrophysical impact of the $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction rate based on a data-driven modified R -matrix analysis of THM data, expanding upon the threshold investigation of Ref. [11]. Our findings challenge recent claims regarding threshold enhancements and reshape our understanding of fluorine nucleosynthesis across different stellar environments. In particular, despite being lower than the Ref. [15] evaluation, our revised rate confirms that the resonance provides an efficient destruction mechanism for ^{19}F in low-temperature, proton-rich stellar environments. This plays a crucial role in low-mass AGB stars undergoing HBB, where it depletes fluorine and influences surface abundance observations. A more detailed investigation of these astrophysical impacts within dedicated stellar models will be addressed in a forthcoming paper, with particular focus on low-temperature, proton-rich environments such as HBB [7]. Conversely, this rate revision holds limited relevance for massive stars, especially at low metallicity. In the core and shell environments where ^{19}F is efficiently synthesized, temperatures are higher than approximately 100 MK, where the contribution of these low-energy threshold structures fades, and the differences between the NACRE, Zhang *et al.* [15], and our newly derived rates become negligible.

Because the primary destruction channel of ^{19}F agrees with the NACRE standard within uncertainties, our results widen the deficit in the galactic fluorine budget. This reopens the “fluorine conundrum” and underscores a requirement for new or more efficient ^{19}F production channels within galactic chemical evolution models to balance net elemental yields.

TABLE II. Total thermonuclear reaction rates for $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$.

T (GK)	Low	Median	High	f.u.
0.001	7.604×10^{-66}	1.742×10^{-65}	6.159×10^{-65}	4.823
0.002	2.509×10^{-49}	3.841×10^{-48}	5.527×10^{-47}	9.641
0.003	1.414×10^{-40}	1.648×10^{-39}	3.283×10^{-39}	5.104
0.004	3.074×10^{-36}	8.310×10^{-35}	2.082×10^{-34}	6.755
0.005	2.633×10^{-33}	4.758×10^{-32}	4.131×10^{-31}	8.425
0.006	6.320×10^{-31}	3.843×10^{-30}	6.565×10^{-29}	7.860
0.007	4.698×10^{-29}	1.627×10^{-28}	2.447×10^{-27}	6.356
0.008	1.559×10^{-27}	5.296×10^{-27}	3.930×10^{-26}	4.981
0.009	3.050×10^{-26}	1.162×10^{-25}	4.128×10^{-25}	4.026
0.010	4.014×10^{-25}	1.747×10^{-24}	3.790×10^{-24}	3.453
0.011	3.792×10^{-24}	1.881×10^{-23}	3.319×10^{-23}	3.161
0.012	2.765×10^{-23}	1.581×10^{-22}	2.557×10^{-22}	3.058
0.013	1.637×10^{-22}	1.085×10^{-21}	1.674×10^{-21}	3.076
0.014	8.148×10^{-22}	6.162×10^{-21}	9.262×10^{-21}	3.165
0.015	3.529×10^{-21}	3.032×10^{-20}	4.466×10^{-20}	3.292
0.016	1.355×10^{-20}	1.297×10^{-19}	1.895×10^{-19}	3.432
0.018	1.499×10^{-19}	1.723×10^{-18}	2.486×10^{-18}	3.692
0.020	1.254×10^{-18}	1.615×10^{-17}	2.317×10^{-17}	3.867
0.025	1.109×10^{-16}	1.493×10^{-15}	2.073×10^{-15}	3.860
0.030	4.281×10^{-15}	4.753×10^{-14}	6.511×10^{-14}	3.510
0.040	1.092×10^{-12}	7.560×10^{-12}	1.026×10^{-11}	2.822
0.050	5.840×10^{-11}	2.831×10^{-10}	3.864×10^{-10}	2.397
0.060	1.217×10^{-9}	4.559×10^{-9}	6.277×10^{-9}	2.132
0.070	1.391×10^{-8}	4.277×10^{-8}	5.916×10^{-8}	1.949
0.080	1.072×10^{-7}	2.791×10^{-7}	3.849×10^{-7}	1.801
0.090	6.556×10^{-7}	1.442×10^{-6}	1.951×10^{-6}	1.650
0.100	3.570×10^{-6}	6.482×10^{-6}	8.522×10^{-6}	1.489
0.110	1.776×10^{-5}	2.674×10^{-5}	3.409×10^{-5}	1.348
0.120	7.893×10^{-5}	1.042×10^{-4}	1.277×10^{-4}	1.249
0.130	3.102×10^{-4}	3.783×10^{-4}	4.453×10^{-4}	1.189
0.140	1.089×10^{-3}	1.264×10^{-3}	1.454×10^{-3}	1.153
0.150	3.474×10^{-3}	3.948×10^{-3}	4.474×10^{-3}	1.134
0.160	1.025×10^{-2}	1.154×10^{-2}	1.302×10^{-2}	1.128
0.180	7.211×10^{-2}	8.180×10^{-2}	9.257×10^{-2}	1.135
0.200	3.899×10^{-1}	4.472×10^{-1}	5.116×10^{-1}	1.147
0.250	9.716×10^0	1.126×10^1	1.301×10^1	1.159
0.300	8.596×10^1	9.997×10^1	1.157×10^2	1.161
0.350	4.029×10^2	4.680×10^2	5.409×10^2	1.160
0.400	1.260×10^3	1.462×10^3	1.690×10^3	1.159
0.450	3.018×10^3	3.497×10^3	4.042×10^3	1.158
0.500	6.006×10^3	6.957×10^3	8.027×10^3	1.157
0.600	1.662×10^4	1.921×10^4	2.216×10^4	1.155
0.700	3.410×10^4	3.937×10^4	4.531×10^4	1.154
0.800	5.864×10^4	6.769×10^4	7.794×10^4	1.156
0.900	9.045×10^4	1.044×10^5	1.206×10^5	1.160
1.000	1.302×10^5	1.500×10^5	1.744×10^5	1.166
1.250	2.660×10^5	3.064×10^5	3.613×10^5	1.178
1.500	4.593×10^5	5.262×10^5	6.229×10^5	1.180
1.750	7.036×10^5	8.010×10^5	9.469×10^5	1.176
2.000	9.824×10^5	1.113×10^6	1.309×10^6	1.169
2.500	1.571×10^6	1.763×10^6	2.050×10^6	1.157
3.000	2.107×10^6	2.349×10^6	2.703×10^6	1.147
3.500	2.600×10^6	2.894×10^6	3.422×10^6	1.148
4.000	4.242×10^6	5.069×10^6	9.431×10^6	1.528
5.000	8.651×10^6	1.212×10^7	3.898×10^7	2.309
6.000	1.381×10^7	2.335×10^7	1.068×10^8	3.133
7.000	1.837×10^7	3.922×10^7	2.326×10^8	4.033
8.000	2.070×10^7	5.990×10^7	4.365×10^8	5.090
9.000	1.903×10^7	8.542×10^7	7.384×10^8	6.566
10.000	1.157×10^7	1.157×10^8	1.157×10^9	10.000

TABLE III. Total thermonuclear reaction rates for $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$.

T (GK)	Low	Median	High	f.u.
0.001	2.019×10^{-70}	4.941×10^{-70}	1.459×10^{-69}	3.100
0.002	5.113×10^{-54}	3.246×10^{-53}	4.483×10^{-52}	8.153
0.003	1.511×10^{-45}	1.057×10^{-44}	6.586×10^{-44}	6.490
0.004	5.395×10^{-41}	3.985×10^{-40}	3.008×10^{-39}	7.024
0.005	6.622×10^{-38}	3.165×10^{-37}	2.955×10^{-36}	6.577
0.006	1.948×10^{-35}	5.869×10^{-35}	3.797×10^{-34}	4.991
0.007	1.961×10^{-33}	5.263×10^{-33}	2.027×10^{-32}	3.682
0.008	9.856×10^{-32}	2.406×10^{-31}	6.599×10^{-31}	2.931
0.009	2.712×10^{-30}	6.358×10^{-30}	1.574×10^{-29}	2.561
0.010	4.764×10^{-29}	1.122×10^{-28}	2.597×10^{-28}	2.391
0.011	6.030×10^{-28}	1.378×10^{-27}	3.178×10^{-27}	2.316
0.012	5.552×10^{-27}	1.302×10^{-26}	2.905×10^{-26}	2.282
0.013	4.147×10^{-26}	9.810×10^{-26}	2.211×10^{-25}	2.266
0.014	2.568×10^{-25}	6.033×10^{-25}	1.362×10^{-24}	2.258
0.015	1.350×10^{-24}	3.139×10^{-24}	7.213×10^{-24}	2.253
0.016	6.145×10^{-24}	1.422×10^{-23}	3.290×10^{-23}	2.249
0.018	9.068×10^{-23}	2.061×10^{-22}	4.855×10^{-22}	2.244
0.020	9.311×10^{-22}	2.100×10^{-21}	4.913×10^{-21}	2.240
0.025	9.848×10^{-20}	2.185×10^{-19}	5.125×10^{-19}	2.231
0.030	3.437×10^{-18}	7.493×10^{-18}	1.786×10^{-17}	2.224
0.040	6.162×10^{-16}	1.318×10^{-15}	3.173×10^{-15}	2.210
0.050	2.518×10^{-14}	5.281×10^{-14}	1.270×10^{-13}	2.198
0.060	4.289×10^{-13}	8.905×10^{-13}	2.120×10^{-12}	2.185
0.070	4.126×10^{-12}	8.611×10^{-12}	2.025×10^{-11}	2.166
0.080	2.903×10^{-11}	5.787×10^{-11}	1.334×10^{-10}	2.089
0.090	2.040×10^{-10}	3.458×10^{-10}	7.077×10^{-10}	1.849
0.100	1.583×10^{-09}	2.193×10^{-09}	3.550×10^{-09}	1.547
0.110	1.086×10^{-08}	1.389×10^{-08}	1.886×10^{-08}	1.352
0.120	6.048×10^{-08}	7.437×10^{-08}	9.353×10^{-08}	1.261
0.130	2.706×10^{-07}	3.263×10^{-07}	3.944×10^{-07}	1.221
0.140	9.949×10^{-07}	1.184×10^{-06}	1.412×10^{-06}	1.199
0.150	3.086×10^{-06}	3.630×10^{-06}	4.290×10^{-06}	1.185
0.160	8.363×10^{-06}	9.760×10^{-06}	1.145×10^{-05}	1.176
0.180	4.391×10^{-05}	5.111×10^{-05}	5.994×10^{-05}	1.170
0.200	1.668×10^{-04}	1.931×10^{-04}	2.300×10^{-04}	1.189
0.250	1.841×10^{-03}	2.192×10^{-03}	2.976×10^{-03}	1.328
0.300	9.205×10^{-03}	1.214×10^{-02}	1.920×10^{-02}	1.506
0.350	3.056×10^{-02}	4.439×10^{-02}	7.814×10^{-02}	1.652
0.400	8.349×10^{-02}	1.282×10^{-01}	2.344×10^{-01}	1.732
0.450	2.081×10^{-01}	3.259×10^{-01}	5.993×10^{-01}	1.744
0.500	4.904×10^{-01}	7.632×10^{-01}	1.386×10^0	1.721
0.600	2.169×10^0	3.540×10^0	6.151×10^0	1.699
0.700	6.986×10^0	1.210×10^1	2.173×10^1	1.730
0.800	1.851×10^1	3.176×10^1	5.802×10^1	1.769
0.900	3.949×10^1	6.934×10^1	1.266×10^2	1.797
1.000	7.399×10^1	1.307×10^2	2.405×10^2	1.812
1.250	2.236×10^2	3.968×10^2	7.412×10^2	1.813
1.500	4.657×10^2	8.169×10^2	1.516×10^3	1.789
1.750	7.978×10^2	1.355×10^3	2.479×10^3	1.754
2.000	1.190×10^3	1.959×10^3	3.515×10^3	1.716
2.500	2.051×10^3	3.213×10^3	5.523×10^3	1.642
3.000	2.941×10^3	4.408×10^3	7.300×10^3	1.578
3.500	3.775×10^3	5.439×10^3	8.735×10^3	1.526
4.000	4.306×10^3	6.515×10^3	1.384×10^4	1.819
5.000	5.016×10^3	8.838×10^3	3.038×10^4	2.599
6.000	5.413×10^3	1.142×10^4	5.424×10^4	3.430
7.000	5.498×10^3	1.445×10^4	8.760×10^4	4.345
8.000	5.226×10^3	1.821×10^4	1.343×10^5	5.430
9.000	4.461×10^3	2.305×10^4	2.003×10^5	6.928
10.000	2.934×10^3	2.934×10^4	2.934×10^5	10.000

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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