Alpha-decay branching ratios of near-threshold states in $^{19}$Ne and the astrophysical rate of $^{15}$O($\alpha,\gamma$)$^{19}$Ne

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Novae are thermonuclear runaways initiated by the accretion of hydrogen- and helium-rich material from stellar companions onto the surfaces of white dwarfs in binary systems. Energy production and nucleosynthesis in the hottest novae are determined principally by the CNO, NeNa, and MgAl cycles. Under high temperature and density conditions, e.g., in accreting neutron stars, breakout from the hot CNO cycles into the $rp$ process occurs, dramatically increasing the luminosity of outbursts and synthesizing nuclei up to masses of 100 u. Several reactions have been suggested as pathways for this breakout, but only two are currently thought to be possibilities: $^{15}$O($\alpha,\gamma$)$^{19}$Ne and $^{18}$Ne($\alpha,p$)$^{21}$Na. In astrophysical environments the $^{15}$O($\alpha,\gamma$)$^{19}$Ne reaction proceeds predominantly through resonances lying just above the $^{15}$O($\alpha$) threshold at 3.529 MeV in $^{19}$Ne, as the direct capture component is very small by comparison. The reaction rate in novae is determined by the $\alpha$-width $\Gamma_\alpha$ of the 4.033 MeV $3/2^+$ state, owing both to its close proximity to the $^{15}$O($\alpha$) threshold and its low centrifugal barrier to $\alpha$-capture.

A previous attempt to determine $\Gamma_\alpha$ for this state was based upon measurements of $\alpha$-transfer reactions to the analog state in the mirror nucleus $^{19}$F. Such determinations, however, are subject to large uncertainties. Direct measurements of the low energy cross section, which require high-intensity radioactive $^{15}$O beams, are planned. At $^{19}$Ne excitation energies relevant to novae and accreting neutron stars, only the $\alpha$- and $\gamma$-decay channels are open, as the proton and neutron separation energies are 6.4 and 11.6 MeV respectively. Hence, by populating these states and observing the subsequent $\alpha$- and $\gamma$-decays, one can deduce the branching ratio $B_\alpha \equiv \Gamma_\alpha/\Gamma$. If $\Gamma_\gamma$ is also known, one can then calculate $\Gamma_\alpha$ and thereby the contribution of each state to the resonant rate of $^{15}$O($\alpha,\gamma$)$^{19}$Ne. A pioneering effort of this kind was made by detecting $\alpha$ particles from the decay of $^{19}$Ne states populated via the $^{19}$F($^3$He,$t$)$^{19}$Ne reaction, but the sensitivity of the experiment was insufficient to measure $B_\alpha$ for the critical 4.033 MeV state, which was expected to be of order $10^{-4}$. Despite vigorous efforts worldwide, up to now no experiment has reached this level.

In an experiment at the Kernfysisch Versneller Instituut, we have obtained branching ratio data of high sensitivity by applying a novel method introduced at Argonne National Laboratory using a different reaction. Populating the important states via the $^{21}$Ne($p,t$)$^{19}$Ne reaction in inverse kinematics with a $^{21}$Ne beam energy of 43 MeV/u, we detected either $^{19}$Ne recoils or their $^{15}$O $\alpha$-decay products in coincidence with tritons in the Big-Bite Spectrometer (BBS). The large momentum acceptance of the BBS $(\Delta p/p = 19\%)$ allowed detection of either $^{19}$Ne recoils or $^{15}$O decay products along with tritons emitted backward in the center of mass system. Positioning the BBS at 0° maximized the yield to the 4.033 MeV $3/2^+$ state in $^{19}$Ne. This state, whose dominant shell-model configuration is $(sd)^5(1p)^{-2}$, was selectively populated by an $\ell = 0$, two-neutron transfer from the $3/2^+$ ground state of $^{21}$Ne. Position measurements in two vertical drift chambers (VDCs) allowed reconstruction of the triton trajectories. Excitation energies of the $^{19}$Ne residues were determined from the kinetic energies and scattering angles of the triton ejectiles. The $\gamma$-decays of states in $^{19}$Ne were observed as $^{19}$Ne-triton coincidences in the BBS, whereas $\alpha$-decays were identified from $^{15}$O-triton coincidences.

Recoils and decay products were detected and stopped just in front of the VDCs by fast-plastic/slow-plastic phoswich detectors that provided energy loss and
The curve is the sum of a constant background and 6 Gaussians corresponding to known states in $^{19}$Ne, the widths of which were fixed by the experimental resolution. The $^{15}$O + $\alpha$ threshold lies at 3.529 MeV.

No statistically significant evidence for $\alpha$-decays from the states at 4.033 and 4.379 MeV was observed. For these states the $\alpha$- and $\gamma$-decay spectra were numerically integrated in 100 keV intervals centered at the known energies of the states. These data were subjected to both Bayesian and classical statistical analyses to determine upper limits on the $\alpha$-decay branching ratios at various confidence levels. The two analyses agreed rather well, with the calculated upper limits differing by less than 20% in all cases. The Bayesian analysis was found to be more conservative, and has been adopted here. As expected, there is no indication in the data of $\alpha$-decays from the states at 4.140 and 4.197 MeV states because these decays are hindered by $\ell = 4$ centrifugal barriers and low decay energies. For the states at 4.549, 4.600, 4.712, and 5.092 MeV, $B_\alpha$ was obtained from the fits described above. The branching ratios are shown in Table 3 along with the results of Refs. [11, 19]. Uncertainties in the present branching ratio determinations are purely statistical. Our 90% confidence level upper limit on $B_\alpha$ for the 4.379 MeV state is a factor of 11 smaller than the central value of Ref. [10], a discrepancy we attribute to imperfect background subtraction in the previous determination. To obtain the resonance strengths we take a weighted average of $B_\alpha$ where more than one measurement is avail-
able, excepting the 4.379 MeV state for which our upper limit is preferred. The adopted values are shown in Table I. The uncertainties given in the table are 1σ values, and we specify all upper limits at the 90% confidence level.

The experimental data on Γγ for states in 19Ne are sparse. Of the six states considered here, measurements are available only for the 4.033 MeV state. The value adopted for this state [20] is the result of a combined analysis of Coulomb excitation and Doppler shift attenuation [21] data using shell-model calculations of the relative strengths of E2 and M1 transitions. In some cases, widths of the analog state from the mirror nucleus 19F have been measured, and we adopt these under the assumption that Γγ(19Ne) = Γγ(19F). Such measurements are available for the 4.549 [18], 4.600 [22], and 4.712 MeV states [18]. For the 4.379 and 5.092 MeV states, measurements in neither nucleus are available, and we adopt the results of shell-model calculations [23], assigning a 1σ uncertainty of 20% to the calculated widths. The values of Γγ and Γα, which is calculated as Γα = Γ2/2, are shown in Table I. For the 4.033 and 4.379 MeV states we calculate upper limits on Γγ at the 90% confidence level using 1.64σ upper limits on Γγ. Earlier compilations of decay widths can be found in Refs. [3, 24].

We have calculated (see e.g. [25]) thermally averaged reaction rates due to these 6 resonances. Both the individual rates and the sum of the resonant and direct capture contributions are shown in Fig. 3. The contributions of the 4.033 and 4.379 MeV states are calculated using our 99.73% confidence level upper limits for their α-widths, 31 μeV and 5.6 meV respectively. We do not show the individual contribution of the 4.549 MeV state because it is insignificant by comparison with the other resonances. The direct capture rate was calculated as in Ref. [2], but is significant only below 0.1 GK. Our upper limit on the contribution of the 4.033 MeV state is much larger than all other contributions to the reaction rate for T ≤ 0.5 GK. On the contrary, the 4.600 and 4.712 MeV states account for most of the reaction rate at the high temperatures of 1.9 GK found in accreting neutron stars [3].

The amount of leakage from the hot CNO cycle via 15O(α,γ)19Ne depends on its rate compared to the β+ decay rate of 16O (t1/2 = 122 s). In order to calculate the reaction rate in a particular environment one needs to know the local He mass fraction Y. We assume here a Y of 0.27, which is the solar value [26] adopted in accreting neutron star models [3], but is approximately twice the maximum value used in nova models [22, 28, 29]. Although the accreted material in novae is usually assumed to be of solar composition, significant mixing with the surface material of the white dwarf occurs prior to the nova outburst [26], rendering the net Y smaller than that of the accreted matter. For this reason and because we adopt a 99.73% confidence level upper limit for the contribution of the 4.033 MeV state, the reaction rate we calculate with this Y represents an extreme upper limit for novae. Fig. 4 shows the boundary in the density-temperature plane at which the rate of the 15O(α,γ)19Ne reaction equals the β+ decay rate of 16O for a Y of 0.27. Also shown are shaded regions corresponding to the peak temperatures and densities reached in nova outbursts and accreting neutron stars. A comparable figure appears in Ref. [31].

Typical nova models reach peak temperatures of 0.2 - 0.3 GK, at which time densities are of order 100 g cm⁻³ [28, 29, 32]. Under such conditions, the β+ decay rate of 16O is more than 3 orders of magnitude faster than the rate of the 15O(α,γ)19Ne reaction. At temperatures below 0.1 GK in novae, energy is generated by the pp chain and the cold CNO cycle. Only at temperatures above 0.1 GK can the 13N(p,γ)14O reaction compete equally with 13N β+ decay, initiating the hot CNO cycle. During a nova outburst the temperature exceeds 0.1 GK for about 1000 s [28, 29], while the mean time required to complete one loop of the hot CNO cycle, determined by the β+ halflives of 14O and 15O and the 13N(p,γ)14O rate, is at least 300 s. Hence no more than a few cycles can be completed during a nova explosion, and the fractional leakage per cycle through 15O(α,γ)19Ne of < 0.001 cannot process a significant amount of CNO material to higher masses. Since the rate of the 18Ne(α,p)21Na reaction appears far too small in novae to compete with 18Ne β+ decay [3, 4], we conclude that appreciable breakout from the hot CNO cycle into the rp process in novae is precluded given our current knowledge of reaction rates and nova physics. This conclusion is consistent with those reached in a recent study of reaction rate variations on nova nucleosynthesis [33], which considered a range of 15O(α,γ)19Ne rates from 0.002 to 30 times the rate used here.

In summary, we have measured the α-decay branching ratios for all of the states in 19Ne relevant to the
FIG. 4: Density at which the rate of the $^{15}$O($\alpha,\gamma$)$^{19}$Ne reaction equals the $\beta^+$ decay rate of $^{15}$O for a He mass fraction of 0.27, the solar value. Below 0.5 GK, the curve represents our 99.73% confidence level lower limit. The shaded regions indicate the peak temperature and density conditions found in novae and accreting neutron stars.

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