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The Angular Distribution of 12-Mev Gamma Rays from Proton Bombardment of B^{11}†

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To investigate possible interference between the three excited states in C^{12} arising from proton bombardment of B^{11} at proton energies of 163 kev, 680 kev, and 1388 kev, the angular distribution of 12-Mev gamma-rays from proton bombardment of thick natural boron targets has been investigated in the energy region between 200 kev and 1100 kev. The 12-Mev gamma rays were resolved with a scintillation spectrometer. The angular distribution with respect to the proton beam was found to be of the form $Y(\theta)=1+A\cos\theta+B\cos^2\theta$, with A vanishing at 200 kev, reaching a value of 0.13 between 300 kev and 350 kev, and remaining approximately constant above this energy up to 1100 kev. The value of B is 0.22 at 200 kev, decreases to 0.09 at 500 kev, and remains approximately constant above this energy up to 1100 kev.

I. INTRODUCTION

THE gamma-ray yield resulting from the B$^{11}(p,\gamma)$C^{12} reaction has been studied for proton energies up to 500 kev by Tangen,[1] up to 1000 kev by Cochran *et al.*,[2] and up to 3000 kev by Huus and Day.[3] Three resonances have been resolved in this energy region, at proton energies of 163, 680, and 1388 kev with level widths of 5, 322, and 1270 kev, respectively. The large widths of the two upper levels suggest the possibility of interference effects, and earlier work at this laboratory showed a cosθ term in the angular distribution of all gamma rays from the proton bombardment of thin boron targets at proton energy of 700 kev. The appearance of the cosθ term indicates interference between at least two states of opposite parity. In the present work, the angular distribution of 12-Mev gamma rays from proton bombardment of thick boron targets has been obtained over the energy range between 200 kev and 1100 kev, inclusive. This component of the gamma radiation from the excited states of C^{12} results from transitions to the well-known 4.45-Mev excited state of C^{12}, which is known to have spin 2 and even parity.[4] Since the spin and parity of the C^{12} level corresponding to proton energy of 163 kev is also known (spin 2-parity even),[5] it was felt that this investigation reveal,ing the energy regions where marked changes in the anisotropy occur might yield information concerning the interfering states.

II. EXPERIMENTAL PROCEDURE

Protons in the energy range from 200 to 1100 kev were obtained from the University of Kentucky electrostatic generator. Beam currents of 1 to 2 microamperes were obtained using a capillary type ion source. The energy calibration of the magnetic analyzer and the beam energy stabilization have been described elsewhere.[2] The magnetic analyzer limits the spread in beam energy to ±0.25 percent.

Owing to the low yield of gamma rays, particularly at the lower bombarding energies, it was necessary to compromise between adequate yield and good geometry, as determined by the beam-defining slit widths. Similar compromise had to be made on the angular resolution used. The detector consisted of a cylindrical thallium activated sodium-iodide crystal $1\frac{1}{2}$ inches in diameter and 1 inch long mounted in optical contact with the face of an RCA 5819 photomultiplier tube and covered with a reflector of aluminum foil. The beam covered a target area 8 mm high and 5 mm wide, and the front face of the detector was 6 cm from the target. The counter was mounted so that it could be rotated in the plane of the beam to angles up to 135 degrees either side of the beam direction. The isotropy of this arrangement was checked with a Cs^{137} gamma-ray source. Amplified pulses from the counter circuit were fed into

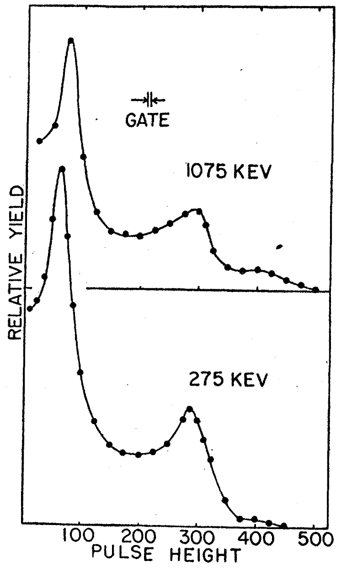

FIG. 1. Gamma-ray spectrum from the proton bombardment of thick natural boron targets at the proton energies shown. Pulse heights are in arbitrary units, with the three maxima corresponding to the 4.45-Mev, 12-Mev, and 16-Mev gamma rays. Statistical counting errors are smaller than the experimental points.

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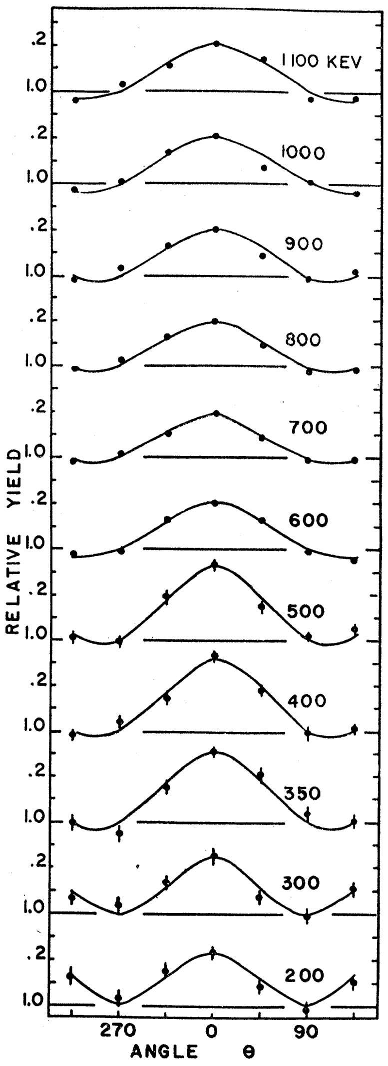

Fig. 2. Angular distribution with respect to the proton beam of 12-Mev gamma-rays arising from proton bombardment of thick natural boron targets. Proton energies are indicated on each angular distribution. Counting statistical errors are shown.

a single-channel differential discriminator. Long time variations in the yield due to circuital drift could amount to about two percent.

The current integrator consisted of a 150-microfarad condenser, a 1.2-megohm resistor, and a neon glow tube arranged as a relaxation oscillator, suitably housed against pickup and wax sealed against dirt and humidity. Frequent tests with a sensitive electronic microammeter gave assurances that the integrator circuit was at all times linear within the magnitudes of the beam currents.

Table I. Angular distribution of 12-Mev gamma rays arising from proton bombardment of thick natural boron targets. The angular distribution is of the form $Y(\theta)=1+A\cos\theta+B\cos^2\theta$, where θ is the angle with respect to the beam direction.

Proton energy (kev)	A	B
200	0.00	0.22
300	0.02	0.21
350	0.13	0.17
400	0.13	0.17
500	0.12	0.19
600	0.12	0.09
700	0.08	0.10
800	0.08	0.11
900	0.08	0.12
1000	0.12	0.09
1100	0.11	0.10

Thick targets were made by drying an alcohol slurry of amorphous boron on thin aluminum backing. The cylindrically symmetrical target chamber was constructed of Plexiglas. The beam-defining slits were 12 inches in front of the target and electrically biased rings were situated between slits and target to prevent error in beam current readings due to secondary electrons.

III. DISCUSSION OF RESULTS

The gamma-ray spectrum resulting from the reaction is shown for the two extremes of bombarding energy in Fig. 1. The three peaks represent the pair lines due to the cascade 12- and 4.45-Mev gamma rays, and the 16-Mev gamma rays. The 16-Mev component appears to be nonresonant at 680 kev,[3] and the increased relative yield of these gamma rays at 1075 kev is then due to the extremely wide resonance at 1388 kev. For the investigation of the angular distribution of only the 12-Mev gamma rays, the discriminator was set so as to accept pulses of size between 225 and 375 arbitrary units on the pulse-height scale. This setting excluded all of the 4-Mev gamma rays and included only a small number of the 16-Mev gamma rays.

The observed angular distribution of the 12-Mev gamma rays, as shown in Fig. 2, is of the form $Y(\theta)=1+A\cos\theta+B\cos^2\theta$. The values of the coefficients A and B obtained by least squares fit to the experimental data and corrected for variation of detector efficiency

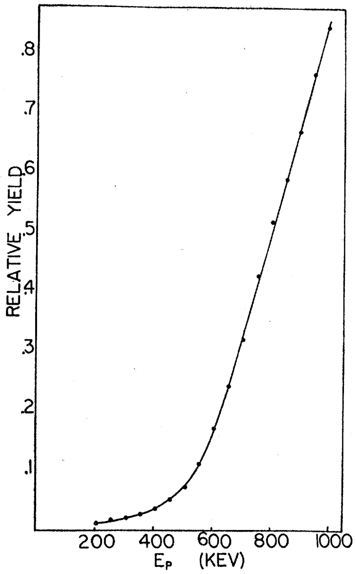

Fig. 3. Thick target yield of 12-Mev gamma rays arising from proton bombardment of natural boron targets. Counting statistical errors are smaller than the experimental points.

with Doppler energy shift and finite solid angle of the detector[6] are presented in Table I for the bombarding energies investigated. These corrections in each case amounted to no more than 6 percent of the coefficient. On the basis of repeated runs, the probable error of the coefficients is less than ± 0.02. In order to correlate the thick target angular distribution data with thin target data, the thick target yield of 12-Mev gamma rays in the beam direction has also been obtained and is shown in Fig. 3.

The angular distribution at proton energy of 200 kev is in agreement with results obtained by others.[5,7] The $\cos\theta$ term begins to appear at 300 kev and has become rather large at 350 kev. The 163-kev resonance has even parity.[5] The sudden appearance and behavior of the $\cos\theta$ term above this resonance means that at least one of the levels at 680 kev and 1388 kev has odd parity. The extremely large level widths of the 680-kev level and 1388-kev level would seem to imply that these levels are induced by *s*-wave protons and have odd parity. The small energy variation of the coefficients in the angular distribution may imply a three level interference between the 163-kev level and the two upper levels.

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The Elastic Scattering of Protons by Lithium*

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The cross section for the reaction $\mathrm{Li}^7(p,p)$ has been measured over the proton energy range 360–1400 kev. Measurements were made at scattering angles of 50, 70, 89.2, 110, 130, 143.4, and 160 degrees in the center-of-mass system. Anomalous scattering was observed near 441.5 kev, the resonance energy for the reaction $\mathrm{Li}^7(p,\gamma)$, and near 1030 kev, the resonance energy for the reaction $\mathrm{Li}^7(p,p')$. Analysis of the results at 441.5 kev indicates a state in Be^8 with $J=1$, even parity, formed by *p* wave protons. The relative stopping cross section for protons in lithium was also measured from 200–1300 kev.

INTRODUCTION

THE transmutation of Li^7 by protons has been of interest for many years. In 1932 Cockroft and Walton[1] first observed alpha particles from the reaction $\mathrm{Li}^7(p,\alpha)$. Gamma rays from the well-known 441-kev resonance in the reaction $\mathrm{Li}^7(p,\gamma)$ were observed in 1934 by Lauritsen and Crane;[2] and the resonance was confirmed by Hafstad and Tuve[3] in 1935. The corresponding anomaly in the reaction $\mathrm{Li}^7(p,p)$ was studied in 1939 by Creutz.[4] Accurate measurements of the resonance energies of the reactions $\mathrm{Li}^7(p,\gamma)$ and $\mathrm{Li}^7(p,p')$ have been made by Fowler and Lauritsen,[5] who give 441.4 ± 0.5 kev for the $\mathrm{Li}^7(p,\gamma)$ resonance and 1030.0 ± 5 kev for the $\mathrm{Li}^7(p,p')$ resonance. Hunt[6] has recently found 441.5 ± 0.5 kev for the resonance in $\mathrm{Li}^7(p,\gamma)$ using an absolute electrostatic analyzer. The angular distribution of the gamma radiation near this resonance has been determined by Devons and Hine[7] who concluded that the excited state in Be^8 has $J=1$, odd parity and is formed by *s* wave protons.

A study of the elastic scattering of protons from Li^7 can be expected to provide additional information which will aid in the determination of the nature of the highly excited states of Be^8. One expects to find anomalies in the scattering corresponding to the resonances in $\mathrm{Li}^7(p,\gamma)$ and $\mathrm{Li}^7(p,p')$ with perhaps a small effect resulting from the broad resonance in the reaction $\mathrm{Li}^7(p,\alpha)$ at 3 Mev. The cross section for the reaction $\mathrm{Li}^7(p,p)$ has been measured by Brown *et al.*,[8] at 89 and 144 degrees in the center-of-mass system (see below). An analysis of their results near 441 kev by Cohen[9] indicated that the state in Be^8 has $J=1$, even parity, and is formed by *p* wave protons. This result is seen to be in disagreement with the results of Devons and Hine.

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