Pair decay of the 7.65-MeV level of ^{12}C†

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The ground-state nuclear pair decay branch from the 7.65-MeV 0^+ level in ^{12}C has been measured using the reaction $^{12}C(p,p')^{12}C$ on a 3.5-mg/cm^2 thick carbon target at $E_p = 10.5$ MeV together with a magnetic pair spectrometer. For normalization the internal pair line due to the 4.44-MeV $E2$ transition from the first-excited state of ^{12}C was used. In separate measurements the corresponding relative populations of the 7.65- and 4.44-MeV states were determined. The angular distribution of the 4.44-MeV γ rays was also measured in order to obtain the correction to the spectrometer efficiency due to nuclear alignment. A pair decay branch of $(7.1 \pm 0.8) \times 10^{-6}$ was obtained for the 7.65-MeV level in agreement with, but somewhat more accurate than previous measurements.

[NUCLEAR STRUCTURE ^{12}C, 7.65-MeV state; measured Γ_π/Γ; deduced Γ_{rad}.]

I. INTRODUCTION

The importance of the nuclear pair decay branch from the 7.65-MeV 0^+ second-excited state of ^{12}C in calculating the reaction rate for 3-α stellar helium-burning processes has recently been reemphasized by Robertson, Warner, and Austin[1] in their report of a new measurement of this branch. The 3-α reaction rate depends directly on the total radiative width Γ_{rad} of the 7.65-MeV level which, in turn, can be found from the relationship

$$\Gamma_{rad} = (\Gamma_{rad}/\Gamma) \times (\Gamma/\Gamma_\pi) \times \Gamma_\pi . \quad (1)$$

Thus the pair decay branch, the inverse of the second factor on the right-hand side of Eq. (1), plays a key role in the determination of Γ_{rad} even though it is by far the smallest of the three possible decay branches of the 7.65-MeV level.

Experimentally the first and third factors in Eq. (1) are now known[1] to ~3% and ~6% accuracy, respectively. Prior to the work of Robertson, Warner, and Austin the only measurement[2] of the pair decay had an accuracy of 30% and this was the major source of error in Γ_{rad}. The earlier experiments used the $^9Be(\alpha,n)^{12}C$ reaction to populate the 7.65- and 4.44-MeV levels of ^{12}C and the two pair lines were measured much as in the present work. Somewhat later the relative (α,n) neutron populations of the 7.65- and 4.44-MeV levels were measured[3] under similar target and beam energy conditions and this allowed the pair branching of the 7.65-MeV state to be determined as $(6.9 \pm 2.1) \times 10^{-6}$.

A completely different technique was used by Robertson, Warner, and Austin in their measurement[1] of the pair decay branch from the ^{12}C 7.65-MeV level. They used the $^{12}C(p,p')^{12}C$ reaction with 10.56-MeV protons which excites the state at a known resonance[4] and they observed the positron-electron pairs in a plastic scintillation detector in coincidence with inelastic protons entering a Si(Sb) particle detector. A branch $\Gamma_\pi/\Gamma = (6.0 \pm 1.1) \times 10^{-6}$ was obtained in agreement with the older measurement[2] but twice as accurate.

Preparations have been under way for several years at this laboratory to remeasure the pair branch of the ^{12}C 7.65-MeV level. The general plan was to use the $^{12}C(p,p')^{12}C$ reaction at the well-known resonance at $E_p = 10.5$ MeV, and to use the magnetic pair spectrometer with a reconstructed detector system for obtaining greater accuracy in the measurements. Aside from a relatively favorable cross section for forming the 7.65-MeV state, one of the main advantages of the $^{12}C(p,p')^{12}C$ reaction (as compared with the α,n reaction, for example) is that the population intensities of the states in ^{12}C can be measured accurately in a supplementary experiment using simple detectors for charged particles. Thus if the relative pair peak intensities of the 7.65- and 4.44-MeV transitions are measured, and if the corresponding state populations have been determined, the pair branching of the 7.65-MeV state can be derived provided that the relative pair spectrometer efficiencies are also known. Spectrometer efficiencies have been calculated[5] for all multipoles and over a wide range of transition energies with relative accuracies thought to be good to a few per cent. However, these calculations apply to nonaligned nuclei, whereas in the most general case the alignment of the nucleus at the time the transition occurs results in either more or fewer pairs entering the acceptance solid angle

of the spectrometer. For the determination of the correction for alignment the method and calculations have been worked out previously.[6] The procedure consists of first measuring the angular distribution of the corresponding γ rays under the same target and beam energy conditions as in the pair spectrometer experiments and finding the coefficients A_2 and A_4 of the Legendre polynomials in the γ-ray angular distribution expressed as

$$N_\theta(\gamma) = N(\gamma)[1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)]. \quad (2)$$

For a pure E_2 transition such as the 4.44-MeV $2^+ \rightarrow 0^+$ γ ray from the ^{12}C first-excited state the corrected efficiency $\mathcal{E}$ of the pair spectrometer is then given by

$$\mathcal{E} = \mathcal{E}'(1 + A_2 \Delta_2^2 + A_4 \Delta_4^2), \quad (3)$$

where $\mathcal{E}'$ is the efficiency for nonaligned nuclei[5] and Δ_2^2 and Δ_4^2 are factors obtained from Figs. 1 and 2 in Ref. 6 for a pure $E2$ transition of 4.44 MeV. In the case of the 7.65-MeV $0^+ \rightarrow 0^+$ transition there is no alignment and hence no correction to the calculated efficiency is required.

II. EXPERIMENTAL METHODS AND RESULTS

A. Pair spectrometer modifications and tests

In the original design[7] of the magnetic pair spectrometer, modified[8] with an improved photomultiplier detector system, the focused positrons and electrons were measured in two scintillation crystals attached to light pipes having a semicircular shape at the detector and with a diameter of 3.18 cm. The detectors were located inside the final focal plane such that the electrons, approaching at an angle of ~51° to the optic axis, were intercepted by the front surface of the detector near its outer edge. Due to the finite spread of the image and edge effects in the crystal it could be shown that there was no advantage in using detecting crystals of more than ~1.3-cm thickness, and even in this case there would be a considerable variation of the diagonal path length through the detector. Tests showed that the pulse-height spectra for transitions up to about 6 MeV, i.e., focused electrons of 2.5 MeV, were reasonably good, but that at 7.6-MeV transition energy (3.3-MeV focused energy) a considerable distortion of the pulse-height spectrum occurred because of incomplete energy absorption of some of the electrons. Such distortions could lead to large uncertainties in the efficiency of the system as a function of focusing energy. A scheme that was tried in order to overcome this defect was to use 2.54-cm thick semicircular crystals of a conical shape, flared from the 3.18-cm diam semicircular match to the light pipe at one end out to a semicircle with a diameter of 6.35 cm at the other end. While these crystals absorbed all of the electron energy at 3.3 MeV the light collection efficiency, and therefore the pulse-height resolution, at the photomultiplier was severely degraded because of internal reflections within the crystal. It was concluded that a crystal in the shape of a right semicircular cylinder gives a very much better light collection efficiency and that good results would be achieved at higher energies only by increasing the diameter of the light pipes to accommodate thicker crystals of correspondingly larger diameter.

A completely new detecting system was therefore constructed similar in its general design to the old detector but differing in size and in other mechanical details. The detecting crystals are 2.54-cm thick NE102 semicircular cylinders of 6.35-cm diam separated by a 2-mm thick W absorber. They are attached with epoxy to light pipes made from Lucite rod of UVT (ultraviolet transparent) quality 6.35 cm in diameter planed and tapered down to a semicircular cross section at the crystal end and to a diameter of 4.8 cm at the photo tube end where RCA 6342A tubes are epoxyed on. All surfaces are highly polished and each light pipe and detector is wrapped in aluminum foil. A new mechanical arrangement allows the detectors to be moved both axially and normal to the axis for alignment purposes. Other details of the coincidence circuitry are essentially the same as in the earlier design.[7,8]

In order to test the performance of the new detecting system the pairs from the 6.05-MeV ^{16}O 0^+ state were produced using the ^{19}F$(p, \alpha)^{16}$O reaction at $E_p = 4$ MeV on a 2-mg/cm^2 thick BaF_2 target. Prior to these measurements the optimum position and alignment of the detector had been established using the conversion electron spectrum from a ^{207}Bi source.

Figure 1 shows the pulse-height spectrum from one of the crystals when the spectrometer was set at a point on the positron-electron continuum corresponding in momentum to the peak of the ^{12}C 4.44-MeV transition, i.e., a focusing energy of 1.71 MeV. The full width at half maximum of this peak is 19.7%. The spectrum from the other detector was practically identical. As previously described[7] a pulse-height window must be imposed on the separate spectra in order to avoid coincidences due to scattering. The arrows in Fig. 1 show the lower and upper limits of the pulse-height window used in all of the present work. A further correction not mentioned previously is to determine what fraction of the total focused spectrum lies within the pulse-height window and how this fraction varies with focused energy. The

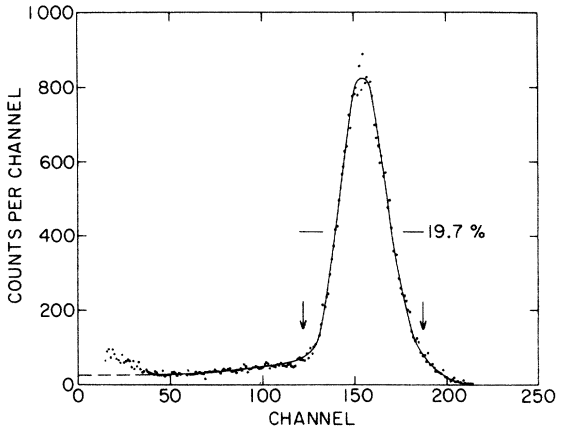

FIG. 1. Pulse-height spectrum from one of the detectors when focusing electrons of 1.71-MeV energy corresponding to the pair peak of a 4.44-MeV transition. Arrows indicate the lower and upper limits of the pulse-height window imposed on the coincidence yield. The dashed line shows the extrapolation used when determining the fraction of total counts lying within the pulse-height window.

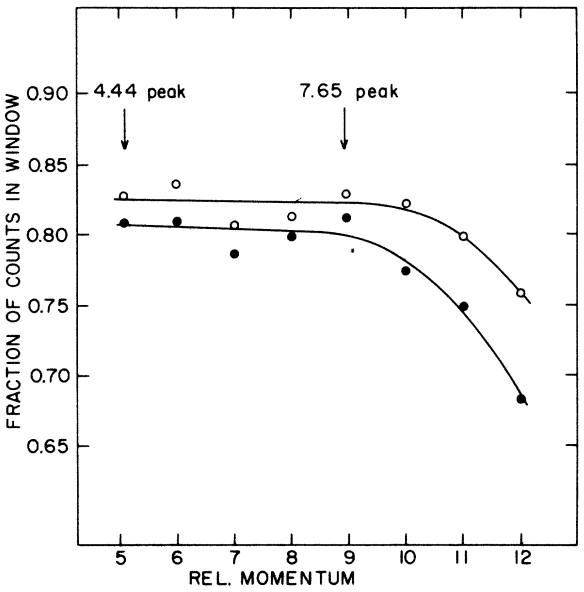

FIG. 2. The fraction of the pulse-height spectrum lying within the window (see Fig. 1) as a function of spectrometer momentum setting for the two detectors (solid and open circles) covering the transition energy region from 4.44 to 10.3 MeV.

pulse-height spectra of both crystals were therefore recorded in eight steps over the focusing energy range from 1.7 to 4.64 MeV corresponding to pair peaks for transitions from 4.44 to 10.3 MeV. In these tests, as in taking all data on pair spectra, the pulse-height windows were held fixed and the gains of the amplifiers were adjusted to place the peak of the spectrum at a standard pulse-height channel. As the focusing energy was increased there was a continuous decrease in the percentage line width such that the detector pulse-height resolution at the 7.65-MeV transition peak was 14.0% full width at half maximum as compared with 19.7% at the 4.44 peak position. However, there was also a slight increase in the relative number of counts in the low-energy tail, possibly because of edge effects. Figure 2 shows how the fraction of counts within the window varied with focusing momentum for the two detectors. In deriving these fractions each spectrum was extrapolated horizontally below channel 40, as indicated by the dashed line in Fig. 1, to remove the effect of low-energy background and tube noise. It is seen from Fig. 2 that the fractions of detected electrons within the window is very nearly constant, at least from 4.44 to 7.65 MeV and in fact the product of the two fractions, which is proportional to the overall efficiency for detecting pairs that reach the crystals, decreases by only about 1% over this energy range. As seen in Fig. 2 above 8-MeV transition energy there is a decline in the fraction of counts in the window showing that some of the focused electrons are no longer completely absorbed by the detector. It thus appears that the new system is ideally suited to the energy range of the present experiment. No further improvement would be gained with a larger size detector and one would only increase background effects if even bigger crystals were to be used.

Tests of the coincidence efficiency were made when focusing at the peak of the 6.05-MeV line, as well as in the $^{12}C(p,p')^{12}C$ reaction at the 4.44-MeV peak. When using a shorted stub in the coincidence circuit[7] of 12.5-cm length, corresponding to a resolving time of 1.0 nsec, the coincidence efficiency was >99% for both peaks.

B. Pair spectrum from $^{12}C(p,p')^{12}C$

The pair spectrum from the $^{12}C(p,p')^{12}C$ reaction was measured using a carbon foil target 3.5 mg/cm^2 thick mounted on a new target tube that was constructed for a recent measurement[9] of the shape of the ^{20}F β-ray spectrum. This design, in which the target foil is cemented over a hole in a thin aluminum support disk, minimizes the scattering of electrons. Beam current is measured in a Faraday cup biased at +300 V, with a separate bias of +300 V on the target so as to reduce the interchange of secondary electrons between the target and cup, thereby insuring an accurate and reproducible beam charge reading. No cooling was provided for the target since the power dissipation in this experiment was only 0.1 W in the target itself. However, the Faraday cup had to

dissipate 8 W and was cooled with air circulating through an attached copper tube.

As anticipated, one of the main problems in the experiment had to do with the background in the region of the 7.65-MeV pair peak. Initial tests were made using Ta for both the beam-defining collimator and the bottom of the Faraday cup. However, the coincidence background with a 10.5-MeV proton beam was quite high and changed very little when the spectrometer annulus was closed so as to stop all focused electrons. It was concluded that the background was being caused mostly by neutrons, produced in the Ta, which reach the vicinity of the detector where they generate secondary γ rays and pairs resulting in coincidence counts. Separate tests were therefore made to measure neutron yields from various materials bombarded with 10.5-MeV protons. A ^3He proportional counter enclosed in paraffin was used to detect neutrons from samples placed in a small target chamber. The materials tried included Ta, Au, W, Pb, Bi, Pt, and U. Neutron yields from the Au, W, and U samples were comparable to each other and about half of the yield from Ta, while Pt was slightly lower than Au. Bi and Pb were the best from the standpoint of neutron production (about 0.6 as great as the Au) but they were rejected as possible materials for the collimator and Faraday cup because of their poor heat conductivities and low melting points. Au was therefore selected as the best compromise. As a means of further reducing the background a paraffin cylinder of about 15 cm diam. with a hole in the center was installed so as to surround the Faraday cup thereby absorbing some of the neutrons.

In all of the experiments the spectrometer was set for maximum transmission and a 10.5-MeV proton beam of about 0.8 μA on target was produced by an MP tandem Van de Graaff. Data were normalized with a current integrator. Coincidences were recorded at each momentum setting after adjusting the amplifier gains so as to bring the pulse-height peaks of the two crystals to a standard channel reading as observed in a pulse-height analyzer. (See Fig. 1 and the previous discussion of the pulse-height windows.)

Figure 3 shows the complete spectrum from the first main run and a portion of the data from a second run having improved statistics. In the region of the 7.65-MeV pair peak the data of the first run were obtained in four passes totaling ~2 h per point. After each pass a count was made at the 4.44-MeV peak to check its yield; no significant variations were noted. The average of all such counts at the 4.44-MeV peak was used in establishing the ratio of the 7.65- and 4.44-MeV

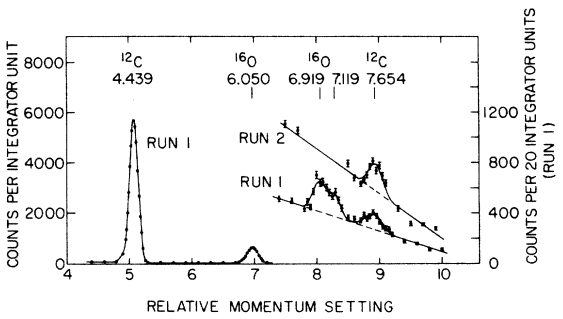

FIG. 3. Pair spectra from a 3.5-mg/cm^2 thick carbon target bombarded with 10.5-MeV protons. The complete data are shown for run No. 1 while only a portion of run No. 2 is shown.

peak intensities. The presence of oxygen in the carbon foil resulted in the relatively strong 6.05-MeV peak due to this $E0$ transition as well as the unresolved 6.92- and 7.12-MeV peaks from the third and fourth excited states of ^{16}O. For the second run the region containing these two ^{16}O peaks was excluded to save time. In making computer fits to the 7.65-MeV peak and background the region of these ^{16}O peaks was also omitted in the first run. For the computer fits both the 7.65-MeV peak position and line width were specified, having been derived from the calibration and line width given by the 4.44-MeV peak. The solid lines in Fig. 3 are those given by the computer fits. It should be noted that all of the peaks in the spectrum except that of the ^{16}O 6.05-MeV transition are expected to be Doppler shifted to higher energy. This was taken into account in deriving the expected positions of the 6.92-, 7.12-, and 7.65-MeV peaks as indicated by the vertical lines in Fig. 3.

As mentioned above, the background in the 7.65-MeV region is caused mostly by neutrons with only about 20% of the background due to random coincidences as established by inserting a delay in one side of the coincidence circuit. The reason that the neutron-induced background decreases with increasing focusing energy apparently has to do with the fact that the amplifier gains are reduced, as the energy is increased, so as to maintain standard pulse heights. Thus a smaller number of background events is expected to lie within the pulse-height windows when the spectrometer is set a higher focusing energies.

The ratio of the 7.65- to 4.44-MeV peak amplitudes is $(1.036 \pm 0.138) \times 10^{-3}$ from the first run and $(0.910 \pm 0.077) \times 10^{-3}$ from the second. A weighted average of $(0.952 \pm 0.070) \times 10^{-3}$ is used below in calculating the branching ratio of the 7.65-MeV level.

C. Proton populations of the 7.65- and 4.44-MeV states

Ideally one would like to be able to measure the proton populations of ^{12}C states in the $^{12}C(p,p')^{12}C$ reaction under conditions identical to those used for the pair spectrum. The usual procedure for doing this is to record the spectrum of inelastically scattered protons over a wide range of angles so as to obtain the relative integrated cross section for forming the 7.65- and 4.44-MeV states. However, the carbon foil target thickness of 3.5 mg/cm^2 used in the pair spectrometer is not only excessive for obtaining good proton line spectra but it cannot be used normal to the incident beam for such angular distribution measurements. The procedure adopted was to use a carbon foil of 120-μg/cm^2 thickness placed at 45° to the beam (+ or −) in a large scattering chamber and a 1000-μm thick Si detector mounted on an arm that could be rotated. For the 3.5-mg/cm^2 thick carbon target the energy loss for a 10.5-MeV incident proton is 137 keV whereas the energy loss in the 120-μg/cm^2 thick foil at 45° to the beam is 6.6 keV. As an approximation to finding the overall population ratio of the 7.65- and 4.44-MeV states the spectrum of scattered protons was measured every 10° from 30° to 160° to the beam and at five energies from 10.4 to 10.5 MeV in steps of 25 keV representing the range of reaction energies within the 3.5-mg/cm^2 thick target during the pair measurements. Each spectrum was analyzed to extract the relative intensities of the 4.44- and 7.65-MeV peaks. A pulser was used for making dead-time corrections. Yields were then multiplied by $\sin\theta$ and summed to give the relative cross sections integrated over the range 30° to 160°.

The ratios of the 4.44/7.65 proton populations found in this way at the five beam energies all fell within the range 3.5 to 4.0 with the ratio of the grand sums being 3.74 ± 0.18. The error of ±5% is an estimate based on possible uncertainties in the yields at large and small angles inaccessible to the measurements as well as the intermediate beam energies lying between those chosen for the tests. This result seems to be consistent with previous measurements of the population ratio in the vicinity of the resonance. Obst and Braithwaite,[10] for example, obtained a value of 3.44.

D. Angular distribution of the 4.44-MeV γ rays

The angular distribution of the 4.44-MeV γ rays produced in the $^{12}C(p,p')^{12}C$ reaction was measured using a beam of 10.5-MeV protons incident on a 3.5-mg/cm^2 thick carbon foil (from the same foil sample used in the pair spectrometer) mounted on a very thin Al frame and placed normal to the beam in a small glass target chamber. A Ge(Li) detector 15% efficiency was located on the arm of a goniometer at a distance of 17.5 cm from the target and spectra were recorded every 10° from 0° to 150° to the beam. A pulser output was also stored and recorded in a scaler in order to correct for dead time. The clearly resolved Doppler-broadened full-energy peak of the 4.44-MeV γ rays was analyzed and the 0° to 90° portion of the angular distribution obtained in one of the runs is shown in Fig. 4. Small corrections were made for Doppler shifting of the γ-ray energy, an effect slightly altering the detection efficiency with angle. A computer fitting program was used to extract the following coefficients of the Legendre polynomials $P_2(\cos\theta)$ and $P_4(\cos\theta)$:

$$A_2 = +0.1885 \pm 0.0068,$$

$$A_4 = -0.2768 \pm 0.0083.$$

Corrections for the attenuation of the angular distribution due to the finite solid angle of the detector were very small but have been included in these results.

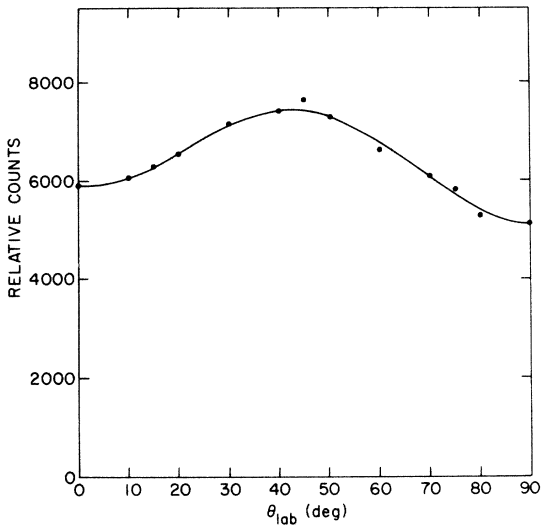

FIG. 4. Angular distribution of 4.44-MeV γ rays from a 3.5-mg/cm^2 thick carbon target bombarded with a proton beam of 10.5 MeV. The solid line is a computer fit leading to the A_2 and A_4 coefficients cited in the text.

III. PAIR BRANCH OF THE 7.65-MeV LEVEL

The peak number of pair counts $N_{7.65}(\pi)$ due to the 7.65-MeV transition is given by

$$N_{7.65}(\pi) = N(p)_{7.65} \times B_{7.65} \times \mathcal{E}_{7.65} \tag{4}$$

when $N(p)_{7.65}$ is the proton population of the state, $B_{7.65}$ is the sought-for pair branching, and $\mathcal{E}_{7.65}$ is the overall spectrometer detection efficiency for

TABLE I. Summary of pair branching measurements Γ_π/Γ of the 7.65-MeV level of ^{12}C.

Reaction	Method	Γ_π/Γ	Ref.
^{9}Be$(\alpha,n)^{12}$C	Mag. pair spec.	$(6.9 \pm 2.1) \times 10^{-6}$	2 and 3
^{12}C$(p,p')^{12}$C	Scint. and solid-state detectors	$(6.0 \pm 1.1) \times 10^{-6}$	1
^{12}C$(p,p')^{12}$C	Mag. pair spec.	$(7.1 \pm 0.8) \times 10^{-6}$	Present work
Weighted average		$(6.8 \pm 0.7) \times 10^{-6}$	

the pair peak. A similar expression applies to the 4.44-MeV transition except that the branching is 100%. Thus, the quantity $B_{7.65}$ can be expressed as

$$B_{7.65} = \frac{N(\pi)_{7.65}}{N(\pi)_{4.44}} \times \frac{\mathcal{E}_{4.44}}{\mathcal{E}_{7.65}} \times \frac{N(p)_{4.44}}{N(p)_{7.65}} . \quad (5)$$

From the earlier discussion the overall pair efficiency $\mathcal{E}$ is the product of three factors

$$\mathcal{E} = \mathcal{E}_s \times c_A \times c_w , \quad (6)$$

where $\mathcal{E}_s$ is the calculated spectrometer efficiency[5] depending on transition energy and multipolarity, c_A is the correction for nuclear alignment,[6] and c_w is the correction for the fraction of counts lying within the pulse-height windows imposed on the spectra for the two crystals. Relative spectrometer efficiencies for pairs (see Fig. 2 of Ref. 5) are 0.912 for the 4.44-MeV $E2$ transition and 563 for the 7.65-MeV $E0$ transition. For the nuclear alignment correction to the 4.44-MeV peak the values of Δ_2^2 and Δ_4^2 from Figs. 1 and 2 of Ref. 6 are +0.524 and −0.430, respectively, which, according to Eq. (3) and the above values of A_2 and A_4, leads to the efficiency correction

$$\mathcal{E}_{4.44} = \mathcal{E}'_{4.44}[1 + 0.1885 \times 0.524 + (-0.2768) \times (-0.430)]$$
$$= (1.218 \pm 0.010)\mathcal{E}'_{4.44} . \quad (7)$$

This is a fairly large correction as compared with many previous cases but it is not unreasonable.

From the pulse-height window analysis discussed previously the relative fractions of coincidences detected are in the ratio $c_{w4.44}/c_{w7.65} = 1.012$. Equation (6) gives an overall spectrometer pair efficiency ratio

$$\frac{\mathcal{E}_{4.44}}{\mathcal{E}_{7.65}} = \frac{0.912}{563} \times 1.218 \times 1.012$$
$$= \frac{1}{501} . \quad (8)$$

The uncertainty in this ratio is conservatively estimated as ±6%. Combining this ratio with the others already discussed gives, according to Eq. (5), a pair branching

$$B_{7.65} = 0.952 \times 10^{-3} \times \frac{1}{501} \times 3.74$$
$$= (7.1 \pm 0.8) \times 10^{-6} , \quad (9)$$

where the error is obtained by combining the individual errors in quadrature.

IV. DISCUSSION

The three measurements that have now been made of the pair branching Γ_π/Γ of the ^{12}C 7.65-MeV level are listed in Table I along with the weighted mean value of $(6.8 \pm 0.7) \times 10^{-6}$. Although the mean value is very nearly the same as the oldest measurement the uncertainty has now been reduced by a factor 3 to ±10%. A revised value for the radiative width Γ_{rad} of the 7.65-MeV state can be obtained from Eq. (1) by using the new weighted mean for Γ_π/Γ together with the values $\Gamma_{rad}/\Gamma = (4.13 \pm 0.11) \times 10^{-4}$ and $\Gamma_\pi = (6.05 \pm 0.39) \times 10^{-2}$ meV taken from Ref. 1. The new value is

$$\Gamma_{rad} = (3.67 \pm 0.46) \text{ meV} . \quad (10)$$

Thus, there is no significant change in Γ_{rad}, previously quoted[1] as (4.03 ± 0.71) meV, but its error has been reduced from 17.5 to 12.4%.

While the confidence in the pair branch has been increased the experience in the case of the γ-ray branching[11] of the 7.65-MeV level of ^{12}C has shown that four or five concordant measurements had to be made before a reliable weighted average value could be accepted for this branch. Thus, further measurements of the pair decay branch would certainly be desirable.

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