PHYSICAL REVIEW VOLUME 124, NUMBER 1 OCTOBER 1, 1961

Gamma-Ray Decay of the 7.66-Mev Level of C^{12}†

DAVID E. ALBURGER
Brookhaven National Laboratory, Upton, New York

(Received May 22, 1961)

Proton-gamma-gamma triple coincidence measurements have been carried out on the $B^{10}(He^3,p)C^{12}$ reaction at $E_{He^3}=2.2$ Mev. Protons were detected in a ¾-in. diameter CsI crystal subtending a solid angle of 27% of 4π at the target, the gamma-ray detectors were 5 in.×5 in. NaI crystals, and the coincidence resolving time was 8×10^{-9} sec. The spectrum of protons in triple coincidence with the two gamma-ray detectors, each channeled from 2.4 to 5.0 Mev, contains a line corresponding to the alpha-emitting 7.66-Mev 0+ second-excited state of C^{12}. This line is interpreted as resulting from the 3.23–4.43-Mev cascade gamma-ray decay of the 7.66-Mev level through the 4.43-Mev 2+ first-excited state. The ratio of the triples to singles counting rates of the 7.66-Mev proton line, when corrected by the appropriate factors for gamma-ray efficiency, leads to a 3.23-Mev gamma-ray branch of $(3.3\pm0.9)\times10^{-4}$ per decay of the 7.66-Mev level. This branch, which compares with a previous theoretical estimate of $\sim2\times10^{-4}$, is stronger than the direct ground-state transition by a factor of 50.

I. INTRODUCTION

THE 7.66-Mev second-excited state of C^{12} is of interest in astrophysics since this level is thought to be responsible for the burning of helium in the "red giant" stars by the successive fusion of three helium nuclei.[1] Although the emission of an alpha particle is the predominant mode of decay[1] of the 7.66-Mev state, energy is released and element buildup occurs only if the level decays to the ground state of C^{12}. Two possible paths of decay to the ground state include the direct transition and the 3.23–4.43-Mev cascade gamma-ray transition through the 4.43-Mev first-excited state. From the work of Cook *et al.*[1] as well as from the results of later experiments,[2,3] it is almost certain that the 7.66-Mev state has a spin and parity of 0+. This means that the transition to the 0+ ground state is an electric monopole or $E0$ radiation and that the gamma-ray cascade through the 2+ first-excited state consists of two electric quadrupoles in a 0-2-0 sequence.

By means of a positron-electron magnetic pair spectrometer, the 7.66-Mev $E0$ transition has been observed[2] in the $Be^9(\alpha,n)C^{12}$ reaction at $E_\alpha=5.81$ Mev. This experiment gave the ratio of the 7.66-Mev transition intensity to the intensity of 4.43-Mev gamma rays, the latter resulting from the direct population of the first excited state of C^{12} in the (α,n) reaction. As a complementary experiment, Ajzenberg-Selove and Stelson[3] later measured the relative neutron-population intensities of the 7.66- and 4.43-Mev states in the (α,n) reaction under similar target and beam-energy conditions as in the pair-line measurement. It was then possible to derive the fractional $E0$ branch from the 7.66-Mev state which is essentially equal to the ratio of the pair width to the alpha width. The ratio obtained was

$$\Gamma_{7.6e\pm}/\Gamma_\alpha=6.6\times10^{-6}.$$

An absolute value for Γ_α is found from this ratio by using the width $\Gamma_{7.6e\pm}=5\times10^{-5}$ ev derived[1,4] from a measurement, by Fregeau,[5] of the cross section for inelastic electron scattering to the 7.66-Mev state. The result, $\Gamma_\alpha=8$ ev, is equal to the Wigner limit of 7.5 ev calculated by Fowler and Lauritsen.[6]

A theoretical single-particle estimate of the partial width for the emission of 3.23-Mev $E2$ gamma radiation from the 7.66-Mev state has been made by Ferrell.[7] His result is $\Gamma_{3.2\gamma}\sim0.0014$ ev with an uncertainty of a factor of 2. By combining this with the alpha-particle width discussed above, the branch $B_{3.23}$ would be

$$B_{3.23}=\Gamma_{3.23\gamma}/\Gamma_\alpha\sim2\times10^{-4}.$$

Since this number is 30 times larger than the measured branching by nuclear pair emission, the predominant mode of formation of C^{12} in its ground state by the $3He^4\rightarrow C^{12}$ process is expected to take place by the emission of 3.23-Mev gamma radiation.

Numerous attempts have been made to detect the emission of 3.23-Mev gamma rays from the 7.66-Mev level. In one of the two most sensitive tests, Kavanagh[8] searched for the 3.23–4.43-Mev gamma-ray cascade in the decay of B^{12} and he placed an upper limit of 0.1% on the partial branch of the 7.66-Mev level by gamma-ray emission. The observation of C^{12} nuclear recoils, associated with gamma-ray decay of the level, was attempted by Eccles and Bodansky[9] who also placed an upper limit of 0.1% on the gamma-ray decay mode. In more recent experiments,[10] the $B^{10}(He^3,p)C^{12}$ reaction was used to excite the 7.66-Mev state and a search was made for the associated proton-gamma-gamma triple coincidences. Pilot-B was used as the proton detector and the gamma rays were detected in 4 in.×5 in. and 5 in.×5 in. NaI crystals. Instead of observing the cas-

---

† Research performed under the auspices of the U. S. Atomic Energy Commission.

[1] For a background review see C. W. Cook, W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Phys. Rev. **107**, 508 (1957).

[2] D. E. Alburger, Phys. Rev. **118**, 235 (1960).

[3] F. Ajzenberg-Selove and P. H. Stelson, Phys. Rev. **120**, 500 (1960).

[4] E. E. Salpeter, Phys. Rev. **107**, 516 (1957).

[5] J. H. Fregeau, Phys. Rev. **104**, 225 (1956).

[6] W. A. Fowler and T. Lauritsen (private communication quoted in reference 3).

[7] R. A. Ferrell (private communication quoted in reference 1).

[8] R. W. Kavanagh, Bull. Am. Phys. Soc. **3**, 316 (1958).

[9] S. F. Eccles and D. Bodansky, Phys. Rev. **113**, 608 (1959).

[10] D. E. Alburger and R. E. Pixley, Phys. Rev. **119**, 1970 (1960).

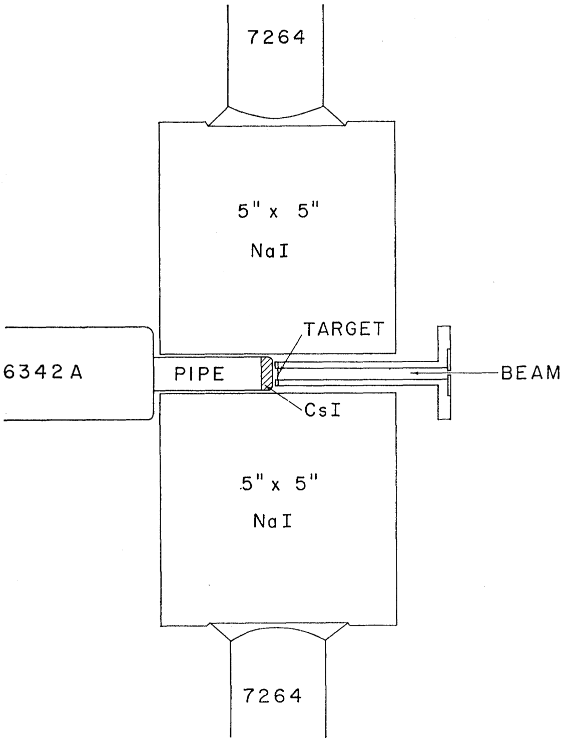

FIG. 1. Experimental arrangement for (p,γ,γ) triple coincidence measurements.

cade in question, a proton line was found in triple coincidence when both gamma-ray counters were channeled from 2.5 to 5 Mev, which corresponded to a new energy level in C^{12} at 9.0 ± 0.1 Mev. Although the "9.0-Mev level" population intensity was found to be only 0.21% relative to the population of the 4.43-Mev level, the strength of the effect was sufficient to obscure a possible proton line associated with the gamma-ray decay of the 7.66-Mev state.

Recently it has been shown[11] that the 9.0-Mev level in C^{12} is nonexistent. The apparent "proton line" in the experiment discussed above actually resulted from inelastic scattering of protons from the carbon of the Pilot-B scintillator. When the Pilot-B was replaced by NaI or CsI crystals the "9.0-Mev line" was not observed.

After the demonstration of this instrumental effect, it was decided to renew the effort to observe the cascade gamma-ray decay of the 7.66-Mev level in C^{12} by using similar techniques but a different type of scintillator for detecting the protons. This paper reports the results of measurements in which the proton detector was a CsI crystal.

II. EXPERIMENTAL METHODS

Figure 1 shows the experimental arrangement used for the proton-gamma-gamma triple coincidence measurements. A 2.2-Mev He^3 beam from the Van de Graaff accelerator was passed through a 1.0-mm diameter aperture in a Ta collimator and struck the center of a B^{10} target. The experiments were carried out with a He^{3++} beam which was produced by a gas stripper located between the base of the Van de Graaff and the analyzing magnet. It was found that the He^{3+} beam contained a small but bothersome HD^+ component even with the stripper in operation. The target[12] consisted of an 80-$\mu g/cm^2$ thick layer of $>99\%$ B^{10} deposited on a 0.5-mil thick aluminum foil. A piece of the target foil was held in place by a 0.3-mil thick nickel foil window sealed with wax at the end of the target tube. Care was taken to prevent the reaction protons from striking any wax.

Immediately in front of the target was located a $\frac{3}{4}$-in. diam by $\frac{1}{4}$-in. thick CsI scintillator covered with a 0.3-mil thick aluminum foil. The crystal was attached with Biggs R-313 bonding cement onto the end of a $\frac{3}{4}$-in. diam by $2\frac{1}{4}$-in. long light pipe which was in turn cemented onto the end of an RCA 6342A photomultiplier tube. This arrangement was found to result in the best proton resolution of a number of geometries tried. The solid angle for the detection of protons from the 1-mm diam target spot was 27% of 4π.

The use of this proton detecting arrangement allowed the two 5 in.$\times$5 in. NaI crystals to be located such that their axes passed through the target, and the front surfaces of the crystal containers were each 0.95 cm from the center of the target. The 0.4-cm distance between the surface of the container and the front surface of the crystal was taken into account in the gamma-ray efficiency calculations. The NaI crystals, made by the Harshaw Chemical Company, are standard units having 3-in. diam windows. In order to operate more easily at short coincidence resolving time, both crystal units were fitted with 2-in. diam RCA 7264 14-state photomultipliers. Optical coupling between the 3-in. diam windows and the round-ended tubes was made as indicated in the figure by means of Lucite adapters together with Dow-Corning silicone grease. The pulse-height resolution with the 0.661-Mev Cs^{137} gamma rays was about 14% in this arrangement.

Triple coincidences were detected by the use of conventional fast-slow circuitry and pulse-height analysis. Satisfactory operation of the coincidence circuit was achieved at a resolving time of 8×10^{-9} sec by running the 6342 A photomultiplier at 1900 v and both 7264 photomultipliers at 1850 v. Since the proton spectrum was to be displayed and long runs were anticipated, the over-all gain of the proton detecting system was stabilized by means of a feed-back circuit designed by de Waard.[13] It was not feasible to control the normally-grounded end of the dynode resistor chain as suggested

---

[11] D. E. Alburger and D. H. Wilkinson, Phys. Rev. **122**, 1508 (1961).

[12] The author is indebted to Dr. D. A. Bromley for the use of this material which had been supplied to him by the Electromagnetic Separation Group, Atomic Energy Research Establishment, Harwell, England.

[13] H. de Waard, Nucleonics 13, 36 (1955).

by de Waard, because of the high current drain being used. Instead only the photocathode was controlled after separating it from ground with a 200-kohm resistor. Regulation was carried out by centering the reference single-channel analyzer on the strong proton line to the 4.43-Mev state and by setting the reference channel width at 0.5 v and the channel wobble amplitude at 1 v rms. When the peak of the 4.43-Mev line was arbitrarily centered at channel 80 in the Penco 100-channel pulse-height analyzer (0.5 v per channel), the variation in the peak position was found to be less than $\frac{1}{2}$ channel during runs spanning periods of up to 70 hrs.

III. EXPERIMENTAL RESULTS

The spectrum of protons from the bombardment of the B^{10} target with a 2.2-Mev He^3 beam in the geometry of Fig. 1 is shown in Fig. 2, Curve A. Protons to the ground state of C^{12} are beyond the range of the 100-channel analyzer. The various high-energy peaks are identified with states of C^{12} produced in the $B^{10}(He^3,p)C^{12}$ reaction except for two small peaks on either side of the 4.43-Mev line. On the left side of the 4.43-Mev line is the ground-state group from the $B^{11}(He^3,p)C^{13}$ reaction resulting from the $\sim 1\%$ of B^{11} in the target. The group on the right side is in the expected position for the $D(He^3,p)He^4$ reaction and presumably results from deuterium embedded in the target during initial runs which were made using the HD^+-contaminated He^{3+} beam. In spite of the large solid angle subtended by the CsI crystal, the full width at half maximum of the 4.43-Mev line is only 3.9%. A noticeable asymmetry of the line may be caused either by the light-piping characteristics or by the variation of proton energy over the large acceptance angle. The estimated background under the proton line leading to the 7.66-Mev state is shown by the dashed line. At a beam current of 0.026 μa the net counting rate of the 7.66-Mev line is approximately 50 counts/sec.

When the proton counter output was channeled on the group leading to the 4.43-Mev state and the output of one of the NaI crystal detectors was displayed in coincidence, Curve A in Fig. 3 was obtained. This spectrum has the normal appearance for 4.43-Mev gamma radiation and it consists of prominent full-energy and one-escape peaks, a weak two-escape peak, and a Compton electron continuum. Arrows indicate the calculated positions of the full-energy and one-escape peaks of 3.23-Mev gamma rays and the long bracket shows the 2.4 to 5.0-Mev channel used in the experiments described below. In all of the work the full-energy-loss peak of the 4.43-Mev gamma-ray spectrum was arbitrarily centered at channel 70 when the output of either gamma-ray detector was displayed.

As an aid in calculating the efficiency for detecting the 3.23-Mev gamma rays, the spectrum occurring in the $C^{12}(d,p)C^{13}$ reaction was studied by bombarding a thick Aquadag target with a 0.0005-μa beam of 1.5-Mev deuterons. At this beam energy only the 3.09-Mev first-

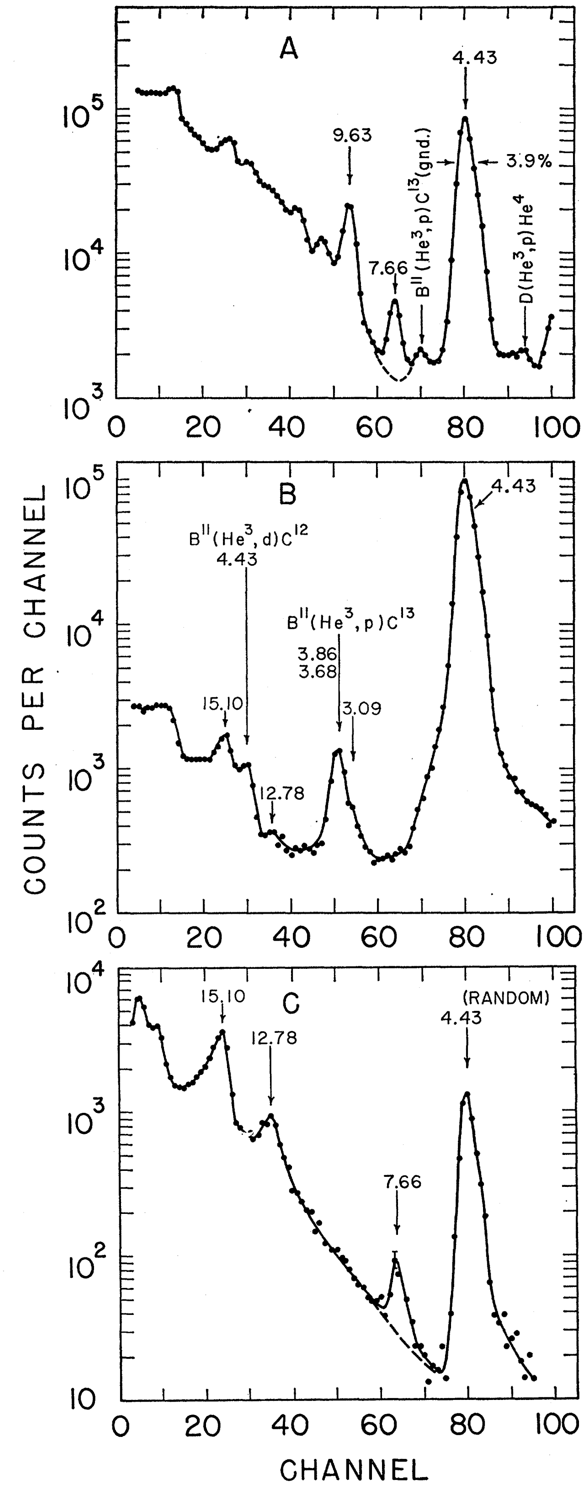

FIG. 2. Curve A—spectrum of protons from $B^{10}+He^3$ at $E_{He^3}=2.2$ Mev using the geometry of Fig. 1; Curve B—spectrum of protons in coincidence with one gamma-ray detector channeled as shown in Fig. 3A (0.05 μa for 18 min); Curve C—spectrum of protons in triple coincidence with two gamma-ray detectors both channeled as shown in Fig. 3A (0.026 μa for 95 hr).

excited state of C^{13} is excited appreciably, although the complete gamma-ray spectrum also contains the 0.51-Mev annihilation radiation resulting from the production of N^{13} positron activity in the (d,n) reaction. For purposes of illustration, Curve B, Fig. 3 shows the spectrum resulting from the superposition of the 3.09-Mev gamma rays together with the 4.43-Mev gamma rays from a source of plutonium-beryllium. The strong 0.51-Mev line from the N^{13} positrons is below the range of the analyzer (the true zero of pulse-height corresponds to -8 channels).

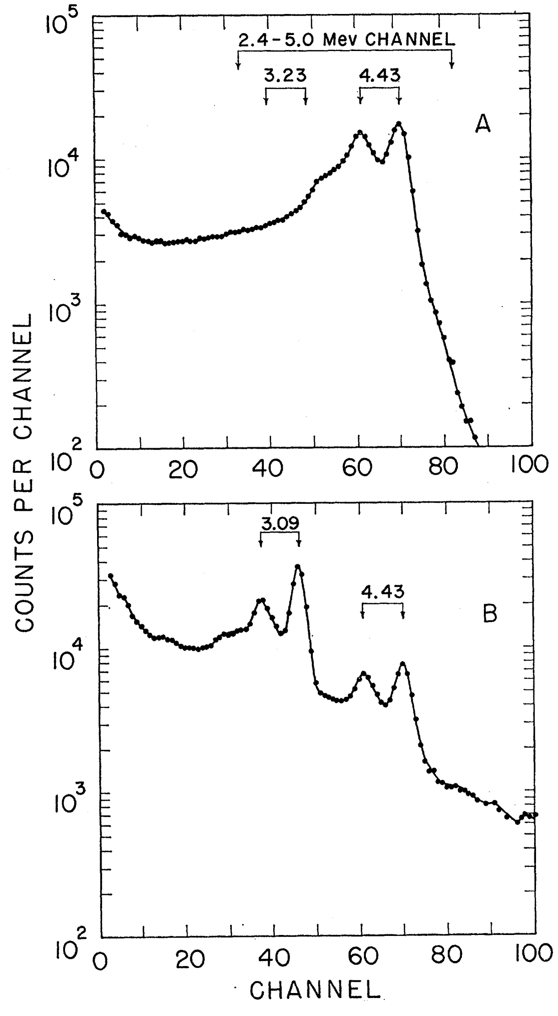

FIG. 3. Curve A—spectrum of gamma rays in coincidence with protons from the $B^{10}(He^3,p)C^{12}$ reaction leading to the 4.43-Mev state of C^{12}; Curve B—spectrum of gamma rays from the $C^{12}(d,p)C^{13}$ reaction at $E_d=1.5$ Mev superposed on gamma rays from a Pu-Be source.

Curve B, Fig. 2, shows the spectrum of protons in coincidence with one NaI crystal channeled from 2.4 to 5.0-Mev as indicated in Curve A, Fig. 3. In addition to the strong line associated with the 4.43-Mev level, the protons leading to the 15.10 and 12.78-Mev gamma-emitting states of C^{12} are observed. Other lines include the complex of protons in the $B^{11}(He^3,p)C^{13}$ reaction leading to states in C^{13} at 3.09, 3.68, and 3.86 Mev and a line corresponding to the $B^{11}(He^3,d)C^{12}$ reaction leading to the 4.43-Mev level of C^{12}. It may be noted that the yield in the vicinity of channel 64 is lower than the 4.43-Mev peak by a factor of 400. According to the gamma-ray branching ratio derived from the triple coincidence measurements described below, the 7.66-Mev peak in the double coincidence spectrum of Fig. 2, Curve B is expected to be ~50 000 times smaller than the 4.43-Mev peak. Such a peak would rise only ~1% above the background in that region. All of the proton lines discussed thus far in connection with Fig. 2, Curves A and B, agree to within one or two channels with the positions calculated for 0° by taking the energy of the protons to the 4.43-Mev level as 17.26 Mev and by assuming a linear energy response of the CsI crystal. The largest deviations from the expected positions occur in the cases of the low-energy lines which apparently have been shifted down as a result of energy loss in the target backing, exit window, and crystal-covering foils.

In order to check the proton-gamma double-coincidence efficiency, when the measured-coincidence resolving time was set at 8.1×10^{-9} sec, the pulse overlap output spectrum from the fast coincidence circuit was displayed under four different slow-coincidence conditions. These included: (a) the proton detector channeled on the line to the 4.43-Mev level and the NaI crystal output channeled as shown in Curve A, Fig. 3, (b) same proton bias as in (a) but the gamma-ray output bias adjusted so as to include only the lower part of the 2.4 to 5-Mev region from channels 33 to 55, (c) the proton detector channeled on the region containing the proton lines to the 15.10 and 12.78-Mev states and the gamma-ray output channeled as in Curve A, Fig. 3, and (d) same proton bias as in (c) but the gamma-ray counter channeled as in (b). The same sets of measurements were carried out on both NaI detectors. It was found that in tests (c) and (d) the overlap spectra were broader and their maxima were at a lower pulse-height value than in tests (a) and (b). However, even in tests (c) and (d), practically all of the overlap pulses were above the selected bias level corresponding to a resolving time of 8×10^{-9} sec. It was concluded that the efficiency is virtually 100% for detecting the 7.66-Mev proton group in triple coincidence with two gamma-ray counters channeled as in Curve A, Fig. 3.

Figure 2, Curve C, shows the sum of runs totaling 95 hr at a beam current of 0.026 μa on the spectrum of protons in triple coincidence with the two NaI detectors, both channeled as indicated in Curve A, Fig. 3. A clearly defined peak appears at channel 64 in Curve C, Fig. 2. The area between this peak and the estimated dashed background curve consists of 225 counts, or a net counting rate of 2.35 counts/hr. In the lower energy region, the protons to the 15.10 and 12.78-Mev states appear as a result of the cascade gamma-ray decays[10,14–16] of these levels through the 4.43-Mev first-excited state. The 4.43-Mev proton line is the result of random coincidences.

Curve C, Fig. 2, was one of two final runs. The second was taken under similar conditions, except that the beam current was 0.05 μa and the time was 50 hrs so that the data were equivalent. A total of 190 net counts was obtained in the 7.66-Mev peak. In this run the 4.43-Mev proton peak was relatively twice as large as in Curve C, Fig. 2, as expected for a random effect. During both of the final runs the singles spectrum was checked periodically in order to correct for a small but measurable diminution of the target yield.

Check runs included one of 28 hr at 0.04 μa, in which one of the NaI crystal's output was biased from channels 33 to 55, while the other gamma-ray detector was biased from channels 55 to 82. Because of the smaller widths of the channels and the restriction that the cascade is detected only when the 3.23-Mev gamma-ray enters that counter biased from channels 33 to 55, a reduction in the 7.66-Mev proton yield per μcoul by a factor of 3 is expected. A reduction by about that amount was observed. Finally a test was made with both gamma-ray detector outputs biased from channels 55 to 82, so as to exclude completely the 3.23-Mev gamma ray. A run of 6 hrs duration at a beam current of 0.026 μa yielded a spectrum similar to Curve C, Fig. 2, with respect to the relative intensities of the 15.10, 12.78, and 4.43-Mev lines. However the total yield of all channels from 60 to 70 was only one count as compared with 30 counts per channel at the peak of the 4.43-Mev line. In spite of the short duration of this run, the quite obvious lack of counts in the region of the 7.66-Mev proton line leads to the conclusion that the bias conditions used in this test made the line disappear.

DISCUSSION

The 7.66-Mev peak in the triple coincidence spectrum of Curve C, Fig. 2 is interpreted as resulting from the 3.23–4.43-Mev cascade gamma-ray decay of the 7.66-Mev level of C^{12}. A comparison of the position of the peak, after subtraction of the background, with the position of the 7.66-Mev singles peak in Curve A, Fig. 2, shows that the two agree within an accuracy of less than one channel, or about 1%. In energy units the agreement is to within ~140 kev. There is no other known reaction that has a high enough Q value to account for these triple coincidences. Furthermore the runs under various gamma-ray bias conditions are consistent with the 7.66-Mev proton line being in triple coincidence with gamma rays of 3.23 and 4.43 Mev, although it has not been proved that gamma rays of precisely these energies are involved.

An alternative explanation of the 7.66-Mev peak in Curve C, Fig. 2, in terms of random coincidences is ruled out on the basis of several considerations. Thus it was found that the ratio of the triples to singles counting rates was approximately the same for the two final runs at beam currents 0.026 and 0.05 μa, all other conditions remaining equal. Another argument can be made after considering the origin of the 4.43-Mev random peak in Curve C, Fig. 2. In general, when triple coincidences are detected which involve counters p, γ_1, and γ_2, the output of counter p being displayed, the random portions of the spectrum will contain contributions other than the completely uncorrelated triple coincidence events if any real double coincidence effects are present. Letting parentheses indicate real double coincidences and letting X indicate random coincidence events, the total counting rate expected for the 4.43-Mev peak in Curve C, Fig. 2, is given by

$$N=2\tau(p\gamma_1)X\gamma_2+2\tau(p\gamma_2)X\gamma_1+2\tau(\gamma_1\gamma_2)Xp \\ +3\tau^2 pX\gamma_1X\gamma_2. \quad (1)$$

In order to calculate the total rate as well as the relative importance of the various contributions of the terms in Eq. (1) when the proton detector is channeled on the 4.43-Mev peak, the gamma-ray counters are channeled as shown in Curve A, Fig. 3, and $\tau=8\times10^{-9}$ sec, the measured counting rates (counts/sec at a beam current of 0.026 μa) may be inserted into Eq. (1). These rates were as follows: $p=1730$, $\gamma_1\cong\gamma_2=2900$, $(p\gamma_1)\cong(p\gamma_2)=213$, and $(\gamma_1\gamma_2)=5.5$. Within an accuracy of 20%, the calculation from Eq. (1) of the counting rate of the 4.43-Mev proton line agrees with the rate observed in Curve C, Fig. 2. The sum of the first two "mirror" terms of Eq. (1) is larger than the third term by a factor of 130, and the fourth term is completely negligible. It is concluded that if there were actually no protons in *real* triple coincidence with gamma rays, the triple coincidence spectrum would be similar in appearance to the real double coincidence spectrum of Curve B, Fig. 2. At least there would be no line in the triples spectrum larger than it is in Curve B, Fig. 2 relative to the 4.43-Mev group. This at once rules out a random coincidence explanation of the 7.66-Mev line in Curve C, Fig. 2 since, according to the preceding discussion and in view of Curve B, Fig. 2, the 7.66-Mev line could then be at most only 1/400 the intensity of the 4.43-Mev line.

Another alternative is that the 7.66-Mev triple coincidence line is the result of an inelastic proton scattering effect of the type found[10,11] in the experiments using a Pilot-B detector. If this were the case the energy of the level involved in the inelastic scattering would have to be such as to reduce the energy of the protons leading to the 4.43-Mev level by just the right amount to give the appearance of a proton group leading to the 7.66-Mev level. Although inelastic scattering cannot be ruled

---

[14] C. N. Waddel, H. E. Adelson, B. J. Moyer, and H. C. Shaw, Bull. Am. Phys. Soc. **2**, 181 (1957); C. N. Waddel, thesis, University of California Radiation Laboratory (unpublished).

[15] E. L. Garwin and A. S. Penfold, Bull. Am. Phys. Soc. **2**, 351 (1957).

[16] E. Almqvist, D. A. Bromley, A. J. Ferguson, H. E. Gove, and A. E. Litherland, Phys. Rev. **114**, 1040 (1959).

out entirely as the explanation for the peak in Curve C, Fig. 2, at channel 64 it seems highly unlikely that a spurious inelastic scattering line would coincide so closely with the expected position of a real line. Another argument against inelastic scattering is that the width of the peak in the triple coincidence spectrum (3.3 channels) is the same, within an accuracy of 15%, as the width of the line in the singles spectrum. Inelastic scattering in carbon[10,11] resulted in a line to an apparent "9.0-Mev level" whose width (in retrospect) is about twice as great as the widths of neighboring lines in the singles spectrum, when the proton resolution is 5%. This width results from the variation in nuclear recoil energy with angle. Therefore the 7.66-Mev line in Curve C, Fig. 2, cannot be caused by inelastic scattering in light nuclei although it is still possible that a level in a heavy nucleus such as cesium or iodine might be responsible.

A feature of the spectrum of Curve C, Fig. 2, that is not completely understood, is the sloping yield between the 12.78 and 7.66-Mev proton lines. From rough calculations it is possible to explain part of this yield, as well as the sloping yield above the 4.43-Mev line, as the result of pulse pileup. In the final run at 0.05 μa the yields in these regions were noticeably higher than in Curve C, Fig. 2. Pileup may well occur in the CsI crystal which has the relatively long light-decay time constant of 1.1 μsec. Inelastic scattering effects may also be responsible for part of this yield.

Under the assumption that Curve C, Fig. 2 results from genuine triple coincidences associated with the gamma-ray de-excitation of the 7.66-Mev state of C^{12}, the 3.23-Mev gamma-ray branching ratio $B_{3.23}$ may be calculated from the expression,

$$N_S B_{3.23} \epsilon_{4.43} \epsilon_{3.23} \times 2C_\theta = N_C. \qquad (2)$$

N_S and N_C are the singles and triples net counting rates of the 7.66-Mev proton line, $\epsilon_{4.43}$ and $\epsilon_{3.23}$ are the efficiencies of each of the gamma-ray counters for detecting gamma radiations of 4.43 and 3.23 Mev, the factor 2 must be included since either gamma ray may go into either counter, and C_θ is a correction factor representing the effect of the angular correlation between the two gamma rays. In order to calculate $\epsilon_{4.43}$, the tables of Vegors *et al.*[17] were used to obtain the total efficiency for detecting 4.43-Mev gamma rays at a distance of 1.4 cm. This was multiplied by the fraction of the spectrum (75%) in the 2.4–5.0-Mev channel obtained from curve A, Fig. 3. The contribution of the low-energy portion of the spectrum was estimated by assuming that the shape of the curve is essentially flat from channel 20 down to the true zero of pulse height at −8 channels. In a similar way $\epsilon_{3.23}$ was obtained after finding the fraction (55%) of the 3.23-Mev gamma-ray spectrum above channel 33. The latter was calculated on the basis of the shape of the 3.09-Mev gamma-ray spectrum, a curve similar to Curve B, Fig. 3 except that the Pu-Be source was removed and the background count with the beam off was subtracted out. The efficiency factors thus derived were $\epsilon_{4.43}=0.152$ and $\epsilon_{3.23}=0.113$.

The effect of the angular correlation of the two cascade gamma rays is difficult to calculate. It is well known that the 0-2-0 *E*2-*E*2 correlation follows the form,

$$W(\theta)=1-3\cos^2\theta+4\cos^4\theta. \qquad (3)$$

This is one of the strongest known correlations and it has a maximum value at $\theta=180°$. An accurate calculation of the effect when using the geometry of Fig. 1 would be exceedingly difficult because of the large solid angles subtended by the detectors. Not only is the efficiency per unit-solid-angle of each detector a function of the entrance angle of gamma rays, but the shape of the spectrum undoubtedly varies considerably with angle. In lieu of an accurate calculation, estimates of the net effectiveness of the angular correlation were made independently by the author and by D. H. Wilkinson. The average of these estimates is $C_\theta=1.15$ where C_θ is the factor by which the counting rate is higher than it would be if the correlation were isotropic.

The value of $B_{3.23}$ is calculated from Eq. (2) by inserting the values of the efficiencies together with the measured ratio $N_C/N_S=1.30\times10^{-5}$ averaged from the two final runs. Errors in the various factors were estimated in a straightforward manner and they were combined in the usual way. The result for the partial branch of the 7.66-Mev level by the emission of 3.23-Mev gamma radiation is

$$B_{3.23}=(3.3\pm0.9)\times10^{-4}.$$

This is slightly higher than the theoretical estimate of $\sim2\times10^{-4}$ mentioned previously, but the agreement can be considered as satisfactory. Whereas the theoretical single-particle estimate[7] of the 3.23-Mev gamma-ray width is

$$\Gamma_{3.23\gamma\mathrm{th}}\sim0.0014 \text{ ev},$$

the present work leads to the experimental value

$$\begin{aligned}\Gamma_{3.23\,\mathrm{exp}}&=(B_{3.23}/B_{7.6e\pm})\times\Gamma_{7.6e\pm}\text{ ev}\\&=(3.3\times10^{-4}/6.6\times10^{-6})\times5.0\times10^{-5}\text{ ev}\\&=0.0025\text{ ev},\end{aligned}$$

with an accuracy of ~50%.

ACKNOWLEDGMENTS

The author is indebted to Dr. R. E. Pixley for collaborating in the development of the fast coincidence circuitry and to Dr. D. H. Wilkinson for helpful discussions of the analysis and results.

---

[17] S. H. Vegors, L. L. Marsden, and R. L. Heath, Philips Petroleum Company Technical Report No. IDO-16370, 1958 (unpublished).