this demonstration the high sweep-rate of 60 cycles per second is made possible by limiting the experiment to a test solution of ferric nitrate. Few substances are so responsive.

Incidentally, the magnetic-resonance spectrometer can also be used for measuring the strength of magnets. The magnet to be tested supplies the biasing field. It is modulated as described above, and the oscillator is adjusted to resonance. The strength of the unknown field in gauss is equal to the frequency of the oscillator when it is at resonance divided by 4,228.5.

4

A HOMEMADE ATOM SMASHER

DIY high vacuum molecular diffusion pump mercury (!) or oil

For less than the average cost of a set of golf clubs, you can equip yourself for playing with electrons — the minute "spheres" surrounding the atom. With this apparatus you can transmute the elements, alter the properties of some common materials and, incidentally, learn much at first hand about the structure of matter. F. B. Lee, a chemical engineer and faculty member of the Erie County Technical Institute in Buffalo, N. Y., tells how to build and operate the machine. Some safety measures are suggested on page 359

THE PARTICLE ACCELERATOR, more popularly known as the "atom smasher," has about the same relationship to nuclear physics that the telescope has to astronomy. The accelerator probes the microcosm; the telescope, the macrocosm. Like the telescope, the accelerator can open exciting vistas to the amateur. But unlike the telescope, the accelerator has failed to attract a large amateur following. The notion seems to have got around that a small particle accelerator is little more than a toy. But in 1932 the British physicists J. D. Cockcroft and E. T. S. Walton did important pioneer work in nuclear physics with a 150,000-volt accelerator of the electrostatic type which today can be built for less than $100. With it Cockcroft and Walton succeeded in transmuting lithium into unstable beryllium, which then broke down into helium with the release of energy on the order of 17 million electron volts – scarcely the performance of a toy. A beam of particles from a machine of this size is capable of cutting the time of chemical reactions, of inducing mutations in living organisms, of altering the physical properties of organic compounds and of producing scores of other interesting effects.

The beam of the machine to be described is brought outside of the apparatus for irradiating targets of substantial area in the open air. The energy of the particles spans a relatively wide range. It is, therefore, of principal interest to the amateur chemist. The physicist usually requires a closely collimated beam in which all particles have about the same energy, whereas the chemist is satisfied with a more diffuse beam in which the energy of the particles varies considerably. Since the targets irradiated by the chemist are usually rather thick, it is almost impossible to provide all sections of the irradiated material with electrons of uniform energy even if this were desirable. Fortunately it is usually satisfactory to have a large percentage of the electrons penetrate the target completely.

The ions produced within the target by the beam are largely independent of the energy of the beam, but the permissible thickness of the target increases with the accelerating voltage. Electrons accelerated to an energy of 250,000 volts will penetrate metallic aluminum to a depth of about .25 millimeter; polyethylene, to a depth of some three millimeters; air, to a depth of some two meters. The depth of penetration is roughly inversely proportional to the density of the target material and to the square of its atomic weight.

With the machine I shall describe amateurs can perform endless experiments based on the ionization of target materials by electrons. In the case of hydrocarbon targets numerous hydrogen atoms are dislodged from their sites in the molecule by the stream of fast-moving charged particles. Some of the atoms promptly combine into molecules of hydrogen (H_2) and escape as gas. Pairs of carbon atoms so stripped can then combine to cross-link the hydrocarbon molecules.

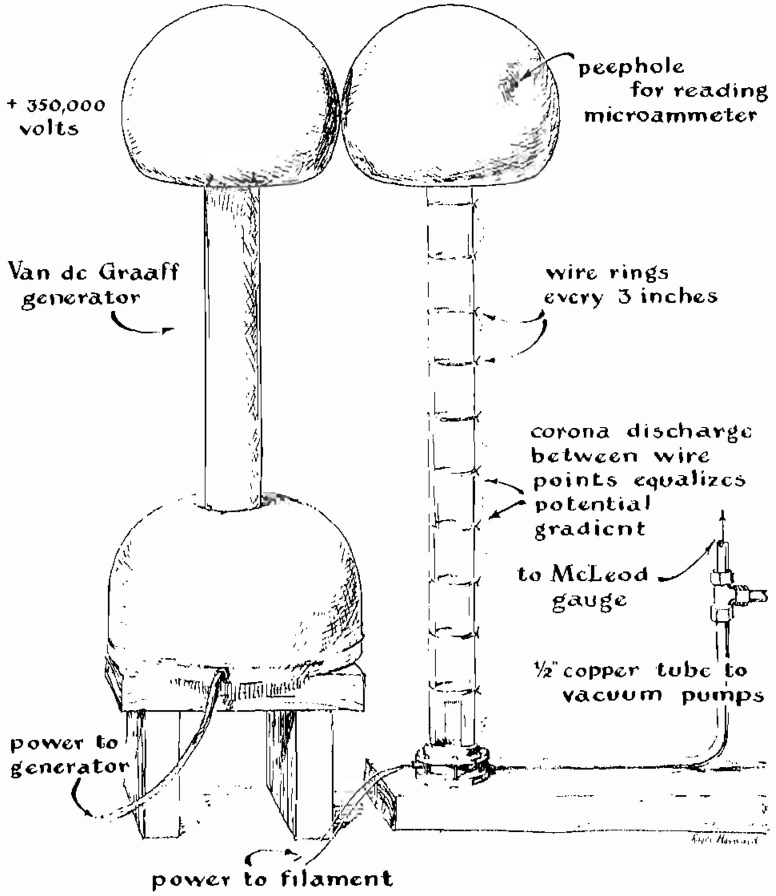
Such cross-linking has a profound effect on the physical properties of the irradiated substance. For example, when molecules of the plastic polyethylene are cross-linked by irradiation, the plastic becomes much harder and melts at a higher temperature. The field is new and full of opportunities for the amateur.

The electrostatic accelerator may be thought of as a highly developed two-element electronic tube. It consists of an evacuated tube fitted with a source of electrons or protons at one end, an accelerating electrode at the other end, and a high-potential electric field between the two. If the accelerating electrode is made positive and the source is either a filament, a radioactive or photoelectric surface, or even a sharp point of metal, the resulting beam will be composed of electrons. If the accelerating electrode is made negative and a tiny amount of hydrogen is admitted to the tube, the gas will ionize and the beam will consist of hydrogen nuclei (protons).

The major requirements for constructing a linear accelerator are a source of high potential and a vacuum system capable of reducing atmospheric pressure (760 millimeters of mercury in a mercury manometer) down to .00001 mm. of mercury. The high potential may be generated by a Van de Graaff machine such as those described in Section IX. A machine capable of delivering 20 millionths of an ampere (20 microamperes) at a potential of 500,000 volts can be built for less than $30.

The tube for my accelerator was constructed from a junked piece of Pyrex pipe two inches in diameter and about three feet long. A 24-inch length would have been preferable, but the dimensions are not critical. A hardwood plank eight inches wide, two inches thick and five feet long serves as a common base for the accelerator and vacuum pumps.

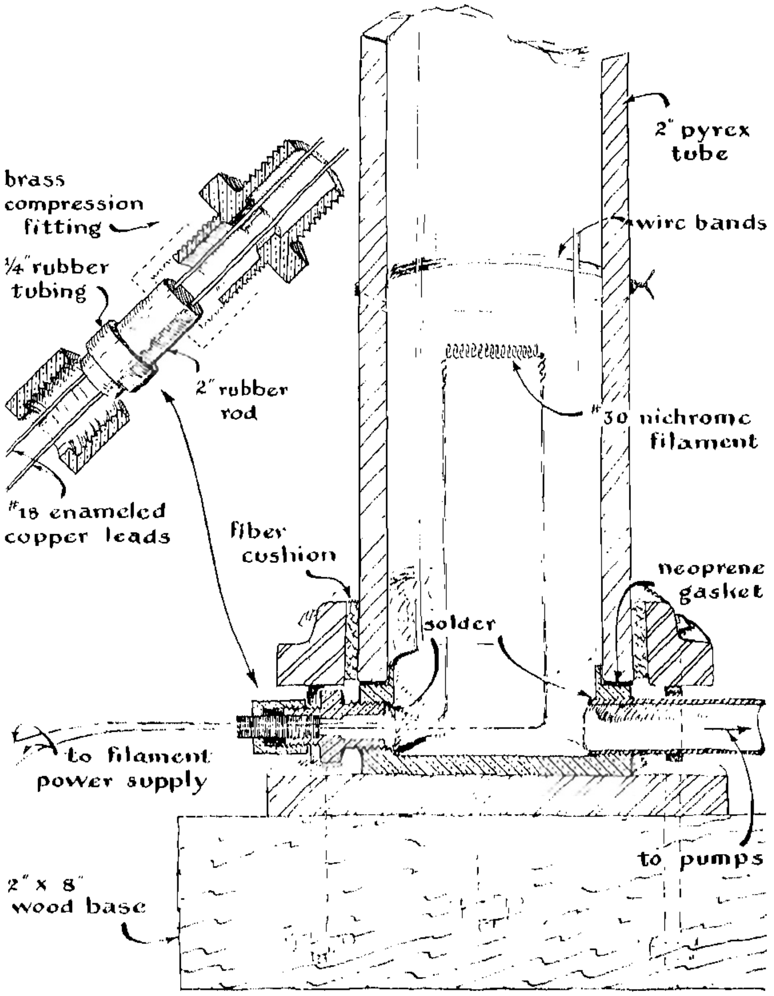
The accelerator tube is mounted vertically near one end of the base, as shown in the accompanying drawing [*see Fig. 149*]. The cathode fitting, which closes the lower end of the tube, was machined from a piece of brass 2½ inches in diameter and one inch thick. A hole is drilled in one wall to receive the half-inch copper pipe which connects the tube to the vacuum pumps. Another hole,



149
An electrostatic particle accelerator with a Van de Graaff generator as its power supply

in which an eighth-inch pipe thread is cut, receives a standard quarter-inch compression fitting which serves as a gland for the filament assembly.

The filament assembly is comprised of a quarter-inch rubber rod about half an inch long, through which two No. 18 enameled copper lead wires are run to support a half-inch length of No. 30 Nichrome wire. The lead wires were coated with vacuum grease before they were forced through the holes in the rod. The rod was then greased lightly and slid into the compression fitting, after which a collar of rubber tubing was slid over it. Finally the compression nut was run home to seal the assembly. Details of the gland



150
Filament assembly and base seal of electrostatic accelerator tube

are shown at upper left in Figure 150. The entire unit is vacuum-tight, easy to assemble and has given no trouble.

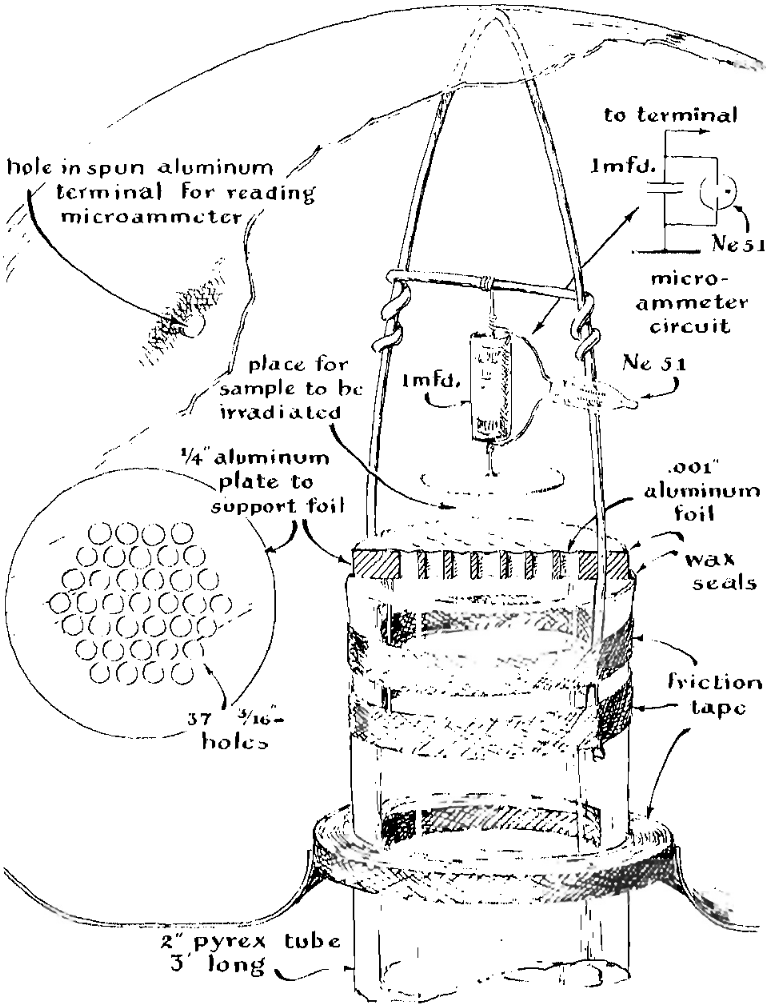
With the Van de Graaff machine suggested, the tube develops a beam of only 10 to 20 microamperes, and the filament operates at a proportionately low temperature. The optimum filament-temperature must be determined experimentally. The temperature is controlled by a rheostat in series with the power supply, which may be a simple doorbell transformer. When the temperature is too high, excessive emission lowers the resistance of the tube and consequently the voltage of the Van de Graaff machine. Lowered tube-voltage of course means lowered beam-energy.

In contrast, low filament-temperature results in scanty filament-emission, which lowers the beam current and increases the tube resistance. Thus at low filament-temperature the tube develops maximum voltage, and proportionately higher energy is imparted to individual particles in the beam. This compensates somewhat for the lower beam-current. For this reason downward departures from the optimum value of the filament temperature are preferable to upward departures.

The electron beam is restricted to the axis of the tube by a symmetrical electrostatic field established by a series of rings spaced at three-inch intervals along the tube. The rings consist of four turns of 26-gauge bare copper wire. The ends of the wire are twisted tightly enough to hold the coil in place on the glass and are spread about half an inch apart. The points so formed act as corona electrodes and pick up charge from the surrounding air until electrical equilibrium is established between the air and the rings. In larger tubes, fixed resistors are substituted for the corona points. This, however, is not necessary in machines operating at 500,000 volts or less.

The upper end of the accelerator is closed by a window of aluminum foil through which the beam passes into the air. To prevent the foil from rupturing under atmospheric pressure, it is supported by an aluminum grid made of quarter-inch aluminum plate. The plate is drilled with 37 holes 3/16 of an inch in diameter and arranged in a hexagonal pattern [*see Fig. 151*]. Approximately 50 per cent of the grid area is thus open. The grid is cemented to the upper end of the tube with vacuum wax. The foil window, which should not exceed .001 inch in thickness, is similarly cemented on top of the grid.

High-vacuum equipment is sealed with special waxes which have a low vapor-pressure, *i.e.*, they evaporate so slowly that their vapors exert very little pressure. These include de Khotinsky wax, which has a vapor pressure of one micron of mercury; Dennison waxes, with a pressure of .01 micron; and Picein and Apiezon-W waxes, with a pressure of .00001 micron.



151
Details of anode window and microammeter for the accelerator

The experimental physicist John Strong recommends a wax made by melting together equal parts of beeswax and rosin. The vapor pressure of this mixture approaches that of Picein and Apiezon-W. It is applied smoking hot with a medicine dropper, and though it adheres well to cold surfaces, it is good practice to warm the glass or metal parts on which it is spread.

I used Picein, which chanced to be available. The parts were heated to the softening point of the wax, after which the joints were rubbed with the wax until a thin coating adhered. The pipe and grid were then pressed together until the wax set. Next the side face of the grid was coated, and the foil was pressed in place. The seal was completed by applying a thin bead of wax around the outside edges of both joints.

A loop of 12-gauge brass wire was then attached to the top of the tube by friction tape as a frame to support the 12-inch spherical terminal. A simple microammeter, which consists of a high-resistance capacitor of one microfarad bridged by a 1/25-watt neon tube, is also supported by the frame. The input terminal of the microammeter is a 1½-inch disk of 12-gauge sheet aluminum supported by one axial lead of the capacitor at a height of 3/4 inch above the aluminum window. The remaining lead of the capacitor is soldered to a cross wire attached to the brass loop [*see Fig. 151*].

The electron beam enters the disk and eventually charges the capacitor to the firing potential of the neon tube, which then flashes and discharges the capacitor. A current flow of one microampere causes the tube to flash at 15-second intervals, the flashing rate being proportional to the intensity of the beam current. A dimple roughly two inches wide and half an inch deep is made in the spherical terminal opposite the neon tube, and a quarter-inch peephole is drilled at the bottom of the depression.

The dimple prevents the concentration of a strong electrostatic field at the sharp edge of the hole and the loss of current through corona discharge. The neon tube can be observed safely at a distance of about two feet. The positive terminal of a 350,000-volt Van de Graaff generator is placed in contact with the accelerator terminal as the source of accelerating potential. Samples of material to be irradiated, such as hydrocarbon compounds or seeds, are placed on a carrier of thin polyethylene sheet between the aluminum-foil window and the disk electrode of the microammeter.

The accelerator tube must be evacuated to pressure on the order of .01 micron of mercury to prevent excessive collisions between the accelerated particles and molecules of gas. Molecules ionized by such collisions are accelerated toward the filament as positive ions, collide with other molecules and at high pressures create still more ions until the resulting avalanche of charged particles paralyzes the tube. At a pressure of .01 micron, gas molecules have a mean free path of 15 feet or more, and collisions are accordingly infrequent.

A vacuum of this quality requires elaborate pumping equipment and extreme care in eliminating leaks. The most inexpensive commercial equipment capable of attaining the desired pressure is priced at about $200; hence there is substantial inducement beyond the mere challenge of an interesting problem to use a home-built substitute – such as the compressor units from old refrigerators.

~$1,610 in 2016

A rough vacuum of 20 millimeters or so is easily pumped either by a water aspirator or a refrigerator compressor (connected backward). Higher vacuums may be attained by connecting two refrigerator compressors of the rotary type in series to make a two-stage unit. Compressors of the piston type are not satisfactory unless they are modified, because the inlet valve which is actuated by gas pressure stops working when the system has been pumped down to a pressure of about 30 millimeters.

It is possible to make a 50 per cent improvement in the performance of piston compressors by bypassing the inlet valves. Rotary compressors, such as are used in the Frigidaire, have no valves and are easily adapted to multistage use. My system uses two secondhand units, one of the piston type and the other of the rotary, as "roughing" pumps. These were purchased from a local dealer in used iceboxes for $5 each, including the motors.

The intake valve of the piston unit was bypassed by drilling a hole in the side of the cylinder just above the low point of the piston's travel. A short length of copper tubing was brazed to this port as the new intake. The piston covers the port as it ascends, thus eliminating the need of gas pressure to actuate the inlet valve. The intake of this unit is connected by a hose to the discharge port of the rotary compressor. A system of pipes and valves permits the discharge from the rotary compressor to be connected either to the intake of the piston unit or to a two-gallon vacuum reservoir.

A similar system of pipe- and valve-connections permits the intake of the rotary compressor to be connected either to the outlet of a diffusion pump or to the reservoir. Connected in tandem and exhausted into the air, the pumps will reduce the pressure to about one millimeter. But by exhausting into the two-gallon reservoir (previously pumped to a pressure of one mm.) it is possible to obtain a final vacuum of about .1 mm.

13.3 Pa
(medium vacuum)

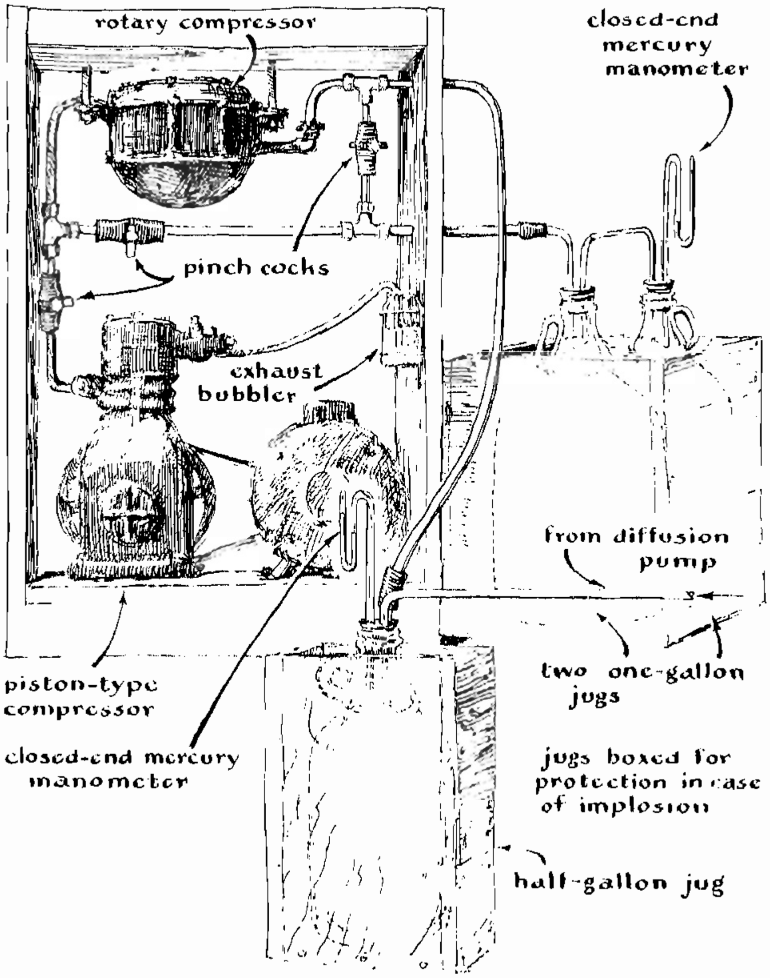
Special oils of low vapor-pressure must be used for lubrication. The pumps are first drained of conventional oil, then filled with about half a pint of paraffin oil, operated for 10 minutes and drained. If the paraffin oil shows traces of the old oil, the pumps are again flushed with paraffin oil.

They are now filled with vacuum oil. Some volatile fractions may still remain. These can be removed by several hours of operation. Unlike conventional vacuum pumps, refrigerator compressors have large areas of contact between the oil and gas on the discharge side of the pump and are accordingly susceptible to volatile fluids.

My vacuum reservoir consists of a pair of one-gallon glass jugs connected with the pumps by half-inch copper pipe inserted through rubber stoppers coated with vacuum grease. The reservoir is first exhausted by the tandem pumps. The pinchcocks are operated to switch the reservoir to the output of the rotary compressor. If the system does not liberate too much gas, one pumping of the reservoir will last many hours.

The final pressure at which the tube works is achieved by means of a diffusion pump. A half-gallon reservoir is connected between the inlet of the rotary pump and the exhaust of the diffusion pump. Pressure in both reservoirs is indicated by a manometer connected as shown [*see Fig. 152*]. When the pressure of either reservoir rises above three millimeters, it is reconnected to the inlet of the rotary unit and pumped down to one mm.

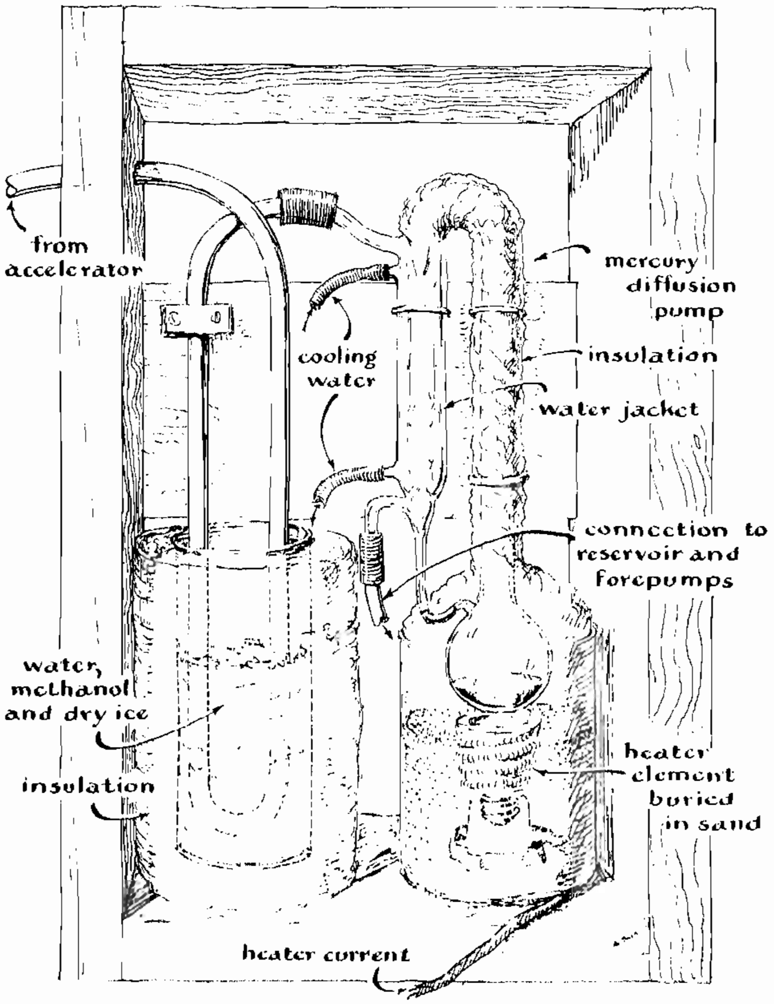
My attempt to make a mercury diffusion pump from spare pipe-fittings did not succeed. I must confess, however, that I did not try very hard. The project should not be difficult for those with access to machining facilities. Diffusion pumps of various designs and capacities are available on the market from $30 up, but a local glass blower turned out one for me at $15. He is willing, for the time being, at least, to supply amateurs with duplicates at this price, plus packing and shipping charges. I will be glad to make the necessary arrangements with him on request. Small pumps require about three pounds of mercury, which costs about $12. A heating unit ranging from 100 to 300 watts must also be provided for vaporizing the mercury. My pump [*see Fig. 153*] was made to operate against a back pressure of about four millimeters. Judging by the literature,



152
"Roughing" pump and reservoirs for vacuum system of the accelerator

many commercial pumps require a back pressure of .3 mm. or less. In general, the rate at which diffusion pumps remove gas from the system varies inversely with the back pressure against which they operate.

The ultimate pressure they produce depends on the vapor pressure of the pumping fluid, which includes various oils in addition to the mercury. Vapor pressure, in the case of mercury pumps, establishes a lower limit of one micron (.001 millimeter) unless the system is equipped with a trap to prevent the mercury vapor from entering the evacuated vessel. A cold trap made by refrigerating



153
Mercury diffusion pump and cold trap for the vacuum system

1.33 mPa
(high vacuum)

part of the plumbing between the diffusion pump and the accelerator tube enables the pump to achieve a pressure of .01 micron if the temperature of the trap is maintained at minus 40 degrees centigrade.

My trap consists of a U-shaped section in the half-inch copper line. The section is inserted in a tin can insulated by a half-inch layer of cardboard covered by aluminum foil. The cooling mixture consists of equal parts of water and wood alcohol to which crushed dry ice is added as required. The trap is not chilled until the system has been pumped to one or two microns. This procedure prevents the formation of ice in the trap which will subsequently release water vapor as low pressures are attained, and thus increase the pump-down time substantially.

The mercury is vaporized by a unit from a radiant heater to which an extra winding was added to reduce its rating to 150 watts. The heater is mounted in a tin can and buried in sand up to the top of the ceramic cone. Heat radiated from the center of the cone is sufficient to energize the pump. A 150-watt incandescent lamp would doubtless work as well. In selecting a site for the apparatus keep in mind that most diffusion pumps require a supply of cooling water.

Once the vacuum system is complete, the easy part of the job is ended. One then locates and seals the leaks. This tedious procedure can consume days or weeks depending upon the experimenter's luck and the efficiency of his leak-detection gear.

At least three closed-end mercury manometers should be provided. These consist of quarter-inch glass tubes about 24 inches long. If soda-lime glass is used, one end can be sealed over a Bunsen burner. A short section six inches from the closed end is then heated to softness and bent 180 degrees so that it lies parallel to the long portion of the tube. The long portion is then heated at the point opposite the closed end and similarly bent 180 degrees. The result is a flat "S."

Enough mercury is introduced into the tubing to fill the closed leg of the "S" and about 20 per cent of the center leg. This can be accomplished by placing the tube in a reclining position and rocking it as the mercury is introduced into the open end. The closed leg must be completely filled without a trace of bubbles. One manometer is inserted in each of the reservoirs and another is temporarily connected to the accelerator tube.

The roughing pumps are now started. If the mercury has not separated from the closed end of the manometer at the end of 15 minutes, the tube may be tapped gently. If this does not cause separation, check the pumps for faulty operation. After the pressure has been reduced to about one millimeter, the individual elements of the system should be isolated by closing all pinchcocks.

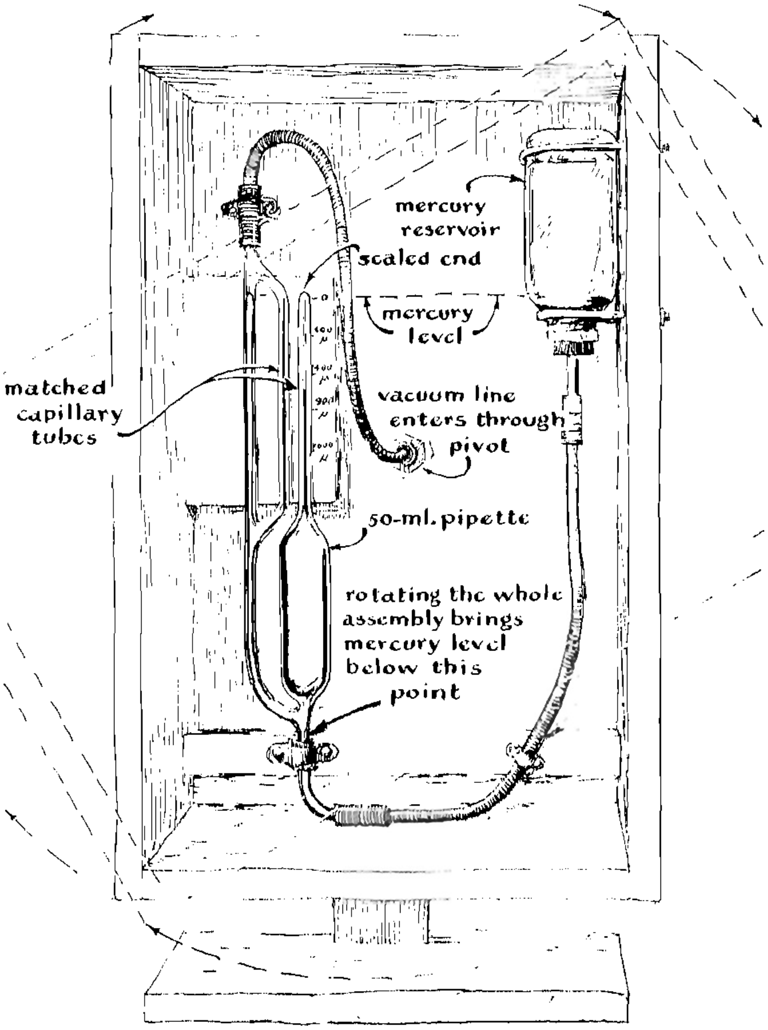
The pumps are then stopped. The manometers may be provided with cardboard scales calibrated in arbitrary units. Manometer readings are recorded at the end of the pump-down and compared with a second set of readings made after an interval of 12 to 24 hours. Each section of the system will doubtless show a rise in pressure. Vacuum grease is then applied to all joints where a leak is suspected and the procedure is repeated. Ultimately the system will appear to be tight. A run can then be attempted with the diffusion pump in operation.

In my system a pressure of one micron is achieved at the end of about 30 minutes, and a usable vacuum in the accelerator tube is attained about eight hours later. The roughing pumps are used for about an hour or until the tube pressure drops to .5 millimeter, after which they are valved off and shut down. The half-gallon reservoir on the outlet of the diffusion pump has sufficient capacity to receive the exhaust for several days of continuous pumping.

Most experimenters will want at least one high-vacuum gauge of the McLeod type to check leaks too slow to show on the manometers. The McLeod gauge operates on the principle of trapping gas in a chamber of substantial volume and then compressing it by a column of mercury into a closed capillary tube. The pressure of the compressed gas is then compared with that in the vacuum system by observing the difference in height to which a column of mercury rises in a matching capillary connected to the system. One of my gauges is shown in Figure 154.

It was made of discarded laboratory pipettes that had broken tips but were otherwise usable. Readings made with it are accurate down to about 10 microns, but gas released from the rubber connections prevents measurements at lower pressures. A second gauge made by my local glass blower detects .1-micron pressures. The instruments require about three pounds of mercury. Dibutylphthalate ($1 per pound) has been substituted for mercury as an economy measure; I have also tried salad oil and olive oil. These are usable if they are boiled for a few minutes at one millimeter of pressure, but they absorb volatile materials easily and in time become erratic.

Several hazards should be noted. First, a large evacuated glass



154
McLeod gauge for measuring low pressure in the vacuum system

vessel can, if it breaks, scatter glass at high velocity over a large area. It is essential that the glass reservoirs be enclosed in wooden or metal containers.

Second, keep in mind that the accelerator is a close relative of the X-ray tube. The penetrating power of X-rays is determined in part by the atomic weight of the target bombarded by electrons. X-radiation emitted by light elements such as aluminum is readily absorbed by glass, thin metal or even air. But heavy metals, such as copper, generate penetrating and dangerous radiation. It is important, therefore, to expose only materials of low atomic weight to the beam.

Third, the inexperienced worker should observe care in handling mercury, particularly when it is confined in glass tubes. If air is admitted abruptly to a manometer of the closed-end type, it is astonishing what damage the "water hammer" (in this case mercury hammer) can do. Enclose the manometers in transparent plastic bags. Just having a few pounds of mercury around constitutes a substantial hazard because the vapor pressure of mercury is high enough to worry about even at temperatures as low as 80 degrees Fahrenheit.

Fourth, although the voltage of the Van de Graaff generator is not necessarily hazardous in itself, an unexpected shock can throw one off balance and thus lead to an accident.

I will be glad to provide assistance in locating supplies. Letters addressed to F. B. Lee, 230 Hampton, Kenmore 17, N. Y., will be answered as promptly as possible.

Some hazards and precautions

JAMES H. BLY of the High Voltage Engineering Corporation in Burlington, Mass., recommends a change in the design of the particle accelerator.

"In general, I think it is fair to say that we like F. B. Lee's design approach to this machine very much. However, we are somewhat concerned over the hazards involved. We agree wholeheartedly with his comments concerning the hazards of glass breakage and the use of mercury. We feel strongly, however, that there is inadequate discussion of the potential hazards due to X-rays and electrons. Even though the experimenter restricts himself to targets of low atomic number, there will inevitably be some generation of high-energy X-rays when using electrons of 200 to 300 kilovolt energy. If currents as high as 20 microamperes are achieved, we are sure that the resultant hazard is far from negligible. In addition, there will be substantial quantities of scattered electrons, some of which will inevitably pass through the observation peephole. Although it is conceivable that it would be safe to look through this peephole from a distance of two feet, we are very doubtful that this is in fact the case. We believe the machine would have been improved considerably if these hazards had been more thoroughly explored."

The apparatus described has been tested exhaustively for radiation hazard. Lee might well have pointed out, however, that one invites trouble by remaining near particle accelerators when they are in operation, or even by staying in the same room with them during prolonged periods of operation. Lee does not share Bly's concern about the hazard of scattered electrons from the peephole. As a precaution, however, the peephole may be covered on the inside by a small piece of window glass which will plug the hole completely for electrons. As an alternative the neon tube can be cemented in the peephole and connected with its circuit through a pair of contacts (an arrangment that would permit the high-voltage terminal to be removed when desired). The lamp could then be observed at a distance with the machine in operation.

5

THE MILLIKAN OIL-DROP EXPERIMENT

Suspend a drop of oil in mid-air by means of electrostatic attraction, and you can accurately measure the charge on a single electron. In effect, the oil drop becomes a balance capable of responding to a force on the order of a trillionth of an ounce

WHILE WORKING with a Wilson cloud chamber in the spring of 1909 Robert A. Millikan, then professor of physics at the University of Chicago, learned how to make a drop of water hang in mid-air like Mahomet's fabled coffin. The drop was poised so