Cost: $0-100 About These Ratings	Difficulty: ■■■■■	Danger 4: (POSSIBLY LETHAL!!)	Utility:

How to Build a Machine to Produce Low-Energy Protons and Deuterons

by C. L. Stong
August, 1971

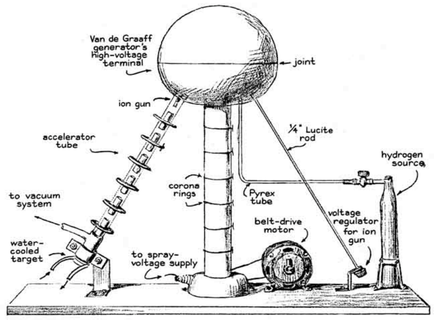
ALTHOUGH radioactive materials for experimental use can be bought in small amounts without a license, some amateurs have made their own with an apparatus that generates a beam of protons. The protons react with the atomic nuclei in a target to liberate neutrons. The neutrons in turn react with the nuclei

in another substance, giving rise to a radioactive isotope.

Small machines that can be made at home do not produce much radioactive substance, but a little goes a long way. An amateur who has made radioactive substances of several kinds is Larry Cress of Pennington Gap, Va. He explains how to build a small proton accelerator and describes experiments that can be conducted with it.

"My accelerator," Cress writes, "consists essentially of a series of electrically insulated copper tubes supported in axial alignment inside a cylindrical vacuum chamber. Hydrogen gas, admitted at one end of the structure, is ionized by a pair of electrodes. The resulting protons (hydrogen nuclei) are accelerated to a target at the other end of the structure by an electrostatic field of high potential. Portions of the field that lie between adjacent ends of the copper tubes act as electrostatic lenses that focus the protons into a beam.

"The accelerating potential is developed by a small electrostatic generator of the Van de Graaff type [*see illustration at right*]. Hydrogen is provided by a tank of compressed gas. Gas pressure in the accelerator tube is controlled by a pair of oil diffusion pumps that operate in series and exhaust into a mechanical air pump.



The proton accelerator built by Larry Cress

"The accelerator is quite versatile. For example, by substituting deuterium (the heavier isotope of hydrogen) for protons one can accelerate deuteron (deuterium nuclei, consisting of one proton and one neutron). Indeed, most of my experiments have been done with deuterium. By closing the target end of the tube with a window of aluminum foil at ground potential and omitting the hydrogen or deuterium, one can use the apparatus to accelerate a beam of electrons that is accessible in the air beyond the window. The electron beam can promote a host of chemical reactions.

"My Van de Graaff generator was bought as a kit from Morris and Lee (1685 Elmwood Avenue, Buffalo, N.Y. 14207). The generator is rated at a potential of a half-million volts at 20 microamperes. The load imposed by the accelerator tube reduces the effective potential to about 250 kilovolts. The belt that conveys charge to the high-potential electrode of the machine is drive by a 1/4-horsepower induction motor.

"To increase the available current an control the polarity and potential of the output voltage of the generator I spray charge on the belt, at a point close t the bottom of the machine, as a corona from a charged needle point. Potential for energizing the needle is developed by an induction coil of the Ford Model T type that operates from a six-volt transformer. The output of the induction coil is converted to direct current by a vacuum diode of the type used in small X-ray machines. The potential of the spray voltage is controlled by a 25-ohm rheostat in series with the primary winding of the induction coil. The charging current is measured with a microammeter in series with the grounded side of the coil. The rectifier is not strictly necessary because the output of induction coils tends to be unidirectional, but the inclusion of the diode decreased the fluctuation of the output voltage and increased the current.

"Electrical connection between the accelerator tube and the high-voltage terminal of the Van de Graaff machine can be made either by fitting the end o the accelerator tube with a duplicate of the high-voltage terminal and placing the two terminals in contact or by inserting the end of the accelerator tube into the high-voltage terminal of the generator. I elected to use the latte scheme, primarily because large hollow terminals of spun aluminum are costly. The high-voltage terminal consists o an unperforated hemisphere that mates with a second hemisphere curving smoothly inward to an opening that admits the charged belt.

"I opened the terminal at the bonding joint of the hemisphere, so that the apparatus for ionizing the hydrogen gas could be placed inside. A hole 1-1/2 inches in diameter was made in the lower surface of the perforated hemisphere to admit the accelerator tube. The edge of the hole was rounded inward and smoothed to prevent sparking or corona discharge, which tends to occur at sharp projections.

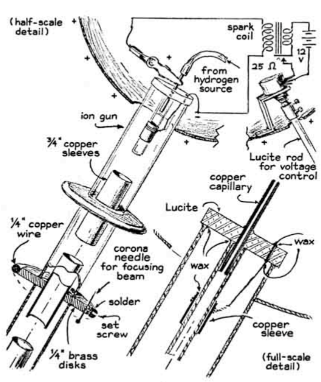
"Both the terminal and the belt are supported by a cylindrical insulating column. Rings consisting of a single turn of bare copper wire were placed around the column at intervals of three inches. Known as corona rings, the wires distribute voltage uniformly along the column and prevent direct discharge down the column to ground.

"The assembly of the machine and the modification of the high-voltage terminal completes the easy part of the job. The hard part consists in making a gas tight accelerator tube by sandwiching electrode assemblies between lengths of 1-1/4 inch Pyrex tubing and closing the ends. The tube must be capable of retaining a pressure of 10 torr.

"The glass is cut into three-inch lengths by filing a nick completely around the tubing and touching the nicked portion to a Nichrome wire that is electrically heated to redness. The glass will crack at the point of contact. By slowly rotating the tubing while it is in contact with the hot wire, lead the crack completely around the glass. If the glass does not part immediately, exert a strong pull on the ends.

"Each electrode assembly includes a circular brass plate 2-1/4 inches in diameter and 1/4 inch thick. Drill a 3/4-inch hole accurately through the center of each disk and through it insert a 2-1/4 inch length of straight copper tubing of 3/4 inch outside diameter. The edges of the cut ends of the tubes must be rounded and preferably polished to minimize corona discharge. The edge of each disk must be similarly rounded. If the experimenter does not have access to an engine lathe, the edges can be rounded by soldering a ring of 1/4-inch copper wire to the perimeter of each disk.

"The copper tubes must be supported in axial alignment by the glass sections. To make the assembly I clamped a dowel vertically in a vise. A *T* fitting of plastic pipe 1-1/4 inches in diameter was slipped over the dowel. The fitting rested on the vise. One of the copper tubes, with its brass disk, was slipped over the dowel and lowered so that the disk was centered with respect to the *T* fitting and rested on the upper end of the *T*. The joint was sealed with Apiezon W-100 vacuum wax. The melted wax was applied with a medicine dropper after the parts had been warmed with a small flame. A glass tube was then slipped over the dowel, centered on the brass disk and sealed in place. The remaining five electrode elements of the tube were assembled in the same way. The completed structure was lifted from the dowel after the wax hardened.



Details of the accelerator tube

"The ion source, which closes the high-voltage end of the accelerator tube, consists of another identical length of Pyrex tubing capped at one end by a disk of clear plastic 1/4 inch thick that supports a straight length of copper capillary tubing [*see illustration, left*]. Tubing of the kind used for the pilot light of a gas stove is adequate. An insulator of glass tubing of any convenient diameter surrounds the capillary and extends about 1/2 inch beyond the copper. Around the glass tube is a metal sleeve.

The lower edge of the sleeve is positioned about 3/4 inch from the end of the glass tube.

"The capillary admits hydrogen or other gases to the accelerator tube and also serves as the positive electrode of the ionizing potential. The metal sleeve is the negative electrode and is supplied with an uninsulated wire of solid copper that extends through the plastic cap. Before sealing the ion source to the accelerator tube, install an adjustable needle point near the edge of the brass disk that is next to the high-voltage electrode. The needle is used to focus the beam.

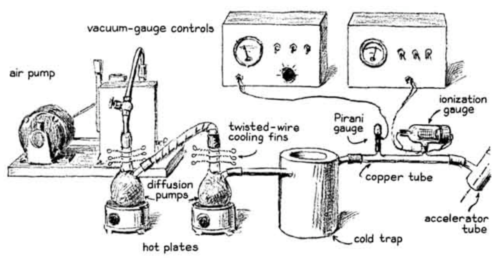
"Energizing potential for the ion source is provided by an induction coil of the Model-T type. Any comparable coil that develops a potential of at least 10 kilovolts can be used. The coil, a pair of six-volt dry batteries and a 25-ohm rheostat are connected m series and installed inside the high-voltage terminal of the Van de Graaff generator. These parts should be spaced at least an inch from the belt and the upper pulley. Access to the rheostat, which also functions as an on-off switch, is gained by removing the upper half of the high-voltage terminal. Alternatively the rheostat can be operated by a plastic rod that passes through a small hole in the high-voltage terminal.

"As mentioned above, the output of induction coils tends to be unidirectional. The negative terminal of the coil is connected to the metal sleeve of the ion source; the positive terminal, to the copper capillary. To determine the polarity of the coil connect its output to a gas- discharge tube that has been exhausted to a pressure of about one torr. At this pressure the glowing gas will separate from one of the electrodes, creating a dark space. This effect, known as the Faraday dark space, identifies the negative electrode.

"An appropriate gas-discharge tube can be improvised by plugging the ends of any glass tube about 15 centimeters long with rubber stoppers. Pierce one stopper with a nail and the other with a short length of copper capillary. The nail functions as one electrode; the copper capillary serves both as an electrode and as a port through which air is pumped from the tube. The pressure can be reduced to one torr with a mechanical air pump. The completed accelerator tube is supported at an angle of about 60 degrees by the high-voltage terminal atop the Van de Graaff machine and by an improvised clamp at the bottom, which is anchored to the base of the apparatus.

"The vacuum system consists of two single-stage Hickman oil diffusion pumps and a mechanical air pump connected in series. Before I bought the mechanical pump I used a pair of refrigerator compressors in reverse. The compressors developed the required low pressure but overheated after several hours of continuous use. Some four hours of continuous pumping are needed to exhaust the accelerator tube from atmospheric pressure to a pressure of 10 torr.

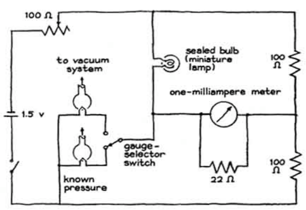
"The diffusion pumps were obtained from Morris and Lee. I use butyl phthalate as the pumping fluid and heat it with small laboratory hot plates operated at a temperature of 350 degrees Fahrenheit. A cold trap, consisting of a copper coil immersed in a slurry of dry ice and alcohol, must be installed between the outlet of the accelerator tube and the inlet to the pumps. The cold slurry is contained in a pint-sized tin can insulated with a thick layer of Styrofoam. The pumps cannot reduce the pressure to the required 10 torr without the cold trap. To prevent ice from forming in the trap I do not add the slurry until the system has been pumped to 10 torr.



Vacuum system of the accelerator

"Pressure in the accelerator tube can be measured down to 10 torr with a vacuum gauge of the Pirani type. The pressure-sensing elements of the gauge consist of three miniature incandescent lamps of identical resistance, which are rated at six volts. I checked the resistance of several lamps with a Wheatstone bridge and selected the most closely matched set. The resistance of each lamp should be about 15 ohms.

"The glass bulbs of two of the lamps must be opened for connection to the vacuum system. Heat the bases in a small gas flame to unsolder the filament leads and soften the cement that bonds the metal to the glass. Pull the base off to expose the tip of the tube through which the lamps were exhausted. Heat the glass tip to redness m the edge of a gas flame and touch it with a wet cloth. The glass will fracture, admitting air to the bulb slowly. After five minutes pick off the fractured tip with a pair of tweezers. Attach a short length of seven-millimeter glass tubing to the opening with vacuum wax. Wire the three bulbs into the Wheatstone bridge circuit.



Circuitry of the Pirani gauge

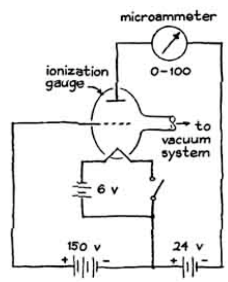
"One of the opened bulbs is used to calibrate the gauge. Connect the bulb to one arm of a glass *T*. To the *T* also connect the vacuum system and a McLeod gauge. An appropriate McLeod gauge can be obtained from Morris and Lee, or it can be made [see "The Amateur Scientist; SCIENTIFIC AMERICAN, December, 1965]. To calibrate the Pirani gauge, switch on the bridge circuit. Operate the two-position switch to connect the calibration bulb into the circuit. Adjust the 100-ohm rheostat for a meter indication of one milliampere. Start the vacuum pumps and, by operating the needle valve, exhaust the system to a series of measured pressures down to 10-3 torr. Tabulate each pressure as measured by the McLeod gauge and simultaneously record the corresponding meter reading. Draw a calibration graph by plotting the known pressures against the meter readings.

"One could dispense with the Pirani gauge and measure the pressure of the accelerator tube directly with the McLeod gauge. Although the McLeod gauge indicates absolute pressure and is universally used for calibrating other instruments, it is inconvenient to operate. The effort expended in making the Pirani gauge is amply repaid by the convenience it affords.

"The remaining opened bulb of the Pirani gauge is connected in the vacuum system. The calibration bulb is normally at atmospheric pressure. It is used to set the meter at one milliampere when the other opened bulb is under vacuum. The current should be checked with the calibration bulb before each pressure measurement.

"For measuring pressures below 10 torr I use an ionization gauge that has a G71-2 triode. This tube is manufactured by the High Vacuum Corporation (Hingham, Mass. 02043). The gauge response is assumed to be linear from 100 microamperes at a pressure of 10[illegible] torr to one microampere at 10[illegible] torr. The mechanical air pump exhausts the system to 10[illegible] torr in about 30 minutes. After this pressure is attained I turn on the heaters of the diffusion pumps. If the system has been opened to the atmosphere, the diffusion pumps require several hours to reduce the pressure to 10[illegible] torr. They do the job in about 30 minutes, however, if the system is maintained at a reasonably good vacuum. I try to keep the system under vacuum at all times. It must of course be opened occasionally to change the target.

"Hydrogen or another gas is admitted to the copper capillary of the ion source from a Pyrex tube that connects through a needle valve and a pressure-reducing valve to the storage tank. The induction coil ionizes some of the gas as it emerges from the capillary. Excess gas is continuously removed from the accelerator tube by the pumps. If the rate at which gas is admitted exceeds the rate at which the pumps can remove the excess, pressure rises in the accelerator tube, as indicated by the ionization gauge. At a sufficiently high pressure both the accelerator tube and the Pyrex tube that leads to the storage tank emit the characteristic glow of a gas-discharge tube. The rate of flow of hydrogen or deuterium must be adjusted accordingly.



Circuitry of the ionization gauge

"Several difficulties may arise when the apparatus is put in operation. The tubing may leak at the joints, as indicated by the failure of the pumps to exhaust the system to 10[illegible] torr. The detection of leaks is an art in itself [see "The Amateur Scientist; SCIENTIFIC AMERICAN, February, 1961]. I shall mention only one detection technique. Spray the wax joints one at a time with rubbing alcohol. If there is a leak, the pointer of the ionization gauge usually jumps slightly. Reheat the wax to seal the leak.

"Gas will be liberated from the internal surfaces of the system during pumpdown, particularly when the beam of accelerated particles strikes the electrodes or other surfaces. When the pressure has fallen to 10[illegible] torr, start the Van de Graaff generator and gradually increase the output voltage by regulating the amount of charge sprayed onto the belt. Watch the ionization gauge. Do not increase the voltage at a rate that causes the pressure to rise above 10 torr.

"When the pressure remains constant at 10 torr with an applied potential of 250 kilovolts, focus the proton beam. The beam can be detected by inserting a thin plate of quartz over the target. The quartz fluoresces, emitting a spot of purple light in the area struck by the beam. Advance or retard the adjustable needle in the brass disk of the accelerator tube nearest the terminal to focus the beam. The spot should focus to a diameter of about one millimeter. The quartz plate is mounted on an improvised pivot so that it can conveniently be swung away from the target when it is not in use.

"The accelerating potential of 250 kilovolts develops a proton beam of relatively low energy compared with the beams of full-scale accelerators. For this reason the amateur experimenter is limited to the investigation of nuclear reactions in elements of low atomic weight. The bombardment of boron and fluoride targets with protons liberates intense gamma rays with energies substantially above 250 kilovolts. The rays can be detected with a Geiger-Müller counter or a sodium-iodide scintillator having a photomultiplier tube and a meter circuit. As the potential of the Van de Graaff generator is gradually increased from zero, the emission of gamma rays from boron is detected at 163 kilovolts and from fluoride at 224 kilovolts.

"Most of my experiments have been conducted by bombarding deuterons with deuterons. The reaction liberates neutrons. Neutrons combine with many elements, which become radioactive as a consequence of the reaction. The elements can be identified by the nature of their subsequent emissions. Neutron absorption also causes some elements, notably uranium, to fission. The half-life of the resulting radioactive products ranges from minutes to millenniums. An appropriate target of uranium can be bought from A. D. Mackay, Inc. (198 Broadway, New York, N.Y. 10038) for $5. The order must be accompanied by a self-addressed envelope.

"The energy levels of radioactive nuclei can be determined by measuring the energy of the emitted gamma rays. A good target for this reaction is a thin film of heavy water (D O). I freeze a thin film of heavy water on the inner surface of a copper target by cooling the exterior surface with liquid nitrogen. Liquid nitrogen can be obtained from dealers in welding supplies. Another satisfactory target is deuterium orthophosphate, which can be made by adding heavy water a drop at a time to a small amount of phosphorus pentoxide until all the material has reacted. The energy of neutrons liberated by the deuteron reaction averages about 2.6 million electron volts. At a Van de Graaff potential of 200 kilovolts and a current of 10 microamperes the reaction will liberate approximately 5   10 neutrons per second. I prepared for the experiments by buying a 25-liter cylinder of deuterium and 100 grams of heavy water from Bio-Rad Laboratories (22 Jones Street, New York, N.Y. 10014).

"A word of warning is appropriate. Although the accelerator is small and the potential of the Van de Graaff machine is relatively harmless, the proton beam and the products of the nuclear reactions are hazardous. In addition to emitting gamma rays, the machine can generate X rays of substantial intensity. The apparatus must be effectively shielded. For shielding I use a double layer of solid concrete blocks 18 inches thick. In addition I surround the target with several blocks of paraffin when experimenting with targets that emit neutrons. I monitor the control side of the shielding at all times with a dosimeter and wear a film badge when working with the accelerator or its products. Dosimeters and film badges can be obtained from the R. S. Landauer Company (Glenwood, Ill. 60425). The experimenter should bear in mind that the U.S. Atomic Energy Commission requires that personnel working with radiation materials receive not more than 100 millirems of radiation per 40-hour week.

"I shall be glad to answer questions from those who undertake the construction of the accelerator. Correspondence can be addressed to Larry Cress, R.F.D. No 1 Pennington, Va. 24277."

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