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Low-energy resonances in $^{13}C(\alpha, n)$

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Two new resonances in the $^{13}C(\alpha, n)$ reaction, at $E_\alpha = 656$ and 802 keV, have been observed and the resonance strengths have been measured. Limits on the (α, γ) strengths have been determined. Strengths for previously known (α, n) resonances at 1053 and 1586 keV are also reported.

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Several investigations of the total cross section for $^{13}C(\alpha, n)$ at low energies have been reported [1–4], motivated by its importance as a stellar neutron source for the *s* process. In none of these reports has there been any indication of resonance structure near $E_\alpha = 656$ and 802 keV, corresponding to known [5] narrow states ($\Gamma < 1$ keV) in the compound nucleus ^{17}O at 6862±2 and 6972 ± 2 keV excitation. The J^π values for these states seen in other reactions have been variously reported [6–9] as $\frac{7}{2}$, $(\frac{1}{2}^{-})$, $(\frac{1}{2}^{-})$, and $\frac{5}{2}^{+}$ for the lower state, and $\frac{5}{2}$, $(\frac{5}{2}^{+})$, $(\frac{5}{2}^{+})$, and $(\frac{7}{2}^{-})$ for the upper state, and $J^\pi \neq \frac{1}{2}^{+}$ for either [10]. Of the known states [5] in the mirror nucleus ^{17}F, only those at 6.70 and 6.77 MeV have about the right excitation to be the analogs, and are not already identified with other states in ^{17}O; they have $J^\pi = \frac{5}{2}^{+}$ and $\frac{3}{2}^{+}$.

In this Brief Report, we report the observation of the two expected resonances in the $^{13}C(\alpha, n)$ reaction, and determination of the resonance strengths for these and for two others previously known at $E_\alpha = 1053$ and 1586 keV. Resonances in $^{13}C(\alpha, \gamma)$ were also sought, but only upper limits for the strengths were obtained. The yields were too small to allow angular-distribution measurements, and no information was obtained to reduce the confusion of spin assignments as cited above.

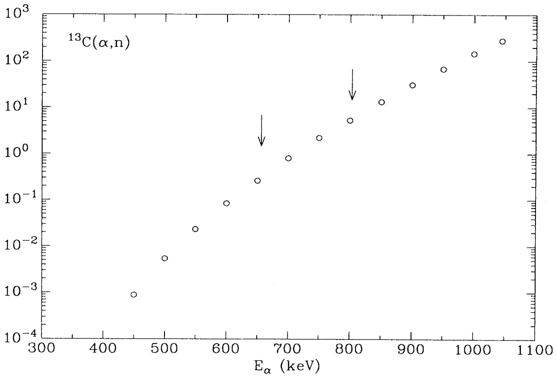

FIG. 1. The $^{13}C(\alpha, n)$ cross section from Ref. [3]. The arrows indicate the resonance energies corresponding to known states in ^{17}O.

$^4He^+$ beams up to 50 μA were provided by the Caltech Pelletron accelerator, with a 90° magnetic analyzer calibrated to ±0.1% in energy as described previously [11,12]. Several thin targets of ^{13}C (99.2% enriched) were made by electron-beam evaporation (at ACF Metals, Tucson) onto 0.75-mm-thick Cu disks, 32 mm in diameter, with nominal ^{13}C areal densities from 0.7 to 3.0 $\mu g/cm^2$. Although not needed in the data analysis, the actual ^{13}C densities were determined from the known (α, n) cross sections, or from the resonance yield of the 1053-keV resonance in $^{13}C(\alpha, n)$, known to be 4434 ± 135 $n/\mu C$ from the average of previous (and consistent) measurements [12,13]. The collimated beams were rastered by magnetic deflectors over a target area of ~ 1 cm^2, and the back surface of the target was directly cooled with flowing Freon or water.

To facilitate resonance profiling, the target assembly was connected to a power supply that was varied from 0.5 to 12 kV in a linear sawtooth pattern with a 40-sec period, leaving the accelerator settings fixed at an energy about 6 keV above the resonance peak. The entire voltage-ramping system was electrically insulated and returned to ground through an ORTEC model 439 current integrator for beam-charge measurement.

The neutron yields were measured using a polyethylene-moderated 4π detector described in more detail elsewhere [14]. With eleven (of the normal complement of twelve) ^3He-filled proportional counters in

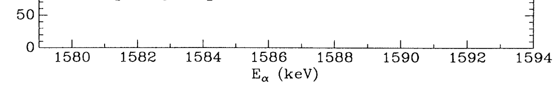

FIG. 2. The $^{13}C(\alpha, n)$ yield in the region of the 1586-keV narrow resonance ($\Gamma < 0.1$ keV), from a run with accumulated α^+ charge of $Q = 3.3$ mC. The curve is a fit with two truncated Gaussians joined at their peaks, with quadratic background.

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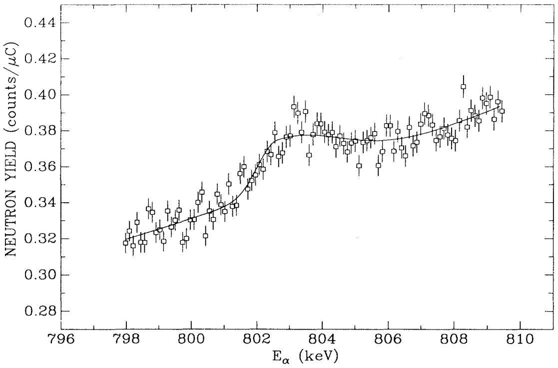

FIG. 3. The $^{13}C(\alpha,n)$ yield near the 802-keV resonance, with a fit as in Fig. 2. $Q = 1.05$ C.

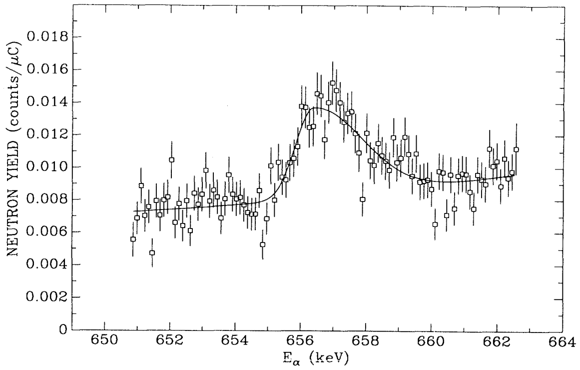

FIG. 4. The $^{13}C(\alpha,n)$ yield near the 656-keV resonance, with a fit as in Fig. 2. $Q = 1.06$ C.

service, the detection efficiency for ^{252}Cf neutrons was 20.2%. The detector counts were stored in a computer, correlated with the 128-channel digitized target voltage, the current-integrator pulses, and a constant-rate pulser (to monitor dead time and ramp linearity).

Figure 1 shows the broad-range behavior of the $^{13}C(\alpha,n)$ cross section below 1 MeV, as measured previously [3] in our laboratory; the positions of the expected low-energy resonances are indicated with arrows. The cross-section scale from Ref. [3] has been enhanced by a factor 1.17 to agree with a later measurement [12] at $E_\alpha = 1$ MeV, where $\sigma = 146 \pm 7$ μb.

Figure 2 shows the yield in the neighborhood of the known [5,11] sharp resonance ($\Gamma < 0.1$ keV) at 1585.2 ± 1.5 keV. (This resonance was checked several times to monitor target loss under bombardment, typically $\sim 50\%$ for 1 C of beam charge.) The nonresonant cross section here was determined to be 1.92 ± 0.10 mb by comparison with the known value at 1 MeV.

From Eq. 66 of Fowler *et al.* [15], specialized here for $^{13}C(\alpha,n)$, the resonance strength may be written numerically as $(\omega\gamma)_n = 0.7418 E_r \int \sigma_r dE$, with energies measured in MeV in the c.m. system and σ_r in barns. Using the known value of the nonresonant part of the cross section, σ_{nr} at E_r, we have

$$(\omega\gamma)_n = 0.7418 E_r \frac{\sigma_{nr}}{Y_{nr}} \int y_r dE \ , \qquad (1)$$

where Y_{nr} is the nonresonant yield at E_r for a given run, and $\int y_r dE$ is the area under the resonant part of the yield curve, in counts × MeV. For thin targets, this expression is independent of target thickness, stoichiometry, and deterioration during the run. Applying Eq. (1) to the data of Fig. 2 and eight other runs, we find $(\omega\gamma)_n = 10.8 \pm 0.5$ eV; the resonance energy is determined to be 1585.7 ± 1.5 keV.

Figures 3 and 4 show data obtained near the two resonances expected at the lower energies, $E_\alpha = 802$ and 656 keV, respectively. The extracted resonance parameters are listed in Table I. The energy and strength for the 1053-keV resonance were deduced from earlier reports cited in the table.

To search for γ rays from the two weak resonances, the thickest target was oriented at 45° to the beam (the energy thickness then being $\Delta E_\alpha = 8$ keV) and a 35% HPGe detector was placed at 45°, 9 mm from the target. Runs of a few hours duration were taken at $E_\alpha = 662$ and 805 keV ($Q = 0.62$ and 0.81 C, respectively), and the 4000-channel γ-ray spectra were examined for (Doppler-shifted) peaks corresponding to transitions to states in ^{17}O at $E_x = 0$, 871, 3055, and 3841 keV. No peak was seen, and the few counts in each peak region were attributable to background. From the calibrated detection efficiencies (0.4–0.9 %) and the sum of the "thick-target" yields in the four regions, upper limits for the resonance strengths were found to be $\omega\gamma < 5$ and < 8 μeV for the 656- and 802-keV resonances, respectively. Such small values are not surprising, since, as shown below, $\Gamma \approx \Gamma_n > 10^6 \Gamma_\alpha$, and only strong $E1$ transitions would exceed these limits.

The neutron widths, Γ_n, for the first two states listed

TABLE I. Parameters of resonances in $^{13}C + \alpha$.[a]

E_α (keV)	E_x in ^{17}O (keV)	σ_{nr} (mb)	$(\omega\gamma)_n$ (eV in c.m.)	$(\omega\gamma)_\gamma$ (μeV)
656.0(7)	6860.8(7)	$3.17(30)\times10^{-4}$	$1.85(20)\times10^{-4}$	< 5
802.2(8)	6972.6(7)	$6.04(40)\times10^{-3}$	$4.54(35)\times10^{-4}$	< 8
1053.18(18)[b]	7164.5(4)	0.308(15)	11.9(6)[c]	
1585.7(15)	7571.7(12)	1.92(10)	10.8(5)	

[a] Errors in last digits are shown in parentheses.

[b] Deduced from the $^{16}O + n$ resonance energy, $E_{\text{c.m.}} = 3020.89 \pm 0.16$ keV, given in Ref. [16], and 1983 masses [17].

[c] Deduced from the resonance yield, 4434 ± 135 n/μC [12,13], and the stopping power in ^{13}C [18].

TABLE II. Partial widths for the 656- and 802-keV resonances for various J^π values.

			$E_x = 6861$ keV		$E_x = 6973$ keV	
J^π	l	Γ_n (keV)	Γ_α (μeV)	θ_α^2 (%)	Γ_α (μeV)	θ_α^2 (%)
$\frac{1}{2}^-$	0	0.50	185	0.039	454	0.0068
$\frac{3}{2}^+$	1	0.25	93	0.046	227	0.0085
$\frac{5}{2}^+$	3	0.17	62	1.8	151	0.28
$\frac{7}{2}^-$	4	0.13	46	23	114	3.4

in Table I may be estimated from the $^{16}O(n,n)$ resonant cross sections shown in Fig. 4 of Ref. [10] (levels numbered 13 and 14 in that paper), from which $\int \sigma dE \approx 0.8$ keV b for each. Then since $\Gamma_n \approx \Gamma$, we have $(J+\frac{1}{2})\Gamma_n \approx 0.50$ keV (c.m.) for each, where J is the level spin in ^{17}O. For each of the J^π values in the first paragraph, Γ_n and Γ_α can then be evaluated as listed in Table II. In addition, using the lowest allowed l value for each J^π, the penetration factor, $P(l)$, is determined [19], and the dimensionless reduced width, $\theta_\alpha^2 = \Gamma_\alpha / \Gamma_W P(l)$, can be calculated. Here Γ_W is the Wigner limit, $3\hbar^2/2MR^2$, with M the reduced mass and R the interaction radius, taken to be 5.5 fm. None of these reduced widths (Table II) exceeds the Wigner limit. The resonance strengths for these two states (Table I) are far too weak, compared to the nonresonant contribution, to affect the stellar reaction rates.

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- [1] C. N. Davids, Nucl. Phys. **A110**, 619 (1968).
- [2] E. Ramström and T. Wiedling, Nucl. Phys. **A272**, 259 (1976).
- [3] S. E. Kellogg, R. B. Vogelaar, and R. W. Kavanagh, Bull. Am. Phys. Soc. **34**, 1192 (1989), and private communication.
- [4] H. W. Drotleff *et al.*, Astrophys. J. **414**, 735 (1993).
- [5] F. Ajzenberg-Selove, Nucl. Phys. **A460**, 1 (1986).
- [6] H. Schmidt-Bocking, G. Brommundt, and K. Bethge, Z. Phys. **246**, 431 (1971).
- [7] M.-C. Lemaire, M. C. Mermaz, and K. K. Seth, Phys. Rev. C **5**, 328 (1972).
- [8] J. C. Kim *et al.*, Nucl. Phys. **A297**, 301 (1978).
- [9] D. M. Manley *et al.*, Phys. Rev. C **36**, 1700 (1987).
- [10] J. L. Fowler, C. H. Johnson, and R. M. Feezel, Phys. Rev. C **8**, 545 (1973).
- [11] C. R. Brune and R. W. Kavanagh, Phys. Rev. C **44**, 1665 (1991).
- [12] C. R. Brune and R. W. Kavanagh, Phys. Rev. C **45**, 1382 (1992).
- [13] J. K. Bair and F. X. Haas, Phys. Rev. C **7**, 1356 (1973).
- [14] T. R. Wang, R. B. Vogelaar, and R. W. Kavanagh, Phys. Rev. C **43**, 883 (1991).
- [15] W. A. Fowler, G. R. Caughlan, and B. A. Zimmerman, Annu. Rev. Astron. Astrophys. **5**, 525 (1967).
- [16] S. Cierjacks *et al.*, Nucl. Instrum. Methods **169**, 185 (1980).
- [17] A. H. Wapstra and G. Audi, Nucl. Phys. **A432**, 1 (1985).
- [18] J. F. Ziegler, *The Stopping and Range of Ions in Matter* (Pergamon, New York, 1977), Vol. 3.
- [19] J. Humblet, W. A. Fowler, and B. A. Zimmerman, Astron. Astrophys. **177**, 317 (1987).