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Total width of the 5.17 MeV 1^- state in ^{14}O and the hot-CNO cycle

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The reaction $^{13}\mathrm{N}(\mathrm{p},\gamma)^{14}\mathrm{O}$ is important in the hot-CNO cycle. At the energies of astrophysical interest, the rate of this reaction is dominated by capture through an $l=0$ resonance corresponding to the 5.17 MeV $J^\pi=1^-$ excited state in ^{14}O. The contribution of this resonance to the total cross section can be determined from a measurement of the total width, Γ, and the γ-decay branching ratio, Γ_γ/Γ, for this state. This method does not require the use of radioactive ^{13}N as either a beam or a target, neither of which is at present technically feasible. Using the $^{14}\mathrm{N}(^3\mathrm{He},\mathrm{t})^{14}\mathrm{O}$ reaction, the total width of this state has been measured to be $\Gamma=38.1\pm1.8$ keV.

Hydrogen burning in the CNO cycle is believed to be prevalent in stellar environments at temperatures greater than about 20×10^6 K such as in the hydrogen burning cores of more massive main sequence ($M\geqslant 2M_\odot$) and red giant stars. The first step in this cycle is $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$. Following this, the ^{13}N may β^+ decay ($t_{1/2}=9.95$ min) as in the normal CNO cycle or at sufficiently high temperatures and densities, proton capture by ^{13}N to form ^{14}O may occur initiating the hot-CNO cycle.[1] The conditions for the hot-CNO cycle are expected in such environments as nova and supernova outbursts, supermassive stars, accreting neutron stars, and dense, inhomogeneous cosmologies.

For the normal CNO cycle, the dominant sequence of reactions is

$$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(\beta^+\nu)^{13}\mathrm{C}(\mathrm{p},\gamma)^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}(\beta^+\nu)^{15}\mathrm{N}(\mathrm{p},\alpha)^{12}\mathrm{C}\,. \tag{1}$$

At low temperatures and densities, the cycle is limited by the rate of the $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ reaction. As the temperature increases, however, the β^+ decay of ^{13}N limits the cycle, and the $^{13}\mathrm{N}(\mathrm{p},\gamma)^{14}\mathrm{O}$ reaction provides a second channel for destruction of ^{13}N. The onset of the hot-CNO cycle occurs when the lifetime for destruction of ^{13}N via the $^{13}\mathrm{N}(\mathrm{p},\gamma)^{14}\mathrm{O}$ reaction becomes comparable to the β^+ decay lifetime, and the dominant sequence of reactions becomes

$$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(\mathrm{p},\gamma)^{14}\mathrm{O}(\beta^+\nu)^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}(\beta^+\nu)^{15}\mathrm{N}(\mathrm{p},\alpha)^{12}\mathrm{C}\,. \tag{2}$$

In this case, the β-decay rates of $^{14}\mathrm{O}(t_{1/2}=70.65\text{ s})$ and $^{15}\mathrm{O}(t_{1/2}=122.25\text{ s})$ limit the cycle. At all but the most extreme densities where electron capture shortens the β^+ decay lifetimes, these β-decay rates determine the upper limit on the rate of energy generation by the CNO cycle. At still higher temperatures and densities the reactions $^{14}\mathrm{O}(\alpha,\mathrm{p})^{17}\mathrm{F}$, $^{15}\mathrm{O}(\alpha,\mathrm{p})^{18}\mathrm{F}$, and $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ will become important and initiate heavy element production via the rp (rapid proton capture) process.

The exact temperatures and densities at which the hot-CNO cycle becomes important depend strongly on the cross section for the $^{13}\mathrm{N}(\mathrm{p},\gamma)^{14}\mathrm{O}$ reaction. Direct measurement of this reaction is not presently feasible since it would require radioactive ^{13}N either as a target or beam, and the currently tabulated thermonuclear reaction rate is therefore based on theoretical estimates.[2] However, since the rate of ^{14}O production at astrophysical energies is dominated by the $l=0$ resonance at 0.547 MeV through the 5.17 MeV, 1^- state in ^{14}O with a small contribution from direct proton capture to the ^{14}O ground state, the resonant cross section and the thermonuclear reaction rate can be determined from measurements of the total width, Γ, and radiative width, Γ_γ, of this state.[3] The measurement of the total width with the Princeton QDDD (quadrupole-dipole-dipole-dipole) spectrograph is reported here. This measured width combined with theoretical calculations of Γ_γ indicate that the γ-decay branching ratio, Γ_γ/Γ, is measurable and therefore that the resonant cross section and the relevant thermonuclear reaction rates can be determined experimentally.

The reaction $^{14}\mathrm{N}(^3\mathrm{He},\mathrm{t})^{14}\mathrm{O}$ was used to populate states in ^{14}O including the 5.17 MeV, 1^- state. The 29.8 MeV ^{3}He beam was provided by the Princeton cyclotron. Targets of melamine ($\mathrm{C_3H_6N_6}$) with a mixture of 81% ^{14}N and 19% ^{15}N were used. The melamine was evaportated to thicknesses of 10–20 μg/cm^2 on 10 μg/cm^2 carbon foils. In addition, a target of 96% ^{15}N enriched melamine was used for energy calibration. Triton momentum spectra were measured with the Princeton QDDD spectrograph. Particle identification by the ΔE-E technique was used to separate tritons from other charged particles. The ΔE and E detectors were a gas proportional counter and a plastic scintillator, respectively. Spectra of position on the QDDD focal plane for tritons at 10° and full aperture (14.5 msr solid angle acceptance) for the mixed ^{14}N, ^{15}N melamine target and for the ^{15}N enriched melamine target are shown in Fig. 1. Separate measurements were performed at 10° with full aperture and half aperture.

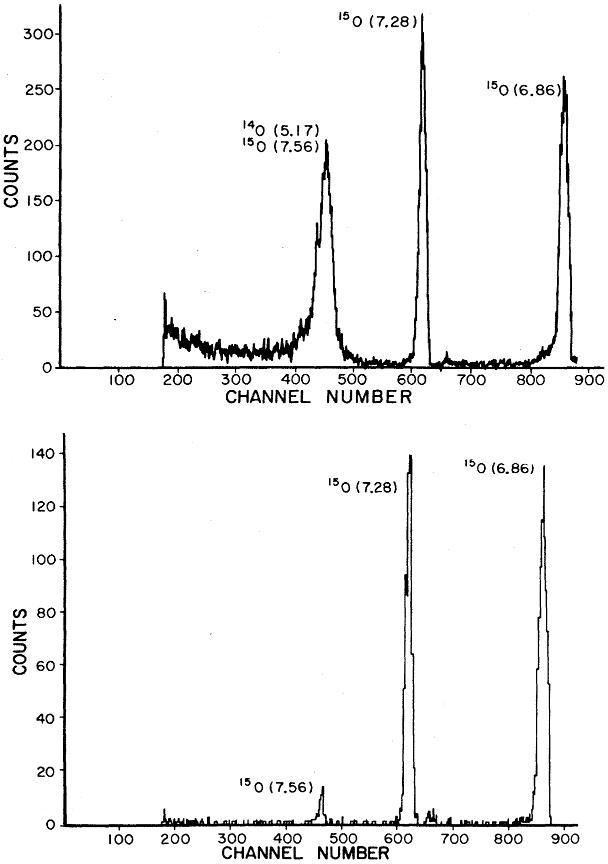

FIG. 1. QDDD focal plane spectra (a) 10°, full aperture with the mixed ^{14}N-^{15}N melamine target, (b) 10°, full aperture with the ^{15}N enriched melamine target.

The ^{15}N enriched melamine target was used to determine the momentum calibration. The three levels in ^{15}O were used to determine the linear dependence of momentum versus channel number. The 6.86 and 7.28 MeV levels in ^{15}O are present in the mixed ^{14}N, ^{15}N target spectrum and provide a check that the calibration was the same for the two targets. Since the 5.17 MeV level in ^{14}O and the 7.56 MeV level in ^{15}O cannot be resolved in the mixed target measurement, the ^{15}N enriched target was also used to determine the relative size of the peaks corresponding to 7.28 and 7.56 MeV levels in ^{15}O and the centroid and width of the 7.56 MeV level in order to allow its contribution to be subtracted. As demonstrated by Fig. 1, the 7.56 MeV level in ^{15}O contributes about 5% to the total area of the peak.

The use of the mixed ^{14}N, ^{15}N target enabled simultaneous measurement of (1) the line shape of the 5.17 MeV level in ^{14}O and (2) the experimental resolution determined by the apparent width of the particle bound, 7.28 MeV level in ^{15}O. This width, s, was extracted by converting channel number to triton energy and fitting the peak to a Gaussian by the χ^2 minimization technique. The observed resolution, $s \approx 10$ keV, was due to a combination of target thickness and the energy resolution of the beam and spectrograph.

The total width, Γ, of the 5.17 MeV level was determined by first subtracting the contribution of the 7.56 MeV level in ^{15}O, converting channel number to triton energy and then fitting the resulting peak to a convolution of a Gussian of width s and a Lorentzian of varied width $\Gamma_{\rm lab}$. The Lorentzian was corrected for the variation of the Coulomb penetrability over the range of laboratory triton energies. This accounts for the tail at lower triton energies (higher proton-decay energies) which skews the line shape.

The results of fits for the 7.28 MeV level in ^{15}O and 5.17 MeV level in ^{14}O are shown in Fig. 2 for the full aperture run. The best fit values of s and $\Gamma_{\rm lab}$ and χ_ν^2's for the separate measurements are given in Table I along with the weighted average results for Γ, the center of mass total width. The contribution to these errors due to the measured focal plane momentum calibration is negligible. The weighted average of the two measurements with center of mass correction given by $dQ/dE_{\rm lab}^{\rm triton} = 0.95$ is $\Gamma = 38.1 \pm 1.8$ keV.

The radiative width, Γ_γ, has yet to be measured, though several attempts to calculate it have been made. The theoretical problem is to reliably calculate the $E1$ strength for the transition from the 1^- state at 5.17 MeV to the ground state, a notoriously difficult task in light nuclei.[4,5] Nevertheless, calculations indicate that Γ_γ is in the range of

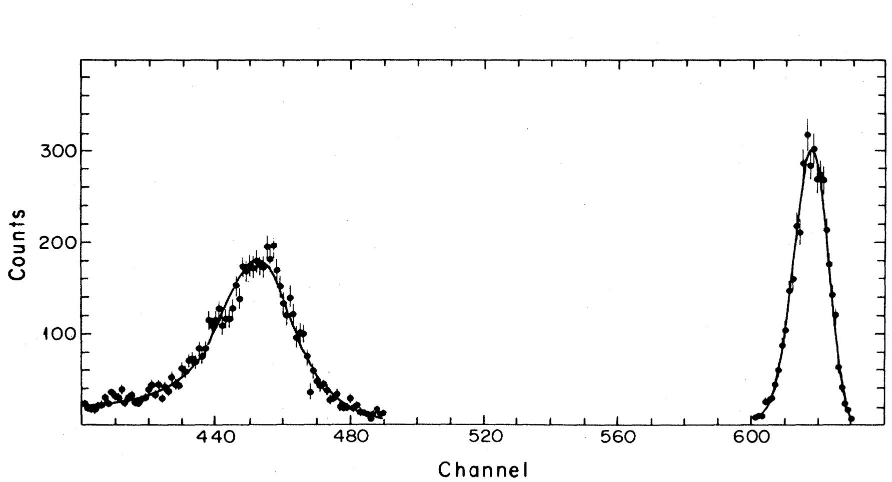

FIG. 2. Fits of the ^{15}O(7.28 MeV) peak to a Gaussian and of the ^{14}O(5.17 MeV) peak (corrected for ^{15}O contamination) to a convolution of a Gaussian and a Lorentzian. These data are from the full aperture run.

TABLE I. Results of fits.

QDDD Angle (aperture)	s (keV)	χ^2_ν	$\Gamma_{\rm lab}$ (keV)	χ^2_ν	Γ (keV)
10° (full)	10.3 ±0.2	1.1	40.1 ±2.0	1.3	38.1 ±1.9
10° (half)	9.3 ±0.8	0.6	40.2 ±5.7	1.0	38.2 ±5.4
			Weighted average		38.1 ± 1.8

2.44 eV (Ref. 6) to 5 eV.[4,5] The significance of these values to the present work is to suggest that the branching ratio for γ decay, Γ_γ/Γ, is on the order of 10^{-4} and therefore may be accessible to measurement. The measurement of Γ_γ/Γ along with the value $\Gamma = 38.1 \pm 1.8$ keV will place the expressions for the resonant cross section and the thermonuclear reaction rate on firm experimental footing.

Finally, we call attention to the theoretical work of Matthews and Dietrich.[6] These authors present calculations of Γ_p and Γ_γ of 34.7 keV and 2.44 eV, respectively. Their value for Γ_p is in good agreement with the measured value of Γ presented here. The value of 2.44 eV for Γ_γ relies on the experimentally determined radiative width for decay from the $\frac{1}{2}^+$ 2.365 MeV state in ^{13}N to the $\frac{1}{2}^-$ ground state, over which, as the authors point out, there is some disagreement. The estimates of $\Gamma_\gamma = 5$ eV (Refs. 4 and 5) also rely on this experimental input.

Note added in proof. The authors have learned of a paper by K. Langanke, O. S. van Roosmalen, and W. A. Fowler [Nucl. Phys. (to be published)] in which calculations are described with the results $\Gamma = 40.1$ keV and $\Gamma_\gamma = 1.50$ eV.

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[5] D. J. Millener (private communication).

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