Gamma-Rays from Beryllium Caused by Proton Bombardment

W. J. HUSHLEY*
Department of Physics, University of Wisconsin, Madison, Wisconsin

(Received October 23, 1944)

In bombarding thin beryllium targets with protons of energy 0.30 Mev to 3.0 Mev, gamma-ray resonances were observed at proton energies 0.975, 1.06, 1.13, 1.36, and 2.52 Mev and a neutron resonance at 2.52 Mev. For 1.04-Mev protons the value obtained for the gamma-ray energy was 7.5 Mev which indicates a radiative capture process. At the 2.52-Mev resonance the measured value of the energy of the gamma-rays was about 3.0 Mev. The most probable explanation of the observed resonance at 2.52 Mev appears to be that it is a resonance for the capture of a proton to form B^{10*} which later disintegrates into (B^9+n^1) and also into $(Li^{6*}+He^4)$ where Li^{6*} emits 3-Mev gamma-radiation in returning to the ground state.

INTRODUCTION

GAMMA-RAYS from beryllium caused by proton bombardment have been observed by several investigators. Crane, Delsasso, Fowler, and Lauritsen[1] observed gamma-rays from a thick beryllium target for proton energies 0.45 Mev to 0.80 Mev. They detected no resonances but found the energies of four gamma-ray lines to be 2.2, 3.7, 4.8, and 6.0 Mev. Hafstad and Tuve[2] found no resonances for proton energies 0.40 to 0.90 Mev. Herb, Kerst, and McKibben[3] extended the work to 1.6 Mev and obtained a broad resonance at approximately 1.0 Mev. Curran, Dee, and Petržilka[4] examined the excitation curve with proton energies of 0.20 Mev to 1.0 Mev for thin beryllium targets of various thicknesses. They reported resonance peaks at 0.35 Mev and at 0.67 Mev. Measurements of absorption of the gamma-radiation by the same investigators showed that for proton energies of 0.40 Mev to 0.80 Mev the gamma-radiation was caused chiefly by the radiative capture process.

In the present investigation the excitation curve was studied for a thick beryllium target for proton energies 0.90 Mev to 1.5 Mev and for thin beryllium targets in the range 0.30 Mev to 3.0 Mev. Measurements of gamma-ray energies were made at each of two resonances.

* Now at the National Research Council of Canada, Ottawa, Canada.

[1] H. R. Crane, L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **47**, 782 (1935).

[2] L. R. Hafstad and M. A. Tuve, Phys. Rev. **48**, 306 (1935).

[3] R. G. Herb, D. W. Kerst, and J. L. McKibben, Phys. Rev. **51**, 691 (1937).

[4] S. C. Curran, P. I. Dee, and V. Petržilka, Proc. Roy. Soc. **A169**, 269 (1938).

EXPERIMENTAL

Thin beryllium targets were made by evaporating beryllium metal within an evacuated brass chamber. The beryllium was heated by placing it in a molybdenum or tantalum boat which was brought to white heat for a fraction of a minute by passing a current of forty to fifty amperes through the boat. Some difficulty in evaporating beryllium is encountered in this method if a V-shaped ribbon is used for a boat since the beryllium forms a low melting point alloy with molybdenum and tantalum so that the ribbon melts before the beryllium evaporates. The boats used were made by taking a ribbon of molybdenum or tantalum metal about 8 mm wide and 5 cm long and rolling it into a cylinder about 3 mm in diameter and 5 cm long. The ends were then pinched so that the cylinder forms a boat which encloses the beryllium completely except for a slot about a millimeter wide along the top. Although the beryllium alloyed with the tantalum or molybdenum, two or three evaporations could be carried out with the same boat before the reaction penetrated the boat so as to make holes in it. The beryllium was evaporated onto a sheet of molybdenum or tantalum target-backing from a boat of the same material.

The protons were accelerated by the Wisconsin concentric-electrode electrostatic generator[5] and the intensity of the gamma-rays was measured by

[5] R. G. Herb, C. M. Turner, C. M. Hudson, and R. E. Warren, Phys. Rev. **58**, 579 (1940).

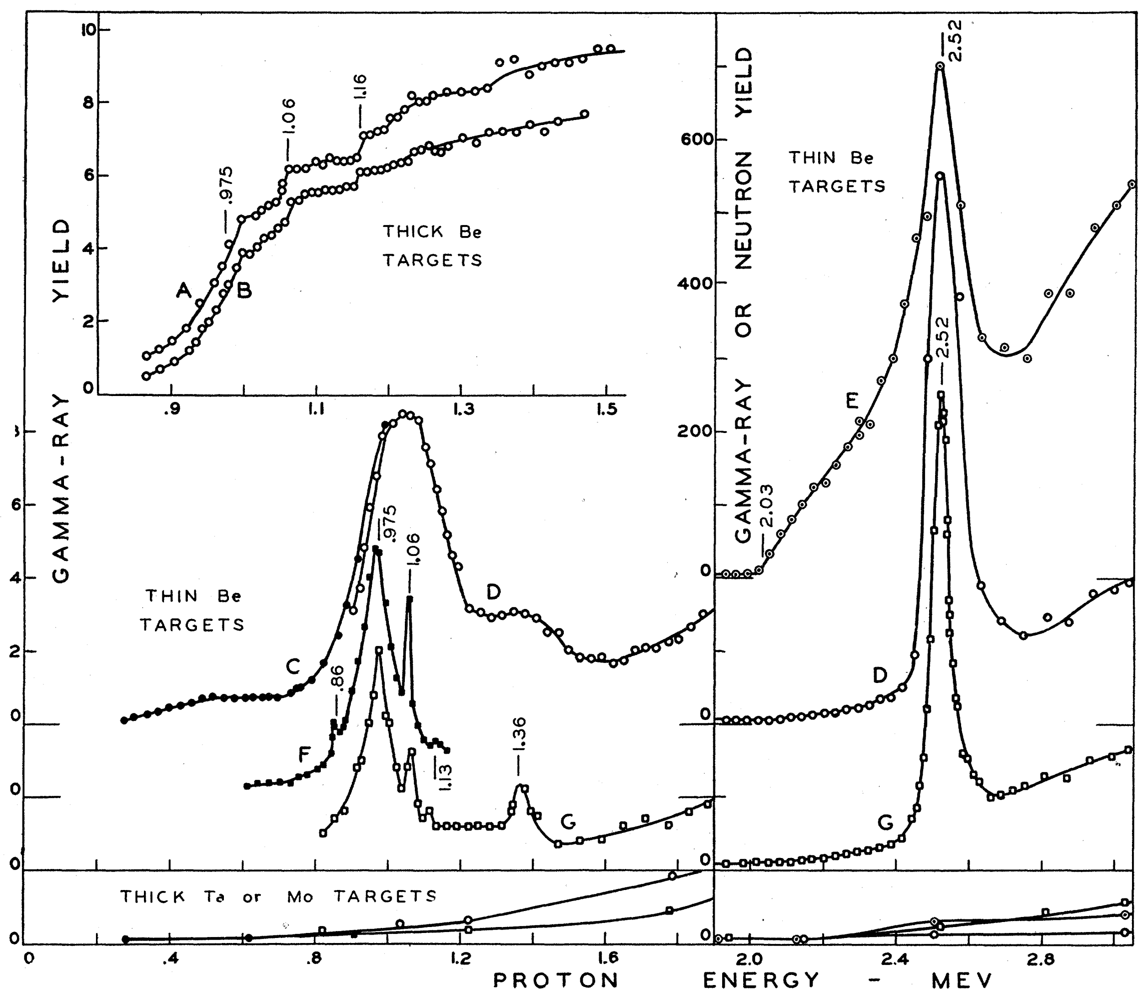

FIG. 1. Gamma-ray and neutron intensities from beryllium as a function of the energy of the bombarding protons. Curve E represents the neutron yield; the remaining curves represent gamma-ray yields. Above the proton energy 1.9 Mev the gamma-ray intensity scale is reduced by a factor of fifty. The background, taken on tantalum and molybdenum targets, is shown at the bottom of the figure by points corresponding to the upper curves.

G-M counters with a target chamber and counter arrangement similar to that used by Plain, Herb, Hudson, and Warren.[6]

PROTON ENERGY SCALE

The proton energy scale for the thin target curves was calibrated against the 2.03-Mev. Be(p, n) threshold by running a neutron yield curve simultaneously with the gamma-ray yield. This value of the threshold had been reported by Haxby, Shoupp, Stephens, and Wells[7] and had also been measured in this laboratory[8] by comparing it to the 0.440-Mev Li(p, γ) resonance. For the thick target curves the generator voltage was calibrated against the 0.862-Mev F(p, γ) resonance which had previously been compared with the 0.440-Mev Li(p, γ) resonance.

An absolute measurement of the Li(p, n) threshold has been made recently by Hanson and Benedict[8] which, if correct, would revise the proton energy scale. Based on this new determination the Be(p, n) threshold would be at 2.06 Mev instead of the accepted 2.03 Mev. In this

[6] G. P. Plain, R. G. Herb, C. M. Hudson, and R. E. Warren, Phys. Rev. **57**, 187 (1940).

[7] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. **58**, 1035 (1940).

[8] A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1944).

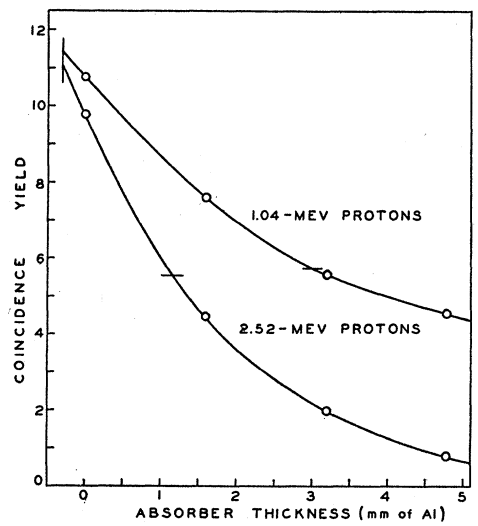

FIG. 2. Absorption curves for secondary electrons caused by gamma-rays from beryllium for 1.04-Mev and 2.52-Mev bombarding protons. The curves are extrapolated back, 0.30 mm, to correct for the absorption by the glass walls of the counters. The short horizontal lines indicate the thickness of aluminum which reduced the yield to one-half.

revised scale all values of proton energies would be raised by 1.5 percent above the previously accepted values which have been used in this report.

EXCITATION CURVES

The gamma-ray yield as a function of the energy of the bombarding protons is shown in Fig. 1 with the yield in arbitrary units. The thick target curves *A* and *B* show resonances at approximately 0.975, 1.06, and 1.16 Mev. Curves *C* and *D* show the gamma-ray yield from a thin beryllium target on molybdenum backing, the molecular beam being used for *C* and the atomic beam for *D*. Curve *E* shows the neutron yield obtained simultaneously with the gamma-ray yield *D*. Curves *F* and *G* show the gamma-ray yield from a thin beryllium target on tantalum backing, the molecular beam being used for *F*, the atomic for *G*. The background yield was taken on a molybdenum target for curves *C*, *D*, and *E* and on a tantalum target for *F* and *G*, and is shown by the corresponding points at the bottom of Fig. 1. Above the proton energy 1.9 Mev, the gamma-ray intensity scale is reduced by a factor of fifty. The thin target yields show resonance peaks at proton energies 0.975, 1.06, 1.36, 2.52, and possibly at 0.86 and 1.13 Mev.

The possibility that the hydrogen-filled G-M counters may have been counting neutrons was tested by placing four cm of paraffin between the target and the counter. The count was reduced by less than one percent showing that neutrons do not make any substantial contribution to the measured gamma-ray yield.

ENERGY OF GAMMA-RAYS

The energy of the gamma-rays was measured by obtaining the coincidence yield of two G-M counters as a function of the thickness of aluminum absorbers placed between the counters. Figure 2 shows the results of the absorption measurements of the secondary electrons caused by the gamma-rays. The abscissa scale gives the thickness of aluminum absorber. To correct for the absorption by the glass walls of the counters the curves are extrapolated back, 0.30 mm, to the short vertical line. This correction figure had been determined by Plain, Herb, Hudson, and Warren.[6] The thickness of aluminum absorber which reduces the coincidence yield to half its vlaue for no absorber is used as a measure of the gamma-ray energy and is shown by short horizontal lines in Fig. 2. The values are 3.3 mm Al for 1.04-Mev protons and 1.5 mm Al for 2.52-Mev protons.

The counters had been calibrated previously[6] by using the 6.2-Mev gamma-rays from fluorine and the 17.5-Mev gamma-rays from lithium giving half-value thicknesses of 2.8 and 7.3 mm Al, respectively. Figure 3 shows the resulting calibration curve. If we assume that the radiation is monochromatic, the energy of the gamma-rays

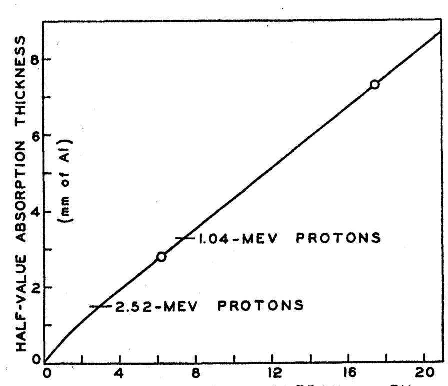

FIG. 3. Calibration curve showing half-value absorption thickness as a function of gamma-ray energy.

from beryllium is found to be 7.5 Mev for 1.04-Mev protons and about 3.0 Mev for 2.52-Mev protons.

Placing 3-mm lead between the target and the counter did not reduce the intensity of the 7.5-Mev radiation appreciably, showing it has no large soft component.

DISCUSSION

Several resonance maxima appear in the excitation curve of Fig. 1 although the group at 1 Mev may not be completely resolved. The maxima at 0.35 Mev and 0.67 Mev reported by Curran, Dee, and Petržilka[4] were not observed.

A summary of the results of the absorption measurements is given in Table I where the values in brackets are obtained if the new proton energy scale is used. The reaction energy given in the table assumes a radiative capture process, i.e.,

$$Be^9+H^1\rightarrow B^{10}+h\nu. \quad (1)$$

This reaction has 6.56 Mev of available energy plus the resonance energy of the protons. For 1.04-Mev protons the total energy available is 6.56 plus 9/10 of 1.04 or 7.50 Mev. This agreement between the gamma-ray energy and the total energy available shows that the reaction is resonance capture with a single transition to the ground state.

The reaction at the 2.52-Mev resonance is more difficult to interpret. In a radiative capture reaction the available energy would be 6.56 plus 9/10 of 2.52 or 8.83 Mev, whereas the energy of the radiation is about 3.0 Mev. The intensity of the radiation was roughly fifty times greater than the intensity at the 0.975-Mev resonance for the thin target G and about one hundred times greater for the thin target D. For the latter target the neutron yield, which also shows a resonance at 2.52 Mev, was estimated roughly to be of the same magnitude as the gamma-ray yield. This suggests that the neutrons and the gamma-rays are produced in the same reaction.

Some other possible reactions are given below. In calculating the reaction energies the following atomic mass values given by Haxby, Shoupp, Stephens, and Wells[7] are used; $Be^9=9.01484$ m.u., $B^9=9.01600$ m.u., $(n^1-H^1)=0.000806$ m.u. Other mass values are taken from Barkas.[9]

A neutron producing reaction is

$$Be^9+H^1\rightarrow B^9+n^1+Q_2, \quad (2)$$

where the reaction energy Q_2 is -1.83 Mev. However, B^9 is unstable and may return to Be^9 by emitting a positron or capturing a K electron or it may disintegrate into Be^8 plus H^1. In the first case

$$B^9\rightarrow Be^9+e^++E_+,$$

where the maximum positron energy E_+ is 0.06 Mev. For K-electron capture, reaction (2) above is followed by

$$B^9+e^-\rightarrow Be^9+Q_2',$$

with an energy evolution Q_2' of $+1.08$ Mev. In the third case

$$B^9\rightarrow Be^8+H^1+Q_2'',$$

where Q_2'' is $+0.10$ Mev. If in place of the latter

TABLE I. Gamma-ray energies.

Proton energy (Mev)	Half-value (mm of Al)	Gamma-ray energy (Mev)	Reaction energy available (Mev)
1.04 (1.05_5)	3.3	7.5	7.50 (7.51)
2.52 (2.56)	1.7	3.0	8.83 (8.86)

the non-capture disintegration

$$Be^9+H^1\rightarrow Be^8+n^1+H^1+Q_2''$$

takes place, then Q_2'' is -1.73 Mev.

Theoretical considerations[10] show that a particle producing process is much more probable than a radiative capture process and since this resonance is above the Be(p, n) threshold it would be expected that the (p, n) reaction would be the most probable. The observed gamma-radiation would have to come from an excited residual nucleus in the Be(p, n) reaction but consideration of the energy evolution in the above three cases of reaction (2) shows that 3.0-Mev gamma-rays are energetically impossible for 2.52-Mev incident protons. It seems certain, then, that the 3.0-Mev gamma-rays and the neutrons are not produced in the same reaction.

[9] W. H. Barkas, Phys. Rev. 55, 691 (1939).

[10] H. A. Bethe, Rev. Mod. Phys. 9, 69 (1937).

Two other processes have been observed by numerous investigators for low energy protons. They are

$$Be^9+H^1\rightarrow Be^8+H^2+Q_3 \quad (3)$$

and

$$Be^9+H^1\rightarrow Li^6+He^4+Q_4, \quad (4)$$

where $Q_3=+0.44$ Mev and $Q_4=+2.03$ Mev if Be^8 and Li^6 are left in the ground state.

Among other factors the probability of a reaction depends on the energy evolution and on the height of the potential barrier to the particle emitted. The probability is greatest for a high energy evolution and for a low potential barrier. The potential barrier is zero for neutrons and higher for alpha-particles than it is for deuterons. It would be expected that reactions (2), (3), and (4) given above are almost equally probable since in each case the energy evolution compensates for the height of the potential barrier. Skaggs[11] has observed that for 0.262-Mev protons the α-particles and the deuterons are emitted in almost equal numbers. It is necessary, then, to examine whether 3.0-Mev gamma-radiation is energetically possible from an excited state of one of the product nuclei of reaction (3) or (4).

In the reaction

$$Li^7+H^1\rightarrow Be^8+Q,$$

Delsasso, Fowler, and Lauritsen[12] observed 17-Mev and 14-Mev gamma-radiation but no radiation between 2 and 10 Mev. This was considered experimental evidence that Be^8 has an excitation level at about 3.0 Mev but the transition from this state to the ground state by gamma-radiation is forbidden. Rather, the Be^8, in the 3-Mev excited state, disintegrates into two alpha-particles with the excitation energy going into the kinetic energy of the alpha-particles. This interpretation has been confirmed experimentally and theoretically more recently by Wheeler[13] and several others who place the excitation level at 2.8 Mev. Furthermore, if the value of the gamma-ray energy measured here is correct the radiation cannot occur in reaction (3) because of energy considerations.

Assuming that the α-particle has no stable excited state, it appears probable that the observed 3.0-Mev gamma-radiation is caused by an excited state of Li^6 in the Be(p, α) reaction. This reaction has 2.03 Mev of available energy plus the energy of the incident protons so that it is energetically possible to have the Li^6 excited up to about 4 Mev. This could be confirmed by determining the energy of the α-particles emitted in the reaction. One would expect α-particles of about 6.2-mm range from the reaction in which Li^{6*} is formed as well as 17.3-mm alphas corresponding to the formation of unexcited Li^6. These values are calculated from the energy-momentum relations given by Livingston and Bethe.[14]

An alternative explanation of the gamma-rays is to assume that radiative capture with cascade emission is as probable as a neutron producing reaction. That is, B^{10}, excited to 8.83 Mev, would return to the ground state in, say, three steps. The known excitation levels of B^{10} are at 0.55, 2.15, 3.45, and 7.50 Mev so that the 3.0-Mev measured value of the radiation would represent the average effect of several different γ-ray lines.

The phenomenon at the 2.52-Mev resonance may then be interpreted as a resonance for the capture of a proton forming B^{10*} which later disintegrates in one of several ways, such as

$$\begin{aligned} B^{10*} &\rightarrow B^{10}+h\nu_1+h\nu_2+h\nu_3 \\ &\rightarrow Li^{6*}+He^4\rightarrow Li^6+He^4+h\nu \\ &\rightarrow B^9+n^1. \end{aligned}$$

It is expected that the last two are the most probable of the three mentioned.

It would have been desirable to repeat the excitation curve using thinner targets and to make more extensive absorption measurements, but the work was cut short before this could be done.

The author is greatly indebted to Dr. A. O. Hanson for advice and help in the experimental work and to the Wisconsin Alumni Research Foundation for financial assistance.

[11] L. S. Skaggs, Phys. Rev. **56**, 24 (1939).

[12] L. A. Delssaso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **51**, 391 (1937).

[13] J. A. Wheeler, Phys. Rev. **59**, 16 (1941) and **59**, 27 (1941).

[14] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).