Some Features of an Electrostatic Generator and Ion Source for High Voltage Research

I. A. Getting,* J. B. Fisk,* and H. G. Vogt
Harvard University, Cambridge, Massachusetts

(Received July 17, 1939)

A compact generator of the Van de Graaff type is described in which several new features have been incorporated. Short-circuit current of one milliampere is available. When operating at 600 kv as voltage supply for accelerating protons or deuterons, 130μa of charged particles at the target have been obtained from an unusual low voltage capillary arc source. In normal operation as a neutron generator, the equivalent of 15 curies of radon-beryllium is readily produced by the reaction Li+D, and 60 curies by the D on D reaction.

In the past few years a number of articles have appeared in various journals[1, 2] in which electrostatic, belt-type generators have been described in considerable detail. The present article describes a generator which has been in use in the Harvard Laboratory for some time and which incorporates certain new features. The fundamental ideas concerning such voltage sources, and many practical considerations for carrying them out are well known. However, inasmuch as generators incorporating recent developments are either in construction or being studied in several laboratories, it seems desirable to make readily available information concerning these developments and details on the performance which may be expected. With the apparatus herein described a continuous current of 130 μa of deuterons can be maintained with the high voltage terminal at a positive potential of 600 kv above ground. This is not the maximum to be expected either of current or of voltage. The voltage can be increased by using gases of high dielectric strength, as is well known, while the current limitation lies in the ion source itself, not at present in the accelerating tube. A useful low voltage capillary arc has been developed giving 250 μa total ion current of which 60 percent is atomic. This ion source requires no liquid cooling. It is, therefore, well suited for operation in a confined space at high potential.

The major portion of the apparatus is shown in Fig. 1. The generator itself, which stands $8\frac{1}{2}$ ft. (about 2.5 m) high, is at the left. The adjoining equipment consists of a high voltage body, housing the ion source and power supplies; a resistance voltmeter; and the acceleration tube suspended from the ceiling. The remaining apparatus (vacuum pumps, target chamber, all of the controls and measuring instruments) is contained within the room above, with no direct mechanical connection to the high speed machinery below.

GENERATOR

The generator was designed to produce a maximum of current in a restricted space. In order to accomplish this the principles sketched in Fig. 2 were applied.[2, 3] In A, a single isolated belt can be charged to a value σ e.s.u. per cm^2, such that its gradient of potential, $2\pi\sigma$, on each side corresponds to about 25,000 volts per cm. The charge which can be put on the belt is thus limited by this gradient which corresponds approximately to the "breakdown strength" of air. In B a common belt arrangement is shown. Here the lines of force are inward, between the positively and negatively charged portions of the belt. If now $2\pi\sigma$ is the maximum field intensity, then $\sigma/2$ will be the maximum charge per cm^2. In C is shown a two-belt system. Here the outer belt may carry a charge of $\sigma/2$ e.s.u. per cm^2 while the inner belt may carry σ e.s.u. per cm^2. In our design a three-belt system is used, similar to the arrangement of C. The pulleys, 3, 4, and 5 inch in diameter, are centered one above the other, making the spacing between belts equal to $\frac{1}{2}$ in. Table I shows the charging current

---

* Society of Fellows.

[1] R. J. Van de Graaff, K. T. Compton, L. C. Van Atta, Phys. Rev. **43**, 149 (1933).

[2] Trump, Merril and Safford, Rev. Sci. Inst. **9**, 389 (1938).

[3] J. B. Fisk and I. A. Getting, Phys. Rev. **53**, 916A (1938).

carried by each of the three belts when the total charging current happened to be 880 μa.

It is evident that considerable improvement is obtained by such an arrangement of belts. One might ask why the belts on the 3-in. and 4-in. pulleys do not carry twice the theoretical maximum for a single belt, rather than 97 percent and 124 percent, respectively. The reasons for this are that a single belt does not in general approach its theoretical limit because of "edge" effects or inhomogeneities of the field, and because the fabric of the belt will only sustain a certain gradient through it as it leaves the pulley without burning or excessive sparking. Hence, any improvement should be measured with respect to currents actually obtained in practice with a single belt.

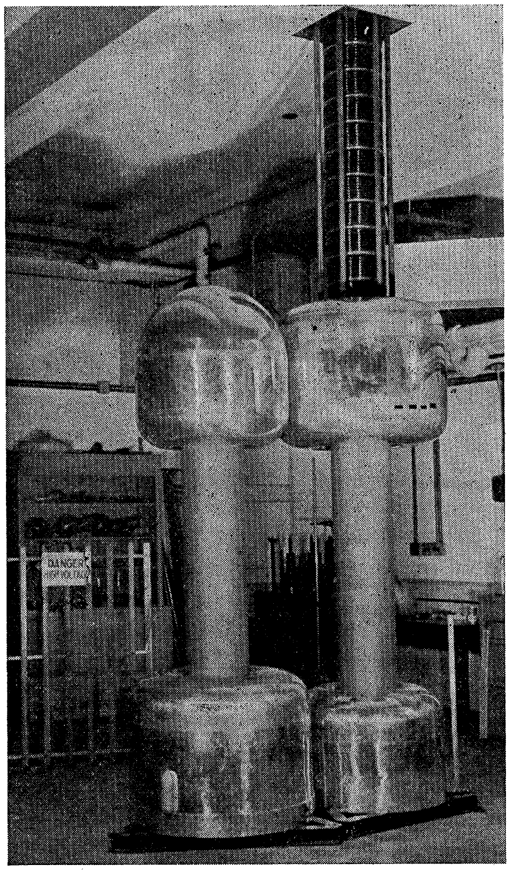

FIG. 1. Generator (left), high voltage body and acceleration tube.

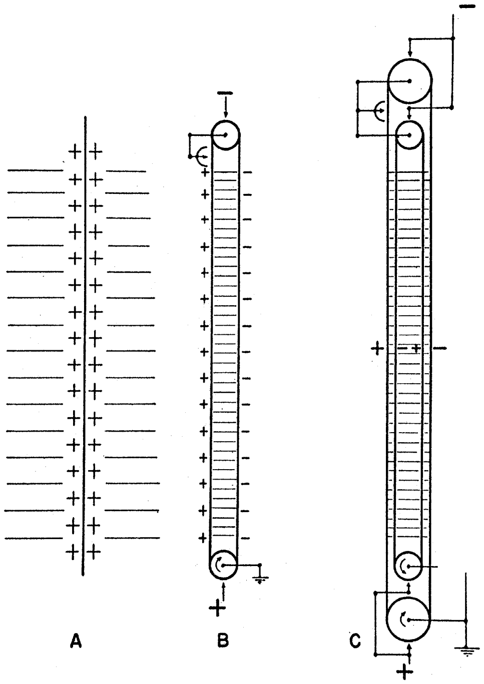

FIG. 2. Lines of force in various belt arrangements.

When running in air at normal pressure and temperature, the maximum "short-circuit" current which the generator will deliver is 980 μa with the terminal positive, 1000 μa with the terminal negative. The spacing between adjacent belts, carrying charge of opposite sign, should be small compared to the belt width, as pointed out by Trump.[2] This is borne out by the results quoted in Table I, where one compares a current of 372 μa (carried by a belt spaced midway between two other belts carrying opposite charges, ½ in. (1.25 cm) from each) with 278 μa (carried by a belt spaced ½ in. from one adjacent belt, 3 in. (7.5 cm) from the other). Other factors may influence these values, such as the effect of greater or less spacing between upper pulleys, etc., but these things are not critical and the numbers quoted would be only slightly altered.

Even though the belts were but ½ in. (1.25 cm) apart, no difficulty was experienced in their successful operation. Windage and flexure losses depend markedly on the type of belt used. Tilton endless woven cotton fabric belts required 1 hp more to drive in this arrangement than Goodyear rubberized Zeppelin fabric. However, with Tilton belts 1000 μa were available compared with 600 μa with Zeppelin fabric belts. This was due in part to the low dielectric breakdown strength of the thin fabric belts prohibiting high voltage on the corona points. Furthermore, with slightly crowned pulleys the thin fabric belts tend to rip.

Positive or negative charge is "sprayed" on belts at the bottoms of the lower pulleys, as indicated at Q in Fig. 3. The spray points (phonograph needles) are mounted uniformly about $\frac{1}{2}$ in. apart and kept at 15,000 volts or less. Each group of spray points is fed from the Kenotron rectifier through an adjustable ballast resistor which takes about one-fourth the total voltage drop. The resistors were adjusted for maximum short-circuit current while the generator was running.

The self-induction scheme for charging the upper terminal is used. This is shown in Fig. 3. The shielded spray "comb," E, is connected directly to the pulleys, while the spray combs, D, are connected in parallel to the aluminum shell, A. The upper pulley assembly, C, is insulated from the high voltage terminal, A, by means of eight canvas-Bakelite screws, G. The position of E along the outer belt, and the position of each spray comb with respect to its pulley, are critical, and adjustment should be made while the generator is running.

Following Trump,[2] re-entrant electrodes were used. The discontinuity between the conducting shell, A, and the dielectric column, J, is made much less abrupt by this means, and the high voltage terminal behaves very nearly as one might expect a charged, isolated sphere to behave. Breakdown at maximum voltage occurs usually as a "spray" of corona from the outer portion of the high voltage electrode where the cylinder joins the re-entrant shape, and not, in general, as damaging sparks down the supporting column.

The supporting column is Textolite, 12 in. (30.5 cm) outside diameter $\frac{3}{16}$-in. (48 mm) wall. Apparently "Textolite" is available with several binders: shellac and Bakelite among them. The columns supplied for this work were bound with Bakelite and were found to be very hygroscopic, and to possess a high negative temperature coefficient of resistance. Considerable difficulty was at first encountered in maintaining a high resistance (i.e., greater than 10^{11} ohms). To prevent absorption of moisture the following procedure was used: The columns, after being scraped to remove dirt and wax, were baked at 110°C for 48 hours. They were then given two coats of glyptal lacquer No. 1202, inside and out, followed by 4 hours baking after each coat. Finally a thin coating of ceresin wax was applied while the columns were still warm. The resistance was then greater than 10^{13} ohms at room temperature. To

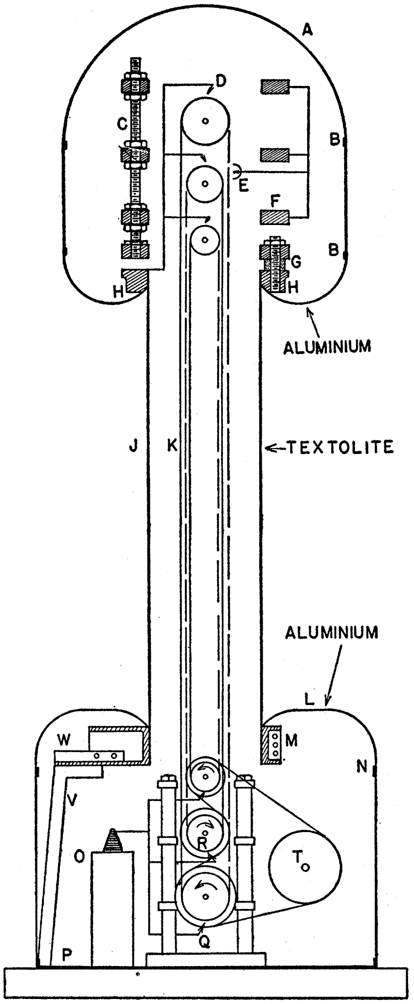

FIG. 3. Schematic diagram of generator.

TABLE I. *Charging current on the belts.*

Radius of Pulley in Inches	R.P.M. of Pulley	Linear Speed of Belt ft./min.	Width of Belt in Inches	Current in μa (Measured)	Ratio of Current Carried to Theoretical Maximum for Single Belt
5	4280	5610	8.75	230	0.74
4	5240	5500	9.75	372	1.24
3	6860	5560	9.75	278	0.97

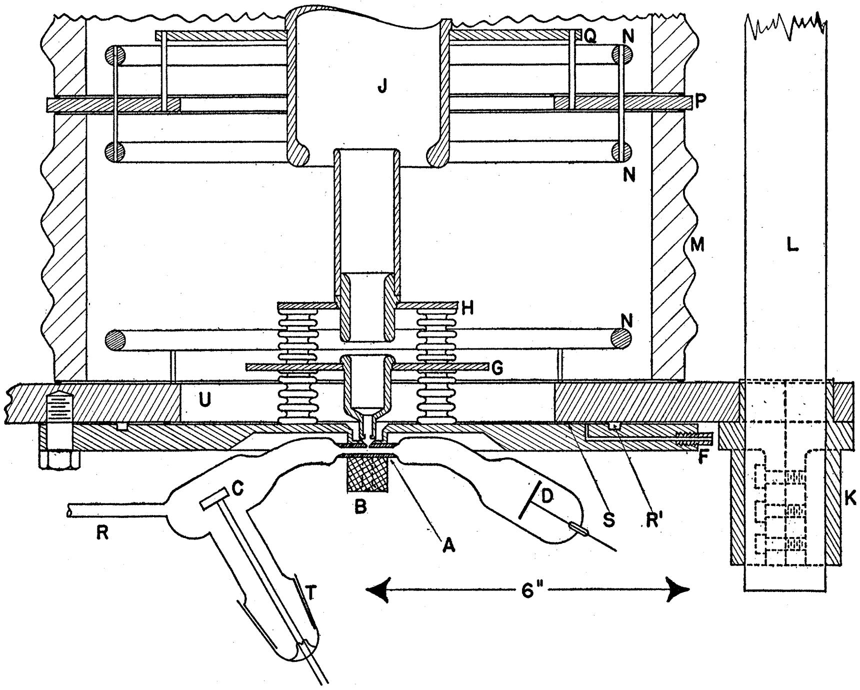

FIG. 4. Diagram of source end of tube showing ion source, endplate, electron-optical system, first tube section and method of holding tube together.

prevent undue heating of the column the temperature of the air within the generator is maintained at about room temperature by means of a small water-cooled radiator and circulating fan in the base of the generator.

The base of the generator is shown in Fig. 3. Three column supports, *V*, are welded to the steel flange, *P*, which, together with the clamp, *M*, form a very rigid structure. The 1.5-hp driving motor has recently been replaced by a 5-hp motor which has been mounted outside the aluminum shield, *L*. The belt for driving the pulleys is an HT4 Tilton endless woven and operates at a linear speed of 7000 ft. per minute. Rockwood paper pulleys are used with this driving belt. The three pairs of charging belt pulleys, upper and lower, were dynamically balanced and mounted in self-aligning bearings.

In order to reduce vibration the upper pulleys are mounted on separate cushion pads, each being isolated from the others, and each being independently adjustable. All charging belt adjustments are made at the upper end.

VOLTMETER

The resistance voltmeter consists of four IRC type MVR resistor units, 10,000 megohms each, total length 80 in. (203.2 cm). The resistors are mounted in series along the axis of a 4 in. (10.2 cm) diameter Pyrex tube which is filled and coated with ceresin. The complete unit stands vertically inside the column shown to the right in Fig. 1. The voltmeter can be shown to be free from corona by comparing meter readings at grounded and high voltage ends of the resistor. To prevent possible corona pick-up on the cable to the instrument panel, both leads are separately shielded. A neon glow lamp bypass to ground is used to protect the microammeter from surges.*

ION SOURCE

A number of different types of ion sources have been described in the literature, among which the

---

* *Note added in proof.*—The resistor units failed at a peak voltage of 600 kv after several months of use. A new generating voltmeter of a type to be described by Trump has been installed and found to be extraordinarily dependable.

low voltage capillary arc[4] is particularly suitable for present application. This type of source has the advantage that the ions, drawn from the plasma of the discharge, are monokinetic as compared to other types of sources (e.g., canal ray) in which the source potential may be as high as 50,000 volts. The positive ion density in the capillary part of the arc (i.e., the constricted portion between C and D in Fig. 4) may be made very high and it is from this region that the ions are withdrawn. Metal, glass and quartz capillaries have been used. Metal and quartz walls encourage recombination; while glass, having low heat conductivity, must be cooled if any appreciable power is to be dissipated from the arc. Even with water cooling the temperature between the inside and outside of a Pyrex capillary may be as much as several hundred degrees when 100 watts is being dissipated in the arc. Hence, either very thin, fragile capillaries must be used or an upper limit must be set to the arc current and voltage.

In the present design this difficulty, and the difficulty occasioned by wearing away of the edge at the small, beveled hole in the capillary wall, is largely overcome by using a "Kovar" capillary lined with Corning 706J glass as suggested by Professor K. T. Bainbridge. The glass lining is but 0.002 in. (0.0051 cm) thick, which gives rise to a temperature drop of less than 10° under fairly severe conditions. Fig. 4 shows the ion source, mounted in position on the plate capping off the high voltage end of the porcelain vacuum tube; the first few focusing electrodes; and some detail of the method of assembly of the acceleration tube. The cathode, C, is oxide-coated, wound in a flat spiral, mounted on a grind, T, and takes 10 amperes at 2.5 volts. Anode, D, is a flat, circular piece of nickel, although several types of anodes have been used with equal success. The anode is made large enough to prevent excessive anode drop and, hence, undue heating in that region. The Kovar capillary is soldered to the end plate, F, and to the copper clamping block, B. Heat is then dissipated from the entire endplate assembly by air convection. The arc operates satisfactorily with the hydrogen pressure between 10^{-2} and 10^{-1} mm Hg. At 10^{-1} mm the arc current may vary from 0.2 ampere at 125 volts to 1.0 ampere at 170 volts through an $\frac{1}{8}$ in. (3.2 mm) capillary 1 in. (2.54 cm) long. There seems to be no simple dependence of useful ion current on total arc current. With a 0.75-mm diameter outlet from a 3.2-mm diameter capillary a current of 250 μa was obtained, 60 percent being protons. Fig. 5 shows an analysis of the ion beam for this source. The effect of a small quantity of water vapor on the relative yields of monatomic and diatomic ions is indicated (cf. Lamar, Buechner and Compton[4]).

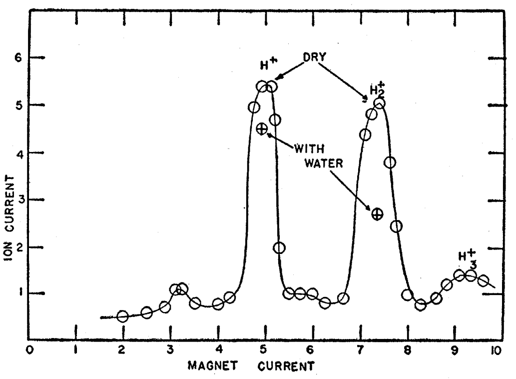

FIG. 5. Mass-spectrographic analysis of ion source.

A source of this description allows a considerable flow of gas into the acceleration tube. The acceleration tube, however, was designed (following Van Atta, etc.[5]) to have high speed of exhaust. Used in conjunction with a 4-in. (10.2 cm) diameter, stainless-steel Hg diffusion pump (of pumping speed 400 l/sec. for H_2) no difficulty was had in maintaining the pressure at the target better than 5×10^{-5} mm Hg. At this pressure there is very little scattering of ions out of the focused beam for this 6-ft. (183 cm) tube, and no difficulty is encountered because of electrical breakdown.

FOCUSING

A number of methods for focusing the ions at the source were tried. The electron-optical lens system which has proven most successful for this purpose is sketched in Fig. 4. The probe, G,

---

[4] E. S. Lamar and O. Luhr, Phys. Rev. **46**, 87 (1934). Tuve, Dahl and Van Atta, Phys. Rev. **48**, 315 (1935). Lamar, Buechner and Compton, Phys. Rev. **51**, 936 (1937). W. H. Zinn, Phys. Rev. **52**, 655 (1937).

[5] Hill, Buechner, Clark and Fisk, Phys. Rev. **55**, 463 (1939).

is held at about −5000 volts, while the electrode, *H*, is held at about −10,000 volts with respect to the end plate, *F*. The entire assembly of *G* and *H* can be adjusted externally for alignment although details of the mechanism are not shown. Electrode *J* is at a potential determined by the over-all voltage on the acceleration tube and is controlled by corona.* An ion beam of 130 μa on the target was focused to a spot $\frac{1}{8}$ in. in diameter by means of this arrangement. The diameter and length of electrode *H* were so chosen that the solid angle subtended from the outlet hole in the capillary source was approximately that subtended by the last tube electrode at the same origin. Hence, under normal operating conditions, few ions strike the tube electrodes, and secondary electrons from the metal surface of these electrodes do not constitute a problem. Secondary electrons from the electrodes *G* and *H* are not troublesome, while secondaries from the target and target chamber are prevented from entering the tube by a large cylindrical electrode near the target which is maintained at a retarding potential of −90 volts.

The Generator as a Neutron Source

To have a measure of the output of the unit, neutrons from a lithium target bombarded by deuterons were used to activate a sheet of rhodium. This activity was then compared with that produced by a calibrated radon-beryllium neutron source. The lithium was forced into a water-cooled copper receptacle by means of an arbor-press. A current of 130 μa of unresolved deuterons bombarded the lithium from a potential of 475 kv. A sheet of rhodium was put between two 1-pound blocks of paraffin placed to one side of the target. Artificial radioactivity induced in the rhodium by the neutrons from the lithium-deuteron reaction was then recorded by a beta-ray counter and taken as a measure of the "neutron producing" efficiency of the unit. A multivibrator circuit[6] and vacuum tube, scale-of-eight counter,[7] were used for the measurements. Use was made of the 4.2-minute period only. The counting rate was much too great to be recorded accurately by this means in the first few minutes.

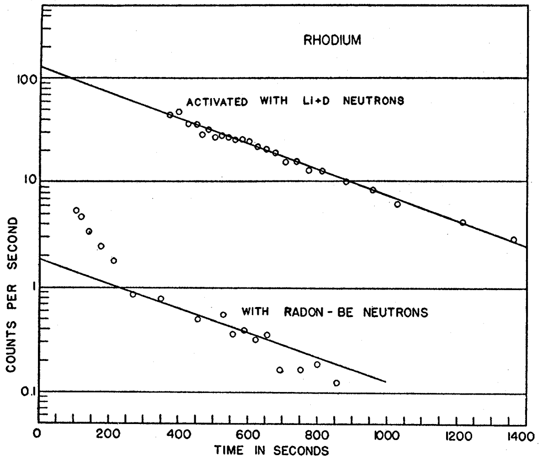

Fig. 6. Decay curves of rhodium activated by: (*a*) 190 mC Rn-Be 20 min. (*b*) neutrons from Li-D reaction for 20 min.

This activity was compared with that induced in the same sample of rhodium by a 190-millicurie radon-Be source, kindly prepared for us by Dr. Cramer Hudson. In this case, however, both the Rn-Be source and the rhodium were completely surrounded by paraffin. The beta-ray counter sensitivity was standardized for the measurements by checking with a radium source held at a fixed distance from the counter before and after each measurement. Fig. 6 gives the results of these measurements. The activity induced by the Li-D reaction neutrons in the rhodium sample was equivalent to at least that which would have been produced by 16.5 curies of Rn-Be. (No allowance was made for the fact that the geometry favored the Rn-Be source.)

This compares reasonably with the datum of Amaldi, Hafstad and Tuve[8] that at 475 kv the Li-D reaction gives 0.380 curie Rn-Be equivalent per μa of deuterons. If their figure is correct we can assume that our ion beam contained at least 36 percent deuterons.

Generator Housing

Recently that part of the apparatus shown in Fig. 1, namely: generator, h.v. body, voltmeter

---

* To prevent sparking along the tube, the corona points on the successive electrodes of the acceleration tube are arranged to point toward the next more positive electrode —never toward the more negative electrode.

[6] I. A. Getting, Phys. Rev. **53**, 103 (1938).

[7] E. C. Stevenson and I. A. Getting, Rev. Sci. Inst. **8**, 414 (1937).

[8] Amaldi, Hafstad and Tuve, Phys. Rev. **51**, 896 (1937).

and tube, has been enclosed in an air-tight, copper-lined room. A $\frac{3}{4}$-hp refrigerating unit has been installed which keeps the humidity below 20 percent in the most humid summer weather. With the introduction of freon at a partial pressure[9] of 5 lb./in.^{2} one might expect to obtain a potential of 1000 kv with a corresponding increase in charging current. If, at the same time, the ion current can be maintained, an increase in neutron yield of from 10- to 100-fold may be expected.

---

[9] Hudson, Hoisington and Royt, Phys. Rev. **52**, 664 (1937).

ACKNOWLEDGMENTS

The authors wish to express their indebtedness to Professor K. T. Bainbridge, who has advised on many difficult points; to Professors J. C. Street and J. G. Trump; and to Mr. A. Grant for considerable technical assistance. They wish to express their thanks to Mr. H. Leighton who is responsible for developing the technique of lining the Kovar capillaries for the ion source.

These developments were supported in part by grants in aid from the Milton Fund and from the Society of Fellows.

DECEMBER 1, 1939 PHYSICAL REVIEW VOLUME 56

Search for a Short Range Group of Protons in the D−D Reaction

F. E. MYERS, R. D. HUNTOON, C. G. SHULL, AND C. M. CRENSHAW
Department of Physics, New York University, University Heights, New York, New York

(Received October 2, 1939)

A thorough search for short range protons arising from the D−D reaction has been made at bombarding energies up to 300 kev, and at angles of 36°, 97°, and 142° to the incident deuteron beam. No evidence for such a group is found. The energy released in the reaction has been rechecked and is found to be in agreement with previous observations.

INTRODUCTION

BONNER'S recent confirmation[1] of previous experiments[2] indicates strongly the presence of a low energy group of neutrons in the reaction $H^2+H^2 \rightarrow He^3+n^1$. The tentative explanation of this group is that the He^3 nucleus is left in an excited state about 1.9 Mev above the ground state. Such an excited state cannot readily be accounted for theoretically,[3] and a search for gamma-rays,[4] internal conversion electrons and positrons[5] has led to negative results within an experimental error far below the expected intensities. In spite of these difficulties, the evidence for a low energy neutron group appears strong, and further study of the D−D reaction is desirable.

If one assumes that the only difference between the neutron emitting reaction and the proton emitting reaction is the Coulomb barrier encountered in the latter case, then there should be a corresponding short range group of protons, presumably accompanied by an H^3 nucleus in an excited state. These protons would be expected to have a range of about 5 cm at 90° to an incident beam of 200-kev deuterons. Myers and Langer,[6] and Hudspeth and Bonner[7] found none ejected in a small solid angle approximately at right angles to the beam of incident deuterons.

Since the angular distribution of the protons and neutrons is not spherically symmetrical[8] there must be in some of these nuclear reactions one or more quanta of orbital angular momentum and as has been pointed out to one of us by Ellett[9] there is a possibility that these inter-

---

[1] T. W. Bonner, Nature **143**, 681 (1939).

[2] T. W. Bonner, Phys. Rev. **53**, 711 (1938); Phys. Rev. **52**, 685 (1937); Baldinger, Huber and Staub, Helv. Phys. Acta **11**, 245 (1938).

[3] Simon S. Share, Phys. Rev. **53**, 875 (1938) and L. I. Schiff, Phys. Rev. **54**, 92 (1938).

[4] Arthur J. Ruhlig, Phys. Rev. **54**, 308 (1938); H. Kallmann and E. Kuhn, Naturwiss. **26**, 106 (1938).

[5] M. H. Kanner and W. T. Harris, Bulletin of Am. Phys. Soc., Princeton Meeting (June, 1939).

[6] F. E. Myers and L. M. Langer, Phys. Rev. **54**, 90 (1938).

[7] E. Hudspeth and T. W. Bonner, Phys. Rev. **54**, 308 (1938).

[8] Kempton, Browne and Maasdorp, Proc. Roy. Soc. **157**, 386 (1936). H. Neuert, Physik. Zeits. **38**, 122 (1937). Haxby, Allen and Williams, Phys. Rev. **55**, 140 (1939).

[9] A. Ellett, private communication to R.D.H.

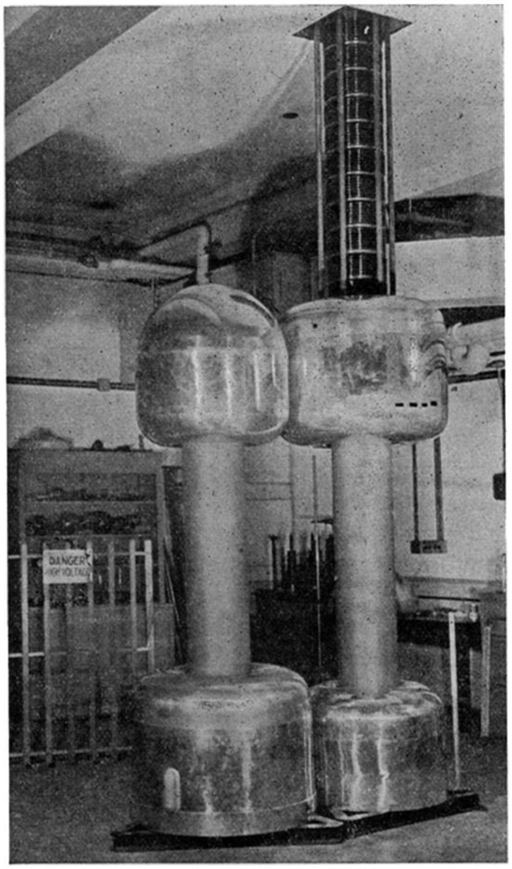

FIG. 1. Generator (left), high voltage body and acceleration tube.