Nuclear structure properties of astrophysical importance for ^{19}Ne above the proton threshold energy

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Knowledge of the ^{18}F$(p,\alpha)^{15}$O and ^{18}F$(p,\gamma)^{19}$Ne astrophysical reaction rates are important to understand γ-ray emission from nova explosions and heavy-element production in x-ray bursts. The rates for these reactions have been uncertain, in part due to a lack of a comprehensive examination of the available structure information in the compound nucleus ^{19}Ne. We have examined the latest experimental measurements with radioactive and stable beams, collected all the structure information in the nucleus ^{19}Ne and its mirror ^{19}F, and made estimates of unmeasured ^{19}Ne nuclear-level parameters. These parameters will be useful for future reaction rate calculations.

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I. INTRODUCTION

Hydrogen is burned explosively in stellar events such as novae [1], x-ray bursts [2], x-ray pulsars [3], supernovae [4], and possibly in other exotic astrophysical environments such as accretion disks around black holes [5]. Temperatures in these environments range from 10^7 to above 10^9 K, and densities from 10^2 to 10^6 g/cm^3. In such sites, nuclear reactions can occur so rapidly that proton capture on radioactive isotopes such as ^{14}O, ^{15}O, ^{17}F, ^{18}F, and others can occur before these isotopes have a chance to decay. Knowledge of proton-induced reactions on radioactive isotopes can play an important role in determining the isotopes synthesized and energy generated in these environments.

In particular, current uncertainties in the ^{18}F$(p,\alpha)^{15}$O and ^{18}F$(p,\gamma)^{19}$Ne stellar reaction rates result in a significant variation in predictions of the amount of ^{18}F in the nova envelope immediately after the explosion, by up to a factor of $\sim$300 [6]. The radioactive decay of this nucleus is the strongest observable γ ray source in novae during the first few hours after the explosion [7]. The observation of γ rays from nova ejecta are thought to provide a rather direct test of the explosion models [8,9], which currently fail to reproduce some global properties such as the total ejected mass [1]. It is difficult to say whether γ-ray observations of ^{18}F in novae are viable without a more precise value of the rates of these proton-induced reactions on ^{18}F.

Knowledge of the proton-induced reactions on ^{18}F are also important for understanding heavy-element production in the extreme temperatures and densities characteristic of x-ray bursts. In these conditions, there may be a transition to heavy element production via the reaction sequence ^{18}F$(p,\gamma)^{19}$Ne$(p,\gamma)^{20}$Na$(p,\gamma)^{21}$Mg...(such as, e.g., Ref. [10]). Whether there is a significant flow through this reaction sequence in x-ray bursts depends sensitively on the competition between the ^{18}F$(p,\gamma)^{19}$Ne and ^{18}F$(p,\alpha)^{15}$O reactions, and thus we need to know their relative rates at high temperatures to realistically model these violent explosions. The rates are determined by the structure properties of the levels in the compound nucleus ^{19}Ne.

In early work, Wiescher and Kettner [11] had made a detailed estimate of the ^{18}F + p reaction rates. After beams of radioactive ^{18}F nuclei became available, measurements were made by Rehm *et al.* in 1995, 1996, and 1997 [12–14], Coszach *et al.* in 1995 [15], and Graulich *et al.* in 1997 [16]. Indirect studies with stable beams were also made by Utku *et al.* in 1998 [17] and Butt *et al.* in 1998 [18]. New rate estimates were made by Utku *et al.* in 1998 [17] and later updated by Coc *et al.* [6] in 2000. In recent years, a number of additional higher precision measurements with radioactive beams have been performed to understand the rates of proton induced reactions on ^{18}F [19–27].

Since an earlier publication of ^{19}Ne properties by Shu *et al.* [28], an updated reaction rate calculation for temperatures above 1 GK was performed by Bardayan *et al.* [26,27]. This calculation included the new observed level at the 1009 keV resonance and the new partial proton widths for the 8-, 38-, and 287-keV resonances, as constrained by the lower energy resonances in the ^{18}F$(d,p)^{19}$F measurements [19–23]. The most recent calculation of the (p,α) rate at nova temperatures 0.1–0.4 GK [22,23] reports a significantly lower rate. Finally, in a recent publication [29], the reanalyzed ^{15}N$(\alpha,\alpha)^{15}$N cross sections of Ref. [30] showed that the energies and widths for the broad ^{19}F levels are different than previously thought and that the level observed in Ref. [18] is most likely not the assigned analog for the 665-keV resonance.

A brief letter of this work was published in 2003 [28], which included a collection of some of the level information for ^{19}Ne and the estimated properties of the missing levels that were unmeasured but have analog states in the mirror nucleus ^{19}F. In this article, we update and expand on this previous study. The structure information of these levels can be used to determine the best rates and uncertainties for the ^{18}F$(p,\alpha)^{15}$O and ^{18}F$(p,\gamma)^{19}$Ne reactions.

II. PARTIAL WIDTHS

The key ingredients to determine a reaction rate are the resonance energy and the resonance strength $\omega\gamma$. The resonance strength is determined in part by the partial widths, as shown in the equation below [31]

$$\omega\gamma = \frac{2J_r}{(2J_1+1)(2J_2+1)}\frac{\Gamma_{\rm in}\Gamma_{\rm out}}{\Gamma_t}, \quad (1)$$

where J_r, J_1, J_2 are, respectively, the spins of the excited state in the compound nucleus, incident, and target particles. $\Gamma_{\rm in}$ and $\Gamma_{\rm out}$ are the partial widths of excited state for the entrance and exit channels, and Γ_t is the total width $\Gamma_t = \Gamma_p + \Gamma_\alpha + \Gamma_\gamma + \cdots$. In the following subsections, we discuss the partial widths (Γ_p, Γ_γ, and Γ_α) for ^{19}Ne in detail.

A. Partial gamma width (Γ_γ)

When possible, the γ widths in ^{19}Ne are adopted with appropriate corrections from measurements of widths of analog states in ^{19}F. The ^{19}F γ widths are mostly deduced from the ^{15}N$(\alpha,\gamma)^{19}$F resonance strength given in Table 19.13 of Ref. [32]. The ^{19}Ne partial γ widths are corrected for the phase space available for electromagnetic decays and the reduced transition probablity; B(EL) and B(ML) [33]. The former is the energy dependence of corresponding transitions available for decay with specific energies which is proportional to E_γ^{2L+1}, where L is the multipolarity of the transition. The latter correction describes the transition probability from initial to final state via emission of a photon of electric (E) or magnetic (M) type with multipolarity L [34]. The correction factor for the phase-space and reduced transition probability can then be expressed by

$$(\Gamma_\gamma)_{^{19}\rm Ne} = \left[\frac{E_\gamma(^{19}\rm Ne)}{E_\gamma(^{19}\rm F)}\right]^{(2L+1)}\left[\frac{B(L)(^{19}\rm Ne)}{B(L)(^{19}\rm F)}\right](\Gamma_\gamma)_{^{19}\rm F}. \quad (2)$$

In cases where sufficient information on the γ decays of mirror states of ^{19}F are available, E_γ of the decays in ^{19}Ne were deduced by the level energy difference of the ^{19}Ne that are analog to the initial and final transition levels in the mirror nucleus ^{19}F (refer to Table 19.33 in Ref. [32]). E_γ was then corrected for the recoil energy (E_γ^2/2Mc^2) before applying the correction factor in Eq. (2). The weighted-average phase-space correction factor was about 0.9.

Most of the γ-ray transitions in this work are of $\Delta T = 0$, $E1$ transitions or $M1$ transitions. Refering to Rule 3 in Ref. [35], the reduced transition probabilty is equal to the mirror for the $E1$ transitions and considering Rule 2 [35], the $M1$ transitions in ^{19}Ne for $\Delta T = 1$ are also equal. For the $\Delta T = 0$, $M1$ transition in mirror nuclei (see Quasi Rule 5 in Ref. [35]), the reduced width is approximately equal for moderately strong transitions. In our work, we assume the reduced transition probabilty to be equal for the isospin mirror nuclei because isovector contribution dominates in the the $M1$ transitions, whereas in the $E2$ transition, the isoscalar contribution dominates [36]. The partial γ widths of states in ^{19}Ne ranged from 0.1 to 6 eV with uncertainties of 50% due to the correction from analog nuclei that includes the fact that assumption of equality in the reduced transition probabilty produces an additional uncertainty. Totally unconstrained γ widths (e.g., for the 26-, 827-, 842-, and 1120-keV resonances) are assumed to be 1 ± 1 eV from systematics.

B. Partial alpha width (Γ_α)

The resonance strength depends on Γ_t, which is dominated by the α width for most ^{19}Ne levels of interest. Hence, the uncertainties for α widths must be considered in the strength uncertainties. The partial width for a particle can be expressed in terms of the reduced width obtained within the framework of a nuclear oscillator model [31]

$$\Gamma_l(E) = \frac{2\hbar c}{R_n}\left[\frac{2E}{\mu c^2}\right]^{\frac{1}{2}} P_l(E, R_n)\theta_l^2, \quad (3)$$

where Γ_l is the partial width, R_n is the radius, θ_l^2 is the reduced width, E is the excitation energy, and P_l is the penetration factor given by

$$P_l = \left[\frac{1}{F_l^2 + G_l^2}\right], \quad (4)$$

where F_l and G_l are the regular and irregular Coulomb wave functions, respectively. In the present work, α widths are scaled from ^{19}F whenever possible by assuming the analog states have the same reduced α widths, θ_α^2, and then correcting for the different Coulomb barrier penetrations [17],

$$(\Gamma_\alpha)_{^{19}\rm Ne} = \left[\frac{\rho}{F_l^2 + G_l^2}\right]_{^{15}\rm O+\alpha}\left[\frac{F_l^2 + G_l^2}{\rho}\right]_{^{15}\rm N+\alpha}(\Gamma_\alpha)_{^{19}\rm F}, \quad (5)$$

where

$$\rho = \left[\frac{\sqrt{(2\mu c^2 E)}}{\hbar c}\right] R_n. \quad (6)$$

The uncertainties of the ^{19}F α widths are assumed to be 50% based on the analysis in Ref. [37]. The scaling from ^{19}F to ^{19}Ne introduces an additional uncertainty of 70% for resonances with reduced widths larger than 0.01 and up to a factor of 5 for smaller-width resonances. In cases where Γ_α information on the analog nucleus ^{19}F does not exist, a mean value of reduced α width of 0.05 ± 0.04 is assumed from systematics, and the corresponding Γ_α is calculated from Eq. (3).

C. Partial proton width (Γ_p)

An alternative technique was used to determine the Γ_p, which was first introduced by Schiffer [38], elaborated by Iliadis [39], and recently applied by Kozub *et al.* [22,23]. For unbound states it is possible to extract the partial proton width, Γ_p, via the expression

$$\Gamma_p = C^2 S \Gamma_{\rm sp}, \quad (7)$$

where C^2 is the isospin Clebsch-Gordon coefficient (= 1 here), S is the single-particle spectroscopic factor, and $\Gamma_{\rm sp}$ is the proton width for a pure single-particle state. The $\Gamma_{\rm sp}$ can be calculated using the technique of Vincent and Fortune [40] which has been incorporated into the DWUCK4 DWBA (Distorted Wave Born Approximation) code [41]. The calculation involves using a Woods-Saxon well potential, having the same radius and diffuseness parameters used in the neutron bound states. This technique, with the assumption that $S_n = S_p$, was used to determine the partial proton widths

($\Gamma_p = S_n \Gamma_{sp}$) in the (d, p) measurement by Kozub *et al.* [22,23]. The advantage of this technique is that the calculated proton width is relatively independent of potential parameters, provided that same parameters are used to calculate the S_n and Γ_{sp}.

For levels where neither the partial proton width of ^{19}Ne nor spectroscopic factors for the mirror nuclei ^{19}F were directly measured, the unknown reduced proton-widths are assumed to be 0.1 and 0.01, respectively, for the positive and negative parity resonances [6,11,17,42] with uncertainties of 100%.

III. ^{19}Ne LEVEL INFORMATION

Assuming isospin symmetry with the mirror nucleus ^{19}F, there should be ~30 levels in ^{19}Ne within the excitation energy range of $E_x = 6.411 - 8.100$ MeV, corresponding to stellar burning over the temperature range of 0.03–3.0 GK, appropriate for novae and x-ray bursts. Nineteen levels have been found, and the others have not been observed. Figure 1 shows a level scheme of the ^{19}F$-^{19}$Ne mirror pair and Table I lists the resonance parameters.

We discuss the levels in order of increasing excitation energy, below. The unknown excitation energies for missing levels are assumed by scaling from their analog states or simply by assuming the energy shifts to be 50 ± 30 keV between the pair of analog states; the shifts and uncertainties being obtained by systematic analysis.

Level 1: $E_x = 6419 \pm 6$ keV, $E_r = 8$ keV, ($J^\pi = \frac{3}{2}^+$). The first state, with an excitation energy of 6419±6 keV (corresponding to a ^{18}F + p resonance at $E_r = 8$ keV) does not have a measured spin or width but is taken to be the analog of the ^{19}F level at $E_x(^{19}\mathrm{F}) = 6497$ keV [6,17,19–21,25,28] with a spin-parity of $J^\pi = \frac{3}{2}^+$. This analog connection is made because of the similarity in their relative excitation energies and the relatively small energy shift expected (~78 keV). In de Séréville's ^{18}F$(d, p)^{19}$F work [19–21], the 6497- and 6528-keV ^{19}F levels were unresolved and the sum of the two spectroscopic factors for the $E_x = 6.5$ MeV group was measured to be about 0.21. More recently, in a separate ^{18}F$(d, p)^{19}$F measurement [22,23], neutron spectroscopic factors of 0.12 and 0.13 were extracted for the $2s_{\frac{1}{2}}$ and the $1d_{\frac{3}{2}}$ transfers, respectively, for the 6497-keV state. Consequently, assuming $S_n = S_p$, the proton widths were deduced by calculating the proton single-particle widths using a Woods-Saxon well with the same radius and diffuseness parameters as used in the neutron bound states. Hence, we adopted $\Gamma_p = (2.2 \pm 0.4) \times 10^{-37}$ keV.

Bardayan *et al.* [29] reanalyzed ^{15}N$(\alpha, \alpha)^{15}$N data, and an upper limit was set on the width of the resonance of $\Gamma_\alpha <$ 0.5 keV. In the present work, using the upper limit of the α width in ^{19}F, we scaled the α width in ^{19}Ne to be less than 0.55 keV and so adopted a value of 0.27 ± 0.27 keV. The γ width for ^{19}F, $\Gamma_\gamma = 0.85 \pm 0.15$ eV, is determined from the ^{15}N$(\alpha, \gamma)^{19}$F resonance strength as reported by Tilley *et al.* [32]. The γ width after correcting for the phase space was then deduced for ^{19}Ne to be 0.77 ± 0.41 eV.

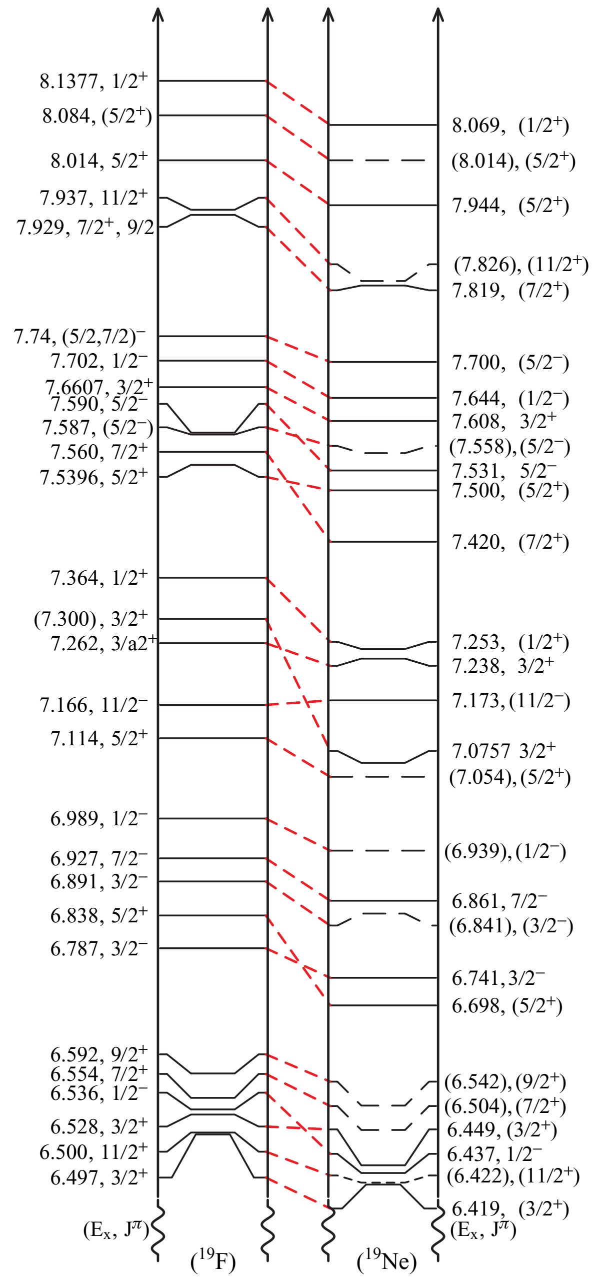

FIG. 1. (Color online) Level scheme of ^{19}F$-^{19}$Ne. The excitation energy in parenthesis stands for missing levels in ^{19}Ne. The spins and parities in parenthesis in ^{19}Ne are taken from the analog states in ^{19}F. The dashed lines connect proposed analog states.

Level 2: ($E_x = 6422 \pm 30$ keV), $E_r = 11$ keV, ($J^\pi = \frac{11}{2}^+$). The second state is assumed to be at $E_x = 6422 \pm 30$ keV (corresponding to $E_r = 11$ keV) and is taken to be the analog of the ^{19}F level at $E_x = 6500$ keV with a spin-parity of $J^\pi = \frac{11}{2}^+$. The excitation energy is scaled from the analog state and the uncertainty was assumed. Because the state has positive parity, θ_p^2 is assumed to be 0.1 ± 0.1 corresponding to $\Gamma_p = (1.8 \pm 1.8) \times 10^{-38}$ keV. The ^{19}Ne α-width, which is >4 eV, is scaled from the ^{19}F alpha width ($\Gamma_\alpha \geqslant 2.4$ eV) [32,43] and the reduced alpha width ($\theta_\alpha^2 \geqslant 0.0082$ [43]). As discussed in Sec. II B, the scaling uncertainty could be as much as 500%

TABLE I. Resonance parameters in ^{19}Ne vs ^{19}F.

^{19}F					^{19}Ne								Ref.
E_x (MeV)	J^π	Γ_γ (eV)	Γ_α (keV)	Γ_{tot} (keV)	No	E_x [a] (MeV)	E_r (keV)	J^π [b]	Γ_γ [c] (eV)	θ_p^2 [d]	Γ_p [d] (keV)	Γ_α [e] (keV)	
6.497	$\frac{3}{2}^+$	0.85	<0.5	<0.5	1	6.419	8(6)	$(\frac{3}{2}^+)$	0.77(41)	0.12(2)	2.2(4)E−37	0.27(27)	[17,19–23,29,32]
6.500	$\frac{11}{2}^+$	0.38	>2.4 eV	>2.4 eV	2	(6.422)	11(30)	$(\frac{11}{2}^+)$	0.35(18)	(0.1)	1.8(18)E−38	20(14)E−3	[32]
6.536	$\frac{1}{2}^-$	–	245	245	3	6.437	26(9)	$\frac{1}{2}^-$	[1(1)]	0.01	1.1(11)E−20	220(20) (M)	[6,17,29,32]
6.528	$\frac{3}{2}^+$	1.2	1.2	1.2	4	6.449	38(7)	$(\frac{3}{2}^+)$	1.1(6)	0.03(3)	4(4)E−15	1.3(10)	[17,20–22,25,29,32]
6.554	$\frac{7}{2}^+$	0.16	1.6	1.6	5	(6.504)	93(30)	$(\frac{7}{2}^+)$	0.14(8)	(0.1)	4.6(46)E−10	0.4(4)	[29,32]
6.592	$\frac{9}{2}^+$	0.33	7.3 eV	7.6 eV	6	(6.542)	131(30)	$(\frac{9}{2}^+)$	0.30(16)	(0.1)	2.7(27)E−12	1.3(11)E−2	[32]
6.838	$\frac{5}{2}^+$	0.33	1.2	1.2	7	6.698	287(6)	$(\frac{5}{2}^+)$	0.29(15)	0.01	1.2(12)E−5	1.2(10)	[17,22,25,29,32]
6.787	$\frac{3}{2}^-$	5.5	4.3	4.3	8	6.741	330(6)	$\frac{3}{2}^-$	5.0(26)	–	2.22(69)E−3	5.2(37)	[17,25,29,32]
6.891	$\frac{3}{2}^-$	3.1	22	22	9	(6.841)	430(30)	$(\frac{3}{2}^-)$	2.8(15)	(0.01)	9.7(97)E−3	25(18)	[17,29,32]
6.927	$\frac{7}{2}^-$	2.4	0.9	0.9	10	6.861	450(6)	$\frac{7}{2}^-$	2.3(12)	(0.01)	1.1(11)E−5	1.2(0.9)	[17,29,32,44]
6.989	$\frac{1}{2}^-$	–	96	96	11	(6.939)	528(30)	$(\frac{1}{2}^-)$	[1(1)]	(0.01)	3.4(34)E−2	99(69)	[29,32]
7.114	$\frac{5}{2}^+$	–	25	25	12	(7.054)	643(30)	$(\frac{5}{2}^+)$	[1(1)]	(0.1)	4.7(47)E−2	29(25)	[29,32]
(7.300)	$\frac{3}{2}^+$	–	–	–	13	7.0757	664.7(16)	$\frac{3}{2}^+$	[1(1)]	–	15.2(1)	23.8(12) (M)	[18,24,29]
7.166	$\frac{11}{2}^-$	0.17	6.7E−3	6.9 eV	14	7.173	762(5)	$(\frac{11}{2}^-)$	0.15(8)	(0.01)	9.8(98)E−8	1.2(10)E−2	[17,32]
7.262	$\frac{3}{2}^+$	–	–	<6	15	7.238	827(6)	$\frac{3}{2}^+$	[1(1)]	–	0.35(35)	6.0(52)	[17,26,29,32,48]
7.364	$\frac{1}{2}^+$	–	–	–	16	7.253	842(10)	$(\frac{1}{2}^+)$	[1(1)]	–	0.2(2)	23(20)	[17,26,32,48]
7.560	$\frac{7}{2}^+$	–	–	<90	17	7.420	1009(14)	$(\frac{7}{2}^+)$	[1(1)]	–	27(4)	71(11)(M)	[26]
7.5396	$\frac{5}{2}^+$	5.8	–	.16±.05	18	7.500	1089(9)	$(\frac{5}{2}^+)$	5.5(29)	–	1.25(125)	0.24(24)(M)	[17,26,32]
7.590	$\frac{5}{2}^-$	–	–	–	19	7.531	1120(11)	$\frac{5}{2}^-$	[1(1)]	–	10(6)	21(11) (M)	[17,26,32]
7.587	$(\frac{5}{2}^-)$	–	Γ_{Lab} <50	–	20	(7.558)	1147(30)	$(\frac{5}{2}^-)$	[1(1)]	(0.01)	1.3(13)	21(18)	[32]
7.6607	$\frac{3}{2}^+$	1.9	–	2.2±.7 eV	21	7.608	1197(11)	$\frac{3}{2}^+$	1.8(10)	–	2(1)	43(15)	[17,32]
7.702	$\frac{1}{2}^-$	–	–	<30	22	7.644	1233(12)	$(\frac{1}{2}^-)$	[1(1)]	–	27(10)	16(6) (M)	[17,32]
7.74	$(\frac{5}{2},\frac{7}{2})^-$	–	–	<6	23	7.700	1289(10)	$(\frac{5}{2}^-)$	[1(1)]	(0.01)	1.7(17)	6.2(53)	[32]
7.929	$\frac{7}{2}^+,\frac{9}{2}$	0.58	–	–	24	7.819	1408(11)	$(\frac{7}{2}^+)$	0.53(28)	–	18(13)	4(3) (M)	[17,32]
7.937	$\frac{11}{2}^+$	0.51	–	–	25	(7.826)	1415(30)	$(\frac{11}{2}^+)$	0.47(25)	(0.1)	6.4(64)E−3	1.7(15)	[32]
8.014	$\frac{5}{2}^+$	–	–	–	26	7.944	1533(15)	$(\frac{5}{2}^+)$	[1(1)]	0.15(3)	5.9(12)	26(22)	[32,52]
8.084	$(\frac{5}{2}^+)$	–	–	$\leqslant 3$	27	(8.014)	1603(30)	$(\frac{5}{2}^+)$	[1(1)]	(0.1)	4.8(48)	2.9(22)	[32]
8.1377	$\frac{1}{2}^+$	–	–	$\leqslant 0.3$	28	8.069	1658(12)	$(\frac{1}{2}^+)$	1.17(59)	0.32(6)	–	0.22(19)	[32,52]

[a]Parenthesized E_x stand for missing levels.
[b]Parenthesized J^π are taken from ^{19}F; others are measured.
[c]γ widths in brackets are assumed; others are taken from analog states, no measured data.
[d]Parenthesized θ_p^2 are assumed and the corresponding p widths are calculated. Other p widths or θ_p^2 are measured or deduced from measurements of the resonance or its mirror analog.
[e]Measured α widths are shown with M; others are scaled from ^{19}F or assumed.

when the reduced width is very small (less than 0.01). For this level, we have adopted $\Gamma_\alpha = 20 \pm 14$ eV. The γ width of ^{19}F is deduced to be 0.38 ± 0.07 eV based on the ^{15}N$(\alpha,\gamma)^{19}$F resonance strength as reported in Tilley *et al.* [32]. The ^{19}Ne γ width is then $\Gamma_\gamma = 0.35 \pm 0.18$ eV after correcting for the phase-space factor of 0.91.

Level 3: $E_x = 6437 \pm 9$ keV, $E_r = 26$ keV, $J^\pi = \frac{1}{2}^-$. The third state, with an excitation energy of 6437 $\pm$ 9 keV [17] (corresponding to $E_r = 26$ keV), is taken to be the analog of the $E_x = 6536$ keV ($J^\pi = \frac{1}{2}^-$) level in ^{19}F based on their similarities in excitation energies and widths ($\Gamma_\alpha = 245$ keV and $\Gamma_\alpha = 220$ keV for ^{19}F [29] and ^{19}Ne [17], respectively). In a previous publication [28], this state, (^{19}Ne) was taken to be the analog state of a ^{19}F state at $E_x = 6429$ keV. However, recent extensive R-matrix analyses [29] of ^{15}N(α,α) data reported the best fit to be at $E_x = 6536$ keV in ^{19}F. It had also been previously reported [28] that $\Gamma_p = (2.8^{+5.6}_{-1.9}) \times 10^{-20}$ keV, which assumed the reduced p width to be $\theta_p^2 = 0.01^{+0.02}_{-0.005}$. However, the latest work by Kozub *et al.* [22] uses a Woods-Saxon potential to get $\Gamma_p = (1.1 \pm 1.1) \times 10^{-20}$ keV. The advantage of using this technique (see Sec. II C) to determine the Γ_p is that the proton width is relatively insensitive to the choice of potential parameters, provided the same parameters are used to calculate the spectroscopic factor and the single-particle width. $\Gamma_\alpha = 220 \pm 20$ keV was determined by Utku *et al.* [17] from the isospin mirror pair identification of the ^{16}O(^{6}Li,^{3}H)^{19}Ne and ^{16}O(^{6}Li,^{3}He)^{19}F experiment. Its unknown γ width is assumed to be 1 ± 1 eV.

Level 4: $E_x = 6449 \pm 7$ keV, $E_r = 38$ keV, ($J^\pi = \frac{3}{2}^+$). The fourth state, with an excitation energy of 6449 $\pm$ 7 keV ($E_r = 38$ keV), is taken to be the analog of the $E_x = 6528$ keV ($\frac{3}{2}^+$) level in ^{19}F. This analog connection is based on the similar excitation energies and an energy shift (79 keV) that is consistent with the shift (78 keV) assumed for the lower energy $\frac{3}{2}^+$ state at $E_x(^{19}\mathrm{Ne}) = 6.419$ MeV. In the ^{18}F(d,p) analysis [22], the spectroscopic factor is deduced to be 0.03$\pm$ 0.03 keV for the $2s_{\frac{1}{2}}$ transfer corresponding to $\Gamma_p = (4 \pm 4) \times 10^{-15}$ keV. The α width is scaled to be $\Gamma_\alpha = (1.3 \pm 1.0)$ keV from the ^{19}F α width in Ref. [29]. The ^{19}F γ width of 1.2 ± 0.2 eV was deduced from the ^{15}N$(\alpha,\gamma)^{19}$F resonance strength reported in Tilley *et al.* [32] and a correction factor of 0.90 gave us a value of $\Gamma_\gamma = 1.1 \pm 0.6$ eV for this ^{19}Ne level.

Level 5: ($E_x = 6504 \pm 30$ keV), $E_r = 93$ keV, ($J^\pi = \frac{7}{2}^+$). The fifth state is missing and assumed to be at $E_x = 6504 \pm 30$ keV, taken to be the analog of $E_x = 6554$ keV ($\frac{7}{2}^+$) state in ^{19}F. The reduced proton width is assumed to be 0.1 ± 0.1 and corresponds to $\Gamma_p = (4.6 \pm 4.6) \times 10^{-10}$ keV. An α width of $\Gamma_\alpha = 0.4 \pm 0.4$ keV is scaled from the ^{19}F α width [29]. $\Gamma_\gamma = 0.14 \pm 0.08$ eV was corrected from the ^{19}F γ width that was determined from the ^{15}N$(\alpha,\gamma)^{19}$F resonance strength reported for the analog state in ^{19}F [32].

Level 6: ($E_x = 6542 \pm 30$ keV), $E_r = 131$ keV, ($J^\pi = \frac{9}{2}^+$). The sixth state, with an assumed excitation energy of 6542 $\pm$ 30 keV (corresponding to $E_r = 131$ keV) is taken to be the analog of the $E_x = 6592$ keV ($J^\pi = \frac{9}{2}^+$) level in ^{19}F. The reduced p width is assumed to be 0.1 ± 0.1 and corresponds to a p width $\Gamma_p = (2.7 \pm 2.7) \times 10^{-12}$ keV. An α width of $\Gamma_\alpha = 13 \pm 11$ eV is scaled from ^{19}F [32] and a γ width of 0.30 ± 0.16 eV is corrected from the width of the analog nuclei ^{19}F.

Level 7: $E_x = 6698 \pm 6$ keV, $E_r = 287$ keV, ($J^\pi = \frac{5}{2}^+$). The seventh state, with an excitation energy of 6698 $\pm$ 6 keV [17] ($E_r = 287$ keV), is taken to be the analog of the $J^\pi = \frac{5}{2}^+$ ^{19} state at $E_x = 6838$ keV. This analog connection is made because of the similarity in the excitation energies. A spectroscopic factor was recently deduced from the ^{18}F(d,p) measurements [22] to be <0.02 and a p width of $\Gamma_p = (1.2 \pm 1.2) \times 10^{-5}$ keV is adopted. An α width of $\Gamma_\alpha = 1.2 \pm 1.0$ keV is scaled from ^{19}F. The γ width ($\Gamma_\gamma = 0.29 \pm 0.15$ eV) was corrected from the of ^{19}F γ width that was deduced from the ^{15}N$(\alpha,\gamma)^{19}$F resonance strength reported in Ref. [32].

Level 8: $E_x = 6741 \pm 6$ keV, $E_r = 330$ keV, $J^\pi = \frac{3}{2}^-$. The eighth state, with an excitation energy of 6741 $\pm$ 6 keV (corresponding to $E_r = 330$ keV) and a spin-parity of $\frac{3}{2}^-$, is taken to be the analog of the $J^\pi = \frac{3}{2}^-$ level at 6787 keV in ^{19}F. This connection is made because of the similar excitation energies, consistent spin-parities, and similar population in the isospin mirror pair identification from the ^{20}Ne$(d,t)^{19}$Ne and ^{20}Ne(d,^{3}He)^{19}F reactions seen by Utku *et al.* [17]. The angular distribution from the decay α particles measured by Visser *et al.* [44] also gave confidence in the spin-parity assignment. This resonance may have been seen by Graulich *et al.* in 1997 [16], but the statistics in that study were too poor and the background subtraction too uncertain to reliably extract a resonance strength. However, a p width of $\Gamma_p = 2.22 \pm 0.69$ eV and the (p,α) strength of 1.48 ± 0.46 eV were directly measured by Bardayan *et al.* in 2002 [25]. Hence we adopted the p width measured by Bardayan *et al.*, which was about 2.4 times less than that of Graulich *et al.* [16]. An α width of $\Gamma_\alpha = 5.2 \pm 3.7$ keV is scaled and a γ width of 5.0 ± 2.6 eV is taken from ^{19}F [32] with the appropriate corrections.

Level 9: ($E_x = 6841 \pm 30$ keV), $E_r = 430$ keV, ($J^\pi = \frac{3}{2}^-$). The ninth state is assumed to be at $E_x = 6841 \pm 30$ keV ($E_r = 430$ keV) and is taken to be the analog of the $J^\pi = \frac{3}{2}^-$ ^{19}F state at $E_x = 6891$ keV. The reduced p width is assumed to be 0.01 ± 0.01 and corresponds to a p width of $(9.7 \pm 9.7) \times 10^{-3}$ keV. An α width of 25 ± 18 keV is scaled from ^{19}F α width in Ref. [29] and a corrected γ width of 2.8 ± 1.5 eV is obtained from the ^{15}N$(\alpha,\gamma)^{19}$F resonance strength reported in Tilley *et al.* [32].

Level 10: $E_x = 6861 \pm 6$ keV, $E_r = 450$ keV, $J^\pi = \frac{7}{2}^-$. The tenth state, with an excitation energy of 6861 $\pm$ 6 keV [17] (corresponding to $E_r = 450$ keV), is taken to be the analog of the $J^\pi = \frac{7}{2}^-$ level in ^{19}F at $E_x = 6927$ keV. This connection is made because of the similar excitation energies and the similar populations observed in the isospin mirror pair identification experiments on ^{16}O(^{6}Li,t)^{19}Ne and ^{16} O(^{6}Li,^{3}He)^{19}F reactions [17]. The spin and parity assignment $J^\pi = \frac{7}{2}^-$ was confirmed from the angular distribution measurements of the α decay of ^{19}Ne recoils produced by the ^{19}F(^{3}He,t)^{19}Ne* reaction [44]. A reduced p width of $\theta_p^2 = 0.01 \pm 0.01$ is assumed and corresponds to $\Gamma_p = (1.1 \pm 1.1) \times 10^{-5}$ keV. A Γ_α width of

1.2 ± 0.9 keV is scaled from ^{19}F α width [29] and a γ width of 2.3 ± 1.2 eV is corrected from the γ width deduced from the ^{15}N$(\alpha,\gamma)^{19}$F resonance strength reported for the analog level in Tilley *et al.* [32].

Level 11: ($E_x = 6939 \pm 30$ keV), $E_r = 528$ keV, ($J^\pi = \frac{1}{2}^-$). The eleventh state is assumed to be at $E_x = 6939 \pm 30$ keV ($E_r = 528$ keV) and is taken to be the analog of the $J^\pi = \frac{1}{2}^-$ level in ^{19}F at $E_x = 6989$ keV. A reduced p width of $\theta_p^2 = 0.01 \pm 0.01$ is assumed and corresponds to a p width of $\Gamma_p = 3.4 \pm 3.4 \times 10^{-2}$ keV, and an α width of $\Gamma_\alpha = 99 \pm 69$ keV is obtained by scaling the width of the analog ^{19}F level [29]. A γ width of $\Gamma_\gamma = 1 \pm 1$ eV is assumed.

Level 12: ($E_x = 7054 \pm 30$ keV), $E_r = 643$ keV, ($J^\pi = \frac{5}{2}^+$). The twelfth state is assumed to be at $E_x = 7054 \pm 30$ keV ($E_r = 643$ keV) and is taken to be the analog of the ^{19}F state at $E_x = 7114$ keV with $J^\pi = \frac{5}{2}^+$. This energy was arrived at by scaling the energies of the neighboring states. The analog state of ^{19}F at $E_x = 7114$ keV has been assigned a $J^\pi = \frac{5}{2}^+$ replacing the original assigment of $J^\pi = \frac{7}{2}^+$ observed by Smotrich *et al.* [30] and an assignment of $J^\pi = \frac{3}{2}^+$ cited by Butt *et al.* [18]. The new spin-parity assignment is based on the reanalysis of Smotrich's data by Bardayan *et al.* [29]. A reduced p width of 0.1 ± 0.1 is assumed and corresponds to a p width of $\Gamma_p = 4.7 \pm 4.7 \times 10^{-2}$ keV. A reasonably good fit for the data for ^{19}F at this resonance was achieved for $\Gamma_\alpha = 25 \pm 4$ keV in Ref. [29]. An α width of $\Gamma_\alpha = 29 \pm 25$ keV is scaled from ^{19}F, and a γ width of $\Gamma_\gamma = 1 \pm 1$ eV is assumed.

Level 13: $E_x = 7075.7 \pm 1.6$ keV, $E_r = 664.7$ keV, $J^\pi = \frac{3}{2}^+$. The thirteenth state has an excitation energy of 7075.7 ± 1.6 keV ($E_r = 664.7$ keV) and a spin-parity of $J^\pi = \frac{3}{2}^+$. It may have an analog in ^{19}F near 7300 keV. This analog connection is made as a result of recent studies by Bardayan *et al.* [29]. This state has $J^\pi = \frac{3}{2}^+$ [24] and would be an s-wave resonance [15,24,45] for the ^{18}F+p system because the ground state of ^{18}F has $J^\pi = 1^+$. Furthermore, it is a broad resonance and therefore plays an important role in the ^{18}F+p reactions over a wide range of stellar temperatures. For these reasons, this state has received considerable experimental scrutiny (see Table I in the study by Bardayan *et al.* (2001) [24]) with stable beams by Uktu *et al.* (1998) [17], and radioactive beam experiments by Rehm *et al.* (1995, 1996, 1997) [12–14], Coszach *et al.* (1995) [15], Bardayan *et al.* (2000, 2001) [24,26,46], and Graulich *et al.* (2000) [45]. Recent studies were done by Visser *et al.* (2004) [44] and Kozub *et al.* (2005) [22]. We take the properties of $E_r = 664.7 \pm 1.6$ keV$(\frac{3}{2}^+)$, $\Gamma_p = 15.2 \pm 1.0$ keV, $\Gamma_\alpha = 23.8 \pm 1.2$ keV, $\Gamma_t = 39.0 \pm 1.6$ keV and $\omega\gamma(p,\alpha) = 6.2 \pm 0.3$ keV measured by Bardayan *et al.* [24]. These values are consistent with those in its previous study in Ref. [46] and the resonance energy and total width are consistent with those of Utku *et al.* [17]. The results from the Visser *et al.* [44] measurement of Γ_p/Γ from the ^{19}F(^{3}He,t)^{19}Ne reaction also agrees well with the direct measurement of Bardayan *et al.* [24]. The total width is also consistent with that of Coszach [15]. The γ width Γ_γ is assumed to be 1 ± 1 eV. In an earlier publication [28], this level was presumed to be the analog of the ^{19}F level at 7100 keV based on the excitation function measured of the $^{15}N(\alpha,\gamma)^{19}$F reaction by Butt *et al.* [18]. However, due to lack of evidence of the 7.1-MeV state from the ^{18}F(d,p) measurements [22], the calculation of Fortune and Sherr [47] that expects the analog to be higher in energy at 7.4 ± 0.1 MeV, as well as the reanalyzed ^{15}N$(\alpha,\alpha)^{15}$N data [30] by Bardayan *et al.* [29], it would appear that this ^{19}Ne level at $E_x = 7075.7$ keV is the analog of a ^{19}F level near $E_x = 7.30$ MeV. Such a group is strongly populated in the ^{18}F$(d,p)^{19}$F reaction [22]. Because no parameter is taken from the analog state, any discrepancy of the analog connections does not directly affect the (p,α) rate.

Level 14: $E_x = 7173 \pm 5$ keV, $E_r = 762$ keV, ($J^\pi = \frac{11}{2}^-$). The fourteenth state, with an excitation energy of $E_x = 7173 \pm 5$ keV [17] (corresponding to $E_r = 762$ keV) is assumed to be the analog of the $J^\pi = \frac{11}{2}^-$ ^{19}F level at $E_x = 7166$ keV. This analog connection is made because of their similarity in the excitation energies. A reduced p width of 0.01 ± 0.01 is assumed and corresponds to a p width of $(9.8 \pm 9.8) \times 10^{-8}$ keV. An α width of $\Gamma_\alpha = 12 \pm 10$ eV is scaled from ^{19}F. The γ width of $\Gamma_\gamma = 0.15 \pm 0.08$ eV is deduced and corrected from ^{15}N$(\alpha,\gamma)^{19}$F resonance strength reported in Ref. [32].

Level 15: $E_x = 7238 \pm 6$ keV, $E_r = 827$ keV, $J^\pi = \frac{3}{2}^+$. The fifteenth state, with an excitation energy of $E_x = 7238 \pm 6$ keV [17] ($E_r = 827$ keV), is taken to be the analog of the $J^\pi = \frac{3}{2}^+$ ^{19}F level at $E_x = 7262$ keV. This analog connection is made because of the similar excitation energies, and the similar populations in the ^{16}O(^{6}Li,t)^{19}Ne and ^{16}O(^{6}Li,^{3}He)^{19}F reactions reported by Utku *et al.* [17]. In the most recent work [48], the excitation function for ^{18}F$(p,\alpha)^{15}$O was measured in the energy range of $E_{cm} = 663$–877 keV to study the interference effects among the $J^\pi = \frac{3}{2}^+$ in the $^{18}F + p$ system. The observed cross section data were compared to the R-matrix code MULTI [49] and a new upper limit of the proton width was obtained which is consistent with the results of a thick target ^{18}F$(p,p)^{18}$F measurement [26]. As the latter work [26] has the more stringent upper limit, hence the new value for the proton width is reduced from 2 keV of the previous work [28] to $\Gamma_p = 0.35 \pm 0.35$ keV. The α width is assumed to be 6.0 ± 5.2 keV, corresponding to its analog state with an α width of $\Gamma_\alpha < 6$ keV [32]. A γ width of $\Gamma_\gamma = 1 \pm 1$ eV is assumed.

Level 16: $E_x = 7253 \pm 10$ keV, $E_r = 842$ keV, ($J^\pi = \frac{1}{2}^+$). The sixteenth state was populated at $E_x = 7253 \pm 10$ keV [32] ($E_r = 842$ keV), which has spin-parity of $\frac{1}{2}^+$. Its analog state is tentatively assigned $E_x = 7.364$ MeV in ^{19}F [26]. A new upper limit was obtained for the proton width in a recent experiment which studied the interference effects among the $J^\pi = \frac{3}{2}^+$ resonances [48]. Its value was consistent with the measurements in Ref. [26] and we have adopted a $\Gamma_p = 0.2 \pm 0.2$ keV which gives the best fit for their data [48]. An α-width of 23 keV was assumed in our earlier paper [28] and was used in the analysis of the R-matrix calculation and experimental data in Ref. [48] which gave a good fit. Therefore we adopt an α width of 23 ± 20 keV and a γ width of 1 ± 1 eV is assumed.

Level 17: $E_x = 7420 \pm 14$ keV, $E_r = 1009$ keV, ($J^\pi = \frac{7}{2}^+$). The seventeenth state, with an excitation energy of $E_x = 7420 \pm 14$ keV [26] ($E_r = 1009$ keV), is taken to be the analog of the $J^\pi = \frac{7}{2}^+$ ^{19}F level at $E_x = 7560$ keV. The analog connection is based on the fact that the ^{19}F level has a rather broad width ($\Gamma = 85$ keV) [50]. The broad width of the assigned analog state is reasonably similar to the $E_x = 7420 \pm 14$ keV ^{19}Ne ($\Gamma = 98$ keV) level that was measured and identified with a thick target ^{18}F(p, p) measurement by Bardayan *et al*. [26]. In their data analysis [26], excitation functions were calculated using the R-matrix code MULTI [49] and fit to the data with a best fit of $\Gamma_p = 27 \pm 4$ keV and $\Gamma_\alpha = 71 \pm 11$ keV. A γ width of 1 ± 1 eV is assumed. This level identified by Bardayan *et al*. [26] was recently scrutinized by Fortune and Sherr [51]. They computed the single-particle proton width and, using the broad proton width $\Gamma_p = 27 \pm 4$ keV [26], determined the proton spectroscopic factor ($S_p = 8$). This value is significantly larger than the theoretical upper limit. They [51] have speculated that either the J^π or the proton width for this level quoted in Ref. [26] is incorrect. However, they have also pointed out that with the experimental proton width of 27 keV, and if the proton has a $l = 0$ (where J^π could be $\frac{1}{2}^+$ or $\frac{3}{2}^+$), the mirror level in ^{19}F will then be unknown. Furthermore, if the spin was less than $\frac{7}{2}$, the experimental proton width extracted from the data in Ref. [26] would be larger than 27 keV and would produce a higher proton spectroscopic factor S_p. Because neither a new J^π nor a reasonable proton width can be suggested for this level, we propose that we use the values suggested in Ref. [26].

Level 18: $E_x = 7500 \pm 9$ keV, $E_r = 1089$ keV, ($J^\pi = \frac{5}{2}^+$). The eighteenth state has an excitation energy of $E_x = 7500 \pm 9$ keV [17] (corresponding to $E_r = 1089$ keV) and is taken to be the analog of the $J^\pi = \frac{5}{2}^+$ ^{19}F level at $E_x = 7539.6$ keV. This connection is made based on the similar excitation energies. The Γ_p/Γ ratio of 0.84 ± 0.04 and Γ_α/Γ ratio of 0.16 ± 0.02 was measured in Ref. [17]. Our previous publication [28] quoted a value of 13.4 keV and 2.56 for Γ_p and Γ_α, respectively. However, Bardayan *et al*.'s [26] analysis of the ^{18}F(p, p) data had shown there there is a discrepancy when using such a broad width. Hence using the ratio of $\Gamma_p/\Gamma_\alpha \simeq 5.25$ at the 90% confidence level, an upper limit was set on the proton width $\Gamma_p < 2.5$ keV [26]. The $\Gamma_p = (1.25 \pm 1.25)$ keV and $\Gamma_\alpha = 0.24 \pm 0.24$ are adopted [26] for this level. The γ width of $\Gamma_\gamma = 5.5 \pm 2.9$ eV is corrected from the γ width that was deduced from the ^{15}N$(\alpha, \gamma)^{19}$F resonance strength reported for the analog [32].

Level 19: $E_x = 7531 \pm 11$ keV, $E_r = 1120$ keV, $J^\pi = \frac{5}{2}^-$. The nineteenth state, with an excitation energy of 7531 ± 11 keV (corresponding to $E_r = 1120$ keV), is taken to be the analog of the $J^\pi = \frac{5}{2}^-$ ^{19}F state at $E_x = 7590$ keV. The analog connection, taken from Ref. [26], is unlike our previous analog assignment of $E_x = 7560$ keV and $J^\pi = \frac{7}{2}^+$ [28]. Instead, the $E_x = 7560$ keV level of ^{19}F is assumed to be the mirror of the $E_x = 7420$ keV level of ^{19}Ne (see level 17). The partial widths [26] of $\Gamma_\alpha = 21 \pm 11$ keV and $\Gamma_p = 10 \pm 6$ keV were taken from Γ_p/Γ and Γ_α/Γ that were determined in the ^{19}F(^{3}He,$t\alpha$)^{15}O and ^{19}F(^{3}He,tp)^{18}F coincidence measurements of Ref. [17]. A γ width of $\Gamma_\gamma = 1 \pm 1$ eV is assumed.

Level 20: ($E_x = 7558 \pm 30$ keV), $E_r = 1147$ keV, ($J^\pi = \frac{5}{2}^-$). The twentieth state is assumed to be at $E_x = 7558 \pm 30$ keV (corresponding to $E_r = 1147$ keV) and is taken to be the analog of the $J^\pi = \frac{5}{2}^-$ level in ^{19}F at $E_x = 7587$ keV. The excitation energy is scaled from its analog state with an uncertainty of 30 keV. An α width of $\Gamma_\alpha = 21 \pm 18$ keV is scaled from ^{19}F where $\Gamma_{\alpha\_\mathrm{Lab}} < 50$ keV [32]. A reduced p width of 0.01 ± 0.01 is assumed and corresponds to a p width of 1.3 ± 1.3 keV. A γ width of 1 ± 1 eV is assumed.

Level 21: $E_x = 7608 \pm 11$ keV, $E_r = 1197$ keV, $J^\pi = \frac{3}{2}^+$. The twenty-first state, with an excitation energy of 7608 ± 11 keV [32] (corresponding to $E_r = 1197$ keV), has been determined to have spin-parity $J^\pi = \frac{3}{2}^+$ [17] and isospin T = 3/2 [32]. This state is assigned to be the analog of the $J^\pi = \frac{3}{2}^+$, T = 3/2 ^{19}F level at $E_x = 7660.7$ keV. This connection is made because of the similar excitation energies and the same spin-parities and isospins. Partial widths of $\Gamma_p = 2 \pm 1$ keV and $\Gamma_\alpha = 43 \pm 15$ keV were measured by Utku *et al*. [17]. A γ width of $\Gamma_\gamma = 1.8 \pm 1.0$ eV is deduced and corrected from the ^{15}N$(\alpha, \gamma)^{19}$F resonance strength for the analog reported in Ref. [32].

Level 22: $E_x = 7644 \pm 12$ keV, $E_r = 1233$ keV, ($J^\pi = \frac{1}{2}^-$). The twenty-second state, with an excitation energy of 7644 ± 12 keV (corresponding to $E_r = 1233$ keV), is taken to be the analog of the $J^\pi = \frac{1}{2}^-$ level in ^{19}F at $E_x = 7702$ keV. The analog connection is based on the similar excitation energies, and an energy shift consistent with the neighboring states. Partial widths of $\Gamma_p = 27 \pm 10$ keV and $\Gamma_\alpha = 16 \pm 6$ keV are taken from Ref. [17]. A γ width of $\Gamma_\gamma = 1 \pm 1$ eV is assumed.

Level 23: $E_x = 7700 \pm 10$ keV, $E_r = 1289$ keV, ($J^\pi = \frac{5}{2}^-$). The twenty-third state, with an excitation energy of $E_x = 7700 \pm 10$ keV [32] (corresponding to $E_r = 1289$ keV), is taken to be the analog of the $J^\pi = (\frac{5}{2}^-, \frac{7}{2}^-)$ ^{19}F state at $E_x = 7740$ keV. This analog connection is based on the similar excitation energies and an energy shift consistent with the neighboring states. We selected one of the spin-parities, $J^\pi = \frac{5}{2}^-$, which corresponds to a larger p width than the other spin-parity ($\frac{7}{2}^-$) does. An α width of (6.2 ± 5.3) keV is scaled from ^{19}F where its analog state has $\Gamma_\alpha < 6$ keV. A reduced p width of 0.01 ± 0.01 is assumed and corresponds to a p width of 1.7 ± 1.7 keV. A γ width of 1 ± 1 eV is assumed.

Level 24: $E_x = 7819 \pm 11$ keV, $E_r = 1408$ keV, ($J^\pi = \frac{7}{2}^+$). The twenty-fifth state, with an excitation energy of 7819 ± 11 keV [32] ($E_r = 1408$ keV), is taken to be the analog of the $J^\pi = \frac{7}{2}^+$ level in ^{19}F at 7929 keV. This analog connection is based on the similar excitation energies. Widths of $\Gamma_t = 22 \pm 16$ keV, $\Gamma_\alpha = 4 \pm 3$ keV, and $\Gamma_p = 18 \pm 13$ keV were reported by Utku *et al*. [17]. A γ width of $\Gamma_\gamma = 0.53 \pm 0.28$ eV is deduced and corrected from the ^{15}N$(\alpha, \gamma)^{19}$F resonance strength reported in Ref. [32].

Level 25: ($E_x = 7826 \pm 30$ keV), $E_r = 1415$ keV, ($J^\pi = \frac{11}{2}^+$). The twenty-sixth state is assumed to be at $E_x = 7826 \pm 30$ keV (corresponding to $E_r = 1415$ keV) and is taken to be the analog of the $J^\pi = \frac{11}{2}^+$ level in ^{19}F at $E_x = 7937$ keV. This excitation energy was scaled from its analog state. The reduced widths of $\theta_p^2 = 0.1 \pm 0.1$ and $\theta_\alpha^2 = 0.05 \pm 0.04$ are assumed and correspond to the partial widths of $\Gamma_p = (6.4 \pm 6.4) \times 10^{-3}$ keV and $\Gamma_\alpha = 1.7 \pm 1.5$ keV, respectively. A γ width of $\Gamma_\gamma = 0.47 \pm 0.25$ eV is deduced and corrected from the ^{15}N$(\alpha, \gamma)^{19}$F resonance strength reported for the analog in Ref. [32].

Level 26: $E_x = 7944 \pm 15$ keV, $E_r = 1533$ keV, ($J^\pi = \frac{5}{2}^+$). The twenty-seventh state, with an excitation energy of 7944 $\pm$ 15 keV [32] (corresponding to $E_r = 1533$ keV), is taken to be the analog of the $J^\pi = \frac{5}{2}^+$ level in ^{19}F at $E_x =$ 8014 keV. This analog connection is based on the similar excitation energies. With the assumption that $S_n = S_p$, the proton width was calculated using the spectroscopic factor $S_n = 0.15 \pm 0.03$ which was extracted from the ^{18}F$(d, p)^{19}$F measurement [52] and the proton single particle width which was calculated using the Wood Saxon potential. A value $\Gamma_p = (5.9 \pm 1.2)$ keV was deduced. A reduced α width of $\theta_\alpha^2 = 0.05 \pm 0.04$ is assumed and corresponds to the partial width of $\Gamma_\alpha = 26 \pm 21$ keV. A γ width of 1 ± 1 eV is assumed.

Level 27: ($E_x = 8014 \pm 30$ keV), $E_r = 1603$ keV, ($J^\pi = \frac{5}{2}^+$). The twenty-eighth state is assumed to be at $E_x = 8014 \pm 30$ keV (corresponding to $E_r = 1603$ keV) and is taken to be the analog of the ^{19}F level at $E_x = 8084$ keV. This excitation energy was obtained by scaling the position of the analog state. A spin-parity of $J^\pi = \frac{5}{2}^+$ is taken from Table 19.21 of Ref. [32]. An α width of $\Gamma_\alpha = 2.9 \pm 2.2$ keV is scaled from an ^{19}F α width that is less than 3 keV. A reduced p width of 0.1 ± 0.1 is assumed and corresponds to a p width of $\Gamma_p = 4.8 \pm 4.8$ keV. A γ width of $\Gamma_\gamma = 1 \pm 1$ eV is assumed.

Level 28: $E_x = 8069 \pm 12$ keV, $E_r = 1658$ keV, ($J^\pi = \frac{1}{2}^+$). The twenty-ninth state, with an excitation energy of 8069 $\pm$ 12 keV [32] (corresponding to $E_r = 1658$ keV) is taken to be the analog of the $J^\pi = \frac{1}{2}^+$ level in ^{19}F at $E_x =$ 8137.7 keV. This analog connection is based on the similar excitation energies. A neutron spectroscopic factor of 0.32 ± 0.06 was obtained in the ^{18}F$(d, p)^{19}$F work of Ref. [52]. We were unable to obtain a solution for $\Gamma_{\rm sp}$, and therefore assign no value for Γ_p for this level. An α width $\Gamma_\alpha = 0.22$ keV for ^{19}Ne was determined by scaling the α width of the analog state that was reported in Table 19.18 [32]. $\Gamma_\gamma = 1.17 \pm 0.59$ eV is deduced and corrected from the resonance measurements in the $^{18}O(p, \gamma)^{19}$F reaction as reported for the analog nuclei in Table 19.18 from Ref. [32].

Other levels: Two levels of ^{19}Ne at $E_x = 7788$ keV and 8091 keV are expected to exist based on their analog connections. The former level is presumed to be the analog of the ^{19}F level at $E_x = 7900$ keV. However, both these states for ^{19}Ne and ^{19}F are uncertain, as the evidence for the 7.788 MeV (^{19}Ne) level studied via the reaction ^{20}Ne(^{3}He, α) ^{19}Ne in Ref. [53] seems to be weak and had been indicated as an uncertain level by the authors. Also its analog assignment (^{19}F) has been based on the assumption that an s-wave resonance does exist at this ^{19}F excitation energy [54], although this state was not obeserved in the ^{18}O(^{3}He,d)^{19}F measurement due to low yield and possible interference effect. The latter level of ^{19}Ne at $E_x = 8091$ keV is proposed to be the analog of ^{19}F level at $E_x = 8160$ keV based on similar excitation energies. We cannot at this time assign any information on the spins, parities, or the partial widths for these levels.

IV. SUMMARY

In summary, extensive work has been done to update the structure information of ^{19}Ne and analog states in the mirror nucleus ^{19}F. Since the previous publication [28], a new resonance at $E_r = 1009$ keV ($E_x = 7420$ keV) has been observed and identified from the ^{18}F(p, p) thick target measurement [26], which we have taken to be the analog of ^{19}F level at $E_x = 7560$ keV. Included in this present work are the results from the ^{18}F(d, p) measurements, which have given us new values for the Γ_p widths of three resonances ($E_r = 8$, 38, and 1533 keV). For cases where there were no spectroscopic factors from measurements, the proton width was deduced from the single-particle width and the reduced width convention used for the even or odd parity. All $\Gamma_{\rm sp}$ calculations were performed with a realistic Wood Saxon potential, which reduced previous estimated of Γ_p by up to a factor of 2. The reanalysis of the ^{15}N$(\alpha, \alpha)^{15}$N reaction [29] had also shed some light on the widths of the important $\frac{3}{2}^+$ states and resulted in the reassignment of the spin of the $E_x = 7.054$ MeV ^{19}Ne level. The reassignment of the analog state for $E_r = 664.7$ keV resonance was based on the the ^{18}F$(d, p)^{19}$F measurement [22,23], calculations of Ref. [47] and the reanalyzed data of ^{15}N$(\alpha, \alpha)^{15}$N [29].

To conclude, future precise measurements with radioactive and stable beams that will provide information on the missing states in ^{19}Ne ($E_x = 6.422$, 6.504, 6.542, 6.841, 6.939, 7.054, 7.558, 7.788, 7.826, 8.014, and 8.091 MeV) are needed to reduce the uncertainties in the ^{18}F$(p, \alpha)^{15}$O and ^{18}F$(p, \gamma)^{19}$Ne stellar reaction rate calculations and consequently provide constraints on nova models.

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