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Letter

s-wave resonances for the ^{18}F(p, α)^{15}O reaction in novae

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Abstract. The ^{18}F(p,α) reaction determines the rate of destruction of ^{18}F in novae. It represents the key nuclear physics uncertainty in modelling the calculated flux of annihilation radiation emitted following the radioactive decay of ^{18}F. The major uncertainties relate to states representing s-wave resonances in the compound system, ^{19}Ne. We report a first study of the ^{19}F$(^3$He$,t)^{19}$Ne reaction at intermediate energies and forward angles. This reaction has a simple, model-independent, mechanism that we use here to identify states near the proton threshold energy in ^{19}Ne corresponding to $\Delta L = 0$ transitions. In particular, we observe a $\Delta L = 0$ state at 6.13 MeV which could significantly affect the ^{18}F(p,α) astrophysical S-factor at nova burning temperatures.

Classical novae comprise some of the most frequent and powerful explosions in the observable universe. Their typical energy release is exceeded only by supernovae and gamma-ray bursts. A nova occurs in a binary star system on the surface of a white dwarf after it has accreted sufficient material to trigger a thermonuclear runaway [1, 2]. Only a few critical reaction rates involving radioactive nuclei are identified as having uncertainties large enough to significantly affect the predictions of nova models [3]. One outstanding problem relates to the amount of ejected material calculated by these models, which give systematically lower values than infrared and radio observations of nova explosions [4, 5]. The resolution of this problem could lie within the models themselves, including the nuclear input data, or with the interpretation of the observations. Astronomers have sought to observe 511 keV γ-rays associated with electron-positron annihilation, following the radioactive decay of ^{18}F ($t_{1/2} = 110$ min). These γ-rays are expected to be observable when the ejected material becomes optically thin [6]. The flux of 511 keV γ-rays could then be used to infer the amount of ^{18}F produced in the explosion [7].

The major nuclear physics uncertainty required to model the amount of ^{18}F produced relates to the ^{18}F(p,α) reaction rate which dominates the destruction of ^{18}F [8]. It is nearly a quarter of a century since the first pioneering direct studies of this reaction were performed using radioactive beams [9, 10]. The rate at high nova burning temperatures is now known to be dominated by a $\frac{3}{2}^-$ state at a resonance energy $E_r = 332$ keV and a $\frac{3}{2}^+$ state at 665 keV [11, 12]. However, at lower burning temperatures a large range of S-factors are reported in the literature [13–18], particularly due to uncertainties in the location of lower-lying s-wave resonances expected to exist near the proton threshold energy in ^{19}Ne (6.4100(5) MeV [19]). These states, including subthreshold resonances, have an influence on the ^{18}F(p,α) reaction cross section at energies too low to be measured directly with presently available beam intensities. However, they can nonetheless influence the burning rate at lower temperatures by interference with higher-lying $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states [20, 13]. Therefore many indirect approaches have been applied to study levels in this region (see, *e.g.*, refs. [15, 21] and references therein). Recent high resolution studies have utilized the ^{19}F$(^3$He$,t)^{19}$Ne reaction at low energies (25 MeV) [22, 23]. This reaction is known to produce non-selectively most states, but the reaction mechanism at these low energies is complex and consequently assignments based on DWBA analyses cannot usually give unique orbital momentum transfer, L, assignments (although distinctions can be made between

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relatively low or high values) [22,24]. In contrast, intermediate energy ($\geq$ 100 MeV/nucleon) (^{3}He, t) reactions at extreme forward angles are well known to be described by a simple underlying one pion charge-exchange mechanism for Gamow-Teller (GT, $\Delta L = 0$) transitions. This reaction mechanism can be used to identify such states in an essentially model independent way [25]. In the present Letter, we present results of the first such measurement of the ^{19}F(^{3}He, t) reaction to identify s-wave states in the ^{18}F(p, α) reaction.

The ^{19}F(^{3}He, t)^{19}Ne experiment was performed at the high-resolution facility of the Research Center for Nuclear Physics (RCNP) [26], Osaka, consisting of the "WS course" beam line [27] and the "Grand Raiden" spectrometer [28] using a 140 MeV/nucleon ^{3}He beam from the $K = 400$ Ring Cyclotron. The target was a 12 μm thick polytetrafluoroethylene (C_2F_4) foil. In order to identify states excited by $\Delta L = 0$ transitions, the spectrometer was set at 0° to analyze the momentum of outgoing tritons within the acceptance of up to 2.5°. An energy resolution of 41 keV (FWHM) was realized by applying dispersion matching techniques between the spectrometer and the beam line [25,29,30].

In order to accurately determine the scattering angle, Θ, close to 0°, angular measurements in both the horizontal (θ) and vertical (ϕ) directions are equally important, where Θ is defined as $\Theta \cong \sqrt{\theta^2 + \phi^2}$. Good resolution in θ and ϕ was achieved by applying the *angular dispersion matching* technique [25,29] and the *over focus mode* in the spectrometer [31], resulting in an angular resolution of $\Delta\Theta \leq 5$ mrad (FWHM, $\lesssim 0.3°$). During the analysis, the acceptance of the spectrometer was subdivided into five angular ranges. Figure 1 shows the spectra for three of these angular ranges (0°–0.5°, 0.8°–1.2°, and 1.6°–2.0°) covering the excitation energy ($E_{\rm ex}$) region between 5.2–8.0 MeV in ^{19}Ne. In analyzing such data to identify $\Delta L = 0$ transitions, corresponding to either $\frac{1}{2}^+$ or $\frac{3}{2}^+$ states, the ratio of the number of counts in a given peak at each angular range was compared to its value at $\Theta \leq 0.5°$ and normalized to the ratio of a known $\Delta L = 0$ benchmark state, in this case the $\frac{1}{2}^+$ state at 5.35 MeV in ^{19}Ne [32]. States excited by GT transitions have maximum cross-sections at 0°, *i.e.*, in the $\Theta = 0°$–$0.5°$ spectrum shown in fig. 1(a). A peak having normalized ratios within ±20% of unity in all angular ranges was identified as a $\Delta L = 0$ transition (for further examples of this approach, see, *e.g.*, refs. [33–38]). In contrast, for example, the known $\Delta L = 1$ $\frac{3}{2}^-$ states at 6.007 and 6.753 MeV shown in fig. 1 have strongly backward-peaked angular distributions. The results are shown in table 1 —all peaks observed in the present work correspond to previously-known levels in ^{19}Ne. The assignments of $\Delta L = 0$ transitions are unchanged if the ground-state of ^{19}Ne (present on the spectrometer focal plane but not shown in fig. 1) is used as the benchmark state. Peak energies shown in table 1 were calibrated using well-known states produced in the ^{22}Ne(^{3}He, t)^{22}Na reaction. Because of the extremely negative Q-value of the ^{12}C(^{3}He, t)^{12}N reaction, no ^{12}N states appear in this $E_{\rm ex}$ region; the ^{16}O(^{3}He, t) reaction can be similarly ruled out as a source of contamination. In addition, the contribution from states of ^{13}N was found to be negligible in this region in comparison with a ^{13}C(^{3}He, t)^{13}N spectrum taken with an enriched target [39]. We therefore conclude that all the peaks in the spectra are associated with excited states in ^{19}Ne.

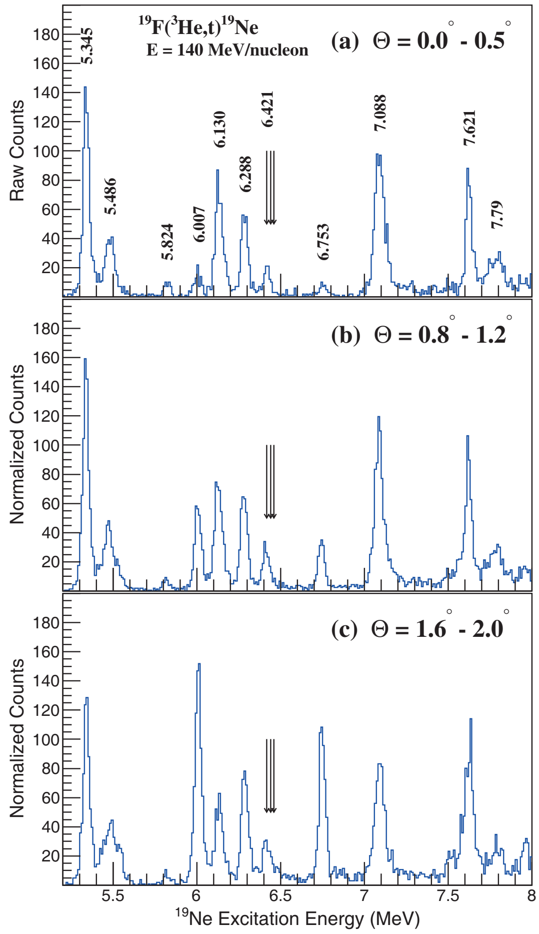

Fig. 1. Excited states populated by the ^{19}F(^{3}He, t)^{19}Ne reaction for different scattering angles, Θ. The spectra at scattering angles $\Theta \geq 0.5°$ are normalized such that the intensity of the benchmark state at 5.35 MeV is the same as in the $\Theta \leq 0.5°$ spectrum in all angular ranges. The arrows correspond to the energies 6.416, 6.440, and 6.459 MeV of Laird *et al.* [22].

The peak at 5.82 MeV agrees with a known energy state in ^{19}Ne and is assigned as a $\Delta L = 0$ transition. This state is most likely the analog of the known $\frac{1}{2}^+$ state at 5.94 MeV in ^{19}F which is similarly well separated from neighboring excited states [32] (see fig. 2).

The peak at 6.13 MeV also corresponds to a known energy state (see table 1) and is consistent with a $\Delta L = 0$ transition. A possible $\frac{3}{2}^+$ assignment would result in a minimum Coulomb energy difference (CED) of 365 keV relative to known $\frac{3}{2}^+$ states in ^{19}F. This would be anomalously large compared to trends in neighboring and lower energy states in the mirror system (see fig. 2 and Table 19.33 in the evaluation of Tilley *et al.* [32]). Alternately

Table 1. ^{19}Ne peaks observed in the present work. Excitation energies in MeV are compared to the most precise values found in the recent literature; superscripts a–c correspond to refs. [32], [22], and [12], respectively. Angular momentum transfer is marked with an asterisk (*) when more than one unresolved state may contribute to the peak.

Literature	Present work	
E_{ex} (MeV)	E_{ex} (MeV)	ΔL
$5.351(10)^a$	5.345(5)	0
$5.463(20)^a$	5.486(15)	0
$5.832(9)^a$	5.824(10)	0
$6.013(7)^a$	6.007(10)	≥ 1
$6.132(5)^b$	6.130(5)	0
$6.289(5)^b$	6.288(5)	*
$6.416(5)^b$	6.421(10)	*
$6.742(4)^b$	6.753(10)	≥ 1
$7.0747(17)^c$	7.088(10)	0
$7.616(16)^a$	7.621(5)	*
–	7.79(3)	0

a more reasonable CED is obtained pairing with the known $\frac{1}{2}^+$ state at 6.26 MeV in ^{19}F. This latter state is strongly populated in the proton stripping reaction ^{18}O(^{3}He, d)^{19}F [40,41]. For comparison, a relatively low resolution study of the ^{18}Ne(d,p)^{19}Ne reaction [42,43] reported a peak of similar spectroscopic strength ($\mathcal{S} \sim 0.2$) around $\sim$ 6.1 MeV with a dominant $L = 0$ transfer component corresponding to a $\frac{1}{2}^+$ assignment. At the time of this latter study, the 6.13 MeV state in ^{19}Ne was not known. Overall, we favor a $\frac{1}{2}^+$ assignment for the 6.13 MeV state, although a $\frac{3}{2}^+$ assignment cannot be ruled out. We note that a recent R-Matrix analysis of the ^{15}O+α elastic scattering showed significant alpha strength near $\sim$ 6.20 MeV [44]. This state was assigned as $J = \frac{1}{2}$ and paired with the mirror candidate of the $\frac{1}{2}^+$ 6.255 MeV state in ^{19}F.

A peak is observed at 6.29 MeV. Very high $L = 0$ strength was previously observed in this region using the ^{18}F(d,n)^{19}Ne reaction, allowing $\frac{1}{2}^+$ or $\frac{3}{2}^+$ assignments [21,45]. Bardayan *et al.* subsequently reported a $\frac{1}{2}^+$ assignment for a peak at this energy based on a DWBA angular distribution analysis of the ^{20}Ne(p,d) reaction [16, 46]. In contrast, Laird *et al.* in their low-energy study of the ^{19}F(^{3}He, t) reaction [22] comment that the state is not "low spin". A later analysis of this same reaction by Parikh *et al.*, including the highest-resolution data, noted that the width of the 6.29 MeV state was broader than the experimental resolution ($\approx$ 10 keV FWHM) and could consist of more than one unresolved state (energies of 6282 and 6295 keV are suggested) or a single broad state with a width of $\approx$ 16 keV [23]. More recently an R-matrix analysis of resonant states in ^{19}Ne produced in the ^{15}O + α scattering system gave a $\frac{5}{2}^+$ assignment for a

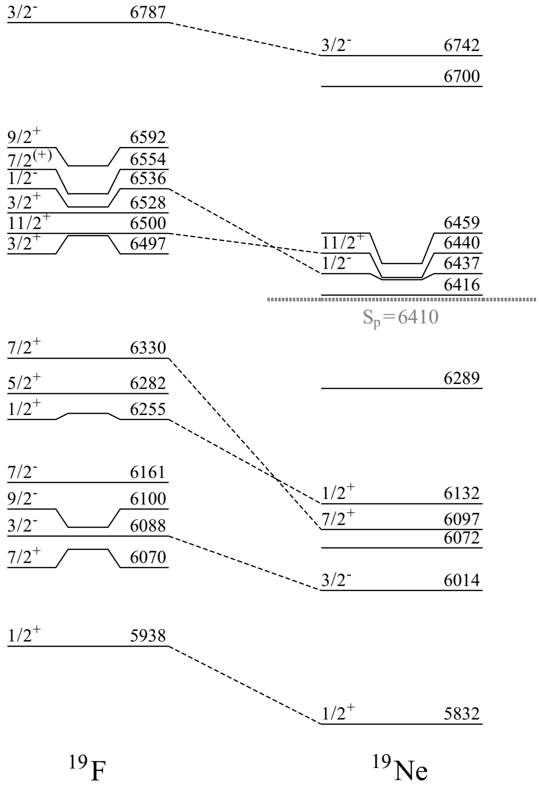

Fig. 2. Energy levels for ^{19}F and ^{19}Ne in the region of the proton threshold energy. Suggested mirror pairs are indicated.

state at $\sim$ 6.28 MeV [44]. Our present data are not compatible with with a pure $\Delta L = 0$ transition populating the 6.29 MeV peak since it increases noticeably in strength at more backward angles, relative to GT transitions. If more than one state is present (at least one of which is a non-GT state), a $\Delta L = 0$ component would be allowed.

We now consider the level structure above the proton threshold at $S_{\text{p}} = 6.4100(5)$ MeV. Laird *et al.* reported three states at 6.416, 6.440, and 6.459 MeV (energies marked by arrows in fig. 1), none of which were said to be consistent with $\frac{3}{2}^+$ assignments [22]. Adekola *et al.* had reported significant $L = 1$ strength to a state at 6.419 MeV in their ^{18}F(d,n)^{19}Ne reaction study [21,45]. We observe a distinct peak-like structure near 6.421 MeV in spectra at all angles (see fig. 1). This peak deviates from the characteristic behavior of a GT transition and is inconsistent with a pure $\Delta L = 0$ transition. A possible $\frac{3}{2}^-$ assignment was suggested by both Adekola *et al.* and Laird *et al.* for the state. Here one can see for the known $\frac{3}{2}^-$ transitions at 6.01 and 6.75 MeV much stronger peaking at backward angles than seen for the 6.42 MeV peak (see fig. 1). In their low-energy (^{3}He, t) study, Laird *et al.* clearly show the 6.440 MeV state must be high spin and suggest a $\frac{11}{2}^+$ assignment; the 6.459 MeV state is tentatively suggested as $\frac{5}{2}^-$. Here, unresolved strength evolves in the more backward angle spectra data at excitation energies above the 6.421 MeV peak which would be consistent with $\Delta L \geq 1$ for the two higher lying states.

Considering level structure well above the proton threshold, we note that the peak in fig. 1 corresponding to the known $\frac{3}{2}^+$ state at 7.09 MeV, is broader than the experimental resolution (41 keV FWHM). We conclude the decay width $\Gamma = 44(6)$ keV is slightly higher, but in reasonable agreement with the most precise previous value reported of 39.0(1.6) keV [12]. A strong peak is observed at 7.621 MeV that is not produced with pure $\Delta L = 0$ transfer in the $(^3\mathrm{He}, t)$ reaction. This would be consistent with a study of elastic scattering of the $^{18}\mathrm{F}+p$ system [47] which required a neighboring $\frac{3}{2}^-$ state to be present, in addition to a previously known $\frac{3}{2}^+$ state at ~ 7.61 MeV [32], for an R-matrix analysis fit. This study [47] also reported a broad state around 7.85 MeV with a $\frac{1}{2}^+$ assignment, consistent with a study by Dalouzy *et al.* of the ^{19}Ne inelastic proton scattering reaction [20]. We see a broad state at 7.79 MeV in fig. 1 whose angular distribution agrees with pure $\Delta L = 0$ transfer, and therefore would be consistent with a $\frac{1}{2}^+$ assignment. Our study would require a smaller width (we obtain a value $\Gamma \approx 130(10)$ keV) than suggested in those studies which did not resolve the 7.79 MeV state from neighboring states.

We now explore the present results in the overall context of the location of $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states in the region of the proton threshold energy in ^{19}Ne. We clearly identify the states at 5.82 and 6.13 MeV as $\Delta L = 0$ transitions and as discussed above favor pairing these states with known $\frac{1}{2}^+$ states at 5.94 and 6.26 MeV in ^{19}F, respectively. This would exhaust all known $\frac{1}{2}^+$ analog states in this region (see fig. 2) —the next highest known $\frac{1}{2}^+$ state in ^{19}F is at 7.36 MeV [32]. However, as noted above, there have been conflicting suggestions in the literature regarding the peak/level structure around 6.29 MeV. In particular, a recent study of the $^{20}\mathrm{Ne}(p,d)^{19}\mathrm{Ne}$ reaction has reported a $\frac{1}{2}^+$ assignment for this state and paired it with the 6.26 MeV state in ^{19}F [16]. Clearly the 6.26 MeV state cannot be paired with both the 6.13 and the 6.29 MeV states in ^{19}Ne, so there remains some unresolved ambiguity here. The observation of high $L = 0$ strength at 6.29 MeV in the $^{18}\mathrm{F}(d,n)^{19}\mathrm{Ne}$ transfer reaction [21] would also allow for the presence of $\frac{3}{2}^+$ state(s), in which case an analog assignment could be made with either the known 6.497 or 6.535 MeV states in ^{19}F [32,48] (see fig. 2). This would be consistent with similar angular distributions, and strengths reported for these (unresolved) states in a parallel study of the $^{18}\mathrm{F}(d,p)$ reaction [45]. The peak observed here at 6.421 MeV at all angles in fig. 1 is a candidate for the location of the second $\frac{3}{2}^+$ state (see, *e.g.*, ref. [49]), but it would require an additional component since it is not fit with pure $\Delta L = 0$.

Calculations of the astrophysical S-factor for the $^{18}\mathrm{F}(p,\alpha)$ reaction using `AZURE2` [50,51] are shown in fig. 3 and compared to experimental values derived from direct measurements of the reaction cross-section [12,11, 14]. The region critical to burning at nova temperatures ($T \sim 0.1$–0.4 GK) corresponds to energies in the range

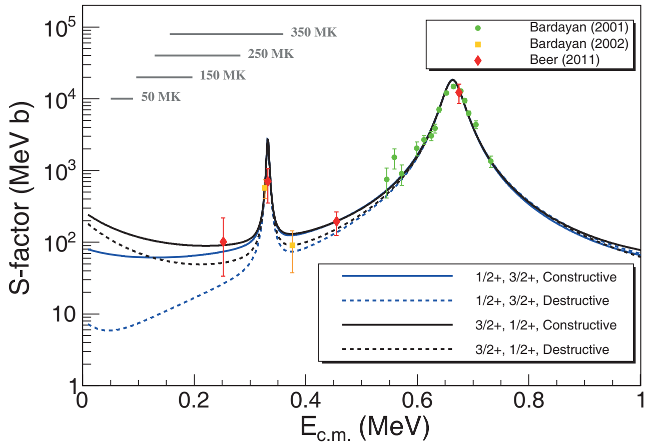

Fig. 3. The astrophysical $S(E)$ for $^{18}\mathrm{F}(p,\alpha)$ is plotted with selected interference signs between $L = 0$ states. The first spin shown in the key represents the assumed spin for the 6.13 MeV state, while the second spin represents the 6.29 MeV state. Calculations where there is a combination of destructive and constructive interference are not included for reasons of visual clarity. These calculations give S-factor curves intermediate between the upper and lower curves in the low energy region. Direct measurements of the S-factor from Bardayan *et al.* (2001) [12], Bardayan *et al.* (2002) [11] and Beer *et al.* (2011) [14] are shown for comparison as the (green) circles, the (orange) squares, and the (red) diamonds, respectively. The Gamow window range for different temperatures are shown in gray in the upper left corner.

$E_{\mathrm{c.m.}} \sim 100$–$500$ keV. The resonances included in our calculations and their properties are listed in table 2. In addition to $L = 0$ states, we also include the $L = 1$ state at 6.742 MeV with measured Γ_{p} strength and demonstrated astrophysical influence [11,14]. Considering subthreshold $L = 0$ states at 6.13 and 6.29 MeV, we have performed calculations for both a $\frac{1}{2}^+$ and $\frac{3}{2}^+$ level ordering and an inversion of this hierarchy. Figure 3 shows calculations for both these configurations allowing for constructive or destructive interference with the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states above the threshold at 7.79 and 7.07 MeV, respectively. The uncertainty caused by the unknown interference sign for a possible $\frac{3}{2}^+$ state at $E_{\mathrm{c.m.}} = 6$ keV is almost negligible in the region of interest and thus its contribution is not depicted. The largest divergence between the calculated rates, corresponding to the lowest value, occurs when the 6.13 MeV state is assigned as $\frac{1}{2}^+$, and there is destructive interference for the $L = 0$ resonances. The direct reaction measurement performed at 250 keV would tend to disfavor this possibility, but clearly further direct measurements at lower energies could decisively rule against this scenario as the rates diverge further as the energy decreases (see fig. 3).

In summary, the first use of the $^{19}\mathrm{F}(^3\mathrm{He},t)^{19}\mathrm{Ne}$ reaction at intermediate energies and forward angles has provided a powerful, model-independent probe of s-wave states influencing the $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction rate in novae.

Table 2. Resonance parameters used in the ^{18}F(p,α) astrophysical calculations. The asymptotic normalization coefficient (ANC) is used for subthreshold states ($E_{\mathrm{c.m.}} < 0$) and the proton partial width, Γ_p, otherwise.

E_{ex} (MeV)	$E_{\mathrm{c.m.}}$ (keV)	$2J^\pi$	ANC, Γ_p (fm$^{-1/2}$), (keV)	Γ_α (keV)
6.132	−278	1^+, 3^+	8^e, $6^{b,e}$	8.6^a, 0.74^a
6.289	−121	3^+, 1^+	59^b, 83.5^b	1.00^a, 11.7^a
6.416	6	3^+	$< 4.2 \times 10^{-45\,b}$	$< 0.5^{\,a}$
6.742	332	3^-	$2.22 \times 10^{-3\,c}$	5.2^a
7.0747	664.7	3^+	15.2^c	23.8^c
7.79	1380	1^+	83^d	47^d

[a] Adopted from mirror level [49,52].
[b] Adopted from ref. [21].
[c] References [11,12].
[d] Present work, using Γ_p/Γ_α from ref. [49].
[e] Corresponds to $\mathcal{S} \approx 0.1$ —a significantly higher value is inconsistent with ^{18}F$(d,p)^{19}$F studies [45,53,54]. The only study showing strength from the $\frac{1}{2}^+$ analog state is ref. [53].

We clearly identified the 6.132 MeV state in ^{19}Ne as a subtheshold s-wave resonance. It was shown that this state could significantly influence the ^{18}F(p,α) reaction rate in nova burning conditions.

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