Beta Decay of B^{12}*

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The 3.23-MeV gamma-ray transition between the 7.66- and 4.43-MeV states of C^{12} has been observed in the beta decay of B^{12} by means of scintillation detectors and coincidence techniques. The B^{12} activity was made by the $B^{11}(d,p)B^{12}$ reaction using a Van de Graaff accelerator and a beam-chopping system for irradiation and delayed counting. All parts of the target-collimator assembly were constructed of beryllium in order to minimize bremsstrahlung production. Beta rays were detected in an 8-in.-diam by $\frac{1}{4}$-in.-thick Pilot-B scintillator and gamma rays were detected in two 5-in.×5-in. NaI counters placed on opposite sides of the source. Gamma-gamma coincidence measurements were made by displaying the output of each NaI detector in coincidence with a channel centered on the full-energy-loss peak of 4.43-MeV gamma rays in the opposite NaI detector. The additional requirement of a coincidence with the beta-ray detector was imposed for beta-gamma-gamma coincidence experiments. In both types of measurements the full-energy-loss and one-escape peaks of the 3.23-MeV gamma rays were observed. Based on the average result of two previous nuclear reaction measurements of the fractional decay of the 7.66-MeV state by the emission of 3.23-MeV gamma rays the present observation of these gamma rays leads to a value of $(1.7\pm0.5)\%$ for the beta-ray branching of B^{12} to the 7.66-MeV state of C^{12}.

INTRODUCTION

CONSIDERABLE importance has been attached to the 7.66-MeV second-excited state of C^{12} not only because the level is thought to be involved in the "helium-burning" mechanism in Red Giant Stars[1] but because of the fundamental nuclear physics interest in the structure of the state and in the various radiations leading to and from it. All three of the possible decay modes of the 7.66-MeV state have now been established including direct observations of the predominant alpha-particle emission[1] to the ground state of Be^8 and the emission of positron-electron nuclear pairs[2] to the ground state of C^{12}, and indirect measurements of the 3.23–4.43-MeV cascade gamma-ray emission[3,4] through the 2+ first-excited state of C^{12} at 4.43-MeV. The apparent absence of a ground-state gamma-ray transition[1] taken together with the predominant alpha-particle decay indicates that the very probable spin-parity assignment to the 7.66-MeV state is 0+. Values for the various partial widths of 7.66-MeV state are based on the result of an experiment by Fregeau[5] in which the level was excited by the inelastic scattering of high-energy electrons. From the cross section for this process an absolute partial width $\Gamma_\pi=5\times10^{-5}$ eV was calculated[1] for the emission of nuclear pairs to the ground state. Positron-electron pairs from the 7.66-MeV level were detected[2] in the $Be^9(\alpha,n)C^{12}$ reaction by means of a magnetic pair spectrometer and measurements were made of the relative pair emission rates from the 7.66- and 4.43-MeV levels. These data together with a determination[6] of the relative populations of these two levels in this same reaction, when using similar target and beam-energy conditions, were sufficient to calculate the ratio Γ_π/Γ_α. By combining this ratio with the value for Γ_π quoted above an experimental value $\Gamma_\alpha=8$ eV was obtained.[6]

The branching of the 7.66-MeV state by 3.23-MeV gamma-ray emission was first determined[3] by using the $B^{10}(He^3,p)C^{12}$ reaction to excite the 7.66-MeV level. Protons leading to the 7.66-MeV state were measured in a CsI scintillation detector both singly and in triple coincidence with two NaI gamma-ray counters, each channeled from 2.4 to 5.0 MeV. From the ratio of triples to singles counting rates the 3.23-MeV gamma-ray branch, or Γ_γ/Γ, was found to be $(3.3\pm0.9)\times10^{-4}$.

More recently, Seeger and Kavanagh[4] have successfully applied nuclear recoil coincidence techniques to the measurement of $(\Gamma_\gamma+\Gamma_\pi)/\Gamma$. The recoil method had been tried earlier by Eccles and Bodansky[7] before the advent of solid-state particle detectors. In Seeger and Kavanagh's work the 7.66-MeV C^{12} level was formed in the $N^{14}(d,\alpha)C^{12}$ reaction and coincidences between the alpha particles leading to the 7.66-MeV level and the corresponding C^{12} recoil nuclei were searched for and found. The observation of such a C^{12} recoil nucleus is possible only if the 7.66-MeV level decays to the ground state of C^{12}, rather than breaking up by alpha-particle emission. Seeger and Kavanagh's result, $(\Gamma_\gamma+\Gamma_\pi)/\Gamma=(2.82\pm0.29)\times10^{-4}$ (in which the contribution of Γ_π is $\sim2\%$ of the total), is in agreement with the earlier value[3] for Γ_γ/Γ but it is considerably more accurate.

Table I summarizes the present information on the branching modes of the 7.66-MeV C^{12} state. It is seen that the 3.23-MeV gamma-ray branch is ~45 times stronger than the ground-state nuclear-pair transition,

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[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] D. E. Alburger, Phys. Rev. **124**, 193 (1961).
[4] P. A. Seeger and R. W. Kavanagh, Bull. Am. Phys. Soc. **7**, 471 (1962); and article in course of publication.
[5] J. F. Fregeau, Phys. Rev. **104**, 225 (1956).
[6] F. Ajzenberg-Selove and P. H. Stelson, Phys. Rev. **120**, 500 (1960).
[7] S. F. Eccles and D. Bodansky, Phys. Rev. **113**, 608 (1959).

TABLE I. Partial branches in the de-excitation of the 7.66-MeV state of C^{12}.

Decay Mode	Partial Branch	Partial Width Γ_{exp}(eV)	Γ_{theo}(eV)
Alpha to Be^8	1	8[a]	7.5 (Wigner limit)[b]
7.66-MeV π	$(6.6\pm2.2)\times10^{-6}$[a]	5×10^{-5}[c]	...
3.23-MeV γ	$(3.3\pm0.9)\times10^{-4}$[d]	2.5×10^{-3}[d]	1.4×10^{-3}[e] (single-particle estimate)
3.23-MeV γ plus 7.66-MeV π	$(2.82\pm0.29)\times10^{-4}$[f]	2.1×10^{-3}	

[a] See Refs. 2 and 6.
[b] W. A. Fowler and T. Lauritsen (private communication quoted in Ref. 6).
[c] See Refs. 1 and 5.
[d] See Ref. 3.
[e] R. A. Terrell (private communication quoted in Ref. 1).
[f] See Ref. 4.

and therefore, is responsible for practically all of the energy released in stellar helium burning.

One of the earlier attempts to detect the 3.23-MeV gamma rays from the 7.66-MeV state of C^{12} was made in a study of B^{12} by Kavanagh.[8] B^{12} is known[9] to decay by beta-ray emission to C^{12} with a half-life of 20.3 msec and with a total energy release of 13.37 MeV. 97% of the beta rays go to the ground state. Several measurements have been made on the beta decay to the 4.43-MeV first excited state. The most recent value[10] of $(1.3\pm0.1)\%$ for this branch is considerably more accurate than any of the previous determinations[9] and it has, therefore, been used throughout this paper. Prior to the present work there had been only one measurement of the B^{12} beta-ray branch to the 7.66-MeV state. This was the experiment by Cook *et al.*[1] in which the alpha-particle breakup of the 7.66-MeV level was observed. From the intensity of alpha particles the beta-ray branch was calculated to be $(1.3\pm0.4)\%$. Very weak beta-ray branching[9,11] also takes place to alpha-particle emitting states in C^{12} above the 7.66-MeV level.

In Kavanagh's work[8] a search was made for 3.23–4.43-MeV gamma-gamma coincidences in B^{12} beta decay by means of scintillation counters. An upper limit of 10^{-3} was placed on the ratio $\gamma_{3.23}/\gamma_{4.43}$ and since the beta-ray branches to the 7.66- and 4.43-MeV states are of nearly equal intensity Kavanagh's result implied that $\Gamma_{3.23\gamma}/\Gamma\leq10^{-3}$ for the 7.66-MeV level. This limit is about three times greater than the actual branch found in the two later nuclear-reaction experiments (see Table I).

The major difficulty in coincidence measurements on B^{12} is associated with the production of bremsstrahlung by those beta rays of 9-MeV end-point energy that lead to the 4.43-MeV first excited state. A background of bremsstrahlung-gamma coincidences makes it difficult to observe the 3.23–4.43-MeV gamma-gamma coincidence effect. Although the details of Kavanagh's experiment were not known, it was felt by the author and Dr. R. E. Pixley several years ago that the background in beta-gamma-gamma triple coincidence measurements on B^{12} might be relatively smaller than in the case of gamma-gamma coincidences and that the 3.23-MeV gamma rays might be detected more easily by observing triple coincidences. In spite of a considerable amount of effort it was not possible to find these gamma rays at that time. A graphite collimator-absorber was used in that work.

Because of recent advances in both equipment and technique it was decided to make another attempt to detect the 3.23-MeV gamma rays in the beta decay of B^{12}. The gamma-gamma and beta-gamma-gamma coincidence experiments reported here include the following features which have contributed to the positive observation of this radiation:

(a) construction of the target-collimator assembly from beryllium in order to minimize bremsstrahlung production,

(b) the use of amplifiers, coincidence circuits, and two RIDL 400-channel pulse-height analyzers which were transistorized throughout,

(c) high-efficiency detection of the gamma rays by the use of two 5-in.×5-in. NaI detectors,

(d) fast-coincidence techniques to reduce random coincidence effects,

(e) the extremely reliable and stable operation of the Brookhaven Van de Graaff accelerator which in one of the runs operated with no interruption of the beam for 235 hr.

EXPERIMENTAL METHODS

During the initial work on B^{12} it was found that the major source of difficulty not only in the gamma-gamma coincidence measurements but also in the beta-gamma-gamma coincidence measurements was associated with the bremsstrahlung produced by beta rays leading to the 4.43-MeV level of C^{12}. In triple coincidence measurements a real beta-bremsstrahlung-gamma coincidence background always occurs even if the beta-ray detector is removed to a great enough distance from the source so that there is a small probability for the bremsstrahlung that is produced in the beta-ray detector itself to enter the gamma-ray detectors. For such an arrangement the background is substantially lower than if the small beta-ray detector were to be located close to the target and in between the two gamma-ray detectors. However, even when a large beta-ray detector is placed at an ample distance from the target such as in the present experiments there remains a real background that results from those beta rays that enter the collimator-absorber, produce bremsstrahlung, scatter out of the collimator, and finally enter the beta-ray detector. Since either the bremsstrahlung or the 4.43-MeV gamma rays can enter either gamma-ray detector the characteristic background in gamma-gamma or beta-gamma-

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[9] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[10] N. W. Glass, R. W. Peterson, and R. K. Smith, Bull. Am. Phys. Soc. **6**, 49 (1961).
[11] D. H. Wilkinson, D. E. Alburger, A. Gallmann, and P. F. Donovan, Phys. Rev. **130**, 1953 (1963).

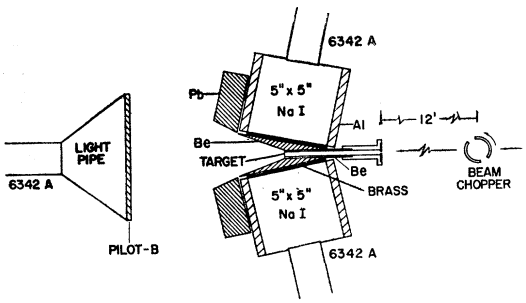

FIG. 1. Experimental arrangement for gamma-gamma and beta-gamma-gamma coincidence measurements on B^{12}.

gamma coincidence measurements is a spectrum consisting of 4.43-MeV peaks superposed on a bremsstrahlung continuum. The only practical way of minimizing this effect is to use material of low Z in the vicinity of the source.

Figure 1 shows the experimental arrangement adopted. The deuteron beam from the Van de Graaff first passed through a chopper located 12 ft from the experimental apparatus. Thereafter, it went through regulating slits (not shown) for control of the Van de Graaff terminal voltage, through a 2-mm-diam tantalum defining aperture and, after passing through a $\frac{3}{8}$-in.-o.d. by $\frac{3}{16}$-in.-i.d. beryllium tube, it struck the target. The target consisted of enriched (>99%) B^{11} metallic powder deposited from a water slurry onto a 4 mg/cm^2 Be foil which was waxed onto the end of the target tube. Enriched B^{11} was used in order to reduce the production of neutrons from the $B^{10}(d,n)C^{11}$ reaction which otherwise would have occurred if the target had been made of natural boron. Even though a substantial number of neutrons was produced in the $B^{11}(d,n)C^{12}$ reaction and these activated the NaI crystals it was felt that unnecessary production of neutrons should be eliminated. Several other precautions in this respect were taken. The B^{11} deposit was made thick enough ($\gtrsim$4 mg/cm^2) and large enough in diameter so that neither the direct deuteron beam nor deuterons scattered from the edges of the collimating aperture could reach the Be supporting foil. As a means of preventing aperture-scattered deuterons from striking the walls of the Be target tube the latter was lined with a rolled-up sheet of thin Ni foil.

A special beryllium collimator-absorber for this experiment was fabricated by the Brush Beryllium Company. The external shape of the collimator is that of a truncated rectangular pyramid (base dimensions 3 in.×4 in.). In the large end the opening is a circular cone of half-angle 23.5° and in the small end the opening is a circular hole of just the right size to fit over the Be target tube. The dimensions and shape of the Be collimator were chosen so as to obtain favorable solid angles of all three detectors at the source and yet to absorb at least 5 MeV of the energy of beta rays moving toward the center of either NaI detector. Beta rays energetic enough to pass through the sides of the collimator were kept out of the gamma-ray detectors by means of $\frac{1}{8}$-in.-thick brass plates. It was anticipated that the bremsstrahlung effects from beta rays reaching the brass plates would be negligible. Thick aluminum cylinders surrounded the NaI crystals so as to absorb scattered beta rays.

Each gamma-ray detector consisted of a 5-in.×5-in. NaI crystal. These units, made on special order by the Harshaw Chemical Company, have 2-in.-diam exit windows which allow them to be used together with 2-in.-diam photomultiplier tubes. RCA 6342A tubes were attached for this work. Although there was an initial doubt as to how good the pulse-height resolution would be for the 2-in. window (versus the 3-in.-diam window normally supplied on Harshaw's 5-in.×5-in. crystals) it was found on receipt of these crystals that one had a resolution of 10% and the other 11% for the 661-keV gamma rays of Cs^{137}. These figures compare favorably with the performance of crystals with 3-in.-diam windows. The NaI detectors were placed as shown in Fig. 1.

The beta-ray detector consisted of an 8-in.-diam by $\frac{1}{4}$-in.-thick Pilot-B scintillator cemented onto a conical lucite light guide which was, in turn, cemented onto an RCA 6342A photomultiplier tube. The thickness of this scintillator was chosen so as to make the output pulse-height spectrum relatively independent of the energy of the incident beta rays, at least for the high-energy beta rays occurring in the decay of B^{12}. Two layers of 0.001-in.-thick Al foil covered the front surface of the Pilot-B crystal. Pulses from one of the dynodes of the 6342A photo tube were fed to a linear amplifier in order to monitor the beta-ray counting rate. The pulse-height spectrum from this detector due to the B^{12} beta rays consisted of a peak having a full width at half-maximum of ~40% and a long high-energy tail of low intensity.

The position of the beta-ray detector indicated in Fig. 1 was such that it subtended a solid angle of 5.5% of 4π at the source. In this position the solid angle subtended by either of the NaI counters at a given point on the beta-detecting crystal was ~2.5% of 4π. Because of this small solid angle and the fact that bremsstrahlung tends to be emitted in the forward direction with respect to the incident beta rays it was expected that the contribution to the background in the triple coincidence experiments due to bremsstrahlung from the beta-ray detector would be small in comparison with the effect of bremstrahlung produced in the collimator-absorber, as discussed earlier. Nevertheless, the NaI counters were partially shielded from the Pilot-B crystal by means of tapered lead bricks. Additional lead bricks (not indicated in Fig. 1) were placed on the opposite sides of the NaI crystals in order to shield these counters from brackground radiations such as annihilation gamma rays from N^{13} activity produced in both the beam collimator and the regulation slits and prompt gamma radiation from the beam chopper.

Fast coincidences were detected by the use of conventional techniques, i.e., the photomultiplier tubes were operated at ~1800 V, their anodes were capacitively coupled to the grids of E280F limiters, and pulses formed by 1-m-long shorted stubs in the E280F plate circuits were fed to a diode adding circuit. Either double or triple coincidences could be detected by this circuit and a resolving time of 8 mμsec was used in all of this work. Fast timing adjustments were made by changing the lengths of the coaxial cables between the limiters and the fast coincidence circuit.

Because of the heavy loading of the NaI detector photomultiplier tubes by prompt gamma radiation during the irradiation part of the cycle, it was necessary to operate their dynode resistor chains at a high current drain by using 25-kΩ resistors together with high-current Northeast Scientific Corporation high-voltage power supplies. Even under these conditions and with no further modifications the voltage fluctuation on any given dynode was sufficient to smear the pulse-height spectrum derived at that point. This effect was counteracted and normal pulse-height resolution was achieved in the NaI detectors by attaching large capacitors to the dynode chain. In the arrangement used the signal for pulse-height analysis was derived from dynode No. 5, the corresponding point on the dynode resistor chain was bypassed to ground with an 8-μF capacitor and dynode No. 6 was bypassed to ground with a 4-μF capacitor.

The dynode No. 5 outputs of the two NaI detectors and the output of the fast coincidence circuit were fed to three transistorized double-delay-line-clipped linear amplifiers. Outputs of these amplifiers were connected to a Cosmic Radiation Laboratory model 801 coincidence circuit and the output of each NaI detector-amplifier was also fed to a separate RIDL 400-channel pulse-height analyzer.

In order to register counts only during intervals between irradiations of the target a synchronized gating circuit was constructed. A timing wheel was attached to the motor shaft driving the chopping cylinder. By means of two narrow radial slots machined in the wheel at 180°, together with a small light bulb on one side of the wheel and a photocell on the other side, a synchronization pulse was produced for each half turn. The photocell pulse triggered a blocked multivibrator which, in turn, produced a broad gating pulse of adjustable width. The broad-gating pulse was arranged to operate four separate input-output channels. Output pulses from two coincidence channels of the model 801 coincidence circuit were allowed to pass through two channels of the broad gating circuit and on to the two pulse-height analyzers only during the desired timing interval. The other two gating channels were used to measure either the beta-ray counting rate or the counting rates in the pulse-height channels imposed on the gamma-ray detector outputs.

The beam chopper consisted of a $1\frac{1}{2}$-in.-diam steel tube having two opposite 30° sectors cut out. This was connected to a motor by means of a $\frac{1}{8}$-in.-diam steel shaft that passed through a lubricated "O"-ring vacuum seal and it was rotated in the path of the beam at 1725 rpm. When the proper phasing and gating adjustments had been made the following sequence totaling 17 msec resulted: irradiation of the target for 3 msec, delay of 1 msec, opening of the counting gate for 12 msec, and 1-msec delay before the start of the next irradiation pulse. Thus, the actual counting time was 70% of the total time. The irradiation interval (observed as an intense group of pulses in the output of one of the gamma-ray detectors) and the relative width and time position of the 12-msec counting gate were monitored continuously by means of a dual-trace oscilloscope. Although the regulation slits for control of the Van de Graaff were located beyond the chopper and close to the target the chopping rate was sufficiently rapid that the feed-back terminal-voltage control system of the Van de Graaff operated satisfactorily.

Coincidence data were taken by recording the output of the North NaI detector on 200 channels of one of the 400-channel pulse-height analyzers and by triggering that analyzer with coincidence pulses (after passage through the 12-msec gate) involving the fast coincidence circuit output (either fast doubles or fast triples), the output of the south NaI detector and a pulse-height channel imposed on the south crystal spectrum. Generally the single-channel pulse-height analyzers on the coincidence circuit were adjusted so as to be centered on the full-energy-loss peak of the 4.43-MeV gamma rays. The channel width included all of the full-energy-loss peak and a part of the one-escape peak. Correspondingly, the analyzer for the south NaI detector was triggered by coincidences derived from the fast coincidence circuit together with the north crystal detector and a similar channel on the 4.43-MeV full-energy-loss peak in that spectrum. The remaining 200 channels of each analyzer were used to make periodic checks on the positions of peaks in the gamma-ray singles spectrum, as well as on the positions of the pulse-height channels, and to adjust amplifier gains when necessary.

Because of the intense radioactivities built up in the NaI crystals by neutrons from the target there was a high-counting rate of small-amplitude pulses. In order to prevent these pulses from contributing to the dead time of the analyzer the sensitivity control on the analyzer was adjusted so as to cut out the first 55 channels. Under these conditions the dead-time correction was negligible.

Periodic checks were made on the timing in the fast coincidence circuit. This was done by examining the shapes of the beta-4.43-MeV-gamma double-coincidence pulse-overlap spectra for each of the NaI detectors. These spectra were recorded when the pulse-height

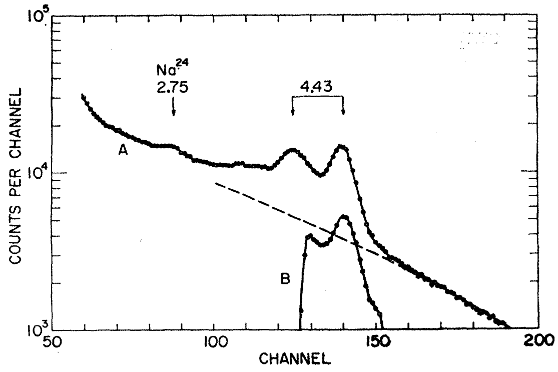

FIG. 2. Curve A, singles spectrum in the north NaI crystal showing the 4.43-MeV gamma-ray peaks superposed on a bremsstrahlung continuum and a peak due to Na^{24} gamma rays. The dashed extrapolation of the bremsstrahlung curve lying under the 4.43-MeV peaks was made as described in the text. Curve B, singles spectrum when imposing the pulse-height channel condition used in the coincidence experiments.

channel was centered in three different positions, i.e., at its normal position [channel 140—see Fig. 2(B)], at channel 70 and at channel 100. From the shapes of these spectra and the position of the peak of the pulse-overlap spectrum relative to a low-level discriminator setting imposed on the fast coincidence pulses, it was possible to show that the coincidence efficiency was close to 100% over the entire range of pulse heights that was displayed.

It was the original intention in this work to improve the statistics by adding together the coincidence data displayed in the two pulse-height analyzers. However, during the course of the experiments one of the NaI detectors developed comparatively poor pulse-height resolution characteristics, thereby making it undesirable to add the data together.

EXPERIMENTAL RESULTS

All of the B^{12} coincidence data were taken when using a 1.5-MeV deuteron beam at an average current of 0.010 μA on the thick B^{11} target. This beam current was established as the safe maximum for taking data since it was found that at currents of 0.015 μA, or higher, instabilities began to appear in some of the circuits and there was a noticeable deterioration of resolution in the displayed pulse-height spectra of the NaI detectors. At 0.01 μA the net counting rate in the beta-ray detector, corrected for scalar dead time and including only those beta rays within the 12-msec gate, was 47 000 per sec. Separate measurements of the beta-ray counting rates with and without the Be collimator-absorber indicated that in the normal arrangement 70% of the beta rays came directly from the source while the remainder arrived at the detector after scattering out of the collimator. Thus, although the beta-ray detector subtended a solid angle of 5.5% of 4π at the source it actually counted 7.9% of all beta rays emitted.

Figure 2(A) shows the singles pulse-height spectrum from the north NaI crystal (having the better pulse-height resolution) taken after several days of continuous operation in one of the runs. The prominent 4.43-MeV full-energy-loss and one-escape peaks and the underlying bremsstrahlung continuum are due to B^{12}. In addition to the weak 4.43-MeV two-escape peak (not identified in the figure), there is a peak at channel 87 and a rise in the yield below channel 65. These latter features resulted from the activation of the crystal by neutrons from the $B^{11}(d,n)C^{12}$ reaction. Three activities that occurred were Na^{24}, I^{128}, and F^{20}. Na^{24} has a half-life of 15 h and resulted in the 2.75-MeV gamma-ray peak at channel 87. The rise in the curve below channel 65 corresponds to beta rays from I^{128} (half-life 25 min and end-point energy 2.12 MeV). Na^{24} and I^{128} were both caused by neutron capture. F^{20}, having a half-life of 11.4 sec, was produced in the crystal by the $Na^{23}(n,\alpha)F^{20}$ reaction. It was a much weaker activity but its presence was indicated by a 1.63-MeV gamma-ray peak at channel 51 in the gamma-gamma coincidence spectrum (this portion of the spectrum was normally cut out by the analyzer sensitivity control). Such coincidences occur when the pulses from the F^{20} beta rays (which have an end-point energy of 5.4 MeV and all decay to the 1.63-MeV first excited state of Ne^{20}) lie within the channel [Fig. 2(B)] and when the 1.63-MeV gamma rays escape and are detected in the opposite crystal.

One of the main problems in this work was to achieve long-term stability of the photomultiplier gains. An ordinary gain-stabilizing circuit could not be used because of the very high intensity of gamma rays during the irradiation part of the cycle. Actually it was found that the 6342A phototubes had a gain that was count-rate-dependent, but that after radioactive equilibrium had been attained the rate of shift of the 4.43-MeV peak at channel 140 was usually less than one channel in 8 h. A method that was used in some of the final runs for reaching equilibrium more quickly was to bombard the target for 15 h with a beam current of 0.02 μA, cut off the beam for $\frac{1}{2}$ h and then bring it back on at the nor-

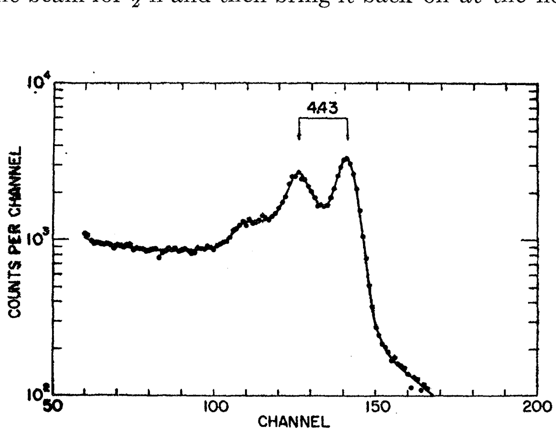

FIG. 3. Spectrum of B^{12} gamma rays in coincidence with beta rays recorded in a 34-min run.

mal current of 0.01 μA. Under these conditions the Na^{24} and I^{128} activities were each in equilibrium and coincidence data could then be taken without difficulties from gain shifts.

Figure 2(B) shows the singles spectrum when imposing the pulse-height channel used for the coincidence measurements. In all of the work the full-energy-loss peak of the 4.43-MeV gamma rays was arbitrarily centered at channel 140 in each of the pulse-height analyzers.

The spectrum from this same NaI detector taken in coincidence with the beta-ray detector is shown in Fig. 3. That this spectrum has very nearly the shape expected for monoenergetic gamma rays of 4.43 MeV was demonstrated by separate experiments in which a target of TiN^{15} was placed in the normal source position and bombarded with 1.3-MeV protons. The $N^{15}(p,\alpha)C^{12}$ reaction, which results almost entirely in 4.43-MeV gamma rays, was used to examine the shapes of the spectra with and without the Be collimator and brass absorber, to check the absorption factors used in the calculations, to find that the fraction of a pure 4.43-MeV gamma-ray spectrum lying within the pulse-height channel as defined in Fig. 2(B) was 0.295, and to obtain a value of 0.256 for the photopeak to total ratio. The coincidence spectrum of Fig. 3 served a number of purposes, one of which was a consistency check on some of the gamma-ray efficiency factors used in the calculations as well as verification that possible corrections for coincidence efficiency and analyzer dead time were indeed small enough to neglect. This check consisted of comparing the measured coincidence rate in Fig. 3 under the full-energy-loss peak (15.1 counts per sec after making a 2.5% correction for random coincidences; see below) with the rate expected according to the beta-ray counting rate, the known beta-ray branch of 1.3% to the 4.43-MeV level, and the over-all photopeak efficiency. The last of these factors was derived from the peak-to-total value of 0.256 given above together with the total efficiency and absorption factors discussed in the next section. An expected coincidence rate of 16.0 counts per sec under the full-energy-loss peak was obtained from this calculation. Although the agreement with the observed rate is very good it must be pointed out that the estimated probable error in the predicted rate is 15–20%.

The coincidence rate obtained from Fig. 3 was also used, together with the two singles rates and the resolving time of 8×10^{-9} sec to calculate the real-to-random ratio for beta-gamma coincidences. In that part of the spectrum corresponding to the channel shown in Fig. 2(B) the calculated real-to-random ratio was 38. This was verified roughly by observing the rate when a long delay cable was inserted in one branch of the coincidence circuit. In this calculation as well as in the random coincidence calculations discussed later the 70% duty cycle for counting was taken into account, but rather than correcting for the 33% decrease in the B^{12} intensity

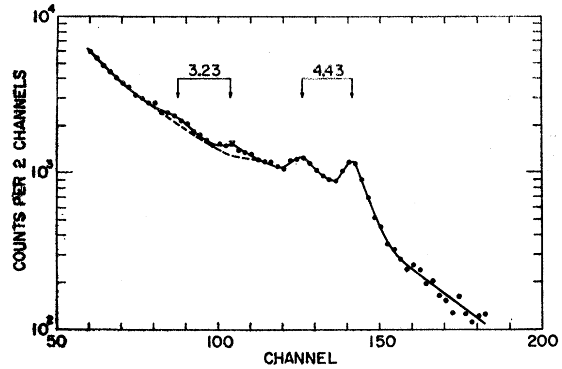

FIG. 4. B^{12} gamma-gamma coincidence spectrum obtained in a 75-h run. The data represent the spectrum of the north crystal in coincidence with a channel [as in Fig. 2(B)] on the 4.43-MeV full-energy-loss peak in the south crystal.

during the 12-msec gate the activity was approximated as having a constant average rate within the counting interval.

By comparing Fig. 3 with Fig. 2(A) it was possible to establish the level of the bremsstrahlung continuum lying under the 4.43-MeV peaks in Fig. 2. The dashed line in Fig. 2(A) has been drawn so that it extrapolates smoothly from the bremsstrahlung continuum above channel 160 and such that when it was subtracted from the total curve the remainder had the same shape as the 4.43-MeV gamma-ray spectrum in Fig. 3 between channels 100 and 150. Having obtained the level of the bremsstrahlung it was calculated that, of the total number of counts within the channel given in Fig. 2(B), 59% resulted from 4.43-MeV gamma rays while the remainder was due to bremsstrahlung.

At this point it may be mentioned that the channel condition on the gamma-ray detector outputs was selected so as to give a favorable ratio of counts due to the 4.43-MeV gamma rays relative to counts associated with the underlying bremsstrahlung continuum, yet to result in a reasonable yield. Had the channel been widened on the low-energy side, to include all of the one-escape peak for example, the coincidence yield of 3.23-MeV gamma-ray counts would have been greater but there would have been a proportionately larger increase in the background, as may be easily seen in Fig. 2 from the way in which the bremsstrahlung yield increases with decreasing energy. In the case of gamma-gamma coincidences another concern was that if the channel were made too wide it might include counts due to the summing of the 1.39-MeV beta rays and the 1.37-MeV gamma rays of Na^{24}. The escape and coincidence detection of the 2.75-MeV gamma ray in the opposite crystal might then result in a bothersome background peak.

The best result on B^{12} gamma-gamma coincidences is shown in Fig. 4. This is the spectrum for the north crystal obtained in a 75-h run in which the data were read out about every 10 h. During this same period the

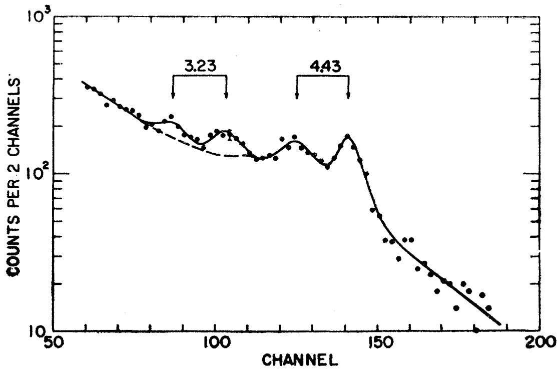

FIG. 5. B^{12} beta-gamma-gamma coincidence spectrum. The output of the north NaI detector was displayed in coincidence with all beta rays and with a channel [as in Fig. 2(B)] imposed on the south-crystal output. These data represent the sum of runs totaling 269 h.

scaler that recorded the south-crystal-channel output registered 1.17×10^8 counts. It is seen that in addition to the 4.43-MeV peaks and the bremsstrahlung continuum there are two additional weak, but statistically well-defined peaks which correspond closely to the expected positions of the full-energy-loss and one-escape peaks of the 3.23-MeV cascade gamma rays. The statistical error is indicated for one of the points on the 3.23-MeV full-energy-loss peak. The dashed line represents the best estimate for the background level under the 3.23-MeV peaks. It has been drawn so as to include a 4.43-MeV two-escape peak centered at channel 110, which according to Fig. 3, should have a net amplitude about 10% as great as that of the 4.43-MeV full-energy-loss peak. The net area in Fig. 4 between the total smooth curve and the dashed background curve amounts to 896 counts in the 3.23-MeV full-energy-loss peak, or 12 counts per h. Because the shape of the background is not known accurately the estimated error in the area of the photopeak is 20%. The net amplitude of the one-escape peak is about half as great as that of the full-energy-loss peak. This is the ratio expected from separate experiments on the $C^{12}(d,p)C^{13}$ reaction in which it had been shown previously that the amplitude ratio of the full-energy-loss to one-escape peaks for gamma rays of 3.1 MeV is close to 2 for this size NaI detector.

A calculation of the random coincidence rate was made for the gamma-gamma coincidence run of Fig. 4. Over the region of the spectrum defined by the channel given in Fig. 2(B) the calculated real-to-random ratio was 6.6. There seemed to be no need for checking this ratio experimentally.

In the gamma-gamma coincidence spectrum of the south crystal recorded during this same run the 3.23-MeV peaks were present, but since they were not nearly so well defined as in Fig. 4 (because of the poorer pulse-height resolution) the data could not be used for calculations. Several previous gamma-gamma coincidence runs of 30 to 70 h duration had been made in which the 3.23-MeV peaks had appeared with varying degrees of credibility.

Figure 5 shows the beta-gamma-gamma triple coincidence spectrum for the north crystal obtained by totaling 269 h of data. The dashed line represents the best estimate of the shape of the spectrum lying under the 3.23-MeV peaks and it includes a 4.43-MeV two-escape peak centered at channel 110. In spite of the poorer statistics (as indicated for one of the points) than in the gamma-gamma coincidence data of Fig. 4, the full-energy-loss and one-escape peaks of the 3.23-MeV gamma rays stand out more clearly in the triple coincidence run. Thus, in the double coincidence spectrum the net height of the full-energy-loss peak is 18% above the estimated background, whereas in the triple coincidence spectrum it is 44% above the background. It may be noted that except for the 3.23-MeV peaks the shape of the triple-coincidence spectrum rather closely approximates the shape of the singles spectrum [Fig. 2(A)].

The triple coincidence spectrum of the south crystal obtained during this same series of runs also defined the 3.23-MeV peaks well enough so that the data could be used for calculations. The separate results based on the north- and south-crystal data differed by 18%. Their average was 245 counts under the 3.23-MeV full-energy-loss peak, or an average rate of 0.91 counts per h. Here again the amplitude ratio of the 3.23-MeV full-energy-loss to one-escape peaks was found to be about 2 in both of the triple coincidence spectra.

Random coincidence calculations were made for the north-crystal triple coincidence spectrum. In this case there were three contributions, including (a) real beta-gamma coincidences (north crystal) in random coincidence with the channel on the south crystal, (b) real gamma-gamma coincidences (with the channel on the south crystal) in random coincidence with the beta-ray detector, and (c) uncorrelated random triple coincidences involving the north crystal, the channel on the south crystal, and the beta-ray detector. By summing these contributions the real-to-random ratio over the region defined by the channel given in Fig. 2(B) was calculated to be 4.6. Of the total random coincidence rate the fractional contributions of effects (a), (b), and (c) were 83%, 16%, and 1%, respectively.

ANALYSIS AND DISCUSSION

During the earliest stages of the present work no measurements had been made on the 3.23-MeV gamma-ray branching from the C^{12} 7.66-MeV state. It had been hoped that the observation of this gamma ray in B^{12} decay would lead to a value for the gamma-ray branching based on the reported beta-ray branching intensities to the 4.43- and 7.66-MeV states. If this approach were still to be followed, the observed 3.23-MeV gamma-ray intensity, taken together with the $(1.3\pm0.4)\%$ beta-ray branch[1] to the 7.66-MeV level, would correspond to $\Gamma_\gamma/\Gamma=(3.8\pm1.5)\times10^{-4}$, a value having a probable error of 40%. (This calculation was similar to those described below.) However, there have now been two nuclear reaction determinations[3,4] of the 3.23-MeV gamma-ray branch which have a weighted mean value of $(2.9\pm0.3)\times10^{-4}$. Since this number is already known with an accuracy of 10% the usefulness of the present work, aside from the direct observation of the 3.23-MeV gamma rays, is that it permits an independent determination to be made of the B^{12} beta-ray branch to the 7.66-MeV state. It has, of course, been assumed that the 3.23-MeV peaks found in these experiments were real and that they were actually associated with B^{12} and not with background reactions or activities that were overlooked. In the calculations that follow, the yields have been treated as having resulted entirely from ordinary beta-gamma-gamma coincidence effects in B^{12} decay, although alternate processes were considered. Thus, it was estimated from the magnitude of the bremsstrahlung-4.43-MeV-gamma coincidence yield in Fig. 4 that there was a completely negligible contribution to the 3.23-MeV peaks in Figs. 4 and 5 arising from coincidences between the 3.23-MeV gamma rays and the bremsstrahlung associated with beta rays feeding the 7.66-MeV state.

By using the gamma-gamma coincidence data of Fig. 4 the beta-ray branching $B_{7.66}$ to the 7.66-MeV state was calculated according to the relationship

$$N_{\gamma\gamma}=N_{4.43}\times(B_{7.66}/B_{4.43})\times(\Gamma_{3.23\gamma}/\Gamma)\times\epsilon_{3.23}\times C_\theta\,, \quad (1)$$

where $N_{\gamma\gamma}$ is the number of counts in the 3.23-MeV full-energy-loss peak, $N_{4.43}$ is 0.59 times the total number of scaler counts recorded for the channel of the south-crystal spectrum, $B_{4.43}$ is the known beta-ray branch of $(1.3\pm0.1)\%$ to the 4.43-MeV level, $\Gamma_{3.23\gamma}/\Gamma$ has the value 2.9×10^{-4} as discussed above, $\epsilon_{3.23}$ is the over-all photopeak efficiency for the 3.23-MeV gamma rays and C_θ is a correction factor allowing for the effect of the 0-2-0 angular correlation between the 3.23- and 4.43-MeV gamma rays. C_θ has been estimated to be 1.10 or slightly less than the factor given in Ref. 3 because of the somewhat different geometry used in this case. The efficiency $\epsilon_{3.23}$ was found by multiplying the total efficiency[12] of 0.132, for a 5-in.×5-in. NaI crystal at a gamma-ray energy of 3.23 MeV and at the source-to-crystal distance of 3.15 cm used in this experiment, by a peak-to-total ratio of 0.30 and also multiplying by a correction factor of 0.77 to allow for the absorption of the gamma rays in the Be and brass. Data given by May and Marinelli[13] were used as the basis for deriving the peak-to-total ratio of 0.30 for 3.23-MeV gamma rays. This ratio and the experimental ratio of 0.256 for the 4.43-MeV gamma rays obtained in the present work are consistent in their relative values with the expected variation of the peak-to-total ratio with gamma-ray energy. The over-all 3.23-MeV photopeak efficiency obtained was $\epsilon_{3.23}=3.05\times10^{-2}$. When all of the numbers are inserted into Eq. (1) the resulting value for $B_{7.66}$ is 1.73×10^{-2} with an estimated probable error of about 30%.

A calculation of $B_{7.66}$ was made from the average of the two triple coincidence spectra, one of which is shown in Fig. 5, by using the relationship

$$N_{\beta\gamma\gamma}=N_\beta\times B_{7.66}\times(\Gamma_{3.23\gamma}/\Gamma)\times\epsilon_{3.23}\times\epsilon_{4.43}\times C_\theta\,, \quad (2)$$

where $N_{\beta\gamma\gamma}$ is the average net area of 245 counts under the 3.23-MeV full-energy-loss peak, N_β is the total number of beta-ray counts (4.9×10^{10}), and the remaining factors, other than $\epsilon_{4.43}$, are the same as in Eq. (1). $\epsilon_{4.43}$ is the efficiency for detecting 4.43-MeV gamma rays within the channel as shown in Fig. 2(B). A value of 3.03×10^{-2} for $\epsilon_{4.43}$ was obtained by multiplying the total 4.43-MeV gamma-ray efficiency[12] of 0.129 by the fraction (0.295) of the total spectrum lying within the channel (derived from the $N^{15}(p,\alpha)C^{12}$ spectrum as mentioned previously) and by an absorption factor of 0.79. When all of these numbers are inserted into Eq. (2), the resulting value for $B_{7.66}$ is 1.67×10^{-2}, with an estimated probable error of about 30%.

An assumption that has been made in the triple coincidence calculations is that the contributions of the various beta-ray branches to the rate N_β were in true proportion to the actual branching intensities. This is almost certainly true for the 70% of the beta rays that passed directly from the source ot the detector. For the 30% contribution of beta rays that scattered out of the Be collimator-absorber and then entered the detector it has been assumed that the fraction of those beta rays leading to the 7.66-MeV level (end-point energy 5.7 MeV) that scattered out was the same as the fraction of the ground-state beta rays (end-point energy 13.37 MeV) that scattered out. Although this approximation is uncertain it is not likely that a large error was introduced into the result by the differences in scattering for these two beta-ray groups since only 30% of the beta-ray counts were involved.

The separate measurements of $B_{7.66}$ from the gamma-gamma and beta-gamma-gamma coincidence work are in accidently good agreement and the average value of $(1.7\pm0.5)\%$ is adopted. A check on the consistency of the separate results can be made by comparing the net yield of 12 counts per hour under the 3.23-MeV full-energy-loss peak in the gamma-gamma coincidence run with the rate of 0.91 counts per h for the triple coincidences. The ratio of these yields is 13.2. Based on the effective solid angle of 7.9% of 4π for the beta-ray detector the yield ratio of double coincidences to triple coincidences was expected to be 12.6. This is in good agreement with the measured ratio.

The B^{12} beta-ray branch of $(1.7\pm0.5)\%$ to the 7.66-

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MeV level of C^{12} found in the present work is slightly higher than the branch of $(1.3\pm0.4)\%$ determined by Cook *et al.*, although the errors overlap. If these separate results are averaged the branch becomes $(1.5\pm0.3)\%$. The previously accepted[9] log *ft* value of 4.2 for this branch would thus decrease by only 0.05 as a result of the present work.

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Study of the $C^{12}(d,p)C^{13}$ Reaction Mechanism: Polarization and $(d,p\gamma)$ Correlations

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Measurements in the deuteron energy range $5.5<E_d<12$ MeV have been made as follows on the reaction $C^{12}(d,p)C^{13*}$: (a) differential cross sections for protons to C^{13} ground state and C^{13*} (3.09 MeV) as functions of angle and energy, (b) proton polarization to C^{13} ground state and C^{13*} (3.09 MeV) as function of energy at 45° (lab system) and as functions of angle (10° to 120° lab) for protons to 3.09-MeV state at $E_d=8.3$, 9, and 10 MeV, and (c) proton-gamma correlation measurements with the gamma-ray detector on the normal to the reaction plane for reactions to C^{13*} (3.68 MeV) and C^{13*} (3.85 MeV). In (b) and (c) a double-focusing magnetic spectrometer selected the proton group in question; the polarization of the selected protons was measured by observing the "left-right" asymmetry from a carbon scatterer. Backgrounds were made negligible in the polarization work by coincidence methods. All the data show fluctuations with deuteron energy throughout the energy range studied; these fluctuations are attributed to compound-nucleus effects which invalidate a distorted-wave Born approximation (DWBA) stripping interpretation of results at isolated energies although direct interaction is the predominant mechanism. It is shown by taking average values over a wide energy range (~4 MeV) that a DWBA stripping description of the direct-interaction part of the reaction almost certainly will require the use of spin-dependent potentials.

A. INTRODUCTION

SINCE the first theories of deuteron stripping in the intermediate energy region over a decade ago[1,2] there have been many different attempts to improve the agreement with experiment by taking account of effects which were at first ignored. In the most successful of these, the plane waves expressing the motion in relative coordinates of the deuteron and proton (in the (d, p) reaction) are replaced by wave functions distorted by the Coulomb and nuclear fields. The distorted wave functions are calculated assuming that the nucleus is represented by a complex potential well whose parameters have been chosen to give agreement with the results of elastic-scattering experiments. If the scattering parameters have been determined in this way, then the distorted-wave theory yields predictions for the corresponding stripping reactions that can be tested by experiment. One objective is to see whether there exists a form of the distorted-wave theory that gives a description of experimental stripping results adequate for the extraction of spins of residual states and absolute values of reduced nucleon widths from experimental data even when distortions are large and thus to provide a valuable tool in nuclear structure studies. In addition, an understanding of the reaction mechanism in itself is, of course, also of great interest.

The first and simplest form of distorted-wave Born-approximation stripping calculation (henceforth referred to as DWBA stripping calculation) entirely neglected effects of spin-orbit and spin-spin terms in the scattering potentials of both the deuteron and the proton. Under these conditions the polarization, P, of protons emitted in a (d, p) stripping process has been shown to be effectively a measure of the direction of the neutron's orbital angular momentum diminished by the geometric factor $\frac{1}{3}$ arising from the deuteron spin coupling and by an additional factor which arises from the coupling of the neutron's spin $\frac{1}{2}$, and its orbital momentum, l_n, in the final nucleus to give a definite total angular momentum j in the final state. The result is[3,4]

$$\begin{aligned} P&=+\tfrac{1}{3}\frac{1}{l_n+1}\langle l_n\rangle \quad \text{for} \quad j=l_n+\tfrac{1}{2}, \\ P&=-\tfrac{1}{3}(1/l_n)\langle l_n\rangle \quad \text{for} \quad j=l_n-\tfrac{1}{2}. \end{aligned} \tag{1}$$

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