Artificial Production of Neutrons

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A porcelain vacuum tube capable of producing currents of positive ions up to 30 microamperes and with energies up to 10^6 electron-volts has been constructed and used for artificial disintegration experiments. Neutrons have been produced by bombarding beryllium with helium ions, and by bombarding lithium and beryllium with the ions of the heavy isotope of hydrogen. The curve obtained for the efficiency of production of neutrons by helium ions as a function of voltage is in agreement with the curve obtained by a downward extrapolation of curves known from work with polonium α-particles. The present paper is mainly a discussion of the apparatus and methods of measurement, since brief reports of the results have already been presented.

INTRODUCTION

DURING the short time neutrons have been known, the relative yields of neutrons from beryllium and from boron as a function of the energy of the bombarding α-particles has been investigated in some detail. With the exception of one, or possibly more than one, resonance level, the excitation curve has been found to be in good agreement with that predicted on the basis of the Gamow theory. The curve is of exponential form, given approximately by $Ae^{-b/\sqrt{V}}$ where A and b are constants and V is the energy of the α-particles. It has been possible, however, by the use of radioactive sources of α-particles, to investigate the excitation curve only down as far as about 1.3×10^6 electron-volts,[1] because of the very rapidly decreasing efficiency, and the limited number of α-particles obtainable from existing radioactive sources. If we take the experimental curve in the region of energy in which it is accurately known and extrapolate it downward according to the exponential formula, we obtain the curve shown in Fig. 1. From this can be determined the relative intensities of α-particle sources necessary to produce a given effect at various voltages. It is evident that if artificial α-particles, or helium ions, are to be used at voltages in the region of 10^6 and below, their extremely low efficiency must be compensated by great numbers. In order to produce an effect in the disintegration of beryllium equal to that produced by the α-particles from 100 millicuries of polonium, it would be necessary to have the following currents of helium ions at the following voltages.

Voltage (10^6 volts)	0.50	0.65	0.75	0.90	1.00
Current (μa)	5000	450	90	20	5

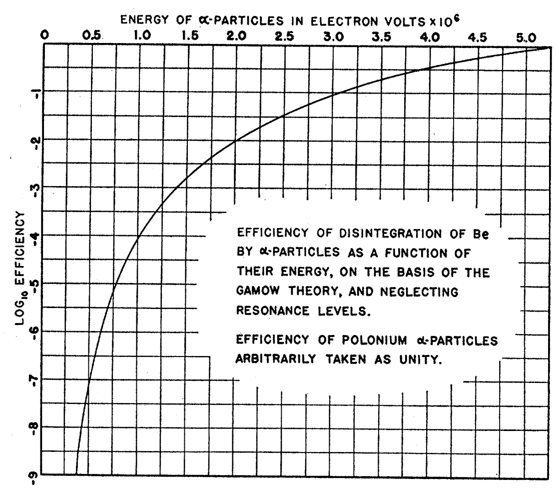

FIG. 1.

The problem undertaken by the authors has been the production of helium ions of energy up to 10^6 electron-volts, in sufficient quantity to give a strong artificial source of neutrons, and to make possible an investigation of the excitation curve in that region of voltage.

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[1] Curie and Joliot, Comptes Rendus **196**, 397 (1933).

Description of Apparatus

The first apparatus used to accelerate helium ions was a modification of a porcelain x-ray tube[2] which had recently been constructed in this laboratory, and which was capable of running on alternating current at 650,000 volts, peak value. With this apparatus, ion currents of the order of 100 microamperes were obtained, and small intensities of neutrons were detected. As can be seen from the above table, only a small effect, at best, should be expected at that voltage and current. In order to reach higher voltages, a tube for accelerating the ions in two stages was then constructed, with two of the same type of porcelain bushings. A sectional view of this tube is shown in Fig. 2. The million-volt (root-mean-square value) cascade transformer set in the High Voltage Laboratory is used as the source of high potential. The top of the upper tube is connected, through a suitable protective resistance, to the high potential end of the transformer set, and the midpoint between the two tubes is connected to the half potential point of the transformer set. The apparatus therefore operates as two separate tubes, each giving the ions half their total acceleration.

The source of the ions is located in the end of the inner electrode of the upper tube. A metal ring in the shape of a doughnut, 3 in. (7.5 cm) in diameter and having a 1 in. (2.5 cm) hole is supported from the bottom plate of the upper tube, about 5 in. (12.5 cm) from the end of the electrode. This modifies the field in a way that is favorable to concentration of the ion beam. From here the ions pass down the hollow central electrode, and receive the second half of their acceleration in the gap of the lower tube. An enlarged view of the ion pipe at the bottom of the tube and the target is shown in Fig. 3. The target consists of a 2 in. (5 cm) brass disk mounted on a shaft, so that either side can be exposed to the ion beam. One side of the disk is covered with the material to be disintegrated, and the other side is covered with some material which gives no effect, such as brass or aluminum, for the purpose of comparison. A paraffin lined electroscope, for detecting neutrons, is located in a lead cylinder of 5 cm wall thickness, in the position indicated in the figure. A magnetic field is applied to the ion beam above the target to bend out any electrons which may arrive during the reverse half cycle of the alternating potential. Some additional lead is placed on top of the cylinder containing the electroscope, so as to

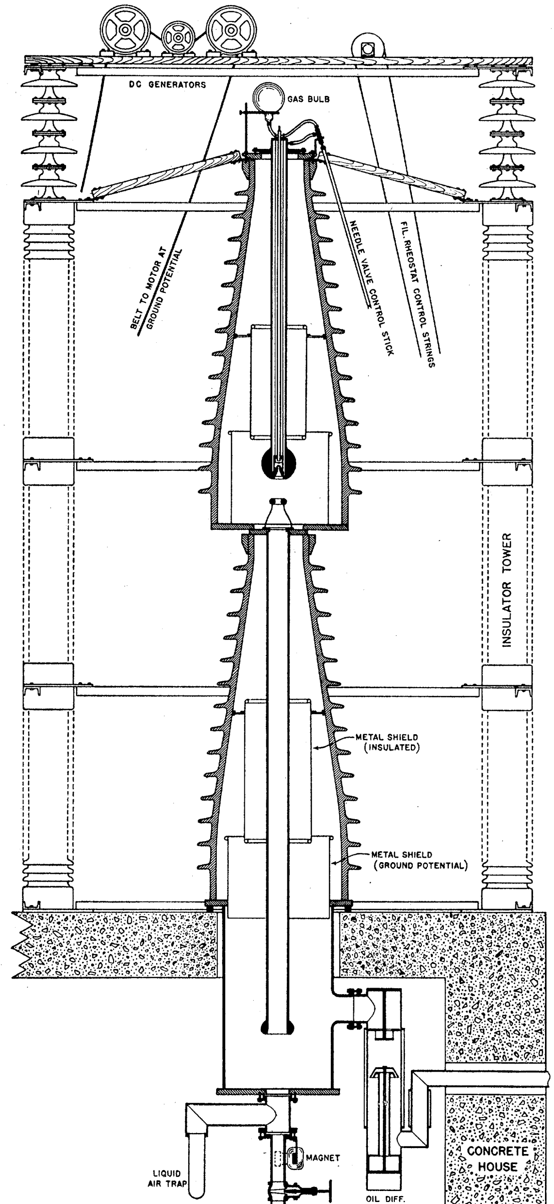


Fig. 2. Sectional view of the entire tube.

[2] Crane and Lauritsen, Rev. Sci. Inst. **4**, 118 (1933).

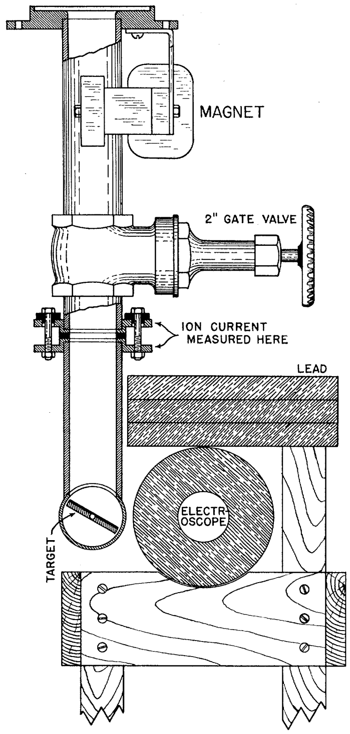


FIG. 3. Part-sectional view of the lower end of the tube, showing the lead shielding and the position of the electroscope with respect to the target.

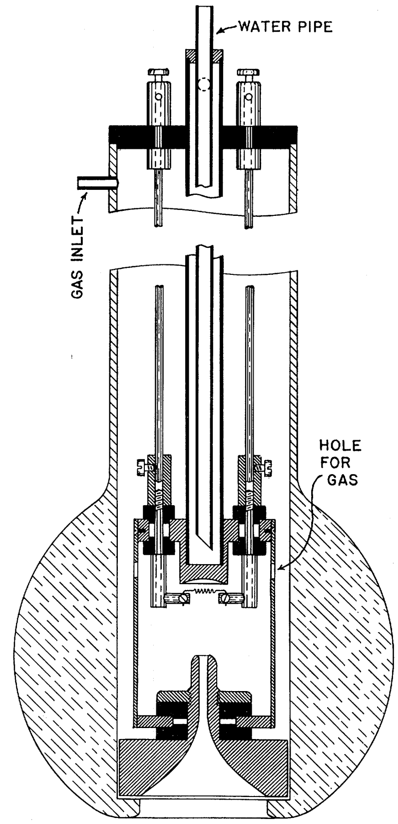


FIG. 4. End of the upper electrode with the ion source in place.

reduce further the effect of x-rays produced by the electrons that are deflected to the wall of the pipe by the magnetic field. The electroscope is placed at the side of the target, rather than below it, so that, a greater thickness of lead can be put in the path of the x-rays, which come principally from above, than in the path of the neutrons. The intensity of neutrons is presumably not quite as great in a direction perpendicular to the ion beam as in the downward direction, but the decrease in the background radiation in the present arrangement probably more than compensates for this difference in neutron intensity.

A 2 in. (5 cm) gate valve is placed in the pipe just above the target. When it is closed, the target chamber can be opened to the atmosphere, and the pressure in the tube does not rise to more than 10^{-1} mm during the operation.

Ion source

A cross section of the end of the upper electrode with the positive ion source in place is shown in Fig. 4. A potential of about 1000 volts d.c. is applied between the filament and the water-cooled anode. The helium or hydrogen from which the ions are made is admitted continuously through a needle valve into the space around the filament, and escapes, together with the ions, through a 1/8 in. canal directly below the filament. By adjusting the needle valve a pressure of between 10^{-2} and 10^{-3} mm is maintained inside the electrode, and this results in a pressure of from 10^{-4} to 5×10^{-4} in the main tube. Because of the very small cross section for ionization of helium and of hydrogen, the tube will operate satisfactorily with pressures of helium up to 10^{-3} and with hydrogen up to 5×10^{-4} mm. With an electron current in the ion source of 0.5 ampere, the current of positive ions escaping through the canal is about 200 microamperes. Of this, about 30 microamperes arrive at the target, which is 11 feet from the source.

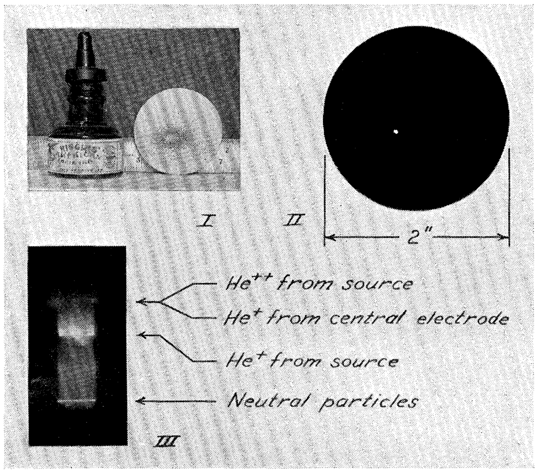


FIG. 5. I, Photograph of a target after many hours exposure to the ion beam. II, Spot produced on a photographic film during a fraction of a second exposure to the ion beam. III, Magnetic spectrum of the ion beam.

The horn shaped opening at the bottom of the canal causes the ions to be in a converging field at the time they are leaving the canal, and consequently when they are moving slowly and are easily influenced by the field. There is probably very little additional concentration of the beam in the gap of the lower tube, because the ions are by that time moving too fast to be much influenced by the field. A photograph of the spot produced on one of the targets after many hours of running is shown in Fig. 5. The spot appears elongated, because the target was inclined at 45° to the incident beam, but it is evident that most of the ions strike within a circle about 1/2 in. in diameter. A photographic film was placed over the target and an exposure of a fraction of a second was made. The ions completely destroyed the emulsion in a spot about 1/16 in. in diameter without producing appreciable photographic blackening over the rest of the film. This shows that while there is some intensity of ions over a spot about 1/2 in. in diameter, a large part of the intensity is confined to a very small area at the center of the spot.

Composition of the ion beam

Since alternating current was used, it was desirable to determine the approximate distribution in velocity of the ion beam. The beam was allowed to fall on a slit and then bent in a magnetic field. A photograph of the resulting spectrum is shown in Fig. 5. It can be seen from this that a very large part of the total intensity is at, or near, the high voltage limit. Such a distribution is to be expected, assuming that the ion current is constant, and knowing that the time spent near the top of the sine wave is much greater than the time spent at any lower voltage. Actually the distribution is even more favorable because the ion current measured at the target is roughly proportional to the voltage, because of better focussing at the higher voltages. If we then multiply the current at each instant by the efficiency of the ions in the disintegration of beryllium at that particular voltage, it is apparent that almost all of the disintegration can be attributed to ions having very nearly the full voltage. Thus the inaccuracy introduced into the experiment by using alternating, rather than constant, potential is very small compared to other sources of error, such as the inaccuracy with which the factor between neutrons and recoil H-particles, and the absorption and scattering of the neutrons in the lead cylinder, are known.

With the present apparatus, no quantitative determination of the amount of doubly ionized helium present in the beam can be made, although some idea of the composition of the beam can be gained from the magnetic spectrum shown in Fig. 5. The ions that originate singly charged at the source and remain singly charged during the whole of their journey are seen in the spectrum as a bright line with a sharp high velocity limit, and it is estimated that this comprises roughly 90 percent of the total ion current. In a position corresponding to $\sqrt{2}$ times the deflection of the above line can be seen a diffuse line representing principally the He^+ which originate as secondaries in the central electrode, and receive acceleration only in the lower gap. These are readily identified, because they are poorly defined in direction, most of them going through the slit obliquely, and giving rise to a line considerably longer than the slit itself. If there were present in the beam any ions which had come through the entire tube in the doubly ionized state, they would fall in the same position as this diffuse line, except that, due to their uniformity of direction, their line would be sharp and only as long as the slit. No such line can be detected in the photograph. The component of He^{++} is therefore assumed to be small enough to be neglected. In the region of 10^6 volts, He^{++} should be about 100 times as effective in disintegrating beryllium as a He^+, since it would acquire twice the energy during its travel through the tube, so He^{++} would have to be present to at least one percent to be as important as the He^+.

Electroscope

A sensitive electroscope, having a cylindrical chamber 5 cm in diameter and 8 cm long is employed as a means of detecting and measuring the intensity of the neutrons. The entire electroscope, including the eyepiece, is enclosed in a lead cylinder, shown in Fig. 3, to shield it from x-rays. A small lead plug in front of the eyepiece is removed when readings are made. The inside walls of the electroscope are coated with a layer of paraffin about 1 mm thick, with a wire gauze over it. The neutrons penetrate the 5 cm walls of the lead cylinder and eject recoil hydrogen particles from the paraffin on the walls of the chamber, the ionization due to these recoil particles giving a measure of the neutron intensity. The sensitivity of the electroscope and the intensity of the background radiation are such that about one recoil particle per minute can be detected with certainty in a one hour measurement.

Results

The yields of neutrons obtained by bombarding various targets with helium ions,[3] and also with deutons[4] and protons,[5] have already been presented in letters to the *Physical Review*, so only a brief resumé of the method of measurement and results will be given here. In plotting the curve of the efficiency of production of neutrons from beryllium by helium ions (Fig. 6, curve III), a series of one hour runs was made at a number of voltages between 6×10^5 and 10^6, with an ion current of 10 microamperes. Two curves were first obtained, one giving the rate of discharge of the electroscope when the beryllium was exposed to the ion beam, and the other giving the rate of discharge when the brass target was exposed to the beam, all other conditions being kept the same. The latter curve is taken to be the background, and is composed of the natural leak of the electroscope plus the rate of discharge due to stray x-rays from the tube. At 6×10^5 volts the total background is not measurably different from the natural leak when the tube is not running, namely, about 4 divisions per hour, and at 10^6 volts it becomes about twice the natural leak. Each of the three curves in Fig. 6 is the observed effect, per microampere, after subtracting the background, and should therefore represent just the effect due to neutrons and possibly also to some γ-rays produced in the disintegration. In order to gain some idea of the intensity of the γ-rays present, measurements were made with the paraffin removed from the electroscope. In each case the effect observed without paraffin was less than half the effect with paraffin. Although this result does not exclude the possibility of the presence of some γ-rays, it indicates that at least the greater part of the effect observed with the paraffin chamber was due to neutrons. It is clear that a quantitative separation of the effects of neutrons and γ-rays

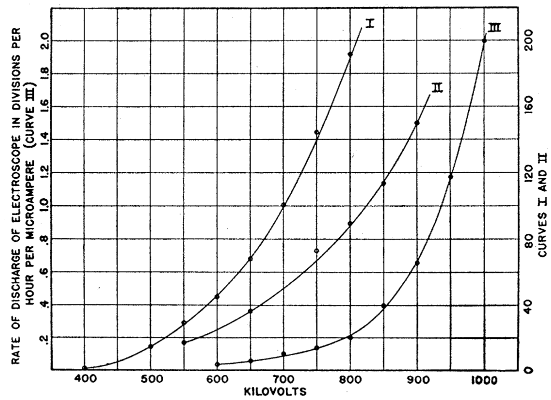


FIG. 6. Relative efficiency of production of neutrons as a function of voltage. Curve I, beryllium bombarded with deutons; curve II, lithium chloride bombarded with deutons; curve III, beryllium bombarded with helium ions.

[3] Crane, Lauritsen and Soltan, Phys. Rev. **44**, 514 (1933).

[4] Crane, Lauritsen and Soltan, Phys. Rev. **44**, 692 (1933).

[5] Crane and Lauritsen, Phys. Rev. **44**, 783 (1933); Lauritsen and Crane, Phys. Rev. **45**, 63 (1934). A rather strong radiation was observed when lithium was bombarded with protons, and was at first interpreted to be neutrons. Later absorption measurements with paraffin and lead showed that at least the greater part of it was γ-radiation of about 1.5×10^6 e.v. energy.

cannot be made simply by comparing the observations with and without paraffin in the chamber, since in either case the chamber is somewhat sensitive to both neutrons and γ-rays. In the disintegration of beryllium by α-particles, Becker and Bothe[6] found that photons of high energy accompany the neutrons, in approximately equal number.

An estimate of the absolute efficiency of the disintegration of beryllium by helium ions can be made by considering the following constants of the experimental set-up.

Sensitivity of the electroscope, as determined with a radium γ-ray source of known intensity: 1 division $= 2.5\times 10^6$ ion pairs $= 70$ recoil H-particles.

Solid angle subtended by the electroscope is 0.127π or 1/30 the total sphere.

Absorption in 5 cm of lead, taking into account scattering, can be assumed to be not more than 20 percent.

Rate of discharge of the electroscope at 10^6 volts with 10 microamperes ion current (from Fig. 6) is 5.5×10^{-3} div./sec., corresponding to 0.4 recoil H-particles/sec.

Assumed factor between the number of neutrons and the number of recoil H-particles is 5×10^3.

10 microamperes is 6×10^{13} ions/sec.

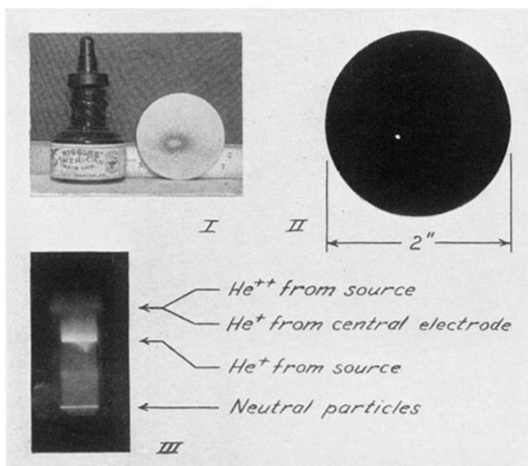
The efficiency, from the above data, is 1 neutron per 10^9 helium ions at 10^6 volts. By comparing the three curves in Fig. 6, an estimate can also be made of the efficiency of production of neutrons from lithium and beryllium by deuton bombardment. At 8×10^5 volts this is, for lithium chloride, 1 neutron per 2×10^7 deutons, and for beryllium, 1 neutron per 10^7 deutons.

The shape of the excitation curve in Fig. 6 for helium ions is in good agreement with that predicted by theory, although there are several disturbing factors which could cause the experimental curve to depart considerably from the theoretical. Thin layers of oxides and deposited material on the target, which are not important in dealing with very fast ions, become increasingly important as the lower limit of the curve is approached. Also a curve of much less intensity but of quite different slope, due to a small component of He^{++} in the ion beam, is superimposed on the true curve. The exponential formula, with the exponent determined from the experimental curve between 750 and 950 kv is $I = Ae^{-640/\sqrt{V}}$ where I is the relative yield of neutrons and V the voltage in kv. The two deuton curves are not so much subject to the above sources of error. The deutons penetrate to a greater depth in the target than the helium ions, making surface conditions less important, and the whole effect can be attributed to one kind of ion, namely $(H^2)^+$, since it is not only predominant in number, but is from 10 to 100 times as effective in disintegration as $(H^1H^2)^+$ or $(H^2H^2)^+$ of the same energy.

As a source of neutrons, it is apparent that the method of production with deutons is orders of magnitude better than the method of production with helium ions. However, by using helium ions, we have been able to plot the curve for the efficiency of excitation, beginning at about the lowest point reached with radioactive α-particle sources, and extending down to 6×10^5 volts, where the efficiency is not more than 10^{-11} neutrons per α-particle.

The work we have described has been supported entirely by the Seeley W. Mudd Fund. We wish to express our gratitude for this aid, and also to Professor G. N. Lewis of the University of California, who furnished the heavy hydrogen used in these experiments.

[6] Becker and Bothe, Zeits. f. Physik **76**, 421 (1932).



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