Angular Distribution of 16.1-Mev Gamma Rays from the 163-kev Resonance in the Reaction $B^{11}(p,\gamma)C^{12}$

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The relative thick-target yield, at a bombarding energy of 168 kev, of 16.1-Mev gamma rays from the reaction $B^{11}(p,\gamma)C^{12}$ has been measured at 0, 60, 90, and 120 degrees. The angular distribution is of the form $1-A\cos\theta+B\cos^2\theta$, with $A=0.19\pm0.06$ and $B-A=0.02\pm0.04$. The $\cos\theta$ term is believed to be caused by interference between a resonance of spin and parity $1-$ at a bombarding energy of 1.4 Mev, and the resonance of spin and parity $2+$ at a bombarding energy of 163 kev.

INTRODUCTION

THE existence of a resonance with a width of about 5 kev for the reaction $B^{11}(p,\gamma)C^{12}$ at a bombarding energy of 163-kev has been demonstrated by a number of groups.[1] The level in C^{12} formed at this resonance has an excitation energy of 16.10 Mev and decays by either alpha-particle or gamma-ray emission. The gamma-ray decay takes place either by 11.6-Mev and 4.45-Mev gamma radiations in cascade, or by a 16.1-Mev gamma ray directly to the ground state.[1] The present paper is concerned with the angular distribution of the 16.1-Mev gamma rays.[2] Kern *et al.*[3] have found the yields of these gamma rays at 0° and 90° to be equal to within ten percent. Glättli and Stoll[4] found a nonisotropic distribution, but the selective-absorption method they used to separate the different gamma-ray components did not completely isolate the 16.1-Mev component from the much stronger 11.6-Mev gamma rays. Grant *et al.*[5] have made measurements on the 16.1-Mev gamma rays, obtaining $I_{0°}/I_{90°}=1.08\pm0.03$ and evidence of an odd-power cosine term in the distribution. The present measurements yield $I_{0°}/I_{90°}=1.02\pm0.04$ and $I_{120°}/I_{60°}=1.20\pm0.06$. This latter ratio requires an odd-power cosine term in the distribution. The difficulty in separating the 16.1-Mev gamma rays from the 11.6-Mev rays, which are thirty times more intense, leads to the relatively low precision of the measurements of this distribution.

METHOD

Thick targets of powdered natural boron deposited on a backing of 0.010-inch thick molybdenum were bombarded with a 200-microampere beam of protons from an accelerator[6] with a maximum voltage of 250 kv. The target and detectors were arranged as shown in Fig. 1. For the measurements at 60° and 120° to the beam, the target was placed perpendicular to the beam: for those at 0° and 90°, it was placed at 45° to the beam. The beam enters in a vertical direction, passes through two collimating apertures one-quarter inch in diameter separated by seven inches, and strikes the target.

Two NaI(Tl) crystals, two inches in diameter and two inches long, mounted on DuMont 6292 photomultipliers, were used to detect the gamma rays. One crystal, used as a monitor on the 11.6-Mev gamma rays, was placed at an angle of 90° to the beam when the target was at 45°, and at 110° to the beam when the target was horizontal. The distance from the center of each crystal to the target was 10.4 inches. The crystals were placed this far away from the target to ensure a small probability of the two gamma rays from the more intense cascade decay being absorbed in the crystal simultaneously. The pulse from the photomultiplier due to such an event is in this experiment indistinguishable from that caused by the absorption of a single 16.1-Mev gamma ray in the crystal. Assuming that the cascade gamma rays have no angular correlation, and that the probability of detection of a 4.45-Mev gamma ray entering the crystal is less than 0.2, the probability of simultaneous detection is less than 5×10^{-4} times the probability of detection of the 11.6-Mev gamma rays. In this experiment the ratio of the yield of 16.1-Mev gamma rays to 11.6-Mev gamma rays was measured to be 3.3×10^{-2}. Thus the simultaneous detection of the cascade gamma rays accounts

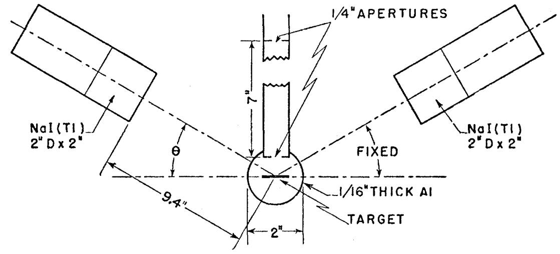

FIG. 1. The angular distribution apparatus with the target shown in a position perpendicular to the beam.

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[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[2] Craig, Cross, and Jarvis, Phys. Rev. **96**, 825 (1954).

[3] Kern, Moak, Good, and Robinson, Phys. Rev. **83**, 211 (1951).

[4] H. Glättli and P. Stoll, Helv. Phys. Acta **25**, 455 (1952).

[5] Grant, Flack, Rutherglen, and Deuchars, Proc. Phys. Soc. (London) **A67**, 751 (1954).

[6] Allen, Almqvist, Dewan, and Pepper, Can. J. Phys. **29**, 557 (1951).

for less than two percent of the observed yield of 16.1-Mev gamma rays.

The output from each photomultiplier was fed through a biased linear amplifier, and onto a multichannel pulse-height analyzer. By displaying the output from both crystals on multichannel pulse-height analyzers, a continuous check of the gain of the system was maintained.

RESULTS

Most of the data were taken at a bombarding energy of 168 kev. A typical pulse-height distribution is shown in Fig. 2. Pulses corresponding to a gamma energy of less than 9.5 Mev have been biased off in the amplifier. The large peak is from the 11.6-Mev gamma rays, the small peak from the 16.1-Mev component. Pulses lying in the channels between the two vertical lines on the right are attributed to the 16.1-Mev gamma rays.

A number of groups have shown that the emission of 11.6-Mev gamma rays exhibits a resonance at a bombarding energy of 163 kev.[1] To confirm previous observations[1] that thel 6.1-Mev radiation is also resonant at this bombarding energy, the relative yield of 16.1-Mev to 11.6-Mev radiation, at a number of energies through the resonance, was measured at an angle of 120° to the proton beam. The ratios of the yields of the two gamma rays were obtained by counting the pulses in a equivalent number of analyzer channels as shown in Fig. 2. These ratios are shown in Fig. 3. The standard deviations shown are applicable only to the relative values of the ratios. There remains the possibility of a constant percentage error in all the ratios, as the relative efficiencies of the crystal for 11.6-Mev and 16.1-Mev gamma rays are not known accurately. A yield curve of 11.6-Mev gamma rays alone, drawn on the same figure, checks the measurement of the bombarding voltage. The constancy of the ratio of the yield of 16.1-Mev radiation to that of 11.6-Mev, as the energy of the bombarding protons goes through 163 kev, indicates that these radiations are both resonant at the same energy. At 0° the intensity of the 16.1-Mev component is measured to be 3.3±1 percent of the 11.6-Mev component. This is in agreement with the value of four percent found by Huus and Day.[7]

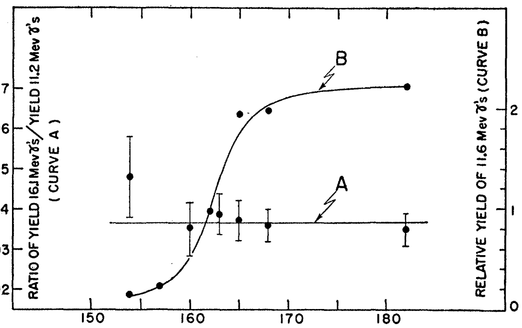

FIG. 3. Curve A shows the ratio of the yield of 16.1-Mev to 11.6-Mev γ rays as a function of bombarding energy, at 120° to the proton beam. Curve B is a yield-curve of 11.6-Mev γ rays as a function of the bombarding energy. The vertical lines through the points of curve A indicate the standard deviations.

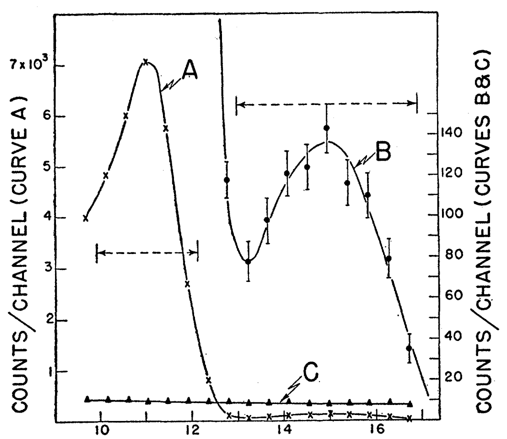

FIG. 2. Curve A is the spectrum of γ rays with an energy greater than 9.5 Mev taken with the crystal at 0°. This curve has been corrected for background. Curve B is a portion of this spectrum with the vertical scale expanded 40 times. This curve has been corrected for background. Curve C is the background. The energy scale was obtained by fixing the large peak at (11.6−0.5) Mev and assuming a linear relationship between pulse height and energy. The vertical lines through the points indicate the standard deviations. The horizontal dashed lines indicate the channels used in comparing the yield of 11.6-Mev and 16.1-Mev γ rays.

The mean ratio for nine runs of the yield of 16.1-Mev gamma rays at 0° to that at 90° is 1.02 with a standard deviation of 0.04. This figure contains a 1.4 percent correction for absorption in the target at 0°. The mean value of seven determinations of the ratio of the yield at 120° to that at 60° is 1.20±0.06. The yield at 60° has been corrected by two percent for absorption in the target. Using this value and the ratio of the yield at 0° to that at 90°, and assuming a distribution of the form $1-A\cos\theta+B\cos^2\theta$, we find $A=0.19\pm0.06$, and $B-A=0.02\pm0.04$.

As a check on these measurements, the ratios of the yield of 11.6-Mev gamma rays at 0° to that at 90°, and at 120° to that at 60°, were determined and found to be 1.18±0.02 and 0.99±0.02 respectively. These values are in accord with the measurements of this distribution by Kern *et al.*[3] who obtained a distribution of the form $1+(0.15\pm0.03)\cos^2\theta$, and of Hubbard *et al.*[8] who obtained one of the form $1+(0.23\pm0.04)\cos^2\theta$ at a bombarding energy of 170 kev.

The ratios of the thick-target yield of 16.1-Mev gamma rays to that of 11.6-Mev gamma rays at a bombarding energy of 240 kev were found to be greater than the ratios for a bombarding energy of 168 kev by

[7] T. Huus and R. B. Day, Phys. Rev. **91**, 599 (1953).
[8] Hubbard, Nelson, and Jacobs, Phys. Rev. **87**, 378 (1952).

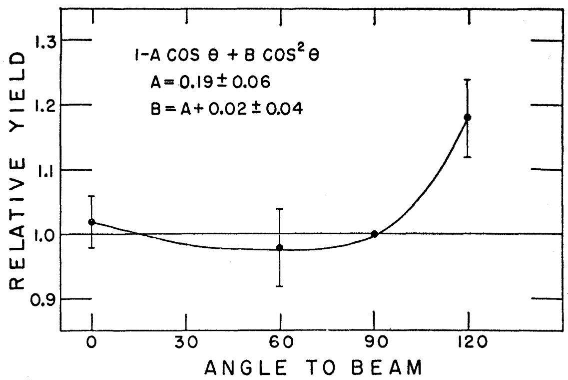

FIG. 4. The angular distribution of the 16.1-Mev γ rays at a bombarding energy of 168 kev. The vertical lines through the points indicate the standard deviations.

the following factors: 120°, 1.6±0.1; 90°, 1.6±0.1; 60°, 1.3±0.2; 0°, 1.1±0.2.

DISCUSSION

The distribution of the 16.1-Mev gamma rays is then of the form $1-A\cos\theta+B\cos^2\theta$, with $A=0.19\pm0.06$ and $B-A=0.02\pm0.04$, or using Legendre polynomials, $1-(0.18\pm0.06)P_1+(0.13\pm0.05)P_2$. This distribution is shown in Fig. 4. The presence of the odd-power cosine term indicates interference with a level of opposite parity which also decays by gamma-ray emission to the ground state of C^{12}. At the low bombarding energies used in this experiment, it is assumed that only *s*- and *p*- wave protons have a significant probability of forming a compound nucleus. The resonance at 163 kev has been ascribed to *p* waves, and has been assigned a spin and parity of 2+.[1]

Resonances at bombarding energies of 1.4, 2.6, 3.14, and 3.6 Mev are the only other ones from which transitions to the ground state have been observed in this reaction.[9,10] The resonance at a bombarding energy of 163 kev corresponds to a level in C^{12} at 16.10-Mev. There are levels in C^{12} lying below the 16.10-Mev level, that are reached by other reactions. However, there is no evidence that one of these low-lying levels, which decays by a ground state transition, has enough width to cause the observed interference.

The level at a bombarding energy of 1.4-Mev has a width of 1.27-Mev[7] and has been assigned a spin and parity of 2+ or 1−.[7,9] If this level is responsible for the interference, its spin and parity assignment is 1−, and it is assumed to be formed by *s* waves. The angular distribution was calculated by following the method of Blatt and Biedenharn,[11] assuming that the expression for the scattering matrix given by them for a single resonance level is applicable to the interfering levels. The partial widths used in the calculations are those given by Beckman *et al.*[12] The ratio of channel spins 1 to 2 was taken to be 0.51±0.03. This ratio is required to fit our observed 11.6-Mev distribution of $1+(0.18\pm0.02)\cos^2\theta$, or $1+(0.11\pm0.01)P_2$, when the 11.6-Mev gamma rays are assumed to be emitted in a pure magnetic dipole transition with no interference from another level of the same parity. This ratio is only slightly higher than that found by Thomson *et al.*,[13] from analysis of their experimental results for the $B^{11}(p,\alpha)Be^8$ reaction, of 0.42±0.02. In calculating the penetrability of the Coulomb barrier, a radius of $1.5A^{\frac{1}{3}}\times10^{-13}$ cm was used. A phase difference of 64° [14] was used for the elastically-scattered protons from the two levels. The phase difference for the emission of gamma rays from the two levels has been assumed to be either 0 or π radians. The calculated angular distribution for the 16.1-Mev gamma rays is $1\pm(0.17\pm0.05)\cos\theta+(0.26\pm0.02)\cos^2\theta$ as compared with the measured distribution of $1-(0.19\pm0.06)\cos\theta+(0.21\pm0.07)\cos^2\theta$.

Within the quoted uncertainties, the experimental and calculated distributions are seen to be in agreement and therefore the 1.4-Mev level can be the interfering level. The calculated magnitudes of the $\cos\theta$ and $\cos^2\theta$ terms are dependent on the ratio of the channel spins which is chosen. The value used, although valid for the 11.6-Mev gamma rays from this level, does not necessarily hold for the 16.1-Mev gamma rays. The uncertainty in the $\cos\theta$ term given above arises from the following sources: the values of $\sigma_{p\gamma0}$ for the 163-kev and 1.4-Mev levels, the nuclear radius used in calculating the penetrability of the Coulomb barrier, and the value of the channel-spin mixture. The values of $\sigma_{p\gamma0}$ for the 1.4-Mev and the 163-Mev levels are assumed to be uncertain by 15 percent[7] and 30 percent respectively. The uncertainty in $\sigma_{p\alpha1}{}^1$ for the 163-kev level does not increase the uncertainty in the magnitude of the $\cos\theta$ term since $\Gamma_{\gamma0}\propto1/\sigma_{p\alpha1}$ and $\Gamma_{p0}\propto\sigma_{p\alpha1}$,[12] and thus $\Gamma_{\gamma0}\Gamma_{p0}$ which appears in the calculation is independent of $\sigma_{p\alpha1}$. The penetrability enters the calculation only as the ratio of penetrabilities at 163 kev and 1.4 Mev and this ratio is relatively insensitive to the radius used. A ten percent change in radius will affect the $\cos\theta$ term by less than five percent.

The widths of the other levels from which ground-state transitions have been observed, at bombarding energies of 2.6, 3.14, and 3.6 Mev, are 0.3, 0.1, and 0.5 Mev respectively.[9,10] The low intensities of the gamma rays from these levels,[10] coupled with their fairly narrow widths, prohibit these from being the interfering levels.

The only other level which might be expected to interfere with the 163-kev level is at 680 kev. This has

[9] H. E. Gove, and E. B. Paul, Phys. Rev. **97**, 104 (1955).
[10] Bair, Kington, and Willard, Phys. Rev. **100**, 21 (1955).
[11] J. M. Blatt and L. C. Biedenharn, Revs. Modern Phys. 24, 258 (1952).
[12] Beckman, Huus, and Zupančič, Phys. Rev. **91**, 606 (1953).
[13] Thomson, Cohen, French, and Hutchinson, Proc. Phys. Soc. (London) A65, 745 (1952).
[14] Sharpe, Gove, and Paul, Atomic Energy of Canada Limited, Report TPI-70 (unpublished).

been assigned a spin and parity of 2− or 3+ by Huus and Day,[7] and Gove and Paul,[9] whereas Grant *et al.*[5] give an assignment of 2+. No ground state gamma rays have been observed from this level, and an upper limit on the cross section for such transitions has been set at 2.3×10^{-6} barn.[7] The width of this level is 330 kev.[7] Using the upper limit on the cross section, an assignment of 2− for the spin and parity, and assuming a channel-spin mixture of 0.51 for spins 1 and 2 respectively, the cosine term from interference with this level was calculated to be nine times smaller than that calculated for interference with the 1.4-Mev level. Interference with the 1.4-Mev level would then seem to provide the better agreement between the calculated and the observed angular distributions. Of the two possible assignments[7,9] 2+ and 1− previously made for the spin and parity of the 1.4-Mev level, only the latter is consistent with the above results.

ACKNOWLEDGMENTS

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Disintegration of Cs^{138}†*

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The decay of the fission product Cs^{138} (32.1 minutes) has been studied with beta- and gamma-scintillation spectrometers and a 141-gauss, 180° permanent-magnet spectrograph. Twelve gamma rays were found with energies of 0.1389, 0.1931, 0.2289, 0.4106, 0.4626, 0.550, 0.87, 1.010, 1.426, 2.21, 2.63, and 3.34 Mev. On the basis of coincidence measurements, intensity data, internal-conversion coefficients, angular correlation data, and the above gamma energies, a consistent decay scheme is proposed which involves levels in Ba^{138} at 1.426, 1.89, 2.21, 2.30, 2.44, 2.63, and 3.34 Mev.

INTRODUCTION

THE radiations emitted by Cs^{138} have been studied by Langer, Duffield, and Stanley[1] and by Thulin.[2] The former authors reported a total energy release in the decay of 4.8 Mev and found the ground-state to ground-state transition to be of unobservably low intensity. The highest-energy beta group, of end point 3.4 Mev, was shown by beta-gamma coincidence measurements to be followed by a gamma ray of 1.44 Mev. Gamma rays of 0.44 and 0.98 Mev were also found and were shown to lead to the first excited state at 1.44 Mev rather than to the ground state. The beta-ray spectrum was found to be very complex, and its accurate analysis into groups was not possible.

Thulin,[2] using sources prepared in an electromagnetic separator, examined the gamma radiation with a scintillation counter. He confirmed the existence of the gamma rays reported above, and found others at 0.128, 0.548, 2.24, and 2.68 Mev. No coincidence experiments were done.

In the present work, the investigation of the gamma radiation following the beta decay of Cs^{138} has been continued with the help of scintillation spectrometers and a permanent-magnet spectrograph. Five more gamma rays have been found, and numerous new coincidence relationships have been established. A consistent decay scheme is proposed.

EXPERIMENTAL METHODS AND RESULTS

Source Preparation

The Cs^{138} used in these experiments came from beta decay of the fission product Xe^{138}, which had been made by bombarding U^{235} with thermal neutrons from the Los Alamos Water Boiler reactor. The U^{235} was irradiated in the form of solid uranyl stearate, $UO_2(C_{18}H_{35}O_2)_2$, a compound from which the 17-minute Xe^{138} is expected to emanate with $\sim$100% efficiency.[3] The uranium compound, contained in a sealed quartz tube, was exposed to a neutron flux of $\sim6\times10^{11}$ neutrons/cm² sec for 30 minutes, allowed to decay for 10 minutes, and then the fission product gas was transferred to a vessel in which it was allowed to decay for 33 minutes. At the end of this period the remaining gas was pumped out and discarded, and the mixture of cesium and rubidium activities was rinsed off the walls

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† A preliminary report of this work was presented at the Chicago meeting of the American Physical Society [Duffield, Bunker, Mize, and Starner, Phys. Rev. **100**, 1236(A) (1955)].
‡ Present address: University of Illinois, Urbana, Illinois.
[1] Langer, Duffield, and Stanley, Phys. Rev. **89**, 907(A) (1953).
[2] S. Thulin, Arkiv Fysik **9**, 137 (1955).
[3] Personal communication from Professor A. C. Wahl, of Washington University, who has made a systematic study of the emanating properties of various compounds.