9.0-Mev Gamma-Emitting Level in C^{12}†

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(Received May 5, 1960)

An energy level in C^{12} at 9.0 ± 0.1 Mev has been detected by means of (p,γ,γ) coincidence measurements on the $B^{10}(He^3,p)C^{12}$ reaction at $E_{He^3}=2.2$ Mev. This state decays by a gamma-gamma cascade through the 4.43-Mev first excited state. An upper limit of 5% is placed on the ground-state gamma-ray transition. The intensity of the proton group leading to the 9.0-Mev state (followed by gamma-ray emission) is (0.21 ± 0.07)% relative to the proton branch to the 4.43-Mev level. Gamma-ray branches from the 15.10- and 12.78-Mev states in C^{12} to the 4.43-Mev level have been determined as (4 ± 1)% and (20 ± 7)%, respectively, relative to the corresponding ground-state transitions. The radiations from the 9.0-Mev level have prevented a sensitive search from being made for the 3.2-Mev gamma radiation from the 7.66-Mev level in C^{12} by means of this reaction.

INTRODUCTION

THE work described in this paper began as a search for the 3.2-Mev gamma-ray de-excitation of the 0+ second excited state of C^{12} at 7.66 Mev. This level, which is known to decay predominantly by alpha-particle emission to Be^8, is thought to be involved in the "burning" of helium in red giant stars.[1] In recent experiments[2] the weak ($\sim7\times10^{-6}$ per decay) $E0$ ground-state transition from the 7.66-Mev level was observed and it was estimated that the fractional branching to the 4.43-Mev first excited state by the emission of 3.2-Mev gamma radiation would be ~0.02% of the total decay of the level if the single-particle estimate[1] of 0.0014 ev is assumed for the width $\Gamma_{3.2\gamma}$. The best experimental upper limit is 0.1% for this branch.[3,4] A very sensitive technique is therefore required in order to detect the 3.2-Mev gamma radiation.

One approach to this problem is to excite the 7.66-Mev state by the $B^{10}(He^3,p)C^{12}$ reaction and to look for the triple coincidence effect due to the proton branch feeding the 7.66-Mev state and the two gamma rays of 3.2 and 4.43-Mev occurring in the de-excitation. Protons from the $B^{10}(He^3,p)C^{12}$ reaction, both singly and in coincidence, have been studied with scintillation detectors by Moak *et al.*[5] and more recently by Almqvist *et al.*[6] At $E_{He^3}=2$ Mev the proton group to the 7.66-Mev state is 25 times less intense than the group to the 4.43-Mev level. Nevertheless we felt that a triple coincidence measurement on the 7.66-Mev state with scintillation detectors might be feasible.

Instead of finding the 3.2-Mev gamma-ray branch from the 7.66-Mev level we have uncovered a new state in C^{12} at 9.0 Mev which de-excites by a gamma-gamma cascade through the 4.43-Mev first excited state. Although the proton branch to the 9.0-Mev state is found to be 20 times less intense than the branch to the 7.66-Mev level the (p,γ,γ) triple coincidence effect due to the 9.0-Mev state has made the search for the 3.2-Mev radiation from the 7.66-Mev state more than an order of magnitude less sensitive than required according to the above-mentioned estimates.

We report here the measurements which have been made on the 9.0-Mev level together with gamma-ray branching studies of the 15.10- and 12.78-Mev levels to the ground and first excited states of C^{12}. The cascade branch from the 12.78-Mev has not been reported previously.

EXPERIMENTAL TECHNIQUES

Since our estimates of the $B^{10}(He^3;p,\gamma,\gamma)C^{12}$ triple coincidence yield involving the 7.66-Mev level in C^{12} indicated a very low counting rate, we concentrated first on developing a proton detector which could be used in large solid-angle geometry and which would also allow two gamma-ray detectors to be placed close to the target. Figure 1 shows the final arrangement used for the experiments. Protons are detected in a $\frac{9}{16}$-in. diameter by $\frac{1}{2}$-in. thick Pilot-B scintillator which is attached to a $\frac{3}{4}$-in. diameter Dumont 6362 10-stage photomultiplier tube and covered with an aluminum foil 0.00035 in. thick. The solid angle for the detection of protons from the target is 27% of 4π. This was the optimum scintillator thickness under large solid-angle conditions, the thickness having been determined by a study of the line width of the proton group in the $B^{10}(He^3,p)C^{12}$ reaction leading to the 4.43-Mev C^{12} level. It was found that the light-piping effect of a thick scintillator results in appreciably better resolution than for detection in a thin scintillator.

We also tried CsI and anthracene for proton detection but the pulse-height resolution was no better than with Pilot-B. Apparently the linewidth results mostly from the photocathode nonuniformity and the variation in

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

[1] For a 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. Letters 3, 280 (1959); Phys. Rev. **118**, 235 (1960).
[3] R. W. Kavanagh, Bull. Am. Phys. Soc. **3**, 316 (1958).
[4] S. F. Eccles and D. Bodansky, Phys. Rev. **113**, 608 (1959).
[5] C. D. Moak, A. Galonsky, R. L. Traughber, and C. M. Jones, Phys. Rev. **110**, 1369 (1958).
[6] E. Almqvist, D. A. Bromely, A. J. Ferguson, H. E. Gove, and A. E. Litherland, Phys. Rev. **114**, 1040 (1959).

illumination occurring when particles enter the scintillator in different directions. Since the resolution under the conditions we were using seemed to be relatively independent of the type of scintillator, we chose Pilot-B because of its short scintillation decay time.

On opposite sides of the target tube are located two 5-in. diameter NaI crystal detectors, one 5 in thick and the other 4 in. thick whose axes are in line with the target. The front surfaces of the two NaI crystals are both 1.2 cm from the beam axis. In this geometry the calculated[7] efficiency-time-solid-angle for 4.4-Mev gamma rays is 21% for each detector.

The target material, which was very kindly supplied by Dr. D. A. Bromley, consisted of an 80-μg/cm^2 thick B^{10} layer deposited on 0.5-mil thick Al foil. A 4×4 mm^2 target foil was cemented at its edges to a 0.5-mil thick Al vacuum window foil which was in turn waxed onto the end of the target tube. A collimator confined the He^3 beam from the Van de Graaff accelerator to a spot 2 mm in diameter.

Standard electronic circuits were used for coincidence detection. We found the best pulse-height resolution and gain stability of the 6362 phototube with a cathode-to-first dynode voltage of 200–250 volts and a total voltage of 700–800 volts. The outputs of three Franklin double-delay-line clipped amplifiers were fed to a standard fast-slow triple coincidence circuit which operates on the passage-through-zero part of the pulse. Fast coincidence resolving time settings were $\tau=(3\text{–}4)\times10^{-8}$ sec and slow channels with $\tau\approx4$ μsec were available on each of the fast inputs. The spectra were displayed in a Penco 100-channel pulse-height analyzer.

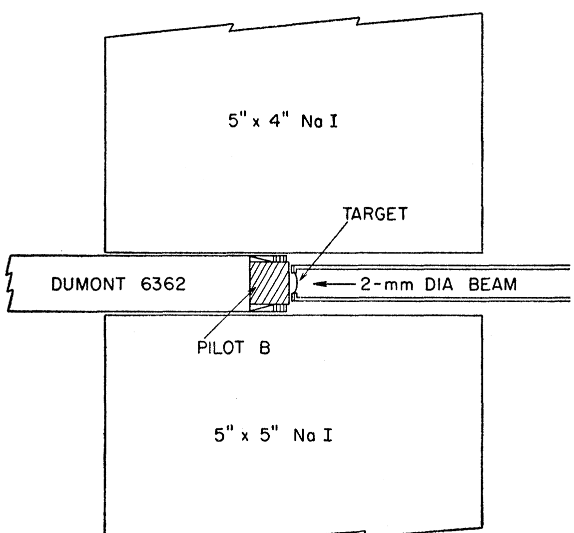

FIG. 1. Experimental arrangement for (p,γ,γ) triple coincidence measurements. *Note.*—2-mm dia beam should read 2-mm diam beam.

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

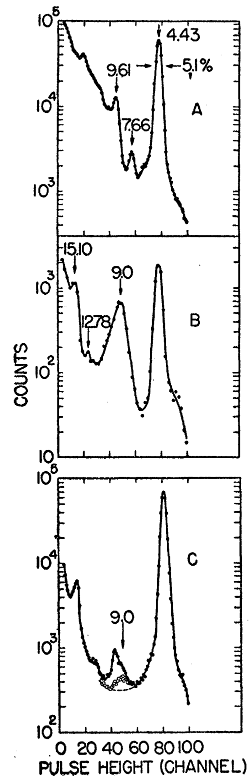

FIG. 2. Curve A proton spectrum from the $B^{10}(He^3,p)C^{12}$ reaction at $E_{He^3}=2.2$ Mev when using the proton detector geometry of Fig. 1; Curve *B*—proton spectrum in triple coincidence when both gamma-ray detectors are channeled between 2.5 and 5 Mev; Curve *C*, solid points—proton spectrum in double coincidence with one gamma-ray counter channeled from 2.5–5 Mev; Open circles—spectrum (normalized to the 4.43-Mev line) when the gamma-ray counter is channeled so as to include only the region containing full-energy-loss peaks of the 4.43- and 4.6- Mev gamma rays. Numbers refer to the energies of levels in C^{12}. Note: In this and all other figures the zero of pulse height is at minus 8 channels on the abscissa.

He^3 beam currents of 0.01 to 0.05 μa were used for the various experiments which are described below.

EXPERIMENTAL RESULTS AND DISCUSSION

A. 9.0-Mev Level in C^{12}

Figure 2(A) shows the singles spectrum of protons from the $B^{10}(He^3,p)C^{12}$ reaction at $E_{He^3}=2.2$ Mev obtained in the geometry of Fig. 1. (The ground-state proton group lies beyond the range of the 100-channel pulse-height analyzer). At a beam current of 0.05 μa the yield in a channel placed around the 4.43-Mev proton group was 6800 counts per second. In our initial runs the proton detector was channeled on the group to the 7.66-Mev level, one NaI detector was channeled on the region containing the three peaks of the 4.43-Mev gamma ray (full energy, one-escape and two-escape peaks) and the spectrum of pulses from the other NaI crystal in triple coincidence was displayed. This spectrum showed only gamma rays of about 4.4 Mev with an intensity very much greater than either the random coincidence rate (see discussion below) or the estimated yield of the 3.2-Mev gamma rays.

As an alternative procedure for establishing the 3.2-Mev gamma-ray de-excitation of the 7.66-Mev level both NaI detectors may be channeled from 2.5–5 Mev, so as to include major portions of the spectra of both the 3.2- and 4.43-Mev gamma rays, and one may look for the 7.66-Mev proton group [at channel 57 in Fig. 2(A)] in triple coincidence. One of the many spectra

taken under these conditions is shown in Fig. 2(B). This exhibits a random peak due to the protons to the 4.43-Mev state, the real peaks due to the protons to the 15.10- and 12.78-Mev states and a prominant peak at a pulse height of 48.5. For values of the beam current ranging from 0.0125 to 0.05 μa the yield of the line at channel 48.5 was proportional to the integrated beam current whereas the relative yield of the 4.43-Mev random peak decreased at lower beam current. The peak at channel 48.5 was still observed when both gamma-ray detectors were channeled on only the full-energy-loss peak of the 4.43-Mev gamma rays (with diminished intensity because of the smaller fractions of the 4.43-Mev gamma-ray spectra accepted) but it disappeared when one gamma-ray counter was channeled above 5 Mev. In order to remove the difficulties which might arise from N^{12} positrons entering the NaI crystals, and also to discriminate against annihilation radiation, the triple coincidence spectrum was run under the conditions of Fig. 2(B) except that $\frac{1}{4}$-in. thick Pb absorbers were placed in front of both gamma-ray counters. The peak at channel 48.5 remained with the same relative intensity when allowances were made for the reduction in solid angles of the gamma-ray detectors and for the absorption of the 4.43-Mev gamma rays in the lead.

We note here than the 4.43-Mev peak in Fig. 2(B) is due to several different effects. In the gamma-ray spectrum there was a strong annihilation radiation line whose intensity immediately after turning the beam off was unchanged indicating that no appreciable amount of N^{12} was formed. The decay of this radiation was found to have a half-life of $\sim$20 min, and we assign the activity to the positron emitter C^{11} produced by the $B^{10}(He^3,d)C^{11}$ reaction. In our experimental arrangement there is a high efficiency for detecting beta-gamma-gamma fast triple coincidences associated with positron activities. Although the pulses from the three detectors are below the channel biases, a slow quadruple random coincidence occurs when the fast coincidence gate is opened by a positron and two 0.51-Mev gamma rays and random pulses appear in their respective channels within the 4-μsec slow resolving time. In the case of the 4.43-Mev proton group, pairs of the pulses in the slow proton and gamma-ray channels can also be in real coincidence. Based on the fast triple coincidence rate and on the slow channel rates, we calculate that about $\frac{2}{3}$ of the 4.43-Mev peak intensity in Fig. 2(B) results from events of this nature. In view of the relative amplitude of the 9.0-Mev proton peak in Fig. 2(B) it is not possible to explain this line as being the result of random events.

We conclude that the peak at channel 48.5 corresponds to protons leading to a new energy level in C^{12}. A scale of energy versus pulse height was derived from the peak positions of the 9.61-, 7.66-, and 4.43-Mev peaks in Fig. 2(A) and an energy value of 9.0$\pm$0.1 Mev for the state was obtained after making a slight adjustment of the 4.43-Mev random peak in Fig. 2(B) to the energy scale. The 9.0-Mev state decays by a gamma-gamma cascade through the 4.43-Mev first excited state. The energy deduced for the first transition is 4.6$\pm$0.1 Mev which means that the two gamma rays would be difficult to resolve with NaI detectors. Since a total energy of $\sim$20 Mev is required to produce this (p,γ,γ) coincidence effect we know of no other reaction that has a high enough Q value to account for our results.

Returning to the first experiment described in this section it may be seen from Figs. 2(A) and 2(B) that a channel placed around the 7.66-Mev proton peak includes $\frac{1}{4}$ to $\frac{1}{3}$ of the proton group leading to the 9.0-Mev state. This account for the 4.4-Mev gamma-ray spectrum which was observed in triple coincidence. Because of the "background" resulting from the 9.0-Mev proton peak and its associated gamma-gamma decay mode we estimate that a 3.2-Mev gamma-ray branch from the 7.66-Mev level smaller than 1% cannot be established in this reaction with our experimental arrangement.

Figure 2(C) (solid points) shows the spectrum of protons in coincidence with one gamma-ray counter channeled from 2.5–5 Mev. In addition to the very strong protons to the 4.43-Mev level and the weak group to the 15.10-Mev state there is a complex distribution having a peak at channel 42. A proton group in the same relative position has been observed previously[5,6] and it has been assigned to the $B^{11}(He^3,p)C^{13}$ reaction feeding levels in C^{13} at 3.68 and 3.86 Mev. We then placed a narrow channel on the gamma-ray detector output so as to bracket the region containing only the full-energy-loss peaks of the 4.43- and 4.6-Mev gamma rays. The resulting spectrum when normalized to the amplitude of the 4.43-Mev solid-point peak is shown by the open circles in Fig. 2(C). It is clear that the peak at channel 42 has disappeared and that a peak at channel 49 remains. The position of the latter corresponds closely in position to the peak in Fig. 2(B). These results confirm the assignment of the proton group in channel 42 to a C^{13} state which emits gamma rays of <4-Mev energy and the proton group in channel 49 to the C^{12} 9.0-Mev state which emits gamma rays of about 4.4 Mev.

The proton branching intensity to the 9.0-Mev level relative to the 4.43-Mev proton branch was calculated from Fig. 2(C) by comparing the area under the open-circle curve (less the dashed estimated background curve) with the area under the 4.43-Mev peak. Allowing a factor of two for the two cascade gamma rays in coincidence with the 9.0-Mev peak the (9.0-Mev level)/(4.43-Mev level) population intensity ratio for protons which are followed by gamma-ray emission is (0.21$\pm$0.07)% at $E_{He^3}=2.2$ Mev. For the purpose of calculating detector efficiencies it has been assumed that there is no (p,γ) angular correlation and that the proton distribution is isotropic. With the large solid angles subtended by both

the proton and gamma-ray detectors, it is felt that the presence of nonisotropic correlations would not greatly affect our results. We did see a small effect of the (p,γ) correlation in the case of the 4.43-Mev state. When a channel was placed around the proton group to the 4.43-Mev state, the measured total efficiency-times-solid-angle of the coincident 4.43-Mev gamma rays was 17.5% compared with the 21% expected for an isotropic correlation. The error that we have placed on the branching ratio includes a 20% uncertainty to cover possible angular correlation effects.

As a check on our interpretation of the open-circle curve in Fig. 2(C), we calculated from its yield the expected yield per microcoulomb of the 9.0-Mev triple-coincidence peak in Fig. 2(B). This was done by multiplying the net peak yield in Fig. 2(C) (open-circle curve) by an efficiency-times-solid-angle factor of 13.4%. The efficiency factor was measured by (p,γ) coincidences on the 4.43-Mev level and it is smaller than the 17.5% total efficiency because of the channel bias condition. We find that the predicted triple-coincidence yield of the 9.0-Mev peak agrees with the yield observed in Fig. 2(B) within 10%.

In order to investigate the possibility of a direct gamma-ray transition to the ground state from the 9.0-Mev level we channeled the proton detector on the region containing the 9.0-Mev proton peak and displayed the gamma-ray spectrum in coincidence. As may be seen in Fig. 3 gamma rays of 4.4 Mev appear together

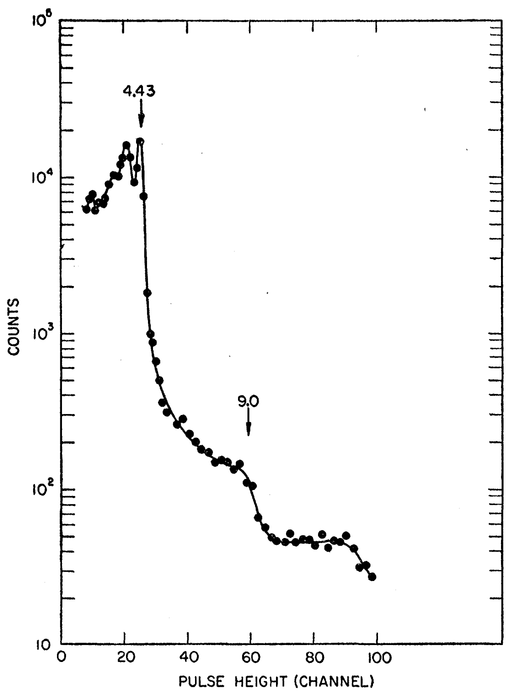

FIG. 3. Gamma-ray spectrum in coincidence with the proton counter channeled on the region containing the group to the 9.0-Mev state. The spectrum ending at about 9 Mev is consistent with "summing" of the 4.6–4.33 Mev cascade gamma rays.

with a weak distribution which falls off at about 9 Mev and a higher energy random background. The 4-Mev and 9-Mev regions of the spectrum are difficult to relate quantitatively because the yield of pulses in the neighborhood of 4 Mev is caused partly by the long low-energy tail of the proton group to the 4.43-Mev state and partly by the gamma rays of 3.68 and 3.86 Mev from the $B^{11}(He^3,p)C^{13}$ reaction. The 9-Mev distribution is consistent, as regards both shape and intensity, with the summing" of the 4.43- and 4.6-Mev gamma rays in the crystal. A 5% ground-state transition would appear as a 1-Mev wide peak near 9 Mev with an additional height equal to the amplitude of the sum spectrum at that energy.

At present we can say little about the relative alpha-particle width of the 9.0-Mev state, since we do not observe the proton line in the singles spectrum. In the singles spectrum measured by Almqvist *et al.*[6] at $E_{He^3}=2$ Mev a proton group to the 9.0-Mev state with an intensity of up to 4% of the 4.43-Mev peak could be present but not be detected. Thus since the branching deduced from gamma-ray emission is 0.21% of the branch to the 4.43-Mev level the alpha-particle width of the 9.0-Mev level could be as much as 20 times larger than the gamma-ray width and still be consistent with existing data. A magnetic analysis of the protons from the $B^{10}(He^3,p)C^{12}$ reaction at $E_{He^3}=2.2$ Mev would be worthwhile as a check on the existence of the 9.0-Mev level in C^{12}. Furthermore a value or limit on the ratio $\Gamma_\alpha/\Gamma_\gamma$ could be obtained by a comparison of the population of the 9.0-Mev state in the singles proton spectrum with the number of protons followed by gamma-ray emission. It would seem likely that appreciable gamma-ray emission could occur only if the alpha-particle emission is parity-forbidden.

B. Gamma-Ray Branching of the 15.10-Mev State

The branching of the 15.10-Mev level to the 4.43-Mev state relative to the ground-state transition has been measured as 9% by Waddel *et al.*,[8] 3.5% by Garwin and Penfold,[9] and 3.1% by Almqvist *et al.*[6] We have determined this branching ratio by combining double and triple coincidence information. The procedure was to set a rather wide channel on the proton group to the 15.10-Mev state, to channel one gamma-ray detector on the 3 peaks of the 4.43-Mev gamma rays, and to display the gamma-ray spectrum first in double coincidence with protons and then in triple coincidence with protons and 4.43-Mev gamma rays.

The double coincidence run, Fig. 4(A), contains the distribution due to the 15.10-Mev ground-state gamma rays whereas in triple coincidence, Fig. 4(B), the 10.7-

[8] C. N. Waddel, H. E. Adelson, B. J. Moyer and H. C. Shaw, Bull. Am. Phys. Soc. 2, 181 (1957); C. N. Waddel, thesis, Radiation Laboratory, University of California (unpublished).
[9] E. L. Garwin and A. S. Penfold, Bull. Am. Phys. Soc. 2, 351 (1957).

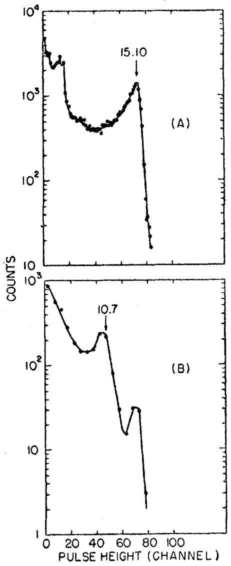

FIG. 4. Curve *A*—Gamma-ray spectrum in coincidence with protons channeled on the group to the 15.10-Mev state. Curve *B*—gamma-ray spectrum in triple coincidence with protons to the 15.10-Mev state and a gamma-ray counter channeled from 2.5–5 Mev.

Mev gamma ray appears together with the 15.10-Mev random distribution. By comparing the intensity of the 10.7-Mev peak in Fig. 4(B) with the 15.10-Mev peak in Fig. 4(A) and by correcting for the efficiency times solid angle for detecting the three 4.43-Mev gamma-ray peaks in the triple coincidence run, the branching ratio is derived. However, since the proton group to the 16.1-Mev state is unresolved, one must correct for the presence of the gamma-ray cascade from the 16.1-Mev level. The proton group feeding this state is twice as strong as the one to the 15.1-Mev state, and its gamma-ray branch[6] to the 4.43-Mev level is 1.4%. Subtracting this contribution and assuming similar angular distributions for the protons and gamma rays, we arrive at $(4\pm1)\%$ for the branching of the 15.10-Mev level to the 4.43-Mev state relative to the ground-state transition.

C. Gamma-Ray Branching of the 12.78-Mev State

An upper limit of 20% has been placed by Almqvist *et al.*[6] on the branching of the 12.78-Mev level to the 4.43-Mev level relative to the ground-state transition. By channeling on the proton group leading to the 12.78-Mev level, we have determined the branching ratio according to the techniques described in the preceding section. The double coincidence spectrum, Fig. 5(A), shows the 12.78-Mev ground-state gamma ray together with the 15.10-Mev gamma ray which appears because the channel on the 12.78-Mev proton group does not completely exclude the much stronger proton group to the 15.10-Mev state. In Fig. 5(B) the triple coincidence run exhibits the 8.4-Mev cascade gamma-ray transition. The gamma-ray branch to the 4.43-Mev state relative to the ground-state transition is calculated to be $(20\pm7)\%$ from these data.

According to Almqvist *et al.*,[6] the yields of the proton groups at $E_{\mathrm{He}^3}=2$ Mev leading to the 15.10- and 12.78-Mev levels are nearly equal. However, the corresponding numbers of protons associated with gamma-ray decay are about 20 to 1 in favor of the 15.10-Mev state owing to the fact that most of the 12.78-Mev states break up by alpha-particle emission. By combining this ratio of $\sim$20 with our ratio of 5 (in favor of the 12.78-Mev state) for the relative cascade gamma-ray branchings to the 4.43-Mev state, the 8.4-Mev cascade gamma ray from the 12.78-Mev state should be $\sim\frac{1}{4}$ as strong as the 10.7-Mev cascade gamma ray from the 15.10-Mev state.

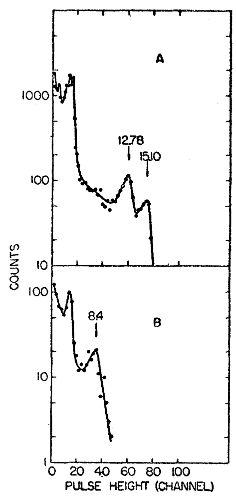

FIG. 5. Curve A Gamma-ray spectrum in coincidence with protons channeled on the group to the 12.78-Mev state. Curve *B*—gamma-ray spectrum in triple coincidence with protons to the 12.78-Mev state and a gamma-ray counter channeled from 2.5–5 Mev.

We have measured the spectrum of high-energy gamma rays in coincidence with a gamma-ray counter channeled from 2.5–5 Mev. Although the statistics of this run were not very favorable, we observe, in addition to the 10.7-Mev peak, a distribution which indicates the presence of the 8.4-Mev gamma ray with an intensity of about $\frac{1}{4}$ of the 10.7-Mev peak.

ACKNOWLEDGMENT

We are indebted to Dr. D. A. Bromley for supplying the target material used in this work and for helpful suggestions in connection with the experimental techniques and the results.