I. LOW VOLTAGE POSITIVE ION SOURCES

II. THE PASSAGE OF FAST NEUTRONS THROUGH LEAD

by

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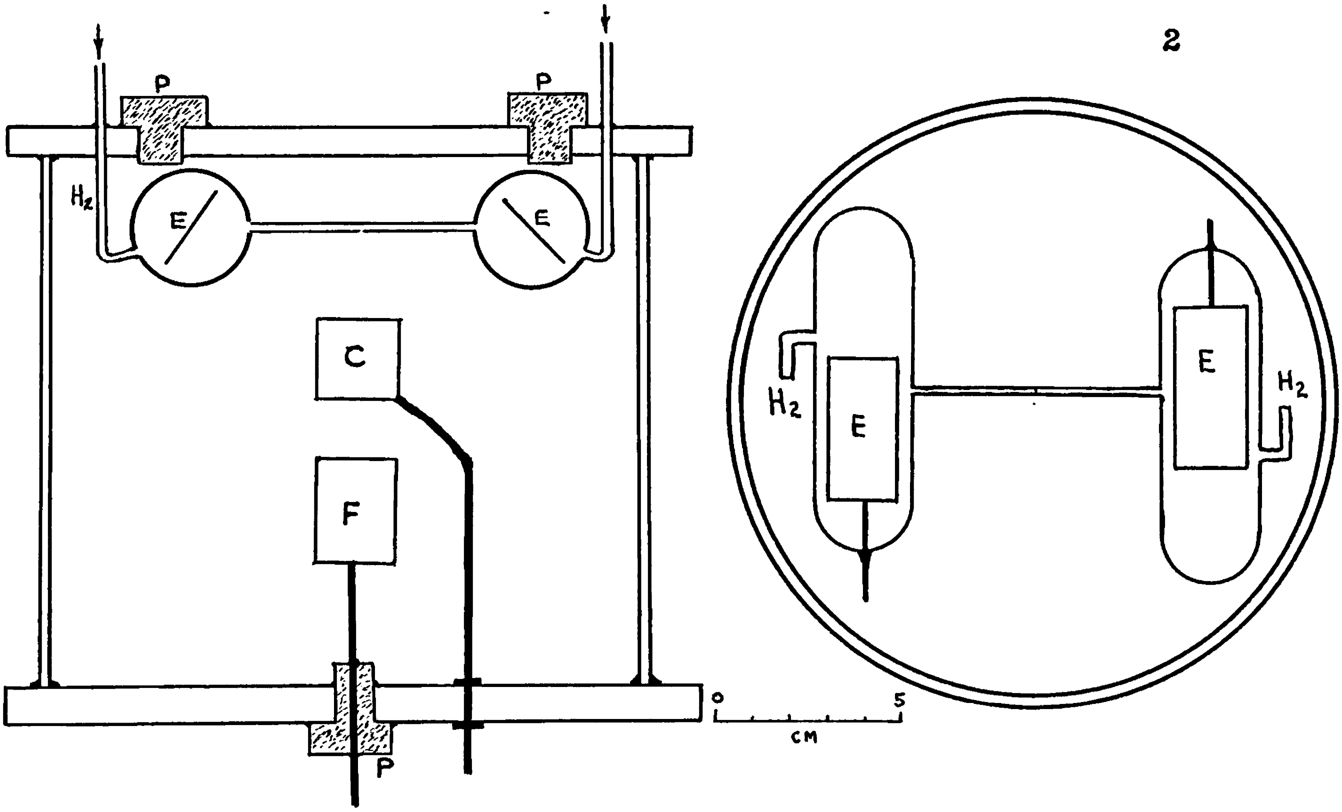
I. LOW VOLTAGE POSITIVE ION SOURCES

Since the pioneer work of Cockcroft and Walton[1] on the transformations of elements by bombardment with swift protons, various types of low-voltage positive ion sources have been developed.[2-5] The purpose of the following investigations has been to determine the possibility of developing a low-voltage positive ion source which could be operated without a filament. The advantage of this type of source is quite marked when used in conjunction with high-potential accelerating apparatus operating at several atmospheres pressure, for it would prevent troublesome filament replacements within the discharge tube.

The first ion source studied was a modification of a capillary tube type first described by Lamar and Luhr[2] and improved in design and total proton yield by Lamar, Samson, and K. T. Compton.[5] A pyrex discharge tube was constructed, having a metal anode and a filament of 20-mil molybdenum wire. The arc was constricted by a small capillary tube 3 mm in diameter; an outlet hole, drilled at about the center of the capillary and about 0.5 mm in diameter, permitted passage of the ions formed in the discharge to the field of the accelerating electrodes. A similar source was constructed, using a metal cathode instead of a filament. The apparatus is pictured diagrammatically in Figure 1.



SIDE VIEW

TOP VIEW

FIGURE 1

Two rectangular nickel electrodes, 2.4 cm in width and 4 cm long, were spot-welded to tungsten leads sealed into one-inch pyrex tubing. A capillary tube 3.5 mm in diameter and with walls about 1.0 mm thick joined the bulbs to form a discharge tube. A hole of about 0.4 mm diameter was drilled in the capillary tube at its center, or about 4 cm from either of the electrodes EE. To serve as gas inlets, two 6 mm diameter tubes were joined to the discharge tube as shown in the diagram. The gas used in these experiments was hydrogen obtained from a Kipp generator, though of course any gas may be introduced to obtain its ions.

To test this source the apparatus shown in Figure 1 was set up. A cylinder of pyrex glass, 15.5 cm in diameter

14 cm high, was used as a "vacuum system". On each end of the cylinder metal plates were sealed with Sealstix wax. Holes in the top plate served as inlets for the hydrogen tubes and the electrode leads; the leads passed through plugs of insulating textolite. The lower plate was connected by a small brass rod, which served as a support, to the aluminum cylinder C, which was three-quarters of an inch in diameter and an inch long. Directly beneath this cylinder was a Faraday cup F, which was also supported by a small brass rod, but which was insulated from the bottom plate by a textolite plug. The large pyrex glass cylinder was evacuated by a mercury diffusion pump operating with a Megavac mechanical pump.

The source of potential was a 2000-volt direct current generator of two-kilowatt capacity. A high resistance of copper sulphate solution was connected across the two metal plates sealed to the pyrex glass cylinder, and the generator furnished potential for the ion source and for acceleration. The cylinder C, being at the same potential as the lower plate and only an inch from the capillary hole outlet, was introduced to serve as a focusing aid. Thus it was hoped that most of the ion current would be recorded by a microammeter connected to the Faraday cylinder F. It was found that the focusing at voltages produced by the generator was not sufficient to bring the ions to so narrow a beam, and consequently the total ion current to the lower plate was measured.

In making test runs with the apparatus, the system was evacuated and a potential applied to the source and between the plates as described above. A small burst of hydrogen was then allowed to enter the discharge tube by opening pinch-clamps on the tubes which lead from the ion source to a small burette which was inverted over a beaker of water and served as a hydrogen container. The rise of water in the burette as the hydrogen flowed out thus indicated the rate of flow of the gas. The introduction of the gas into the ion source was usually sufficient to start a discharge, and a momentary current of three or four microamperes would be registered at the Faraday cylinder and bottom plate, indicating the arrival of positive ions (protons, ionized hydrogen molecules). However, the gas filling the region below the discharge tube increased the pressure immediately after a burst was allowed to enter to such an extent that internal spark-over occurred between the leads to the electrodes, and the discharge across the ion source ceased. This could probably have been eliminated by thorough insulation of the electrode leads and by the passage of very small currents, and correspondingly small gas flow, through the ion source; but the positive ion current would then have become inappreciable. Faster pumping speeds would possibly have been of value, but the gas flow necessary for operation of such a discharge would have become exhorbitant. The voltage drop across the ion source was about 500 volts with a discharge current of 7 milliamperes, and the gas flow necessary for operation was about 200 cc per hour.

In order to more closely simulate actual operating conditions for the ion source, a second type, similar in design to the source just described, was constructed. Two nickel electrodes EE (Figure 2), in the form of cylinders 4.6 cm in length, were sealed into bulbs of pyrex glass tubing three-quarters of an inch in diameter. A small capillary tube, similar to the one described in the first apparatus, joined the bulbs. Since the apparatus in which the tube was tested had high potential plates fixed at about 50 cm from the opening for an ion source, it was necessary to enclose the ion source itself in a long brass cylinder; long leads were provided for the electrodes and gas flow, and the ion source was so oriented with respect to the accelerating cylinders of the high potential apparatus that the capillary hole passed ions directly into the field. A potential of 1000 volts was placed across the electrodes, in series with several thousand ohms variable resistance. Again the discharge was started by the admission of a burst of gas into the source, and the current was measured at 6 milliamperes. With an accelerating potential of 50 kV or less the positive ion current showed

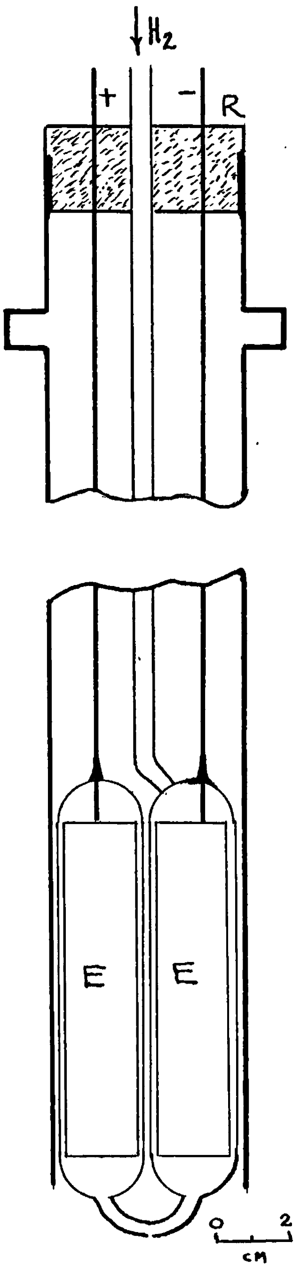


FIGURE 2

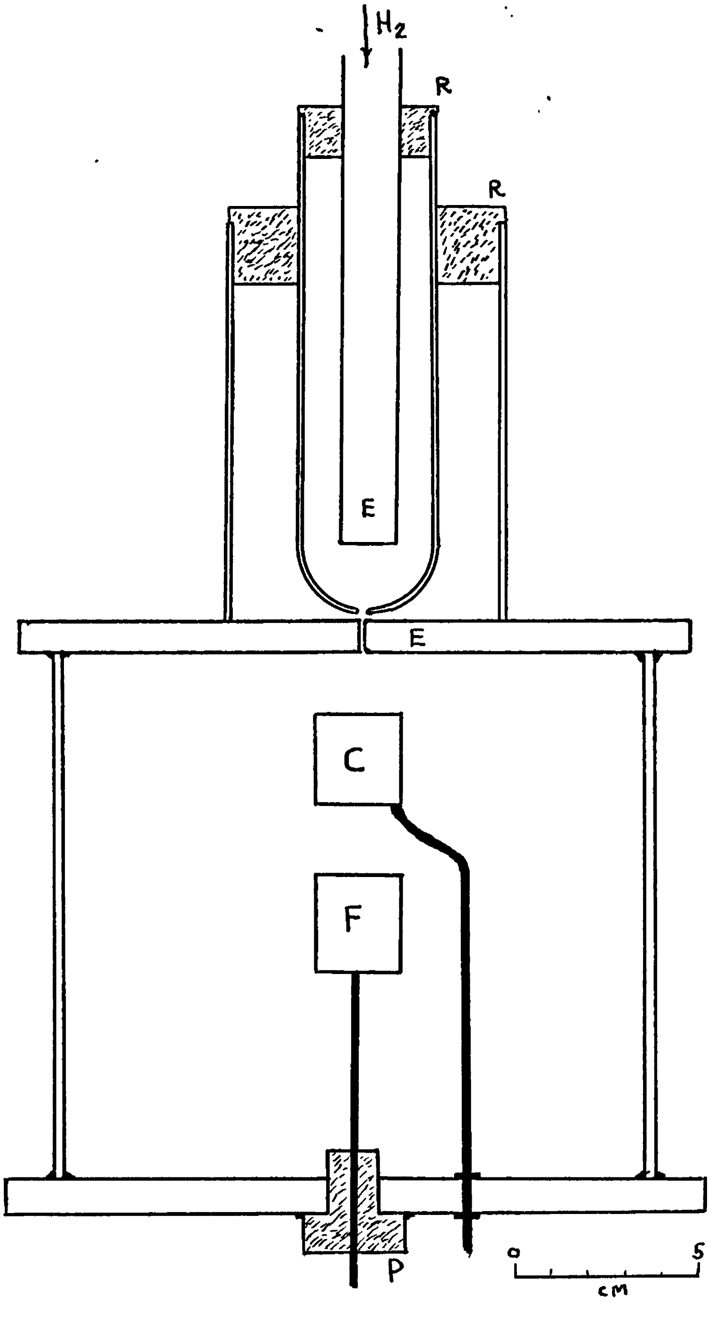


FIGURE 3

no stability and maximum values did not exceed a few microamperes. With potentials greater than 50 kV internal discharge occurred within the accelerating tube. The pressure developed within the system when the source was operating gave a Pirani gauge deflection of about 50 cm, as compared with 3 to 5 cm for the ion source ordinarily used with the high potential apparatus.

To obtain greater currents through the ion source itself, and a consequent larger positive ion current, it appeared necessary to increase the pressure within the source without appreciably altering the pressure in the system. This would diminish the rate of flow of the gas and help overcome internal sparkover due to increased pressure. In order to have the smallest possible voltage drop across the electrodes of the ion source, these should be made as large as possible. An apparatus meeting these requirements was constructed as shown in Figure 3. Utilizing the same accelerating system as that shown in Figure 1, the ion source had aluminum electrodes EE. Through the upper plate of the pyrex glass cylinder a hole 0.5 mm in diameter was drilled; this served as an outlet for the positive ions, and since the hole was nearly 1.8 cm in length, the gas flow was reduced considerably. An aluminum cylinder 7.6 cm in diameter was sealed to this upper plate, and these together served as a single electrode.

The second electrode consisted of an aluminum tube 0.7 cm in diameter, and hydrogen was passed through it into the ion source. The arc was constricted by placing a pyrex test tube of 1.9 cm diameter around the second electrode, and the discharge was forced to pass through a one-eighth inch hole in the bottom of the tube. A larger positive ion outlet hole and focusing rings, insulated to take up field potential, were not sufficient to constrict the gas flow. The length of the outlet also limits the positive ion current, so that it must not be too long.

With the apparatus as described and a potential between the plates given by two B batteries, various voltage was applied between the electrodes of the ion source. The corresponding positive ion currents to the Faraday cylinder and lower plate and the arc current are given in the following table:

P. D. Across Ion Source (volts)	Arc Current (amperes)	Hydrogen Flow (cc/hour)	Ion Current (microamp.)
380	0.20	180	4.0
390	0.30	180	6.0
400	0.33	180	8.0
420	0.40	180	10.0
450	0.50	120	7.0
570	0.40	60	4.0
690	0.44	120	13.0
800	0.60	40	5.0
1200	0.80	40	8.0
1410	0.90	30	12.0
1700	1.20	30	18.0

The ion beam was not analyzed to determine the relative abundance of the different types of ions. However the total current is somewhat too small for certain reactions, while it might possibly be used for other transformations of large yield. Proton currents of only one microampere were used by Cockcroft and Walton[1] in their early experiments, but their apparatus was later improved to yield currents of about 100 microamperes.[6] It should be pointed out that this was accomplished, in the absence of a filament, only when 20,000 volts potential was placed across the tube and an arc current of 10-100 milliamperes was passed. The anode was about a meter in length. Because of the high vacuum required in the system in which the tube is placed, there is no cooling of the walls by convection. It was therefore necessary to circulate transformer oil through insulating tubes in order to dissipate the heat. The cathode was run red hot, losing its energy by radiation. The ion beam at first consisted of nearly all molecular ions, but after operation the proton current was greatest.

In conclusion it should be pointed out that satisfactory results have been obtained with small positive currents derived from two-electrode ion sources. Difficulties inherent in this type are the dissipation of the heat energy associated with the necessary power for satisfactory operation and the satisfactory control of ion current. While the filament type source occasionally requires attention, it has been found that replacement is necessary only after quite long operation with low currents (corresponding to those given by the apparatus described above) are used. The life of a filament is further prolonged when only instantaneous currents are drawn, e.g. in photographing cloud chamber tracks from nuclear disintegrations.

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[4] Tuve, Dahl and Hafstad, Phys. Rev., 48, 241 (1935).

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II. THE PASSAGE OF FAST NEUTRONS THROUGH LEAD

The absorption of neutrons by passage through matter has been studied for many elements. Such observations have been made[1] by using ionization chambers to record the presence of ionizing nuclei projected by fast neutrons within the chamber. Dunning and his co-workers have thus been able to determine the mean free path of fast neutrons in various absorbers and to calculate the neutron-nucleus collision cross-sections. Their measurements are bas~~s~~ed on the assumption that the absorption of fast neutrons is due entirely to scattering.[2]

The interaction of neutrons and electrons has been studied by Dee[3]. The neutrons were obtained from bombardment of beryllium with the alpha-particles from polonium. The recoil tracks produced in nitrogen by such neutrons have been studied by Feather[4], using an automatic expansion chamber. The impact of a neutron from this reaction with an electron should communicate to the latter a maximum velocity of 6.6 x 10^9 cm. per second, which corresponds to an energy of 13,000 electron volts. The tracks of such electrons should be about 3.4 mm in length. Dee searched for such tracks and by their scarcity was able to set an upper limit to the number of ion pairs formed by fast neutrons. Although hampered by secondary beta-rays and the background of drops produced by other ionizing products (protons), he demonstrated that the probability of interaction of a neutron with an electron is less than one per cent. of the probability of similar interaction with a nitrogen nucleus and that the ionization along the path of a fast neutron is less than one ion pair per three meters of air.

Other workers[5,6] have studied the interaction of neutrons with matter to produce gamma-rays, but such processes involve a nuclear reaction with the absorber.

Since in none of these experiments continuous energy losses by a neutron in traversing matter would have been observed, it is the purpose of the present work to compare the energy distribution of neutrons before and after interposing an absorber.

A diagram of the apparatus used is shown in Figure 1; the circuit used to produce the accelerating potential is represented by Figure 2. The ion source (Figure 1) was supplied with heavy hydrogen which diffused through a hot palladium leak. The source itself contained a spiral tungsten filament made of 10 mil "Caltung" and was operated at 1000 volts from a transformer. Ions produced in the source may pass through a one-eighth inch outlet in the bottom of the ion tube and enter the field produced by the high voltage transformer (Figure 2). Here

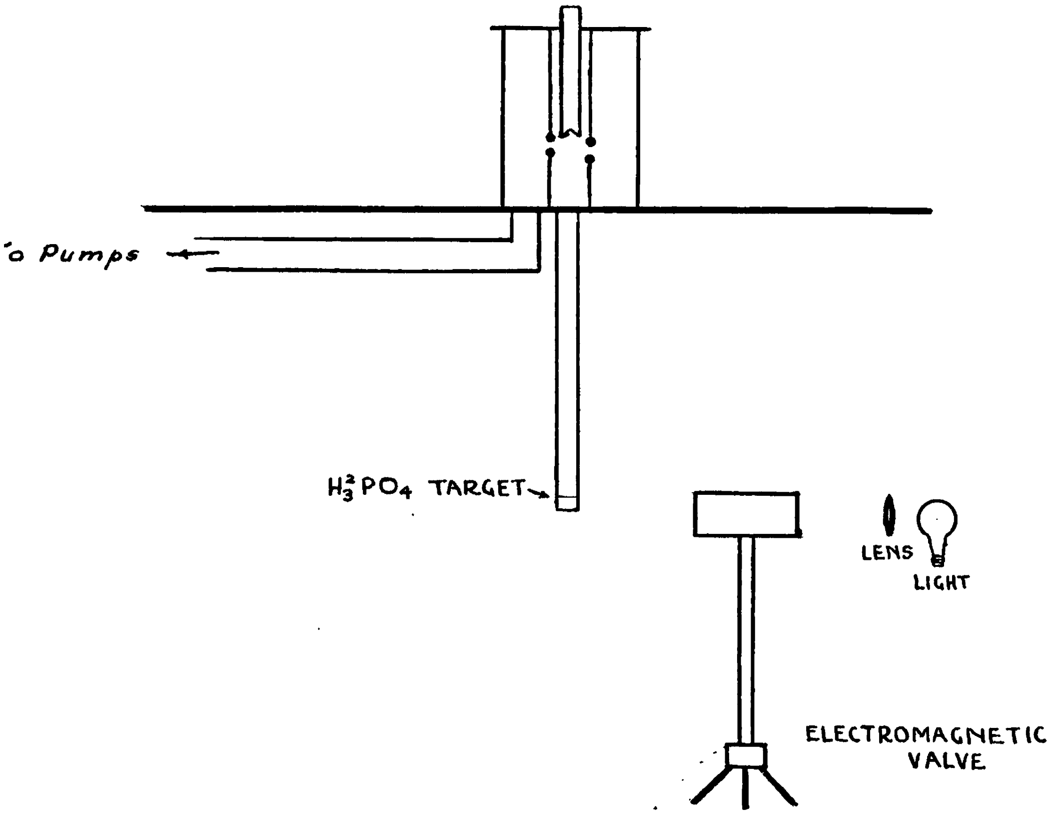


FIGURE 1

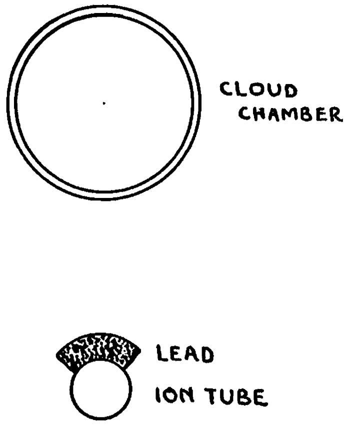


FIGURE 3

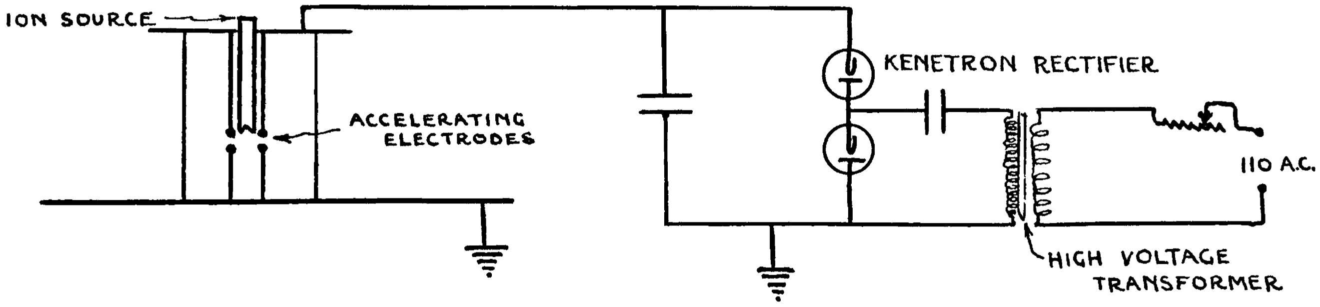


FIGURE 2

they are focused and accelerated, in this work, to an energy of about 110 kV, and pass into the long glass tube beneath the accelerating electrodes. At the bottom of this tube is placed a brass cup which contains a heavy hydrogen target. The target is phosphoric acid, used because of its low vapor pressure, and is prepared by the action of heavy water on phosphorous pentoxide.

When the swift ${}_1H^2$ ions produced as described above strike the ${}_1H^2$ nuclei contained in the target, the following reactions, of about equal probability, are thought to occur:

$${}_1H^2 + {}_1H^2 \rightarrow {}_1H^3 + {}_1H^1$$

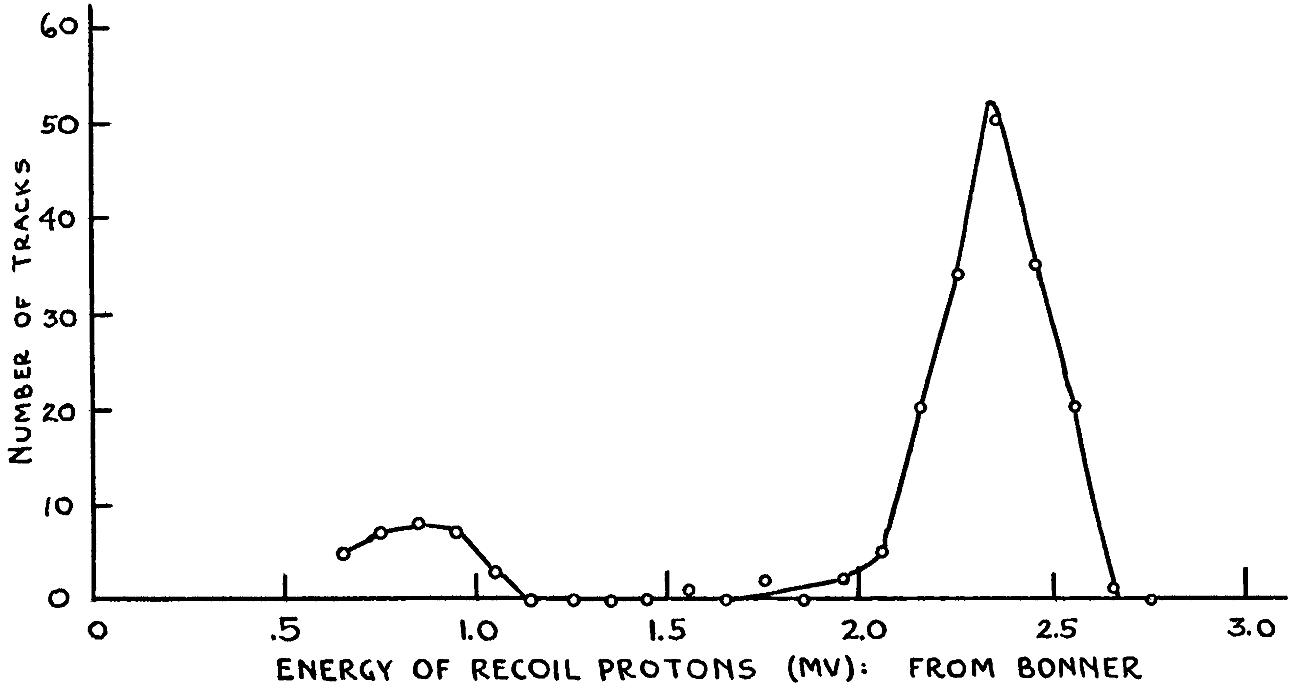
and

$${}_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1.$$

Both of these reactions have been studied by observing the energy of the protons or of the recoil protons produced by neutrons in a cloud chamber. With the apparatus set up as shown in Figure 3 except for the lead absorber, Bonner[7] has obtained the energy distribution curve for the recoil protons which occur in the second of the two possible reactions. The products in the first reaction and the ${}_2He^3$ are of course absorbed within the target wall. The neutrons are supposed to pass from the target and into the cloud chamber without appreciable loss of energy; here they may produce elastic collisions with hydrogen nuclei, imparting to them various fractions of their energy depending on the angle of collision. Those protons which are projected in the forward direction in the chamber have received very nearly all of the original energy of the neutron, since the mass of the neutron and proton differ by a negligible amount. Hence to obtain the energy distribution of the neutrons only those protons which are projected in the forward direction (within 10°) are selected for measurement of track length. For such experiments the gas within the cloud chamber should contain as much hydrogen as possible (keeping the stopping power at a reasonable figure), and hence in this case methane (CH_4) was used. The stopping power was obtained from the range of polonium alpha-particles ejected from a source inside the chamber.

Under such conditions, Bonner[7] obtained the distribution curve shown at the top of page 16. It is interesting to note that a careful study of the recoil protons from the reaction between heavy hydrogen showed the presence of a low energy group of neutrons of energy about 1.1 MV, which indicates the existence of an excited He^3 nucleus.

This experiment was now repeated with a lead absorber of 3 cm thickness interposed between the target and the cloud chamber. About 5600 stereoscopic pictures


NUMBER OF TRACKS
60
50
40
30
20
10
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.5
1.0
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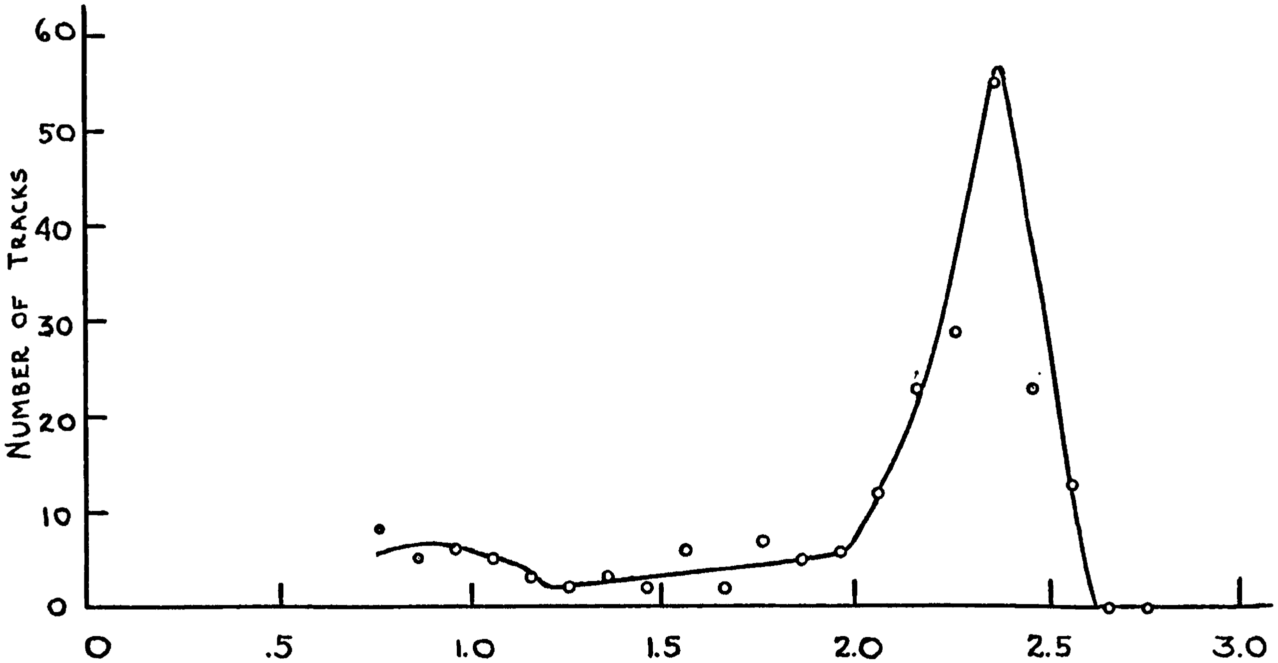
3.0
ENERGY OF RECOIL PROTONS (MV): FROM BONNER


NUMBER OF TRACKS
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ENERGY OF RECOIL PROTONS (MV): ABSORBER INTERPOSED

of cloud chamber expansions were made, and from the recoil proton tracks observed 215 were found which satisfied the condition that they be within 10^{o} of the forward direction. During operation pictures were taken on standard 35 mm moving picture film about every 30 seconds. The ion source, operating to yield a deuteron (and other positive ion) current of about 50 microamperes, was turned on just preceding an expansion, a burst of heavy hydrogen which had diffused through the hot palladium leak was permitted to enter, and immediately thereafter the chamber was expanded and the camera shutter opened for about one-fifth of a second. The pictures so obtained were re-projected through the same camera oriented in a fixed manner with respect to a mirror which produced an image of the cloud chamber for stereoscopic photography. Thus the plane of the tracks was determined. By following this procedure the 215 tracks referred to above were obtained.

By reference to the second graph on page 16, which shows the energy distribution of the recoil protons obtained after passage of the fast neutrons through 3 cm of lead, it is immediately obvious that the effect of the absorber is quite small. The maximum energy of the recoil protons is apparently about 2.63 MV, which is equal, within the experimental error of 0.1 MV in this work, to the maximum energy of the recoil protons obtained in the absence of the absorber, which was 2.66 MV. These protons have a track length of about 11.5 cm. This result demonstrates that there was no large continuous loss of energy by neutrons in their passage through the lead absorber.

Between 1.2 and 2.0 MV, 30 tracks were observed in this experiment, while Bonner had previously observed only three tracks in this interval. This indicates that about 15% of the high energy neutrons make inelastic collisions in the lead with energy losses of from 0.5 to 1.3 MV. Using Dunning's[1] value of 6.09×10^{-24} cm^2 for the collision cross-section of a fast neutron in lead, one finds that about 50% of the neutrons would make elastic collisions. Because of the great difference in the mass of a neutron and a lead nucleus, elastic collisions of the usual type would result in only a slight diminution in the energy of a fast neutron, regardless of the angle through which it is scattered. Furthermore, only neutrons scattered less than about 10° (see Figure 3) by the lead absorber could enter the cloud chamber.

Bethe[8] has pointed out the possibility that elastic collisions between a fast neutron and a heavy nucleus might result in a much greater decrease in the energy of the neutron if it actually entered the nucleus (instead of suffering an elastic rebound); here it could impart energy to various protons and neutrons comprising the nucleus itself, finally emerging with only a fraction of its original energy, or nearly "thermal" velocity. While this is a point of interest, such interactions would show no decrease in the maximum energy of fast neutrons after passage through an absorber; no continuous loss of energy can result from this process, as this experiment shows.

Two processes in addition to elastic collisions may account for the loss of neutron energy by passage through an absorber: (1) The neutron may escape capture but cause a nuclear re-arrangement, or (2) a non-elastic collision may result, yielding an excited nucleus and a subsequent gamma-radiation. Dee[3] has already shown that the cross-section for interaction between a fast neutron and an electron is exceedingly small (surely less than 1.6×10^{-23} cm^2). Hence one may properly conclude: (1) That the maximum energy of fast neutrons in the lead absorber is unaffected within the experimental error, and that there is therefore no continuous loss of energy by fast neutrons under these conditions; (2) that about 15% of the high-energy fast neutrons make inelastic collisions of the two types[9] given above.

For many suggestions and for direction of my work during this year I am warmly grateful to Professor H. A. Wilson. I am keenly indebted also to Dr. T. W. Bonner, with whom I was privileged to work in the study of neutrons cited in the second half of this paper. His apparatus was generously appropriated for a test of the second ion source described.

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