period (Table II). Pool[1] reports that for the n-$2n$ reaction the 8-day period cross section is greater than the 25-min. period cross section.

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Disintegration of Beryllium by Electrons

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The beryllium nucleus has been disintegrated by fast electrons whose energies exceeded the photoelectric threshold. The source of the electrons was a 1.8-Mv Van de Graaff generator. As was predicted by Guth, neutrons were produced, and the radioactivity which these neutrons induced in silver was used as a measure of the rate of disintegration. The possibility that the observed disintegration was not due to the direct action of the electrons, but resulted from stray x-rays, or x-rays produced in the beryllium by the electrons was eliminated. The yield curve for disintegration by electrons was obtained, and fixed the threshold for this process at 1.63 ± 0.05 Mev. At 1.73 Mev the cross section was found to be 10^{-31} cm^2, in good agreement with theory.

The yield curve for photodisintegration by continuous x-radiation was also obtained, and the threshold was found to be identical with that for disintegration by electrons.

SEVERAL attempts have been made in the past to disintegrate atomic nuclei with electrons.[1] Cathode rays and positrons with energies up to 800 kev have been used to irradiate a wide variety of elements, but no evidence of nuclear disintegration has been reported. Recently, however, one of us[2] has presented a theoretical treatment of this problem and has indicated clearly the conditions under which disintegration by electrons may be expected to take place. His theory points out a similarity between this process and that of photodisintegration and states that before disintegration by electrons may occur the energy of the electrons must exceed the photoelectric threshold of the nucleus.

It was to be expected then, that disintegration by electrons would be most likely to succeed with the element beryllium, since it has the lowest known photoelectric threshold. The threshold has been estimated[3] to be about 1.6 Mev which fortunately is somewhat lower than the maximum potential of our Van de Graaff generator. The reaction predicted is the following

$$Be^9+e_v\rightarrow Be^8+n+e_{v'},$$

where v and v' indicate energies of electrons before and after disintegration. If Be^8 is unstable, on which point there is some disagreement,[4] it would soon disintegrate into two low energy helium nuclei. The cross section of this process for electrons having energies a few 100 kilovolts above the threshold is estimated[2] to be about 10^{-31} cm^2. It was decided to allow the neutrons produced by the above process to induce radioactivity in another element and to use this induced radioactivity as a measure of the rate of disintegration by electrons. Considera-

[1] J. J. Livingood and A. H. Snell, Phys. Rev. **48**, 851 (1935); W. B. Lewis and W. E. Burcham, Camb. Phil. Soc. Proc. **32**, 503 (1936); G. P. Thomson and J. A. Saxton, Phil. Mag. **23**, 241 (1937).

[2] E. Guth, Phys. Rev. **55**, 412 (1939).

[3] J. Chadwick and M. Goldhaber, Proc. Roy. Soc. **151**, 479 (1935).

[4] Allison, Skaggs, Smith, Phys. Rev. **56**, 288 (1939).

tions involving the expected cross section for the process, the strength of the available electron beam, which was equivalent to the β-rays from about 20 kilograms of radium, and the sensitivity of the detecting method indicated that measurable activities would result.[5]

Apparatus

High voltage generator

Inasmuch as a detailed description of the generator has not been published, a brief account will be given here. The generator is of the Van de Graaff type, mounted on a tripod similar to that of Tuve, Hafstad and Dahl[6] and housed in a 40-foot cubical room. The high voltage electrode consists of two hemispherical shells 12 feet in diameter joined by a 2-foot cylindrical section. (See Fig. 1.) The shells were made by tacking thin copper sheeting to a wood framework. The supporting tripod is constructed from Textolite tubing 12 inches in diameter, $\frac{3}{8}$ inch thick and 24 feet long.

Charge is carried to the copper shell by two belts, each 30 inches wide and 70 feet endless length. Various types of materials were used; including paper, balloon silk and conveyor belting. The black rubber 3-ply conveyor belting, 8 ounces per square foot, has been very satisfactory. The spray voltage is supplied by a transformer Kenotron rectifier set and may be varied from 10 kv to 30 kv. The charging current is strongly dependent upon the humidity and during normal winter conditions (relative humidity about 30 percent) is about 200 μa per belt with a belt speed of 70 feet per second.

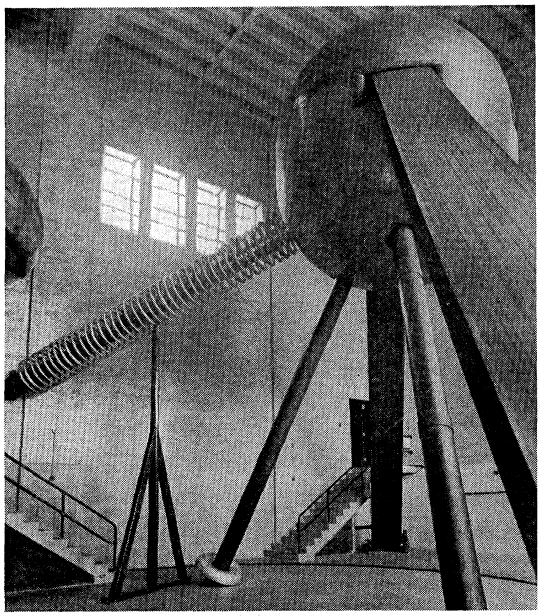

FIG. 1. View of 1.8-Mv generator and accelerating tube.

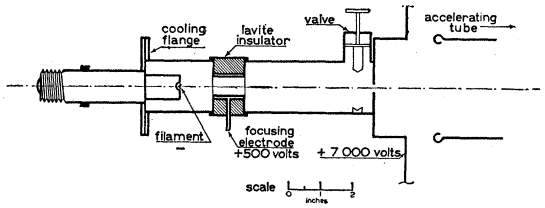

FIG. 2. The electron source.

The accelerating tube consists of six, 4-foot sections of 9-inch Pyrex glass tubing supported by a 4″×6″-redwood beam, which was kiln dried and coated with Victron varnish. Twenty cylindrical brass electrodes are used to accelerate the electron beam. These electrodes are connected to alternate aluminum hoops which surround the supporting beam and accelerating tube. Each hoop (there are some 40 in all) carries 3 pins pointing to the adjacent lower ring so that negative point-to-positive plane corona results. The first two accelerating electrode potentials are varied by adjusting the corresponding pins which provides an excellent control of the focusing of the electron beam.

The electron gun is illustrated in Fig. 2. The filament assembly is from an old x-ray tube. A rheostat operated by strings from the observation room controls the filament current and hence the electron current down the accelerating tube. The voltages for focusing and accelerating the electrons in the gun are produced by a small transformer Kenotron set operating on 110 volts a.c. generated by a rotary converter run from storage batteries. Currents up to 150 μa can be obtained and focused to a $\frac{1}{4}$-inch spot on the target.

The lower end of the accelerating tube passes through the wall of the generator room into the adjacent observation room. A large solenoid, 18 inches long fits over the last section of the ac-

[5] Collins, Waldman and Polye, Phys. Rev. **55**, 412 (1939).
[6] Tuve, Hafstad and Dahl, Phys. Rev. **48**, 315 (1935).

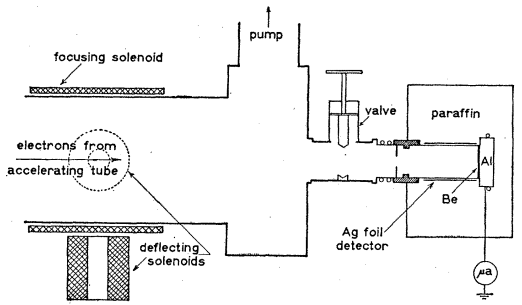

FIG. 3. Target arrangement.

celerating tube. This solenoid concentrates the focal spot from 1 inch to $\frac{1}{4}$ inch in diameter. Two small solenoids, with their axes perpendicular to each other and the accelerating tube, are used to control the position of the beam on the target.

The pumping system consists of a 4-inch oil diffusion pump, backed by a 2-inch oil diffusion pump and a Hypervac. The normal operating pressure is approximately 10^{-5} mm of mercury.

Voltage measurement

A generating voltmeter, fastened to the ceiling directly above the copper shell, is used to measure the voltage. The voltmeter operates on a balancing principle with a null detector, the details of which will be published soon. The voltmeter was calibrated over its entire range by direct measurement of the deflection of an electron beam in a magnetic field. The absolute value of the voltage is known to within 50 kv. A grounded set of corona points, whose distance from the copper shell is adjustable, controls the potential of the generator.

It was found necessary to swing the earth's magnetic field parallel to the axis of the accelerating tube in order to avoid a deflection of the electron beam. This was accomplished, following a suggestion of Dr. Breit, by constructing two pairs of Helmholtz coils 30 feet in diameter and placing one set on the walls and the other set on the roof and floor of the generator room. About 1000 ampere turns for each coil were necessary.

The maximum voltage obtainable is 1.75 Mv to 1.8 Mv depending upon the number of sparks per minute permissible. These discharges occurred along the belts and down the legs of the generator. Sparks along the belts can be prevented by reducing the spray voltage on the charging circuit, though this also reduces the available electron current if the voltage is to remain constant.

The magnetic deflection chamber used to calibrate the voltage afforded a means of determining the homogeneity of the beam. The maximum spread in energy of the beam was estimated to be 10 kev and was due almost entirely to fluctuations of the generator voltage.

Target arrangement

Figure 3 shows the target arrangement. The focused electron beam impinged on the beryllium plate (placed at the end of the Faraday cage) which was soldered to an aluminum block for cooling. The neutrons emitted in the reaction were diffused by the paraffin and induced activity in the detector (usually silver). The activity of the silver was measured with a thin-walled glass Geiger-Müller tube coupled to a scale-of-16 vacuum tube recorder[7] by the Neher-Harper circuit. The background count was about 16 per minute inside 2 inches of lead.

The bombarding current ranged from 5 to 15 μa and the time of irradiation for a silver detector was one minute. Fifteen seconds elapsed between the cessation of bombardment and the recording of the activity of the detector. The activity is expressed in net counts per 10 μa during the first minute of recording.

RESULTS

In every case when the beryllium target was bombarded with electrons whose energy exceeded 1.63 Mev, activity was induced in the detectors, either silver, rhodium, or indium, which decayed with the appropriate period. A typical run with rhodium as a detector gave 126 net counts in the first minute, and a similar run, with silver gave 208 counts. In both cases 8 microamperes of 1.75-Mev electrons bombarded the beryllium for 50 seconds.

Numerous runs were made under widely different conditions as regards voltages, activation times, and beam currents, and consistent data were obtained. A run with the beryllium removed gave negative results. There is thus no doubt

[7] H. Lifschutz and J. L. Lawson, Rev. Sci. Inst. **9**, 83 (1938).

that the disintegration of beryllium had occurred with the emission of neutrons.

The possibility existed, however, that the observed activity was not due to the direct action of the electrons on the beryllium, but resulted from photoneutrons produced by the action of x-rays induced in the beryllium by the fast electrons. Considerable care was taken to eliminate this possibility and the following paragraphs are concerned with this question.

Two methods of attack were used to determine which process was responsible for the activity. The first consisted of interposing thin targets of lead, aluminum and carbon before the beryllium, and comparing the resulting activities induced in the silver detector. These targets were thick enough to reduce the energy of the electrons to a value less than the threshold of beryllium. Their purpose was to eliminate the direct effect of the electrons and produce x-rays of varying intensity by a change in the atomic number of the target. Table I gives the results of this experiment and shows the activity induced in a silver detector for two electron energies. The thickness of the beryllium was 0.20 cm.

The high activity obtained with the lead target was interpreted as being due to the photoneutrons produced by the relatively strong x-rays set up in the lead. The activity obtained with targets of aluminum and carbon is seen to be less, as would be expected because less intense x-rays were produced in these targets of lower atomic number. If the activity observed upon exposing the beryllium was due entirely to photoneutrons from beryllium, the activity obtained should have been still less, because the atomic number of beryllium is less than that of carbon. The observed increase (column 5) must then be attributed to the disintegration of beryllium by electrons. Changes in geometry could not have accounted for the increase in activity obtained because the size of the beryllium sheet was large compared with the size of the focal spot of the electrons.

Additional evidence that the electrons were directly responsible for the disintegration of the beryllium was obtained in the following manner. Since many centimeters of beryllium would be needed to absorb appreciably these hard x-rays, the photodisintegration process should be proportional to the thickness of the beryllium target. On the other hand, since the effective range for disintegration of 1.75-Mev electrons in beryllium is only about 0.035 cm, the disintegration by electrons should not increase for thicknesses above this value. This difference in the behavior of x-rays and electrons then provided a means of distinguishing between the two effects. Additional trials were then made on a thin beryllium target with a thickness (0.038 cm) about equal to the effective range of the electrons. Table II is a comparison of the results of these trials with those obtained using the thick target (0.20 cm). It will be noted that nearly identical activities were obtained from the thick and thin targets showing clearly that the activity was essentially all due to the direct action of the electrons.

The experimental cross section for the process has been obtained by means of a calibration experiment to determine the sensitivity of the detecting method. 71 millicuries of radon in glass were placed in the center of 30 grams of beryllium and this was surrounded by the silver foil and paraffin blocks used to obtain the data given in Table II. Assuming that 2.8×10^{7} effective gamma-rays are emitted from one millicurie of radon per second, and that the cross section for photodisintegration by these gamma-rays is 3×10^{-28} cm^2 it was calculated that the sensitivity of the detecting apparatus is such that 300 neutrons per second produce 1 count per minute from the silver foil. At 1.73 Mev and 10 μa 79 counts per minute were obtained from the thin target. These data combined with the sensitivity

TABLE I. *Activities induced in a silver detector with various targets placed in front of 0.20 cm of beryllium. The last column gives the induced activity with the beryllium exposed.*

Electron Energy	Type of Target			
	Pb	Al	C	
1.73 Mev	2880	72	12	80
1.69	300	—	14	24

TABLE II. *Comparison of activities induced in silver by electron bombardment of thick and thin targets of beryllium.*

Electron Energy Mev	Induced Activity	
	0.20 cm Be	0.038 cm Be
1.75	228	260
1.73	80	79
1.69	24	28

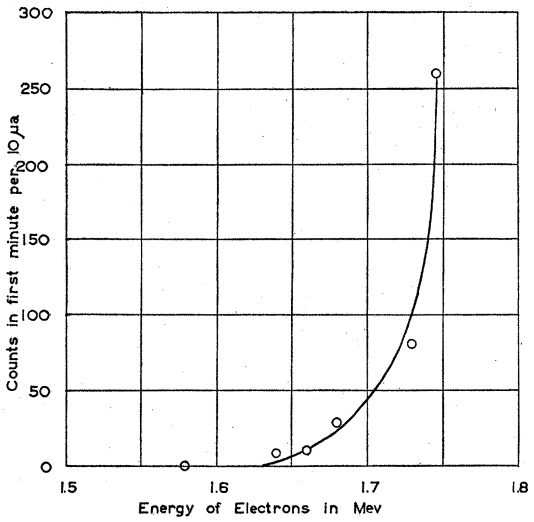

FIG. 4. Yield curve for disintegration of Be by electrons.

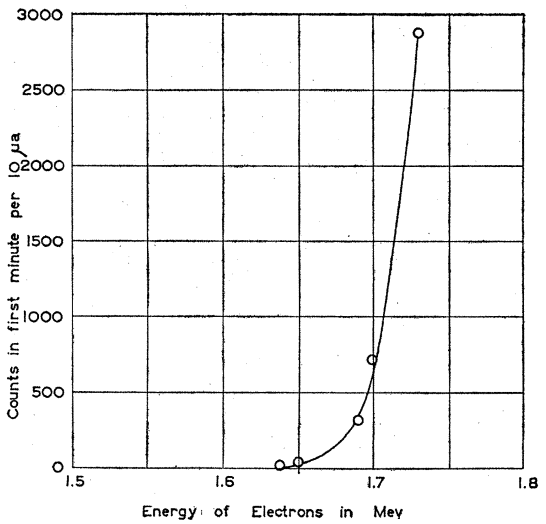

FIG. 5. Yield curve for photodisintegration of Be.

stated above and an effective beryllium thickness of 0.030 cm yield a cross section of 1×10^{-31} cm^2. It is probably significant only as far as order of magnitude is concerned, but is in excellent agreement with the theoretical value predicted by Guth. As may be seen from Fig. 4 this cross section is very sensitive to the electron energy.

Figure 4 is the yield curve for electron disintegration obtained by bombarding the 0.038-cm beryllium target with electrons of various energies. From this curve the threshold for the process is fixed at 1.63 ± 0.05 Mev. Uncertainties in the voltage measurement prevent one from attaching too much significance to its exact shape. Its steep rise however may be explained by the cross section and effective range of the electrons, both of which increase with increasing electron energy.

The disintegration of beryllium by continuous x-radiation has been reported by Brasch and co-workers.[8] They used however a surge generator to accelerate the electrons which made it impossible to obtain an excitation curve or an exact threshold for the process. We repeated the experiment under more favorable conditions by bombarding a lead target placed before a 0.20-cm beryllium plate with "monochromatic" electrons of various energies. The detecting arrangement was the same as that used for the electron-disintegration experiments. Fig. 5 is the yield curve obtained in which the silver activities are plotted against the energy of the electrons which corresponds to the maximum energy of the x-rays. From this curve the threshold for photodisintegration is fixed at 1.63 ± 0.05 Mev which is the same as the threshold for electron-disintegration. It also agrees very well with the value 1.62 ± 0.02 obtained by Skaggs[9] from mass and energy relationships based on experiments involving the proton bombardment of beryllium. It is noteworthy that for the same electron energy and current one obtains ten times the activity from photodisintegration as is obtained from electron-disintegration. This is due principally to the greater amount of beryllium available for the photodisintegration process, since for a given electron current the cross section for electron-disintegration times the number of electrons is about equal to the cross section for photodisintegration times the number of effective x-ray quanta produced.

The authors wish to acknowledge the important assistance given by Mr. Richard S. Schager and Mr. Alex A. Petrauskas whose work was essential to the successful operation of the generator.

[8] Brasch, Lange Waly, Banks, Chalmers, Szilard and Hopwood, Nature **134**, 880 (1934).

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

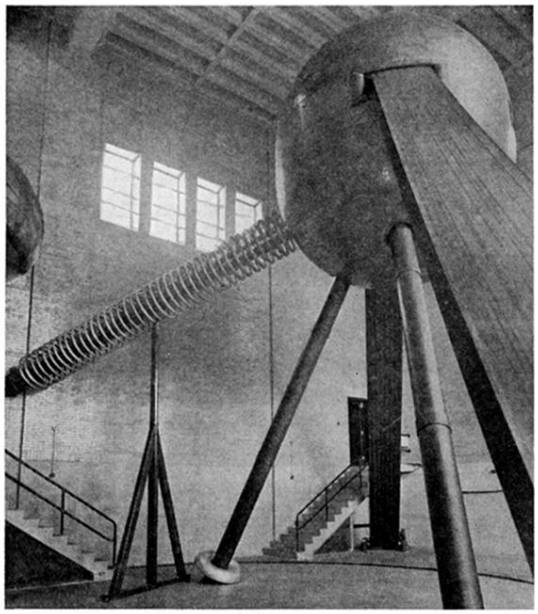

FIG. 1. View of 1.8-Mv generator and accelerating tube.