TABLE III. *β-ray counts from natural potassium.*

Collector Deposit	Counting Ratio	Probable Error
67.2 mg KCl on Ni foil	3.22	0.12
Clean Ni foil	1.03	0.05

$R-R_0=N_3/(N+N_1)$, is thus proportional to the number of beta-particles emitted by the deposit.

The data of Tables I and II are presented graphically in Fig. 4.

There are 32.9 mg of K^{39} in 67.2 mg of KCl. The activity of this sample, after correcting for absorption of both bands of the beta-particles in KCl on the assumption that the mass absorption coefficients are the same as for aluminum,[18] is 2.58. The correction for absorption in tungsten in Tables I and II is quite negligible. Measurements by Bocciarelli[19] show that 60 percent of the emitted beta-rays lie in the low energy band and the remainder in the high energy band. Taking the weighted mean of the measured activity of K^{40} from Tables I and II, reducing to a standard sample of 20 mg, and comparing with the activity to be expected from the measurements of Table III, also reduced to 20 mg, we have, for the three possible assumptions as to which bands belong to K^{40}, the results shown in Table IV. This clearly indicates that K^{40} is responsible for the entire known activity of potassium.

TABLE IV. *Comparison of the measured activity of K^{40} with that to be expected upon various hypotheses.*

Hypothesis	Measured Activity		Expected Activity
	$c=0.75$	$c=0.5$	
K^{40} emits high energy band	1.08	1.62	0.63
K^{40} emits low energy band	1.08	1.62	0.94
K^{40} emits both bands	1.08	1.62	1.57

Acknowledgments

We wish to acknowledge our debt to those who have worked on this problem in its earlier stages, particularly Dr. West, and to Mr. Harper, who lent us his amplifier and assisted in some of the counter work. We are grateful also for the assistance in the laboratory of Mr. R. H. Mansfield.

[18] N. R. Campbell and A. Wood, Proc. Camb. Phil. Soc. **14**, 15 (1907).

[19] D. Bocciarelli, R. C. Accad. Lincei (6) **17**, 830 (1933).

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The Disintegration of Beryllium by Protons*

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The disintegration of Be by protons of energies from 45 to 125 kv has been studied. The yield curve for a thick target has been determined and the ratio of the number of alpha-particles and deuterons ejected from the target has been determined for various voltages. The ratio was very close to unity. The ranges of both groups of particles were found to be 7.1 mm. From the energy relations the mass of Be^8 was found to be 8.0074. The experimental value of the effective area for collision was found to be of the same magnitude as that predicted by Gamow's theory of the penetration of a potential barrier by protons having zero angular momentum.

Although much work has been done on the disintegration of Be by protons, it seemed worth while to investigate the two possible reactions in order to determine their relative probability of occurrence. According to Oliphant, Rutherford and Kempton,[1] the two reactions are:

$$_4Be^9+{}_1H^1={}_3Li^6+{}_2He^4, \quad (1)$$

$$_4Be^9+{}_1H^1={}_4Be^8+{}_1H^2. \quad (2)$$

They found that the H^2 and the He^4 particles

* A dissertation submitted to the faculty of the division of the physical sciences in candidacy for the degree of Doctor of Philosophy. Private edition, distributed by the University of Chicago Libraries, Chicago, Illinois.

[1] Oliphant, Rutherford and Kempton, Proc. Roy. Soc. **A150**, 241 (1935).

were present at all bombarding energies and were in the ratio of 4 to 3 singly charged to doubly charged particles. The observed range of both groups was 7.4 mm of air. Neuert[2] investigated the same reactions by means of a Wilson cloud chamber and found a group of particles with a range of 7.5 mm of air. He concluded that they were alpha-particles and that the second reaction was improbable.

Another object of this research was to determine the form of the yield curve for thick and thin targets and to find the effective area for collision from these data. The excitation curve was compared with that predicted from Gamow's theory of the penetration of the potential barrier around the Be nucleus by protons of zero angular momentum.

Apparatus and Method

A. Production of protons

The proton source was of the low voltage arc type similar to that used by Tuve, Hafstad and Dahl.[3] The ions were drawn from the arc by a probe at a potential 3 kv negative with respect to the metal body of the arc space. This divergent beam was focused by a cylindrical lens having a potential of 10 kv. Total ion currents of the order of 40 microamperes were obtained. The proton current was about one-third of the total ion current.

The accelerating tube had two sections with cylindrical electrodes 3.5 cm in diameter and 11.6 cm long with a separation of 2.5 cm. The system was evacuated by two stages of oil diffusion pumps. The tube was operated at a pressure of 5×10^{-5} mm of Hg.

The high potential source consisted of a 200 kv transformer with half-wave rectification. The output of this transformer as well as that of the proton source was filtered with condensers so that the energy spread of the proton beam was not more than a few percent. The high potential source was calibrated both by means of a spark-gap and by the energy of the protons as measured in the magnetic field.

B. Target assembly

A diagram of the target assembly is given in Fig. 1. The proton beam was bent through 90°

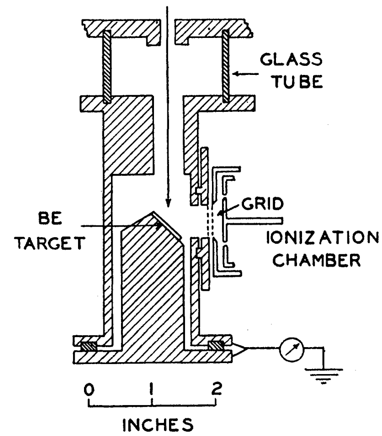

FIG. 1. The target assembly and ionization chamber.

in the arc of a circle of 9.2 cm radius and its position was limited by two 1.0 cm holes at the edges of the magnetic field. The strength of the magnetic field was measured with a Bi spiral previously calibrated at the National Bureau of Standards. The field was found to be quite uniform out to the edges of the pole pieces. The fact that this same target assembly and magnetic field had been used by H. D. Doolittle[4] for a study of the disintegration of Li by protons furnished an additional check on these measurements. The targets of metallic Be were supported at an angle of 45° with the proton beam.

The window for allowing the disintegration particles to pass into the ionization chamber was supported on a thin phosphor-bronze sheet having 71 holes, each 0.046 cm in diameter. The windows were made in the following manner. A drop of a mixture of 50 percent Merck flexible collodion and 50 percent amyl acetate was placed upon a surface of distilled water. After the film had dried for 15 minutes it was removed on a wire frame and dried at a temperature of 100°C. The films were waxed to the grid with paraffin. In this manner windows having an air equivalent of about 2 mm were prepared.

C. Amplifier and measurement of proton current

A four-stage linear amplifier using Dunning's[5] circuit was utilized. The ionization chamber was 1.5 cm in diameter and 2.5 mm deep. In order to

[2] Neuert, Physik. Zeits. **36**, 629 (1935).
[3] Tuve, Hafstad and Dahl, Phys. Rev. **48**, 241 (1935).
[4] H. D. Doolittle, Phys. Rev. **49**, 779 (1936).
[5] Dunning, Rev. Sci. Inst. **5**, 387 (1934).

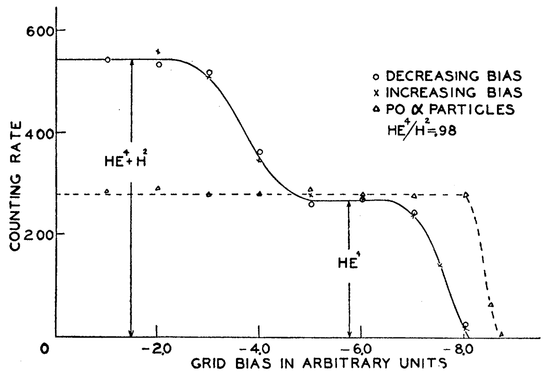

FIG. 2. The variation of the counting rate with thyratron grid bias for protons having an energy of 104 kv.

insure a uniform field between the collecting electrode and the grid the front of the chamber was covered with a metal grid. The particles were recorded by means of a thyratron scale-of-two counting circuit and a Cenco impulse counter. The magnitude of the pulses could be observed visually by means of a cathode-ray oscillograph.

The proton current was measured by a microammeter which could be read to 0.05 microampere. Readings were taken every half-minute and the results averaged to give the proton current. The currents ranged from 1 to 6 microamperes.

RESULTS AND CONCLUSIONS

A. Range measurements

In order to remove the uncertainty in the range measurements introduced by the use of a grid in front of the ionization chamber, it was calibrated with Po alpha-particles. The air equivalent of the window was determined for Po alpha-particles about one cm from the end of their range. Using a window of 3.5 mm air equivalent, the counting rate was determined as the ionization chamber was moved away from the window. For protons of 80 kv energy the range was 7.1 mm. There was no indication of a group of particles with another range.

B. Energy relations

The energy released in reaction (1) is given by:[6]

$$9.0138+1.0081=6.0163+4.0034+E.$$

From this relation E is 0.0022 mass unit and the velocity of the ejected alpha-particle is 7.7×10^8 cm/sec. From the data of Blackett and Lees[7] this corresponds to a range of 6.9 mm in air. The observed value of 7.1 mm is seen to be in good agreement with that predicted from nuclear masses.

According to the relation derived by Bethe,[8] the range of a particle of mass M, and charge Z, is proportional to M/Z^2. Thus, a deuteron should have twice the range of an alpha-particle of the same velocity. Assuming this relation to hold, the velocity of the deuterons ejected in reaction (2) is equal to 4.4×10^8 cm/sec. This corresponds to a release of energy equivalent to 0.0003 mass unit. The mass of Be^8 is then given by:

$$Be^8=9.0138+1.0081-2.0142-0.0003,$$
$$Be^8=8.0074.$$

This value is somewhat higher than the mass of 8.0071 determined by Oliphant, Rutherford and Kempton[1] from the same nuclear reaction.

C. Relative number of ${}_2He^4$ and ${}_1H^2$ particles

Since an alpha-particle produces many more ions along its path in air than does a deuteron of the same velocity, if both reactions (1) and (2) exist, two types of pulses should appear on the oscillograph. It was found that for all proton energies there were two types, one about twice the height of the other.

In order to determine the relative number of the two groups, a curve shown in Fig. 2 was plotted between the number of particles and the negative grid bias on the thyratrons. Since the amplification of the recording circuit was approximately linear, the amount of ionization produced by the passage of a particle through the ionization chamber was proportional to the height of the pulses. The counting rate decreased

TABLE I. *Ratio of He^4/H^2 at various voltages.*

V	He^4/H^2	NUMBER COUNTED
47,000	0.9	200
66,000	0.7	1000
81,000	0.8	3000
93,000	0.8	10000
105,000	1.2	5000
116,000	1.0	8000

[6] The values of the nuclear masses used in this paper are as given by Oliphant in the paper by Cockcroft and Lewis, Proc. Roy. Soc. London **A154**, 261 (1936).

[7] Blackett and Lees, Proc. Roy. Soc. **A134**, 663 (1932).
[8] Bethe, Ann. d. Physik **5**, 325 (1930).

rapidly whenever the grid bias was slightly greater than the height of a particular type of pulse. Thus, the solid curve represents two groups of particles, one producing about twice the ionization of the other. The former must be alpha-particles since they produce about the same ionization as Po alpha-particles near the end of their range as indicated by the dotted curve. From curves similar to Fig. 2 the proper grid bias for recording just alpha-particles or both groups was determined and observations were made on the relative number in the two groups. Table I gives the relative numbers at various proton energies and also the total number counted for any given voltage. The ratio He^4/H^2 appears to increase with the energy of the protons. The increase at 47 kv may be due to the rather large probable error in the determination of the counting rate since only about 200 particles were recorded. From 1000 to 10,000 particles were recorded for each of the other two ratios. The data seem to suggest that the ratio approaches unity at higher proton energies.

At first it was thought that the two types of pulses were due to two particles entering the ionization chamber within the resolving time of the amplifier. Due to the small time constants of the circuit, this was unlikely, but it was checked by reading at very slow and very fast counting rates. The ratio did not change appreciably with the counting rate. This proved that the two types of reaction actually did occur.

D. Excitation curve

To obtain the excitation curve the grid bias was adjusted so that both groups of particles were recorded. Due to the appearance of a brown carbon deposit, the targets were not used for more than 10 minutes. With the exception of the points at the two lowest voltages, 10,000 particles were counted for each point. Since there were two grids between the target and the ionization chamber, and since they were separated by only 2.1 cm, there was considerable uncertainty in the calculation of the solid angle subtended by the window. In Fig. 3 the excitation curve for a thick target is shown.

The shape of the curve is similar to that for the disintegration of Li by protons. Disintegrations were detected at 46 kv. From the curve the threshold voltage for disintegration to occur is at about 45 kv. No disintegration was detected below this voltage.

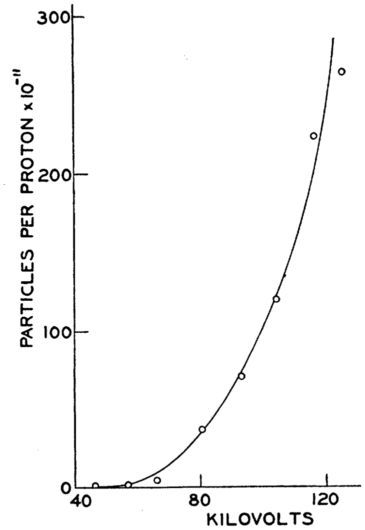

FIG. 3. The excitation curve for a thick target of beryllium. Thyratron grid bias set for the recording of both groups of particles.

Kv	47	57	66	81	93	104	116	125
Particles per proton	0.3×10^{-11}	1.6	4.6	37	71	120	224	264

A thin film yield curve was determined by differentiation of the thick target yield curve in a manner similar to that used by Herb, Parkinson and Kerst.[9] However, the yield was determined for a film of sufficient thickness to reduce the energy of the protons by 5 kv. According to the work of Blackett and Lees[7] and Mano,[10] the range of protons in air is given approximately by $R=KV^{0.7}$ where R is the range in cm, K is a constant, and V is the energy of the protons in electron volts. This relation holds only for energies from 45 to 130 kv. Since there are no data concerning the range of protons of various energies in Be, this relation was assumed to hold instead of the usual $R=KV^{1.5}$.

According to Gamow's theory the probability of disintegration by protons for a thin target is proportional to:

$$(1/E_p)\exp-(e^2/\hbar)(2m_p/E_p)^{\frac{1}{2}}Z(2U_0-\sin 2U_0),$$

where $$\cos^2 U_0=r_0E_p/Ze^2.$$

E_p and m_p are the energy and mass of the

[9] Herb, Parkinson and Kerst, Phys. Rev. **48**, 118 (1935).
[10] Mano, J. de phys et rad. **5**, 628 (1934).

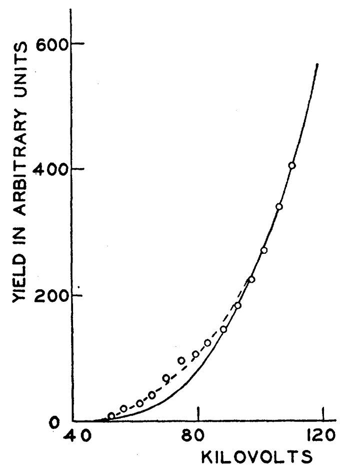

FIG. 4. Excitation curve for a thin target of beryllium. Dash line, experimental curve; solid line, Gamow's theory.

protons, e is the charge of the electron, Z is the atomic number of the bombarded nucleus, and r_0 is the nuclear radius. The nuclear radius was assumed to be 5×10^{-13} cm. When the numerical values of the constants have been substituted into the equation above the yield is given to a close approximation by:

$$Y=\frac{C}{V}\exp 3.84\times10^3\cdot V^{-\frac{1}{2}},$$

where V is the energy of the protons in electron-volts. In Fig. 4 the thin target data are compared with the curve given by the equation above. The experimental values of the proton energies have been multiplied by 0.9 to correct for the recoil motion. The value of the constant C, was adjusted so that the experimental and theoretical curves coincided at 110 kv. For low energies the experimental yield rises more rapidly than does the theoretical curve. This discrepancy is made still worse if the range of the protons is assumed to be given by $R=KV^{1.5}$.

The collision cross section σ for either reaction may be determined from the relation $Y=RN\sigma$ where Y is the thick target yield at a given voltage, R the range of the protons in the target and N is the number of Be nuclei per cc of the target. From the data of Blackett and Lees[7] the range of a proton of 100 kv in air is 0.15 cm. The atomic stopping power[11] of Be relative to air is about 0.75. From this information we find that protons of 100 kv have a range of 0.81×10^{-4} cm in Be. At this energy Y is 1.0×10^{-9} and N is 1.24×10^{23}. The value of σ is then 5×10^{-29} cm². The value of σ calculated in a similar manner from the thin target data is 25×10^{-29} cm².

The effective cross section for a thin target may be calculated from Gamow's equation. It is then given by:

$$\sigma=\frac{\pi\hbar^2}{2m_pE_p}\exp -3.84\times10^3\cdot V_p^{-\frac{1}{2}}\text{ cm}^2,$$

where E_p is the energy of the protons in ergs and V_p is the energy in electron volts. The value obtained at 100 kv is 3.2×10^{-29} cm². Since σ increases rapidly with the energy of the protons, the thin target value should be somewhat higher than that for thick films. The experimental results agree with this prediction, but the thin target value is about eight times that predicted by Gamow's theory. This discrepancy may be due to the use of an incorrect range relation. The value of the thin target σ would be affected more by an error in this relation than the thick target value. The disagreement may also be due to an error in the calculation of the solid angle although it is doubtful whether this could cause an error greater than 20 percent. Finally, there is some doubt as to how accurately the cross section is expressed by Gamow's relation. However, we may conclude that the effective cross section is between 5 and 25×10^{-29} cm².

In conclusion, the author wishes to express his appreciation to Professors A. J. Dempster and S. K. Allison for their valuable advice and discussions throughout the course of this work.

[11] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, pp. 97–100.