PART VI

ATOMIC AND ELECTRONIC PHYSICS

IONIZATION AND CONDUCTION IN GASES

HIGH-PRESSURE PHENOMENA

A-1. Ionization in Air. The production of ions in air by various agencies can be demonstrated with a pair of parallel wires 1 cm or so apart supported on glass insulators above the lecture table. These wires are connected with a generator or battery of about 100 v and a Zeleny electroscope in a projection lantern. A reversing switch may be included to show that the effects are independent of the polarity of the wires. If a flame or a Bunsen burner is held beneath the wires, the electroscope will oscillate. Ultraviolet light from a quartz mercury arc will produce the same effect, doubtless owing in part to photoelectric effect on the wires. The number of ions produced in this way is not very large, and the effect may be enhanced by shining the light between two condenser plates attached to the wires. An x-ray tube mounted in such a position as to irradiate the region between the wires produces a copious supply of ions. The electroscope will also oscillate if the ions are produced by small samples of radioactive materials mounted on cards, by corona discharge from a needle mounted on a static machine terminal, or by a spark gap and induction coil (A-7) mounted at one side of the wires, with a jet of air blowing the ions along them.

A-2. Saturation. If a battery or a generator of 1000 or 2000 v is available, the phenomenon of saturation and the preliminary stages of the Townsend discharge can be shown. A small radioactive source is mounted on a card a few millimeters below a horizontal copper gauze of coarse mesh 3 to 5 cm square. The gauze serves as one electrode of an ionization "chamber," and the other is a metal plate mounted horizontally a few millimeters above the gauze. The gauze and plate are connected in series

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1 See footnote, p. 501.

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with a vibrating-leaf (Zeleny) electroscope $E$ and a potentiometer and voltmeter $V$ across the battery (Fig. 332). As the potential difference between the plate and the gauze is increased, the rate of oscillation of the electroscope leaf (which is a measure of the current) increases until all of the ions produced by radiation from the source are collected as fast as they are formed. Further increase in potential has no effect on the electroscope rate until additional ions are produced by collision; then the electroscope rate rises again.

**A-3. Ion Mobilities.** If the arrangement shown in Fig. 332 is modified by the addition of a second gauze between the first and the plate, separated from each by a few millimeters, the order of magnitude of the mobility of ions in air can be demonstrated. The field between the two gauzes is provided by the battery, and an additional alternating potential is applied between the second gauze and the plate (Fig. 333). A sinusoidal alternating potential is satisfactory unless a quantitative experiment is contemplated, in which case it is desirable to use a battery with reversing commutator and to mount the gauzes, plate, and radioactive material in a bell jar, so that the pressure can be reduced to 10 or 20 cm of mercury and larger spacings between the elements can be used.

The battery potentiometer is set to give saturation current between the two gauzes. Ions of one sign are thus drawn toward the upper gauze, and some pass through it into the region between it and the plate. If the product of the magnitude and the period of the alternating potential between the upper gauze and the plate is sufficiently great, some of these ions are drawn across during a half period, and the electroscope registers a small current. If the alternating field is not applied in the proper sense for a long enough time or if its magnitude is too small, the ions will be drawn back to the gauze during the reverse half of the
cycle, and none will reach the plate. Thus as the alternating potential is increased by means of a potential divider, a point will be reached at which the electroscope $E$ begins to oscillate slowly. A square wave form, such as that produced by a commutator, will obviously improve the sharpness of the point at which the electroscope begins to record. Likewise, if the spacing between the elements is large in comparison with the mesh distance, more uniform conditions are obtained, and a more accurate value of the mobility can be found. However, with an alternating potential of only 100 v or so this requires reduced pressure. As the mobility $\mu$ is the velocity per unit potential gradient, and the critical velocity is given by $2d/t$, where $d$ is the separation between the upper gauze and the plate and $t$ is the period of alternation of the field, $\mu = 2d^2/tV$ approximately. Here $V$ is the average value of the potential; the root mean square value as read by an a.c. meter $V$ is sufficiently accurate for demonstration purposes.

**A-4. Recombination of Ions.** The phenomenon of recombination of ions can be studied in a semiquantitative way by drawing the ions produced by a discharge or a flame past a series of plates at a constant rate. A horizontal glass tube (Fig. 334) about 30 cm long has a metal-strip electrode lying upon its lower surface and a series of four or five shorter strips drawn up against the upper surface by wires passing through holes in the top of the tube and held by wax. Ions are produced at the open end of the tube by x-rays, radioactive material, or some other convenient method (the more intense the ionization the better) and are drawn down the tube by an aspirator attached to the other end. The rate of flow can be regulated by a pinchcock and measured roughly by admitting smoke and timing its passage. The lower plate is grounded through the battery, and the electroscope is connected to measure the saturation current to each of the upper plates in turn. Its rate of oscillation is most rapid on the first plate, and

![Fig. 334.—Method of showing recombination of ions.](image-url)
when the rate of flow of the air is properly adjusted, very little ionic conduction to the last plate can be observed. Thus almost all of the ions recombine before reaching that plate, and few have a life exceeding the time given by the ratio of plate distance to rate of flow.

A-5. Smoke Precipitation. The phenomenon of attachment of ions to smoke and dust particles and their precipitation in a strong electric field can be demonstrated with an artificial chimney and a static machine (Fig. 335). A fine wire (No. 30) is strung from glass insulators down the axis of a vertical pipe of sheet iron (spouting) 2 in. in diameter and 2 ft long. An inverted funnel at the lower end facilitates the introduction of dust or smoke into the chimney. The particles are carried up through the chimney by thermal convection from a burner or by an air blast from a small fan or compressor. Cigarette or wood smoke can be used, but ammonium chloride fumes are generally more effective. Bottles of ammonia and hydrochloric acid, with their stoppers removed, are held beneath the chimney, or these liquids are poured into small dishes. One terminal of a static machine is connected to the chimney, and the other to the central wire. When a strong field is established between the two by operation of the machine, a slight corona discharge takes place at the surface of the wire, the ions produced attach themselves to the smoke particles, and these are drawn to the electrodes. Thus, in the absence of a field, smoke issues from the top of the chimney; but when the field is established, the discharge of smoke ceases.

In this connection, the condensation of a vapor on ions may be mentioned. Meteorological phenomena can be discussed from this point of view, and the action of the Wilson cloud chamber, which is described in A-1, serves as an excellent illustration (see H-89).

A-6. Corona Discharge in Air. The mass motion of air induced by corona discharge can be shown in a number of ways. If a needle or other sharp point connected to one terminal of a static machine is directed at a candle flame, the electric breeze
set up when the machine is operated will disturb or even extinguish the flame. If a thread is attached to a static machine terminal, it will jump about owing to the reaction from small point discharges along its length. A pinwheel in the shape of a small-scale lawn sprinkler whose arms terminate in sharp points will rotate rapidly when connected to a static machine because of corona discharge from these points. Attention can be called to the somewhat different appearance of the corona at positive and negative points. If the point is negative, the discharge resembles a closely fitting purplish sheath, caused by ionization close to the point. If the point is positive, the discharge is more reddish and generally exhibits a branching structure, probably accounted for by ionization by electrons as they enter the intense field in the neighborhood of the point by various paths. It may be noted in connection with the general question of corona discharges that point and tube particle counters, which are elsewhere described (A-118, 119), depend on this mechanism for their operation.

A-7. Spark Discharge. Ordinary sparks can be produced by a static machine or high-voltage transformer with spark gap. Condensed discharges can be demonstrated with the circuit described in connection with high-frequency oscillation (A-29). The convection motion of the spark paths and the periodic phenomena occurring in the case of 60-cycle sparks can be analyzed by means of a rotating mirror (E-268) with its axis approximately parallel to the spark path. The heating effect in flaming arcs and condensed discharges can be demonstrated by the burning away of points and the thermal convection of the arc path. The discharge in a horn gap is very spectacular. Two heavy copper wires are bent as shown in Fig. 336 and mounted on insulating supports. The separation at the bottom is such that the arc will strike across it. The arc warms the air around it, which therefore rises by convection and carries the arc with it, until the separation between the wires becomes so great that the arc finally goes out. It strikes again at the bottom, and the process is repeated.

A-8. Arcs. The nature of an ordinary carbon arc can best be demonstrated with a pinhole camera (L-16). The arc is set up in an enclosed but well-ventilated chamber (a projection lantern
with the lenses removed is satisfactory) with sufficient resistance in series to limit the current to 20 amp or less. A pinhole is made in one side of the arc enclosure, and the image is observed on a screen. The flaming gases and vapors, incandescent particles, and glowing electrodes can all be seen. If the arc is run on direct current, it will be evident that the major thermal phenomena take place at the anode, where the highest temperatures are produced. Salts of sodium, strontium, potassium, zinc, etc., can be packed into a cavity in either electrode and the colors that they impart to the arc on vaporization exhibited. A 60° prism placed over the pinhole may illustrate qualitatively the spectrum of the arc. The fundamental role played by the temperature of the anode can be shown by attempting to obtain an arc with a heavy copper rod for anode. The copper dissipates heat so rapidly that it is difficult to develop the requisite anode temperature for an arc.

**A-9. Resistance Characteristic of Carbon Arc.** The falling volt-ampere characteristic associated with an arc can be demonstrated by measuring the current and the potential difference across it as the series resistance is varied. A rather small arc drawing 1 or 2 amp is best for this purpose. The explanation may be somewhat along the following lines. The number of current-carrying ions produced in the arc is approximately proportional to the rate at which energy is expended. A small increase in current results in the formation of more ions, which enables the arc to carry still more current. The system is unstable, and the current rises and voltage falls until the minimum potential necessary to maintain the arc at the final value of the current plus the $IR$ drop in the series resistance is equal to the applied emf.

**A-10. Singing Arc.** The instability of an arc may be demonstrated by the singing arc, which is an ordinary carbon arc shunted by a condenser and inductor in series (Fig. 337). The condenser has from 1- to 10-$\mu$ capacitance; the inductor consists of several hundred turns of heavy copper wire (without iron core). Together they form a resonant circuit with its natural frequency somewhere within the audible range. Oscillations of this frequency are produced, and
the arc acts as its own loudspeaker. The pitch of the sound may be varied by altering either the capacitance or the inductance.

**LOW-PRESSURE PHENOMENA**

**A-11. Glow-discharge Tube.** The general nature of a cold-cathode discharge can best be shown with a tube in which the pressure can be varied. A rather large tube, at least 3 ft long and 2.5 or 3 in. in diameter, is best for demonstration purposes. The electrodes should not be at the ends but several inches in and supported from the sides. The electrodes are fairly heavy (50- or 60-mil) nickel disks, somewhat smaller in diameter than the inside of the tube, with a 0.5-in. hole through the center. They are inserted through the ends of the tube before it is closed and are screwed or welded to nickel extensions of tungsten rods or wires sealed through small side tubes. The tube is mounted well above the lecture table by clamps as inconspicuous as possible. It is sealed to the pumping system (A-57). The behavior of the tube will not be reproducible, and the form of the discharge will not be constant, until the tube has been run for some time and the major part of the gas and grease layers removed. This process can be considerably expedited by heating the glass with a flame and outgassing the electrodes with an induction furnace, but this procedure is not essential.

The tube can be operated by a high-voltage transformer, but this method has the disadvantage that it obscures the roles played by cathode and anode. A protective resistance must be placed in either the secondary or the primary circuit to prevent damage from excessive current. The transformer produces a symmetrical discharge, and unless the tube is viewed through a mechanical stroboscope (which is itself an interesting experiment), the characteristic regions of the discharge are not clearly brought out. An induction coil, which produces an almost unidirectional current, is a suitable source of excitation. A transformer-rectifier system with a capacity of about 0.5 kw at 10,000 v can be constructed with a small transformer and phanotron tube. A rheostat in the primary permits easy adjustment, and the outfit is rugged and dependable. Such a high-voltage source, though convenient, is not necessary. A much lower voltage can be used, provided that the discharge is once started with a leak tester, small Tesla coil, or induction coil.
Provision may be made to introduce various different gases into the tube if desired. Illuminating gas shows interesting variations from air. Neon or mercury-vapor discharges can be produced, which superficially exhibit quite different phenomena from the ordinary air discharge. With these gases, the tube may display a continuous red or blue glow, with no evidence of striations. However, for most demonstration purposes, the ordinary air or hydrogen discharge is preferable. The diffusion pump is necessary for producing the final x-ray stage. If the tube is evacuated with the potential applied to it, care should be taken to limit the current during the typical glow-discharge stage so that the electrodes will not become too hot or the glass melt. Care must also be taken in the final or x-ray stage to prevent cathode rays and positive rays from melting or otherwise damaging the ends of the tube. If much of this type of demonstration is contemplated, it is well to protect these ends with additional metal-disk electrodes for heat radiation.

A-12. Glow Discharge. Since the various phenomena of discharge are described in most texts, their characteristics will be only outlined here. At atmospheric pressure, no discharge occurs unless excessively high voltages are applied. As the pressure is reduced, long streamers of spark discharge appear between the electrodes. At a pressure of a few millimeters, these have disappeared and have been replaced by the typical glow-discharge sheaths. As the pressure is further lowered, the cathode sheath expands, and the various regions, the Crookes and Faraday dark spaces and the negative glow and positive column, make their appearance. The dependence of the character of the discharge on the electron mean free path may be pointed out here. When the thickness of the cathode sheath has increased to the point where it no longer penetrates the hole through that electrode, positive rays and cathode rays begin to appear behind the electrodes. As the pressure is further decreased, these rays produce visible effects for several inches of their path. The striations of the positive column gradually expand and move into the anode. If the progress of evacuation is halted at this stage, the current carried by the discharge may be varied by adjusting the rheostat in series with the primary of the induction coil or transformer, and the dependence of sheath thickness on current density illustrated. In the final high-vacuum stage of the discharge, the room should
be darkened to make visible the fluorescence of the glass under cathode-ray bombardment. An external spark gap in parallel with the tube provides an alternative path, which is taken by the discharge both at high and at low pressure. Numerous variations of the tube that has just been described will suggest themselves. If the cathode is made in the form of a short cylinder with its axis parallel to that of the tube, the streaming of positive and negative rays from its two ends can be made more striking. If sufficient power is available to increase the discharge current to the Schuler stage, the sheath will shrink until the entire discharge is confined within the cathode. The rare gases are generally used for this purpose. If the cathode is made in such a way as to have sharp points, say a triangular plate, discharge streamers from the intense fields at these points will be observed in the early stages of the discharge. If a small electrode is used as cathode, it can be heated to incandescence by the discharge.

A-13. Special-purpose Discharge Tubes. In addition to the type of tube that requires a pumping system, tubes specially prepared to illustrate various phenomena can be obtained from scientific supply houses. A set of tubes containing various gases shows the different line and band spectra emitted (L-104). A set of these tubes containing air at different pressures shows the salient features of the discharge previously described. These Geissler tubes can be operated by an induction coil. Tubes are also available for illustrating the heating effect of cathode rays and the fluorescence of various minerals under bombardment. The normal emission and rectilinear motion of cathode rays can also be demonstrated with special tubes for the purpose. A tube in which a small paddle wheel is mounted illustrates the mechanical motion that can be produced by these moving charged particles, both by their momentum and by the radiometer effect that they produce by local heating of the vanes. A tube with a longitudinal fluorescent screen is useful for showing the bending of cathode rays in a magnetic field.

A-14. Potential Required for Glow Discharge. Neon glow lamps illustrate very well the minimum voltage necessary for the maintenance of a cold-cathode discharge. This is of the order of the normal cathode fall characteristic both of the nature of the cathode surface and of the gas. Some of these lamps will light on
the peak of the 110-v a.c. wave but will not light on 110-v d.c. Others will light on this d.c. voltage and will show the glow surrounding one electrode. The minimum d.c. voltage for initiating the discharge can be measured with a voltmeter and potential divider. It will be found that the discharge may be maintained at a much lower voltage once it is started.

A-15. Electrodeless Discharge. Commercial glow lamps can also be used to illustrate the fact that electrodes are not necessary for the maintenance of the discharge. If the lamp base is held in the hand and the envelope brought near the end of a Tesla coil or the inductor in a high-frequency circuit, the typical glow can be clearly seen. This phenomenon can be more strikingly demonstrated with cylindrical or spherical glass bulbs several inches in diameter containing helium, neon, argon, or mercury vapor at low pressure (10⁻⁴ or 10⁻⁵ mm of Hg). The more powerful the electromagnetic field to which they are subjected the brighter does the glow appear. Any high-frequency system can be used, e.g., A-31. If a bulb is inserted in the baking coil of an induction furnace, the ring shape of the discharge illustrates the predominant role played by the magnetic field. Attention may be called to the necessity of high-frequency excitation for this type of discharge. Ordinary gas-filled incandescent lamps can be used to illustrate the existence of a glow, but the experiments that can be performed with them are not very striking. A bulb containing pure nitrogen can be used to demonstrate the afterglow.

A-16. Hot-cathode Discharges. Discharges using a hot cathode can also be demonstrated with various tubes that are readily available. The Tungar rectifier bulb in series with 18 v and a small control rheostat illustrates the necessity of auxiliary electron emission from the cathode to maintain a low-voltage discharge (Fig. 338). No discharge appears until the filament is heated; but after the discharge is once started, positive ion bombardment of the filament or an auxiliary cathode point keeps it at incandescence, and the discharge continues after the filament circuit is opened. The phonotron, or mercury-vapor rectifier, also illustrates the fundamental role of cathode emission in a discharge. Inverse voltages up to several
thousand volts can be applied without initiating a discharge; but when a potential of 15 or 20 v is applied in the proper sense, the discharge occurs (Fig. 339).

A-17. Thyratron Tube. The function of the grid in a discharge tube can be shown with a thyratron. One of the small types such as the FG-57 or FG-67 is suitable. If a negative voltage is applied to the grid, the cathode is shielded from the field of the plate, and a high potential must be applied to the plate before breakdown occurs but a low positive potential applied to the grid will start the discharge. Once the discharge has started, however, the shielding effect of the grid ceases. It is surrounded by a very thin space-charge sheath that insulates it from the rest of the discharge, and the current from cathode to plate is quite independent of grid potential. A suitable circuit for demonstrating these tubes is shown in Fig. 340. A current-limiting resistance must be included in series with the plate.

The proper values of the potentials, safe currents, etc., are given in bulletins accompanying the tubes.

A-18. Electron Beams. A number of striking and illustrative experiments dealing with the path of an electron beam can be performed with a lime-spot hot cathode. Such a cathode is made by putting a small spot of lime on a platinum strip that can be heated to incandescence by current from a battery. Sealing wax or a mixture of barium, strontium, and calcium oxides in paraffin similarly heated produce satisfactory electron sources. The beam of cathode rays issuing from such a lime spot is characterized by its extreme compactness and brilliance. No diaphragm is necessary for limiting the beam. The electrons produce a long, narrow column of ionization in the residual gas, and only a low potential is necessary, so that the electrons move relatively slowly and are readily deviable. The disadvantage of this type of cathode is that the lime spot loses its activity after a few hours of operation; hence provision must be made for renew-
ing it. The most satisfactory arrangement is to mount the platinum strip on a ground-glass joint. The anode, of course, is permanent and can be placed at any convenient point. The pressure in the tube is reduced to about 1 mm, the cathode heated, and the potential applied. The pressure and the cathode temperature are then adjusted until a satisfactory beam is obtained. The larger the heating current the more brilliant is the beam, but also the shorter is the life of the cathode. The beam shows the typical cathode phenomena of Crookes and Faraday dark spaces, as well as the negative glow and intense positive column. The variation of these with gas pressure, current (by varying the cathode temperature), and anode-to-cathode potential can be shown. Excellent beams can be obtained in mercury vapor. A drop or two of mercury is placed in a small appendix to the tube and the vessel is pumped out completely. The vapor pressure is controlled by the temperature of the appendix, an ice bath generally producing about the right conditions.

A horizontal tube 30 or 40 cm long can be used to illustrate the deviation of the beam in a magnetic field. A bar magnet brought up in a horizontal plane produces a vertical deflection of the cathode rays. A loosely wound helix of heavy wire may be placed over the tube (Fig. 341), and a current of about 20 amp sent through it. The beam is undeflected when it is parallel to the axis of the helix, but if the beam and axis are inclined to one another at an angle of 10° or 20°, the beam assumes a spiral form. The effect of compressing or extending the loosely wound helix can be shown.

A-19. "Aurora Borealis." If a large bulb (12-l capacity is satisfactory) is available, an experiment illustrating the aurora borealis can be shown with a lime-spot cathode such as that described in A-18. The cathode leads are introduced through a ground joint sealed to the stem of the flask. One pole of an iron-core solenoid, producing a powerful divergent magnetic field, is brought up to the bulb in the general region opposite the stem. The cathode rays are directed toward the pole of the magnet, but

1 Gas is emitted by the hot cathode; therefore pumping should be continued until stable conditions are attained.
after progressing a short distance their paths become divergent helixes. The form of the paths can be varied by changing the strength of the field or the position of the pole relative to the beam. The envelope of the helixes resembles the northern lights (Fig. 342).

**A-20. Magnetic Deflection of Cathode Rays.** The cathode beam may be made to describe a (nearly) circular path by applying a suitable magnetic field (Fig. 343). The cathode may be placed in a bulb 15 or 20 cm in diameter and surrounded by two Helmholtz coils capable of carrying a current of several amperes. Alternatively, the cathode can be inserted in the side of a cylindrical glass jar, and a heavy piece of plate glass waxed over the front. The coils for producing the magnetic field are wrapped snugly around the jar. The magnetic field is adjusted until the electrons follow a circular path about 10 cm in diameter. If the radius of curvature of the path is measured, an approximate value of $e/m$ for electrons can be calculated from the strength of the magnetic field and the potential applied to the cathode. The jar must, of course, be evacuated. (For other $e/m$ experiments, see A-72-74.)

**A-21. Electron Focusing.** A cathode-ray oscilloscope tube can be used to illustrate the phenomenon of electron focusing. In the case of the older type of tube, the focusing of the beam is accomplished by a positive ion sheath formed in the residual gas. The intensity of ionization is a function of the potential applied to the tube and of the beam current. The behavior of the spot on the screen can be noted as these two factors are varied. In the newer tubes, electrostatic focusing is used, and the sharpness of the spot can be varied by means of the focusing potential. The proper values of the potentials are given in bulletins accompanying the tubes. Magnetic focusing can also be demonstrated with either type of tube. The tube is placed within a solenoid about twice its length. The spot is first made diffuse by improper adjustment and is refocused by the magnetic field of the solenoid.
ELECTRICAL OSCILLATIONS

A-22. Mechanical Analogue of Electrical Resonance. A mass \( M \) (Fig. 344) is supported at the junction of two vertical helical springs, such as screen-door springs, one above and one below. The upper end of the upper spring is attached to a rigid frame support, and the mass is set into vertical shm by periodic extensions of the lower spring. With a little practice, this may be accomplished manually. The motion is more uniform, and the phase relations may be studied in more detail, if the lower end of the lower spring is driven by a small variable-speed motor equipped with a Scotch yoke (Fig. 100) for vertical motion. If such a device is not available, the mass may be drilled for vertical guide rods, and the spring actuated by an eccentric pin on a disk attached to the motor shaft. The figure indicates the use of guide rods and eccentric drive. At low frequencies, the motion of the mass lags behind that of the lower end of the spring; at resonance, the motions are in phase, and a large amplitude is developed; and at higher frequencies, the motion of the mass leads that of the driver. The spring-condenser, mass-inductor, and friction-resistor analogues may be pointed out clearly and in as much detail as the mathematical ability of the students warrants. The electric circuit analogous to this arrangement of weight and springs is included in the figure for comparison.

If a thread is substituted for the lower spring, a large amplitude may be produced at resonance by the periodic application of a small force. A 20-lb weight bolted to the end of an automobile spring leaf may thus be set into motion by properly timed impulses.

A-23. Alternator for Very Low Frequency. Several elementary a.c. and radio-circuit phenomena may be demonstrated with currents of very low frequency, \( i.e., \) of the order of 1 cycle per sec. In this range, the circuits can be metered with instruments normally used for direct current by which the changes in the
instantaneous values of the current and voltage are made visible.

Ordinary alternators, run slowly, generate too low a voltage for this purpose; however, a d.c. source and rotary potential divider may be used to generate the alternating current. A dilute solution of common salt carries a steady direct current between metal plates fixed on the inside of a cylindrical container, made of insulating material. Another pair of metal plates, set flush with the periphery of an insulating cylinder \( B \) (Fig. 345) coaxial with the first, are connected to slip rings and are rotated with \( B \) in the solution. As the cylinder is rotated, the potentials of the plates vary approximately sinusoidally, and an alternating current may be taken by brushes from the slip rings. The frequency of the alternation is that of the rotation of the cylinder.

Figure 346 shows the circuit used for demonstrating the phase relationships between the current and voltage for different circuit elements. The load \( K \) may be a resistance (400 ohms is satisfactory), an inductance (3000 turns of No. 22 d.c.c. copper wire on a closed Stalloy or Alnico core about 6 in.\(^2\) in cross section), or a capacitance (about 150 \( \mu \)). \( G_1 \) and \( G_2 \) are similar, well-damped, center-zero galvanometers (2-0-2 milliammeters) and act as voltage and current indicators respectively. \( G_1 \) is in series with 5000 ohms, and \( G_2 \) is shunted with 10 ohms. A battery of from 12 to 24 v is applied to the fixed plates of the potential divider, and the rate of revolution set to about 1 cycle per sec. Though this may be done by hand, it is more satisfactory to use reducing gears or pulleys and a small low-speed motor. According as resistance, inductance, or capacitance is used, the pointer of \( G_1 \) is in phase with, leading, or lagging behind that of \( G_2 \).
The motion of the pointer is not in phase with the current through the instrument coil, but if the meters are of the same construction, this phase difference will be the same in each, and the relative pointer readings will still be significant. By making the load $K$ of both inductance and capacitance, series and parallel resonance may each be shown. It is generally not practicable to vary the frequency on either side of resonance with a constant load as the mechanical period of the galvanometer movements is in the range of the a.c. period used. It is more satisfactory to add capacitance, say, at a constant frequency and study the resonance phenomena in that way. The resonant combination may be shown to have the same natural period as that of the applied potential. This is done by removing the inductance and capacitance from the circuit and connecting them in series with one of the galvanometers. The condenser is charged to about 80 v, and on removing the battery connection to one terminal of the condenser the charge oscillates back and forth through the circuit, the current being indicated by the galvanometer. The larger the inductance in comparison with the product of the resistance and the capacitance, the smaller is the damping and the more satisfactory the experiment. With the circuit elements suggested previously, about three complete periods may be timed.

**A-24.** A three-electrode tube may be used to generate oscillations of this low frequency. If the inductor is not center-tapped, a Colpitts type of circuit should be used (Fig. 347). This low-frequency circuit is considerably less efficient than a radio circuit; hence for the same amplitude a tube of moderate power is necessary, e.g., type 10. The circuit described in A-27 employing a type-57 tube may also be used. The series and shunt resistances for the meters depend on the tube and potentials available and must be determined by trial.

**A-25.** With the rotary potential divider and a vacuum tube in one of the standard circuits, both rectification and amplification can be demonstrated. Colored celluloid pointers attached radially to the shaft of the potential divider may be used to illustrate better the half of the cycle rectified, relative phases of voltage and current, etc. If a variable-speed alternator is available, these meters may be used to illustrate the phenomenon of...
beats between the 60-cycle power supply and the variable frequency. Beats may also be illustrated by two standard incandescent lamps in series with the 60-cycle mains and the variable-speed alternator.

A-26. Resonance at 60 Cycles. For resonance at 60 cycles, the product of inductance in henrys and capacitance in microfarads should be 7. If a fixed 1-henry inductor is available, a battery of condensers, variable in steps of 1 μf from, say, 2 to 12, is suitable to demonstrate the phenomenon; or a variable inductor consisting of a large solenoid with a movable iron core may be used. An ordinary incandescent lamp is a good indicator of the magnitude of the current. Standard a.c. voltmeters will measure the drop across the various circuit elements. To illustrate the phase relations a wattmeter, or, better, an oscilloscope, should be used.


A very simple and convenient circuit for generating oscillations over a very wide range of frequencies is shown in Fig. 348. The type-57 tube displays a negative transconductance, and if a resonant circuit is connected to the terminals AB, oscillations will be generated with the natural period of this circuit. The size of the condenser C' depends somewhat on the frequency of the oscillations to be generated, 0.01 μf being a convenient value for the audio-frequency range. The inductance should be of the order of 0.1 henry. An amplifier-loudspeaker combination makes the oscillations across its terminals audible to the class. The demonstration is improved if an oscilloscope is also used to make the wave form visible.

With the resistance R at zero, the capacitance C is varied in steps from, say 0.1 to 1 μf (a decade condenser is very convenient). A pure musical note is produced by the loudspeaker, and its sine curve is visible on the oscilloscope screen. With a suitably tuned bank of 10 or 12 condensers arranged with separate keys, tunes can be played as if on a piano. The proper capacitances

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to produce a musical scale can be calculated if the value of the inductance is known. The corresponding condensers can be assembled from ordinary radio parts, although the final adjustment may require a little empirical tuning.

Any of the standard types of circuit\(^1\) may be used for an audio-frequency oscillator, but it is difficult to make the capacitance or the inductance easily and rapidly adjustable to cover a large range of frequencies. The most convenient instrument for this purpose is the beat-frequency oscillator, in which an audio frequency is produced by beats between two radio-frequency circuits. A small fractional change in frequency of one of the circuits suffices to cover the entire audio range, and this can be accomplished by the variation of a single air condenser. One

suitable circuit is shown in Fig. 349. Numerous other circuits will be found in the literature of radio. Complete oscillators are commercially available.

A-28. Damped Oscillations. If the resistance $R$ (Fig. 348) is increased, a critical value will be reached at which the oscillations cease. In this condition, the circuit, though not self-oscillatory, still has a small decrement. If a coil, in series with a small battery and key, is loosely coupled with the inductor $L$, the circuit may be set in oscillation by tapping the key. The note and oscilloscope pattern both persist for some seconds, the sound resembling somewhat that of a plucked string. As the resistance is further increased, the damping increases and the duration of the note becomes very short.

A-29. High-frequency Oscillations Generated by Spark Discharge. Damped high-frequency oscillations can be generated with a high-voltage transformer, spark gap, and tuned circuit. Twice each cycle, the condensers are charged by the transformer to the breakdown potential of the gap. Once the gap breaks down, it has a low resistance, and the tuned circuit oscillates. If the circuit connections are well made, the damping is small, and various resonance phenomena can be demonstrated. The circuit is shown in Fig. 350. $T$ is a 25,000-v, 1-kw transformer. $G$ is the spark gap, which should preferably be of the rotary type. The condensers $C$ should be capable of withstanding the peak voltage of the transformer; hence series connection of Leyden jars with capacitances of about 1000 $\mu$F is indicated. The two coupling inductors $L_2$ should each have five turns of heavy copper wire or $\frac{1}{4}$-in. copper tube, which is sufficiently rigid to keep the turns well apart. If lighter wire is used, it should have heavy insulation for this purpose. These helices may be wound loosely on a horizontal wooden cylinder about 30 cm in diameter. The coupling can be varied by moving the coils together or apart. The two inductors $L_1$ are continuously variable. They are composed of 30 or 40 turns of copper tubing or heavy copper strip wound edgewise in a helical groove on a wooden cylinder about
20 cm in diameter. The pitch should be about 1 cm. A central metal axle with end bearings is provided with an insulating crank for rotating the cylinder. The support should be made so as to permit either horizontal or vertical mounting. One end of the helix is brought to a heavy brass slip ring on the axle; contact with both sides of this ring is made with spring-brass or phosphor-bronze brushes. The sliding contact is a brass block with a groove fitting loosely over the copper tubing or ribbon, mounted on the end of a flat spring-brass strip that presses it against the turns of the helix. The center of this strip may be mounted on a tube sliding along a brass rod, with the lower end held out by a second brass rod so that the upper end is pressed against the helix; or the strip may be carried on a length of rectangular tubing sliding over a square rod to accomplish the same purpose.

The diagram (Fig. 350) shows the circuit arrangement for series resonance. A lamp or thermal meter \( L \) in the secondary circuit \( S \) indicates the current. \( L_1 \) in either circuit may be varied to pass through the resonant condition. The fact that the product of inductance and capacitance must be the same for each circuit may be shown qualitatively by changing the capacitance by one or more units and making the necessary alteration in the inductance. The effect of coupling may be shown by altering the separation of the coils \( L_2 \).

A-30. Parallel Resonance. To demonstrate parallel resonance, the primary circuit remains as before (Fig. 350), and the secondary is arranged as in Fig. 351. Three indicating lamps (e.g., 110 v, 40 w) or meters are used, one in each branch. Below resonance, the lamp in series with \( L_1 \) is brighter than that in series with \( C \); at frequencies above resonance, the reverse is the case. The lamp in series with \( L_2 \) goes out at the resonant point. If the frequency is varied by means of \( L_1 \) in the primary, it should be noted that the induced emf in the secondary increases with the frequency and it is the relative rather than the absolute brightness of the lamps that is significant. (\( L_2 \) is again the coupling inductor as in Fig. 350.)

A-31. Tesla Coil. Many interesting experiments of the Tesla-coil type can be performed with a coil whose natural period (due
to distributed circuit capacitance and inductance) lies in the range of frequencies of the high-frequency spark oscillator (A-29). A convenient Tesla coil or resonant secondary can be made by winding closely No. 28 s.c.e. copper wire on a wooden dowel about 3 cm in diameter and 150 cm long. The ends should be covered with short metal caps to prevent the wire from burning away. It is most convenient to mount this coil vertically by pressing its lower end into a hole in a wooden base. It may be glued in place permanently if desired, but neither nails nor screws should be used. The elements of the previously described secondary circuit (A-29, 30) may be included either in series or in parallel as the primary for the Tesla coil so that a large frequency range may be covered by that circuit. The Tesla coil may be electrostatically coupled to the primary by connecting the lower end through a 110-v lamp directly to one condenser plate. Or it may be electromagnetically coupled by grounding one end of the coil through the lamp and placing the $L_2$ coil of the primary around the coil near its base as shown in Fig. 352. In either case, the length of the coil is a quarter of the fundamental wave length. The free end is a potential antinode and current node. The grounded end is a potential node and current antinode. This latter is indicated by the lighting of the lamp at resonance. If a needle is mounted in the upper metal cap, long streamers of discharge are produced by the potential antinode at resonance.

Many other interesting demonstrations are possible with this apparatus. A metal disk about 20 cm in diameter is attached to one end of a wooden rod about 1 m long, and a wire is run along the rod through a lamp mounted at its center to a metal foil wrapped around the other end. This foil handle is grasped firmly in the hand, and as the disk is brought near the upper end of the Tesla coil, the lamp glows brightly. The high-frequency current flows over the skin of the demonstrator, but there is no unpleasant sensation if good contact is made with the foil. Glass tubes 1 or 2 cm in diameter and 60 or 70 cm long containing air, helium, neon, or mercury vapor at a few millimeters pressure make very colorful demonstration wands. When held in the
hand and brought near the upper end of the Tesla coil, they glow brightly. These demonstrations are enhanced if the lecture room is darkened.

If the coil is grounded through a lamp at each end, the fundamental is characterized by a current antinode at each end and a potential antinode at the center. If neither end of the coil is grounded, potential antinodes exist at the ends, and a current antinode at the center. Both these modes of oscillation correspond to a half wave length along the coil. By adding condensers in series to increase the frequency of the primary circuit, at least three overtones or harmonics of each of the quarter- and half-wave fundamentals can be obtained. The current antinodes can be detected easily only if they occur at the ends of the coil. The potential antinodes along the coil may be detected by the wands previously described or by a small neon lamp, which may be fastened to the end of a wooden rod and which, as the glass envelope is moved along the coil, glows brightly in the neighborhood of a potential antinode. For the highest frequencies—those exhibiting the largest number of potential antinodes—it may be necessary to remove $L_1$ from the primary circuit entirely and to have as many as 8 or 10 Leyden jars in series. It may also be necessary to reduce the number of turns in the coupling coil $L_2$.

**A-32. Continuous-wave High-frequency Experiments.**

Continuous or undamped oscillations with a frequency in the neighborhood of 10 megacycles, which is of the same order of magnitude as that generated by the spark-discharge apparatus of A-29, can be generated with a vacuum tube. A convenient circuit is shown in Fig. 353. If a constant source of plate potential is available, the oscillations generated are of uniform amplitude. However, “raw” 60-cycle alternating current may be used for the plate supply as shown, and this arrangement has certain advantages. The plate of the tube is heated for only half of each cycle, and hence there is less energy to be dissipated than in the case of a d.c. plate supply. Furthermore, the output of the oscillator is
modulated with a 60-cycle frequency and its harmonics. The radiation may be detected by any simple receiving circuit (A-33) tuned to the oscillator frequency, and the 60-cycle note and its harmonics may be amplified and heard in a loudspeaker. The low-power oscillator of Fig. 353, suitable for wavemeter demonstrations, lecture-table radiation, etc., can be constructed with the following circuit elements: $T$ is a transformer supplying about 500 v, and the tube is a type 10. Its filament can be heated with a storage battery or a small 7.5-v transformer. The blocking condenser $C_1$ is 0.02 $\mu$F, and the grid condenser $C_2$ is 0.0002 $\mu$F. A grid leak $R$ of about 10,000 ohms is satisfactory. The tuned circuit is composed of a copper tube helix of 10 or 15 turns about 3 in. in diameter, and a variable air condenser with a maximum capacitance of 100 or 200 $\mu$F. A condenser of 0.01 $\mu$F in the filament circuit is not absolutely necessary, but it improves the distribution of the high-frequency current between the two legs. The choke coil $L_1$ is No. 28 d.c.c. copper wire wound on a mailing tube 1½ in. in diameter and 3 in. long. The oscillations may be detected by a small neon lamp with its envelope held near the inductor $L$. The filament current should be adjusted until the oscillations are strongest.

**A-33. Wavemeter.** The use of a wavemeter may be illustrated with the simple circuit shown in Fig. 354. The inductor is made of about six turns of No. 18 copper wire wound on a mailing tube 3 in. in diameter. The variable condenser is of the same size as that used in the tuned circuit of the oscillator (A-32). A small flashlight bulb $L$ in series with these elements indicates the resonant condition as the condenser on the wavemeter is varied. If this circuit is brought close to the oscillator, the interaction results in two resonance peaks instead of one.¹

**A-34. Radio Transmission and Reception.** If the oscillator (A-32) is coupled to an antenna, the phenomena associated with radio transmission and reception may be illustrated. For lecture-table work, this antenna can be small and of almost any convenient form. A wire running along the lecture table or simply a ½-in. brass rod 3 or 4 ft long stuck in a vertical drill hole in the wooden oscillator base serves admirably. It may be con-

A simple receiving circuit is illustrated in Fig. 355. The tuned circuit is the same as that of the wavemeter described in A-33, with the flashlight omitted. The sending and receiving antennae may be identical. Any small diode or three-electrode tube with the grid and plate connected will serve as a detector. C is a by-pass condenser of the order of 0.01 $\mu$F. If the input of an amplifier and loudspeaker combination is connected across the terminals of this condenser, the 60-cycle note of the oscillator may be plainly heard. The harmonics increase the audibility but make the note of very poor quality. An a.c. meter in place of the loudspeaker may allow quantitative measurements of antenna efficiencies, etc., to be made. The functions of the different parts of the circuits and the wave forms throughout may be further illustrated by diagrams on the blackboard.

A-35. Continuous-wave Tesla Apparatus. Oscillators in the same general frequency range of the type described in A-32 may be used for Tesla-coil experiments such as those of A-31 by the addition of a Tesla coil coupled to the oscillator coil L (Fig. 356). However, the oscillator that has been described (A-32) is suitable only for very small-scale demonstrations. For satisfactory lecture work with the Tesla type of tuned secondary, an oscillator capable of supplying 200 or 300 w should be used. It is more economical to use two tubes in a push-pull circuit such as that illustrated in the following experiment (Fig. 357). Magnetic coupling should be used for best results, and the coils should be designed to give as favorable a coupling coefficient as possible. The rest of the technique is the same as that previously described.

A-36. Ultra High-frequency Apparatus. Electromagnetic waves from 0.5 to 3 m long may be generated by suitable circuits employing modern low-capacity tubes. Suitable ones are the following: of the order of 0.5 w, RCA 954 and 955; 10 to 50 w,
W.E. 304-B and RCA 834. The bulletins that accompany these tubes describe various circuits and give appropriate values for the constants. A simple circuit that gives good results is illustrated in Fig. 357. The plate inductor is a single turn of No. 10 bare copper wire about 2 in. in diameter. For the highest frequency, the capacitance is simply that of the tube plates. The frequency may be reduced and varied over a considerable range by connecting a one- or two-plate variable condenser with a maximum capacitance of about 10 μf between the plates. The plate coil is supported directly by the plate leads, which come from the tops of the tubes. The grid coil, which is similar but reversed in sense, as indicated in the diagram, is supported in the same way. If any other supports are used, they must be of very low-loss insulating material such as “isolantite” or “victron.” The value of the grid resistance R depends on the type of tube used. It may be determined from the rated mean values of the grid voltage and current recommended for the tube in this class of operation.

The midpoints of the plate and grid coils are at zero radio-frequency potential, but owing to small asymmetries it is difficult to locate these points exactly, and a choke coil L should be included in the plate lead. This may be about 10 or 15 turns of No. 18 wire spaced about ¼ in. apart on a ½-in. wooden dowel or glass tube. If the proper d.c. plate potential is available from a generator or power pack, it is more satisfactory than the simple transformer shown in the diagram. The power output of these tubes drops off rapidly as the frequency increases beyond 200 or 300 megacycles, but there is generally enough power from such an oscillator for Lecher-wire and radiation demonstrations.

**A-37. Lecher Wires.** The phenomenon of standing electromagnetic waves on wires may be demonstrated. Two No. 18 bare copper wires 4 or 5 m long and 5 or 10 cm apart are stretched on wooden supports above the lecture table (Fig. 358). These wires are joined at one end by a loop that is magnetically coupled
with the oscillator. If the oscillator frequency is variable, the other end of the pair of wires may be left open, and the oscillator tuned; if the oscillator frequency is fixed, the wires may be tuned by a small variable capacitance across their open end. This capacitance may be formed by two brass plates of about 10-cm² area, screwed to the sides of small wooden blocks for support. The plates are connected by short flexible wires with the parallel-wire system; the blocks rest on the lecture table, and the capacitance is varied by moving them apart or together. Short stiff wires are soldered to the terminals of a small neon glow lamp (0.5 w or less) so that it may be slid along the Lecher system to locate the potential antinodes. Its presence may change the tuning somewhat, and if a number of lamps are used simultaneously, the adjustment for maximum brilliance must be made by a series of successive approximations. A sensitive radio-frequency meter may be used as a detector in place of the lamp, though this is usually less satisfactory for demonstration work. The distance between lamps set at successive potential antinodes is one-half wave length.

**A-38. Radiation and Polarization.** The phenomenon of polarized dipole radiation is illustrated by coupling an antenna to the oscillator (A-36). A satisfactory antenna may be made from a piece of thin-walled ½-in. copper tubing about 3 ft long with a loop about 2 in. in diameter at its center. The central loop is supported by a wooden block and coupled magnetically with the oscillator loop. The tuning is accomplished by varying the extension of short lengths of copper wire sliding in the ends of the tube. The resonant condition is detected by the brightness of a small neon lamp placed near one end of the antenna. Detection of radiation from this antenna is possible with a straight antenna of copper tubing with similar adjustable ends for tuning; a 6-v
flashlight bulb mounted on a wooden block is connected in series with the antenna at its center, where a current antinode exists at resonance. The second antenna is held parallel with the first. The phenomenon of polarization is illustrated by rotating this detecting antenna in a plane perpendicular to a line normal to the two antennae and joining their centers. The light is most brilliant when the antennae are parallel and goes out when they are normal to one another. The action of an optical polarizing or analyzing medium such as tourmaline may be illustrated by a square wooden frame, one-half wave length on a side, across which in one direction are stretched copper wires 1 or 2 cm apart. The detecting antenna is placed parallel to that of the transmitter and one or two wave lengths away. The frame is then placed midway between the two and rotated in a plane normal to the line joining their centers. The maximum energy absorption occurs when the wires on the frame are parallel to the antennae. When the frame is in this position, the flashlight bulb in the detecting antenna glows very dimly or goes out entirely. When the wires are perpendicular to the antennae, they have very little influence on the brightness of the lamp. If a large enough plane metal surface is available, reflection and standing waves can also be demonstrated. Refraction and dispersion are not easy to show at these wave lengths as the apparatus required is inconveniently large. Diffraction and the principles underlying the use of beam antennae can be demonstrated with this equipment, but the space available in the average lecture room is inadequate for the best results. (See A-39.)

**A-39. Directional Antenna Effects with Ultra High-frequency Waves.** Ultra high-frequency oscillators are convenient for showing that radio waves have many of the properties of light. Waves less than 1 m long may be generated by the circuits shown
in Fig. 357 or Fig. 359. They may be radiated and received by half-wave antennae consisting of stiff copper wires (Fig. 360). The length \( AB \) on each antenna is one-half wave length above the parallel copper wire \( CD \). The transmitting antenna has two feeder wires with a loop that fits just above the tank circuit \( GPC \) of Fig. 359. A tuning bar \( TK \) is connected below the points at which these feeder wires reach the antenna system. The receiving antenna has a crystal rectifier at \( D \). Radiation received by it is detected by the lecture galvanometer with adjustable (Ayrton) shunt.

For directional effects, one or more copper wires are placed parallel to the radiator at suitable distances. Excellent results are obtained with the arrangement of Fig. 361, in which \( A \) is the radiating antenna, \( B \) the receiving antenna, and \( C, D, E, \) and \( F \) are half-wave-length copper rods mounted on a stand that can be turned about \( A \) so that \( A \) and \( B \) do not move with respect to one another. With the distance between \( A \) and \( B 3 \) m, it is easily possible to obtain a difference of 1000 to 1 in the radiation received by \( B \) when the directors are as shown in Fig. 361, as compared with the radiation when the frame carrying \( C, D, E, \) and \( F \) is turned through 180°.

**A-40. Modulation of High-frequency Oscillations.** If the plate supply of the oscillator (A-36) is modulated at an audio frequency, radio transmission can be demonstrated. A suitable circuit for plate modulation is shown in Fig. 362. The signal may
be from a microphone or a phonograph, suitably amplified. Grid modulation, though less satisfactory, can also be used. In this case, the audio frequency is simply applied across the resistance \( R \), or some fraction of it, in the grid circuit of the oscillator. The detecting circuit is the same as that shown in the diagram of A-34, Fig. 355, except that the small tuned circuit is placed at the center of two symmetrical antenna arms. The tuned circuit itself is simply a coil of four or five turns of No. 12 bare copper wire, \( \frac{3}{4} \) in. or so in diameter. Tuning is accomplished by pulling the coil apart or pushing it together, so as to vary the inductance and the distributed capacitance. The rectifier tube should be one of small interelectrode capacitance, such as the type 879. Alternatively, these frequencies can be amplified and detected by the use of acorn tubes, types 950 and 955. Suitable circuits and directions for the use of these tubes will be found in the bulletins accompanying them.

**KINETIC THEORY AND ATOMIC STRUCTURE**

A-41. Kinetic-theory Illustrative Models. A number of largescale models may be devised to illustrate chaotic motion and other phenomena of kinetic theory. The accompanying diagram (Fig. 363) represents one such device. A fan with four beveled blades turns at 10 or 15 rps in contact with a horizontal steel plate about 10 in. in diameter. The outer edge of the blades fits closely the inner edge of a low steel ring on the surface of the plate. The fan is driven by a variable-speed motor below the plate. A glass cylinder with inside diameter equal to the outside diameter...
of the steel ring and 8 or 10 in. high is waxed to the ring. Its top is closed by a metal cover. Several hundred steel balls about \( \frac{1}{4} \) in. in diameter are put inside, and when the fan blades rotate, these balls are driven upward against the top and walls of the container, forming a cloud of steel balls in chaotic motion. If a few larger balls of wood or pith, 0.5 in. or so in diameter, are suspended by threads a few inches below the cover, they will execute random motions of small amplitude, quite similar in appearance to the Brownian motion.

The pressure exerted by this cloud of steel balls may also be shown. A hole 3 or 4 in. in diameter is cut in the cover, and a light plate is balanced in the opening as indicated in the figure. The plate should fit the hole fairly closely, and its motion should be limited so that none of the balls can escape. Alternatively, if a small model is used, the entire circular top of the cylinder can be suspended from the balance arm, and its motion observed. A pointer mounted on the balance arm indicates the displacement of the plate when the balls are driven against it by the fan. If this motion is not sufficiently visible to a large class, the shadow of the pointer may be projected on a screen.

The model should be set in front of a white background and strongly illuminated.

**A-42.** A simpler, though somewhat less flexible, demonstration of the same nature can be performed with an electrically driven tuning fork. One tine of the fork itself or a piston driven by it forms the bottom of a rectangular cell made from two glass plates 10 cm square and about 1 cm apart. The cell contains 50 to 100 small steel balls, depending on the power available from the fork. When the fork is energized, chaotic motion of the balls ensues. A piston may be lowered into the cell to decrease the volume and to illustrate the change in density and pressure. If the fork is not sufficiently powerful to keep the balls in chaotic motion when the cell is vertical, the apparatus may be tilted at an angle so that the pressure of the balls on the prong of the fork is not so great.
A-43. A large glass vessel closed at the top with a wire grill and connected at the bottom with a source of compressed air contains a dozen or more ping-pong balls. When a blast of air is sent through the vessel, the "large molecules" execute chaotic motion simulating the motion of molecules in a gas. If one or two of the balls are brightly colored, their individual motions may be followed.

A-44. Beads or pellets of a light material can be kept in chaotic motion by the vapor rising from a pool of boiling mercury. With the exception of certain spasmodic bursts, the behavior of the beads resembles that of particles executing true Brownian motion; in fact, this visible motion is caused by bombardment from invisible molecules of mercury. The demonstration may be seen directly by the class, or it can be projected with a lantern. A pyrex tube 3 cm in diameter and about 30 cm long is closed and rounded at one end. A few milliliters of mercury is poured in, and enough colored glass beads are dropped on the surface to form a layer about 5 mm deep. The beads should not be particularly clean, for ordinary layers of grease and dirt on the tube and beads reduce the disturbing effects of frictional electrification. The tube is then evacuated and the mercury gently boiled while pumping is continued, before sealing off. The tube is mounted vertically in a projection lantern, and the mercury pool is gently heated by a Bunsen flame to set the beads in rapid chaotic motion up and down the tube. When the flame is removed, the motion gradually subsides, and the beads vibrate in a mass for a minute or so above the mercury surface. The analogy between this latter state of motion and that of molecules in a liquid may be pointed out.

A-45. A more spectacular model consists of a larger tube, 5 to 10 cm in diameter and 50 to 100 cm long, enclosing a number of pith balls, 6 or 7 mm in diameter, above a pool of mercury. If one or two of the pith balls are colored, their individual motions may be followed.¹

A-46. The foregoing models have the disadvantage that they operate with a strong gravitational component of motion. For many purposes, it is better to have a model in which the motion of the balls representing molecules takes place in a horizontal

¹ For successful results, the balls should first be out-gassed and then soaked in glyptal or shellac.
plane. The model consists of a frame in which the balls are agitated; it may be either large enough to use 0.5-in. steel balls and 45° projection or small enough to mount upon the platform of a lantern for vertical projection. The principle is the same for each, and each may be made to show the same effects. "Diffusion" may be shown by dividing the frame into two sections with a central partition in which there is an aperture; balls of different sizes are put in the two sections before the frame is shaken. "Rise of temperature" may be shown by more vigorous agitation of the frame.

Large Model. A square frame 40 by 40 cm is made from 3- by 3-cm hard wood; it is covered with a glass top and rests upon a large sheet of plate glass. A dozen or more steel balls are introduced, and the frame is grasped with both hands and given a motion such that each point describes a small circle. The balls travel about on the glass plate and rebound from the moving walls of the frame to simulate the motion of gas molecules. The class may observe the model in a large plane mirror set at 45° above the lecture table. For large classes, the motion of the balls may be made clearly visible by mounting the apparatus on a light box with opal-glass top (Fig. 364). The balls will thus be shadowed against a strong background illumination.

Small Model. Similar effects may be produced with a small model suitable for projection. A rigid metal frame 10 by 10 by 1 cm with a glass cover is set on a piece of plate glass mounted on the stage of a vertical projection lantern. Numerous small steel balls are introduced, and the frame is agitated; the balls rebound from the walls and collide with one another, and their chaotic motion may be observed by projection. The frame may be moved by hand, or it may be attached to a crank driven by a variable-speed motor in such a way as to be given a reciprocating circular motion.

A-47. Distribution of Molecular Velocities. An inclined board, containing diagonal rows of nails, is fitted with a system of parallel chutes at the base. A single sphere if released from the
top of the board at the center will, after striking some of the nails, land in some chance chute at the bottom. The exact chute is not predictable before the release.

A large number of spheres (lead shot) is released from the center of the top of the board. The number landing in the central chute is large, while the number landing in neighboring chutes is less the farther the chute is from the center. The number falling in each chute is predictable before the release of the spheres, and the accuracy of the prediction increases with the total number of spheres. The piles of spheres in the various chutes form a probability curve similar to that representing the distribution of velocities in the molecules of a gas.

**A-48. Brownian Motion.** It is difficult to demonstrate Brownian motion to a large class. As individual observation is simple, it is generally to be preferred. The simplest method is to blow a little smoke into a glass cell and illuminate it intensely from the side with the light from an arc. The motion of the smoke particles may be observed through a low-power microscope. Dark-field illumination is preferred but not required.

**A-49.** The Brownian motion of colloidal particles suspended in a liquid makes a more permanent demonstration. Colloidal metal suspensions may be made by sparking metal electrodes under water. A few storage batteries may supply adequate energy, or 110 v may be used if sufficient resistance is included to limit the current to 10 or 15 amp. Silver or gold electrodes produce the best suspensions, though almost any metal can be used. If the suspension is then allowed to stand, the large particles settle out, or they may be filtered off. These suspensions may be kept for considerable periods of time. A colloidal suspension can be made by dissolving a little powdered gamboge in alcohol and pouring a little of the solution into a large quantity of water. The colloidal suspension is poured into a shallow glass cell suitable for mounting on a microscope stage. It is illuminated from the side by the light from an arc or projection lantern. The motion is observed individually through a microscope of moderate power, or the field may be projected by an inclined mirror onto a ground-glass screen, thus enabling a small group to observe the phenomenon without having the room in total darkness.

**A-50.** Rotatory Brownian motion may be observed under low magnification in a dilute suspension of lead carbonate crystals.
Two grams of potassium carbonate and 1 g of lead acetate are each dissolved in 100 ml of distilled water. These solutions may be stored for use at any time. One milliliter of the first solution and 0.5 ml of the second are each diluted to 300 ml, and the suspension is prepared by mixing the latter two solutions. Under strong horizontal illumination, the suspension of flat lead carbonate crystals shows countless starlike particles, which twinkle as they rotate.

The motions may be projected more or less satisfactorily by microporation with a lantern or by means of a good microscope from which the eyepiece has been removed so that the image formed by the objective falls directly upon a ground-glass or flashed-opal screen. The screen is set in a vertical plane inside a protecting black box, and light from the microscope is directed upon it by a plane mirror or 45° prism at the top of the ocular tube (Fig. 365). A slide containing a few drops of gamboge or lead carbonate suspension is placed upon the microscope platform and strongly illuminated from below. It is necessary to show the experiment in a darkened room.

**A-51. Optical Arrangement for Viewing Brownian Motions.** Observation of Brownian motions by means of an enlarged virtual image may be accomplished as illustrated in Fig. 366. A cell
containing a lead carbonate suspension is illuminated near the surface by a convergent beam of light from an arc. A lens of short focal length is placed just above the cell so as to form a virtual image of the illuminated particles. Above this lens is set a plane mirror at 45°, and a large reading glass is mounted vertically in front of the mirror. Thus, by looking through the reading glass, the student may see an enlarged virtual image of the moving particles. In a darkened room, the motion may be seen at a distance of 20 or 30 ft. If the whole system is mounted upon a rotating stand, it may be turned slowly from side to side so that all members of the class may see the phenomenon (L-54).

A-52. Order of Magnitude of Molecular Dimensions. One upper limit to molecular dimensions can be set by measuring the thickness of gold leaf. The most convenient method is to weigh 10 or 15 sheets and divide by the product of the density and the area. The thinnest gold leaf gives a limit of the order of $10^{-5}$ cm. A soap film illuminated and projected by the method of L-67 will show before it breaks a black region where it is too thin to produce interference by reflection from front and back surfaces. The film is then of the order of $10^{-7}$ cm thick.

A-53. An upper limit may also be set by determining the thickness of oil films on water or of soap-bubble films. A dilute solution of stearic acid in alcohol or a mixture of about 1 part of petroleum oil to 10 parts of xylol forms a suitable film. A tray about 18 in. square, preferably with a dark bottom, is filled to a depth of 1 cm or so with water, and the surface lightly dusted with talc. A brisk current of water overflowing the vessel prior to dusting with talc will assure a clean surface. A large mirror may be set above the tray at 45° for class observation. When a single drop of the solution is allowed to fall on the surface from a pipette, a film spreads out, shoving the talc before it. The area may be estimated with a meter stick or by means of cross-rulings.
on the bottom of the tray. The volume of the film can be estimated from a knowledge of the concentration of the solution and the number of drops per milliliter. Stearic acid forms films of the order of $2 \times 10^{-7}$ cm thick. Oleic acid films are somewhat thinner.

**A-54. Diffusion of Gases.** The dependence of the average molecular velocity and hence the rate of diffusion on the molecular mass may be demonstrated as follows.¹ A thin-walled unglazed porcelain cup is waxed over the end of a glass J-tube, the bend of which is filled with water colored with a little ink or dye to serve as a manometer (Fig. 367). If a paper cone is placed around the porous cup, vertex downward, and a stream of carbon dioxide is directed into it, the manometer will indicate a decrease in pressure within the porous cup as the air diffuses out of the cup more rapidly than the carbon dioxide diffuses in. After a time, the internal and external pressures become equal again. If the cone is now removed, air will diffuse into the cup more rapidly than carbon dioxide diffuses out, and the pressure inside the cup will exceed atmospheric for a short time. If a beaker is held over the cup and illuminating gas is directed into it, the converse process will take place. The gas, being composed of light molecules, diffuses into the container more rapidly than the air or carbon dioxide diffuses out. Hydrogen shows an even more pronounced effect. *Caution:* Do not blow hydrogen through a new rubber tube into a confined space, as an explosion may result from interaction of the hydrogen and the white powder inside the tubing.

**A-55.** A little liquid bromine is placed in the bottom of each of two cylinders, one containing air and the other hydrogen. Bromine and hydrogen interfuse much more rapidly than bromine and air.

**A-56. Diffusion and Pressure.** The influence of the pressure of a gas on the rate of diffusion of a vapor and the rectilinear

¹ It may be pointed out that the order of magnitude of molecular velocities in gases is the same as that of the propagation of sound. See also S-86.
motion of vapor molecules in the absence of any residual gas can be illustrated in the following way. Two pyrex containers, each of about 1-l capacity, are joined by a short length of 1-cm glass tubing, as shown in Fig. 368. A few iodine crystals are introduced, and connection is made to a vacuum pump. If the crystals are heated by a Bunsen burner at atmospheric pressure, prior to pumping, a considerable time will elapse before the iodine vapor fills the upper bulb. If the crystals in the lower container are now cooled in an ice or solid carbon dioxide bath, the iodine vapor disappears. Now if the apparatus is evacuated and the iodine is heated for a few minutes, a small deposit of crystals will be observed to form on the top of the upper vessel some time before the entire apparatus becomes filled with vapor. The molecules travel directly through the constriction from the lower surface of the bottom vessel to the upper surface of the top one. Also the iodine vapor disappears from the bulb when it is immersed in an ice bath much more rapidly when it is evacuated than when it is full of air (II-84).

A-67. Vacuum System. A portable high-vacuum system is an invaluable piece of auxiliary apparatus for lecture-demonstration work in this and other fields. Such equipment can be obtained from scientific supply houses, or the parts may be constructed and assembled as in Fig. 369. A vessel on the low-vacuum side of the diffusion pump serves the purpose of reservoir and drying chamber to protect the oil pump. A small manometer indicates the pressure in this chamber. The diffusion pump is of ordinary design, preferably of the two-stage type. Beyond it are a McLeod gauge, liquid-air trap, and large-bore stopcocks. Oil diffusion pumps are somewhat less useful for general purposes than the mercury type as they are more easily damaged by oxidizing gases and overheating. Liquid air need not be used on the trap for most work, since solid carbon dioxide in carbon tetrachloride reduces the pressure of mercury vapor to a
negligible amount, and precautions can be taken to remove water vapor if pressures above $10^{-3}$ mm mercury are objectionable.\(^1\)

It is convenient to mount the complete apparatus on a wooden or metal frame that can be clamped to the lecture table. Air can be admitted through the three-way stopcock above the fore pump, but it is sometimes convenient to have a small stopcock in the neighborhood of the McLeod gauge also for this purpose.

The diffusion pump itself serves as an excellent illustration of the phenomenon of diffusion at low pressures. The calibration and use of the McLeod gauge illustrate the gas laws (M-319).

The adsorption of gases by shabazite or charcoal can be shown by sealing a tube containing one of these materials to the system beyond the second stopcock. The tube is pumped out and torched or baked at 400° to 500°C for 15 or 20 min. The two large stopcocks are then closed, and air is admitted through the middle stopcock to a pressure of a few centimeters of mercury, forcing the mercury down the stem of the McLeod gauge. The stopcock to the charcoal is then opened, and the decrease in pressure noted when the charcoal is cooled with solid carbon dioxide or liquid air (H-116).

**A-58. Viscosity and Pressure.** The phenomenon of viscosity (M-61) and its dependence on pressure in the low-pressure region,

together with the radiometer effect (H-164) and a qualitative demonstration of light pressure, can be illustrated with the apparatus shown in Fig. 370. Two vanes of aluminum leaf a few millimeters square are affixed with drops of shellac to the ends of a very light glass rod about 2 cm long. A stirrup of very fine wire to which a small mirror is attached supports this glass rod at its center and is in turn supported by a fine quartz fiber attached to it by a drop of wax as shown. The upper end of the fiber is attached by a drop of shellac to a heavy wire passing through the wax seal in the top of the glass envelope. The envelope may have the shape shown in the figure, though this is immaterial. Its open end is waxed to a steel or copper plate 5 or 6 cm in diameter, resting on a rugged support on the lecture desk, the whole system being as well protected from vibration as possible. The wax used throughout should be one of the low-vapor-pressure vacuum waxes. The moment of inertia of the moving system should be calculated at the time of construction.

The angular position of the system is shown by a spot of light reflected from the small mirror to a scale visible to the class.

If a fairly soft wax is used for the upper joint, the system can be set into oscillation by giving a small rotation to the heavy wire passing through the seal. The decrement of the system may then be determined by noting the period and the amplitudes of the successive maxima.\(^1\) This will be found to be approximately constant at high pressures and to decrease with the pressure when the mean free path is of the order of the dimensions of the apparatus, thus giving evidence of decrease of viscosity at low pressure.

**A-59. Radiometer.** The radiometer effect may be demonstrated over a wide range of pressures, from 10 or 20 cm down to a fraction of a millimeter, by focusing the light from an arc or tungsten lamp on one of the vanes of the instrument shown in

\(^1\) The method of computing the mechanical factors of the system, such as decrement and torsion constant, is given in many laboratory texts, usually in conjunction with experiments on moment of inertia or ballistic galvanometers.
Fig. 370. By periodically interrupting the light beam at the natural frequency of oscillation of the vane system, a very large amplitude can be developed. The reversal of the radiometer effect at some point in this pressure range may also be shown. If the period of oscillation is timed and the moment of inertia is known, the restoring constant of the fiber and hence the torque can be computed.

A-60. Light Pressure. The order of magnitude of the pressure exerted by radiation can also be determined with the apparatus of Fig. 370. The moving system is brought to rest, and the best possible vacuum is obtained (of the order of 10⁻⁴ mm mercury). Then one vane is illuminated by the arc as before, and a small deflection will be observed. The amplitude can be increased by the resonance procedure indicated previously (A-59), but the static deflection is simpler for computation. The torque and hence the pressure on the illuminated vane can be calculated from the deflection and the constants of the apparatus previously determined. To complete the experiment, the radiation may be directed on a small soot-covered bulb containing 10 or 15 ml of water, and the temperature rise during a measured time interval noted. These results will provide a rough check on the equality between the radiant energy density in front of the vane and the pressure exerted by the radiation.

A-61. Conduction of Heat in Gases. Heat conduction in various gases and its dependence upon the pressure may be illustrated by sealing or waxing a carbon filament lamp onto the vacuum system. Sealing is preferable if a graded seal is available; if wax is used, provision must be made for cooling the joint if it is close to the lamp envelope. The system is filled with nitrogen, and the lamp is connected to the 110-v supply. The nitrogen is slowly pumped out, and after a certain pressure is reached, the filament begins to radiate visibly. The brightness of the filament, which is an inverse function of the rate at which heat is conducted away, may be studied qualitatively as a function of the pressure. At high pressures, the heat conduction is approximately independent of the pressure. If hydrogen is used instead of nitrogen, the lamp will not be observed to glow until a considerably lower pressure is reached. The hydrogen molecule with the same capability of energy absorption has only 0.07 the mass of the nitrogen molecule, and so it moves three or four times
as fast, makes correspondingly more impacts, and carries heat away from the filament at a much greater rate. The effects produced are somewhat complicated by the negative temperature coefficient of resistance of carbon, but the general aspect of gaseous conduction of heat predominates.

ATOMIC FORCE MODELS

A-62. Equilibrium Configurations. There are a few types of large-scale model that may be used to illustrate the nature of atomic and molecular forces. It should be emphasized in this connection that atomic models are not to be confused with other types of model, such as model steam engines, etc. They are figurative or allegoric representations of entities having no real macroscopic analogues. They must not be confused with realities but are to be considered as very imperfect bases for the illustration of a few of the fundamental atomic concepts.

One of these models shows the equilibrium configurations of steel balls floating on a mercury surface in the field of an electromagnet and suggests a simplified picture of electron configurations in atoms, or atomic configurations in crystal lattices. An ordinary iron-cored solenoid wound for 110-v direct current is set in a vertical position, and the core is covered with an iron disk about \( \frac{1}{4} \) in. thick and 2 in. in diameter. On this is placed a shallow glass tray filled to a depth of about 0.5 cm with mercury. A number of steel balls about \( \frac{1}{2} \) in. in diameter is also provided. A 45° mirror mounted over the tray and magnet renders the mercury surface visible to the class. It is very important to have the mercury, dish, and balls entirely free from grease and dirt. The mercury should be freshly distilled, and the dish and balls should be cleaned with benzene, hot cleaning solution, and potassium hydroxide and then rinsed in distilled water. They may be dried by natural evaporation or over a low flame. Nothing should be touched subsequently with the fingers. The balls may be stored between clean watch glasses and handled with brass forceps. As the balls are laid one by one on the mercury surface, they assume equilibrium configurations under the influence of the field of the magnet and the magnetic moments induced in each ball.

The static model just described can be made into a moving one by the addition of electrodes beneath the surface of the mercury.
One is a ring of about the diameter of the vessel, and the other occupies a small area at the center of the ring. Thus a radial current may be established through the mercury from center to ring. When such a current exists, the mercury is set into motion and carries the balls with it, but they do not follow its simple circular motion. If there are 2 balls on its surface, one revolves planetwise about the other for a short time and then replaces the other at the center while the second revolves about it. Thus the balls take turns at the center: Similar motions occur with three or four balls. Usually with six balls, they arrange themselves in a circle with none going into the center. As more balls are added one by one, the configuration becomes more difficult to keep stable, but with care as many as 32 balls can be put in motion in concentric rings. It should not be supposed that this model is necessarily an accurate representation of the structure of any atom.

A-63. Alpha-particle Scattering—Magnetic Model. Alpha-particle scattering and the inverse square law of force near the nucleus can be illustrated by the repulsion between magnetic poles. An iron cap in the form of a sphere or hemisphere is mounted on top of the solenoid used in A-62. A second solenoid with either an air core or an iron core terminated in a ball is suspended by its leads from the ceiling of the lecture room. The suspended system may be reinforced with a light bamboo rod to eliminate undesirable oscillations. It is convenient to provide a rheostat in series with this solenoid to vary the repulsive field between the two. The lower end of the suspended solenoid should just clear the upper end of the fixed one. If the stationary solenoid is directly below the point of suspension and the pendulum solenoid is displaced a few feet and released, it will be repelled more or less back toward its starting point, illustrating a head-on collision. If the lower solenoid is displaced a few inches from the direct line of swing, a hyperbolic orbit will be described by the pendulum, illustrating the general trajectory of an alpha particle deflected by a heavy nucleus. A semiquantitative study of these trajectories may be carried out by moving the lower solenoid a few centimeters at a time and always releasing the pendulum from the same point.

If the sense of the magnetization of one of the solenoids is reversed so that an attractive field exists between the poles,
circular and elliptical orbits can be demonstrated. Various orbits passing through the point of release can be illustrated by varying the magnitude and direction of the original impulse given the pendulum. These may be used to illustrate qualitatively the nature of electron or planetary orbits. Strong permanent cobalt-steel magnets may be used instead of solenoids.

A-64. Alpha-particle Scattering—Electrostatic Model. A variation of A-63 that has a number of advantages involves electrostatic rather than electromagnetic forces. A sphere about 6 in. in diameter is charged by means of a Wimshurst or Van de Graaff generator. A ping-pong ball coated with aluminum paint is suspended by a silk thread from the ceiling in such a way that it swings a foot or so above the sphere. The ball can be charged if desired, but this is generally unnecessary as it will charge itself by corona from the large sphere and induction plays a role as well. On being pulled aside and released, the ball can be made to describe the various conic-section orbits. The most effective method of observation is to place an arc light some distance below the spherical electrode and cast the shadow of the moving ping-pong ball on the ceiling.

A-65. Nuclear-disintegration Model. A watch glass 5 in. in diameter is mounted convex side upward in a box, so as to cover the condenser lens of a vertical projector. The “nucleus,” which occupies the center of the field of view, is a short piece of ½-in. brass tubing standing on three narrow legs (Fig. 37). The projection of this tube on the screen is a circle. The tube is fitted with an opaque cap that can be removed, if desired, to show “internal structure” of the nucleus. The nucleus houses a number of steel balls of two contrasting sizes (e.g., ¼ and ½ in.) ready to emerge as “neutrons” and “protons” when struck by fast “alpha particles.” The projectile particles are ⅛- or ¼-in. steel balls whose speed and direction of approach are controlled by rolling them down an inclined brass tube, one at a time. A thin ring of brass, of the same diameter as the nuclear housing, serves as a base for the three legs supporting the latter and at the same time acts as a low “potential barrier” to prevent the
escape of balls within the nucleus until they are struck by impinging particles having sufficient energy to cross the barrier. At low speeds, the paths of the alpha particles may be curved, as if they were repelled from the nucleus; at higher speeds, the particles may penetrate the nucleus, where they may be captured or may cause "nuclear disintegration" with the ejection of one or more other particles, previously planted within the housing.¹

A-66. Electron-configuration Diagrams. Blackboard diagrams illustrating electron configurations may be supplemented by the following arrangement. A piece of plywood about 18 by 36 in. is laid out in two sets of concentric circles to represent the K, L, M, etc., shells of two atoms. Each of these circles has the appropriate number of small holes drilled around its circumference: two for the K, eight for the L, etc. A hook or peg at the center supports a small circular card showing the charge and mass of the nucleus to be illustrated. Small red plugs (golf tees are convenient) inserted in the holes around the circles represent the extranuclear electron structure. Atomic configurations are represented by the use of one set of circles, and diatomic molecules by the use of both. To preserve the proper relative scale for different atoms, the outer circles should be used for the K shells of hydrogen and helium, and the pattern compressed as heavier atoms are illustrated.

ATOMIC ENERGY LEVELS

A-67. Ionization and Radiation Potentials. The first critical potential and the ionization potential of mercury can be demonstrated with a hot-cathode mercury-vapor discharge tube such as the FG-57. The tube is mounted in a small oven, care being taken that the thermometer and heating coils do not touch the tube envelope. The ionization potential is measured at room temperature. A battery of 1 or 2 v maintains the plate negative with respect to the cathode; this is accomplished by setting the switch S in position 1 (Fig. 372). The grid potential, measured by the voltmeter V, is supplied by a potential divider and battery of about 18 v. The grid is slowly made more and more positive with respect to the cathode; and when the ionization potential of the vapor is reached, the galvanometer in the plate circuit will register a deflection, showing the arrival of positive ions at the vapor.

¹ For further details, see R. M. Sutton, Am. Phys. Teacher, 2, 115, 1934.
plate. A protective resistance of a few thousand ohms should be included in series with the galvanometer. For the detection of critical or resonance potentials, the tube is heated in the oven to about 200°C. With the switch in position 2, the plate is kept 1 or 2 v negative with respect to the grid. As the potential of the grid is now increased, the galvanometer registers an electron current, and the curve of galvanometer deflection against grid potential will exhibit one or two peaks about 5 v apart. The shape of this curve and the number of peaks observed can be varied by changing the oven temperature.

With the tube at room temperature, the mean free path of the electrons is of the order of magnitude of tube dimensions. As the electron energy is increased by raising the grid potential, the electrons collide harder and harder with mercury atoms until they are finally able to produce a few positive ions. These are drawn to the plate by the potential gradient between it and the grid, and the current due to them is detected by the galvanometer. When the tube is at a higher temperature, the electron free path becomes very short on account of the increase in mercury-vapor pressure. When the potential of the grid is below about 5 v, the electrons are unable to lose energy to the mercury atoms and hence are able to surmount the small potential barrier between the grid and the plate, and the current through the galvanometer rises with voltage. When the electron energy is a little greater than the first critical potential, the mercury atoms are able to accept energy from the electrons, which are then unable to proceed against the retarding field from the grid to the plate, and the galvanometer current decreases. At a higher potential, electrons that have undergone two inelastic collisions are unable to reach the plate, and a second minimum appears. A lecture-table voltmeter V enables the students to follow the variations of cathode-to-grid accelerating potential.

**A-68. Resonance Radiation of Iodine Vapor.** A large Florence flask containing a few crystals of iodine is evacuated and sealed off. When the flask is heated and held in the cone of light from
the condensing lens of a carbon arc lamp, the light path within the bulb becomes visible to a large audience.

**A-69. Emission Spectra—Balmer Series.** The spectra emitted by gases during electric discharge can be observed individually with a prism or grating instrument, or if the room is sufficiently darkened and an intense source is used, they may be projected on a screen. The projection of bright-line spectra has been described in L-104. A semiquantitative experiment on series spectra can be performed on the Balmer lines of the grating spectrum of hydrogen. The angular deviations of the three or four lines that can be observed (Hα, Hβ, Hγ, possibly Hδ) are measured, and the wave lengths and frequencies calculated from the grating constant. It may be shown that these wave lengths obey the Balmer formula, \( \lambda = \frac{k}{m^2 - \frac{1}{4}} \) where \( m \) has values 3, 4, 5, ...; and that the corresponding frequencies follow the Balmer-Ritz equation \( \frac{v}{c} = \frac{R}{n^2 - \frac{1}{4}} \), where \( R \) is Rydberg’s constant and \( n \) is any integer greater than 2, from which an approximate value of the Rydberg constant can be calculated.

**A-70. Absorption Spectra.** The absorption of light by gases can be demonstrated with sodium vapor. A steel tube about 2 in. in diameter and 3 ft long is provided with a connection for attachment to a small fore pump. A small piece of sodium is placed in the center of the tube, and glass windows are waxed on the ends. Coils of lead pipe wrapped around the ends carry cooling water and keep the wax from melting. The tube is evacuated and the sodium vaporized by placing one or two Bunsen burners beneath the center of the tube. If light from a sodium-vapor lamp and an ordinary arc or incandescent lamp is observed through the tube, a great difference in the relative diminution of intensity will be seen. If the tube is placed in the light path before a demonstration spectroscope, the phenomenon may be shown in more detail. With a sodium-lamp source, the yellow D lines are greatly reduced in intensity, and the remaining lines are relatively unaffected. If a continuous source is used, dark lines will be observed at the positions that the yellow D lines would occupy. A sodium flame of the spray type (atomized salt solution sprayed into the burner with compressed air) will serve
moderately well, but metallic sodium vaporized by a blast lamp is better (L-108).

Absorption by sodium vapor can be shown by the incandescent lamp (heated) into which sodium has been electrolytically introduced (E-211). The lamp easily shows surface reflection by the vapor, and absorption of sodium light from a sodium arc. It must be heated almost hot enough for sodium to attack the glass in order to widen the line enough to be seen against a continuous spectrum with low dispersion.

Absorption bands may be shown by passing the light from a carbon arc through flasks containing bromine or iodine vapor and thence through a spectroscope. Iodine vapor may be produced by heating a few crystals of iodine in an evacuated flask (A-68).

**PROPERTIES OF ELECTRONS**

**A-71. Deflection of Cathode Rays.** A cylindrical glass tube contains a plane electrode at each end. A mica screen in front of one electrode, the cathode, is provided with a slit to limit the beam of cathode rays to a thin horizontal lamina. The tube is connected to an induction coil or static machine. The path of the rays is shown by the line of light excited on a fluorescent screen in the tube, placed so as to make a slight angle with the direction of the beam. The cathode particles can be deflected either by the electric field of a charged rubber rod or of a pair of plates connected to a static machine or by the magnetic field of a bar magnet or of a solenoid. In the case of an electric field, the deflection is toward the positive charge. In the magnetic field, the force is perpendicular to the magnetic lines of force and to the path of the beam, in the sense opposite to that given by the motor rule for a positive current moving with the beam. Both of these experiments show that the cathode rays are negatively charged particles moving with high speed. Discharge tubes suitable for the experiment can be obtained from scientific supply houses.

**A-72. Measurement of e/m.** A rough measurement of e/m may be carried out with a commercial cathode-ray oscilloscope tube. In such a tube, the electrons from a hot filament are accelerated by a potential that can be measured. The velocity of the particles is then given by the relation \( \frac{1}{2}mv^2 = Ve \), where \( V \) and \( e \) are both measured in esu. If the tube is mounted on a horizontal axis with the direction of the beam perpendicular to the
lines of force of the earth's magnetic field, the spot on the fluorescent screen will be deflected in one direction; and when the tube is rotated through 180°, the spot will be deflected in the opposite direction. The position in which the beam is exactly perpendicular to the field is found in each case by tilting the tube up and down to find the position of maximum deflection. The total distance between the two positions of the spot is measured. Calling this distance 2x and the distance from anode to fluorescent screen L, the value of e/m is calculated. Since in the magnetic field \( \frac{mv^2}{r} = \frac{Hev}{c} \), we have, combining with the previous equation, \( e/m = \frac{2Ve^2}{H^2r^2} \) esu per g, where H is the value of the earth's field (assumed to be known approximately) and r is the radius of curvature of the path of the electrons, which is given by

\[
1/r = \frac{2x}{x^2 + L^2}
\]

or \( r = L^2/2x \) approximately.

The experiment is somewhat simplified by mounting the tube axis horizontal and then rotating it about a vertical axis from the east-west to the west-east position. The total deflection of the spot in a vertical direction is then caused only by the horizontal component of the earth's field, and the same equations apply.

In each experiment, the deflecting plates of the tube are connected to the anode and a known potential applied between the anode and the filament. The spot may be focused by adjusting the filament current to the best value.

**A-73.** Instead of the earth's field, the magnetic field of a solenoid may be used. The energy of the electron beam is known as before from the applied accelerating potential, and the radius of curvature can be computed from the displacement of the spot and other significant dimensions. The magnetic field producing the deflection is furnished by two large coaxial solenoids, one on either side of the tube (Fig. 373). The deflection of the spot is measured as a function of the separation between these two coaxial solenoids operated at constant current. The resulting curve is then extrapolated to determine the deflection that

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would result if the two coils formed one continuous solenoid normal to the axis of the tube. The region of the magnetic field is considered to be the cross section of the solenoid.

A-74. A somewhat more accurate method is to string two wires 1 to 2 m long on either side of the cathode-ray oscilloscope tube and parallel to its axis. A current \( i \) is sent through the circuit formed by these wires, and the field \( H \) (in emu) along the beam is approximately uniform and equal to \( 8i/d \), where \( d \) is the separation of the wires. The radius of curvature \( r \) is \( l^2/2x \), where \( l \) is the length of the beam and \( x \) is the displacement of the spot. The value of \( e/m \) is then calculated from the equations of A-72.\(^1\)

A-75. Model of Oil-drop Experiment. A large model of the Millikan oil-drop experiment may be constructed as shown in Fig. 374. \( A \) and \( B \) are galvanized iron plates, about 2 or 3 ft in diameter and 1 ft apart (the size should be that best adapted to the size of the lecture room), mounted on insulating supports. A ping-pong ball or small rubber balloon, coated with aluminum paint to render the surface conducting, is suspended between the plates by a thread passing through a hole in the upper plate and fastened to the end of a light stick balanced on a knife-edge. If a balloon is used, it may be filled with hydrogen to the proper volume so that it will float in air and the balancing mechanism may be dispensed with. The ball may be given a small charge by induction, using a charged rubber rod, or better, by directing a beam of \( x \) rays on it or bringing up a sample of radioactive material on the end of a long insulating rod. The two plates are connected to the terminals of a static machine, and the upward or downward force on the ball is clearly evident. The direction of motion may be reversed by introducing the radioactive material between the ball and the plate toward which it is moving.

\(^{1}\)For details, see Smyth and Curtis, \textit{Am. Phys. Teacher}, 6, 158, 1938.
A-76. Oil-drop Experiment for Determining $e$. In small classes, the oil-drop experiment itself can be shown. Students may look individually through the microscope and see the oil drops rising or falling in the field. One drop may be isolated and timed on successive trips by a student or by the instructor, to obtain the data from which the charge can be computed.$^1$

An apparatus that may be constructed in any laboratory and that, if carefully made, gives good results is shown in Fig. 375. The plates are of steel, 2 in. square and $\frac{1}{4}$ in. thick, separated by hard rubber strips $\frac{1}{4}$ in. thick. The lower plate is fitted with a rod (either metal or an insulator) by which the apparatus is clamped to a stand. In the center of the upper plate are drilled several small holes through which oil drops are admitted. A metal cover is provided to close these holes during observation. Glass plates for viewing the oil drops are provided between the steel plates on two opposite sides. The potential applied to the plates need be only 90 to 135 v. An ordinary flashlight serves as an excellent source of light, and a telescope of short focal length with a scale in the eyepiece is used for observation. Nye's watch oil (obtainable from any jeweler) or light mineral oil sprayed from an atomizer supplies the drops, which are allowed to fall through the holes in the upper plate.

![Diagram of apparatus for determining $e$ by the oil-drop method.]

THERMIONIC EMISSION

A-77. Thermionic Effect in Air. An attachment for the Zeleny electroscope (E-4) consists of a length of resistance wire mounted on an insulating support so that a heating current can be sent through it while it is in position near the plate of the electroscope. A 6-v battery and a 20-ohm rheostat capable of carrying 5 amp are connected in series with the filament. The charging electrode of the electroscope is connected to the positive terminal of a 90-v battery. When the current through the filament is increased until the wire glows bright red, the leaf of the electroscope will

begin to oscillate, indicating the passage of electrons to the plate; and the oscillations become more rapid as the temperature of the filament is increased. With an oxide-coated wire or in the presence of air, both positive and negative ions are formed at the hot filament in addition to the electrons emitted by it. Therefore the leaf of the electroscope oscillates whether it is positive or negative. (See also A-82.)

A-78. Thermionic Effect in Vacuum. Any standard two- or three-electrode tube may be used to show thermionic emission; in the case of a three-element tube (e.g., type 01A), the plate and grid are connected. However, the experiment is more striking if a large tube of the kenotron type is used, in which the filament is plainly visible. An effective tube can be made by sealing a filament consisting of a 10-mil tungsten wire into one end of a pyrex flask and a plate of nickel in an additional neck joined to the opposite side. This tube may then be exhausted, and thermionic emission demonstrated. If desired, it may be evacuated and sealed off after the filament, plate, and bulb have been thoroughly heated. In pumping out, a diffusion pump with a trap cooled by liquid air or dry ice is necessary (A-57). The circuit is connected as shown in Fig. 376. The filament can be heated with a battery or with a transformer. A 180-v B battery with potential divider (2000 ohms) is used in the plate circuit. A voltmeter reading to 150 v and a milliammeter reading to 10 ma are suitable. The temperature of the filament and the potential on the plate are varied, and saturation curves of the type shown in Fig. 377 are obtained.

A-79. Thermionic Rectifier (Kenotron Type). The apparatus of the previous experiment is used, with the addition of an a.c. source and two d.p.d.t. switches. The circuit is shown in Fig. 378. With switch $B$ in position 1, the milliammeter shows a current only when switch $A$ is in such a position as to make the plate positive. Several rapid reversals of switch $A$ give the effect of a very low-frequency alternating current and show how the
meter indicates an "average" value. A rotating reversing switch whose speed can be gradually increased is also effective. With switch B in position 2, the current is about half that obtained with direct current, since there is current in the plate circuit only during the positive half of the a.c. cycle. This experiment gains greatly in effectiveness if the wave form of the rectified current is shown on an oscilloscope.

**A-80. Rectifying Property of a Diode.**

Two neon lamps A and B are connected as shown in Fig. 379. A diode rectifier tube $T$ or nearly any triode with grid and plate joined is placed in series with A. When a 110-v a.c. line is connected as shown, both electrodes of B glow, whereas A does not glow at all until the filament of $T$ is heated, and then only one plate of A glows (see also A-87).

**A-81. Characteristic Curves of Three-element Tube.** The filament of a three-electrode tube (e.g., type 01A) is heated with a battery or a transformer; the plate potential is provided by a B battery and a potential divider; the grid potential is furnished by a C battery with taps at 0, 1.5, 3.0, 4.5 v, etc. The circuit is connected as shown in Fig. 380. First, one or two plate-current curves are taken at different grid voltages. Next, small changes are made in the grid voltage to show that they produce as much change in plate current as large changes in plate voltage. The amplification factor of the tube is the ratio of change of plate voltage to change of grid voltage necessary to keep the plate current constant. Finally, the change in plate current for a given change in grid voltage is determined at one or two values of plate voltage, from which can be found the transconductance $\Delta i_p/\Delta e_g$ (usually expressed in micromhos, i.e., microamperes per volt). The meters used in these experiments should be such as can be seen and read by the entire class.
A-82. "Fresh Air Three-electrode Tube." A Zeleny electroscope is arranged with supplementary external filament, grid, and plate as shown in Fig. 210, with electrical connections as shown in Fig. 381. An oxide-coated filament $F$, heated in air by battery $B$, furnishes ions that pass to the plate $P$ beyond the grid $G$. Plate potential and grid potential are controlled independently by potential dividers. The plate current is measured in terms of the rate of oscillation of the electroscope leaf. This simple arrangement makes possible the qualitative determination of several important characteristics of three-electrode tubes, such as the dependence of plate current upon electrode separations, electrode potentials, filament temperature, and gas pressure. The last may be shown by placing the whole apparatus under a bell jar and exhausting with a vacuum pump.\footnote{For further details of this and related experiments, see Roger Barton, *Rev. Sci. Instruments*, 2, 217, 1931.}

A-83. Mechanical Analogue of Three-electrode Tube. The device used in E-58 for showing potential distribution in an electric field may be employed to show how a grid controls electron flow in a triode. A sheet of rubber dam is fastened between the rings of an embroidery-hoop "plate" $P$. The center of the dam $F$ ("filament") is pinned with a thumbtack to a dowel rod so that it may be raised or lowered with respect to the "plate" level. Small steel balls representing electrons will roll from filament to plate when $F$ is above $P$ but not when $F$ is below $P$ (rectifying action of diode). If $F$ is fixed above $P$ (as shown in Fig. 382), the "potential gradient" between $F$ and $P$ may be controlled by a tube $G$ ("grid"), which may be pushed up and down below the rubber dam. A lamp chimney is suitable for this
grid. When \( G \) is above \( F \), no "electrons" can reach \( P \). If desired, the function of the "filament" may be made still more realistic by pouring fine shot through a funnel upon the center of the rubber dam.

![Mechanical model to illustrate action of triode](image)

**Fig. 382.**—Mechanical model to illustrate action of triode.

**A-84. Three-element Tube—Electrostatic Control.** The plate current of a three- or four-element tube may be controlled electrostatically as follows. Any standard tube with a suitable plate and filament supply can be used, but one with a control grid contact at the top of the glass envelope is particularly suitable. The grid of the tube is connected directly to a metal sphere on an insulating stand, such as is used in electrostatic experiments, care being taken that the insulation is good (Fig. 383). The plate circuit includes a small relay (telephone or "pony" telegraph
(type) that operates a doorbell, automobile headlight, or other indicating device. The relay is adjusted so that, when the grid is floating, the plate current just fails to close the relay contacts.

When a positively charged rod is brought near the sphere, the positive charge induced on the grid of the tube increases the plate current and causes the relay to operate. A negatively charged rod has no effect. If the rod is held in position near the sphere for a few seconds, the positive charge on the grid is neutralized by electrons from the filament, and the relay opens. Removing the rod for a few seconds and then returning it will cause the relay to close again. The charged rod is thus a "magic wand." Attention may be called to the exceedingly small amount of power required to operate the grid as compared to that controlled by the relay. In place of the relay, a small flashlight bulb may be included directly in the plate circuit.

**A-85. Multistage Amplifiers.** Every laboratory should have at least one good three- or four-stage audio-frequency amplifier.
with sufficient output to operate a loudspeaker. Its uses are many. A suitable circuit is shown in Fig. 384. The output power of this amplifier is 5 w, and the gain is about 75 db. An alternative higher-power output circuit is shown in Fig. 385.

![Circuit Diagram](image)

**Fig. 385.—Alternative higher-power output circuit for amplifier of Fig. 384.**

Class A (no grid current), 14 watts, 2 % harmonic distortion. Peak grid-to-grid voltage, 35.6. $T_1$, speaker transformer, 5000-ohm primary; $R_1 = 125$ ohms; $V_t = V_p = 250$ v; $i_t = 10$ ma (no signal), 15 ma max; $i_p = 120$ ma (no signal), 130 ma max.

Class AB1 (no grid current), 32 watts, 2 % harmonic distortion. Peak grid-to-grid voltage, 57. $T_2$, speaker transformer, 6600-ohm primary; $R_1 = 200$ ohms; $V_t = 300$ v; $V_p = 400$ v; $i_t = 7$ ma (no signal), 16 ma max; $i_p = 112$ ma (no signal), 128 ma max; $C_i = 50 \mu F$, 25 v, by-pass condenser.

**A-86. Mechanical Model of Amplifier.** An interesting model of a two-stage vacuum-tube amplifier consists of a mousetrap arranged so that it can be sprung by lowering a small weight onto the trigger by a string. Another string connects the spring of the trap to the trigger of a rat-trap, whose spring in turn is connected by a stout cord to a weight resting on the edge of the table. By loading the trigger of the second trap to adjust the sensitivity (“biasing the grid”), by adjusting the tension in the strings (“changing the plate load”), and by other devices, many of the characteristics of the thermionic amplifier may be illustrated by analogy. Obviously the trigger plays the part of the grid, which is actuated by a small amount of energy but which controls a much larger amount of energy in the plate circuit, represented by the trap spring.

**A-87. Gas-filled Tubes—Two-element Type.** In a gas-filled tube, the ionized gas neutralizes the space charge around the cathode, permitting large currents to flow at low voltage. Thus in a mercury-vapor rectifier, the drop across the tube may be only 10 or 20 v even for currents up to its rated capacity, while several hundred volts would be required in a similar high-vacuum tube.
The circuit of Fig. 386 includes a mercury-vapor rectifier (e.g., type 66), a filament supply, a 0- to 25-v voltmeter, a 0- to 1-amp ammeter, and a 100-ohm rheostat. The operation of the tube is demonstrated by varying the resistance $R$ from a large value down to a value where the full rated current of the tube is flowing, noting that the voltmeter shows little change. Switching to the a.c. supply shows the rectifying action of the tube. The operation of this tube is then compared with a similar high-vacuum type. In using the gas-filled tube, it is important that the rheostat should always be set so that its resistance is high enough to limit the current to the rated value, since a short circuit will destroy the tube.

**A-88. Gas-filled Tubes—Grid Controlled.** The thyratron or grid-glow tube (see A-17), in which the starting of the discharge is controlled by a grid, may be used for a variety of demonstrations. The type 885 is a convenient and inexpensive thyratron for low currents, but many other types of higher rating are available.

The circuit of Fig. 387 is convenient for demonstrating grid action. With the switch set for d.c. operation, no anode current exists unless the grid is made more positive than some critical value at which the current suddenly sets in. This critical value is more negative the higher the anode voltage. Changes of grid potential during discharge have no effect whatever on the plate current on account of the protective sheath of positive ions that forms about the grid. With the switch set for alternating current on the anode, a change in the potential of the grid will start or stop the discharge. In this case, the discharge can take place only on the positive half of each cycle and then only if the grid potential is above the critical value. Also, in this case, the rectified current will depend on the grid voltage, since this determines the fraction of the cycle during which the tube operates. Thus, if the grid is less negative, the discharge starts earlier in the cycle, before the plate voltage has risen to its peak value, and the
conducting time will be greater. A still more elegant method of control is to operate the grid on alternating current with provision for shifting the phase of the potential, thus controlling the conduction time during each cycle.¹

Since the anode current in a thyratron is relatively large (ranging from 0.5 amp for the smaller sizes to 15 amp in larger sizes and up to several hundred amperes in the large commercial tubes), the operation of the tube may be made more striking if this current is used directly to operate a 50-w lamp, a small d.c. motor, or other similar device.

PHOTOELECTRIC EMISSION

A-89. Surface Photoelectric Effect. To the knob of a gold-leaf electroscope or, better, a Zeleny electroscope, is attached a zinc plate about 1 in. in diameter. A source of ultraviolet light (such as a quartz mercury or carbon arc or a spark discharge between zinc or aluminum electrodes) is arranged to illuminate the plate. The zinc surface must be sandpapered immediately before using so as to remove the oxide layer that forms on exposure to air. The electroscope leaf is charged positively, and the natural rate of leak determined both with and without illumination by the light. There should be no appreciable difference. The leaf is then charged negatively, and there results a great increase in the rate of leak when the plate is illuminated, because of electrons leaving the plate under the action of the light. A glass plate held in the beam stops the effect, while a quartz plate produces no change. The plates should be held only a short distance in front of the source so that all of the light reaching the zinc plate must pass through them. This shows that for zinc the effect is due to the ultraviolet only. Other materials, such as aluminum or brass, may be used, but the effect is much smaller, although all clean metals will show the photoelectric effect to some extent with the ultraviolet light from a quartz mercury arc.

A zinc knob may be substituted for the usual negative electrode of a static machine, and the positive terminal grounded. By exposing the zinc knob to an intense ultraviolet source, the sparking of the machine when in operation will be reduced (or can

¹ A number of experiments are described in the General Electric Bulletins on experimental electronics GET 620 and GET 644, where other vacuum-tube experiments will also be found.
be made to stop entirely if the machine is not working too vigorously. Because of electron emission from the zinc, the charge on the electrode builds up slowly. The zinc must be clean. Sandpapering or fresh amalgamation with mercury helps.

A-90. Discovery of Photoelectric Effect. A 15,000-v transformer is connected to a variable spark gap consisting of two zinc rods, the ends of which are freshly sandpapered. The separation of the tips of the rods is adjusted so that a spark just will not pass. When ultraviolet light is allowed to fall on one or both ends, the spark will pass, because of electrons liberated from the two terminals of the gap. Quartz and glass plates may be used as in the preceding experiment to show that the effect is due to the ultraviolet light. (But a spark is not a necessary accompaniment of the photoelectric effect!) It was by an experiment somewhat like this that Hertz discovered the photoelectric effect in 1887.

A-91. Alkali Metal Photocell. Some of the more important characteristics of the photoelectric effect may best be demonstrated with a cell whose sensitive surface is pure or “sensitized” sodium or potassium. (The commercial caesium cell is not suitable for these particular experiments.) Laboratories well equipped for vacuum and glass-blowing work may make their own cells by distilling sodium in vacuum through several bulbs and finally onto the inside surface of a flask equipped with a contact and collecting electrode, finally sealing off the distillation bulbs and the cell; or a cell may be made by electrolysis of sodium through glass (E-211, 212).

A sodium cell is set up in a circuit such as that shown in Fig. 388. The protective resistance may be of the “grid-leak” type, about 10,000 ohms; a sensitive galvanometer should be used. An intense source of light, such as a carbon arc or 500-w projection lamp, without a condensing lens, is used to illuminate the cell; and it is shown that the photocurrent is approximately proportional to the light intensity, i.e., inversely proportional to the square of the distance from the cell to the source (L-11).

A-92. Photoelectric Threshold. By means of a large lens, an intense beam of light is focused upon a sodium cell arranged as in the preceding experiment. In the light path are placed filters of
various colors—red, orange, yellow, green, blue. The currents from the cell depend on the transmission properties of the filters and on the nature of the source. For equal intensities of the various colors, the effect should be greatest for the blue and zero for the red, exhibiting a characteristic “threshold” or “long wave” limit. If a sensitive thermopile is available, the intensity transmitted by each filter can be measured, and a rough “color sensitivity” curve plotted. The significant fact is that red light produces no effect, regardless of its intensity.

A-93. Velocity of Photoelectrons. If the collecting plate (anode) in the cell is fairly large (not a small wire), it is possible to illustrate the photoelectric equation $h\nu = Ve$. The positive potential on the collector is gradually reduced to zero with a potential divider, and, if necessary, a small retarding potential is applied until the current measured by a sensitive galvanometer is reduced to zero. Then it can be shown that this stopping potential is the same for a given color of light regardless of its intensity and that it is greater for blue than for green light. This experiment will not work if the anode is coated with a thin layer of alkali metal so that it is photosensitive, giving a reverse current when the potential is reversed. Also, since the anode metal is always electronegative to the cathode, the contact potential must be added to the applied potential, giving a stopping potential apparently positive. Since only relative values are of interest, this factor does not alter the effectiveness of the experiment.

A-94. Commercial Photocells—Vacuum Type. Photocells of the caesium-on-oxidized-silver type are available commercially at low cost, and many experiments may be carried out with them, using the circuit shown in Fig. 388. A low-sensitivity galvanometer or a microammeter (0 to 1 $\mu A$) may be used. The proportionality of the photocurrent to intensity of illumination may be demonstrated as in A-91. The experiment on photoelectric threshold (A-92) now shows a maximum of sensitivity in the red, the threshold being in the infrared, about 12000 $\AA$. Because of the small size of the anode in these cells, the experiment on stopping potentials (A-93) does not work satisfactorily, since most of the electrons miss the anode unless a fairly large accelerating potential is applied.

A-95. Commercial Photocells—Gas-filled Type. Many of the commercial cells are argon filled and are excellent for illustrating
the phenomenon of ionization by collision. The circuit of Fig. 388 may be used with the battery augmented by a 10,000-ohm potential divider for varying the potential applied to the anode.

With a fixed light intensity, the photocurrent is measured as a function of the anode potential. Ionization by collision (A-67) will set in at about 40 v, and there will be a rapid rise in the current above this point (Fig. 389). The ratio of the current at the rated anode potential (usually 90 v) to that in the flat part of the curve is called the "gas amplification factor." Caution: Do not exceed the voltage and current ratings stated in the specifications of the tube; otherwise a glow discharge will set in that may damage the sensitive surface.

A-96. Barrier-layer Cell (Rectifier Cell). Cells of the photovoltaic type are commercially available under various trade names. They may be connected directly to a 0 to 100 microammeter without a battery since they generate a small electromotive force when illuminated. The current produced in such a cell by illumination from a tungsten lamp may be compared with that produced in an ordinary caesium gas-filled cell under equal illumination. These cells are utilized in a number of light-sensitive instruments, such as foot-candle meters or photographic-exposure meters. They may be used without amplifiers to operate sensitive relays.

A-97. Photoelectric Relays. There are dozens of demonstrations that may be performed with a photocell and relay of sufficient capacity to operate motors, lights, bells, etc.

If a photovoltaic cell is used, it may be connected directly to a sensitive relay (one that operates on 25 μa or less) whose contacts operate the exciting circuit of a power relay capable of handling many amperes. The power relay may be of a type operated by a storage battery, or better, by direct or alternating current from the mains.

If a vacuum or a gas-filled cell is used, one stage of amplification is necessary to operate the first relay. A simple circuit is shown in Fig. 390. A housing to shield the cell from stray light is desirable. The grid potential should be adjusted (a potential divider may be useful) until the relay does not operate with the
photocell dark. A 6-v headlight lamp or a projection lamp in a housing provided with a condenser lens is a suitable source of illumination. The relay should have a double contact so that the power circuit may be turned either on or off by light falling on the cell.

The following are a few of the demonstrations that may be performed. (1) The cell and light are arranged so that the light beam is interrupted by a student entering the classroom, thus ringing a bell or flashing a lamp. (2) The cell may be arranged to turn on a bank of lamps when the classroom is darkened. This illustrates the use of a photocell in turning on electric signs when daylight fades or in operating a stand-by

circuit when the main power goes off, etc. (3) The power-relay circuit may be connected to the primary of a high-voltage transformer (operating a spark, neon tube, etc.) through a circuit breaker, which opens and stays open when the current fails. An operator approaching the high-voltage lines interrupts the beam of light, thus turning off the transformer. This illustrates the use of a photocell as a safety device near high-voltage equipment. (4) If an electromagnetically operated valve for the water (or gas or compressed-air) line is available, a beam of light can be used to open or close it, thus illustrating, for example, the operation of an automatic drinking fountain. Using a compressed-air valve, a lighted match held in front of the cell may be blown out by the blast of air. A small motor-driven blower may be used for this purpose. (5) The source of light is adjusted so that light reflected from a white object falls on the cell, turning on a lamp or ringing a bell, while no effect is produced when a black object is substituted for the white one. With some care in adjustment and with the aid of color filters, the cell can also be used to distinguish between red and blue or even different shades of red, etc. Commercial sorting machines of various types, based on the detection
of color differences, are being widely used. A simple illustration can be readily set up, in which several black and white balls roll down a track and an electromagnetically operated arm ejects balls of one color while allowing the others to pass.

**A-98. Photocell-thyratron Relay.** A thyratron may be used in place of a sensitive mechanical relay for performing many experiments. For photocell operation, the double-grid thyratron (e.g., FG 95 or 98) should be used, since it operates with small power in the grid circuit. A simple relay circuit is shown in Fig. 391.

Striking experiments may be shown if the photocell is used in a phase-control circuit so that the intensity of the light controls the current through the thyratron. The circuit of Fig. 392 shows one possible arrangement. In this case, the photocell serves as a variable resistor. As the light intensity increases, the resistance decreases, bringing the grid potential more nearly into phase with the anode potential and increasing the average rectified current. The anode current may be made to operate a small d.c. motor to which is attached a perforated disk that interrupts an air blast (a siren). The pitch of the siren may thus be altered by moving the source of light toward or away from the cell. The sensitivity of the circuit may be increased by decreasing the capacitance, but if this is made too small, the thyratron will operate with the cell dark.

**A-99. Transmission of Sound by Light.** Several striking sound-light experiments can be performed with a commercial photocell of the caesium gas-filled type connected to the input of a good audio-frequency amplifier (A-85). (The photovoltaic type of cell is not suitable for this purpose.) The output of the ampli-
fier is connected to a loudspeaker. An intense source of light, such as a projection lamp or carbon arc, is arranged with condenser and projector lenses as shown in Fig. 393. The following demonstrations are a few that can be carried out. (1) An obstacle such as a comb is passed across the beam of light at the focal point \( F \), and the resulting sound in the loudspeaker noted. (2) The source of light is operated first on direct current and then on alternating current; in the latter case, a 120-cycle hum will be heard. (3) A vibrating tuning fork held at the focal point will modulate the light falling on the cell, and a note of its frequency will be heard from the loudspeaker. (4) A "photoelectric siren" may be demonstrated by placing a rotating disk with holes (S-120) in the focal plane at \( F \). This is an excellent way of showing the principle of the sound motion picture. (5) The transmission of music or speech may be accomplished by mechanical or electrical modulation of the light. In the first case, a steady source of light is used to illuminate a variable slit whose

![Fig. 393.—Optical setup for use with photocell and amplifier.](image)

width is controlled by a magnetic loudspeaker unit. In the second case, the intensity of the source itself is modulated. A bright neon glow tube is connected as shown in Fig. 394 to the output of an electric phonograph or a microphone.

**A-100. Photochemical Reaction.** A 600-ml pyrex beaker is half filled with hydrogen by water displacement. The remaining half is filled with chlorine. The beaker is sealed by a rubber ball of larger diameter than the beaker and then set on the lecture table. A large-sized photoflash bulb with reflector is touched off

![Fig. 394.—Circuit for modulating light beam with sound: \( M \), microphone; \( T \), 1:1 transformer; \( N \), neon "crater" glow tube; \( R \), parabolic reflector; \( F \), adjustable potential for \( N \).](image)

\[ ^1 \text{Sutton, R. M., } \textit{Am. Phys. Teacher}, 2, 173, 1934. \]
near the beaker. The resulting explosion of gas sends the rubber ball to the ceiling.

**A-101. Electron Multiplier.** The recently developed electron multiplier photocell can now be obtained commercially. With this tube, all of the experiments of A-99 can be performed. The multiplier tube is connected directly to the loudspeaker, and no amplification is required; a source of high voltage (2000-v direct current) is, however, necessary. In the multiplier tube, the original photoelectron stream is deflected by a magnetic field to the first of a series of nine plates, from which about five times as many electrons emerge on account of secondary emission. This electron stream is bent to strike the second plate, and the multiplying process is repeated from plate to plate.

The secondary emission of electrons is, itself, well worth showing. The arched path of the electron beam can be made visible by the insertion of a willemite-covered mica vane parallel to the plane of the electron paths (Fig. 395).

**X RAYS**

**A-102. X-ray Tubes and Equipment.** The type of equipment available for demonstrations in x rays will, of course, vary widely in different institutions, and no attempt can be made to describe the various tubes, transformers, etc., that are available. Laboratories that are seeking to secure such equipment at low cost would do well to consult the nearest x-ray supply house, where used or rebuilt tubes are often available. (For example, a small high-
voltage transformer from an old dental x-ray unit is admirably suited for lecture work.) The gas type of tube obtainable from all supply houses may be operated from an ordinary induction coil. (Do not use a transformer for a gas tube except for very short periods, since such a tube is not self-rectifying, and the cathode may be damaged by overheating.)

If a good vacuum system with diffusion pump and liquid-air (or dry-ice) trap is available, a Coolidge-type tube may be built and operated on the pump, using either a transformer giving 25,000 to 40,000 v or an induction coil. The design for such a tube is shown in Fig. 396. The filament assembly with pyrex tube may be purchased complete from the General Electric X-Ray Corporation, Chicago, Ill. ready to seal onto the neck of a 1-l pyrex flask. The target assembly shown may be readily constructed if simple shop equipment is available. When water-cooled, the tube can handle about 0.75 kw. It must be pumped on a good high-vacuum system 15 to 45 min or until all trace of luminous discharge upon application of high voltage has disappeared.

Since the water-cooled target of such a tube is grounded, the filament supply must be insulated to withstand high voltage. A storage battery mounted on a glass-legged table is suitable but cumbersome. Filament transformers may be purchased from
electric manufacturing companies, or a simple insulating transformer may be constructed as shown in Fig. 397. A wooden form for the core is made by cutting a disk of wood 15\(\frac{1}{2}\) in. in diameter and 1\(\frac{1}{4}\) in. thick. The core is made of strips of silicon-steel transformer iron, 2\(\frac{1}{2}\) in. wide and \(\frac{3}{16}\) in. thick. Such strips come about 9 ft long and can be purchased from transformer makers; 40 lb is necessary. These iron strips are carefully wound on the form and temporarily tied in place with a few wires. The core is then removed from the form and carefully wrapped with cloth tape, 1 or 2 in. wide, removing the temporary wires as convenient. It is covered with a layer of friction tape, and then a primary of 300 to 400 equally-spaced turns of No. 16 cotton-covered copper wire is wound. The secondary consists of 45 turns of No. 10 or 12 copper wire, heavily insulated (for stiffness), tapped after 20, 25, 30, 35, 40, and 45 turns. The coil is wound with tape to keep it in place. The wooden form for winding the secondary is shown in the figure. Staples are driven into the wood as necessary to keep the wire from slipping off during winding. After the coil is wound, the form is removed. The secondary and primary are mounted as shown in the figure, being supported in a suitable wooden frame.

Caution: Prolonged exposure to x rays may produce bad burns. Do not expose any part of the body for more than a few minutes. Individuals differ greatly in their susceptibility to such burns, and it is well to keep in mind the hazard involved. Moreover, the instructor should take great care to protect himself and his students from contact with the high-voltage source.

A-103. Ionization by X Rays. An ordinary electroscope is charged, either positively or negatively, and a beam of x rays is directed toward it. The gold leaf will be observed to fall much faster than its normal rate. With a good Coolidge tube, this effect is easily evident with the tube 20 ft or more from the electroscope.

Three rubber balloons filled with hydrogen or illuminating gas and attached to a common point on the table by silk threads make an effective large-scale electroscope. When charged, they will
stand far apart but will come together promptly when an x-ray beam is turned on them.

**A-104.** A simple ionization chamber may be constructed by mounting two metal plates, about 4 to 8 in. in diameter (such as electrophorus plates), on insulating supports facing each other and 1 to 3 in. apart. One plate is connected to the electroscope knob and charged with an ebonite rod; the other plate is grounded. A beam of x rays is directed between the plates, and it will be found that the leaf of the electroscope falls faster when the plates are far apart (but not too far) than when they are close together, since ionization by x rays is essentially a volume effect.

The ionization plates may be mounted as described in the preceding paragraph but with each plate connected to one terminal of a Leyden jar placed on an insulating stand. An electrostatic voltmeter, also insulated, is used in place of the electroscope. The plate B (Fig. 398) is grounded, and the Leyden jar is charged with a static machine; the ground connection is then broken. When an x-ray beam passes between A and B, B gradually becomes charged, as shown by the motion of the voltmeter needle. If a wire mounted in a brass block is placed inside the voltmeter case at C, then when the needle touches the wire, it is discharged and falls back. The ion current from A to B is then measured by the rate of oscillation of the needle. The device is thus a simple ticking electroscope of the Zeleny type but much less sensitive.

**A-105. Fluorescence by X Rays.** If the x-ray tube is enclosed in a light-tight box (to cut off the light of the filament), the fluorescence of many materials may be shown. Some materials especially useful are anthracene, eosin, esculin, fluorescein, naphthalin, quinine sulfate, resorcin blue, rhodamine.¹

The light coming from fluorescent substances is very much weaker than ordinary lecture-room illumination. Hence it is highly desirable to have the students' eyes adapted to the dark before presenting these experiments. Fluorescence that is

¹ A card of 20 samples of fluorescent salts giving a variety of colors may be obtained from the Patterson Screen Co., Patterson, N. J. These fluoresce strongly in ultraviolet light, as well as in x rays.
scarcely visible in a suddenly darkened room will seem brilliant after a few minutes' adaptation. Since a waiting period of 5 or 10 min. is undesirable, it is well to plan such experiments to come after others requiring darkness or dim light. If this is not feasible, it is useful to connect a rheostat in series with the room lights (if they are not already equipped with dimmers) for gradual dimming. If the rheostat is cut in gradually over a period of 15 or 20 min. before the lights are turned completely off, the students will unknowingly have had their visual sensitivity increased a thousandfold or more. At the same time this will not interfere with the regular course of the lecture. The increased effectiveness of fluorescence demonstrations following such preparation is well worth the effort.

A-106. Penetration of X Rays. The relative opacity of various substances to x rays can most easily be shown by the ionization method (A-103). One can easily compare roughly the rate of leak of the electroscope as sheets of metal, cardboard, glass, wood, etc., are held between it and the x-ray tube. It is of especial interest to compare their opacity to x rays with that to visible light. Thus a sheet of paper or cardboard opaque to light is quite transparent to x rays, while a sheet of lead glass, transparent to light, is quite opaque to x rays.

If a tube and fluorescent screen visible to the whole class are available (or for small classes a fluoroscope), it is easy to demonstrate the relative transparency of different materials in striking ways. Shadow images of the bones in the hand (Caution: Do not overexpose the hand), coins in a purse, nails in a block of wood, etc., may be demonstrated. It is easy to “see through” a 500-page physics book with x rays! Again one may compare sheets of different materials as suggested in the preceding paragraph. A piece of lead glass may be mounted over a hole in a board. In the x-ray image, the glass appears dark against a light background, while with visible light the reverse is the case.

A-107. Absorption Coefficients. If the x-ray tube is enclosed in a lead-covered box with a small opening so that a fairly well-defined beam emerges, one can compare the thickness of various materials required to cut the intensity to one-half (or to 1/e) and thus compare the absorption coefficients. This experiment must be interpreted with caution, however, since the x-ray beam is not monochromatic and therefore it includes components hav-
ing different absorption coefficients. Hence it is well to filter the original beam through a thin sheet of aluminum (used as a window in the box) whose thickness is chosen to reduce the full intensity to one-half or less. This largely eliminates the softer components.

One may test to see whether successive sheets of aluminum reduce the intensity in the same proportion. If so, the "effective" wave length of the beam may be determined by comparing the absorption coefficient with those found in tables. It is well to prepare in advance sheets of various materials of proper thickness so that each reduces the intensity to about one-half.

**A-108. X-ray Diffraction.** Diffraction of x rays can usually best be demonstrated by models of crystals and by lantern slides. However, if time and facilities permit, the following demonstration of Laue spots is effective. Bore a hole 2 mm in diameter in a lead plate, and cover with a chip of rock salt 1 mm or less in thickness. Mount this close to the x-ray tube so that x rays strike the crystal face normally. (Use optical reflection, if necessary, to determine this.) About 5 cm beyond the crystal, place a photographic film wrapped in black paper. With a current of 10 ma in the tube, sufficient exposure will be obtained in about 5 min. X-ray film with an intensifying screen fitting tightly against it is best but is not necessary. If the lecture room can be darkened, develop the film before the class; or use a light-tight box with armholes and tight-fitting sleeves. By using a desensitizer (obtainable from a photographic supply house), lights may be turned on after a minute or so, and development continued in the light. The developed film may then be projected.

**A-109. X-ray and Electron Diffraction Model.** The x-ray diffraction pattern of a powdered crystal (Hull method) or the diffraction pattern produced by electrons shot through a thin metallic film (G. P. Thomson method) is a series of concentric rings. A beautiful example of the transition from Laue-spot pattern to ring pattern is given by rotating a crossed grating (L-79). A bright point source of light is observed through a piece of fine-mesh wire gauze, giving the characteristic crossed-grating effect. If now the gauze is rotated rapidly in its own plane about an axis coinciding with the line of sight from observer to light, the diffraction pattern becomes a series of concentric
rings of light. The gauze may be mounted in a ring that revolves on an external bearing in the manner described for the projection centrifuge (M-152).

A-110. X-ray Spectra—Illustrative Model. Electrons falling on a metallic target excite an x-ray spectrum that consists of a continuous background and a superposed line spectrum. The continuous background increases in intensity with increasing energy of the electrons and has a high-frequency limit given by the Einstein relation \( E = h\nu \). The line spectrum consists of the K, L, M, etc., radiation characteristic of the target.

This situation may be illustrated by dropping small steel balls or lead shot from various heights onto the bottom of an overturned pie or cake pan. As the balls are poured down, one hears a noise background (continuous spectrum) superposed on which is a note of recognizable pitch (line spectrum) characteristic of the shape, size, and material of the pan. Several different pans will have different frequencies accompanied by a similar noise background.

RADIOACTIVITY

A-111. Sources of Radioactivity. Radioactive ores and salts, such as carnotite, uranium and thorium nitrates, may be obtained from scientific supply houses. The effects produced by them are not very striking. Old radon seeds (obtainable from hospitals possessing a radium supply or sold by supply houses) afford a strong source of alpha and beta radiation, strong enough to show ionization, stopping power, etc. If a plate or a wire is exposed for several hours to a number of such tubes, which have been freshly crushed, an active deposit of polonium is formed, giving a pure source of alpha particles. The activity is greatly increased if the wire is charged to a high negative potential during exposure to the residual radon. A milligram of radium sulfate in a sealed tube gives a strong source of beta and gamma radiation. The expense involved in securing strong sources of radiation is, for many laboratories, prohibitive. However, small samples are obtainable at low cost.¹

¹A "smear" of 1 microgram of radium salts on a watch glass may be obtained from Hammer Laboratories, 624 Monaco Blvd., Denver, Colo., or from U. S. Radium Co., 535 Pearl St., New York, N. Y.
**A-112. Electroscope Experiments.** Simple experiments to show the relative penetrating and ionizing power of alpha, beta, and gamma rays may be carried out with an ordinary gold-leaf electroscope whose leaf is projected onto a screen with a scale. A Zeleny electroscope is still better. Radioactive material spread on a card or in a flat metal dish may be inserted in the electroscope case itself, although this is likely to contaminate the instrument and increase its natural rate of leak. It is better to use the ionization-chamber arrangement described in A-104.

A few sheets of thin paper will stop alpha particles, which, from sources such as uranium, polonium, or old radon tubes (opened), account for most of the ionization. Beta rays may be stopped by a few millimeters of cardboard or by thin aluminum foil, while gamma rays will penetrate, with rapidly decreasing intensity, up to several centimeters of lead. The gamma-ray ionization is usually very weak unless a strong source such as a milligram of radium is available.

That the electroscope leakage is due to ions in air may be shown by placing a source of alpha rays (polonium or open radon tubes) near the electroscope but with the direct rays interrupted by a block of wood (Fig. 399). The electroscope leak increases when an air jet is blown from the source toward the electroscope but disappears when the air jet is blown in the opposite direction.

**A-113. Range of Alpha Particles.** The range of alpha particles in air may be measured roughly with the charged electroscope arrangement shown in Fig. 400. With the source of radon seeds or polonium (A-111) close to the grid, ionization may be observed by deflection of the electroscope but it falls off and suddenly ceases as the distance between grid and source is increased up to 3 to 5 cm. Alpha particles pass through thin aluminum foil substituted for the grid.

**A-114. Scattering of Alpha Particles.** The principle of Rutherford's scattering experiment, which is the keystone of the modern theory of atomic structure, may be shown by placing a point source of alpha particles 2 cm from a Geiger counter (A-119). When the direct path between source and counter is blocked by a
metal straightedge, the counts diminish but do not cease altogether because of scattering by air. If a thin metal foil is now introduced in the path of the alpha particles near the obstacle, the number of counts per minute increases because of scattering. Moving the counter shows that the number of scattering particles decreases with increase in the angle of scattering.

A-115. Radioactive Decay. The half life periods of RaA, RaB, RaC, and thorium emanation are sufficiently short to show appreciable loss of activity in a few minutes. However, the difficulty of obtaining samples of these materials with which to demonstrate the effect is too great to make the experiment possible in most laboratories. For those interested in showing radioactive decay, it is suggested that reference be made to some standard text on radioactivity for details of handling these short-life products.¹

A hydraulic analogue of radioactive equilibrium is instructive. Several cylindrical vessels are placed one above the other as shown in Fig. 401. Each vessel discharges water through an outlet of controllable size into the vessel beneath it. If the topmost vessel (larger than the others) is filled with water and kept at constant level while water is allowed to pass into the one below it, etc., equilibrium is soon reached. The level of water in each vessel then depends both upon the rate of inflow and the rate of discharge and is steady when these two rates are equal. The height of water in each vessel will then be inversely proportional to its aperture. The analogy to decay rates in a radioactive series is good; for those products that have a short life will be found in small quantity compared with those having a long life, just as the level in the vessel with a large orifice is lower than that in the one with a small orifice.

A-116. Wilson Cloud Chamber. The cloud chamber has become such an important tool in modern research that every student should have the opportunity to see one in operation. The Knipp type of chamber with rubber bulb for compression and expansion and alpha-particle source is available from supply houses and makes a very satisfactory apparatus for small groups.

¹ For these details, see Bainbridge and Street, *Am. Phys. Teacher*, 6, 99. 1938.
For best results, the chamber should be kept in a cool place before the lecture so that its temperature is somewhat below that of the room. If the bulb is compressed very slowly and held in the compressed position for 10 sec or more and then released suddenly, alpha-particle tracks will be seen on nearly every expansion and will be clear and sharp. The apparatus may be equipped with a large reading lens and mirror for viewing horizontaly by larger groups. The optical arrangement is like that shown in Fig. 366.

A-117. For large classes, some form of cloud chamber in which the tracks are projected on a screen is highly desirable. One type is shown in Fig. 402. It is composed of three pieces of plate glass with fittings mounted on three supporting rods and separated by sections of sylphon tubing 6 in. in diameter. The central plate slides along the rods, its motion being limited by stops. The end plates are fixed. The sylphons are soldered to the brass fittings into which the glass plates are waxed. A valve is provided to adjust the pressure to about 1 atm in the right-hand section, which carries the source of radioactive material. Expansion is produced by opening a valve connecting the left-hand chamber to a vacuum reservoir. Alcohol or water in the right-hand section maintains a saturated vapor. The apparatus is mounted directly in a lantern, preferably with a water cell between it and the arc.

A-118. Geiger-Müller Tube Counter. The tube counter consists of a fine wire suspended along the axis of a metal cylinder, contained in a glass tube filled with gas at suitable pressure. Almost any type of construction is satisfactory. A simple type is shown in Fig. 403a. The wire may be of tungsten or nickel, preferably polished with very fine emery paper and then carefully washed. It should be about 0.004 in. in diameter, although this is not critical; but larger wires require higher operating voltages. The cylinder, of nickel or other metal, may be about

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1 Many types of cloud chamber are described in current literature. A projection type is detailed by M. S. Livingston, *Am. Phys. Teacher*, 4, 33, 1936.
1 cm in diameter and from 2 to 4 cm long and somewhat shorter than the wire. The wire is spot-welded to tungsten leads sealed through pyrex glass. The metal cylinder may also be welded to a tungsten lead sealed through the side of the tube, acting also as a support. The tube is evacuated, filled to a pressure of about 10 cm of mercury with air or nitrogen, and then sealed off. Or it may be joined to the pump through a stopcock and a short length of rubber tubing. When the pressure is right, the cock is closed, and the rubber connection removed.

A simpler type of counter may be made without glass blowing by using a brass tube about 3 in. long and $\frac{3}{4}$ in. in diameter, with a hard-rubber plug waxed into each end and a small brass tube soldered in the side for pumping (Fig. 403b). A nickel wire is attached between heavier brass leads that are waxed through small holes in the rubber plugs and is stretched taut along the axis of the tube. This tube can be exhausted on an ordinary pump, and dry air admitted to a pressure of about 10 cm of mercury; it is then ready for use. This counter can be made sensitive to beta rays as well as to gamma rays by boring an array of small holes in the side of the tube and waxing over them a thin piece of aluminum foil (0.001 in.)

Various types of amplifier and recorder circuit may be used. For lecture purposes, almost any type of three- or four-stage resistance-coupled amplifier with sufficient power to feed a loudspeaker will serve. A typical counting circuit is shown in Fig. 404. The most critical part is the first stage, which requires a resistor of about $10^{10}$ ohms. The condenser in the first stage, of 10- or 20-$\mu$F capacitance, must also be carefully chosen. Commercial radio condensers are not sufficiently well insulated for the purpose. A brass plate about $\frac{1}{4}$ in. in diameter soldered directly to the grid cap of the first tube and separated by a few millimeters

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1 The auxiliary circuit for extinguishing the counter suggested by Neher and Harper (Phys. Rev., 49, 940, 1936) greatly facilitates operation.
from a similar plate mounted on a glass or hard-rubber rod attached to the shielding case forms an effective condenser.

The high-voltage source should be capable of supplying a variable voltage up to 1500 or 2000 v and should be well filtered and quite constant. An electrostatic voltmeter is convenient for measuring the voltage, or one may connect five ordinary 10-megohm resistors in series with a 0 to 20 microammeter. The rectifier circuits of Fig. 405 serve satisfactorily.

To operate the counter, the voltage is raised gradually until occasional clicks can just be heard in the loudspeaker. Then the voltage is raised only 20 to 50 v above this point and is held constant. With a tube of the dimensions suggested, there will be a background count of 10 to 30 per min caused by cosmic rays and radioactive contaminations. A luminous watch dial (radium paint) brought near to it increases the rate very considerably, as does any other weak radioactive source. If the tube is equipped with a quartz window waxed on so that light may pass through it and through a small hole or slit into the cylinder, the photoelectrons ejected by the ultraviolet light from a match flame held a meter or more away will cause very rapid counts. Such a
photon counter is the most sensitive known method of detecting small amounts of ultraviolet radiation. If a very thin glass or cellophane window is provided, the tube may be used to count alpha or beta rays.

**A-119. Geiger Point Counter.** A simple type of point counter is shown in Fig. 406. The operation of such a counter is critically dependent on the point. An ordinary steel phonograph needle serves well, although several may have to be tried before the one is found that operates best. Care must be taken to clean off dust particles from the point. Such a counter may be connected to a high-voltage supply and amplifier just as a tube counter is connected. A simple circuit for making the counter operate a grid-glow tube directly (without amplification) is shown in Fig. 407. Such a counter is particularly useful for counting alpha rays, which are excluded from the ordinary type of counter unless a very thin window is provided. The point counter operates at atmospheric pressure, and no window is necessary; therefore it is possible to show very quickly the range of alpha particles in air. One can also determine the stopping power of thin aluminum foils for beta particles. (The beta rays from most radioactive substances penetrate about 1 mm of aluminum.)

**A-120. Water-jet Counter.** A very simple counter for quanta and for ionizing particles operates by electrostatic control of the stability of a water jet (E-41). A fine jet of water impinges on a stretched rubber diaphragm placed just short of the point where the jet becomes unstable. A metal electrode is placed close to the jet where it issues from the nozzle. This electrode is connected to the positive terminal of a 2000-v supply (transformer and rectifier) through a 200-megohm resistor and to one side of a spark gap. The other side of the gap is connected to the negative terminal of the high-voltage supply and to the

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nozzle from which the water jet issues. The control electrode is placed just far enough from the jet that sparking does not occur.

The gap is made as small as possible without sparking. When the gap is made conductive by ionization of the air or by emission of photoelectrons from the cathode, a rapid succession of clicks is heard from the rubber diaphragm. With a copper cathode, ultraviolet light from a match flame several meters away will operate the counter. If the cathode is of zinc, an electric light will set off the counter.

A-121. Coincidence Counters for Cosmic Rays. If two Geiger-Muller tube counters are arranged with their axes parallel and a few inches apart, they may be connected in a selecting circuit that will give an output signal only when the two tubes are discharged simultaneously. A few simultaneous discharges may occur accidentally, but most will be caused by penetrating cosmic-ray particles. When the plane of the counters is vertical, the number of coincidences will be greater than when the plane is horizontal. It is desirable to mount the two counter tubes on a simple wooden frame that can be rotated through 90° about a horizontal axis from the vertical to the horizontal position. The number of coincidences is only slightly reduced when a thick plate of iron or lead is placed between the two tubes. This gives a striking demonstration of the presence of very penetrating electrons due to cosmic rays.

Many types of coincidence circuit have been suggested and used. For demonstration purposes, a suitable type is one that feeds into a loudspeaker or an impulse counter, as shown in the simple circuit of Fig. 408.\footnote{Mouzon, J. C., \textit{Rev. Sci. Instruments}, 7, 467, 1936.}