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The  $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$  reaction produces  $^{19}\text{F}$  in asymptotic giant branch (AGB) stars, where the low energy tails of two resonances at  $E_{c.m.} = 1323 \pm 2$  and  $1487 \pm 1.7$  keV are estimated to contribute about 30% of the total reaction rate in these environments. However, recent measurements have shown discrepancies in the energies, the strengths, and the corresponding alpha widths of these two resonances, resulting in an increase in the systematic uncertainty of the extrapolated cross section to helium burning energies. With this motivation, we have undertaken new measurements of the  $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$  at the University of Notre Dame Nuclear Science Laboratory. The setup consisted of an alpha particle beam impinged on a solid Ti  $^{15}\text{N}$  target with gamma-ray spectroscopy accomplished using a high purity germanium detector. Using the Doppler corrected gamma-ray energies, we confirmed the lower resonance energy to be  $1321.6 \pm 0.6$  keV and found a value for the higher one of  $1479.4 \pm 0.6$  keV that is more consistent with those found from previous elastic scattering studies. We found that the resonance strengths for both were consistent with most values found in the literature, but a larger alpha width has been recommended for the  $E_{c.m.} = 1487$  keV resonance. The larger alpha width suggests a reaction rate increase of about 15% at temperatures  $T < 0.1$  GK relevant to low mass AGB stars. The impact of the increased reaction rate requires further investigations.

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### I. INTRODUCTION

Fluorine is a key element in stellar evolution, geochemical, and biogeochemical systems [1], yet the astrophysical origin of  $^{19}\text{F}$  is still unclear. The abundance of  $^{19}\text{F}$  in the universe is not fully explained by stellar models because of open questions and discrepancies in experimental nuclear physics inputs. Thus, theoretical calculations of  $^{19}\text{F}$  production and destruction rates still have large uncertainties.

Several stellar environments, including core-collapse supernovas [2], Wolf-Rayet stars [3], and asymptotic giant branch (AGB) stars [4], have been proposed to contribute to  $^{19}\text{F}$  production. The element's production has only been observed in AGB stars and the reported abundance was up to 30 times that of solar [4]. However, subsequent studies have revised this number downward by up to a factor of 6 (see Refs. [5–7]) because of corrections to the evaluation of the star spectroscopy [8].

The abundance of  $^{19}\text{F}$  in AGB stars depends on its production and destruction rates. References [9,10] provide detailed reviews on the different  $^{19}\text{F}$  reaction channels in AGB stars. The destruction of  $^{19}\text{F}$  primarily relies on the  $^{19}\text{F}(p,\alpha)^{16}\text{O}$  and  $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$  reactions. The proton capture reaction has

been studied extensively in recent years, reducing the reaction rate uncertainties significantly at relevant temperatures [11–15]. For the alpha capture reaction, the experimental efforts face the challenge of a higher Coulomb barrier. One direct measurement in the energy range  $E_{c.m.} = 0.66$ – $1.6$  MeV has been reported by Ugalde *et al.* [16]. The cross section was measured and an  $R$ -matrix fit was performed. The computed reaction rate at relevant temperatures has large uncertainties of about 50% for most temperatures. Recently, a Trojan horse method (THM) measurement [17] suggested an increase of up to a factor of 4 in the reaction rate at astrophysical temperatures. This uncertainty in the reaction rate further complicates the understanding of  $^{19}\text{F}$ 's destruction rate in AGB stars, especially in higher mass AGB stars where alpha capture reactions are more efficient because of higher temperatures [10].

Several reaction chains have been proposed as the production paths of  $^{19}\text{F}$  in AGB stars, with two leading. The first nuclear reaction chain  $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(p,\alpha)^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$  was proposed by Ref. [4]; however, subsequent AGB modeling calculations suggested the need for additional reaction chains to reproduce the observed abundance. Forestini *et al.* [18] proposed that a second nuclear reaction chain,  $^{14}\text{N}(n,p)^{14}\text{C}(\alpha,\gamma)^{18}\text{O}(p,\alpha)^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ , could also lead to the production of  $^{19}\text{F}$  in AGB stars. Both proposed reaction chains depend on  $^{14}\text{N}$ , the primary composition of the CNO ashes.

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The final stage of both reaction chains depends on the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction, which is the main contributor to the production of  $^{19}\text{F}$  in AGB stars according to model calculations [10]. The reaction rate at AGB temperatures ( $T < 0.3$  GK) mostly depends on alpha direct captures (DC) (dominates at  $T < 0.1$  GK) and narrow resonances, especially the  $E_{c.m.} = 364$  keV resonance with a corresponding  $J^\pi = 7/2^+$ . The  $E_{c.m.} = 364$  keV resonance has been studied only once through an indirect measurement, which resulted in a resonance strength uncertainty of about 100% [19]. It may play an important role in a temperature range between 0.1 and 0.2 GK.

In addition, the low energy tails of two resonances at  $E_{c.m.} = 1323$  and 1487 keV can also contribute to about 30% of the total reaction rate [20] at  $T < 0.1$  GK because of their relatively large total widths (dominated by the alpha widths). To calculate their contributions to the production of  $^{19}\text{F}$ , accurate knowledge of their resonance energies, alpha widths, and resonance strengths is needed. Recent measurements have shown discrepancies for these quantities. In this paper, we present a new gamma-ray spectroscopy study of the  $E_{c.m.} = 1323$  and 1487 keV resonance properties in the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction performed at the University of Notre Dame Nuclear Science Laboratory (NSL) [21]. The experimental method used here is not appropriate to study the DC or the  $E_{c.m.} = 364$  keV resonance contribution because of the extremely low cross sections.

The paper is structured as follows. Section II discusses the literature status on these two resonances. Section III provides a description of our experimental setup, methods employed, and details regarding the target properties. In Sec. IV, we discuss the analysis methods and results obtained from our measurement. We then compare our results with literature values and provide some discussions in Sec. V. In Sec. VI, we compare the astrophysical reaction rates to those given in Iliadis *et al.* [22]. Finally, in Sec. VII, we summarize our results and the future directions this research suggests.

## II. LITERATURE REVIEW

To avoid confusion, as inconsistent reference frames for the  $E_{c.m.} = 1323$  and 1487 keV resonances have been used in the past, we will discuss these two resonances in the center of mass frame and in  $^{19}\text{F}$  excitation energies using masses from AME2020 [23].

### A. Review of the study of the $J^\pi = 1/2^+$ , $E_x = 5337$ keV level or $E_{c.m.} = 1323$ keV resonance

Price [24] first directly measured this resonance in 1957 in forward kinematics with thick tantalum nitride solid targets, which were made by heating tantalum foils in an atmosphere of  $^{15}\text{N}$  enriched ammonium nitrate. The emitted gamma rays were detected by NaI(Tl) crystals. Using nuclear mass values available at the time [25], Price [24] determined the alpha beam energy corresponding to the resonance from the thick-target yield and converted it to an excitation energy of  $5313 \pm 3.9$  keV. When revised using modern mass tables [23], the excitation energy becomes  $5341 \pm 3.9$  keV.

This excitation energy was later measured again by Rogers *et al.* [26]. Instead of relying on beam energy, they measured the emitted gamma-ray energies and determined that the corresponding excitation energy was at  $E_x = 5336 \pm 2$  keV, a value consistent with that given in Price [24]. This excitation energy was further solidified by experiments populating the state with channels other than  $(\alpha, \gamma)$  and the excitation energy reported in the compilation [27] was determined to be  $5337 \pm 2$  keV (see Table 19.9 in the compilation [27] and references therein).

However, this excitation energy has recently been challenged by Di Leva *et al.* [20], who proposed a larger value of  $E_x = 5345.2 \pm 1.6$  keV (deduced from the reported center of mass energy) from their inverse kinematics studies with the European Recoil Separator for Nuclear Astrophysics. In addition, using the Detector of Recoils and Gamma-Rays of Nuclear Reactions (DRAGON) at TRIUMF, Canada, Frost-Schenk [28] also investigated this resonance in inverse kinematics and reported the resonance to be at  $E_x = 5337.4 \pm 0.3$  (deduced from the reported center of mass energy) although the work has not been peer reviewed. Most recently, Neto *et al.* [29] performed the time-inverse photodissociation measurement  $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ . They reported an excitation energy of  $5345 \pm 15$  keV, adding more uncertainties to the exact excitation energy of this level. Therefore, one of the motivations of this paper is to investigate the excitation energy of this level.

Resonance strength studies were pioneered by Aitken *et al.* [30] followed by Dixon and Storey [31]. They first reported a resonance strength of  $\omega\gamma = 1.30 \pm 0.20$  eV, making a measurement relative to the  $E_\alpha = 1532$  keV resonance in the  $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}$  reaction [32]. Dixon and Storey [31] reported three different resonance strengths in their study. First, they made the same type of relative resonance strength measurements and reported a resonance strength of  $\omega\gamma = 1.63 \pm 0.20$  eV. They then also did a relative measurement to the  $E_p = 898$  keV resonance in the  $^{15}\text{N}(p, \alpha_1\gamma)^{12}\text{C}$  reaction and found  $\omega\gamma = 1.72 \pm 0.20$  eV. Lastly, they reported an absolute measurement finding  $\omega\gamma = 1.5 \pm 0.3$  eV. Their recommended resonance strength was the weighted average of all three methods  $\omega\gamma = 1.64 \pm 0.16$  eV, which has been reported in the latest compilation [27]. However, a reevaluation of this value is necessary due to updates in the resonance strengths of reactions that Dixon and Storey [31] relied on for their relative measurements. See the Appendix for details.

More recently, Wilmes *et al.* [33] and Di Leva *et al.* [20] reported measurements of the  $E_{c.m.} = 1323$  keV resonance strength that are compatible with Dixon and Storey [31]. On the other hand, Frost-Schenk [28] reports a resonance strength of  $\omega\gamma = 0.92 \pm 0.11$  eV, which is 40% lower than those in Refs. [20,31,33]. The discrepancy needs to be investigated further because the strength of this resonance is used to normalize the strengths of 17 others in the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction at higher energy [26,34]. Any change to the  $E_{c.m.} = 1323$  keV resonance strength would therefore have a significant impact on the reaction rate over a wide temperature range. A summary of the values from the literature for this level has been presented in Figs. 1(a) and 6(a).

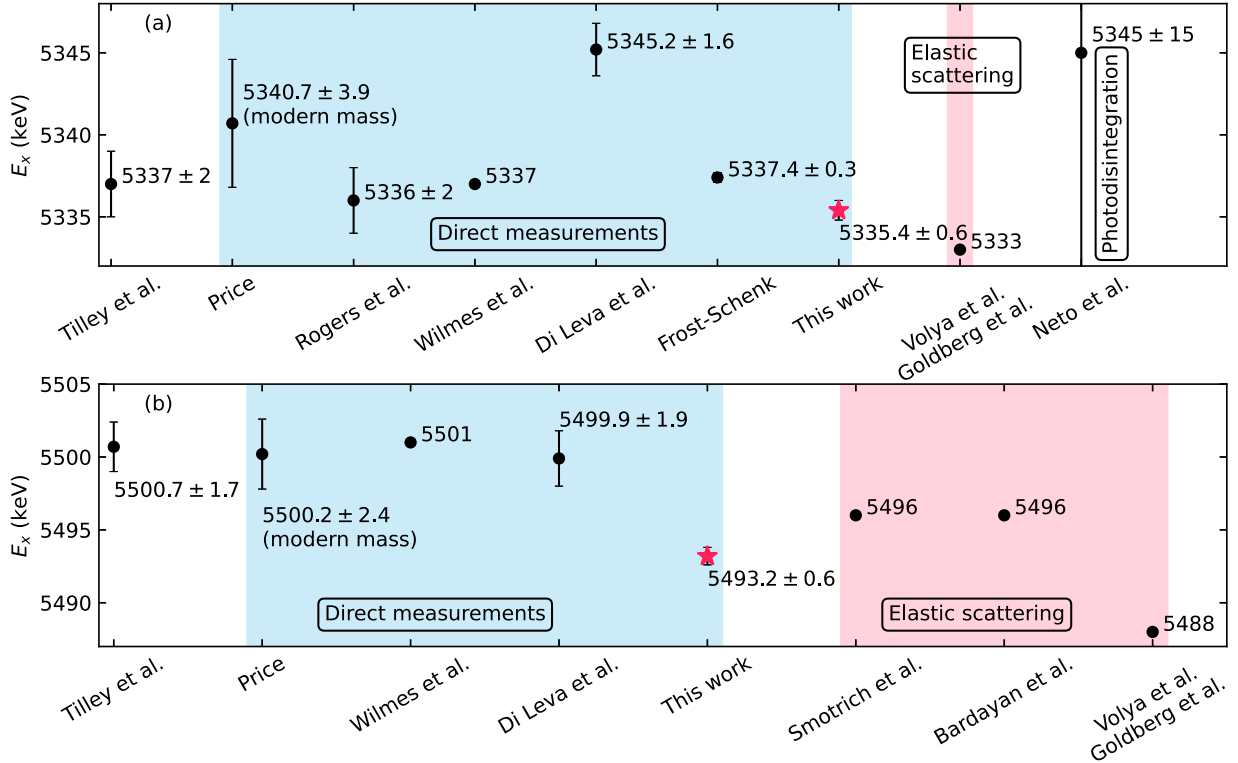


FIG. 1. Status of this paper and literature (a) on the  $E_x = 5337$  keV excitation energy and (b) on the  $E_x = 5501$  keV excitation energy. Different methods of studying these two excitation energies are labeled and shaded accordingly.

### B. Review of the study of the $J^\pi = 3/2^+$ , $E_x = 5501$ keV level or $E_{c.m.} = 1487$ keV resonance

Direct ( $\alpha$ ,  $\gamma$ ) studies of the  $E_x = 5501$  keV level are limited in the literature. Price [24] first determined its energy to be  $E_x = 5500 \pm 2.4$  keV (revised using modern mass tables) in the same measurement campaign where the lower energy level was investigated. The next direct energy measurement of this level was made by Di Leva *et al.* [20] in inverse kinematics, which is consistent with that of Price [24].

Properties of this state have also been investigated using elastic scattering. Smotrich *et al.* [35]'s study found this level to have an excitation energy of 5475 keV. However due to change in nuclear masses, revisions have become necessary, motivating reanalysis of part of the original data of their work, at  $\theta_{c.m.} = 169.1^\circ$  and excitation energy up to 7300 keV, by Bardayan *et al.* [36]. They concluded that the excitation energy should be 5496 keV, suggesting a lower value for this state. Using elastic scattering and gamma-ray spectroscopy studies, Wilmes *et al.* [33] claimed that they confirmed the excitation energy of this state as well, which is the value adopted by the compilation [27]. However, they did not provide the data used to reach this conclusion and the uncertainties were not discussed in detail. More recently, Volya *et al.* [37] and Goldberg *et al.* [38] again reanalyzed the data from Smotrich *et al.* [35], where they included the data at all measured angles and over the complete energy region up to 8330 keV excitation energy. In addition, they also measured the excitation functions of the elastic scattering of several low lying and broad resonances including the corresponding  $E_x = 5501$  keV

state. They concluded that the excitation energy of this level is 5488 keV, indicating that a lower energy is more likely.

To date, only two publications discuss the corresponding resonance strength of this level. One is the inverse kinematics measurement of Di Leva *et al.* [20] and the other is that of Wilmes *et al.* [33]. Yet, these resonance strengths are inconsistent with each other. It is also worth mentioning that a third value is proposed in the compilation [27], but it is a value deduced by Rogers from the resonance strength corresponding to the  $E_x = 5337$  keV level from Ref. [31] through a private communication (see Table 19.7 in Ref. [39]). This calculated value has a 25% uncertainty, which makes it compatible with the published values in Wilmes *et al.* [33] and Di Leva *et al.* [20]. A summary of the literature for this level is presented in Figs. 1(b) and 6(b).

### III. EXPERIMENTAL SETUP AND PROCEDURES

The experiment discussed here aims to address the literature discrepancies in the energies (see Fig. 1) and strengths of the  $E_{c.m.} = 1323$  and 1487 keV resonances. Additionally, this paper investigates discrepancies in the total widths (dominated by the alpha width) as shown in Fig. 2, which may impact the reaction rates at temperatures relevant to AGB stars by up to 15% [20].

The experiment was performed at the NSL using the 5 MV Stable Ion Accelerator for Nuclear Astrophysics (Sta. ANA). A singly ionized  $^4\text{He}^+$  beam was produced over a laboratory energy range from  $E_\alpha = 1.6$  to 1.9 MeV with typical

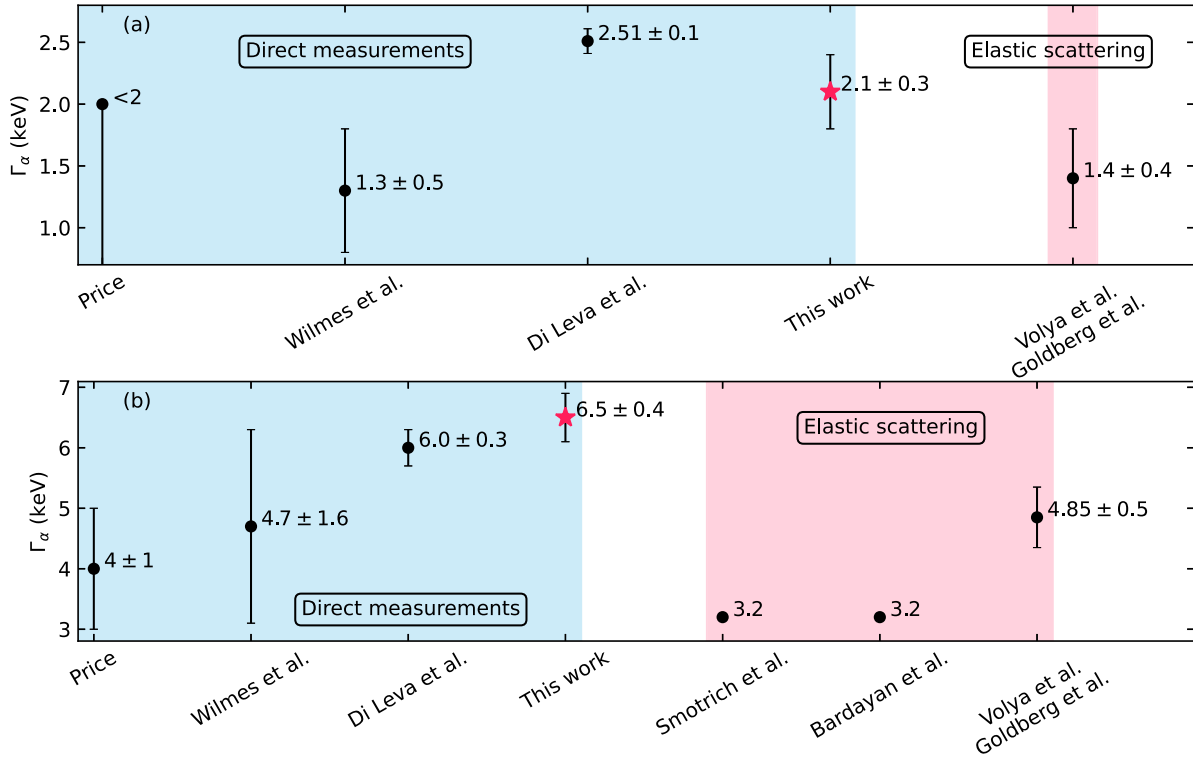


FIG. 2. Status of this paper and literature (a) on the  $E_x = 5337$  keV alpha width and (b) on the  $E_x = 5501$  keV alpha width. Different methods of studying these two alpha widths are labeled and shaded accordingly.

beam intensities of  $\approx 10$  e  $\mu$ A on a Ti  $^{15}\text{N}$  target with a thick Ta backing. The energy uncertainty of the beam was measured to be better than 1 keV using the well-known, narrow,  $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$  resonance at  $E_p = 992$  keV [40].

The targets were mounted on a target holder tilted at  $45^\circ$  with respect to the beam axis. To keep the targets from overheating under beam bombardment, the target backings were water cooled. A copper tube cold trap, biased to  $-400$  V and cooled with liquid nitrogen, was installed in front of the target to limit carbon buildup and suppress secondary electrons from the target. The position of the beam at the target location was defined by a pair of vertical and horizontal slits. Moreover, the scintillation light emitted by the interaction of the beam and the target was observed continuously to monitor the beam position.

Gamma rays were detected using a high purity germanium (HPGe) detector with a relative efficiency of 104%. The HPGe detector was mounted on an electrically isolated sliding platform, allowing for convenient adjustment of the distance between the detector and the target. The majority of the measurements were conducted at a close distance of 4.4 cm from the target. In addition, a few measurements were performed at a farther distance of 20 cm to evaluate and correct for summing effects and the relative efficiency between the close and far distance setups. To mitigate angular distribution effects, the detector was positioned at an angle of  $55^\circ$  relative to the beam axis, as this angle corresponds to the minimum of the second-order Legendre polynomial [41].

### A. Target

The Ti  $^{15}\text{N}$  target was fabricated at the Forschungszentrum Karlsruhe through reactive sputtering of Ti in a 99.5% enriched  $^{15}\text{N}$  environment. LeBlanc *et al.* [42] verified the target's stoichiometry to be within a tolerance of  $\leq 2\%$  compared to the nominal stoichiometry of 1:1.

The energy loss of the beam in the target at  $E_{c.m.} = 1323$  keV was deduced from the excitation function (see Sec. IV B) to be  $11.7 \pm 0.7$  keV in the center of mass frame using the full width at half maximum (FWHM) from the thick target yield. The stability of the target was verified by checking the yield of the  $E_{c.m.} = 1323$  keV resonance at various times throughout the experiment. No target material loss was observed during the close distance measurements. However, a 23% reduction in Ti  $^{15}\text{N}$  content was observed after depositing 0.7 C of beam from the longer duration, far distance, measurements at  $E_{c.m.} = 1323$  keV. In addition, the uncertainty in the alpha width of the  $E_{c.m.} = 1487$  keV resonance prevented the use of the FWHM method to deduce the energy loss for this resonance. For this reason, the energy loss of the beam in the target for the  $E_{c.m.} = 1487$  keV resonance measurement was determined to be  $8.5 \pm 0.7$  keV in the center of mass frame by scaling the beam energy loss determined from the  $E_{c.m.} = 1323$  keV excitation function to the corresponding stopping power as a function of beam energy [43] and accounting for the target material loss. No additional target degradation was observed for the  $E_{c.m.} = 1487$  keV close distance excitation function measurements.



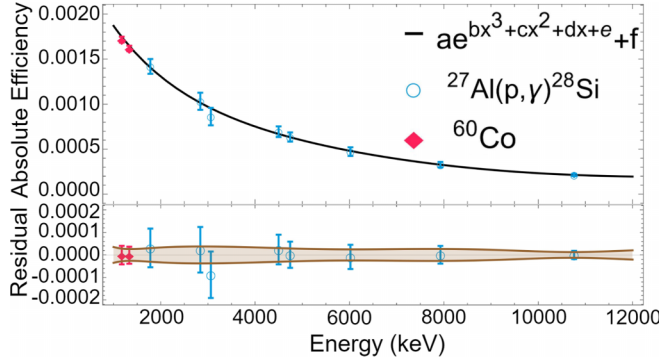


FIG. 3. Absolute efficiency curve for the HPGe detector. The measured photopeak efficiencies were fitted with an exponential function indicated by the solid line. The  $1\sigma$  confidence band is shown as the shaded region in the residual plot.

### B. HPGe detector

The energy calibration of the detector and the determination of its absolute efficiency were carried out using a calibrated  $^{60}\text{Co}$  source and the  $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$  resonance at  $E_p = 992$  keV. The branching ratios, angular distributions, and the absolute yield of  $(1.08 \pm 0.06) \times 10^{-9}$  gamma rays (1779 keV) per incident proton were well known for this resonance [44].

The detector energy calibration was characterized with a few gamma-ray transitions from the populated excited state of  $^{28}\text{Si}$ . To accurately determine the resonance energy of the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction, a precise energy calibration of the HPGe detector was necessary. Corrections for the Doppler shift and recoil shift in the measured gamma-ray energies were considered and the calibration was thus determined to better than 1 keV between  $E_\gamma = 1.2$  and 10.8 MeV.

The absolute efficiency curve for the HPGe detector was obtained as shown in Fig. 3. The efficiency at higher energies was normalized to the efficiency of the 1779 keV gamma ray from the  $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$  resonance. The low-energy end was obtained from a calibrated  $^{60}\text{Co}$  source. The uncertainty in the absolute efficiency was dominated by the yield uncertainty of the  $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$  resonance, which was known to better than  $\pm 7\%$  in the energy region of interest.

## IV. RESULTS

### A. Resonance energy

The excitation functions over the  $E_{c.m.} = 1323$  and 1487 keV resonances in the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction were measured. Figure 4 shows the gamma-ray spectrum for both resonances. All measurements were performed at  $55^\circ$  relative to the beam axis. No peaks associated with background or target contamination interfered with the gamma rays of interests over the 0–10 MeV range of the spectrum. The measured gamma-ray energy  $E_{\gamma, m}$  at an angle  $\theta$  relative to the beam axis is related to the excitation energy by (adapted from

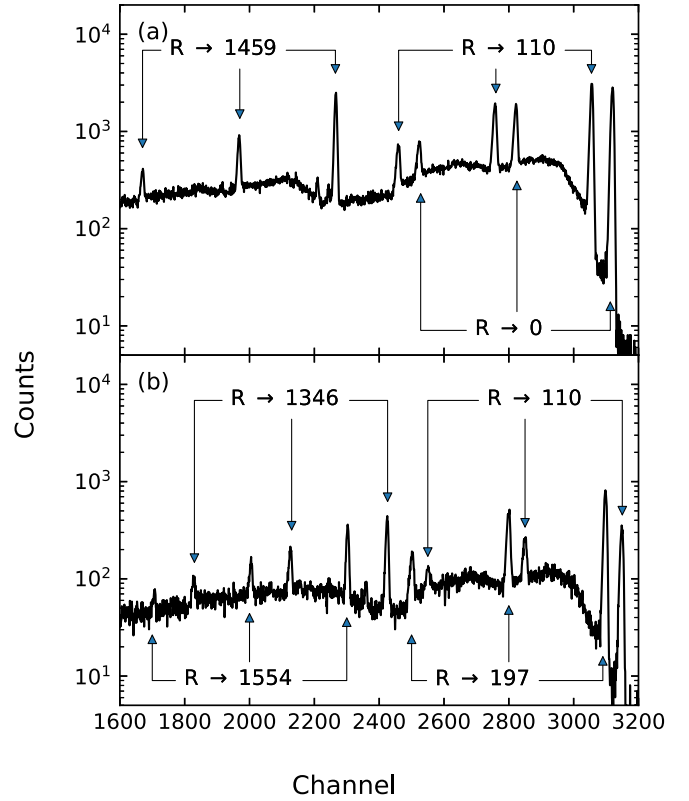


FIG. 4. The energy spectrum measured by the HPGe detector when populating (a) the  $E_x = 5337$  keV state and (b) the  $E_x = 5501$  keV state using the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction. Transitions, including the single and double escape peaks to different final states, are labeled in each panel.

Ref. [45])

$$E_{\gamma, m} = E_x - E_f + 4.63367 \times 10^{-2} \frac{\sqrt{m_a(E_x - Q)(m_a + m_A)}/m_A}{m_B} \times (E_x - E_f) \cos \theta - 5.36772 \times 10^{-4} \frac{(E_x - E_f)^2}{m_B}, \quad (1)$$

where  $E_f$  is the final state energy,  $Q$  is the  $Q$  value of the reaction, and  $m_a$ ,  $m_A$ , and  $m_B$  are masses of the projectile, target, and product nuclei, respectively. Here, all energies are in units of MeV and the masses are in units of u.

Using the gamma transitions to the ground state (GS),  $E_x = 109.894$  keV state, and  $E_x = 1458.7$  keV state [27] and correcting the measured gamma-ray energies for the Doppler shift as described by Eq. (1), three excitation energies are found and shown in Table I. The weighted average of those three values results in an excitation energy of  $E_x = 5335.4 \pm 0.6$  keV or  $E_{c.m.} = 1321.6 \pm 0.6$  keV for this state.

Using the same approach for the  $E_{c.m.} = 1487$  keV resonance, the energy for each transition could be determined individually. The results for each transition from the populated  $E_{c.m.} = 1487$  keV resonance are presented in Table II. The weighted average of the corresponding excitation energy

TABLE I. Doppler shift corrected photopeak energies for the  $E_{c.m.} = 1323$  keV resonance in the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction.

$E_\gamma^a$ (keV)	$E_f^b$ (keV)	$E_x^a$ (keV)	$E_{c.m.}^a$ (keV)
5335.3(9)	GS	5335.3(9)	1321.5(9)
5225.9(9)	109.894(5)	5335.8(11)	1322.0(11)
3876.4(9)	1458.7(3)	5335.1(10)	1321.3(10)
Weighted avg.		5335.4(6)	1321.6(6)

<sup>a</sup>This paper.

<sup>b</sup>Ref. [27].

deduced from the four transitions is  $E_x = 5493.2 \pm 0.6$  keV ( $E_{c.m.} = 1479.4 \pm 0.6$  keV).

### B. Resonance strength

The general expression for the experimental yield is [45]

$$Y(E_0) = \int_{E_0 - \Delta E}^{E_0} dE' \int_{E_i=0}^{E_i} dE_i \times \int_{E=0}^{E_i} \frac{\sigma(E)}{\epsilon(E)} g(E_0 - E_i) f(E_i - E, E') dE, \quad (2)$$

for a beam of mean energy  $E_0$ , an energy distribution  $g(E_0 - E_i)$ , stopping power  $\epsilon(E)$ , energy loss in the target  $\Delta E$ , and energy loss and straggling described by  $f(E_i - E, E')$ .

Assuming the resonance cross section follows the Breit-Wigner distribution, and that the effective stopping power  $\epsilon_{\text{eff}}$ , the de Broglie wavelength  $\lambda_r$ , and the corresponding partial widths  $\Gamma_i$  of the resonance can be treated as independent of the energy over the resonance width, the experimental yield can be expressed as

$$Y(E_0) = \frac{\lambda_r^2 \omega\gamma}{2\pi \epsilon_{\text{eff}}} \left[ \arctan \left( \frac{E_0 - E_r}{\sqrt{\Gamma^2 + \Delta_{\text{beam}}^2/2}} \right) - \arctan \left( \frac{E_0 - E_r - \Delta E}{\sqrt{\Gamma^2 + \Delta_{\text{beam}}^2 + \Theta_{\text{target}}^2/2}} \right) \right], \quad (3)$$

where  $\Delta E$ ,  $\Delta_{\text{beam}}$ , and  $\Theta_{\text{target}}$  represent the beam energy loss in the target, beam energy resolution, and target inhomogeneity effect, respectively. The effective stopping

TABLE II. Doppler shift corrected photopeak energies for the  $E_{c.m.} = 1487$  keV resonance in the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction.

$E_\gamma^a$ (keV)	$E_f^b$ (keV)	$E_x^a$ (keV)	$E_{c.m.}^a$ (keV)
5383.7(22)	109.894(5)	5493.6(22)	1479.8(22)
5296.6(9)	197.143(4)	5493.7(11)	1479.9(11)
4147.1(10)	1345.67(13)	5492.8(11)	1479.0(11)
3938.7(13)	1554.038(9)	5492.8(14)	1479.0(14)
Weighted avg.		5493.2(6)	1479.4(6)

<sup>a</sup>This paper.

<sup>b</sup>Ref. [27].

power in the center of mass frame is [45]

$$\epsilon_{\text{eff}} = \frac{m_{^{15}\text{N}}}{m_{^4\text{He}} + m_{^{15}\text{N}}} \left[ \epsilon_{^{15}\text{N}} + \left( \frac{N_{\text{Ti}}}{N_{^{15}\text{N}}} \right) \epsilon_{\text{Ti}} \right], \quad (4)$$

where  $m_{^4\text{He}}$  and  $m_{^{15}\text{N}}$  are the masses of the beam and active target nuclei in units of u,  $N_{\text{Ti}}/N_{^{15}\text{N}}$  is the stoichiometry of the target, and  $\epsilon_{^{15}\text{N}}$  and  $\epsilon_{\text{Ti}}$  are the stopping powers of the beam in  $^{15}\text{N}$  and Ti respectively. The stopping powers were obtained from the computer code SRIM [43]. At the two resonance energies under study in this paper, the uncertainties of these stopping powers are 5 and 4% for  $^{15}\text{N}$  and Ti, respectively [46].

For the analysis of the  $E_{c.m.} = 1323$  keV resonance, where the populated level has a  $J^\pi = 1/2^+$ , the emitted gamma rays are isotropic. However, the gamma-ray emission of the  $E_{c.m.} = 1487$  keV resonance is not expected to be isotropic because this level has a  $J^\pi = 3/2^+$ . Nevertheless, the HPGe detector location at  $55^\circ$  strongly reduces the dependence on higher order Legendre polynomial contributions to the gamma-ray yield [45]. Price [24] has also demonstrated that the fourth order Legendre polynomial is negligible. Therefore, angular distribution corrections are negligible for this resonance as well with the present setup.

The excitation functions for both resonances were fitted with Eq. (3) using the least square fit (LSF) method with the free parameters  $\omega\gamma$ ,  $\Gamma$  ( $\approx \Gamma_\alpha$ ), and  $\Theta_{\text{target}}$ . The best fits are shown in Fig. 5. The yield point-to-point uncertainties in the figure are only the statistical uncertainties. The reduced  $\chi^2$  of each best fit was 4.35 and 2.27 for the lower and higher energy resonance, respectively. The uncertainties of  $\omega\gamma$  and  $\Gamma$  ( $\approx \Gamma_\alpha$ ) were estimated using a Monte Carlo (MC) procedure. The excitation functions were fitted numerous times with the value of both the target thickness and the stopping power of the beam being randomly generated on a Gaussian distribution with their systematic uncertainty as the standard deviation. The standard deviation of the distributions of the  $\omega\gamma$ ,  $\Gamma_\alpha$ , and  $\Theta_{\text{target}}$  resulting from 10 000 iterations was added quadratically to the statistical uncertainty of the original LSF resulting in the total fitting procedure uncertainty on those parameters.

For the resonance strength  $\omega\gamma$ , in addition to uncertainties determined from the MC procedure described above, the uncertainties in the branching ratios of the primary gamma transitions, the efficiency of the detector, the summing effect, and the charge collection are treated as common-mode systematic uncertainties, which are propagated to deduce the final uncertainties of the resonance strength. Table III summarized the systematic uncertainties for the two resonance strengths.

## V. DISCUSSION

We determined the resonance energy, strength, and total width ( $\approx$  alpha width) for the two resonances of interest and their values as shown in Figs. 1, 2, and 6, respectively. We first discuss the resonance energy for both resonances studied here. For the lower energy resonance, the corresponding excitation energy of  $5335.4 \pm 0.6$  keV, determined from this paper, is compatible with the accepted value in the compila-

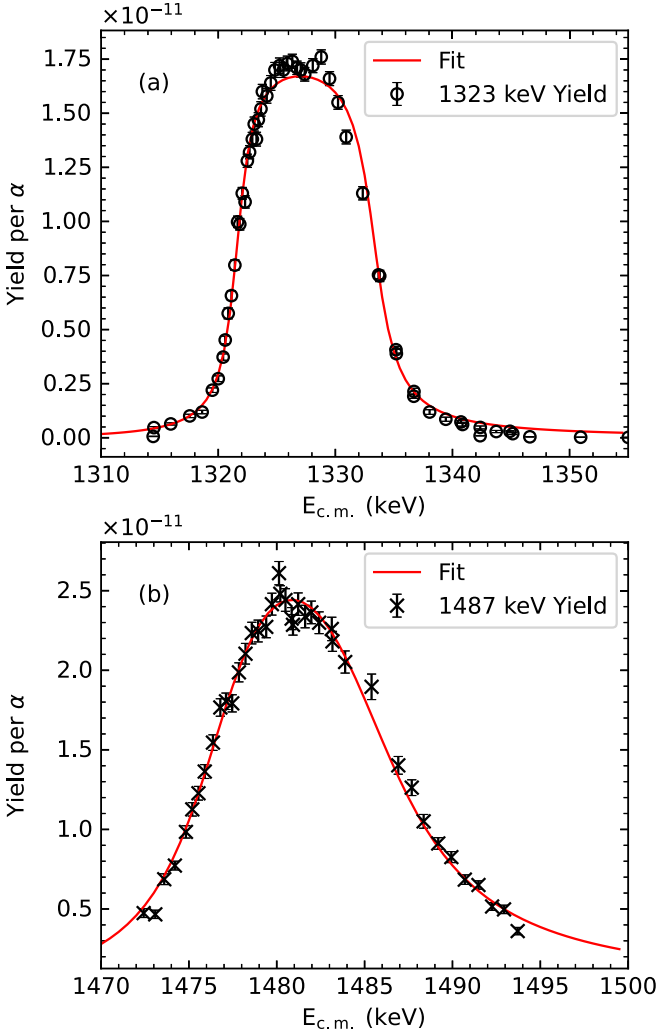


FIG. 5. Yield per incident  $\alpha$  particle for the (a)  $E_{c.m.} = 1323$  keV and (b)  $E_{c.m.} = 1487$  keV resonances, obtained using the close geometry setup described in Sec. III. The red lines indicate the fits to the data using Eq. (3).

tion [27], as well as those of Price [24], Rogers *et al.* [26], and Frost-Schenk [28]. This suggests that the proposed value of  $E_x = 5345.2 \pm 1.6$  keV in Ref. [20] is unlikely, thus further investigation is required. For the  $E_x = 5501$  keV level, our result of  $5493.2 \pm 0.6$  keV is 7.5 keV lower than the accepted value of  $E_x = 5500.7 \pm 1.7$  keV [27]. Contrary to most prior

TABLE III. Summary of systematic uncertainties for  $\omega\gamma$ .

Relative contribution	$\omega\gamma_{1323 \text{ keV}}$ (%)	$\omega\gamma_{1487 \text{ keV}}$ (%)
MC procedure	7.9	9.3
Branching ratio [33]	2.7 ( $R \rightarrow 110$ )	3.5 ( $R \rightarrow 197$ )
$\epsilon_{\text{det}}$	4.6	4.6
Summing effect	0.6	0.6
Charge collection	3.0	3.0
Target degradation		2.6
Total	10.0	11.7

studies, our analysis is independent from the beam energy. In addition, as discussed in Sec. II B, the analysis of elastic scattering data [36,37] showed additional evidence that the corresponding level energy may be lower than the accepted value.

The strengths obtained from this paper are compared with those from the literature as shown in Fig. 6. For the  $E_x = 5337$  keV level, our corresponding resonance strength of  $1.65 \pm 0.17$  eV is compatible with the accepted value of  $1.64 \pm 0.16$  eV [27], and most of the literature values. However, the reevaluation of Dixon and Storey [31]’s work (see the Appendix) using the updated resonance strengths for the reactions that were used for the relative measurements gives a much lower value of  $1.26 \pm 0.10$  eV, and this is somewhat inconsistent with others in the literature (see Fig. 6). Given the result of this paper and those of Wilmes *et al.* [33] and Di Leva *et al.* [20], the accepted value [27] of  $1.64 \pm 0.16$  is favored over the reevaluated one. Nevertheless, as Rogers *et al.* [26] and Dixon and Storey [34] rely on the strength corresponding to the  $E_x = 5337$  keV level to normalize the corresponding strengths of several higher energy levels in  $^{19}\text{F}$ , additional studies are needed. For the  $E_x = 5501$  keV level’s corresponding resonance strength, our result of  $4.20 \pm 0.49$  eV is compatible with the two published values in Wilmes *et al.* [33] and Di Leva *et al.* [20], and the accepted value of  $4.2 \pm 1.1$  eV in the compilation [27].

Finally, the alpha width for the  $E_x = 5337$  keV level determined from this paper is compatible with those of Refs. [24,33,37,38]. However, the larger alpha width proposed by Di Leva *et al.* [20] is incompatible with our paper. For the  $E_x = 5501$  keV level, our result confirms the larger alpha width suggested by Di Leva *et al.* [20] and is compatible with those of Refs. [24,37,38]. The discrepancies of the alpha width for both levels require further investigations, as they have a large impact on the astrophysical reaction rates of the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction at temperatures relevant to low mass AGB stars, which we discuss in the following section.

## VI. ASTROPHYSICAL REACTION RATES

The total reaction rate for the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction was determined using the computer code RATESMC+ [47], which calculates total reaction rate and uncertainty from resonant and nonresonant input parameters using the Monte Carlo method described in Longland *et al.* [48].

Using the RATESMC+ input file provided in Ref. [49], which includes resonances in the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction from  $E_{c.m.} = -15$  to 6397 keV, and modifying it for the two resonances using parameters found in this paper and those of Di Leva *et al.* [20], two reaction rates are calculated. The comparison between those two rates and that of Iliadis *et al.* [22] is presented in Fig. 7.

For  $T < 0.1$  GK, Di Leva *et al.* [20] and Buompane *et al.* [50] suggested an increase of about 15% to the median reaction rates due to the increased alpha widths for both resonances, while the uncertainty has been reduced by about 5%. Both of these suggestions are confirmed by this paper

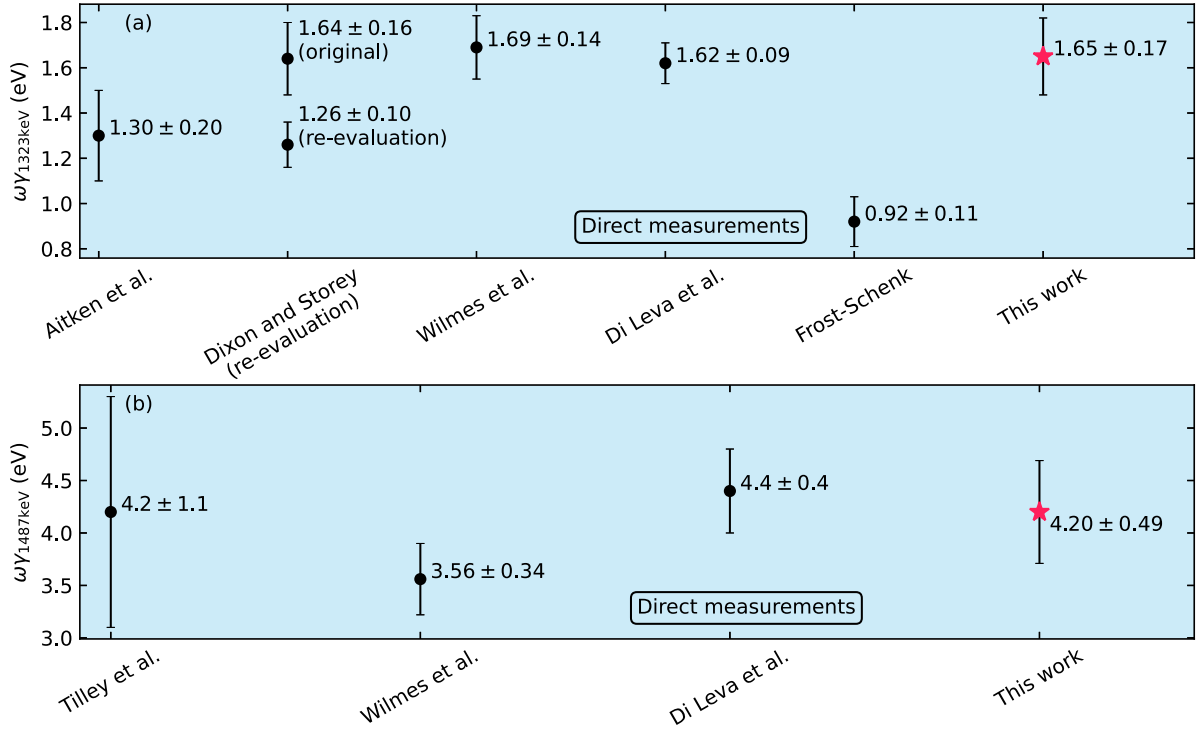


FIG. 6. (a) Comparison of  $\omega\gamma(E_{c.m.} = 1323$  keV) from this paper and from Refs. [20,28,30,31,33]. The reevaluation of Dixon and Storey [31] is discussed in the Appendix. (b) Comparison of  $\omega\gamma(E_{c.m.} = 1487$  keV) from this paper and from Refs. [20,27,33].

for the same reasons. In addition, our paper has reduced the reaction rate upper limit by about 5% at temperatures near 0.1 GK. The impact of the updated reaction rates at temperatures relevant to AGB stars will be investigated and discussed elsewhere.

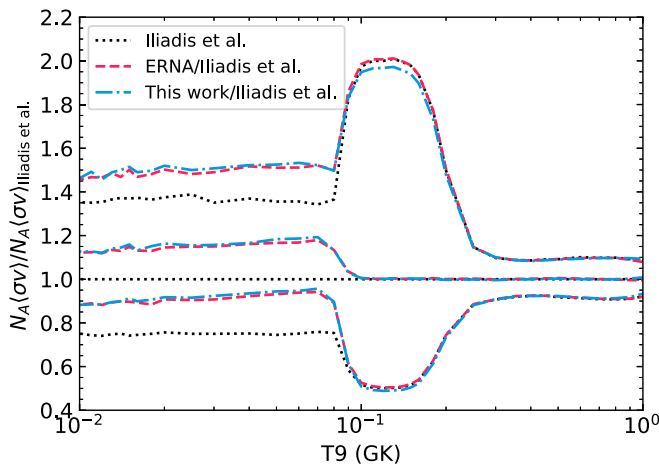


FIG. 7. Ratio of the total reaction rates calculated from this paper and Di Leva *et al.* [20] to that of Iliadis *et al.* [22], including respective error bands. The ratio of this paper is shown in blue dash-dotted lines, Di Leva *et al.* [20] is shown in red dashed lines, and Iliadis *et al.* [22] is shown in black dotted lines.

## VII. SUMMARY AND CONCLUSION

The resonances at  $E_{c.m.} = 1323$  and 1487 keV in the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction have been studied using gamma spectroscopy. We determined the excitation energies of these two resonances. Our results are consistent with the accepted value of  $1323 \pm 2$  keV for the lower energy resonance, but differ from the value of  $1331.4 \pm 1.6$  keV reported in Ref. [20]. For the higher energy resonance, our measurement indicates an energy that is 7.5 keV lower than the accepted value of  $1487 \pm 1.7$  keV. This value is consistent with the elastic scattering measurements of Smotrich *et al.* [35], Volya *et al.* [37], and Goldberg *et al.* [38], but is not consistent with other radiative capture measurements. We recommend a value of  $5493.2 \pm 0.6$  keV for the excitation energy, or a center of mass energy of  $1479.4 \pm 0.6$  keV for this resonance.

Although the  $E_{c.m.} = 1323$  keV resonance strength in the compilation [27] should be updated with those of the latest measurements, we found the original published value is compatible with our present paper. The two resonance strengths studied in this paper are consistent with most literature values. An updated reaction rate is calculated using our results for the higher resonance energy, the alpha widths, and resonance strengths. We confirmed the 15% reaction rate increase at  $T < 0.1$  GK from Ref. [20], a temperature range important for low mass AGB stars, indicating that the increased reaction rate impact to the  $^{19}\text{F}$  abundance in AGB stars needs further investigation.



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**APPENDIX: REEVALUATION OF THE  $E_{c.m.} = 1323$  keV ( $E_x = 5337$  keV) RESONANCE STRENGTH OF DIXON AND STOREY [31]**

In Dixon and Storey [31], three values have been reported for the  $E_{c.m.} = 1323$  keV resonance strength (see Sec. II B). They reported a resonance strength relative to that of the yield of the  $E_\alpha = 1532$  keV resonance in the  $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}$  reaction given by Parker [32]. They first corrected a mistake in Parker [32] by properly treating the  $E_\alpha = 1532$  keV resonance strength in the center-of-mass frame. Then, using updated stopping power tables, they concluded that the corrected resonance strength of the  $E_\alpha = 1532$  keV resonance in the  $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}$  reaction was  $\omega\gamma(^{18}\text{F}; 1532 \text{ keV}) = 1.34 \pm 0.11$  eV [31]. We reevaluated this strength by comparing the yield of the resonances at  $E_\alpha = 1140$  and  $1532$  keV that were provided in Parker [32]. Using the more recent  $E_\alpha = 1140$  keV resonance strength of Görres *et al.* [51] and modern stopping power tables [43], we calculated an updated resonance strength for the  $E_\alpha = 1532$  keV resonance of  $1.20 \pm$

0.09 eV by comparing the ratio of these two strengths:

$$\begin{aligned} \frac{\omega\gamma(^{18}\text{F}; 1532 \text{ keV})}{\omega\gamma(^{18}\text{F}; 1140 \text{ keV})} &= \frac{\epsilon_r(1532) \lambda_r^2(1140) Y(1532)}{\epsilon_r(1140) \lambda_r^2(1532) Y(1140)} \\ &= \frac{\epsilon_r(1532) E_r^{\text{lab}}(1532) Y(1532)}{\epsilon_r(1140) E_r^{\text{lab}}(1140) Y(1140)}. \end{aligned} \quad (\text{A1})$$

With this new value, we updated the Ref. [31] resonance strength for the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  resonance to  $1.46 \pm 0.17$  eV, about 10% lower than the original published value.

Dixon and Storey [31] also calculated the relative strength using the  $E_p = 898$  keV resonance in the  $^{15}\text{N}(p, \alpha_1\gamma)^{12}\text{C}$  reaction reported by Gorodetzky *et al.* [52], whereas Ref. [31] calculated the resonance strength for the  $E_p = 898$  keV resonance as  $480 \pm 48$  eV. Using a more recent publication [53] for the strength of the  $E_p = 898$  keV resonance, we calculated a value of  $293 \pm 38$  eV, which is almost 40% lower than that of Dixon and Storey [31]. Zijderhand and van der Leun [53] report that their significant decrease in the  $E_p = 898$  keV resonance strength likely comes from a background contribution from the  $^{15}\text{N}(p, \alpha_0)^{12}\text{C}$  reaction in which the  $^{12}\text{C}$  (GS) recoils were not accounted for in the charged particle spectroscopy of Ref. [52]. With this updated value, the strength of the  $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$  reaction that corresponds to the  $E_x = 5337$  keV level was reduced to  $1.05 \pm 0.15$  eV. The primary source of uncertainty was from the uncertainty in the strength of the  $(p, \alpha_1\gamma)$  resonance. Following the Dixon and Storey [31] approach, the weighted average of the results of the two reevaluated relative methods and the absolute resonance strength reported in their work yields  $\omega\gamma = 1.26 \pm 0.10$  eV (see Fig. 6), significantly lower than their original weighted average strength of  $1.64 \pm 0.16$  eV.

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