SPECIALIZED
TELEVISION ENGINEERING

TELEVISION TECHNICAL ASSIGNMENT

ELECTRON PHYSICS AND ELECTRON THEORY

708D

ELECTRON PHYSICS AND ELECTRON THEORY

FOREWORD

It requires little imagination in this era of atomic energy and the atomic bomb to appreciate the importance in any technical field of a modern understanding of the structure of matter. In the daily press and in the semi-technical magazines we read about the new and tremendous importance of the rare elements Uranium and Thorium, and the man-made element Plutonium. Still, in CREI assignments of almost 20 years ago we studied the use of thorium in the manufacturer of filaments for radio tubes and also the structure of the atom.

Radio and television in their modern aspects are extremely dependent upon the characteristics of the various elements. The long life and low power consumption of modern receiving tubes is due to the high electron-emitting characteristics of certain of the rare earths when heated to moderate temperature. The highly sensitive television pickup tube is made possible by the fact that the rare element caesium in an oxide combination with silver emits electrons freely when light shines on it. The television picture tube (kinescope) operates because of the fact that certain phosphors emit visible light when struck by a fast-moving beam of electrons proceeding through an evacuated space, and the intensity of the light varies in accordance with the intensity of the electron beam.

The vacuum tube which makes modern radio possible functions because certain elements, when heated, will emit electrons into the surrounding evacuated space, and these emitted electrons can be drawn through space from one tube electrode to another and accurately controlled by the application of positive and negative voltages to the tube components.

Finally, we find that such elementary factors as positive and negative voltages are due to the fact that electrons in various pieces of apparatus and in their connecting wires, can become dis-associated from particular atoms and can move quite freely through the so-called solid substances so that an excess of electrons accumulates at one point and a deficiency at another.

It is shown that the only difference between what we call a conductor and what we call an insulator lies in the structure of the atoms and molecules making up these two substances—that under certain conditions the "resistance of a conductor will greatly increase and that under other conditions an insulator will break down and become a conductor.

In addition to the great importance of this assignment to the radio and television engineer and technician, he will find it extremely interesting. His entire professional career is based upon the fact that molecules, atoms and electrons behave as they do. His basic job is to understand that behavior and the methods of controlling it.

E. H. Rietzke,
President.

- TABLE OF CONTENTS -

ELECTRON PHYSICS AND ELECTRON THEORY

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-TABLE OF CONTENTS-

ELECTRON PHYSICS AND ELECTRON THEORY

To the radio engineer a good basic understanding of the structure of matter is an absolute necessity, not only so that he may have a proper conception of how a current flows through a conductor or through a vacuum tube, but also that he may understand the reaction of various substances to chemical action, (as in a battery), and to temperature changes. The latter is particularly important because in radio transmitters, receivers, tubes, and circuit elements temperature is a major factor to be considered.

The study of physics is as old as the history of civilization and surprisingly accurate theories were evolved hundreds of years ago mostly from observation and deduction. The invention of Calculus by Newton (1642-1727) and Leibnitz (1646-1716) provided a means of mathematically developing many theories and of coordinating the results of observation and measurement. The results of Newton's studies provided a base upon which modern physics has been built and since his day there has been a constant advance in science. Early scientists were badly handicapped by a lack of accurate measuring devices and it is thus logical that many of the modern theories, while conceived many years ago, awaited substantiation and development during the twentieth century. It is also easy to see how modern measuring apparatus, particularly the development of the vacuum tube. high voltage X-rays, etc., has accelerated the research into atomic physics until today atomic energy has been harnessed and promises to revolutionize our future existence. The startling predictions of Albert Einstein have been confirmed by the discoveries and tests made by such men as Enrico Fermi and Arthur Holly Compton, as well as by many other distinguished physicists. Among the older scientists whose names are familiar to all those who have any connection with radio and electricity are Maxwell and Faraday whose experiments, although performed with very crude apparatus, are still the basis of many of the laws of electrical circuits.

Before going into the study of the structure of matter, the writer would like to quote from the concluding remarks of G. E. M. Jauncey in his book, "Modern Physics". Mr. Jauncey writes, "Modern physicists do not take physical theories as seriously as they used to do. Sir William Bragg says that on Mondays, Wednesdays and Fridays one uses the quantum theory, while on Tuesdays, Thursdays and Saturdays one uses the wave theory. One uses the quantum theory to 'explain' a certain group of phenomena and the wave theory to 'explain' another group of phenomena. Possibly the real truth lies somewhere between the two theories. The author's own opinion is that the word 'explain' in its usually accepted meaning has no place in modern physics. Just what does one mean by 'explaining' the Compton

Effect in terms of bouncing billiard balls--after all, neither light nor electrons are billiard balls... . If a theory correlates a large number of observable and measurable phenomena, the theory is worthwhile. It is the object of the theory to 'correlate' rather than to 'explain' ... . The final equations of a theory must contain experimentally measurable quantities--in other words the readings of thermometers, voltmeters, ammeters, meter sticks, clocks, etc. "

As an illustration of the meaning of the above remarks, if one has an ammeter in an electrical circuit and notes its reading, he can correlate it by means of a formula known as Ohm's Law with the reading of a voltmeter across a portion of the circuit and the impedance of that portion as measured by means of a third device known as an ohmmeter. This was done before the nature of an electric current was known, and even today the nature of a resistive impedance, for example, is not understood in any great detail.

In other words, all that is expected of science is that it can find the laws or relationships between various phenomena, without necessarily knowing the true nature of the phenomena themselves. Thus one can measure the mass and magnetic properties of silicon steel without really knowing how the silicon produces certain desirable magnetic effects in the steel.

Nevertheless, human beings do demand a physical picture of the things they deal with, and as one delves into the submicroscopic, such as into the heart of the atom, the concepts desired are in terms of large objects that can be seen. Probably many nuclear physicists in private think of electrons as billiard balls even when they are concerned with the wave aspects of the particle, and a particle of light known as a photon is probably thought of as a small ball bearing impinging upon matter. Such concepts are useful guides, *provided their limitations are appreciated,* and will therefore be employed as far as possible in these texts.

COMPOSITION OF MATTER

FUNDAMENTAL PARTICLES.--Even in the days of the ancient Greeks matter was considered divisible into tiny particles which were called atoms. The school of philosophers who held this theory had no sound basis for such a supposition; the ancient Greeks, like many moderns, were often quite arbitrary in their hypotheses.

Today there are innumerable reasons and a vast accumulation of evidence to indicate that all matter can be built up from a few elementary building blocks. Probably the two most important are the *electron* and the *proton,* but other particles that are recognized as having independent existence are the *neutron,* the *photon,* the *positron, mesotron,* and *neutrino.* Some of these are supposed to exist because of a "hole" in a mathematical equation which they plug up; others, so far, are detected in cosmic rays only, and special machines will have to be built, such as the Betatron, in order to be able to manufacture them on this earth.

Electrons and Protons.--Consider the two most important particles: the electron and the proton. They make their presence known by three effects:

1. They have a certain amount of mass, and exhibit effects similar to those of large bodies, such as billiard balls.

2. They seem to have a wave motion associated with them. At present this effect is not completely understood, but it has been measured, and serves to explain certain characteristics of their behavior.

3. They exhibit forces of attraction or repulsion for other particles of their kind. Thus two electrons *repel* one another through the intervening space; two protons repel one another in similar fashion. On the other hand, electrons *attract* protons and vice versa.

Only the first and third effects are of interest here. The electron has a mass of

$$m_e = 8.99 \times 10^{-28} \text{gram}$$

which is an exceedingly small quantity, but nevertheless is of importance in many branches of electronics. The proton is found to have a mass of

$$m_p = 1.661 \times 10^{-24} \text{ gram}$$

so that it is 1,847 times that of an electron. This enormous difference in mass will serve to explain many phenomena that will come up later in this assignment.

The forces between the particles are described in terms of a certain property of the particles known as electric charge. The electric charge is an inherent property of the particle, and does not appear to be separated from it. The charge on an electron is said to be negative; that on a proton, positive. The force is then explained as being due to the fact that

Like charges repel; unlike charges attract.

Actually the existence of the charges is based upon the forces observed, rather than the existence of the forces depending upon the charges. Nevertheless it is convenient to think of certain particles having charges, and that these charges produce the forces actually observed.

Consider the following experiment, illustrated by Fig. 1. An

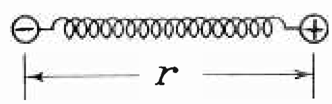


Fig. 1.—Force of attraction between an electron and a proton.

electron and a proton are placed in free space, and separated from each other by a distance r. A force of attraction through space appears between them, tending to make them approach one another. (Since the electron has so little mass compared to the proton, it will move the major portion of the distance between them.) The force is illustrated in Fig. 1 as a stretched spring tending to make them approach one another.

If the distance is increased to 2r, it will be found that the force between them (before they start approaching each other) is only one-quarter as great as before; if the distance is made 3r, the force is only one-ninth as great, and so on. This is summarized by saying that *the force varies inversely as the square of the distance.*

Next consider the case of two electrons or two protons placed as shown in Fig. 1. In *either* case a force of repulsion will be observed, and the force of repulsion *will be exactly equal in magnitude to the previous force of attraction,* and will vary with distance in exactly the same manner.

Now suppose that two electrons are held together (in spite of their repelling force on one another) in the manner shown in Fig. 2, and a proton is placed at a distance r from them. It will now be observed

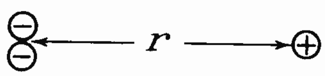


Fig. 2.—**The force of attraction is doubled if two electrons act on a proton instead of one electron.**

that the force of attraction is exactly twice that noted in Fig. 1, but that it also varies inversely as the square of the distance.

If two protons close together are employed instead of two electrons, the force of attraction will still be double and vary inversely as the square of the distance. If two electrons and two protons are employed, the force of attraction between the two pairs will be *four* times that for one of each.

Suppose two protons are employed instead of two electrons in Fig. 2. Then the force on the right-hand proton will be one of repulsion rather than one of attration, *but its magnitude will be equal to that for the two electrons acting on the proton.* From this arises the notion that electrons and protons have *equal and opposite charges;* in this respect they differ from ordinary gross particles of matter, which do not exhibit such forces and are therefore assumed to be uncharged.

Coulomb's Law.—Since the force and the distance are quantities that can be measured, the charges are defined in terms of these. The relation is known as Coulomb's Law, after its discoverer Charles Augustin Coulomb (1736-1806). It is as follows:

$$F = K\frac{Q_1Q_2}{r^2} \qquad (1)$$

where F is the force in dynes, r is the distance in centimeters, and Q_1 and Q_2 are the charges on the two particles under test. The quantity K is a constant of proportionality, and for free space is taken to have the value of unity (one). If the two charges are both positive or negative, their product is *positive,* as is therefore also F. A *positive* force is taken as one of *repulsion.* If the two charges are of opposite sign, their product is negative and a *negative* F denotes a force of *attraction.*

If the two charges are equal ($Q_1 = Q_2$), the distance of separation r is 1 cm., and if F is observed to be one dyne, then either charge is defined as having a magnitude of 1 *statcoulomb.* In short, the charge is arbitrarily defined in terms of the other quantities that have been established in mechanics.

The practical unit of charge is the coulomb, which is equal to 3×10^9 statcoulombs. Hence the statcoulomb is a very small quantity of charge compared to that used in ordinary electrical measurements, but the situation is exactly the same as in ordinary measurements of length, where the inch or the mile may be employed, depending upon the length to be measured.

The electron and the proton have equal but opposite charges. The magnitude is

$$e = 4.770 \times 10^{-10} \text{ statcoulombs}$$

$$= 4.770 \times 10^{-10}/(3 \times 10^9)$$

$$= 1.590 \times 10^{-19} \text{ coulombs}$$

All observed charges, positive or negative, are found to be integer multiples of the above value. This indicates that the electron and proton are the elementary particles so far as charge is concerned; a charged body has its charge by virtue of having so many excess electrons or protons in it.

As a simple example of the application of Coulomb's law, let the force of attraction be calculated between a group of three electrons and a group of four protons, as shown in Fig. 3. The three electrons have a total charge of

$$-3 \times 4.770 \times 10^{-10} = -14.310 \times 10^{-10} \text{ statcoulombs (negative charge)}$$

and the four protons have a total charge of

$$4 \times 4.770 \times 10^{-10} = 19.080 \times 10^{-10} \text{ statcoulombs (positive charge)}$$

Suppose the separation between the two groups is 10^{-8} cm. Then by Eq. (1) the force is

$$F = \frac{(-14.31 \times 10^{-10})(19.08 \times 10^{-10})}{(10^{-8})^2}$$

$$= \frac{-273 \times 10^{-20}}{10^{-16}}$$

$$-273 \times 10^{-4} \text{ dynes}$$

Since it is negative, it is a force of *attraction*. This may appear to be a very small force, but when account is taken of the exceedingly small mass of these charges, the force is enormous in comparison. For example, all bodies attract one another by virtue of another force known as that of gravitation. This is the force that is exerted by the sun on the earth to hold it in its orbit. The gravitational force is in proportion to the mass, and for the tiny masses involved in the above problem it would be exceedingly minute. In comparison, the above electrical force of

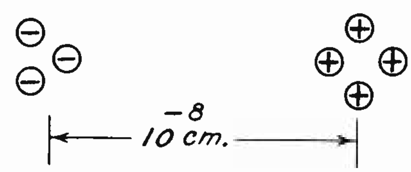


Fig. 3.—Force of attraction between three electrons and four protons.

-273×10^{-4} dynes is enormous, and serves to explain why electrical forces can be employed to produce large amounts of power in a relatively small space.

Exercises

1. A group of 3 electrons is separated by 2.5×10^{-8} cm. from a group of 8 electrons. What is the magnitude and character (repulsion or attraction) of the force between the two groups?

2. A body has a positive charge of 2 statcoulombs, and is separated from another body that has a positive charge of 10^{-3} statcoulombs, by 3/5 cm. What is the magnitude and character of the force between the two bodies?

3. Two bodies are separated by 2 cm. A force of 1,000 dynes, repulsion is desired between them. It is further desired that both bodies have *equal* charges. What must be the magnitude and polarity of the charges to accomplish this?

Neutrons.—When an electron is permitted to approach a proton in such manner that the strong attractive force does not accelerate it to a high velocity, the two charges may merge, whereupon their force effects are tied up in one another and no external force on any other electrons or protons is observed. The combination therefore seems to have lost its charge, and is considered a new particle, and is called a *neutron.*

The neutron is a particle with approximately the same mass as the proton but devoid of any electrical charge. Whether it actually is a close union of an electron and proton, or is a totally new particle is not definitely known at the present time; the evidence tends to indicate that it is a close combination as described in the previous paragraph.

The neutron was first discovered by Chadwick in 1932, and has assumed a tremendous importance with the disclosure of the atomic bomb. Its very lack of charge gives it this importance: it is unaffected by charges such as electrons or protons, and hence can penetrate to the very heart of an atom; i.e., the nucleus, and disrupt the latter. Indeed, it is only by such effects that a neutron can be detected, and today its measurement has become of great importance in the regulation of nuclear fission. More will be said of this presently.

Other Particles.—The other particles mentioned previously are not as yet of practical importance, although future discoveries may completely contradict this statement. The *positron,* discovered by C. D. Anderson in 1932, is a particle having a positive charge equal to that of a proton, but having the mass of an electron. The *neutrino* is a particle having the mass of an electron but having no charge. The *mesotron,* a negatively charged particle found in cosmic rays, is between 100 and 200 times the mass of an electron, and has a very short life of about one microsecond. More is expected to be learned about it by the use of a Betatron.

THE ATOM.—The preceding discussion has cleared the way for a description of the atom, which is the smallest particle of any given element, such as iron, that can exist as such an element. In Fig. 4 is illustrated the relation between a drop of water, its constituent molecules, their constituent atoms, it is this constant *ratio* of volumes (regardless of the quantity of water used) that led to the modern atomic hypothesis of matter.

At the right in Fig. 4 is shown how water is obtained by the combination of hydrogen and oxygen.

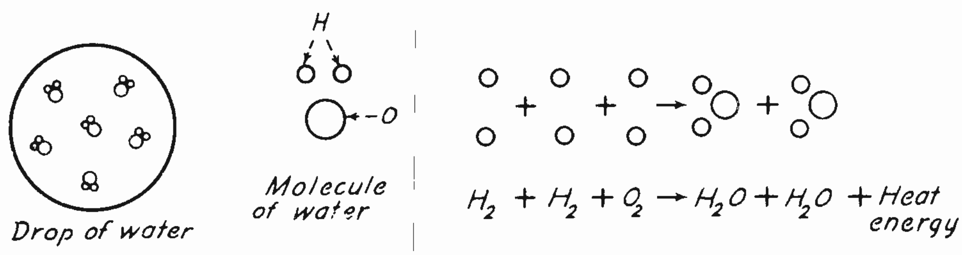


Fig. 4.—Illustration of chemical composition of drop of water and reaction producing it.

and the chemical reaction that produces the molecule from the atoms. An ordinary drop of water is composed of billions upon billions of molecules of water. If the drop were divided in half, each half then divided in halves, and so on, ultimately there would come a point where the parts could no longer be subdivided and still remain water. One would have come to the ultimate, smallest possible particles of water, known as *molecules*. Some of these are shown in the drop of water in Fig. 4.

The molecule, if subdivided, would break up into *atoms*. Each molecule would furnish two atoms of hydrogen and one of oxygen. One method of breaking a molecule apart is to pass an electrical current through it (electrolysis). If the drop of water is thus electrolyzed, two volumes of hydrogen are obtained for each volume of oxygen; Such an activity is known as a *chemical reaction*. Hydrogen and oxygen gas are normally composed of molecules that contain two atoms each. Thus the hydrogen molecule is composed of two atoms of hydrogen (written H_2), and the oxygen molecule is composed of two atoms of oxygen (O_2). To form water, *two* molecules of hydrogen combine with *one* molecule of oxygen to form *two* molecules of water, as shown. An important additional component liberated is heat energy; this is often the reason for promoting such a reaction, as in the oxy-hydrogen torch.

Composition of the Atom.—For a long time atoms were considered the ultimate particles. Substances whose molecules have one kind of atom, such as hydrogen or oxygen, are known as *elements;* substances whose molecules are composed of two or more *different kinds* of atoms, are known as *compounds*. Water is a compound, so is salt (sodium chloride, NaCl), carbon dioxide (CO_2), etc. Chemistry is concerned with the interactions of atoms that produce compounds from elements, break up compounds to form elements, or cause compounds to react with one another to produce new compounds or elements.

There are over 94 different elements known, and more are being added as artificial transmutation of the atoms of one element into those of another are produced. All the hundreds of thousands or millions of possible substances in the universe are made up of combinations of the atoms of these elements. Some of the combinations are simple, such as water (H_2O); some are exceedingly complex, such as the organic compounds formed of carbon, together with hydrogen, oxygen, etc. There seems to be no limit to the number of possible combinations of atoms which the chemist can obtain. As an example, consider the thousands of chemical combinations or compounds produced from coal tar. A few of the diverse products are high-grade perfumes, beautiful dyes, medicines, and the vast group of plastics. In all these processes, however, the individual atoms remain intact; it is merely their combinations with one another that are altered.

Shortly before the turn of the century evidence began to appear that certain atoms, such as radium, spontaneously disintegrated to form new atoms with the release of an enormous amount of energy. This process was called radioactivity, and caused a revolution in the concepts of matter. These concepts are still in the process of revision, but sufficient is known at this time to furnish a reasonably clear picture of the nature of the atom. In passing it is of interest to note that the old dream of the alchemists—to transmute one element into another—which was deemed impossible by the chemists and physicists of the 18th and 19th centuries, has now become a reality, and new elements, such as plutonium, have been made from another element, uranium.

The present-day picture of the atom is that it is made up of an inner core, called the nucleus, surrounded by a number of electrons rotating around the nucleus in orbits in much the same manner as the planets revolve around the sun. Chemical and ordinary electrical processes have to do with the orbital electrons of the atom; a new branch of engineering called *nuclear engineering* is appearing on the horizon, and has to do with the nucleus itself.

The Nucleus.—The nucleus consists of protons and neutrons, bound together by a new force of attraction which at such close quarters overrides the mutually repelling effects between the protons and causes them and the neutrons to be bound together very tightly.

Reference to Eq. (1) indicates that if the distance of separation r between the charges becomes zero, the coulomb force F becomes infinite. However, for sub-atomic distances, as in the nucleus, Coulomb's law is not believed to hold; the force F does not increase indefinitely as r decreases, but levels off to a constant value, and a new force of attraction comes into play. Very little is know of this force of attraction, but presumably it falls off very rapidly with distance, possibly inversely as the cube or a higher power of the distance, so that at distances greater than that within the nucleus, Coulomb's law assumes control and gives rise to the electrical forces normally observed.

The simplest atom of all is that of hydrogen; its nucleus contains but one proton and no neutrons. The nucleus thus has but one positive charge, and there is one single orbital electron whose negative charge just balances the nuclear positive charge, thereby producing an atom of hydrogen that is electrically neutral. The hydrogen atom is illustrated in Fig. 5. It is assumed that the high velocity of the electron in

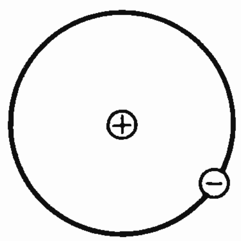


Fig. 5.--**Schematic representation of the hydrogen atom.**

its orbit produces sufficient centrifugal force to balance the force of attraction of the proton so that the arrangement is stable, similar to the solar system, where the gravitational force of attraction of the sun for the planets is just balanced by their centrifugal forces in revolving in their orbits.

In addition to its orbital motion, the electron may also spin on its axis, just as the earth does. This electron spin is of importance; in a later lesson it will be shown how this produces magnetic properties in iron, nickel, etc.

Since the electron's mass is but 1/1847 that of the proton, the mass of the hydrogen atom is practically the same as that of a proton, namely, 1.661×10^{-24} gram. In general, the mass of any atom is very closely equal to the sum of the masses of the protons and neutrons comprising its nucleus; the mass of the orbital electrons can in general be disregarded. A further point to note is that the estimated diameter of the hydrogen nucleus is on the order of 2.06×10^{-16} cm.; that of the electron is 3.76×10^{-13} cm.; and that of the orbit is 10^{-8} cm. The greater size of the electron compared to the proton is based on the theory that the mass of a particle depends upon how concentrated in space is its charge; the electron and proton have the same charge, hence the greater mass of the proton must be due to the charge being concentrated into a smaller volume.

The above dimensions are so exceedingly small that it may be more informative to magnify them all proportionately. If the hydrogen atom were magnified so that its nucleus had a diameter of 1 inch, the electron would have a diameter of 1800 inches or 150 feet, and would be at a distance of about 54,000,000 inches or 852 miles! From this it is apparent that the hydrogen atom has more empty space than matter in it, so that in turn a cubic cm. of hydrogen gas is mainly empty space. This is true even for the densest and hardest materials, such as tungsten and steel; the hardness of steel is due to the enormous electrical forces of attraction between the parts of the atom and between the various atoms, rather than to any close packing of the constituents.

The next atom to be studied is that of helium. For the moment it will be considered to have a nucleus composed of two protons and two neutrons, so that it has a net positive charge of two units; i.e., $2 \times 4.770 \times 10^{-10}$ statcoulombs. As a result it requires *two* orbital electrons to make up the ordinary, *neutral* helium atom. Its configuration is shown in Fig. 6. Compared to hydrogen it has about four

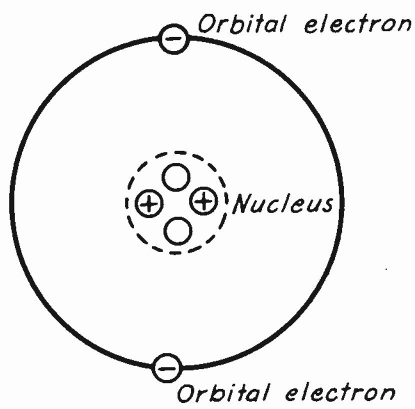


Fig. 6.--Schematic representation of a helium atom.

times the atomic weight. Since hydrogen is the lightest gas known, helium is next in weight, and is therefore useful for balloons and other lighter-than-air craft; indeed, it is preferred to hydrogen because it is chemically inert and therefore non-inflammable. An interesting point to note is that it is so inert that the helium atom does not combine with another helium atom to form a helium molecule, as do hydrogen, oxygen, and most other gases. Instead, the helium molecule and the helium atom are identical. The weight of a given volume of gas depends upon the molecular rather than the atomic weight. On this basis the *monatomic* helium molecule He weighs only *twice* as much as the hydrogen molecule H_2, so that actually in bulk form helium gas is only twice as heavy as hydrogen gas.

The chemically inert nature of helium (also that of neon, argon, etc.) make these gases of great value to the radio engineer. Gaseous discharge tubes such as voltage regulators and rectifiers which employ these gases under low pressure, will not have the metallic electrodes, such as the cathode or plate, attacked by these gases, whereas gases like oxygen or chlorine, for example, would soon disintegrate the electrodes.

More Complex Atoms.--More complex atoms can be built up in much the same manner by adding more neutrons and protons to the nucleus, and a number of orbital electrons corresponding to the increased number of protons. Not all combinations are necessarily possible, but a surprising variety of atoms can be produced by this procedure.

The next atom in the order of complexity is lithium (Li), a metal. Its nucleus consists of three protons and four neutrons, and there are three orbital electrons to balance the three protons. It is illustrated by Fig. 7. Note that the number of neutrons exceeds the number of protons by one which is unusual for such a light atom. For the lighter atoms the number of protons and neutrons are about equal, but as the atoms become more

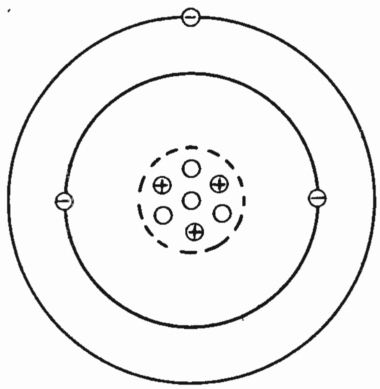


Fig. 7.--**Schematic representation of a lithium atom.**

complex, it is found that more neutrons are required than protons in order to maintain a stable nuclear structure.

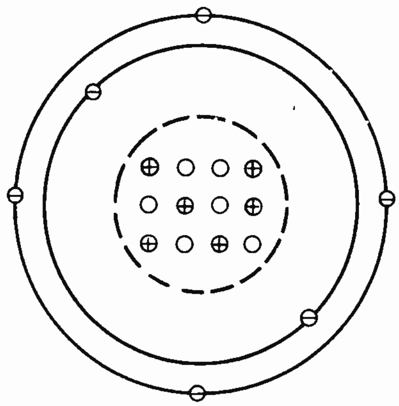
Another important point is that two of the orbital electrons are in one orbit or rather "shell", as it is called, just as in the case of the helium and hydrogen atoms. The third electron is in an outer shell, From this results some important chemical and electrical characteristics, which will be discussed presently.

In Fig. 8 are shown some other atoms, in order to furnish an idea of still more complex atoms. Note that the number of protons equals the number of neutrons until sodium is reached, whereupon the number of neutrons exceeds the number of protons by one. As mentioned previously, it has been found that as the atom becomes more complex, more neutrons than protons are required in the nucleus in order to prevent it from disintegrating.

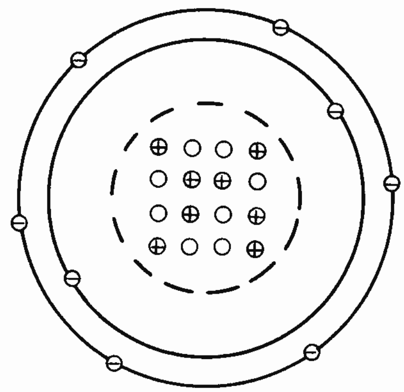
Even then the nucleus ultimately becomes unstable as its complexity (and mass) increases until when the atom of uranium, for example, is reached, the nucleus is definitely unstable and tends to disintegrate even though it has 146 neutrons and only 92 protons. Such disintegration, as mentioned previously, is known as radioactivity.

The instability of the nuclear structure is particularly marked in a somewhat lighter nucleus having 88 protons and 138 neutrons. This is the radium nucleus. It disintegrates spontaneously with the liberation of vast amounts of energy, as well as other atomic by-products, particularly helium, and ultimately becomes transformed into an atom of lead.

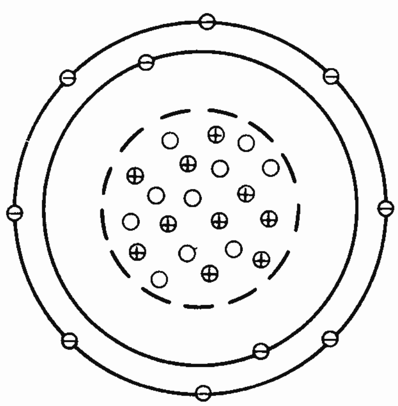
Today physicists have learned how to produce such radioactivity artificially, and in such manner that the disintegration continues until a large part of the material has been transmuted in a fraction of a second. The result is the atomic bomb. It is found that the nucleus can be split apart by bombarding it with neutrons, and this is particularly true in the case of uranium and its nuclear by-products, such as plutonium. The final nuclear configurations are more stable; enormous amounts of energy are liberated as the less stable nucleus transmutes itself into a more stable configuration. The most stable nuclei are those of medium mass, such as nickel, iron, chromium, cobalt, manganese, etc.; heavier atoms, such as uranium and thorium, are promising sources of atomic energy; but lighter atoms, such as hydrogen and



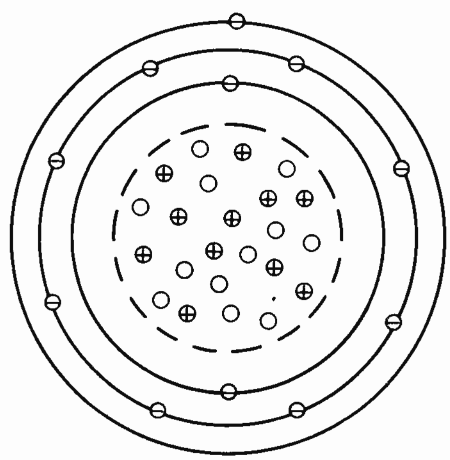
CARBON.--Element No. 6.
Atomic Weight 12.
6 Protons, 6 Neutrons,
6 Orbital Electrons.



OXYGEN.--Element No. 8.
Atomic Weight 16.
8 Protons, 8 Neutrons,
8 Orbital Electrons.



NEON,--Element No. 10.
Atomic Weight 20.183.
10 Protons, 10 Neutrons,
10 Orbital Electrons.



SODIUM.--Element No. 11.
Atomic Weight 23.
11 Protons, 12 Neutrons,
11 Orbital Electrons.

Fig. 8.--Schematic representation of more complex atoms.

helium can liberate energy as they combine to form the more stable medium-weight atoms. So far no practical method has been devised to bring this about. If this can be accomplished, the cost of atomic energy will probably decrease markedly, as the lighter atoms are far more abundant on this earth than the heavier atoms such as uranium.

CHEMICAL REACTIONS.—It was stated previously that chemical reactions depend upon interactions between the orbital electrons of the various atoms. For example, in the case of water, the two orbital electrons of the two hydrogen atoms become more or less associated with the oxygen atom, and fill out its outer, second shell, so that the latter now contains 8 instead of six electrons.

From a charge viewpoint the oxygen atom has now two excess negative charges, and the two hydrogen atoms now have each a positive charge (that due to the proton remaining). The two hydrogen atoms are therefore attracted to the oxygen atom by Coulomb's law, and thus form the very stable (tightly bound) water molecule H_2O. The reason why the oxygen atom can extract two electrons from the hydrogen atom appears to be due to a peculiarity of the atomic structure: each shell is most stable and saturated when it has a certain number of electrons in it.

The first shell nearest the nucleus is saturated when it has two electrons in it. It then has no tendency to take electrons from other atoms, and so becomes chemically inert. Reference is made to the helium atom which has this structure. On the other hand, if the first shell has but one electron, as in the case of hydrogen, it may take up a second electron from some other atom such as potassium, so as to form potassium hydride, but the tendency is generally in the reverse direction: it tends to give up its electron to an element like oxygen.

In the case of the second shell, saturation occurs when it has 8 electrons. The element lithium, that has but one electron in the second shell, does not show any tendency to acquire 7 additional orbital electrons for this shell, but instead acts like hydrogen, and tends to give up its electron to an atom like oxygen. Since each lithium atom has but one electron in its outer shell, and oxygen desires two electrons to complete its outer shell, *two atoms* of lithium must combine with *one* of oxygen to form lithium oxide, Li_2O, just as in the case of hydrogen, H_2O.

Valence.—In the case of copper, there are two electrons in the outer shell, so that copper can give up one or two electrons, as required. Thus if copper is heated in conjunction with a limited amount of oxygen, it gives up one electron to each oxygen atom, forming cuprous oxide, Cu_2O (Cu is the chemical symbol for copper). Note that this enables the maximum number of copper atoms to combine with the limited number of oxygen atoms.

On the other hand, if the number of copper atoms is limited relative to the oxygen atoms, then each copper atom gives up both electrons to each oxygen atom, forming cupric oxide Cu O. In the first case, copper is said to have a *positive valence* of one; i.e., it gives up one orbital electron in reacting with a suitable other atom to form a compound. In giving up this electron, it becomes itself positive and adheres to the atom which it has made correspondingly negative by bestowing an electron on it. Lithium and hydrogen have positive valences of one.

In the case of cupric oxide, copper has a positive valence of *two*, because it has given up two electrons to the oxygen atom. On the other hand, oxygen has a *negative valence* of *two*, because it has taken on two (negative) electrons. For some reason not known directly, oxygen generally has a negative valence of *two*, but at least one compound is known in which its valence is one, namely, hydrogen peroxide, H_2O_2. (It will be recalled that this was used as a propellant for the buzz bombs.)

Sometimes an element can have either a positive or negative valence. Phosphorous. for example, can have a negative valence of 3 and a positive valence of 5. In the first case it takes on 3 electrons in addition to the 5 present in the outer shell, to make up the total of 8 required for saturation. By taking on 3 electrons from other atoms willing to furnish them, it acquires a negative charge of 3 units; it therefore has a negative valence of three. On the other hand, phosphorous can also be induced to yield the five electrons in its outer shell to atoms, such as of oxygen, that have a sufficiently strong affinity (desire) for the electrons. In doing so, the phosphorous acquires a positive charge of 5 units; it has a positive valence of five. In general, atoms whose outer shell are about half full exhibit such dual valence.

Atomic Number.—Chemical reactions therefore involve the electrons of the outermost shell only. The first shell is saturated when it has two electrons, as in the case of helium; such an atom is chemically inert. The second shell is saturated when it has eight electrons as in the case of neon, another inert gas. Beyond the second shell the conditions for saturation become more involved, but it is unnecessary for the purpose of this assignment to pursue this phase of the subject any further.

Instead, it is of interest to note that the number of orbital electrons just equals the number of protons in the nucleus in the case of a normal, neutral atom. This number is known as the *atomic number*. It is more definitely associated with the number of protons in the nucleus. The reason is that it is possible to remove (at least temporarily) one or more orbital electrons by a process known as ionization, but until recently, no means were known for changing the number of protons in the nucleus.

In the accompanying table of Atomic Weights, the names, symbols, atomic numbers, and atomic weights of the various chemical elements are given. Observe that in the case of hydrogen, the atomic number and weight are practically unity, whereas for the other elements the atomic weight is the greater. This follows at once from the fact that the nucleus contains neutrons as well as protons (except in the case of hydrogen); the neutrons add to the weight, but being uncharged, require no corresponding orbital

ATOMIC WEIGHTS*

NAME	SYMBOL	ATOMIC NO.	ATOMIC WEIGHT	NAME	SYMBOL	ATOMIC NO.	ATOMIC WEIGHT
Actinium	Ac	89	(227)	Mercury	Hg	80	200.61
Alabamine	Ab	85	(221)	Molybdenum	Mo	42	96.0
Aluminum	Al	13	26.97	Neodymium	Nd	60	44.27
Americum	..	95	.....	Neon	Ne	10	20.183
Antimony	Sb	51	121.76	Neptumium	Np	93	(239)
Argon	A	18	39.944	Nickel	Ni	28	58.69
Arsenic	As	33	74.93	Nitrogen	N	7	14.008
Barium	Ba	56	137.36	Osmium	Os	76	190.8
Beryllium	Be	4	9.02	Oxygen	O	8	16.000
Bismuth	Bi	83	209.00	Palladium	Pd	46	106.7
Boron	B	5	10.82	Phosphorus	P	15	31.02
Bromine	Br	35	79.916	Platinum	Pt	78	195.23
Cadmium	Cd	48	112.41	Plutonium	Pn	94	(239)
Calcium	Ca	20	40.08	Polonium	Po	84	(210)
Carbon	C	6	12.00	Potassium	K	19	39.10
Cerium	Ce	58	140.13	Praseodymium	Pr	59	140.92
Caesium	Cs	55	132.81	Protoactinium	Pa	91	......
Chlorine	Cl	17	35.457	Radium	Ra	88	225.97
Chromium	Cr	24	52 01	Radon	Rn	86	222
Cobalt	Co	27	58.94	Rhenium	Re	75	186.31
Columbium	Cb	41	93.3	Rhodium	Rh	45	102.91
Copper	Cu	29	63.57	Rubidium	Rb	37	85.44
Curium	..	96	.....	Ruthenium	Ru	44	101.7
Dysprosium	Dy	66	162.46	Samarium	Sm, Sa	62	150.43
Erbium	Er	68	167.64	Scandium	Sc	21	45.10
Europium	Eu	63	152.0	Selenium	Se	34	79.2
Fluorine	F	9	19.00	Silicon	Si	14	28.06
Gadolinium	Gd	64	157.3	Silver	Ag	47	107.880
Gallium	Ga	31	69.72	Sodium	Na	11	22.997
Germanium	Ge	32	72.60	Strontium	Sr	38	87.63
Gold	Au	79	197.2	Sulfur	S	16	32.06
Hafnium	Hf	72	178.6	Tantalum	Ta	73	181.4
Helium	He	2	4.002	Tellurium	Te	52	127.5
Holmium	Ho	67	163.5	Terbium	Tb	65	159.2
Hydrogen	H	1	1.0078	Thallium	Tl	81	204.39
Illinium	Il	61	(146)	Thorium	Th	90	232.12
Indium	In	49	114.8	Thulium	Tm	69	169.4
Iodine	I	53	126.92	Tin	Sn	50	118.70
Iridium	Ir	77	193.1	Titanium	Ti	22	47.90
Iron	Fe	26	55.84	Tungsten	W	74	184.0
Krypton	Kr	36	83.7	Uranium	U	92	238.17
Lanthanum	La	57	138.92	Vanadium	V	23	50.95
Lead	Pb	82	207.22	Virginium	Vi	87	(224)
Lithium	Li	3	6.940	Xenon	Xe	54	131.3
Lutecium	Lu	71	175.0	Ytterbium	Yb	70	173.3
Magnesium	Mg	12	24.32	Yttrium	Y	39	88.92
Manganese	Mn	25	54.93	Zinc	Zn	30	65.38
Masurium	Ma	43	......	Zirconium	Zr	40	91.22

*Values in parentheses are approximate only and have not been adopted by the Committee on Atomic Weights.

electrons to balance.

Hence, to sum up, the atomic number is a measure of the number of protons in the nucleus, and therefore of the number of orbital electrons in the case of a neutral atom (one that is not ionized). If the atomic number is known then, by the rules of atom construction, it is possible to calculate the number of electrons in each shell, and thus finally the number of electrons in the outermost shell. Once the latter fact is known, a very good idea of chemical (and even of the electrical and heat properties) of the atom can be predicted.

ISOTOPES AND ISOBARS.—An inspection of the table on atomic weights reveals that the atomic numbers are integers (whole numbers), but that the atomic weights are not. By specifying the atomic weight of oxygen as 16, most of the other atoms have weights that are more nearly whole numbers, but still there are appreciable discrepancies. Hydrogen, for example, has a relative atomic weight of 1.0078 instead of exactly one, and zinc has an atomic weight of 65.38.

This seems to contradict the idea that all atoms are built up of neutrons and protons, for then all elements should be integral multiples of hydrogen (having one proton) in weight. The discrepancy is found to be due to two factors, of which the most important is that of mixtures of two *isotopes* of the given element.

Isotopes.—An *isotope* is an element that has the same atomic *number* and hence the same chemical properties as another element, but has a different mass. The reason is relatively simple. Take the case of hydrogen: its nucleus consists of one proton; its atomic weight is one, and it therefore has one orbital electron and a positive valence of one. Suppose a neutron is added to the nucleus. The atomic weight is now *two* instead of one, but the atomic number is still *one*, and the new atom, called deuterium (heavy hydrogen), has also only one orbital electron and a positive valence of one.

Deuterium is an *isotope of hydrogen*. They are chemically indistinguishable, and are present in nature in the ratio of about 8 parts of deuterium to 1,000 parts of hydrogen. Consequently ordinary hydrogen gas does not have an atomic weight of one as measured, nor of two, but has an *average weight* of 1.0078. The same is true of practically all the other elements; the presence of isotopes makes the average atomic weight as measured come out other than an integer multiple of any one atomic weight chosen as a reference, such as that of oxygen. In passing it is to be noted that heavy water contains deuterium instead of hydrogen.

An isotope that has come into prominence is that of uranium 235. Ordinary uranium has an atomic weight of 238. If three neutrons are removed from the nucleus, the atomic weight drops to 235. The new element uranium 235 *has the same chemical properties as uranium 238*, but the nuclear structure is unstable and can be split by neutron bombardment into new atoms of lower atomic weight. Under the proper conditions this occurs with explosive force.

Another isotope of interest is that of helium. It will be recalled that ordinary helium, as extracted from natural gas, has an atomic weight of four. It has a nucleus composed of two neutrons and two protons; its atomic number is therefore two. Certain so-called alpha particles, positively charged and ejected by radium, have also been identified as helium atoms. However, the nuclei in these particles consist of but one neutron and two protons. The atomic *number* is still two, but the atomic *weight* is only three. Thus the alpha particle has the same atomic number and hence chemical properties (mainly that of being inert) as the ordinary helium atom; it is therefore an isotope of the latter.

Isobars.—An isobar is an atom that has the same atomic *weight* as another atom, but has a different atomic *number*, and hence different chemical properties. In short, its nucleus has the same sum of protons and neutrons as the other nucleus, but the division of the sum into protons and neutrons is different.

At present there are not many isobars known, nor do they appear to have any great practical importance. It is necessary to point out in connection with isobars and isotopes that one cannot remove or add protons or neutrons to a given nucleus at will; only certain combinations are permitted by nature, and of these only certain combinations are relatively stable. However, even within this limitation, a large number of new atoms have been artificially produced in the laboratory that have not been found in nature, and as a result mankind is now entering a new era in physical science and industry.

MATTER AND ENERGY.—Up until about 1905 two separate principles were recognized:

1. The law of the Conservation of Matter, and
2. The law of the Conservation of Energy.

The first law stated that matter can neither be created nor destroyed; it can only be transformed from one kind of matter to another kind.

The second law stated that energy can neither be created nor destroyed; it can only be transformed from one kind to another, such as electrical energy into heat energy, etc.

Einstein's Law.—From the study of high speed electrons, whose mass increases indefinitely as their velocity approaches that of light, and from other considerations, Einstein enunciated a famous law in 1905 that energy can be converted into mass, and mass into energy. His law is in itself a very simple expression:

$$M = W/c^2 \qquad (2)$$

Where M is the mass in grams, W is the energy in ergs that is equivalent to M, and c is the velocity of light, 3×10^{10} cm./sec. For example, if a body has an amount of energy, such as kinetic energy owing to its velocity, of say 10^{16} ergs, then its mass is increased by an amount

$$M = 10^{16}/(3 \times 10^{10})^2 = 10^{16}/9 \times 10^{20}$$

$$= 11.11 \times 10^{-6} \text{ grams}$$

$$= 11.11 \times 10^{-9} \text{ milligrams}$$

The amount of increase in mass is very small even for considerable amounts of energy, owing to the factor c^2 that occurs in Eq. (2). Nevertheless, the fact that one can be converted into the other and vice-versa leads to a combined law of conservation; namely, that the *sum total* of the mass and energy of a system is *constant*, and cannot be created nor destroyed. But mass may be converted into energy, and energy into mass; the proportions are given by Eq. (2) above.

It is not the purpose of this technical assignment to go into an extended discussion of nuclear physics, since this would require very advanced mathematics and moreover would not be directly pertinent to radio engineering. However, the implications of Eq. (2) are so vast as to justify a brief discussion of this principle here.

It may appear puzzling to many how matter presumably can be converted into energy and energy into matter, since energy in general implies matter in motion, and it appears absurd to say that matter can be converted into motion, for the latter is an attribute or property of the former. However, Eq. (2) does not actually say this; Eq. (2) merely states that one *property* of matter, namely its *mass*, can be converted into another property, its *energy*.

What the ultimate nature of matter is may never be known; one can only be aware of it through its effects on the five senses. Any substance is recognized by virtue of its *inertia:* the effect is measured in terms of a quantity called *mass*. It is the gravitational pull of the earth upon the *mass* of a substance that gives the substance weight and produces a corresponding pressure on the hand supporting the substance. It is the same characteristic of mass that causes an automobile to coast after the clutch is released.

In the past the mass of an object was assumed to be constant regardless of the velocity of the object, and the kinetic energy of the moving object was expressed as

$$K.E. = (1/2)mv^2 \qquad (3)$$

where m is the mass (assumed constant) and v is the velocity. Experiments with very high-speed electrons, such as in television projection picture tubes and X-ray tubes, indicate that when the electron moves with a velocity comparable to that of light, its mass becomes very much greater than its rest-mass (stationary mass).

This was an unexpected result, and was ultimately explained by Einstein by his special relativity theory. The law given in Eq. (2) is a consequence of this theory and of a study of the phenomena involved in radiation. What happens is that at high velocities, the energy of the particle is in part associated with its velocity and in part associated with its increase in mass; no additional matter has presumably been created, only a fundamental *property* of the original substance, namely its *mass*, has been increased.

Atomic Energy.--Einstein's law has the following significance with respect to the atom. It was mentioned that the atomic weight of various elements are not integer multiples of hydrogen. The main reason given was that actual measurements were made on mixtures of isotopes of the given element, so that the average weight measured was different from that of any one isotope itself. Even in the case of a single isotope, its mass differs from the sum of the masses of its constituent protons and neutrons. The difference, if a deficit, represents energy liberated by the formation of the element; if an excess, it represents energy put into the element in its formation.

Elements below silver in weight absorb protons or neutrons or both to form heavier elements that are slightly deficient in mass. Thus the process of fusion liberates energy. Elements above silver in weight absorb protons and neutrons to form heavier elements slightly excessive in weight. Here fusion absorbs energy. If the heavier element decomposes into lighter elements (fission) the above energy is liberated once more.

The sun and stars furnish energy by *fusion*. On the earth, the only known source of atomic energy is that of *fission;* specifically that of U235 and plutonium (possibly thorium) into lighter elements. Although the energy liberated is but a fraction of that theoretically available, a relatively small atomic bomb liberates as much energy as that of 20,000 tons of TNT! The reason why silver plays a central role is owing to the short-range attractive forces and longer range Coulomb repelling forces mentioned previously. For light nuclei of small dimensions the short range attractive forces predominate and promote fusion with the release of energy. For heavy nuclei of large dimensions the Coulomb forces predominate and promote fission with the release of energy. In silver the two types of forces about balance so that neither fusion nor fission tends to occur.

Normally, nuclei are in a semi-stable or metastable state, and a certain amount of *activation* energy is required to start the reaction of fusion or fission as the case may be.

The amount of energy liberated can be calculated from Einstein's law: multiply through Eq. (2) by C^2; and obtain

$$W = Mc^2 \qquad (4)$$

where M is the loss in mass, and W is the energy thereby liberated.

Heat Energy.—One of the most important forms of energy is heat energy. It represents the sum of the *kinetic energies* of the atoms, molecules, and free electrons in a substance. Thus warmth, the sensation conveyed to the brain, is really due to a helter-skelter dashing about of the particles in the substance touched. The hotter the substance (the higher the temperature) the more furiously do these particles dash about or vibrate, and the greater is the total kinetic energy in the substance.

It may be argued that a moving car has a sum total of kinetic energy equal to that of all its molecules, atoms and electrons yet may be cool to the touch. The answer is the motion of all parts of the car is coordinated (in one direction) whereas in the case of heat energy, the motion of the various particles comprising the car are uncoordinated: one molecule may move a small distance one way while another moves in another direction. Such *random motion of the particles* represents *heat or thermal energy;* the car as a unit does not move.

When a body is heated by contact with a hotter body, such as a flame, the faster moving particles of the flame speed up the slower moving particles of the cooler body, whereupon its heat energy and temperature begin to increase. If the body is a solid, its molescules, etc. begin to vibrate faster and faster, but still maintain their average positions, so that the body still remains a solid.

As the temperature goes up, the vibrations become so intense that the forces of attraction between the molecules are broken down, and the body melts, becoming a liquid. The molecular forces are still sufficient to prevent the molecules from flying apart and increasing the volume of the body, but they are no longer able to maintain their shape of the body, and it therefore assumes the shape of the containing vessel. This is characteristic of a liquid.

As the temperature is still further increased, the vibrations become so intense that the molecules can no longer hold together, and they fly apart. The liquid is now said to vaporize and become a gas. The volume now becomes that of the vessel completely enclosing the gas, otherwise the latter will tend to expand indefinitely.

More will be said about heat energy in relation to thermionic emission and the like, but the above brief description affords a satisfactorily clear picture of the basic phenomenon.

APPLICATIONS TO RADIO ENGINEERING

FREE ELECTRONS.—Radio engineering, like chemistry, is mainly concerned with the behavior of the orbital electrons, particularly those in the outermost orbit (the "valence" electrons). In certain substances these electrons become detached from their atoms and wander about more or less freely inside of the substance. They are then known as *free electrons*, and they can be caused to drift through the substance, whereupon they constitute an *electric current flow.* The substance is then said to have *electrical conductivity.*

Under certain conditions of heating, the free electrons can be "boiled out" of the material into free space; this is known as *thermionic emission*, and is the fundamental basis of vacuum tube action. In the case of certain substances, light is capable of causing electron emission; this is known as *photoelectric emission*, and is the fundamental basis of operation of phototubes. Since these effects are of such great importance to electrical engineering in general, and radio engineering in particular, it is clear that a more detailed discussion is in order.

Metals.—It was shown previously that certain atoms have but one, two, or three electrons in the outermost orbit, and that such atoms have a tendency to give these electrons to another kind of atom whose outermost orbit is nearly saturated, rather than to take on sufficient electrons to saturate their own outermost orbits. In short, the rule appears to be that if the outermost orbit has few electrons and is far from being saturated, the atom during a chemical reaction gives away the few electrons; if the outermost orbit is almost saturated, the atom during a chemical reaction takes on sufficient electrons to saturate the orbit.

Atoms that give away electrons become positively charged in the process, and are known as electropositive elements. In general metals have this characteristic.

Atoms that take on electrons become negatively charged as a result, and are called electronegative elements. Examples of these are oxygen, chlorine, fluorine, etc. Many atoms have a large, but not too large, number of electrons in their outermost orbits; these may be considered as either electropositive or electronegative. Two examples of this type are carbon and sulphur.

The metals are normally electropositive. The ease with which they give up electrons depends upon their atomic structure. If there is but one electron in the outermost orbit, the metal loses this electron more readily than if there are two or three. If the outermost orbit is at a considerable distance from the nucleus; i.e., if there are many intervening orbits, then if the atom has but one electron in this orbit, it can release this electron more readily than an atom that has but few orbits and one electron in the outermost orbit.

For example, from Fig. 7 it is clear that lithium has two orbits, with a single electron in the second orbit. This electron can be given up with moderate ease. From Fig. 8 it is seen that sodium has three orbits, with a single electron in the third orbit. The sodium atom can yield its electron more readily than can lithium. Potassium has four orbits, with a single electron in its fourth orbit. Rubidium has five orbits, with a single electron in its fifth orbit, and caesium has six orbits, with a single electron in its sixth orbit. From the rule given above it follows that the caesium atom will give up its outermost orbital electron most readily, and is therefore most electropositive; rubidium comes next, followed by potassium, sodium, and lithium, and finally hydrogen, which has one and only one electron and orbit.

Crystalline Structure of Solids.--Mention was made that atoms combine to form molecules; a molecule of hydrogen contains two hydrogen atoms, (H_2), and a molecule of water contains two atoms of hydrogen and one of oxygen (H_2O). It is found, however, that in the case of a true solid, the molecular configuration ceases to have significance, and is replaced by the crystal. The crystal is an orderly arrangement of the atoms, that can be expanded indefinitely so as to form crystals of any size. For example, ordinary salt consists of equal numbers of sodium and chlorine atoms. Fused salt (liquid form) probably consists of individual molecules, each composed of one atom of sodium and one atom of chlorine ($NaCl$).

Solid salt, however, consists of orderly rows of sodium and chlorine atoms, arranged in alternating sheets or planes. The arrangement is shown in Fig. 9. Observe how each atom of one kind, such as sodium (Na), is surrounded by atoms of the other kind, chlorine (Cl). The lines between the atoms represent the coulomb forces of attraction between opposite charges; the chlorine atom being negative and the sodium atom being positive, because the sodium atom gave up its outer orbital electron to the chlorine atom. It is apparent from the figure that this pattern, cubical in form, can be continued indefinitely in all directions, so that as small or as large a crystal as desired may be built. Other compounds may have

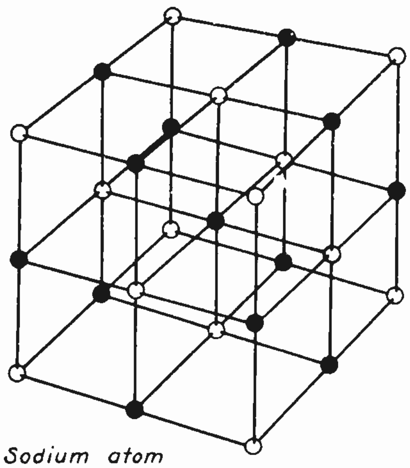


Fig. 9.--Structure of a salt crystal.

other configurations; various types of crystals are found in nature.

Thus the crystal is the unit of structure rather than the molecule, unless one wishes to consider the crystal as a kind of super-molecule. When the crystal is heated, the thermal agitation of the atoms increases to a point where the atoms break their bonds at some particular temperature, and the crystal melts. The melting point is quite definite, but even in the liquid state, some vestiges of the crystal structure persist.

Some materials, such as glass, ordinarily do not form a definite crystalline pattern even when cooled to room temperature or below. Such materials are regarded as super-cooled liquids, and their rigidity is considered due to the viscosity or friction between molecules (much like cold grease) rather than to a fixed pattern of bonds holding them in place, as in the crystal. Hence glass (sealing wax, many plastics, etc.) do not exhibit a definite melting point; instead, they progressively soften as the temperature is raised. Presumably some bonds are stronger than other bonds, and as the temperature is raised, the weaker bonds break first, giving rise to a progressive softening rather than a definite melting point.

In the case of glass a point of practical importance is that at room temperature, it is much too viscous to permit its ionic constituents to flow past one another when a potential is applied across two opposite surfaces; i.e., it is an insulator. As the temperature is raised, and the glass becomes softer and less viscous, more and more ionic motion occurs, which may further heat the glass, making it softer, thereby increasing its conductivity, and so on until it fuses and becomes a good conductor. This effect is sometimes noticed in vacuum tubes. The glass seals surrounding high-voltage plate leads begin to soften and become conductive, particularly if the seals are allowed to become hot. An example of this is a radar pulse tube which, if not air-cooled, will develop enough heat at the seals to produce appreciable conductivity with consequent breakdown and disintegration of the seals.

ELECTRICAL CONDUCTIVITY.—Returning to the crystalline structure, metals in general have a crystalline structure even though their atoms are of one kind, apparently because metals have outer orbital electrons that are easily released from the atom and so are readily shared by the various atoms. This sharing effect tends to hold the atoms together in patterns of in-definite size; i.e., in crystalline configuration. In actual practice large crystals are rare because any sudden change in temperature or pressure may result in deforming or breaking up the crystal into smaller crystals. As a result most large objects are really made up of a large number of tiny crystals interlaced and held together thereby, perhaps in the same way that the fibers of paper or felt are matted together. Nevertheless large crystals of copper, for example, have been produced by exercising care in growing the crystal from the molten liquid.

Forces Within a Crystal.—Consider a crystal of a metal, such as sodium. As shown in Fig. 10, the plus signs represent the nuclei;

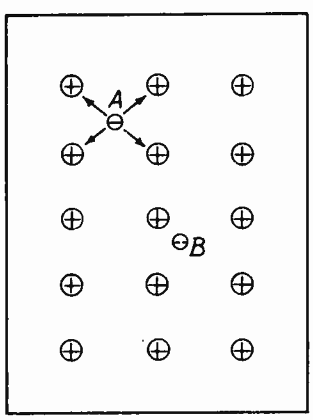


Fig. 10.—Interior of a crystal of sodium.

and the circles, the various electrons in the shells surrounding the nucleus, except the outermost shell. The electron in each outermost shell is more or less free to wander about inside of the crystal. Consider an electron at a point A centrally located with respect to the top four left-hand atoms. It is clear that the coulomb forces of attraction of the atoms (indicated by arrows), will be equal and will therefore balance one another. The result is as if there were no forces on the electron at this point and it were completely free.

On the other hand, an electron situated at B will clearly be attracted more strongly by the atom above it to the left than by another atom, so that the electron will be captured by this atom and will tend to revolve in an outermost orbit around it. However, the force of attraction is not very strong, and the heat energy in the crystal will soon knock the electron loose. Thus, *on the average,* electrons permeate the space in the crystal between atoms, and dart around mainly as free electrons. Occasionally they are captured by some atoms, only to be free once more, hence at any moment a certain number of electrons can be considered to be free to move around in the crystal.

Electric Current.—Now consider a metallic loop, as shown in Fig. 11, into which is inserted an electron pump or electrical generator, which produces a force on the electrons tending to make them move in a clockwise direction. The orbital or bound electrons may be influenced somewhat, but the effect is small. The free electrons, on the other hand, can be readily made to move, and will circulate in a clockwise direction around the loop. This flow or circulation constitutes an electric current; even though the electrons may be simultaneously darting about owing to thermal agitation, the drift superimposed

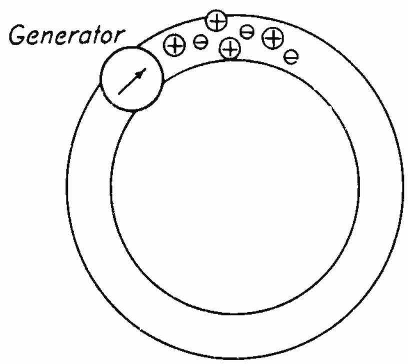


Fig. 11.--Electrical Circuit.

on such haphazard motions by the electrical generator is the electrical current normally observed by its magnetic effects, heating, etc. The metal in which this drift occurs is said to have *electrical conductivity*. The electrons are capable of moving not only within the crystal, but also from one crystal to another, and thus around the closed loop or circuit.

Thermal Noise.-- It may be asked why the haphazard thermal motion of the electrons are not considered currents also. The answer is that such motions do represent currents too, but on the average, as many electrons in any small region are moving in one direction as in the opposite direction, so that such current effects tend to cancel. On the other hand, the *coordinated* drift of *all* the free electrons *in the direction imposed by the generator* represents a large total current effect, even though the actual velocity of drift of the individual electrons may be considerably less than their simultaneous, uncoordinated thermal velocities.

However, the cancellation of the thermal currents is not complete; there remains at any moment a certain *net* current, first in one direction and then in the opposite direction. Specifically, in the case of Fig. 11, the electrons not only dart back and forth across the conductor, but also along its length. At one moment more may be moving in a clockwise direction along the loop; at the next moment more may be moving in a counterclockwise direction. The result is a tiny current fluctuating in direction, so that it may be regarded as an alternating current. Since it is purely haphazard in its alternations, it is known as a *noise* current or simply noise, because when its amplified effects are impressed on a loudspeaker, a loud toneless sound is heard.

Thermal noise effects are of paramount importance in amplifiers used to amplify the minute signals generated by microphones, iconoscopes (used as pickup tubes in television), and similar sources. Desired signals must be above a certain amplitude if they are to override the undesired thermal noise signal, and the latter imposes a limitation on how weak the former can be. A great deal more will be said about noise in subsequent technical assignments; what is desired to be emphasized here is the fundamental nature of this quantity.

THE VOLT, COULOMB, AND AMPERE.— The force developed by the generator in circulating the electrons, and the amount of circulation are measured in certain units. A more extended discussion will be given at the appropriate points in the course;

what is desired here is a basic knowledge of these quantities.

Potential.—The generator developes a difference in potential between its two terminals. This means that by some means, whether it be chemical action, the cutting of magnetic lines of force, thermo-electric effect, or other action, it forces electrons within it to its negative terminal, thereby making it negative; and away from its positive terminal, thereby making this terminal positive. This is indicated in Fig. 12. A rotating armature type of gener-

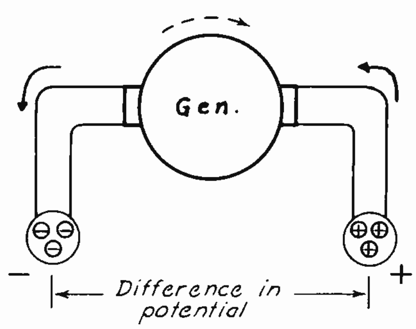


Fig. 12.—**Action of a generator in developing a difference in potential.**

ator is indicated. The solid arrows indicate the direction in which the electrons in the armature are forced by its rotation. The negative terminal accumulates an excess of electrons; the other terminal has a deficit and hence becomes positive because of a corresponding relative excess of protons.

If the armature should cease rotating, the electrons would immediately flow back from the negative terminal into the armature and to the positive terminal, thereby equalizing their density throughout the winding and producing an overall neutral effect. Evidently the rotation of the armature produces a force on the electrons in the direction of the arrows, and thus displaces them from their neutral positions.

This force is called an *electromotive force* (E. M. F.), and produces a *difference in potential* between the generator terminals. This difference in potential, or the E. M. F. causing it, is measured in a unit called the *volt*, after Allesandro Volta (1745-1827). It is an indirect, rather than a direct measure of the force on the electrons; actually it measures the work done in transporting the electrons around a circuit. But since the work done depends upon how much force has to be exerted on the electrons to move them around the circuit, and also upon the length of the circuit, it is clear that for a given circuit the potential difference between two points of it (such as the generator terminals) will indicate the force required to push the electrons from one point to the other. In short, a high-voltage circuit indicates large forces acting on the electrons, and a low-voltage circuit indicates small forces acting on the electrons.

Charge.—It was indicated previously that the quantity of negative charge associated with an electron was 4.770×10^{-10} statcoulombs. In ordinary practical circuits a much larger unit of charge is employed, corresponding to that of an enormous number of electrons. It is called the *coulomb*, and is a unit that is 3×10^{9} times as large as the statcoulomb.

It therefore corresponds to the amount of charge of $(1/4.470 \times 10^{-10})(3 \times 10^{9}) = 6.28 \times 10^{18}$ electrons. It will be observed that the coulomb is analogous to gallons in water power; a gallon represents a quantity of water corresponding to billions of billions of water molecules.

Current.—Coulombs of charges, like gallons of water, are of no value as regards power, unless they are in motion. Hence the coulomb in itself is not of such importance as regards electrical power as is the *flow* of coulombs of charges. Consider a conductor of circular cross section, as shown in Fig. 13. At some cross section, electrons pass through at a certain rate.

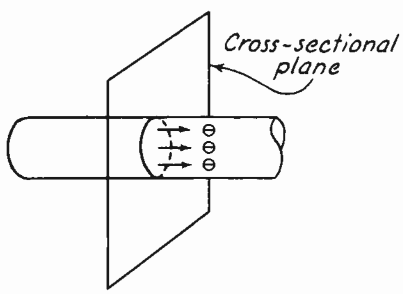


Fig. 13.—Flow of electrons through a conductor.

Suppose 6.28×10^{18} electrons pass through this cross section in one second. Then one coulomb has passed through in one second.

This corresponds to one gallon of water passing through a pipe in one second. If one coulomb of charge passes through a cross section of a conductor in one second, *one ampere of current is said to flow.* The unit is named in honor of André Marie Ampère (1775-1836), a French mathematician and physicist.

In a circuit having no branches (shunt paths), as many electrons as pass through one cross section must pass through every other cross section. If at some cross section fewer electrons passed through, there would be a piling up of electrons at this point. Since electrons repel one another with very strong coulomb forces, no appreciable accumulation can occur in a closed circuit in which a steady current flow is taking place, so that it is immaterial at which cross section the number of coulombs per second (amperes) is measured; i.e., the same number of amperes is measured at all points in the circuit.

A point worthy of note is that if there is a constriction in the cross section at some point in the circuit, fewer electrons can flow through as a *simultaneous group.* It is therefore necessary for them to scurry through the constriction more rapidly in order not to pile up at this point; their drift velocity here is higher than at the wider cross sections of the conductor, but the *number per second will be the same at all points.* The action is exactly similar to that of a brook: at a constricted part or narrows the water flows through more rapidly than it does at a broad part. Another example is a two-lane and four-lane highway; the same number of cars can be passed on either if the cars travel twice as fast on the two-lane highway.

Direction of Current Flow.—At this point it is necessary to discuss the direction of current flow. The preceding discussion has spoken of electron flow. Normally these are the charges that are transported through a circuit. Their direction of flow is illustrated in Fig. 14. *Within the generator proper* they flow from *the positive to the negative terminal;* in *the external circuit* they flow from *the negative to the positive terminal* in order

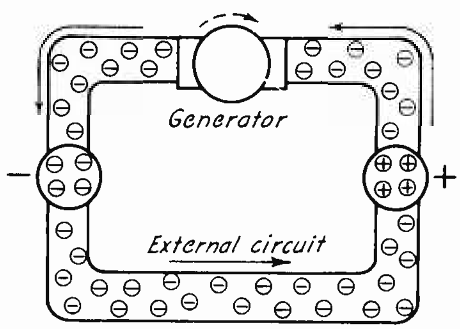


Fig. 14.--Showing direction of current flow.

to complete their circuital flow.

Before the nature of electricity was known, it was recognized that something flowed through the wire. One theory held that there were two fluids, one positive and one negative, that flowed in opposite directions through the circuit. This was known as the *two-fluid theory.*

Another theory, championed particularly by Benjamin Franklin, held that only one fluid flowed through the wire (one-fluid theory). Since one fluid is a simpler concept than two, it gained in favor to a point where it virtually superseded the other, two-fluid theory. The question then arose, "Which way did this single fluid flow?" Since nothing of its nature was known at the time, a direction was arbitrarily chosen; namely, from negative to positive within the generator, and from positive to negative in the external circuit.

Today it is known that in most circuits free electrons flow, and these flow in the direction indicated in Fig. 14 and hence *opposite* to the direction assumed. This is unfortunate because a great deal of work has already been done based upon the previous assumption: machines have been built and labeled as per that assumption; texts have been written wherein are given rules as to motor and generator actions that are based on the old assumption of current flow; and in general the old rule has become rather firmly established, particularly in the power field.

As a consequence, wherever motors, generators, and magnetism are discussed in these assignments, the old assumed direction of current flow (from plus to minus in the external circuit), will be employed. However, wherever thermionic vacuum tubes, and radio circuits in general are discussed, *the electron flow will be employed.* Since these circuits occupy the major portion of this course, it can be stated that in general the electron flow, which is from *negative* to *positive* in the *external circuit,* will be employed, and that only in special cases will exceptions be made, and the older assumed direction of current flow used.

Perhaps the most unfortunate aspect of this is that actually the older concept of current flow is not entirely incorrect. If a flow of protons could be established in space, then they would produce exactly the same effects as a flow of electrons *in the opposite direction.* Ordinarily the protons, or positively charged atoms of a conductor (those that have lost electrons) are too bulky to move, and are moreover held together by atomic forces or bonds which prevent their motion. Instead the lighter and hence more mobile free electrons move through the spaces within the conductor.

But in the cyclotron, a device used in nuclear investigations, a stream of *positive ions* is whirled around in it in order to attain sufficient velocity to bombard the nuclei of targets placed in their path. In this case the current flow is actually that of positive charges, and they move *from plus to minus.*

In an electrolytic solution, such as salt water, when a potential difference is established between two electrodes immersed in the brine, *positive* sodium ions move from the *positive* to the *negative* electrode, and an *equal* number of *negative* chlorine ions move from the *negative* to the *positive* electrode. Thus *half* of the current flow is in the direction originally assumed, and half in the more modern electron direction; both directions are at least half right.

This is the way nature acts; there can be no quarreling with her edicts. Fortunately for the student, in *most cases* the modern electron flow is correct, and the older assumed direction of flow need be adopted in this course only in certain special cases. One must have a flexible mind in science; this question of current flow is a simple example of such a requirement.

RESISTANCE.—It has been shown above that the free electrons in a conductor are able to move through it, and in so doing produce an electric current. The fundamental reason for such freedom of motion is that matter is really more empty space than substance, as was indicated previously. However, the electrons are hampered to some extent by the atoms in the crystalline arrangement (called a crystal lattice structure). Presumably the electrons collide with the atoms, or at least are swerved by them if they come too close to the "sphere of influence" of the atoms, whereupon their coordinated drift motion is converted, at least in part, into haphazard thermal motion. Thus the electrical energy is partially converted into heat, and forms the basis of action of the electric stove, electric furnace, and the incandescent lamp, as well.

The opposition to the drift motion of the electrons by the crystal lattice structure is called *resistance.* It is measured in a unit called the *ohm,* named in honor of George Simon Ohm, (1787-1854) a famous scientist who first correctly gave the relationship between the current flow in amperes, the electrical pressure in volts, and the resistance in ohms (Ohm's law). This law will be given in a subsequent technical assignment.

Factors Determining Resistance.--The resistance of a conductor depends upon the following factors:

1. The material of which the conductor is composed.
2. The cross-sectional area of the conductor.
3. The length of the conductor.
4. The temperature of the conductor.

The material determines the resistance in two ways: the number of free electrons it furnishes, and the configuration of the crystal lattice structure. As regards the first, metals whose outermost orbital electrons are loosely held in their orbits, like caesium, have a large number of free electrons and are therefore good conductors (have a low resistance). Indeed, caesium is the best conductor known, followed by rubidium, potassium, sodium, and lithium. Unfortunately these metals are either rare or highly reactive chemically, so that they oxidize and disintegrate in the air, and react violently with water to form the corresponding hydroxide, such as sodium hydroxide (lye).

Fortunately, certain other metals, such as copper, have a low resistance. Although copper does not have as many free electrons as caesium, for example, its crystal lattice structure is such that the electrons can pass through it with great ease, thus affording a low electrical resistance for the material. Another material is silver, which has a slightly lower resistance than copper. On the other hand, iron has a much higher resistance, and certain alloys have a resistance more than 50 times that of copper. From an economic viewpoint, copper is the most important metal for conducting electricity when a low resistance is required, and the above-mentioned alloys are important when the heating effect is desired, as in an electric stove.

It is readily apparent that the resistance of a conductor should be less as the cross section is increased, since there is more room for the electrons to flow, just as in the case of a water pipe of large cross section. It is also readily apparent why the resistance goes up as the length of the conductor is increased, since the electrons will have a greater length of crystal lattice structure to struggle through, just as in the case of a long water pipe.

Specific Resistance.—Hence, in order to compare various conductors as to their resistance, it is necessary to specify their cross-sectional area and their length. As a basis for comparison, a cube of the conductor 1 cm. on a side (hence a volume of 1 cu. cm.) is employed and the resistance of this cube is given. Thus in the case of copper, the specific resistance, as it is called, of commercially annealed copper is given as 1.7241×10^{-6} ohms per $cm.^3$, or 1.7241 microhms/$cm.^3$, and for hard-drawn copper it is 1.771 microhms. For silver the specific resistance is 1.59 microhms; for aluminum, 2.824; for Advance of Constantan (an alloy), 44, etc. These values are for 20° C.

Suppose a cube of hard-drawn copper is used whose dimensions are 3 cm. $\times$ .5 cm. $\times$ .5 cm. This is shown in Fig. 15. In (A) the current flows parallel to the 3 cm. dimension; in (B) perpendicular to that dimension. The arrows clearly indicate the direction of current flow.

Let R_s equal the specific resistance of the material; A, its cross sectional area in sq. cm.; and l, its length in cm. along which the current flows. Then the resistance of any given shape is given by

$$R = R_s \frac{l}{A} \qquad (5)$$

In Fig. 15(A), the area is $.5 \times .5 =$

$.25$ cm.^{2}, and $l = 3$ cm. Also R_s = 1.771 microhms/cm^3. Then, by Eq. (5)

$$R = 1.771 \times \frac{3}{.25}$$

$$= 21.25 \text{ or } 21.3 \text{ microhms}$$

$$= 21.3 \times 10^{-6} \text{ ohms}$$

In Fig. 15 (B), the area is $3 \times .5 =$ 1.5 cm.^{2}, and $l = .5$ cm. Then

$$R = 1.771 \times \frac{.5}{1.5}$$

$$= .590 \text{ microhms} = .590 \times 10^{-6} \text{ ohms}$$

Note the difference in resistance for

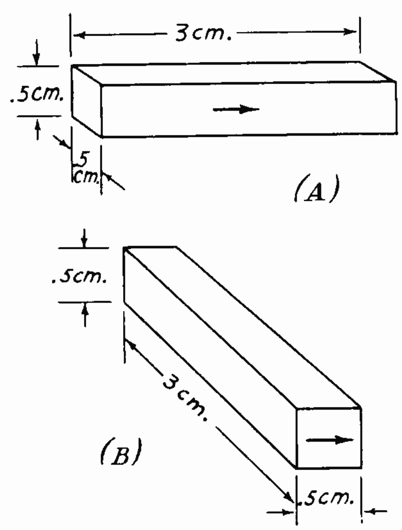


Fig. 15.--Copper conductor in which current flows.

the same piece of copper owing to the difference in direction of current flow.

Exercises

4. Perform the same calculations for annealed copper.

5. Perform the same calculations for aluminum as in Fig. 15 (A).

6. How much must the aluminum bar be shortened so that its resistance is no greater than that of an annealed copper bar of the same cross section and the full 3 cm. length?

Temperature Coefficient.—The specific resistance of a material is ordinarily given at 20° C. The reason is that in general the resistance changes with temperature: for most metals it increases with temperature, for some non-metals, such as carbon, it actually decreases as the temperature is raised. A material for which the resistance increases with temperature is said to have a *positive temperature coefficient:* one for which the resistance decreases with an increase in temperature has a *negative temperature coefficient.*

The reason for the increase in resistance in general is that as the temperature is raised, the random thermal motions of both the free electrons and atoms of the crystal lattice structure are increased, so that they get in each other's way more often. Thus there are more collisions and more opportunities for the crystal lattice structure to interfere with the drift motion of the electrons.

On the other hand, there is a somewhat greater tendency for the atoms to lose free electrons as the temperature is raised, so that the number of free electrons should increase with temperature and thus lower the resistance. In the case of a metal there appears to be sufficient free electrons ordinarily so that an increase with temperature does not materially lower the resistance in this respect, but the greater number of collisions, on the other hand, tends to raise the resistance. In the case of relatively poor conductors, such as carbon, increase in temperature either increases the number of free electrons, or else modifies the crystal structure in a favorable direction, or both, so that the resistance decreases. In the case of resistance standards, such as are used in measurements, it is highly desirable that their resistance does not vary with temperature; i.e., a zero temperature coefficient is desired. Many alloys have been developed for this purpose, particularly manganin, an alloy of copper, manganese, nickel and some iron, which has a practically zero temperature coefficient, and is also particularly stable in resistance with time.

If the temperature coefficient of a metal is known, the actual resistance of a conductor of that metal at a given temperature may be easily calculated. The temperature coefficient is expressed in terms of the decimal variation in resistance per degree C. The formula for computing the multiplying factor is

$$F = 1 + \alpha T \qquad (6)$$

where F is the factor by which the resistance is to be multiplied, T is the *temperature change* from 20° C, and α is the temperature coefficient. A simple problem will make the use of this formula clear:

A coil is wound with 450 feet of No. 30 copper wire, the resistance of which at 20° C is 103.2 ohms per thousand feet. What is the resistance of the coil at 50° C? At 20° C, the resistance is

$$R = 103.2 \times 450/1,000$$

$$= 46.44 \text{ ohms}$$

From tables the temperature coefficient α of commercial annealed copper is found to be .00393. (The temperature coefficient of most *pure* metals in the range of ordinary temperatures is between .003 and .005 so that an approximation of .004 will allow a workable calculation if tables are not available. This does *not* apply to alloys.) The temperature T is to be increased from 20° to 50°, a change of $50 - 20 = 30^{\circ}$ C. Then, from Eq. (6)

$$F = 1 + (.00393 \times 30) = 1.118$$

so that

$$R = 46.44 \times 1.118 = 51.92 \text{ ohms}$$

This is a variation of $(51.92 - 46.44)/46.44 = 11.8$ per cent for a 30° C rise in temperature. Such a change can be of marked importance in many types of radio equipment. While the value of α is strictly speaking correct only at 20° C, it may be used over other temperature ranges with no appreciable error; i.e., the same coefficient may be used from below 20° C to as high as 1000° C.

At very low temperatures some metals, notably tin, mercury, and lead show extremely low resistance; indeed, practically none at all. This condition is known as "superconductivity", and can be explained only by very advanced theories and methods known as "quantum mechanics", which are beyond the scope of this course. The resistance decreases with temperature in the form of a curve until a certain critical temperature is reached (close to absolute zero, which is 0° K or -273° C), at which point the resistance apparently drops to zero. For tin the critical temperature is 3.74° K; for mercury, 4.19° K; and for lead, 7.20° K. Liquid helium is used for such cooling purposes.

Below the critical temperature, if a ring of the metal is employed, and a permanent magnet suddenly thrust in it, the cutting of the closed conductor by the magnetic lines of force will induce a momentary voltage, which in turn will cause a current to flow for days. This is an interesting phenomenon, even though there does not appear to be any practical use for it at present.

Exercises

7. Calculate the resistance of a length of copper wire at 60° C when its resistance at 20° C is 140 ohms.

8. A radio coil of 0.1 ohm resistance at 20° C is employed in an airplane receiving set. During flight a temperature of -50° C is encountered. What is the resistance of the coil at the latter temperature.

9. On the ground the temperature in the plane may reach 80°C. What is the resistance of the coil under these conditions?

INSULATORS.—Many materials do not conduct electricity; they are known as *insulators*; and are just as important as conductors. The reason is that by surrounding conductors with insulating covers, the electric current flow can be confined to the desired conducting paths. Thus insulators act as the walls of a water pipe; the conductor, as the hole in the pipe.

The lack of conductivity exhibited by insulators is owing to a lack of free electrons in the material. Most electro-negative atoms, such as sulphur, make excellent insulators, because it will be recalled that these atoms tend to capture electrons rather than to yield them up as free electrons. However, most compounds containing metals are good insulators. For example, while sodium is one of the best conductors known (as explained previously), sodium chloride is a good insulator in the crystalline form. This is because the normally free electron of the sodium atom is held tightly by the chlorine atom in sodium chloride, and hence is no longer free to provide conductivity.

In spite of the fact that insulators have no free electrons (or very, very few) to provide conductivity, nevertheless momentary currents, known as charging currents, can flow in them. The reason is best explained by means of Fig. 16. A source of potential G is applied to two conducting plates P_1 and P_2. For the polarity shown for the generator, P_1 has an excess of electrons and is negative; P_2 has a deficit of electrons and hence a relative excess of protons, and is therefore positive. Between the two plates is an insulating material, I. The atoms in this material have no free electrons, but the orbital electrons are acted upon by the Coulomb forces owing to the charges in the two plates.

As a result the orbits are distorted as shown. The electrons

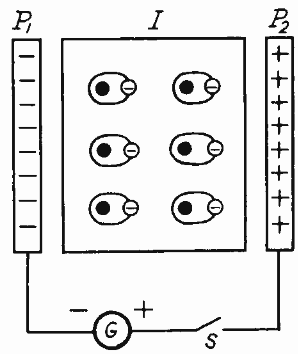


Fig. 16.--Distortion of orbits of electrons in atoms of an insulator.

are *on the average* closer to the positive plate P_2 than they are to the negative plate P_1. When the switch S was first closed, electrons were forced into P_1; electrons were drawn out of P_2, and the electrons in I changed from approximately circular orbits around the nuclei into the distorted forms shown.

The momentary flow of electrons into P_1 and out of P_2 represented a *momentary* current flow; corresponding to this there was a momentary charging current flow in I. This came about as follows: When the electrons were revolving in approximately circular orbits about their nuclei, they were as much to one side of the nuclei as to the other side; *their average positions were about the same as those of the nuclei*. But when the orbits are distorted, their *average positions are slightly to the right of the nuclei*. This average displacement can justifiably be regarded as a *momentary electron flow* to the right, and thus there occurs in the insulator I a momentary current flow, known as a charging current, equal and corresponding to the electron flow in the metallic parts of the circuit.

After the momentary flow ceases, the plates are charged as shown, and represent *a condenser* that has been charged to the potential of G. If the potential of G were to be reversed, an opposite distortion in the orbital paths of the electrons of I would occur, and a momentary *opposite* flow of current in the system would occur. Thus, if G is an alternating- instead of a direct-current generator, a steady alternating current can flow in the circuit, even though I is an insulator. This will be discussed in greater detail in later assignments.

Even in the best of insulators there are some free electrons, produced by various causes, so that some conductivity occurs. The amount is so small, however, that for most practical purposes it can be taken as zero, and many insulators can be regarded as well-nigh perfect. However, if the potential applied to the insulator is made sufficiently high, the electron structure can be disrupted, and free electrons produced, whereupon the insulator suddenly becomes a conductor. The attendant arc or spark through the material in general disintegrates it, so that it no longer functions as an insulator when the voltage is reduced. Some materials exhibit partial conductivity and are known as partial conductors. An example is cuprous oxide. Often the conductivity is affected by light shining on the material and liberating free electrons, as in the case of selenium. Such effects are special and not too clearly understood at the present time.

THERMIONIC EMISSION.—Mention was made that electrons can be forced out of a conductor by heating it to a sufficiently high temperature. Such emission is known as thermionic emission, and is the basis of the vacuum tube as used today. The fundamental action is quite easy to understand, although the details are in many cases not so simple.

Consider a conductor, as shown in Fig. 17. Within the conductor

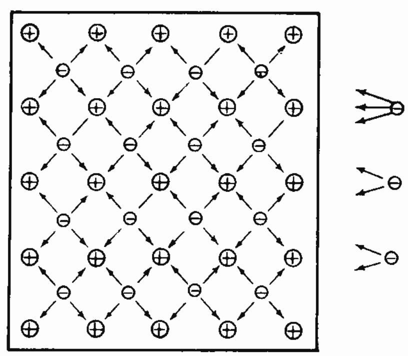


Fig. 17.—Forces on free and on emitted electrons.

are the nuclei of its atoms, with the tightly bound shells or orbital electrons around each nucleus. In between are the free electrons, darting around within the interior much like the atoms of a gas. As shown in the figure, the coulomb forces of attraction of the positive atoms for these free electrons are more or less balanced, as indicated by the arrows, so that the electrons are more or less free to move about as they please.

The action of the positive atoms (positive because they have lost outer orbital electrons) upon the free electrons they have lost is well illustrated by Fig. 18.

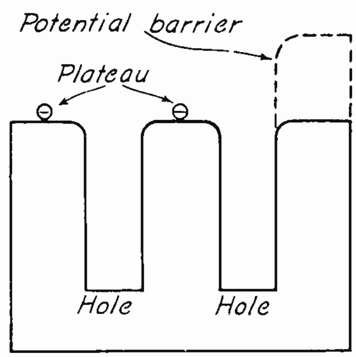


Fig. 18.—Use of gravitational field to illustrate conditions in and around a conductor.

Here the position of each nucleus or atom is represented by a hole in a plateau. The sides of the hole are relatively steep, to represent how rapidly the coulomb forces fall off in magnitude with distance. For quite a distance between the atoms the plateau is practically flat; this is the region where the forces are very small, and moreover tend to balance one another, thereby leaving a resultant force that is practically zero.

As long as an electron is on the plateau, it is free to roll around as it pleases. If it comes too close to one of the holes, it will roll down and be captured. If however, it approaches a hole with sufficient velocity, it will be able to hurdle it and proceed on the next plateau, much like a ski jumper hurdles over a depression.

The gravitational model presented can also illustrate the action of heat: suppose the model is shaken vigorously; it is clear that electrons will be jiggled out of the holes onto the plateaus in a manner similar to that by which the outer electrons of the atoms are knocked out of their orbits by heat energy.

So far all that has been described is the production of free electrons. Returning to Fig. 17 consider an electron that tries to pass through the boundary surface of the conductor. The moment this occurs, all the positive atoms left behind now unite in trying to pull the electron back. This is illustrated by the three electrons shown to the right of the conductor in Fig. 17; the arrows show that the forces are to the left and hence of attraction, tending to pull the electron back into the conductor.

Compare these with the forces on an electron inside of the conductor and it will be clear that an electron must have a far greater velocity to escape from the conductor than to wander around in it. The same effect is illustrated in Fig. 18 by the dotted line hill labelled "Potential Barrier". An electron requires excess velocity and hence kinetic energy to surmount this potential barrier and escape from the conductor.

Once the electron escapes and moves to a sufficient distance from the surface, the coulomb forces of attraction pictured in Fig. 17 become so weak that it is free to wander about in free space. Thus, in a vacuum tube, electrons emitted from an electrode called a cathode, into the vacuum within the glass envelope, can now be attracted to any other positive electrode in the enclosure, such as a plate, and give rise to the plate current flow in the tube.

It is clear that a much greater amount of energy must be imparted to a conductor to cause electron emission from its surface than is required merely to free orbital electrons so that they can wander freely within the material. The required energy can be imparted to the electron in several ways. One important way is to radiate the surface with light energy of the proper wavelength; such emission is known as *photoelectric emission,* and will be discussed farther on.

Another method is to heat the conductor, thus agitating the atoms and free electrons to such an extent that the latter are forced out of the surface. This is known as *thermionic emission.* The amount of energy required to cause an electron to hurdle the potential barrier is known as the *work function,* and depends upon the material used and the nature of its surface. The work function is measured in volts, because volts times charge equals energy, just as volts times current equals *rate* of energy dissipation or power.

This will be made clearer by reference to Fig. 19. Again two plates or electrodes are shown, with a vacuum in between. (It is desirable in general that there be no obstructions, such as oxygen or nitrogen atoms from the air, to prevent the free motion of the electrons.) Suppose the plates are given the charges shown by means of a generator or battery so that a difference of potential V exists between the plates.

An electron placed as shown, and having a charge e, will be acted upon by a force of repulsion by the left-hand plate, and a force of attraction by the right-hand plate, so that there is a total force accelerating it to the right. The electron gains in velocity and

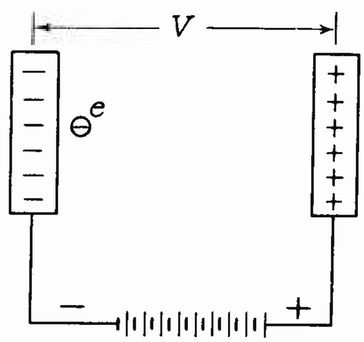


Fig. 19.—**Conversion of potential energy into kinetic energy; electron falling through a difference in potential.**

hence kinetic energy at the expense of potential energy of position. Thus, when it is next to the left-hand plate it has a maximum amount of potential energy, equal to Ve, but no kinetic energy, since it is assumed at rest there. When it reaches the right-hand plate, it has a maximum amount of velocity and hence kinetic energy, but it has no potential energy. All the potential energy has been converted into kinetic energy. The latter is given by Eq. (3), so

$$Ve = (1/2)\ mv^2 \qquad (7)$$

The action is similar to that of a ball falling from a height: at the height the ball has potential energy of position but no kinetic energy; at the ground it has a high velocity and hence kinetic energy, but no more potential energy. In the same way, an electron (or other charged body) is said to fall through a difference in potential, and often its velocity is expressed in electron volts; i.e., in terms of the difference in potential through which it would have to fall to acquire the given velocity.

Even if the electron acquires its velocity through thermal agitation, its velocity can nevertheless be expressed in terms of so many electron volts. Consider now the critical velocity that will carry an electron past the surface potential barrier. This can be expressed in terms of so many volts, *and the required work function is therefore measured in volts.* For example, the work function for tungsten is 4.54 volts.

This is a very high value, and requires that the tungsten cathode be heated to about 2400° K. before appreciable thermionic emission occurs. Fortunately, this high temperature is safe because the melting point of tungsten is 3655° K. This brings out an important characteristic of a thermionic emitter: *it must have as high a melting point together with as low a work function* as possible in order to be a practical emitter. The significance of this is that the bonds or forces holding the crystal lattice structure together must be as great as possible, and the potential barrier for the electrons must be as low as possible, in order that heating the material will produce copious emission at a temperature insufficient to melt or vaporize the material.

For this reason caesium, which has a work function of but

1.81 volts, is not suited for thermionic emission because it vaporizes so easily; it would tend unduly to evaporate even at the low temperature required for satisfactory emission. On the other hand, it is exceedingly well adapted for photoelectric emission, in which case it is operated at practically room temperature. More will be said about this later.

It is found that for medium-voltage tubes an emitter consisting of thorium and tungsten is preferable to pure tungsten. The reason is that the work function is only 2.63 volts, so that at a safe operating temperature of 1800 to 2000° K. the emission is many times that from tungsten. At the same time it must not be overlooked that the lower operating temperature of the thoriated-tungsten cathode means that much less electrical heating power is required, so that the vacuum tube operates at a higher overall efficiency as a result.

An even more efficient emitter is a mixture of barium and strontium oxides on a special base metal such as Konel metal. This composite cathode at 1000° K. emits as many electrons as a tungsten filament at 2300° K. Unfortunately this type of emitter is sensitive to positive ion bombardment and cannot be heated to as high a temperature as tungsten for the purpose of outgassing the tube, so that it is limited to the lower-voltage tubes, such as small transmitting tubes and the ordinary receiver tubes. However, such large quantities of the latter are employed that the oxide-coated cathode is nevertheless the most-used type of thermionic emitter.

PHOTOELECTRIC EMISSION.--Ordinarily light, heat, and radio energy are regarded as being electromagnetic waves in space or radiant energy. A wave motion in a medium is characterized by its filling or pervading the medium *uniformly*. Thus *every* point in a medium through which radiant energy is passing is regarded as partaking in the wave motion.

In spite of this, there is evidence to show that the above electromagnetic energy does not spread uniformly through space, but is confined to little pellets or bundles of energy called *photons*. The picture concerning this is not clear, as was indicated in the quotation from G. E. M. Jauncey's book at the beginning of this technical assignment. Certain properties of light, such as diffraction and interference effects in general, are explained in terms of wave motion only, whereas such effects as photoemission, for example, are explained in terms of photons of light.

Probably both wave motion and particle properties are associated with the phenomenon known as radiant energy; each property is used where it explains best the results noted. For example, when weak blue light falls on a suitable surface, a few electrons are emitted from it with certain rather high velocities. A strong blue light causes *more electrons* to be emitted, but *each* has the *same velocity* as the few emitted by the weak blue light.

On the other hand, a strong red light will emit as many electrons from the surface as the strong blue light, but each electron will come out *with a much lower* *velocity*. A weak red light will produce *the same velocity of emission;* fewer electrons will be emitted.

From the viewpoint of wave motion this is a very puzzling phenomenon. A strong red light on say, a square foot of the surface should represent a higher but uniform energy density on the surface than a weak blue light. Thus each free electron of the surface should receive more energy from the strong red light than from the weak blue light.

The received energy is partly used up to overcome the work function of the material, and the rest appears in the form of kinetic energy of the emitted electron; i.e., the electron issues from the surface with a certain amount of velocity of emission. According to the theory of wave motion, the velocity of emission of the electron should be greater for a strong red light than for a weak blue light.

Since the opposite is found to be the case, the only explanation is that energy is confined to small pellets or *quanta* of energy. These quanta are given the special name of *photons* in the case of radiant energy. Apparently there is more energy in a photon of blue light than in a photon of red light, and a weak light consists of few photons whereas a strong light consists of many photons. If a photon impinges upon an electron, the latter absorbs it in its entirety if the energy content is above a certain minimum amount, and thereupon emerges with a corresponding velocity of emission.

The energy content W of a photon is given by a very simple formula:

$$W = hf \qquad (8)$$

Where h is a constant of nature equal to 6.55×10^{-27} erg sec. and is named after Max Planck, a famous German physicist, and f is the frequency of the wave motion. For example, the frequency of a certain hue of blue light is 0.7×10^{15} c.p.s., (cycles per second) hence the energy in one photon of blue light is

$$W_b = 6.55 \times 10^{-27} \times 0.7 \times 10^{15}$$

$$= 4.59 \times 10^{-12} \text{ erg}$$

The frequency of a certain shade of red light is 0.45×10^{15} c.p.s., hence the energy in one photon is

$$W_r = 6.55 \times 10^{-27} \times 0.45 \times 10^{15}$$

$$= 2.95 \times 10^{-12} \text{ erg}$$

or considerably less than that in blue light.

The kinetic energy owing to the velocity of emission was first given by Einstein in the form of a very simple law:

$$\text{K.E.} = hf - \phi e \times 10^7 \qquad (9)$$

Here K.E. is the kinetic energy of the electron and, by Eq. (3), is equal to $1/2\ mv^2$, where m is the mass of the electron and v is its velocity (of emission). The quantity hf is the energy in ergs if the photon impinging on the surface is given by Eq. (8); ϕ is the work function of the surface in volts; and e is the charge on the electron in *coulombs*, namely, 1.59×10^{-19} coulombs.

As an example, suppose blue light evaluated above impinges upon a caesium surface, whose work function is 1.81 volts. The energy in one photon of the above light was calculated to be 4.59×10^{-12} erg. The kinetic energy of emission, by Eq. (9), is

$$K.E. = 4.59 \times 10^{-12} - 1.81 \times 1.59 \times 10^{-19} \times 10^{7}$$

$$= 4.59 \times 10^{-12} - 2.88 \times 10^{-12}$$

$$= 1.71 \times 10^{-12} \text{ erg}$$

This is the kinetic energy per electron emitted, and is equal to $(1/2)/mv^2$, where $m = 8.99 \times 10^{-28}$ gram. Thus

$$K.E. = (1/2)\, mv^2$$

If both sides of the equation be multiplied by 2, and then divided by m, there is obtained

$$\frac{2\ K.E.}{m} = v^2$$

Now take the square root of both sides, and obtain

$$v = \sqrt{\frac{2\ K.E.}{m}} \text{ cm./sec.} \qquad (10)$$

For the values given above, namely, $K.E. = 1.71 \times 10^{-12}$ erg, and $m = 8.99 \times 10^{-28}$ gram, the velocity is found to be, by substitution in Eq. (10):

$$v = \sqrt{\frac{2 \times 1.71 \times 10^{-12}}{8.99 \times 10^{-28}}} = \sqrt{38.1 \times 10^{14}}$$

$$= 6.18 \times 10^{7} \text{ cm./sec.}$$

This represents the *maximum velocity* with which an electron is emitted. Most of the electrons encounter atoms on the surface which extract some energy from them, so that they emerge with lower velocities.

Exercises

10. Calculate the maximum velocity of emission for the red light described above.

Eq. (9) brings out another very important point besides that of velocity of emission. Suppose the frequency of the radiation is very low. The energy content in its photons will be also low. Suppose the work function of the material is high. In that case $\phi e \times 10^{7}$ may exceed the photon energy content hf, so that the kinetic energy K.E. comes out negative, and the corresponding velocity will be imaginary. This simply means that actually the electrons will not be emitted.

Indeed, for some particular frequency of the radiation hf will just equal $\phi e \times 10^{7}$ and K.E. will then be zero. This means that at this frequency the electrons are just emitted with no left-over velocity. The frequency at which this occurs is known as the *threshhold frequency.* It is found very simply from Eq. (9) by setting K.E. equal to zero and solving for f. Thus

$$0 = hf - \phi e \times 10^{7}$$

Transposing,

$$hf = \phi e \times 10^{7}$$

or

$$f = \frac{\phi e \times 10^{7}}{h} \qquad (11)$$

An important point to note here is that the higher the work function of the material, the higher is the threshhold frequency at which photoemission begins. Thus for tungsten, with a work function of 4.54 volts, photoemission does not begin to occur until the radiation is well into the ultra-violet. Caesium, on the other hand, has a threshhold frequency well into the infra-red.

The threshhold frequency, and the velocity of electron emission above this frequency both have an important bearing on the design and construction of photoelectric devices, particularly the iconoscope, orthicon, and image orthicon, which are television pickup tubes.

A typical photoelectric cell is shown in Fig. 20. It is found

(Courtesy RCA)

Fig. 20.--Typical photoelectric cell.

that a composite cathode has more emission than a cathode of pure metal, just as in the case of a thermionic vacuum tube. In the case of the photoelectric cell, the cathode has a surface of silver on which is a mixture of caesium and caesium oxide. The result is a tube that has maximum emission in the greenish-yellow part of the light spectrum; i.e., its response is very similar to that of the eye. Another feature is that argon gas under low pressure is present, so as to ionize in controllable amounts. The result is a further increase in output of five to six times that of a vacuum. The subject of gaseous ionization will be considered next.

IONIZATION.—Mention has been made that both heat and light can cause the free electrons in a conductor to overcome the potential barrier of the surface and be emitted, thus leaving behind positively charged atoms from which these free electrons orginated, The positively charged atoms are known as positive ions; any particle having a charge is an ion. Thus an electron is a negative ion; an electron attached to one or more atoms is known as a *negative-ion cluster;* a proton is a positive ion; any atom that has lost one or more electrons is a positive ion.

In the case of a gas, the molecules are so far apart that they do not interfere with one another, and hence there is no particular tendency for free electrons to be spontaneously produced by their interaction as in the case of a metal, at least at room temperature. Nevertheless gas atoms can be ionized; i.e., caused to lose one or more orbital electrons if sufficient energy is imparted to the atoms.

The practical sources of energy are radiant energy and the kinetic energy of high-speed electrons, protons, heavier atoms, and neutrons. Of these, the most important in radio work is that of high-speed electrons. Consider two electrodes between which is placed some gas that it is desired to ionize, see Fig. 21. A source of potential V is applied to the plates.

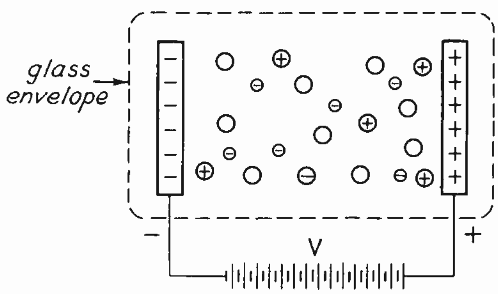


Fig. 21.—Gas to be ionized by electron bombardment.

Owing to cosmic rays and minute amounts of radioactive material in the glass walls, a few gas atoms are split apart by these agencies into electrons and positive ions.

Under the action of the applied potential, the electrons move to the positive plate, and the positive ions to the negative plate. The electrons, having little mass, move rapidly; the ions, being relatively heavy, move much more leisurely.

However, the electrons cannot proceed without interruption to the positive plate because of the presence of the neutral (unionized) gas atoms. Thus the electrons accelerate in a free space up to a certain velocity, strike a gas atom, from which they may rebound in an entirely different direction, but the impressed electric field continues to urge them toward the anode (positive electrode) so that they start out again, are accelerated to a certain velocity when they strike another atom, and so on.

The net velocity gained in a forward direction between collisions clearly depends upon the *mean* (average) spacing between atoms. This is known as the *mean free path*. If the number of gas atoms in the enclosure is decreased (pressure is reduced), then the mean free path is increased, and the electrons can acquire a higher velocity and hence greater kinetic energy between collisions. Or, if the pressure is not reduced, but the potential V is increased, a higher kinetic energy will be obtained in the original mean free path.

If the kinetic energy attained is sufficient, the bombarding electron may be able to knock out one or more electrons from an atom of the gas, thus producing more free electrons as well as a positive ion. This process is known as *ionization by collision*, and by its means a large number of free electrons and positive ions are produced in the enclosure.

It is immediately evident that the gas now resembles the interior of a metal, in that free electrons and positive ions are present, (except that the ions and atoms of the gas do not exhibit the uniform pattern of the crystal lattice structure of a metal). The gas therefore becomes a conductor, but there is one important difference: in a metal the voltage drop is directly proportional to the length and inversely proportional to the cross-sectional area of the metal, whereas in a gas the voltage drop is more or less fixed and rather independent of these factors. The voltage drop is known as the *ionizing potential*, and its value depends upon the structure of the atom; i.e., upon the nature of the gas. For each gas a certain amount of kinetic energy is required of the electrons to disrupt the atoms they bombard; corresponding to this there is a certain ionizing potential. For mercury vapor this is about 15 volts; for neon gas, 21.5 volts, and so on.

Consider the process in somewhat more detail. As a result of ionization, an appreciable electric current can flow. The positive ions produced help to cancel the repelling coulomb forces between the electrons (known as *space charge effects*) so that very little voltage is required to make the free electrons move. However, as soon as they deposit on the anode they are lost to the ionized gas, so that fresh electrons must be produced by new ionization. Hence, once breakdown of the gas (ionization) occurs, the potential drop across the gas need be no greater than that required to disrupt the gas atoms.

For the *initial breakdown* of the gas, the mean free path and the applied potential must both be large enough so that the initial electrons can acquire sufficient kinetic energy between collisions to ionize the atoms. Thus, for air at ordinary atmospheric pressure, about 30,000 volts per cm. is required between the two electrodes. Once breakdown occurs, the voltage drops to a value closer to the much lower ionizing potential for the gas.

Many important practical applications result from this phenomenon. For example, if two condenser plates are separated by air insulation, the maximum voltage that can be applied between the plates is limited to somewhere around the value given above, namely 30,000 volts per cm. separation. (For high-frequency r.f. voltages the spacing must be somewhat greater.) On the other hand, if the plates are placed in a chamber, and air is pumped in so that the pressure is greatly increased, the mean free path is *decreased*, and the condenser can withstand a much greater voltage before breakdown occurs. Such pressure condensers have been employed to a great extent in radio work.

Suppose the air is partially pumped out of the chamber. The mean free path increases, and less voltage is required to break down the condenser. But suppose the air is further removed. Ultimately the mean free path is increased until it is greater than the electrode spacing. When this occurs, the probability of an electron striking a gas atom as it moves from the cathode to the anode is small, so that no appreciable ionization occurs. In this case the electron behaves as if it were in a true vacuum, and enormous potentials must be applied before electrons can be literally pulled out of the cathode against the potential barrier there (field emission). Thus the *vacuum condenser* obtained is again capable of withstanding very high voltages even with small electrode spacings. Such condensers are found to be particularly valuable in the case of ultra-high frequency work. This is because they furnish a sufficient amount of capacity at a high-voltage rating in a small space, in a frequency range where size of the components must be kept to a minimum.

Even when the mean free path exceeds the electrode spacing there are still enormous numbers of gas atoms present in the enclosure, but as stated previously the effect is very much as if a perfect vacuum existed. The greater the electrode spacing, the greater must the mean free path be and the greater must be the degree of evacuation. Thus large transmitter tubes must be pumped to a higher vacuum than small receiver tubes and subjected to a greater degassing process.

Mention was made that once ionization takes place in a gas the applied voltage can decrease close to the ionizing potential of the gas in order to maintain further current flow. This is true providing no energy from the electrical source is required to move the electrons out of the surface of the cathode as for example, if the latter has a thermionic or photoelectric-emitting surface.

The conditions are shown in Fig. 22. The thermionic emitter is

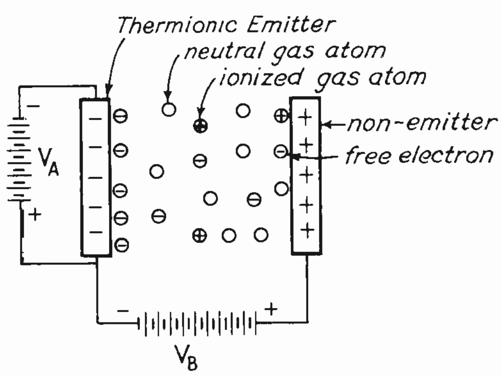


Fig. 22.--Essentials of gaseous rectifier tube.

heated electrically by a local source V_A, to a temperature at which it emits a copious stream of electrons. The potential V_B accelerates these electrons, as well as those produced in the gas by cosmic rays to a velocity sufficient to ionize the gas or vapor present at low pressure in the enclosure. When ionization occurs, the potential required between the electrodes is merely the ionizing potential of the particular gas used.

On the other hand, if the potential V_B is reversed so that the non-emitting, cold plate now becomes the cathode, a far greater potential will be required: not to ionize the gas, but to draw electrons out of the cold plate. Thus a high potential drop occurs close to the cathode surface; it is known as the cathode drop, and can be very high if the proper surface is employed.

The result is a device that conducts more readily in one direction than in the other. It is known as a gaseous rectifier tube, and ordinarily employs either an inert gas like argon, that will not attack the electrodes, or else mercury vapor produced by pellets of mercury in the tube. (Mercury vapor also does not attack the electrodes, and automatically has the correct pressure at and around room temperature to furnish the desired mean free path.) The important function of the gas is to overcome the space charge effect of the moving electrons constituting the bulk of the current in the conducting direction, although the opposite direction of flow of the ions constitutes a part of the current flow. This amounts to only about 3 per cent, however, because of the leisurely motion of the relatively heavy ions. More will be said about these matters farther on in the course.

ELECTRIC FIELDS.--Throughout this assignment one thing has been apparent, and that is that the coulomb forces between the electrically-charged particles have a major role in explaining chemical action, ionization, conductivity in a metal, and the like. It will be found farther on in the course that radiation from antennas, wave motion in transmission lines, wave guides, and cavity resonators, etc., all depend upon the properties of the electric field. Hence an elementary description of the electric field and its characteristics is in order here.

Single Charge.—In Fig. 23 is shown a negatively charged body, such as an electron. As stated

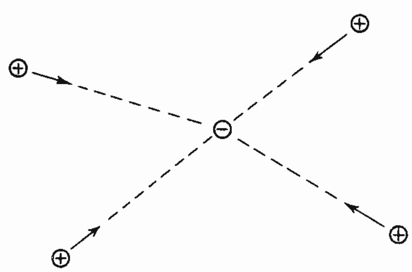


Fig. 23.--Force on a unit positive test charge in an electron field.

previously, it exerts a force of attraction on a positive charge anywhere in space. The force varies inversely as the square of the distance, as given by Coulomb's law, Eq. (1), so that the force of attraction becomes exceedingly small at any great distance from the electron. Nevertheless, theoretically, the force exists even at an infinite distance, and is directed *radially* inward toward the electron.

To represent this force effect of the electron (or any other charged particle), Michael Faraday, an eminent English scientist, assumed that there were *tubes* or *lines of force* existing in the space around the electron. In the case of a single charge isolated in space, these lines were directed radially from or to the charge. By convention (just as in the case of current flow), these lines of force were considered *converging* on a *negative charge*, such as the electron, and *diverging from a positive charge*, such as the proton. In short, the direction of the line of force is that in which a positive charge would move when exposed to the action of the given charge.

The magnitude of the force depends upon the magnitude of the given charge, and the distance from the charge of the point in space at which the force is measured. The fact that the force decreases as the square of the distance indicates that if a series of radial lines be drawn about the charge, the way in which they spread out through space will follow exactly this inverse square law. Hence the *number of lines*, passing through any region; i.e., their density, should indicate the magnitude of the force in that region.

This will be more evident from Fig. 24. Here a positive charge is assumed isolated in space. From it emanate a series of electric field lines in *all* directions *to infinity*, so that the charge looks like a gigantic pin cushion.

At a certain distance from the charge imagine a spherical surface enclosing the charge. On this surface consider a small area

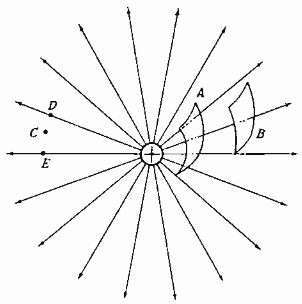


Fig. 24.--Electric field about a positive charge isolated in space.

of 1 sq. cm. as at A in Fig. 24. As shown, four lines pass through this unit area. The field intensity or strength is *four lines per sq. cm.* and measures the force of repulsion on a unit positive charge placed at A.

Now imagine a spherical surface of *twice* the radius, and consider an area of 1 sq. cm. on this surface (shown as B in Fig. 24). It is clear from the figure that the four lines passing through A will diverge sufficiently so that most of them will miss area B; indeed, from the geometry of the figure only one of the four lines will pass through B. The field intensity here will therefore be only 1 line per sq. cm. instead of 4 lines/sq. cm., or one-quarter as great. But by Coulomb's law, the force on a test charge twice as far away from a given charge is but one-quarter as strong, hence the lines per sq. cm. decrease in the same manner as the force measured decreases, and thus the lines in themselves serve as a measure of the force.

A unit charge of 1 statcoulomb is assumed to send one electric field line through every square centimeter of area on a sphere of 1 cm. radius surrounding the charge. This is indicated in Fig. 25. (Note that the sphere merely represents a certain volume of space.) Since a unit sphere (one

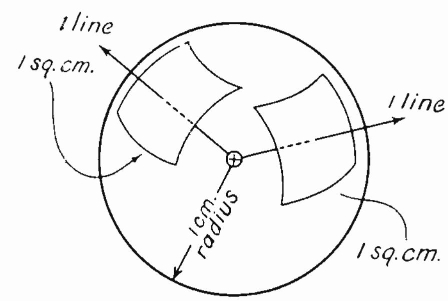


Fig. 25.--A unit charge sends out one line through each sq. cm. of a unit sphere surrounding it.

having 1 cm. radius) has an area of 4π sq. cm., there will be 4π lines total emanating from the charge.

At this point it is well to point out that electric field lines are merely an attempt to present a geometrical picture of the forces or strains existing in the space surrounding a charged body. Actually every part of the surrounding space has forces existing in it; the forces are not localized merely along the field lines shown. Thus, if a tiny charged body were placed at point C in Fig. 24, between the two field lines shown, a certain force would be experienced just the same as if the tiny charge were placed on the field lines at D or E. The concept of field intensity in terms of lines per sq. cm. is merely a convenient method of portraying or visualizing the field of force around one or more charged bodies.

Two or More Charges.—Now consider two oppositely charged bodies separated by a certain distance, as indicated in Fig. 26. What are the magnitude and direction of the

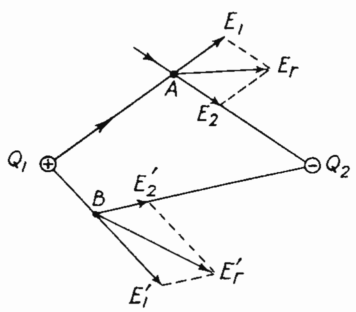


Fig. 26.—**Resultant field for two charged bodies.**

forces on a third, test charge, in the surrounding space? To answer this question, consider each charge by itself. As explained above, radial lines of force issue from it or converge to it (depending upon its polarity) in the manner illustrated in Figs. 24 and 25. For the left-hand positive charge Q_1 a series of lines of density depending upon the strength of the charge emanate from it like a pincushion. For the right-hand negative charge Q_2 a similar series of lines of density depending upon the strength of the charge converge on it in a similar manner. Each set is called an *elementary field.*

Each set of lines can be assumed to exist in space independently of the other set; the lines of one set can cross those of the other. The reason for this is that each set represents *forces*, and at any point in space there can exist as many forces as there are charges to produce these forces. However, *at any point in space* the several forces can be combined into a *resultant* force by the parallelogram or vector method of combination. When this is done, a series of *resultant field lines* will be obtained such that *no one line crosses the other,* for if two lines did cross, they could be combined into a single resultant line that does not cross itself.

The method of obtaining the resultant will be discussed in greater detail in an assignment following this very shortly. At this point a brief outline of the method will be given, with particular reference to Fig. 26. Consider a point A in space between the two charges. At A a force is produced by Q_1 along the direction Q_1A, and another force is produced by Q_2 along the direction AQ_2.

Each force has a certain magnitude, and also a certain direction, as mentioned above. A quantity, that has both magnitude and direction is known as a *vector,* and is represented by a line whose direction in space coincides with the vector, and whose length represents the magnitude of the vector. Thus the force (vector) owing to Q_1 is represented by AE_1. The length AE_1 represents the magnitude of the force, and becomes shorter as A is moved farther away from Q_1; the direction of AE_1 is—as shown—along Q_1A. In a similar fashion the force owing to Q_2 is represented by AE_2; note that it is directed toward Q_2, because Q_2 is negative, and a unit test charge would be attracted by it (and repelled by Q_1).

To find the resultant force, draw a line E_1E_r (shown dotted) that is parallel to AE_2, and another (dotted) line E_2E_r that is parallel to AE_1. The lines form a parallelogram in conjunction with AE_1 and AE_2; this is known as the *parallelogram of forces*. The diagonal AE_r of this parallelogram is the resultant of AE_1 and AE_2; i.e., it is the single force which, acting on a body placed at A, will produce the same motion as the two forces AE_1 and AE_2 acting simultaneously on the body. Thus, if a unit positive test charge were placed at A, it would not move along AE_1 nor AE_2, but along AE_r.

As a further example, consider point B in Fig. 26, close to Q_1. The force owing to Q_1 is now quite strong because B is close to Q_1. It is denoted by BE_1'. The force owing to Q_2 is relatively small because B is relatively far from Q_2. It is denoted by BE_2'. The resultant, E_r', is found in exactly the same way as E_r. Observe, however, that it is more nearly in line with E_1', and not very much greater than it. The significance of this is that near either charge the resultant field is practically coincident with the charge's elementary field; at points between the charges the resultant field is quite different from either charge's elementary field.

If the resultant field is vectorially determined at each point in space, it will have the configuration shown in Fig. 27. Observe that the lines join the two charges; that they do not cross one another; and that they appear to repel one another. This is the field that would be experimentally observed for the two charges, but it can be obtained by the vector

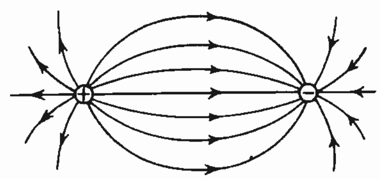


Fig. 27.—Resultant field between a positive and negative charge.

method of combination from the elementary fields. In Fig. 26 the force owing to either charge was represented by a single line whose length represented the magnitude of the force, such as AE_1. Previously it was stated that the force or field strength was represented by the *number* of lines passing through a unit area enclosing the point in question rather than by the length of a single line or vector.

Clerk Maxwell, the eminent English mathematician and physicist, has shown how to combine the latter concept of density of lines with the parallelogram method of vector combination to obtain the resultant electric field pattern. The method is a graphical one, and leads to the configuration shown in Fig. 27.

In passing, it is of interest to observe the resultant field configuration for two like charges. In Fig. 28 this is shown for two positive charges. Note once again that the field lines do not cross one another and seem to repel each other laterally (sideways). Faraday interpreted the effect as follows: The lines act as stretched rubber bands, and tend to pull together the positive and negative charges

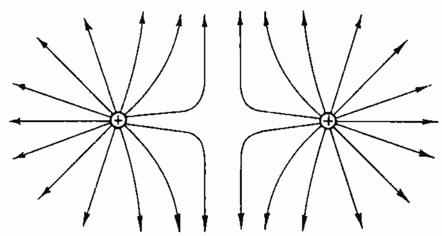


Fig. 28.--Resultant field for two positive charges.

they connect. This accounts for the force of attraction between unlike charges (see Fig. 27). The greater the magnitude of each charge, the more lines connect them, and the greater is the force of attraction.

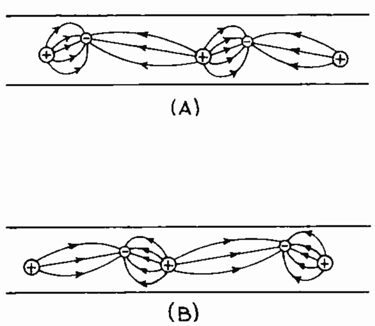


Fig. 29.--Resultant electric fields in a conductor.

For two like charges, Faraday explained the force of repulsion on the basis that the lines repel one another laterally, and by reaction force the two charges apart, (see Fig. 28). While this explains the forces actually observed, in many cases it is preferable to study the behavior of the elementary fields, because the analysis of current flow, radiation, etc., is greatly simplified thereby. This will be discussed in the next section.

Moving Charges.—It was shown that the motion of the free electrons through a conductor constitutes a current flow. Fundamentally, however, it is not the motion of the electrons as such that constitutes the electric current, but rather the movement of their associated electric fields. The actual, observed, or resultant field is a very complicated pattern that is continually varying with time. Consider a portion of the conductor at some instant of time. Within it are free electrons and positive ions (atoms that have lost free electrons and have therefore excess protons in their nuclei). In Fig. 29, two electrons and two positive ions are shown in a portion of a complete circuit. In (A) each electron is closer to the positive ion to its left; in (B), each is closer to the positive ion to its right, because it is assumed to be drifting from left to right under the impress of an electromotive force somewhere in the circuit.

Note how the configuration changes in shape from (A) to (B). If in addition to the drift, the random motions of the electrons and positive ions owing to thermal energy are taken into account, the actual resultant field configuration would become so hopelessly complicated as to defy analysis. Fortunately, it is not necessary to consider the resultant field; instead, *only the elementary fields of the moving electrons* need to be studied, and in addition, only the drift component of motion need be taken into account.

Hence, the conductor may be considered as composed of a line of electrons, all moving with a slow drift velocity in a closed path. Consider each individual electron. Its elementary field has the pincushion arrangement shown in Fig. 24, and as it moves, its pincushion of lines of force moves with it. It is the total effect of the motion of all these pincushions that represents the electric current flow.

It is possible, however, to simplify the picture even still further. The individual pincushions can be combined into a resultant field, that of the moving electrons alone. This resultant field will be in essence a *partial resultant;* the complete resultant would have to contain the stationary proton fields as well. However, since the latter are essentially stationary, they contribute nothing to the current flow and can therefore be omitted, so that the partial resultant stated above will be sufficient to account for all the effects produced by the current flow.

To effect such a partial resultant, consider a line of electrons as shown in Fig. 30. In (A) is shown the field configuration as it appears in the plane of the paper. Since like (negative) charges are involved, the field is essentially the same as that shown in Fig. 28.

However, where so many billions upon billions of electrons are involved, they may be regarded as being practically one next to the other,* in which case the

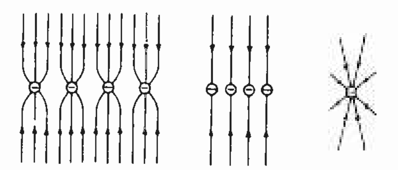


Fig. 30.--**Partial resultant electric field of a line of electrons.**

electric field lines form practically a series of straight parallel lines, as shown in (B). In perspective, they form a series of radial spokes, as portrayed in (C); i.e., the pincushions have been compressed into radial lines in planes *perpendicular* to the line of moving electrons.

These spokes, in moving broadside, produce the various effects of current flow, such as magnetic lines of force and radiation. These will be described in later assignments; what is intended to be presented here is the groundwork for such discussions. Thus, it has been shown that in spite of the fact that there are positive and negative charges in a conductor, only the fields of the moving

***Although actually there are electrons all through the conductor, it will be found that they behave as if they were concentrated along the axis of the conductor, at least as far as effects external to the conductor are concerned.**

charges need be considered, and in the case of an ordinary metallic conductor, these fields can be combined into a partial resultant field that is perpendicular to the direction of motion of the charges.

RESUMÉ

This concludes the assignment on electron physics and theory. It has been shown that the most important fundamental particles of nature are the electron and the proton, and that a close combination of these produces the neutron. An atom is in general a combination of protons and neutrons forming a nucleus, together with a group of electrons equal in number to that of the protons, and rotating in certain shells or orbits about the nucleus.

The chemical and ordinary electrical properties of the atoms are explained in terms of the orbital electrons, particularly those in the outermost shell. Electrons having but few electrons in the outer shell are electro-positive or metallic in nature, and exhibit the important property of electrical conductivity owing to the presence of free electrons in the crystal lattice structure.

Insulators are materials that do not have an appreciable number of free electrons, and hence do not exhibit electrical conductivity. They can, however, exhibit momentary current flows by the distortion of the electron orbits, and this explains the charging current that flows in the dielectric of a condenser.

Free electrons can be emitted from the surface of a metal by the action of heat, and this gives rise to thermionic emission. Electrons can also be dislodged from the material (even an insulator) by the action of radiant energy; this is known as photoelectric emission. Finally, electrons can be dislodged from the atoms of a gas; this is known as ionization.

As a concluding topic, electric fields are analyzed, and it is shown that the actual electric field observed between a system of charges can be explained in terms of the elementary fields associated with the individual charges.

ANSWERS TO EXERCISE PROBLEMS

1. 87.37×10^{-4} dynes repulsion.
2. 55.6×10^{-4} dynes repulsion.
3. 63.2 statcoulombs positive or negative.
4. (A) 20.7×10^{-6} ohms.

   (B) $.574 \times 10^{-6}$ ohms.
5. 34×10^{-6} ohms.
6. 1.172 cm. long.
7. 162 ohms.
8. 0.0725 ohms.
9. 0.1236 ohms.
10. 1.27×10^{7} cm./sec.

V-9174-33

ELECTRON PHYSICS AND ELECTRON THEORY

EXAMINATION

1. (A) The two most important elementary particles are the (electron, mesotron, neutron, proton, photon, positron, neutrino).

   (B) An electron will attract a (proton, neutron, electron).

   (C) A proton will repel a (neutron, proton, electron).

   (D) The proton has a mass that is 1847 times that of an electron.

   (E) The proton has a charge that is one times that of an electron.

2. (A) A group of five electrons is separated from a group of eight protons by 2×10^{-8} cm in free space.

   (a) The force is one of (attraction, repulsion).

   (b) The magnitude of the force is -227×10^{-4} dynes. (Show all work.)

Charge on 5 electrons $= -5 \times 4.77 \times 10^{-10} = -23.85 \times 10^{-10}$ st. coulomb.
Charge on 8 protons $= 8 \times 4.77 \times 10^{-10} = 38.16 \times 10^{-10}$ " "

$$F = \frac{Q_1 Q_2}{R^2} = \frac{-23.85 \times 38.16 \times 10^{-20}}{4 \times 10^{-16}} = -(23.85 \times 9.54)\,10^{-4} = -227 \times 10^{-4} \text{ dynes.}$$

   (B) The two groups are separated by a distance of 5×10^{-8} cm. What is the magnitude of force between them?

$$F = \frac{(-23.85 \times 38.16 \times 10^{-20}}{25 \times 10^{-16}} = -36.4 \times 10^{-4} \text{ dynes}$$

3. (A) A chemical reaction (alters, does not alter) the nuclei of the individual atoms.

   (B) The nucleus, in general, is composed of Protons & Neutrons.

   (C) How does the hydrogen nucleus differ from that of any other atom?

   Has no neutron, only a proton

4. (A) There are the following number of orbital electrons in an atom of:

   (a) Radium: 88 (b) Lithium 3.

   (c) Thallium: 81 (d) Iron 26.

   (B) The atomic number of carbon is 6.

   (a) How may orbital electrons does it have? Six

   (b) How many orbital shells does it have? Two

   (c) How many electrons are there in each shell? Two in inner shell Four in outer shell

   (d) It has a (positive, negative, dual) valence.

5. (A) Given two atoms: one has 92 protons and 146 neutrons; the other has 92 protons and 143 neutrons. Are these atoms isotopes or isobars. Isotopes

   (B) Can you identify these atoms? What are they?

   Uranium 235 & Uranium 238

6. Atoms of a gram of a certain material are split apart, and it is found that their mass is increased by 0.01 per cent. How much energy is absorbed by this increase in mass in the

ELECTRON PHYSICS AND ELECTRON THEORY

EXAMINATION, Page 3.

6. process of splitting them apart, for the entire gram of the material?

$W = MC^2$ $M = .01$ gram. $C = 3 \times 10^{10}$ $(.01\% = .0001)$

$W = \cancel{.01}(3 \times 10^{10})^2 = 9 \times 10^{18}$ ergs.

$.0001$ 9×10^{16}

(B) A gram of another material is split apart, and in the process 5×10^{20} ergs of energy are liberated. By how much is the mass decreased?

$M = \frac{W}{C^2} = \frac{5 \times 10^{20}}{(3 \times 10^{10})^2} = \frac{5}{9} = 0.556$ gram

7. (A) Conductors are substances that have (free electrons in their crystal lattice structure, the highest melting point, all their orbital shells saturated, high vapor pressures.

(B) Thermal noise is owing to (thermionic emission, mechanical vibration of the material, crystalline structure of the material, random motion of the free electrons).

8. (A) Electromotive force is the force produced by (a generator, the coulomb action, radioactivity) that causes the (electrons, protons, inoized atoms) to move in a metallic conductor, and is measured in (amperes, volts, coulombs, dynes, degrees Centigrade).

(B) The coulomb is the unit of (charge, rate of flow of charge, potential between two condenser plates, force of repulsion between two electrons).

(C) Electrical current is measured in (amperes per second, ampere-seconds, ergs, amperes, kilovolts, coulombs per second, microamperes, millivolts, milliamperes, microfarads, milliwatts, megohms). (Check *all* correct answers.)

9. The specific resistance of aluminum is 2.824 microhms (at 20°C.). An aluminum bus bar has a length of 20 meters, and a square cross section of 2 cm on a side. What is its resistance?

$R = \frac{R_s L}{A}$ $R_s = 2.824$ microhms $L = 2000$ cm $A = 4$ sq. cm.

$R = \frac{2.824 \times 2000}{4} = 1412$ microhms or 0.001412 ohms

10. (A) What *two* factors determine the suitability of a material for thermionic emission? 1. Low work function. 2. High melting point.

(B) Which of these factors is of no importance in the case of photoelectric emission? Melting point.

(C) A spark plug, when tested in the air, operates satisfactorily, but when installed in the cylinder of a gasoline engine, fails to ignite the mixture. The reason for the failure is:

(a) The work function of the electrodes is too high and does not permit the escape of electrons from their surfaces.

(b) The light shining on the electrodes produces photoelectric emission. In the dark cylinder this action is absent, and the spark cannot be produced.

(c) The mean free path of the gas mixture is less than that of free air because of the compression in the cylinder. This raises the breakdown voltage above that generated by the ignition system.