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Measurement of the internal pair emission branch of the 7.654-MeV state of ^{12}C, and the rate of the stellar triple-α reaction*

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The internal pair decay of the 0^+ 7.65-MeV state of ^{12}C has been observed in coincidence with inelastic protons from $^{12}C(p,p')^{12}C(7.65)$, using a plastic scintillator of essentially 4π sr solid angle. The branching ratio measured, $\Gamma_\pi/\Gamma = (6.0 \pm 1.1) \times 10^{-6}$, is in excellent agreement with the previous measurement by Alburger, and reduces the uncertainty in the stellar triple-α reaction rate by almost a factor of 2. Implications for the astrophysical production of ^{12}C and ^{16}O are discussed.

[NUCLEAR STRUCTURE ^{12}C, 7.654-MeV state; measured Γ_π/Γ. Stellar helium burning.]

I. INTRODUCTION

The steps by which a star burns helium to produce ^{12}C and ^{16}O seem now to be well understood. Öpik and Salpeter[1] showed that the gaps in the chain of stable nuclides which occur at $A = 5$ and $A = 8$ could be bridged by the triple-α process, the fusion of three α particles to form ^{12}C. In the next stage of helium burning, ^{16}O is formed by the $^{12}C(\alpha,\gamma)^{16}O$ reaction, which eventually competes with the triple-α reaction for use of the available ^4He. Consequently, at the completion of helium burning, the relative abundance of ^{12}C and ^{16}O depends on the specific nuclear parameters governing the rates of the two reactions. To the extent that the end product is returned to the interstellar medium without further modification, the $^{12}C:^{16}O$ ratio calculated should correspond to the observed cosmic ratio.

Hoyle[2] realized this helium burning process could account for the observed abundances of ^{12}C and ^{16}O if the triple-α reaction were resonant in both the 2-α and 3-α systems. It was already known that the 0^+ ground state of ^8Be lay at about 100 keV in the 2-α system, and Hoyle was able to infer the existence of a low-lying 0^+ state in the 3-α system. The excitation energy and radiative width of this state, now known to be the second excited state of ^{12}C, play a crucial role in the triple-α process and have thus become the subject of intensive experimental work.

The rate $P_{3\alpha}$ for the triple-α reaction can be written[3]

$$P_{3\alpha} = n_\alpha{}^3\hbar^5\left(\frac{2\pi\sqrt{3}}{kTM_\alpha}\right)^3\Gamma_{\rm rad}\exp(-Q_{3\alpha}/kT)\ {\rm cm^{-3}\,sec^{-1}}\,, \tag{1}$$

where n_α is the number density of α particles, M_α the atomic mass of ^4He, T the temperature, $Q_{3\alpha}$ the energy released in the decay $^{12}C(7.6541) \to 3\,^4He$, and $\Gamma_{\rm rad}$ the radiative width of the 7.65-MeV state of ^{12}C. The value of $Q_{3\alpha}$ has recently been measured to be (379.38 ± 0.20) keV,[4] a value sufficiently precise that its uncertainty no longer influences that in $P_{3\alpha}$. On the other hand $\Gamma_{\rm rad}$ is known only to ±31%, and has become the chief limitation in the accuracy with which $P_{3\alpha}$ can be calculated.

Experimentally $\Gamma_{\rm rad}$ is determined indirectly as the product of three quantities:

$$\Gamma_{\rm rad} = \left(\frac{\Gamma_{\rm rad}}{\Gamma}\right)\left(\frac{\Gamma}{\Gamma_\pi}\right)(\Gamma_\pi)\,, \tag{2}$$

where Γ is the total width of the 7.65-MeV state and Γ_π its partial width for the $E0$ internal pair transition to the ground state. The total radiative width $\Gamma_{\rm rad}$ is the sum of Γ_π and Γ_γ, the partial width for photon decay, essentially all of which proceeds through the 2^+ state at 4.44 MeV. The value of $\Gamma_{\rm rad}$ has been the subject of several recent experimental studies (summarized by Markham, Austin, and Shahabuddin[5]), resulting in a recommended weighted average of $(4.13 \pm 0.11) \times 10^{-4}$ for that quantity. Electron scattering measurements[6,7] of the $E0$ matrix element connecting the ground and 7.65-MeV states yielded a value for Γ_π of (60.5 ± 3.9) μeV. Thus, by far the largest contribution to the uncertainty in $\Gamma_{\rm rad}$ came from the remaining quantity, Γ/Γ_π, the reciprocal of the pair branching ratio. The single measurement of this ratio prior to the present work was that of Alburger.[8] Alburger excited the 4.44- and 7.65-MeV states of ^{12}C by the $^9Be(\alpha,n)$ reaction and compared the intensity of internal pairs from the two states. Since the 4.44-MeV state must decay radiatively its pair branch could be calculated

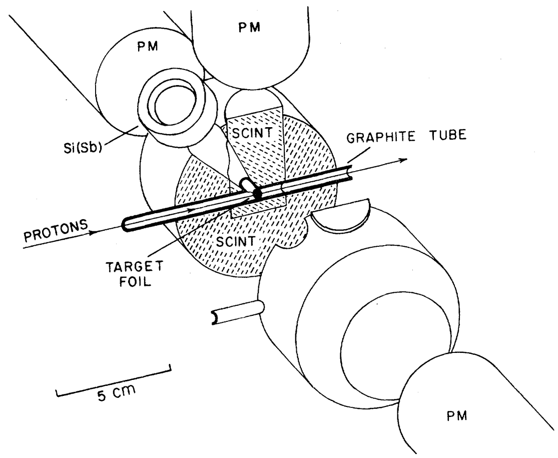

FIG. 1. Exploded view of apparatus used to detect e^+e^- pairs in coincidence with inelastically scattered protons. See text for details.

theoretically. Subsequent measurements[9] of the relative cross sections for the ^{9}Be(α,n) reactions leading to the two states permitted extraction[9] of a value of $(6.9\pm2.1)\times10^{-6}$ for the pair branch of the 7.65-MeV state. Despite the extreme weakness of the branch, a redetermination of its strength became essential to improve the precision of the value of $P_{3\alpha}$ and to confirm its correctness.

II. EXPERIMENTAL METHOD

The present approach was to excite the ^{12}C 7.65-MeV state by ^{12}C(p,p') and observe e^+e^- pairs in coincidence with the inelastically scattered protons. The ratio of the coincidence to singles proton counts in the 7.65-MeV inelastic peak is the pair branching ratio. This approach is very direct and is independent of cross sections, current integration, target thickness, and proton detector solid angle, though it does require knowledge of the efficiency of the pair detector. It has the additional advantage of being entirely independent of Alburger's method.

Both to maximize the coincidence counting rate and to reduce uncertainties in detection efficiency of the pair detector, a plastic scintillator subtending almost 4π sr at the target was constructed. A principal concern when a plastic scintillator is used is its sensitivity to γ rays. A scintillator large enough to stop the most energetic electrons from the pair decay (6.6 MeV) also detects about 10% of the 4.44-MeV photons from decay of the strongly excited 4.44-MeV state of ^{12}C. This fraction was reduced by dividing the scintillator into inner and outer regions ("cylinder" and "ball," respectively), and requiring that a signal be obtained from the cylinder. The linear signals from cylinder and ball were then summed, leaving the sensitivity to charged particles unchanged at ~100%, but reducing the γ sensitivity to about 3%.

An exploded view of the apparatus is shown in Fig. 1. The ball is approximately a sphere of NE 102 plastic scintillator (SCINT) 3.8 cm in radius and viewed by two RCA 8575 photomultipliers (PM). A 0.28-cm radius hole along a diameter allows the beam to pass through the pair detector. The hole is lined with graphite tubing of wall thickness 32 mg cm^{-2}, sufficient to stop 10.6-MeV protons. On the average, pair events lose a total of only 0.6 MeV in this tubing. A 1.3-cm radius well was bored into the top of the ball to accept a cylinder of NE 102 optically isolated from the ball by a wrapping of 13-μm Al foil and viewed by a third 8575 photomultiplier. A hole for the beam was also drilled through the cylinder and lined with graphite tubing and a thin target was placed at the center, mounted on a section of the graphite tube. The target is exposed to a 150-mm^2 area, 0.7-mm thick silicon detector [Si(Sb)] through a conical hole in the scintillators at 135° to the beam direction.

The $\theta=135°$ excitation function for the ^{12}C$(p,p')^{12}$C(7.65) reaction has[10] a particularly favorable resonance near $E_p=10.5$ MeV where the cross section reaches 50 mb sr^{-1}. (At this point the ground, 4.44-, and 7.65-MeV states are populated approximately in the ratio 8 : 3 : 1.) A beam of 10.56-MeV protons from the Michigan State University cyclotron passed through 1.0- and 1.5-mm diameter circular collimators before entering the detector assembly. A lead shield 10 cm thick was interposed between the collimators, which were themselves made of lead. The beam emerging from the target passed through another lead shield and was absorbed in a Faraday cup 2 m away.

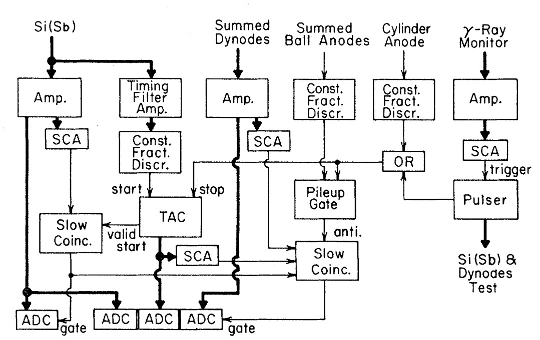

FIG. 2. Simplified block diagram of electronics. Analog signals are carried on the heavy lines. The three ADC's in the right-hand group are gated simultaneously. For clarity, preamplifiers, delays, logic shapers, ratemeters, scalers, the monitor prescaler, and some other units are not shown here.

Targets were 100 $\mu g/cm^2$ self-supporting foils of 99.98% enriched ^{12}C. For calibration runs in which the pair decay of the 6.05-MeV level of ^{16}O was studied, targets of 60-$\mu g/cm^2$ Formvar ($\sim C_5H_8O_2$) were prepared.

A simplified schematic of the electronics used for signal processing is shown in Fig. 2. The dynode signals from all three photomultipliers were summed and amplified. Fast timing signals from the cylinder were, however, kept separate and stopped a time-to-amplitude converter (TAC) which received start signals from the silicon detector. Pileup rejection was employed on the plastic scintillators to reject events separated by 0.008 to 6.0 μs in the cylinder alone or in the cylinder and ball. Losses were monitored in the following manner: A NaI(Tl) detector outside the vacuum chamber produced pulses (chiefly from 4.4-MeV γ rays) at a rate proportional to the beam current. Every tenth count triggered a tail pulser. These pulses were injected into the silicon detector and photomultiplier preamplifiers and also were converted to fast logic signals to be OR'ed with those from the cylinder photomultiplier anode. Thus, by comparing the pulser counts observed in the singles spectrum from the silicon detector with those observed in the coincidence spectra, an accurate correction for losses incurred through pileup, differing analog-to-digital-converter (ADC) dead times, and logic dead time could be made. Three signals gated by the coincidence requirement, the silicon detector, the summed dynodes, and the TAC, were digitized and recorded event by event on magnetic tape. All signals from the silicon detector for which there was a valid start in the TAC and a logic pulse from the silicon detector single-channel analyzer (SCA) were recorded as a "singles" spectrum by a fourth ADC. The SCA was used in an integral mode with a low threshold in order to generate logic signals.

III. CALIBRATION AND TESTS

Since the e^+e^- pairs deexciting the 7.65-MeV state are detected with virtually 100% efficiency, measurement of the branching ratio consists, to an excellent approximation, of dividing the number of pair events observed by the number of inelastic protons observed feeding the state. There are, however, a number of corrections and uncertainties which are considered in this and the next section.

A. Dead time corrections

As described above, these corrections were made by recording simultaneously in the singles and coincidence spectra pulses from a pulser triggered randomly at an average rate proportional to the beam current. These corrections ranged from 3–8%.

B. Contamination of pair spectrum by γ rays

Although the ball-and-cylinder geometry discriminates strongly against detection of γ rays relative to charged particles, the pair branch is extremely weak, and two sources of γ rays can significantly influence the pair spectrum. The first is the two-photon cascade from the 7.65-MeV state via the 4.44-MeV state to the ground state, which cascade is about 60 times more probable than the pair decay. Since the γ branching ratio is known,[5] the contribution to the pair spectrum can readily be calculated once the sensitivity and response function of the detector are known. The geometry of the detector lends itself to an experimental determination of these quantities. From the scintillator spectrum measured in coincidence with protons exciting the 4.44-MeV state, the response to the 4.44-MeV photons can be obtained. The response to 3.21-MeV photons was assumed to be adequately approximated by scaling the line shape of the 4.44-MeV distribution by the ratio of the Compton edge energies, and the efficiency by the ratio of the Compton interaction probabilities in plastic. For a two-photon cascade to be detected only one photon need interact in the cylinder. Therefore, in order to obtain a spectrum of photons interacting in the ball alone, a measurement of the ball spectrum in coincidence with protons exciting the 4.44-MeV level, but in anticoincidence with events in the cylinder, was also made. Again, the equivalent response to 3.21-MeV photons was obtained by scaling, and finally the full two-photon response was derived by Monte Carlo techniques from the one-photon measurements. (The one-photon efficiencies measured agreed very well with analytical calculations based on the geometry of the scintillators and the interaction probabilities for 4.44-MeV photons). The γ-ray cascade from the 7.65-MeV level causes a background under the e^+e^- peak of approximately 7% MeV^{-1}.

Another potentially serious source of γ rays is target contaminants. Fortunately, proton elastic scattering could be monitored to provide a continuous and reliable indication of target impurities during the course of the experiments. ^{13}C, ^{14}N, ^{16}O, ^{28}Si, and $^{35,37}Cl$ were detected in the targets, in addition to ^{12}C. Of these, ^{28}Si was the most significant because (p,p') reactions excite γ-emitting levels in ^{28}Si at outgoing proton energies near that from $^{12}C(p,p')^{12}C(7.65)$. Indeed, early runs with a simple 4π-sr scintillator indicated that substantial contributions from $^{28}Si(p,p'\gamma)$ were present in the e^+e^- spectrum. This problem was reduced by (i) adopting the separated-ball-and-cylinder geometry, (ii) improving the vacuum system and introducing a cold trap, (iii) changing targets when appreciable ^{28}Si buildup had occurred, and (iv) reducing the beam energy from 10.62 to 10.56 MeV to avoid a resonance which appears in the $^{28}Si(p,p')^{28}Si(1.78)$ excitation function.[11] Although some weak ^{28}Si lines still appear in the final proton coincidence spectra, there was no evidence for significant population of the three levels in the vicinity of the ^{12}C 7.65-MeV line, the levels at 8.413 (4^-), 8.543 (6^+), and 8.589 (3^+) MeV in ^{28}Si. This conclusion was checked in a separate experiment by comparing the spectrum of protons in coincidence with plastic pulses above 5 MeV with corresponding spectra from two runs on a natural SiO target. For convenience in the latter runs a NaI(Tl) crystal was used instead of the plastic scintillator. The possibility of unknown narrow resonances in the $^{28}Si(p,p')$ reaction and the difficulty in reproducing the beam energy precisely introduce some uncertainty into the interpretation of the results.

C. Correction for background

Background spectra in the scintillator were obtained in the usual way by setting equal width windows on either side of the proton peak from $^{12}C(p,p')^{12}C(7.65)$. A slight renormalization was applied in order to account more accurately for the nonlinearity of the continuum underlying the 7.65-MeV proton peak. In fact, however, background in the e^+e^- spectrum was negligible above 5 MeV.

D. Correction for accidental coincidences

Particular care was taken with chance coincidence subtraction because it comprised the largest correction made to the raw data, about 50%. In principle, the chance peaks which occur in the TAC spectrum because of the pulsed beam can be used to extract correctly normalized chance spectra, but only if the beam intensity is perfectly steady. Otherwise, as is well known, the chance contribution to the "true" peak may be underestimated because it depends on the average value of the square of the beam current, rather than the average value of the product of currents in unrelated beam bursts. A more attractive alternative which avoids this difficulty is to use a spectrum which is known on physical grounds to be purely chance, such as the spectrum in coincidence with elastically scattered protons. Unfortunately, in the present case, the elastic peak is at the same energy as a peak resulting from chance pileup of two inelastic protons from the 4.44-MeV level. Therefore we have taken advantage of a peak in the scintillator spectrum which results from protons passing through a small gap in the graphite tubing and entering the scintillator. These protons can only by chance be in coincidence with protons in the Si detector. Therefore the scintillator spectra obtained by setting windows on the chance peaks in the TAC spectra could be normalized to eliminate the proton peak from the scintillator spectra gated on the prompt TAC peak. This could be done with high statistical accuracy—normalizing to just the center channel in the proton peak leads to a 4.5% contribution to the uncertainty in Γ_π/Γ from chance subtraction. A further reduction to 2.5% can be obtained by normalizing to the entire spectrum below 4 MeV, if it be assumed to arise altogether from chance coincidences (after correction for the cascade γ rays). The latter approach has been adopted in the final analysis of the data, but an uncertainty of 5% from chance subtraction has been assumed, to encompass the result and uncertainty from the former, more conservative, method. Correcting the raw data in the manner described for cascade γ radiation, background and chance removed all statistically significant features from the e^+e^- spectrum except for the 7.65-MeV pair peak.

E. Response and efficiency of pair detector

In view of the low statistics obtainable for the 7.65-MeV pair decay, a precise *a priori* calculation of the peak position and shape is essential, so that only the amplitude need be fitted to the data in order to extract the decay intensity. Furthermore, to calculate a branching ratio, the absolute efficiency of the pair detector must be known. These parameters were obtained by Monte Carlo calculations, whose accuracy was verified by measurement of the pair decay branching ratio of the 6.05-MeV 0^+ level in ^{16}O.

The angular distribution and energy dependence of $E0$ $0^+ \to 0^+$ pair emission is given by[12]:

$$P(\theta)dW_+d\Omega \sim p_+p_-(W_+W_- - 1 + p_+p_-\cos\theta)dW_+d\Omega ,$$

where θ is the angle between e^+ and e^- momenta (p_+ and p_-, respectively), and $W^2 = p^2 + 1$. Values of θ and W_+ following this joint distribution were obtained from appropriately weighted random number generators. Subject to the constraint on θ, the lab directions of the electron and positron were randomized.

Although the path of electrons through matter is tortuous, it seemed reasonable to assume rectilinear motion, both because of the low Z of the stopping material and because the detector subtended nearly 4π sr. The empirical Katz-Penfold relationships[13] were used to describe the range and energy of the electrons. The intrinsic scintillator and photomultiplier response was taken to be a symmetric Gaussian (found to have a standard deviation of about 0.3 MeV at $E=5$ MeV). No attempt was made to simulate possible variations in light collection efficiency from different regions of the scintillator. Reasonable choices for the energy dependence, E^n, of the intrinsic linewidth from $n=0$ to 1 have little influence on the relative shapes of the 6.05- and 7.65-MeV pair peaks because of the small energy difference and the minor contribution of the intrinsic width to the total width ($n=\frac{1}{2}$ was used in the final calculations).

The principal effects which degrade the line shape are energy loss in the graphite tube absorbers and escape of particles, both of which may be treated straightforwardly given the directions and momenta of the e^+ and e^-, and range-energy relationships.

Bremsstrahlung losses were treated in an approximate manner by assuming that the total rate of energy loss $dE/dx\,|_{\text{tot}}$ for electrons is independent of energy, and that the radiative loss is given by[14]

$$\left.\frac{dE}{dx}\right|_{\text{rad}} = \frac{EZ}{700}\left.\frac{dE}{dx}\right|_{\text{tot}},$$

where E is the energy in MeV. The photon spectrum from radiative losses in a thin lamina was assumed to have constant energy per unit frequency up to the maximum possible.[15] From these considerations the total probability for emission of bremsstrahlung (20% per particle for photons of energy > 0.1 MeV), and the resultant photon spectrum, could be estimated.

Annihilation in flight can prevent positrons from depositing their full kinetic energy in the stopping medium. For low-Z materials, only two-quantum annihilation is of importance, and an expression for the cross section derived by Bethe[16] was employed in the Monte Carlo calculations. Approximately 25% of the positrons annihilate in flight.

Interaction of γ rays resulting from bremsstrahlung, annihilation in flight, and annihilation at rest was treated by considering such γ rays as originating at a distance from the center of the scintillator equal to the average range of the electrons. Rectangular Compton distributions were assumed, and multiple interactions and pair production were ignored. Although the treatment of bremsstrahlung, annihilation in flight, and interaction of secondary γ rays was not very accurate those effects are small and chiefly influence the shape, not the detection efficiency.

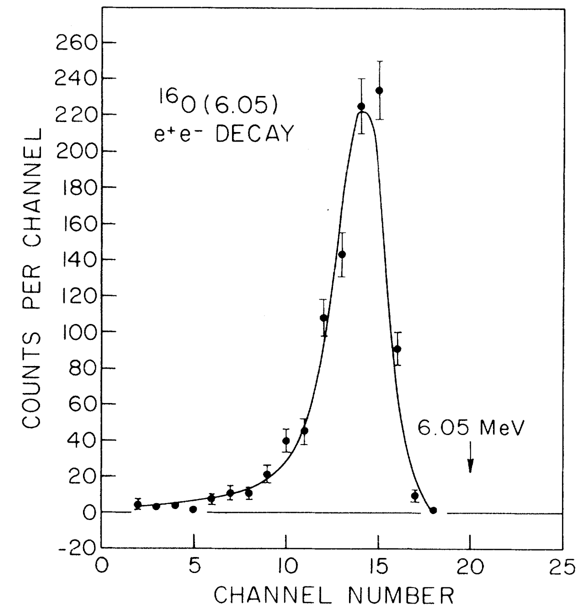

FIG. 3. Observed spectrum of pair decays following inelastic proton excitation of the 6.05-MeV state in ^{16}O. The solid curve is a Monte Carlo calculation fitted by least squares to the data by varying the amplitude, abscissa scale, and the width of the intrinsic scintillator response.

The Monte Carlo calculations were very successful in reproducing the shape and intensity of the e^+e^- peak from the decay of ^{16}O(6.05), as will be shown below. They also showed that less than 0.5% of pair events fail to leave a signal greater than 0.1 MeV in the cylinder.

IV. RESULTS AND CONCLUSIONS

The e^+e^- decay of the ^{16}O 6.05-MeV level was observed by bombarding targets of Formvar with 10.5-MeV protons. A collimator was placed in front of the proton detector in order to reduce kinematic broadening sufficiently to permit the 6.05- and 6.13-MeV states to be resolved. The pair spectrum after correction for background and chance is shown in Fig. 3. Also shown is the Monte Carlo calculation fitted by least squares to the data. Since the Monte Carlo calculation predicts that the peak should fall at 4.29 MeV, the fitting procedure determines the energy calibration for the pair detector. The fit is qualitatively good, although $\chi^2=52$ for 14 degrees of freedom, indicating the presence of small systematic deviations. However, the extent of the agreement with relatively high-statistics data permits complete confidence in using the Monte Carlo predictions to fit the ^{12}C 7.65-MeV pair peak. The branching ratio measured for the e^+e^- (and internal conversion) decay of the 6.05-MeV state

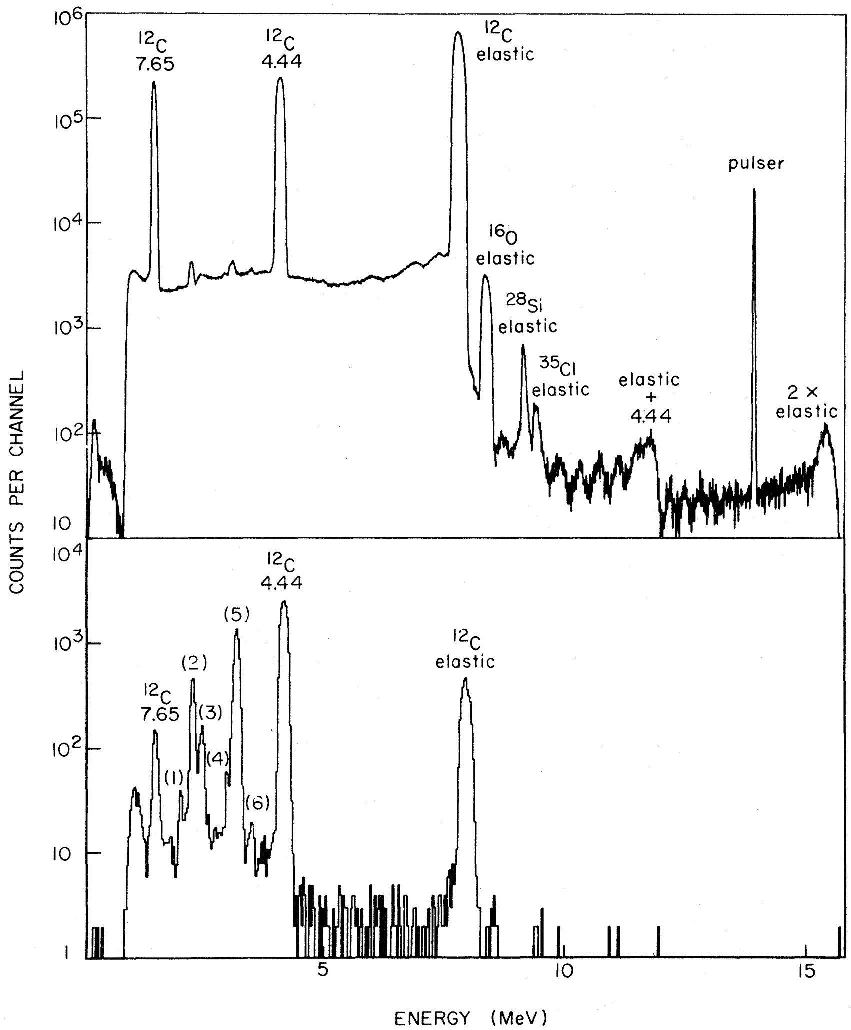

FIG. 4. Spectra observed in proton bombardment of ^{12}C in singles (top) and in coincidence with scintillator pulses greater than 5 MeV (bottom). No correction has been made for background or chance coincidences. Numbered impurity peaks on the lower spectrum are as follows: (1) ^{28}Si(7.93), (2) ^{16}O(7.12), (3) ^{16}O(6.92), (4) ^{28}Si(6.88 + 6.89), (5) ^{16}O(6.13 + 6.05), (6) ^{28}Si(6.28). The oscillations in the pileup region are caused by the pulsed nature of the beam.

is $(100.1 \pm 2.0)\%$, in excellent agreement with unity.

Measurements of the e^+e^- decay of the ^{12}C 7.65-MeV level were made in two runs, "I" and "II," at beam energies ranging from 10.54 to 10.58 MeV. The full area of the proton detector was used, and at a beam current of 5 nA the following count rates were typical: Si detector: 800 sec^{-1}; cylinder: 2200 sec^{-1}; ball: 5000 sec^{-1}; pileup: 260 sec^{-1}. The proton spectra observed in singles and in coincidence with scintillator pulses >5 MeV (no chance or background subtracted) are shown in Fig. 4. In run I, 8.886×10^6 counts were detected in singles in the 7.65-MeV peak, and in run II, 7.629×10^6.

The scintillator spectra in coincidence with the 7.65-MeV peak were corrected as described in the previous sections for cascade γ radiation, background, and chance. The Monte Carlo prediction for the 7.65-MeV e^+e^- peak shape was then fitted (in amplitude only) to the data. Because the numbers of counts in the channels of interest were small, the data were fitted not by least squares, but by an iterative maximum-likelihood procedure assuming Poisson statistics for the raw counts. The combined data for runs I and II (corrected) are shown in Fig. 5 together with the fitted Monte Carlo spectrum. As described in the previous section, two experiments on Si$(p,p'\gamma)$ at beam energies of 10.61 and 10.63 MeV, indicated the need for -1% and -7% corrections, respectively, to the ^{12}C result. The Si data were

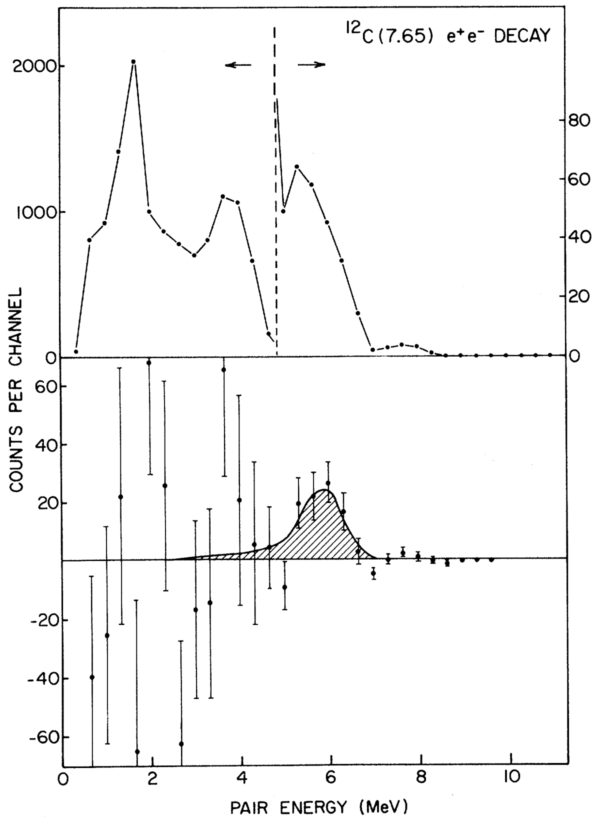

FIG. 5. Observed scintillator spectra in coincidence with inelastic protons from $^{12}C(p,p')^{12}C(7.65)$. The upper graph shows the uncorrected raw data. The lower graph shows the same data corrected for background, change coincidences, and cascade γ radiation from the 7.65-MeV state. The shaded area is the Monte Carlo calculation of the line shape for the e^+e^- decay of the 7.65-MeV state, normalized to the data in amplitude only. The large uncertainties below 4 MeV reflect the large chance correction in this region.

normalized to the ^{12}C data via the ^{28}Si 7.933-MeV line, which appears weakly in the ^{12}C coincidence proton spectrum (Fig. 4). In view of the uncertainties and the small size of the effects, a correction of $(-4\pm4)\%$ has been adopted in deriving the final value for Γ_π/Γ. The results for the branching

TABLE I. Summary of data on the pair branching ratio of $^{12}C(7.65)$.

Source	$10^6\Gamma_\pi/\Gamma$
Present Run I	6.7 ± 1.5
Run II	5.8 ± 1.5
Corrected average [a]	6.0 ± 1.1
Alburger [b]	6.9 ± 2.1
Weighted average	6.2 ± 1.0

[a] Corrected for ^{28}Si (see text).
[b] References 8 and 9.

TABLE II. Summary of nuclear parameters for helium burning.

Parameter and value	Contribution to uncertainty in $P_{3\alpha}$ (%)
$\Gamma_\pi=(60.5\pm3.9)\ \mu eV$ [a]	6
$\Gamma_\pi/\Gamma=(6.2\pm1.0)\times10^{-6}$ [b]	16
$\Gamma_{rad}/\Gamma=(4.13\pm0.11)\times10^{-4}$ [c]	3
$\Gamma_{rad}=(4.03\pm0.71)$ meV [d]	18
$Q_{3\alpha}=(379.38\pm0.20)$ keV [e]	2 [f]
Combination	18
$^{12}C(\alpha,\gamma)^{16}O$ process:	
$S(0.3\text{ MeV})=0.08^{+0.05}_{-0.04}$ MeV b [g]	

[a] References 6 and 7.
[b] From Table I.
[c] Reference 5.
[d] Computed according to Eq. (2).
[e] Reference 4.
[f] At $T=10^8$ K.
[g] References 18 and 19. The former reference gives a formula for S as a function of E.

ratio are summarized in Table I. The two ^{12}C runs are in good agreement which each other, and the combined result,

$$\Gamma_\pi/\Gamma=(6.0\pm1.1)\times10^{-6},$$

is in excellent agreement with Alburger's measurement.[8,9] The quoted uncertainty arises almost entirely from the statistical uncertainty in the raw data on the 7.65-MeV pair decay. As the present result agrees well with the previous one, no significant change in the helium burning process is implied. The uncertainty in the triple-α reaction rate is reduced by a factor of 2.

The present status of the experimentally measured nuclear parameters relevant to helium burning is summarized in Table II. In order to derive Γ_{rad}, the present and previous experimental results for Γ_π/Γ, Γ_{rad}/Γ, and Γ_π have been combined and inserted into Eq. (2), giving

$$\Gamma_{rad}=(4.03\pm0.71)\text{ meV}.$$

It is clear that the rate of the 3α reaction is now known with sufficient precision for all practical purposes, although there is considerable uncertainty in the $^{12}C(\alpha,\gamma)^{16}O$ rate.

Fowler, Caughlan, and Zimmerman, in their recent review,[17] tabulate a quantity $N_a{}^2\langle\alpha\alpha\alpha\rangle$, related to $P_{3\alpha}$ by

$$N_a{}^2\langle\alpha\alpha\alpha\rangle=6N_a{}^2n_\alpha{}^{-3}P_{3\alpha}\ \text{cm}^6\,\text{sec}^{-1}\,\text{mole}^{-2},$$

where N_a is Avogadro's number. To correct that tabulation for recent experimental results (as

TABLE III. Values of $^{12}C/^{16}O$ for several stellar masses. The helium burning process is assumed to take place at 2×10^8K.

$M/M_\odot$ [b]	$^{12}C/^{16}O$ [a] Lower	Central	Upper
10	1.9	3.7	27
30	1.0	1.8	5.1
50	0.73	1.3	3.4

[a] The column labeled "central" gives the value of $^{12}C/^{16}O$ calculated with Arnett's Eq. (37) (see Ref. 20) and the adopted values of the reaction rates. The fourth and second columns are upper and lower bounds taking into account estimates of the uncertainties in the reaction rates for the 3α and $^{12}C(\alpha,\gamma)^{16}O$ reactions.

[b] The stellar masses are in units of the solar mass $M_\odot$.

summarized in Table II) it is necessary to multiply the values of $N_a{}^2\langle\alpha\alpha\alpha\rangle$ given by a factor

$$1.019\exp(8.3\times10^6/T)\,.$$

Detailed calculations of $^{12}C/^{16}O$, the ratio of atoms of ^{12}C to atoms of ^{16}O resulting from helium burning, have been performed by Arnett.[20] The result depends on the stellar mass as well as on the nuclear parameters discussed above. Values of $^{12}C/^{16}O$ calculated from the reaction rates of Table II using the formula given by Arnett[20] are given in Table III. Production of ^{12}C is dominant for the lighter stars and the $^{12}C/^{16}O$ ratio remains larger than the solar system ratio of 0.55 [21] even for the stars between 30 and 50 solar masses which dominate[22,23] the production of ^{12}C and ^{16}O. It is not clear that there is a fundamental discrepancy, both because highly evolved stars do not eject into the interstellar medium a representative sample of the ^{12}C and ^{16}O made during helium burning, and because there are uncertainties in the stellar model calculations[23] and in the observed abundances.[24,25] However, the helium burning reaction rates themselves are now sufficiently well known that it seems germane to reexamine carefully the astrophysical models of helium burning stars.

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