In helium burning stars ^4He is converted to ^{12}C and ^{16}O by the successive reactions

$$3\alpha \rightarrow {}^{12}C \text{ (3}\alpha\text{ reaction)}, \quad {}^{12}C(\alpha,\gamma)^{16}O$$

with reaction rates $r_{3\alpha}$ and $r_{\alpha 12}$ respectively. The ratio of ^{12}C present to ^{16}O at the exhaustion of ^4He depends strongly on the ratio $r_{3\alpha}/r_{\alpha 12}$.[1] Consequently accurate values of $r_{3\alpha}$ and $r_{\alpha 12}$ are necessary to provide the initial conditions for calculations of subsequent stages of stellar evolution. Such calculations are now an active research area in nuclear astrophysics. Aside from trivial factors, the helium burning rates depend on the temperature T, the density, and a total of four nuclear parameters. One finds that

$$r_{3\alpha} \propto \Gamma_{rad} \exp - [(E_x - 3M_\alpha c^2)/kT]$$

where E_x and Γ_{rad} are the excitation energy and radiative width of the 0^+ state near 7.6 MeV in ^{12}C and M_α is the mass excess of ^4He. The rate $r_{\alpha 12}$ depends mainly on θ_α^2, the dimensionless reduced width of the 1^- state at 7.12 MeV in ^{16}O.

a. Excitation Energy of the 7.6 MeV State in ^{12}C

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Recently[2] we have measured this excitation energy to be E_x=7654.00±0.20 keV. A comparison of this value with other available information in shown in Fig. 1. From the weighted average given one obtains

$$-Q = E_x - 3M_\alpha c^2 = 379.38 \pm 0.20 \text{ keV}.$$

b. The Radiative Width of the 7.6 MeV State in ^{12}C

R.G. Markham, S.M. Austin and M.A.M. Shahabuddin

The radiative width of this state is determined from a product involving the total, radiative and pair (π) emission widths

$$\Gamma_{rad} = \frac{\Gamma_{rad}}{\Gamma} \cdot \frac{\Gamma}{\Gamma_\pi} \cdot \Gamma_\pi$$

Here Γ_π is known to an accuracy of 7% from electron scattering.

The ratio $\frac{\Gamma_{rad}}{\Gamma}$ was thought to be well known until the recent measurement of Chamberlin, et al.[3] gave $(4.2\pm0.2)\times10^{-4}$, nearly 45% higher than the earlier value[4] of $(2.9\pm0.3)\times10^{-4}$. Since this discrepancy was the dominant uncertainty in $r_{3\alpha}$, we undertook a new measurement of the ratio, using conservative redundant techniques to reduce as far as possible, various corrections to the data.

The 7.6 MeV state was populated via the $^{12}C(\alpha,\alpha')^{12}C^*$ reaction at 40 MeV beam energy. Inelastically scattered alphas were detected in a surface barrier detector at θ_{lab}=54°; ^{12}C nuclei were detected in a gas-solid-state telescope having two-dimensional position sensitivity. This device allowed identification of the ^{12}C recoils by their characteristic ΔE, E, TOF (time of flight) and spatial distribution. Simultaneous detection of the inelastically scattered alpha particle and a stable recoiling ^{12}C ion signifies that the state was formed and decayed by a radiative transition as opposed to particle emission and breakup. Thus, the number of coincident events divided by the total number of inelastic events gives the branching ratio Γ_{rad}/Γ.

Data was stored event by event on magnetic tape for later analysis. Five parameters were digitized: The alpha particle energy E_α, the time difference between the α and ^{12}C detectors, the carbon E, ΔE, and position. These signals were gated by the output of a single channel analyzer on E_α. Non-coincident events were stored as E_α with zeros for the other parameters. In this manner the coincidence and singles events experienced the same system dead time.

The ^{12}C events were defined by boundaries in the two dimensional (2D) spectra: ΔE_C vs TOF, E_C vs ΔE_C, E_C vs position. System efficiency was obtained from pulser events recorded during the experiment and from a determination with equivalent 2D boundaries of Γ_{rad}/Γ for ^{12}C(4.44 MeV) which always decays radiatively. Small corrections for ^{13}C, ^{14}N and ^{16}O impurities in the target were evaluated experimentally. The spectrum of a α's in coincidence with a ^{12}C ion is very clean as shown in Fig. 2.

We obtain: $\frac{\Gamma_{rad}}{\Gamma} = (3.87\pm0.25) \times 10^{-4}$

This result is compared with other available data in Fig. 3; all recent results are in good agreement. The final weighted average is:

$$\frac{\Gamma_{rad}}{\Gamma} = (4.13\pm0.11) \times 10^{-4}$$

c. A Measurement of Γ_π/Γ for the 7.6 MeV State in ^{12}C

R.G.H. Robertson, R.A. Warner and S.M. Austin

Since there is now consensus as to the experimental value of Γ_{rad}/Γ, and the value of Γ_π is well determined from electron scattering, determination of the astrophysically important quantity Γ_{rad} rests on the sole measurement of Γ_π/Γ made by Alburger in 1960. The uncertainty in that result ($\Gamma_\pi/\Gamma = (6.9\pm2.1)\times10^{-6}$) dominates Γ_{rad}, and has motivated us to measure the pair branching ratio by a new and independent method.

Our approach is very direct--the 7.6 MeV state is populated by ^{12}C (p,p') at 10.54 MeV (where the reaction is strongly resonant), and the number of e^+e^- pairs observed in coincidence with inelastic protons is compared to the singles inelastic protons to obtain the branching ratio.

Of course, the extreme weakness of the pair branch necessitated some special precautions. The total energy of pairs was obtained by stopping them in a spherical plastic scintillator of almost 4π solid angle (see Fig. 4). The beam passed through a hole along a diameter and protons emerging from a $100\ \mu g\ cm^{-2}$ 99.98% ^{12}C target mounted at the center were detected in a Si detector at 135°. The holes were lined with graphite which was sufficiently thick to stop 10.5 MeV protons, but which caused an average loss of only 600 keV for pairs. The sensitivity of the scintillation detector to γ-rays was reduced by dividing it into inner and outer regions which were optically isolated and viewed by separate photomultipliers. Charged particles always trigger the inner scintillator whereas many γ-rays only interact in the outer region. When the inner scintillator detected an event, the output from both inner and outer volumes were summed.

Detailed attention was paid by experimental tests and by Monte Carlo calculations to line shapes and efficiencies, and to effects caused by the γ-ray cascade from the 7.65 MeV state, impurities in the target, pileup, accidental coincidences, and other effects. The final spectrum obtained after a preliminary analysis of the corrections is shown in Fig. 5. The result for Γ_π/Γ is in excellent agreement with that of Alburger.

Γ_π/Γ ($\times 10^6$)	Source
6.9±2.1	Alburger; Obst, et al. (Ref. 7)
7.3±1.2	Present work (Preliminary)
7.2±1.0	Mean (Preliminary)

d. The Value of θ_α^2 for the 7.1 MeV State in ^{16}O.

R.G.H. Robertson and S.M. Austin

In spite of the almost heroic efforts devoted to measurements of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at low energies,[8] the value of the dimensionless reduced α-width θ_α^2 for $^{12}C(\alpha,\gamma)^{16}O$ is still substantially uncertain, the quoted errors allowing factor of 4 differences in $r_{\alpha 12}$.[9] In an early analysis of much of the available data, Barker[10] used the line shape of the interfering 1^- levels (at 7.1 and 9.6 MeV) which was obtained from the α-spectrum following β decay to ^{16}O. It appeared to us that it would be possible to obtain equivalent results from a study of line shapes obtained in direct reaction. The $^{15}N(^3He,d)^{16}O$ reaction seems to be a suitable choice because it overwhelmingly populates the 7.1 MeV state as compared to the 9.6 MeV state.[11] In the region of astrophysical interest and above, the line shape is dominated by the "ghost" of the 7.1 MeV state lying above the alpha emission threshold. Since this "ghost" has a peak amplitude of only about 0.1%/MeV of the total intensity of the state,[11] it is necessary to obtain exceedingly clean spectra.

We have begun a study of the $^{15}N(^3He,d)^{16}O$ reaction at 35 MeV using targets of Uracil and of Melamine, enriched in ^{15}N. Deuterons were detected in a slanted-cathode proportional counter in the focal plane of the Enge split-pole spectrograph. Initial results are promising. Peak to background ratios $\gtrsim 10^4$ were obtained in the neighborhood of the 7.1 MeV state and the line shape of the 9.6 MeV state could be clearly discerned despite its large width and weak population ($\lesssim$5% of the 7.1 MeV state). (See Fig. 5).

Most interesting, however, is the fact that the angular distribution for the 7.12 MeV state has a typical L=0 shape with a sharp dip near 11°, while that for the 9.6 MeV state varies only slowly in this angular region. Perhaps two-step processes dominate the cross section for the 9.6 MeV state. But whatever the reason for this behavior, it provides a means for varying the relative amplitudes of the 9.6 state and the underlying ghost of the 7.1 MeV state by slightly changing the reaction angle. If the relative size of the amplitudes changes one expects the line shape in the neighborhood of the 9.6 MeV state to change with angle. We have observed such changes, consistent with those expected from the known parameters of the two states.

We intend to use gas targets of ^{15}N to eliminate certain impurity peaks and also to extend these measurements to other energies and other transfer reactions, e.g. $^{15}N(\alpha,t)^{16}O$. Hopefully the ability to vary the amplitude of the ghost of the 7.12 MeV state will permit a less ambiguous evaluation of $r_{\alpha 12}$ than has previously been possible.

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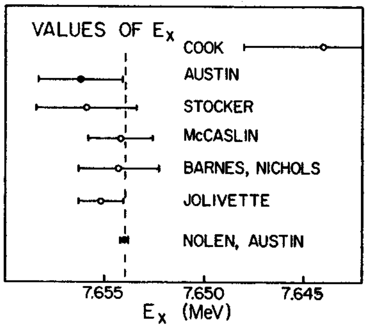

Fig. 1.--Summary of measurements of E_x with the present result labelled "Nolen, Austin". (For detailed references see ref. 2) The dashed line is the weighted average (excluding the point of Cook, et al.) at 7654.07±0.19 keV.

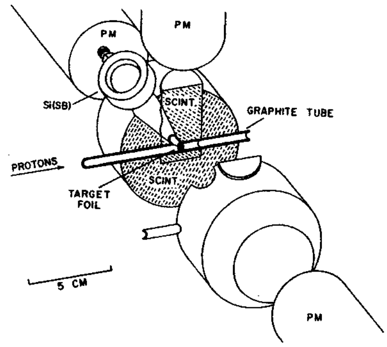

Fig. 4.--Schematic diagram of detectors used in measurement of Γ_π/Γ.

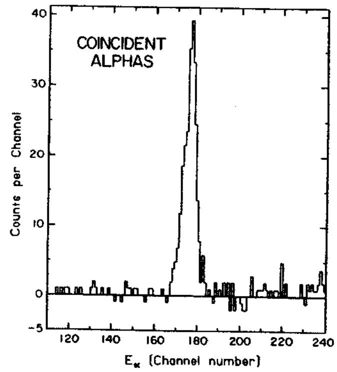

Fig. 2.--Spectrum of α particles in coincidence with a ^{12}C ion. The peak corresponds to E_x=7.654 MeV in ^{12}C.

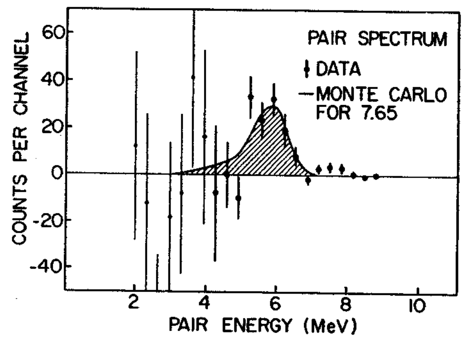

Fig. 5.--Total energy spectrum of e^+e^- pairs de-exciting 7.65 MeV state. Corrections have been made for accidentals, background and γ-ray detection. The shaded area is the prediction of a Monte-Carlo calculation, adjusted for amplitude only.

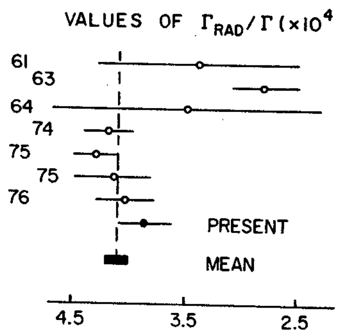

Fig. 3.--Summary of measurements of Γ_{rad}/Γ (The numbers give the date of earlier measurements- for detailed references see ref. 5). The dashed line is the weighted mean $(4.13\pm0.11)\times10^{-4}$,[6] excluding the 1963 value of Seeger and Kavanagh.

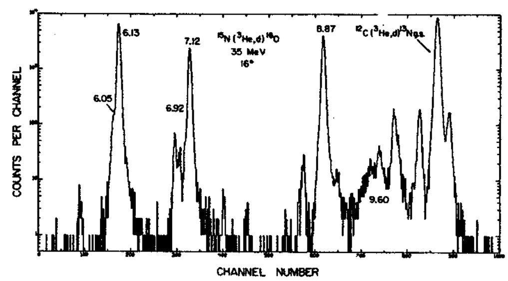

Fig. 6.--Spectrum of $^{15}N(^3He,d)$ reaction to excited states in ^{16}O, taken with the delay-line slanted cathode proportional counter, at θ_{lab}=16°. The energy resolution is about 35 keV. The peak-to-background ratio is in excess of 10^4, permitting clear observation of the shape of the 9.6 MeV state.