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The "hot CNO cycle" $^{13}N(p,\gamma)$ resonance energy and the ^{18}Ne mass

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The masses of ^{18}Ne, and of the ^{14}O first excited state that dominates the astrophysical $^{13}N(p,\gamma)$ reaction rate, were measured using the $^{16}O(^3He,n)$ and $^{12}C(^3He,n)$ reactions. We found mass excesses of 5316.8 ± 1.5 keV for the ^{18}Ne ground state and 13163.4 ± 2.0 keV for the first excited state of ^{14}O. The ^{14}O mass corresponds to an $^{13}N(p,\gamma)$ resonance energy of 528.8 ± 2.0 keV. This is consistent with the result from a recent $^{13}N+p$ study, but disagrees with the previously accepted value. Implications for the thermonuclear $^{13}N(p,\gamma)$ rate are discussed.

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The "hot" CNO cycle is an important source of stellar energy generation when the $^{13}N(p,\gamma)$ reaction rate becomes faster than the ^{13}N β-decay rate. The $^{13}N(p,\gamma)$ rate is dominated by a low-energy s-wave $E1$ resonance corresponding to the 5.17 MeV first excited state of ^{14}O. For a given stellar temperature and pressure, the reaction rate depends sensitively on the parameters of this low-energy resonance—especially its radiative width Γ_γ and its excitation energy E_R.

The radiative width was recently determined by three entirely different means that gave concordant results—measurements of the γ-ray branching ratio of $^{14}O(5.17)$ yielded Γ_γ values of 2.7 ± 1.3 eV [1], 7.6 ± 3.8 eV [2], and 12 ± 7 eV [3], while a radioactive-beam study of $^{13}N(p,\gamma)$ gave 3.3 ± 0.9 eV [4]. These four results can be combined to yield a "best value" of $\Gamma_\gamma = 3.36 \pm 0.72$ eV. The good agreement among these four independent measurements, $\chi^2/\nu = 1.01$, suggests that the errors were properly assigned and that our quoted uncertainty in the "best value" is reasonable. Furthermore, this "best value" is in excellent agreement with the values $\Gamma_\gamma = 3.1 \pm 0.6$ eV [5] and 2.4 ± 0.9 eV [6] determined indirectly from the breakup of ^{14}O projectiles in the Coulomb field of ^{208}Pb.

On the other hand, a disagreement has arisen concerning the value of E_R. The accepted value [7] for the excitation energy of the ^{14}O first excited state, $E_x = 5173 \pm 10$ keV, implies $E_R^{c.m.} = 545 \pm 10$ keV, while an analysis of $^{13}N+p$ scattering [4] yielded $E_R^{c.m.} = 526 \pm 3$ keV. This discrepancy is significant; Fig. 1, which displays the effect of this change in E_R on the $^{13}N(p,\gamma)$ reaction rate as a function of temperature, shows that a 19 keV reduction in $E_R^{c.m.}$ would increase the reaction rate at $T = 4 \times 10^6$ K by 40%.

Because of the disagreement of the radioactive-beam result [4] with both the accepted value [7] and a $^{14}N(^3He,t)$ magnetic spectrometer measurement [8], which gave $E_x = 5168.5 \pm 1.8$ keV or $E_R^{c.m.} = 540.5 \pm 1.8$ keV, we have remeasured the excitation energy of the ^{14}O first excited state. As a byproduct of this work we also determined the mass of the ^{18}Ne ground state which was known with a relatively large uncertainty of ± 5 keV.

Our work relied on $(^3He,n)$ studies using the University of Washington pulsed-beam time-of-flight (TOF) spectrometer [9]. We were able to make rather precise measurements by exploiting a differential technique. The spectrometer was used to compare the TOF of a neutron group of interest to an essentially equal TOF of a well-known calibration group produced in a different target at the same bombarding energy.

Specifically, we first determined the mass of the ^{18}Ne 1.89 MeV excited state by comparing neutron TOF spectra for $^{16}O(^3He,n)^{18}Ne(1.89)$ and $^{11}B(^3He,n)^{13}N(T = 3/2)$ reactions at a beam energy of 7.31 MeV (see Fig. 2). The oxygen target was prepared by anodizing tantalum to produce a thin surface layer of Ta_2O_5, while the boron target was made by evaporating ≈ 10 $\mu g/cm^2$ of enriched ^{11}B onto a tantalum substrate. Two liquid-scintillator neutron detectors were employed: a 2.5-cm-thick detec-

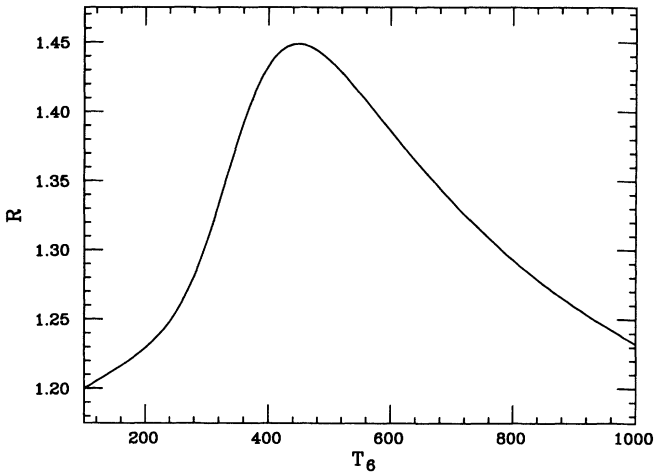

FIG. 1. Effect of a 19 keV reduction in $E_R^{c.m.}$ on the $^{13}N(p,\gamma)$ reaction rate as a function of stellar temperature. The quantity R on the vertical axis is the reaction rate for the resonance at $E_R^{c.m.} = 526$ keV divided by the rate for the resonance at $E_R^{c.m.} = 545$ keV; the quantity on the horizontal axis is the temperature in units of 10^6 K. The rate was computed using our "best value" for Γ_γ and the accepted value for Γ.

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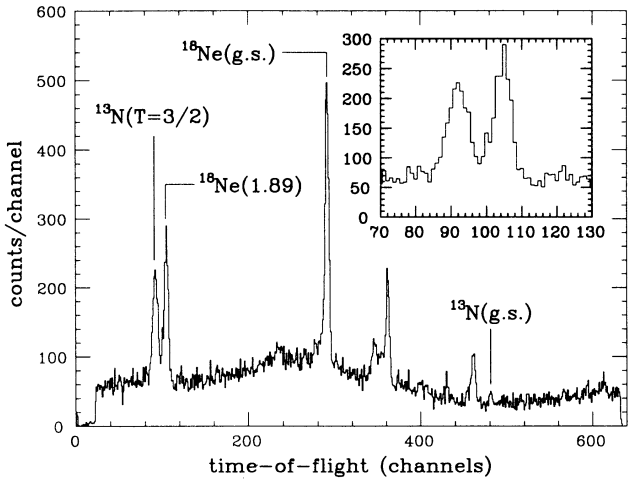

FIG. 2. Neutron time-of-flight spectra taken at a beam energy of 7.31 MeV and a neutron detector angle of $\theta_n = 8.75°$. Top: target containing ^{11}B and natural oxygen. Bottom: natural oxygen target.

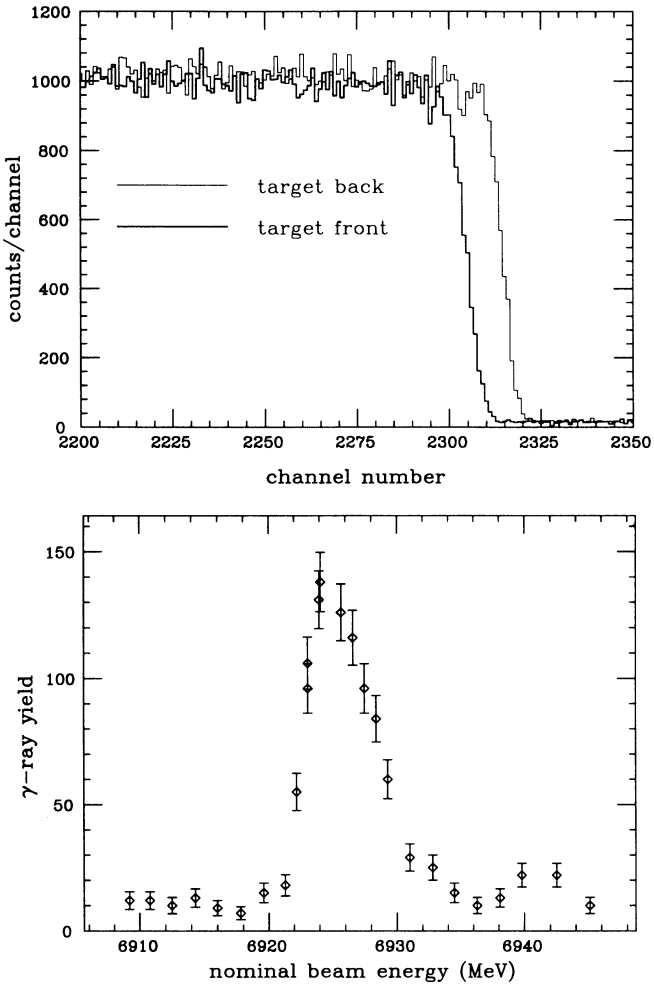

FIG. 3. Top panel: spectra of elastically scattered 7.02 MeV α's used to measure the C target thickness. Bottom panel: excitation function over a narrow ^{16}O(α,γ) resonance used to measure the O target thickness.

tor at $\theta_n = 8.75°$ with a flight path of 3.605 m and a 5.0-cm-thick detector at $\theta_n = 0.0°$ with a flight path of 3.600 m. The ^{13}N $T = 3/2$ level has a mass that is known to ± 0.4 keV [7], and produces a neutron group whose TOF is very close to that of the ^{16}O(^{3}He,n)^{18}Ne(1.89) group. Therefore, it provided a convenient Q-value calibration: a 50 keV error in the beam energy, or a 1.0° error in the angle of the $\theta_n = 8.75°$ detector, or a 1.5% error in the time scale calibration would be required to produce a 1 keV error in our result for the ^{14}O(5.17) excitation energy. The only significant correction to our results was for differences in the ^{3}He energy loss in the ^{11}B and ^{16}O targets. (Because our ^{11}B target contained an oxygen contaminant, this one spectrum alone provided an excellent result.) The energy loss of ^{3}He ions in the boron target was inferred from a separate measurement in which we observed the energy spectrum of 7.00 MeV α's elastically scattered at $\theta_\alpha = 150°$. By comparing the maximum energy of the α's scattered from the bare Ta backing to those scattered from the boron-coated side, we deduced that the mean energy loss of 7.31 MeV ^{3}He ions in our boron target was 4.7 ± 0.5 keV [10]. The energy loss in our oxygen target was found by measuring the ^{16}O(α,γ) excitation function over the narrow ($\Gamma \leq 0.3$ keV) $E_\alpha = 6928 \pm 4$ keV resonance [11] corresponding to the lowest $T = 1$ level in ^{20}Ne. From its observed lab width of $\approx$6 keV (see the upper panel of Fig. 3) we inferred a ^{3}He energy loss of 4.9 ± 0.4 keV at $E_{^3\mathrm{He}} = 7.31$ MeV. The good agreement of our oberved resonance energy, $E_\alpha = 6924$ keV, with the accepted [11] value demonstrates that beam-energy uncertainties gave a negligible contribution to our errors.

Using the above results we found a ^{18}Ne(1.89) mass excess of 7204.1 ± 1.5 keV. When this is combined with the known [11] excitation energy, $E_x = 1887.3 \pm 0.2$ keV, we obtain a ^{18}Ne ground-state mass excess of 5316.8 ± 1.5 keV, which should be compared to the accepted value [11] of 5319 ± 5 keV.

Having established this secondary standard, we determined the mass of ^{14}O(5.17) by comparing its TOF in the ^{12}C(^{3}He,n) reaction at a bombarding energy of 9.02 MeV and angles of $\theta_n = 0°$ and $\theta_n = 7.81°$ to that of the ^{18}Ne(3.38) group populated in ^{16}O(^{3}He,n) at the same energy and angle (see Fig. 4). The ^{16}O(^{3}He,n) Q value of -6.568 ± 0.002 MeV was obtained by subtracting the

TABLE I. Recommended ^{13}N(p,γ) reaction rate. We list 1σ errors arising from experimental uncertainties in "best values" for Γ_γ, E_R, and Γ.

T_6	$N_A\langle\sigma v\rangle$ (cm^{3}s^{-1})	T_6	$N_A\langle\sigma v\rangle$ (cm^{3}s^{-1})
50	$(8.20 \pm 1.33) \times 10^{-10}$	550	$(1.89 \pm 0.41) \times 10^{+1}$
100	$(2.93 \pm 0.49) \times 10^{-6}$	600	$(3.88 \pm 0.86) \times 10^{+1}$
150	$(1.60 \pm 0.27) \times 10^{-4}$	650	$(7.16 \pm 1.58) \times 10^{+1}$
200	$(2.07 \pm 0.36) \times 10^{-3}$	700	$(1.21 \pm 0.27) \times 10^{+2}$
250	$(1.36 \pm 0.24) \times 10^{-2}$	750	$(1.90 \pm 0.42) \times 10^{+2}$
300	$(6.35 \pm 0.12) \times 10^{-2}$	800	$(2.81 \pm 0.63) \times 10^{+2}$
350	$(2.57 \pm 0.51) \times 10^{-1}$	850	$(3.97 \pm 0.88) \times 10^{+2}$
400	$(9.42 \pm 1.94) \times 10^{-1}$	900	$(5.37 \pm 1.20) \times 10^{+2}$
450	(3.00 ± 0.64)	950	$(7.01 \pm 1.57) \times 10^{+2}$
500	(8.12 ± 1.75)	1000	$(8.90 \pm 2.00) \times 10^{+2}$

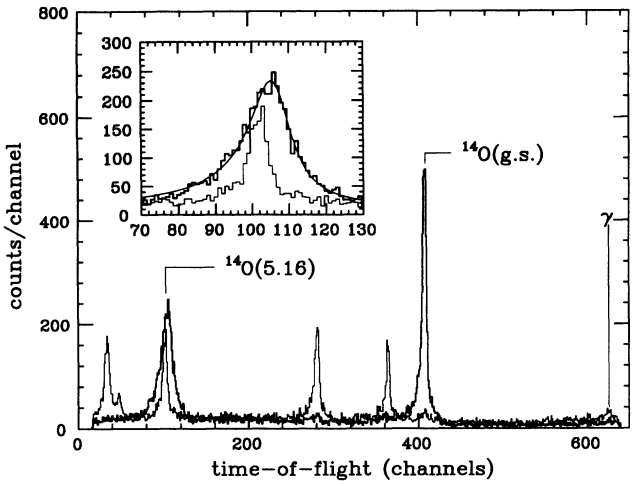

FIG. 4. Neutron time-of-flight spectra taken at a beam energy of 9.02 MeV and a neutron detector angle of $\theta_n = 8.75°$. Heavy line: natural carbon target. Light line: natural oxygen target. The smooth curve shown in the inset is the best fit to the ^{14}O(5.16) resonance.

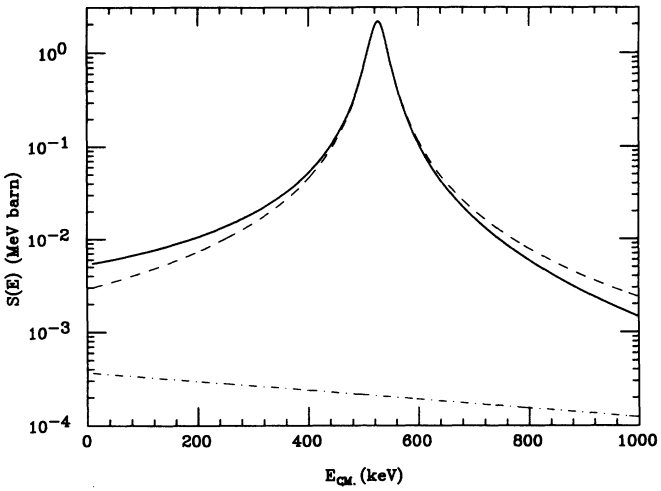

FIG. 5. Recommended S factor for the ^{13}N(p,γ) reaction as a function of center-of-mass proton energy. The dashed and dash-dotted lines show the resonance and direct capture contributions to S, respectively.

known [11] excitation energy, 3376.2 ± 0.4 keV, from the ground-state Q value, -3.1940 ± 0.0015 MeV, determined above. We used the same oxygen target employed in the ^{18}Ne mass measurement, and a commercial ≈ 20 μg/cm^2 natural carbon foil mounted on a thick gold backing. The ^{3}He energy loss in the carbon target was found using the α-scattering technique described above. From the result shown in the lower panel of Fig. 3 we inferred an energy loss of 8.0 ± 0.8 keV at a beam energy of 9.02 MeV.

The ^{14}O(5.17) peak was fitted with a line shape whose instrumental resolution was computed using the procedure described in Ref. [9] and the resonance yield in the c.m. system was assumed to have the form

$$\sigma(E) \propto \frac{G\Gamma}{(E - E_\lambda - \Delta_\lambda)^2 + (\Gamma/2)^2} , \qquad (1)$$

where the formation width G is essentially constant over the resonance, the decay width is $\Gamma = 2P(E)\gamma_\lambda^2$, the level shift is $\Delta_\lambda = -S(E)\gamma_\lambda^2$, and the resonance energy is given by $E_R = E_\lambda + \Delta_\lambda(E_R)$.

This comparison yielded a ^{14}O(5.17) mass excess of 13163.4 ± 2.0 keV, where the error has a significant contribution from the uncertainty in the tails of the detector response function. This result implies an excitation energy of 5156.8 ± 2.0 keV and a ^{13}N(p,γ) resonance energy of 528.8 ± 2.0 keV. The latter is in excellent agreement with the 526 ± 3 keV value inferred by Decrock *et al.* [4] from ^{13}N+p data and in strong disagreement with an earlier magnetic spectrometer value [8] of 540.5 ± 1.8 keV. The previously accepted value [7] for the excitation energy 5173 ± 10 keV differs significantly from our more precise result. The resonance width extracted from our data, $\Gamma(E_R) = 37 \pm 3$ keV, agrees well with the values 38.1 ± 1.8 keV and 37.0 ± 1.1 keV obtained by Chupp *et al.* [12] and Decrock *et al.* [4], respectively. Thus our work has confirmed the radioactive beam measurements, which had to be made under difficult conditions where the beam energy resolution and target thickness were large compared to the resonance width.

In Fig. 5 we display our recommended S factor for the ^{13}N(p,γ) reaction. The calculation is based on the "best value" for Γ_γ quoted above, the total width $\Gamma = 37.3 \pm 0.9$ keV found by combining Refs. [4,12], the resonance energy $E_R^{\text{c.m.}} = 527.9 \pm 1.7$ keV obtained by combining our result with that of Ref. [4], and the direct-capture contribution inferred from ^{13}C(p,γ_1) data as discussed in Ref. [1]. The corresponding reaction rate is listed in Table I. The rate in cm^3 s^{-1} is well approximated by the expression

$$\begin{aligned} N_A\langle\sigma v\rangle(T_9) = {} & (4.34 \times 10^5) T_9^{-3/2} \exp(-6.126/T_9) \\ & + (1.05 \times 10^9) T_9^{-2/3} \exp(-15.1679/T_9^{1/3}) I_{[0,0.68]}(T_9) \\ & \times (1 - 11.81 T_9^{1/3} + 56.27 T_9^{2/3} - 126.5 T_9 + 135.2 T_9^{4/3} - 54.55 T_9^{5/3}) , \end{aligned} \qquad (2)$$

where $I_{[0,0.68]} = 1$ if $0 < T_9 < 0.68$ and $I_{[0,0.68]} = 0$ otherwise.

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