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The Cyclotron: A Nuclear Transformer[1]

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ALTHOUGH THE cyclotron is popularly known as an "atom smasher," it is in more scientific terms a "nuclear transformer," for it deals not as much with the atoms themselves as with the ten thousand times smaller *nuclei* of the atoms, and instead of smashing them completely it *transforms* them into new forms.

ATOMIC STRUCTURE

To appreciate the action involved in "atom smashing," or man-made transformations of nuclei, we need first to picture the atom as a whole and then to enlarge upon its tiny center, the nucleus. An atom may be conceived as being an infinitesimally small solar system, as shown schematically in Figure 1.[2] While the diameter of the solar system is about one hundred thousand million times greater than the height of a man, that of an atom is only about one one hundred thousand millionth as large as a man. Or roughly, man is mid-way in the scale of size between the solar system and an atom. The atom is so small that in one cubic centimeter of air, which we consider as being quite tenuous, there are about ten billion billion atoms, or as many as the number of red blood cells in one million people. Besides being very small the atom is mostly empty space. At its center is the nucleus, like the

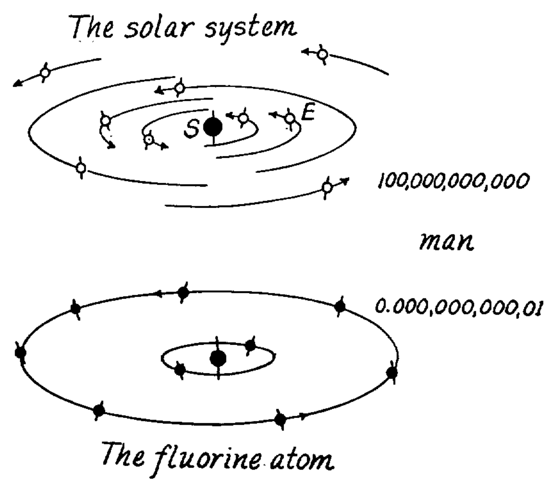

Fig. 1. A schematic diagram of a fluorine atom as compared with the solar system. The atom is as much smaller than a man's height as the solar system is larger. Though held together by different forces in a different structural arrangement, they are similar in that they both have a heavy concentrated central body about which revolve much lighter planetary bodies in a large expanse of empty space.

sun at the center of the solar system, which contains nearly all of the mass of the system. Around this nucleus revolve electrons in orbits, like planets in the solar system. As small as the atom is, the nucleus is still ten thousand times smaller in diameter, or about one million millionth of a centimeter in diameter. In order to

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[2] Figures 1, 2, 3, 5, 6, 10, and 12 are illustrations used in Professor Harvey E. White's book *Classical and Modern Physics* (Van Nostrand Co.). The author is grateful to Professor White for permission to use them.

visualize this, we may think of a nucleus as a steel ball one centimeter in diameter. On this scale the much lighter electrons could be considered as small balloons revolving in a sphere one hundred meters in diameter or in a volume that of a cubic city block.

While the solar system is held together by gravitational forces between masses, the atomic system is maintained by electrical forces between charges. Each electron has just one unit negative charge. No charge exists smaller than this amount, and larger charges are even multiples of this unit. Whereas the planets in the solar system are different, the electrons are all the same. Moreover, they are the same in all atoms. Nuclei, on the other hand, are charged positively and differ from element to element. They are found in nature containing anywhere from one to ninety-two plus charges. In a neutral atom the nucleus is surrounded by a nebulous swarm of electrons equal in number to the number of plus charges on the nucleus. Thus the charge on the nucleus of an atom determines the number of electrons that the neutral atom can possess. As a consequence, the nuclear charge also determines the chemical identity of the element, for the chemical nature of the element depends on the number and arrangement of its electrons, which are its means of contact and combination with other atoms. The charge on the nucleus is accordingly called the "atomic number," often symbolized by Z, for its value places the atom in a definite place in the atomic, or chemical, table.

NUCLEAR STRUCTURE

Nuclei are composed of small indivisible units. These nuclear building units are two heavy little particles, almost alike, except that one, the proton, has a positive charge and the other, the neutron, is electrically neutral. Each is about two thousand times heavier than the electron. How these may be conceived as being combined in some of the lighter nuclei is shown diagrammatically in Figure 2. The simplest nucleus is that of the ordinary hydrogen atom, a single proton. It is one of the indivisible units found more abundantly in heavier nuclei. In a neutral hydrogen atom a single electron attracted by the unit positive charge of the proton revolves about the proton at distances from it many thousands of times the diameter of the proton itself. The other elementary building unit, the neutron, is as heavy as the proton but has no charge. It does not exist as a free element in nature but is found only in nuclei heavier than hydrogen. It has the property of adding mass but no charge to the nucleus that contains it.

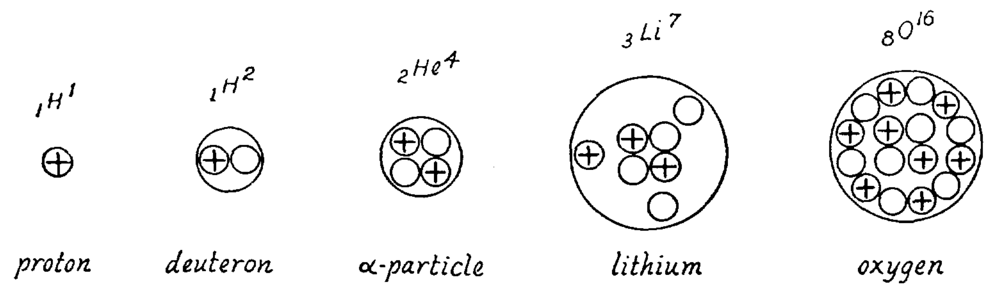


Fig. 2. A schematic representation, in two dimensions only, of the structure of some light atomic nuclei, showing protons and neutrons as the building units. Protons are marked with a plus because of their plus charge while the uncharged neutrons are left blank. As the number of protons in the nucleus increases, the nuclear charge, hence the atomic number, Z, increases. A neutron adds about as much to the mass, M, as does a proton, but adds no charge. There are additional natural forms of the nuclei of lithium and oxygen not shown, a lithium nucleus with only 3 neutrons, M = 6, and oxygen nuclei with 9 and 10 neutrons, M = 17 and M = 18, respectively. Nuclei having the same nuclear charge but different masses are called isotopes of each other.

Neutrons and protons are considered as

able to attract each other only when in close contact, somewhat as though they had sticky, glue-like surfaces. Composite nuclei are thus pictured as composed of neutrons and protons packed closely together. Instead of being arranged two-dimensionally as sketched in the figure, the particles are actually in three-dimensional clusters. Moreover, the components probably do not maintain fixed arrangements but mill around one another in a state of agitation, somewhat as in a ball mill.

A combination of just one proton and one neutron forms a heavy hydrogen (deuterium) nucleus, or a deuteron. This nucleus can attract only one orbital electron; hence, as an atom, it behaves chemically like hydrogen, though its nucleus is about twice as heavy as ordinary hydrogen ($Z = 1$, $M = 2$). Hydrogen and deuterium are isotopes (iso = same, tope = place). Isotopes have the same atomic number (nuclear charge) but different masses. Each is called an isotope of the particular element.

Two protons when combined need two neutrons associated with them in order to form a stable unit. Thus the nucleus of the second element in the periodic table, helium, contains two protons and two neutrons. This unit was first observed coming out of the naturally radioactive elements and is therefore often referred to as an alpha particle. Having two positive charges, it attracts two orbital electrons in forming a neutral helium atom. Three protons can be associated with either three or with four neutrons to form lithium nuclei of weights 6 or 7. (Only lithium 7 is pictured in the figure.) Either lithium nucleus will attract only 3 electrons in forming a neutral atom.

We now jump to a consideration of a more complex nucleus, one with eight protons (oxygen). Most of the oxygen nuclei contain only eight neutrons, making the well known oxygen of mass 16. There are, however, stable isotopes of oxygen that contain nine and ten neutrons, making oxygen of masses 17 and 18. These are not diagrammed in Figure 2 but could be illustrated by the addition of more blank circles in the nucleus. Since the chemical properties are determined by the interaction of orbital electrons with electrons of other atoms, their chemical properties will be identical. In chemical processes the isotopes act alike and can be separated only by physical means depending upon the differences in mass.

The heavier nuclei, up to the element 92, uranium, are built up in a similar manner to those shown. Some of the elements have only one stable isotope, whereas others have as many as ten. The number of neutrons in stable association with a given number of protons is nearly equal for the light elements, but becomes greater than the number of protons for heavy elements, as uranium of mass 238, having 146 neutrons and 92 protons. In designating a specific isotope of an element the total mass is written as a superscript on the upper right of the chemical symbol, as Li^6, Li^7, O^{16}, O^{17}, and O^{18}. Although the chemical symbol is sufficient to designate an element, it is often useful to write the atomic number as a subscript to the left of the symbol, as ${}_1H^2$, ${}_3Li^6$, ${}_8O^{16}$.

NATURAL RADIOACTIVITY

The nuclei past 83, or Bi, in the periodic table are all unstable. They have too much mass for the attractive forces holding them together. These are the naturally occurring radioactive elements. Early workers showed that the radioactivity is not affected by chemical or physical reactions of the atom and thus is a property of the nucleus. Until the discovery of radioactivity in 1895, it was thought that the building blocks of nature were the atoms, indivisible and non-destructible entities. The isolation of various natural radioactive elements showed that some elements develop from others. In fact, element 92 gives rise by a stepwise process to a sequence of elements from 92 to 82, as shown in Figure 3. Thus, the natural radioactive elements are naturally undergoing transmutation; that is, they are being transformed from one element to another. When Uranium I, $_{92}U^{238}$, ejects an alpha particle, $_2He^4$, its charge drops two units and its mass four units, thus periodic table. The mass does not change appreciably, however, as compared with the loss of a heavy particle, so the total mass is not written as changed. For ex-

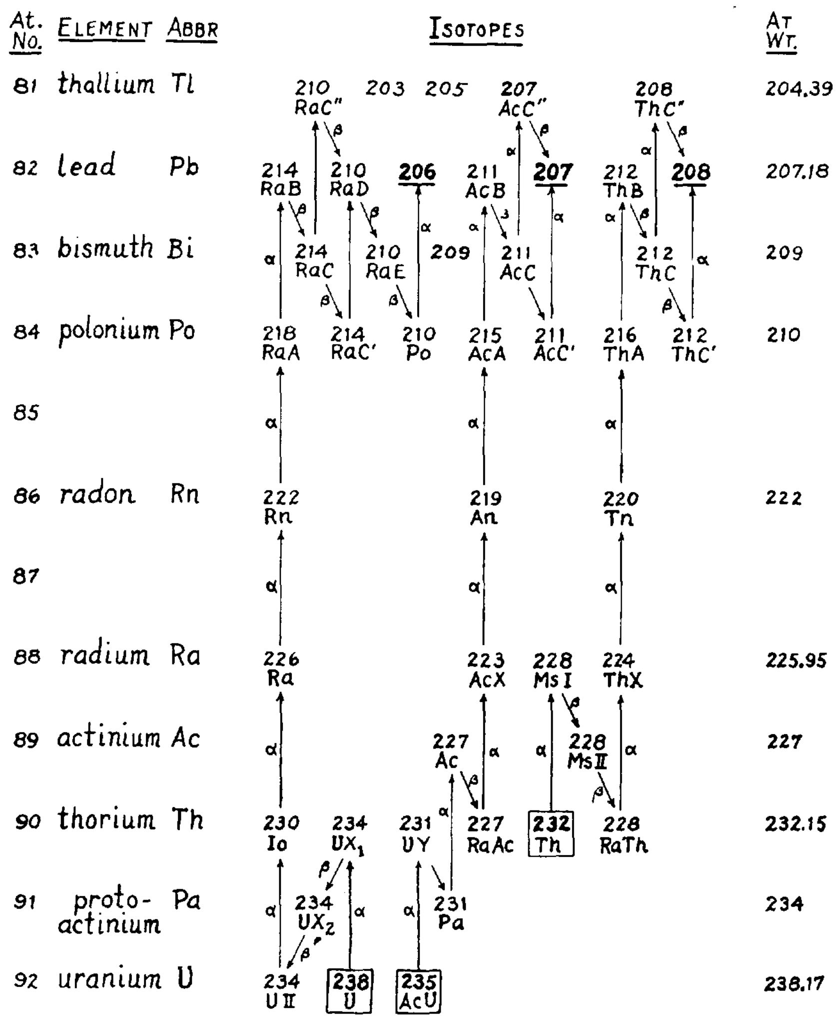


Fig. 3. A chart showing the sequences of disintegrations that take place spontaneously in the natural radio active elements. There are three separate sequences: the radium, actinium, and thorium series. The first two start from the two heaviest isotopes of uranium and end in stable isotopes of lead, 206 and 207, respectively, while the third series starts from a thorium isotope and ends in lead 208. The elements are listed with those of greatest charge at the bottom. When an alpha particle is emitted, the nucleus, by losing two positive charges, moves up two places to an element two smaller in atomic number and simultaneously lessens its mass by four units. When a beta particle is emitted, the nucleus, by losing a negative charge, moves down a position, as though it had gained a plus charge, but does not change its mass.

becoming $_{90}UX_1^{234}$. If a beta particle is emitted from a nucleus, the loss of the negative charge amounts to the gaining of a positive charge and the element formed is the one of next greater charge in the ample, $_{82}RaB^{214}$, emits a beta particle ($_{-1}e^0$) to become $_{83}RaC^{214}$.

By a sequence of alpha and beta particle emissions, it can be seen that the uranium series finally ends in the stable element lead, $_{82}Pb^{206}$. It will be noted, however, that during the sequence there are two unstable forms of element 82, mass 214 or radium B and mass 210 or radium D. (The elements called radium A to radium G are not isotopes of radium but are derivatives from radium.) This was the first case noted of a stable element having unstable isotopes. In fact, the first use of a radioactive isotope for tracing the behavior of a stable isotope was the use of radium D by Hevesy as a tracer for the behavior of lead.

It is also interesting to note that the gamma rays, for which radium is useful, are not emitted from the element radium itself but from some of its subsequent products, elements 84 and 81. Radium C, a strong gamma ray emitter, is a radioactive isotope of the stable element 81 or thallium.

TRANSMUTATIONS

Not only did the discovery of radioactivity demonstrate the phenomenon of transmutation and give some evidence of the structure of nuclei, but it also furnished experimenters with a highly energetic particle, the alpha particle, which was found to have the property of penetrating into nuclei and producing transmutations artificially. Figure 4 illustrates the first artificially produced transmutation, discovered incidentally by Rutherford in 1919. The transversal of alpha particles through nitrogen gas was being studied. It was observed that particles were detected at a much longer range from the alpha particle source than the alpha particles could possibly reach. Investigation proved that these long range particles were protons ejected with great energy as a result of the collision of an alpha particle with the nucleus of nitrogen. As shown, the final result is the stable oxygen 17 nucleus. Thus nitrogen was transmuted to oxygen. Also, experimental evidence was thereby afforded that protons are a constituent of nuclei.

It was first conceived that nuclei, be-

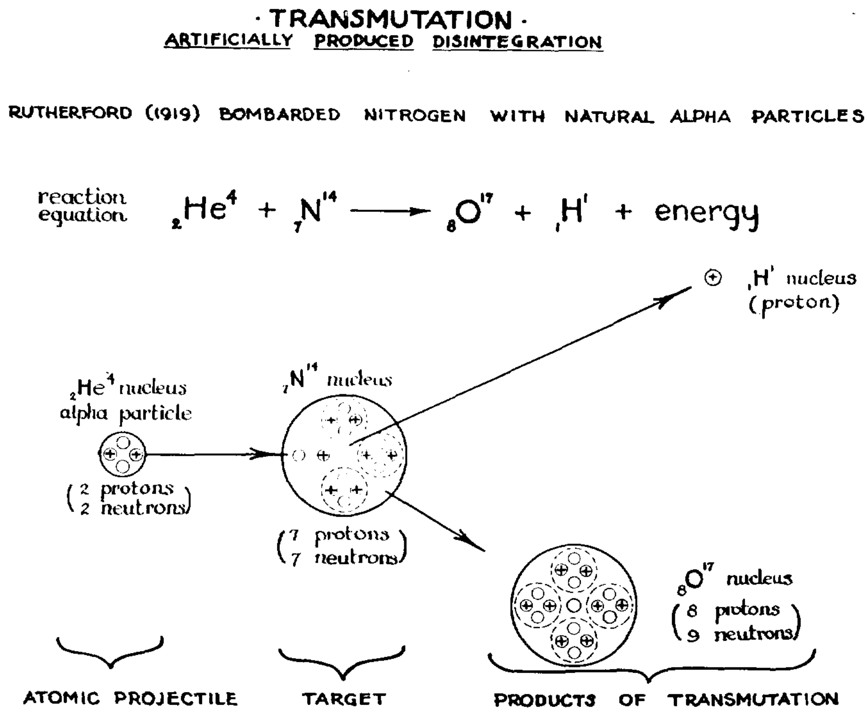


Fig. 4. A schematic presentation of the first transmutation to be demonstrated by man. Energetic natural alpha particles were the atomic bullets that penetrated into nitrogen nuclei and transformed them into oxygen nuclei.

sides containing protons, must also contain electrons in order to have counterbalancing electrical forces to hold the protons together. On this conception oxygen 18 would contain eighteen protons and ten electrons (a mass of 18 and a total charge of 8). Since the discovery, however, that neutrons are also ejected from nuclei, which will be discussed later, and from theoretical considerations, it is now believed that nuclei are composed only of neutrons and protons.

Instead of electrical forces between positive and negative particles to hold the nucleus together, the physicist now evokes short range forces which act only when the particles are in contact; that is, cohesive forces such as would exist if there were glue on the surfaces of the particles. An easily visualized way of representing the forces that hold particles in a nucleus is to illustrate the potential energy they have. According to this scheme, the particles may be pictured as being in a deep cup, or well, so that normally they cannot get out (see Fig. 5). The ground level is the potential of the outside world (ground potential) and the particles in the well are at a lower level (lower potential). It would take considerable work or energy to get a particle out of the well. The particles are not motionless but are stirring about somewhat like molecules in thermal agitation in a drop of liquid. In the case of a stable isotope the nuclear well is deep enough and the agitation of the particles in it not great enough to result in the throwing out of a particle during the random motions occurring in the well. In an unstable isotope the particles are moving about with more energy of agitation and occasionally a particle (or particles) is ejected as the result of an extra-energetic random impulse.

To cause a change in a stable nucleus one has to introduce into it some additional particle or particles to upset its normal balance. If the particle to be introduced is charged, such as a proton, it is repelled by all the positive charges inside the nucleus, and the effect on the entering proton is that of having to climb a barrier around the nucleus. This repellent barrier is pictured as a potential hill by the dotted lines. It is a result of the inverse square law electrical force which acts between the protons in the nucleus and the entering proton, and the more charges there are in the nucleus, the higher is the barrier. An uncharged particle, such as a neutron, would not be acted upon by electrical forces and could come into the nucleus at ground potential; that is, a neutron does not need any energy to enter a nucleus. The nucleus may be imagined as a hole on

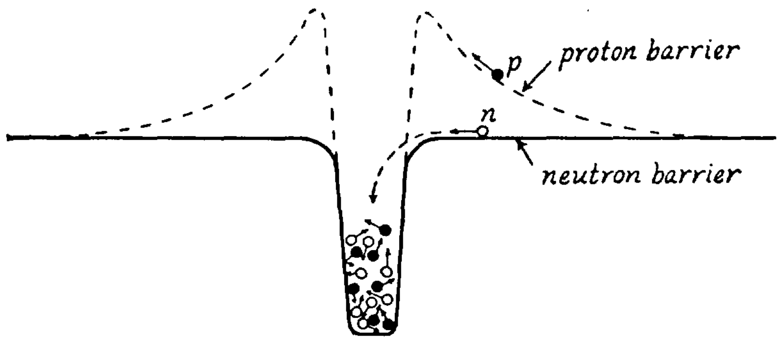


Fig. 5. A diagram used to illustrate by analogy the forces and potentials considered to exist in and around a nucleus. The nucleus is pictured as a deep cup or "potential well" in which the protons and neutrons move about at a lower level of energy (potential) than that of the outside world, *i.e.*, it would take energy to get them out. When a proton tries to enter the nucleus, it is repelled by the protons already in the nucleus with the same result as though it had to climb a volcano-like hill, a "potential barrier," around the nucleus. A neutron, however, is not repelled and may enter the nucleus without climbing any potential hill or barrier.

a golf green. To a neutron ball approaching the hole the surrounding ground is level, but to a proton ball the cup is surrounded by a volcano-like hill. To knock the proton up the slope into the hole it must be given a hard putt. The heavier the nucleus which the hole represents the higher the surrounding hill will be and the harder the ball will have to be hit to climb up into the hole. As will be noted later, early disintegration experiments were tried only on the lightest elements because of the difficulty of getting particles with an energy high enough to climb the potential barrier of heavier nuclei. Although neutrons can enter nuclei with ease, they are not available as particles for shooting at, or bombarding, nuclei until they are first produced in other nuclear reactions.

When an alpha particle approaches a nucleus, it has two positive charges that are repelled by the nuclear charge. It thus has to climb a potential barrier twice as high as a proton does before it can enter the nucleus. Consequently, singly charged particles are more feasible to use for nuclear bombardments than are alpha particles. Although energetic alpha particles from natural radioactive elements were thus available for early nuclear bombardments, physicists sought for very energetic singly charged particles.

It was around 1930 when means of accelerating hydrogen nuclei were developed. One of the first processes studied with accelerated protons was the bombardment of lithium. As shown in Figure 6, the bombarding proton may be considered as entering the lithium nucleus and coalescing momentarily to form a compound, or intermediate, nucleus containing four protons and four neutrons. This intermediate nucleus is very unstable and almost immediately breaks up into two very stable components, two helium nuclei. As will be explained later, energy is liberated in this process so that the helium nuclei are each given about 8 1/2 million electron-volts of energy. The disintegration is verified by the observation of the energetic alpha particles.

Since the discovery of heavy hydrogen in 1934, it has been possible to use the nucleus of deuterium, or the deuteron, as

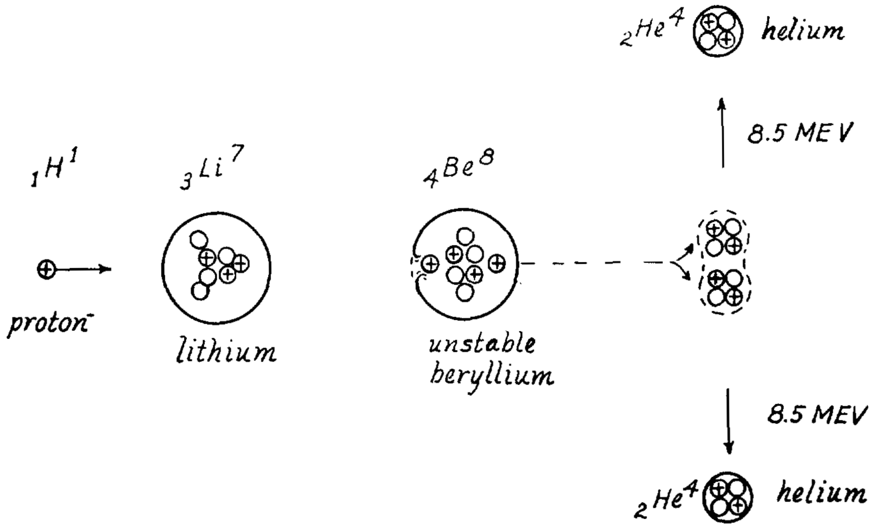


Fig. 6. A diagrammatic representation of the first nuclear transformation to be produced by particles accelerated to high energy in a laboratory. A high-speed proton shoots into a lithium nucleus of mass 7. The resultant nucleus of charge 4 and mass 8 is highly over-energetic and breaks apart into two high-speed alpha particles. More energy is released in each transformation than is supplied to the entering proton. So many shots (protons) miss their targets (nuclei), however, that the total energy expended per transformation is less than the amount returned.

a bombarding particle. Inasmuch as the deuteron is a singly charged particle, it suffers no more repulsion by the nucleus than does a proton. However, because either the proton or the neutron of the deuterium nucleus may enter the bombarded nucleus, bombardment with deuterons is more fruitful. Deuterons have now been accelerated by means of a cyclotron to energies as high as sixteen million electron-volts and at these energies produce transmutations in copious amount and of many kinds.

The transformation may be written as a reaction equation with the reagents on the left side and the products on the right, *i.e.*, ${}_1H^2 + {}_{15}P^{31} = {}_{15}P^{32} + {}_1H^1$. Since charge is not destroyed and no protons or neutrons (total large mass units) are destroyed, both sides of the equation should have the same total numbers of electrical charges and total numbers of neutrons plus protons, *i.e.*, the sum of the subscripts on one side equals that for the other side, and likewise for the superscripts. This is the means of balancing the

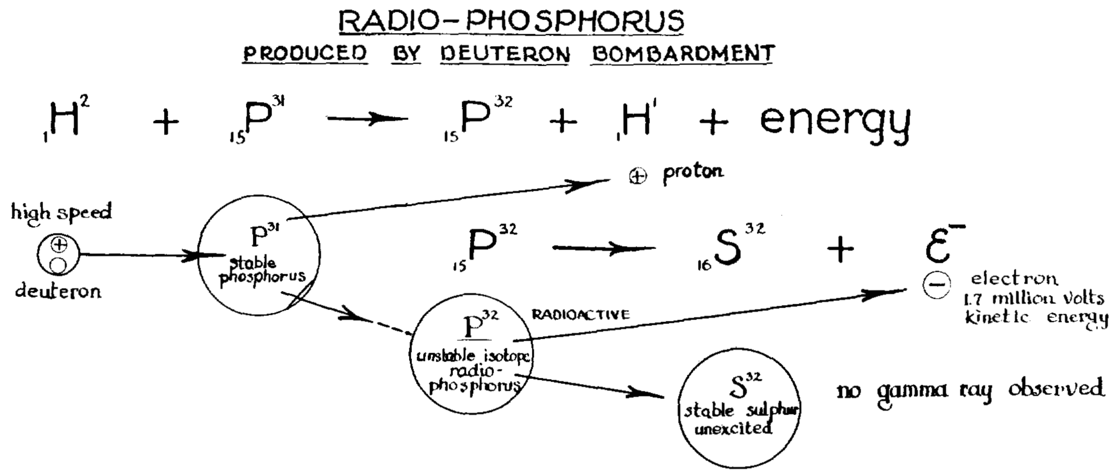


Fig. 7. Production of radiophosphorus by deuteron bombardment of phosphorus. Only the neutron from the deuteron gets into the nucleus and stays, changing the nucleus from mass 31 to mass 32. The mass 32 phosphorus is not stable and subsequently gets rid of energy and its imbalance of mass to charge content by emitting a negative electron. Half of a given number of phosphorus 32 nuclei will have thus broken up or "decayed" in 14.2 days. The nucleus left after the beta particle is emitted is sulphur 32, a stable nucleus, in a normal energy state so that no gamma ray results.

equation. If one is interested in the energies required or released, an energy balance must also be made. The reaction above has excess energy on the products side (exothermic). The subsequent decay of the radiophosphorus is written ${}_{15}P^{32} = {}_{16}S^{32} + {}_{-1}e^0$.

It is the emission of the beta rays that makes it possible to detect the presence of this new form of phosphorus. The beta rays have energies up to as high as 1.8 Mev (million electron-volts), while the average energy is roughly 0.6 Mev. Although the nucleus is one heavier than ordinary phosphorus, the chemical behavior is the same as that of ordinary phosphorus because both have the same

INDUCED RADIOACTIVITY

The use of the deuteron as a bombarding particle is illustrated in Figure 7, which depicts the formation of radioactive P^{32}. All the phosphorus in nature is of the stable form, having fifteen protons and sixteen neutrons, ${}_{15}P^{31}$. When a high-speed deuteron encounters the phosphorus nucleus, the proton may be repelled, while only the neutron may enter and stay in the bombarded nucleus. The result is that the charge is not changed but the mass is increased by one. Consequently, the element still remains phosphorus but becomes the isotope ${}_{15}P^{32}$. This isotope is not stable and will eventually give out an electron and change to ${}_{16}S^{32}$ which is stable.

system of fifteen orbital electrons with which they encounter other atoms. Consequently, P^{32} can be used to trace the action of ordinary P^{31} in any system by following the radioactivity of a small added amount of "tracer" phosphorus, P^{32}, through that system. This artificially produced radioelement has several physical properties that make it advantageous for biological and therapeutic uses: (1) since its half life, that is, the time during which a group of these atoms will decay to half their number, is 14.2 days, in a few months an administered dose of radiophosphorus will decay to an imperceptible amount; consequently, there is not the danger of overdose by prolonged exposure as with elements having very long half lives; (2) since there are no gamma rays emitted during the disintegration process, the phosphorus affects only the local regions in which it is deposited; (3) it is used by any system in the same manner as is the ordinary phosphorus.

Many other biologically useful radioelements are produced in the same manner by deuteron bombardment. In each case the deuteron is shot at the nucleus only for the purpose of adding its neutron to the bombarded nucleus. Thus Na^{23} is made into radioactive sodium, Na^{24}, and Fe^{55} into Fe^{56}, etc. In the induced isotopes that are heavier than normal there is a greater proportion of mass to charge than for stability. They decay by emitting a negative charge, beta ray, thus increasing the positive charge of the nucleus without changing the mass and coming to a stable ratio of charge to mass, that is, of protons to neutrons plus protons.

The result of bombarding with a deuteron also may be the capture of a proton instead of a neutron. In this case the neutron is emitted and the resulting transmutation forms an element with one more charge and mass than that bombarded. For example, the process most generally used for the production of neutrons is that illustrated in Figure 8, in which beryllium is bombarded by deuterons. It is conceived that for a very short time there is a coalescence of all the particles into a compound nucleus, ${}_5B^{11}$, which is highly unstable and ejects a neutron with a great amount of kinetic energy. The particles of the residual nucleus ${}_5B^{10}$ which are left in a state of agitation return immediately to normal merely by emitting a gamma ray. Thus in this process a radioactive residual nucleus does not result. In many cases of proton capture, however, the residual nucleus is radioactive, so that one gets both the emission of a neutron and the production of a radioactive element by the deuteron bombardment. A commonly used case is the deuteron bombardment of tellurium to form radioactive iodine. In the case of neutron capture, the radio-isotope is that of the bombarded element, while in proton capture, the radio-isotope is that of the next element up the atomic table.

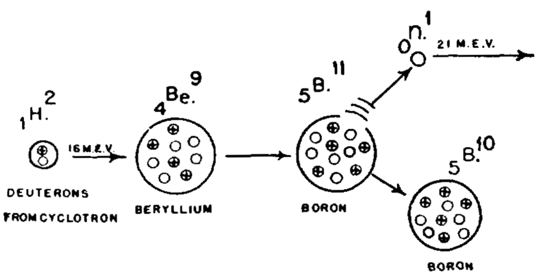
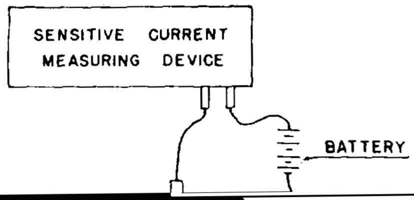


Fig. 8. Diagram of the nuclear process for producing the largest yield of high-energy neutrons, bombardment of beryllium by energetic deuterons. It is conceived that there is a momentary coalescence of the deuteron and the beryllium nucleus into a compound nucleus, boron 11, which is extremely unstable and which immediately breaks up by emitting a neutron. The neutron may have an energy up to 4.8 Mev greater than that of the bombarding deuteron, but generally has less, the difference being emitted as gamma radiation. Since it is the proton which stays in the nucleus in this case, the final nucleus has one unit charge as well as one unit mass greater than beryllium 9, *i.e.*, boron 10. No radioactive nucleus is formed in this case, for the excess energy of the nuclei formed is disposed of immediately. This is the bombardment used to produce fast neutrons for therapy.

By referring to Figure 5, showing the potential barrier around a nucleus, one can see that there is a force which tends to split the deuteron apart as it approaches the nucleus. The proton is repelled and must climb the potential barrier, while the neutron is unrepelled. It takes 2.2 million electron-volts of energy to separate the



DETECTION OF RADIATIONS AND RADIOELEMENTS

The induced radioelements may emit beta particles (high-speed electrons) alone, gamma rays alone, or both simultaneously. Radiophosphorus and radiostrontium give apart, in order that they can be collected and measured as a current. As shown in the diagram, it is an enclosed case in which there is an insulated central rod so that a difference of potential may be applied between the rod and the case; thus ions of one sign will travel to the rod and those of the other sign to the case. One end of the case has a thin window (generally very thin aluminum is used) through which the beta particles from the radioactive sample may enter. The current is generally small but can be measured in a variety of ways, either by an electrometer or an electrometer vacuum tube device.

The gamma rays, since they do not have an electrical charge, do not ionize directly as they pass through the chamber. They are detected by the secondary electrons which they eject from the material in which they are absorbed. Some of the gamma rays are absorbed in the enclosed gas or in the inside wall of the case and knock the electrons into the ion-collecting region. These secondary electrons then, like beta rays, produce ion pairs and register in the measuring instrument. A sample that emits gamma rays may be detected at a distance from the ionization chamber because the gamma rays, like light, can go a long distance before being absorbed. Also, it is not always necessary to have a thin window in the chamber in order for gamma rays to enter the chamber and eject electrons from the inside wall. On the other hand, beta rays, since they are continually losing energy by forming ions as they pass along through material, go only a certain distance, called their range, before they lose all their energy. Thus, beta ray activity can be detected only in the immediate neighborhood of the sample. Because beta rays have a definite limited range, substances which emit only beta rays are of most use in radiation therapy. The areas treated will be those in the immediate region in which the radioelement is deposited. In the case of gamma ray-emitting substances the effect will not be so localized.

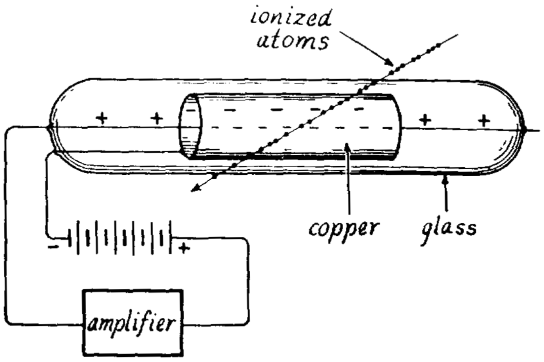


Fig. 10. An illustration of the essentials of a Geiger counter, a very sensitive detector of radiation. The counter tube consists of a sealed glass tube, containing a suitable gas at low pressure, in which are mounted coaxially a fine wire at high positive potential and a surrounding copper cylinder connected to the negative side of the potential supply. Any ions formed near the wire are in such a high electric field that they are given enough energy to produce other ions; these in turn gain energy in the field and produce more ions, finally building up to an avalanche of ions that registers as a pulse in the amplifier. In a counter tube a single charged particle, by producing ions in the sensitive region, can be detected, whereas in the ionization chamber method a number of particles need to produce ionization before a measurement is possible. The diagram illustrates a cosmic ray particle capable of penetrating through the counter tube, but tubes can be made with thin walls and mesh cylinders suitable for measuring very soft radiation.

Another commonly used means of detecting beta and gamma rays is the Geiger counter, whose features are shown in Figure 10. A fine wire surrounded by a metal cylinder is sealed in a glass tube. The tube is filled with a suitable gas at a pressure of 5 to 10 cm. of mercury. A positive potential of the order of about 1,000 volts is applied to the fine central wire and the surrounding cylinder made negative. If the walls of the tube and cylinder are thin enough, or a thin window is installed, it is possible for beta particles to produce ion pairs inside the space between the wire and the cylinder. These ion pairs are formed in such a strong electrical field that they are given considerable acceleration and are able to produce other ion pairs. These in turn are accelerated and produce further ion pairs, resulting in a multiplication of ionization (an avalanche) that momentarily causes a sudden surge of charge to flow along the electrical circuit. These surges are then amplified electrically and counted on a registering instrument. A Geiger counter thus counts particles

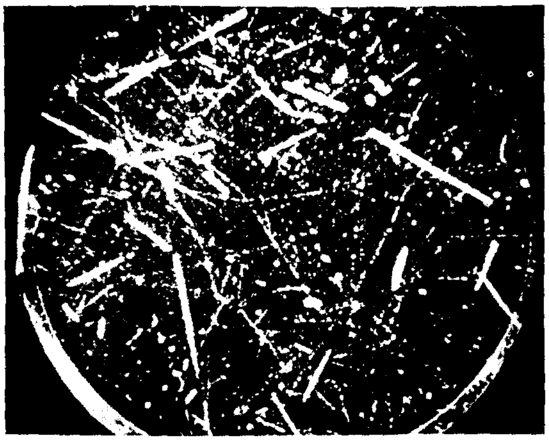


Fig. 11. A photograph of the ionization produced in a cloud chamber on which both neutron and gamma radiation were falling. The photograph was taken looking down axially through the glass top of the cloud chamber cylinder toward the black-topped piston below. When the piston expanded, the supersaturated vapor in the cylinder condensed on the ions formed by the passage of charged particles through the vapor and made the paths visible under bright illumination as tracks of white fog droplets. The heavy thick swaths are the result of recoil nuclei hit by fast neutrons. The thin, irregular, sparsely ionized tracks are those of secondary electrons produced by gamma rays.

that shoot through the sensitive region of the detecting tube. In the case of gamma rays, the walls of the counter do not need to be thin, because gamma rays can penetrate the walls and eject secondary electrons into the sensitive region of the counter.

Another means of detecting the ionization produced by radiation is by the use of a cloud chamber. This chamber is a cylinder with a transparent top at one end and a movable piston at the other. The region in between is filled with a gas and nearly saturated with water or alcohol vapor. When the piston is pulled down suddenly so that the gas is expanded, a fine fog is formed throughout the region by the consequent cooling of the vapor. If there are ions present in the chamber, the fog condenses on them to form droplets. Thus if a beta particle has gone through the chamber, a series of fog droplets will appear all along the path of the particle where ion pairs have been formed, and by brilliant illumination from the side the droplets can be seen clearly against a dark background. In Figure 11 one sees the appearance of a cloud chamber on which gamma rays and neutron rays were falling. The gamma rays ejected secondary electrons from the walls of the chamber. The electron paths are the irregular dotted, tenuous tracks along which there are individual droplets of fog. Unlike gamma rays, the neutron rays, or fast neutrons, do not enter into collisions with the very light electrons in matter but only with the more massive nuclei, for only the latter are heavy enough to take energy away from neutrons when they are hit. Neutron rays, consequently, produce their ionization in a secondary manner as the result of their collision with nuclei. If the nucleus that the neutron hits is hydrogen, it will, on the average, suffer a loss of half its energy, something like the random collision of two billiard balls of equal mass. The heavier nuclei will also recoil from neutron collisions, but the heavier they are the smaller the amount of energy with which they will recoil. In any case, a recoiled nucleus is a heavy, slow moving charged particle which will behave in producing ionization much like an alpha particle. In a cloud chamber these recoiled nuclei appear as short, thick tracks of about one hundred times greater density of ionization than that along the tracks of beta particles. In Figure 11 the thick straight tracks are those of nuclei hit by neutrons. Cloud chambers are particularly useful in detecting the types of ionizing particles and in determining their range or energy. Neutrons may also be detected by the secondary ionization they produce in especially designed or sensitized ionization chambers or by the induced radioactivity they are capable of producing in many elements.

ACCELERATION OF BOMBARDING PARTICLES

As stated previously in regard to Figure 5, the nucleus is surrounded by a repellent potential barrier. When physicists first began to consider the possibility of transmuting elements by bombarding them with laboratory-accelerated particles, it was evident from transmutation experiments with the natural bombarding particles that the bombarding particles would have to have very high energies. Some of the first experimenters thought to harness lightning, or the high potentials existing on storm clouds. They strung cables between mountain peaks to pick up charges at high voltage during storms, but they were unable to control the erratic and too powerful discharges; moreover, it was extremely dangerous and there was loss of life. A method much more controllable for utilizing the potential acquired by the accumulation of charge on an insulated body, similar to the accumulation of charge by a cloud, is the method developed by Van der Graaf, in which a large sphere is insulated from the earth and is fed with a continuous stream of charge along an insulated belt. This scheme has been used successfully to accelerate particles, using up to above four million volts. When the charged sphere attains more than four million volts, it is difficult to prevent lightning-like discharges from shooting to the surrounding walls or to the earth, down the charging belts or insulating supports. Another method tried very early in the search for means of producing high voltages was the cascade arrangement, in which a series of transformers, each capable of stepping the voltage up to around two hundred thousand volts, were mounted in cascade and insulated so that the voltages could be added in a succession of steps.

Cockroft and Walton, in England, when they had attained only about five hundred thousand volts by a cascade scheme, undertook nuclear bombardments (1932). They accelerated protons and used them to bombard elements with small nuclear charge, lithium and boron. The result in the case of lithium was as shown in Figure 6. The surprising thing was that the proton was able to penetrate into the lithium nucleus with such a low bombarding energy, for the repellent force of the three charges in the lithium nucleus is enough to require a proton with around two million volts energy to climb completely up the repelling barrier. Although physicists in their estimates had expected that they would need much higher energies to produce transmutations, once the transmutations were found to occur for these lower bombarding energies, suitable explanations were found. According to the theories of modern physics, the proton does not always have to climb completely up the potential barrier of the bombarded nucleus, but has a probability of sneaking into the nucleus directly through lesser heights of the barrier. This arises from laws governing bodies as small as nuclei and electrons with which we have nothing comparable in the world of large, macroscopic bodies. Higher bombarding energies are desirable, nevertheless, because the chance of getting into a nucleus becomes greater the farther up the potential barrier the bombarding particle climbs. Even when the bombarding particles have enough energy to climb completely over the barrier, an increase in their energy generally results in a greater yield of transmutations because the particles penetrate further into the target material and encounter more nuclei.

THE CYCLOTRON

While others were seeking methods of attaining very high voltages, Professor E. O. Lawrence conceived the idea of speeding a particle up to very high energies by giving it successive accelerations. On this scheme, instead of trying to attain a potential at some point in an apparatus great enough to give a particle all of its energy in one push, a much lower voltage would be used to give the particle a series of pushes. This idea led to the invention of the cyclotron, the principle of which is shown in Figure 12. The essentials are a large electromagnet with circular poles, a vacuum chamber, and two electrodes that alternate in potential. The vacuum chamber is placed between the poles of the electromagnet and inside of it are placed two hollow semicircular electrodes labelled D_1 and D_2. These electrodes are referred to as Dees because they have the shape of a capital D. The particles to be accelerated are introduced at the center of the circular system between the two Dees. These particles are generally protons or deuterons formed by removing the electrons from hydrogen or deuterium atoms. This is accomplished by electron bombardment of the hydrogen or deuterium gas in an ion source at the center of the moving in a magnetic field is brought about by the same principle that causes a wire carrying a current to revolve in a magnetic field, the principle used in an electric motor. After the particle describes a half circle it emerges from D_2 and is again in the accelerating gap. If the two Dees are still positive and negative in the

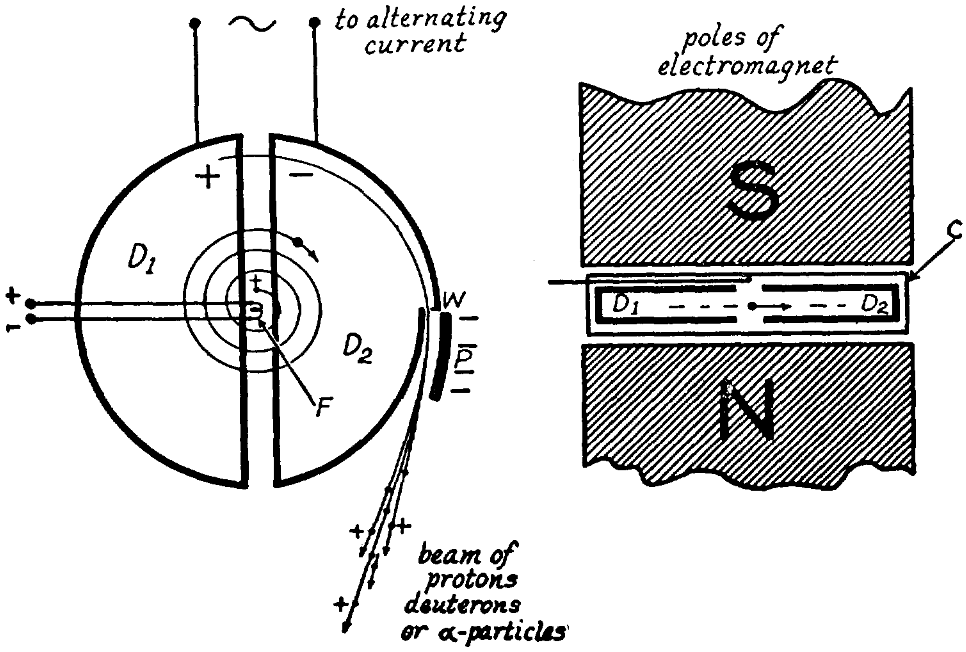


Fig. 12. A diagram to illustrate the principle used in the cyclotron of adding together a series of accelerations to produce an ion with a final very high energy. On the right is a vertical cross-section through the magnet poles showing the vacuum chamber, C, between the poles. The ions are accelerated by the voltage difference across a gap between two insulated, hollow, semicircular electrodes, D_1 and D_2. On the left is a horizontal section illustrating the path taken by a positive ion as the result of repeated accelerations across the gap between D_1 and D_2. The ions to be accelerated, nuclei of only the lightest elements, are produced by an ion source at the center at F. The voltage must be alternated so that, when the ion crosses the gap between the Dees, going from left to right, D_1 is positive and D_2 negative; when it goes from right to left at the other side of the semicircular path imposed by the constantly applied magnetic field, D_1 is negative and D_2 positive.

vacuum chamber. Alpha particles or helium nuclei may also be introduced, in which case helium gas is used in the ion source. A positive ion introduced between the Dees is pushed by the positive D and pulled by the negative one, thus being accelerated across the gap between the Dees (from D_1 to D_2). Once it is shot into the hollow D_2, the electrical force no longer acts on the particle but the magnetic field which is constantly applied makes the particle move in a circular path. This circular motion of a charged particle same direction as previously, the particle will be slowed down and stopped. By reversing the signs of potentials on the Dees (D_1 now minus and D_2 plus), however, the particle will again be accelerated, this time being pushed by D_2 and pulled by D_1. Once inside D_1 the particle, again traveling under the influence of the magnetic field alone, goes around another semicircle and comes out into the accelerating gap where, if the Dees are again alternated in sign, the particle will be given another acceleration. This process continues to be

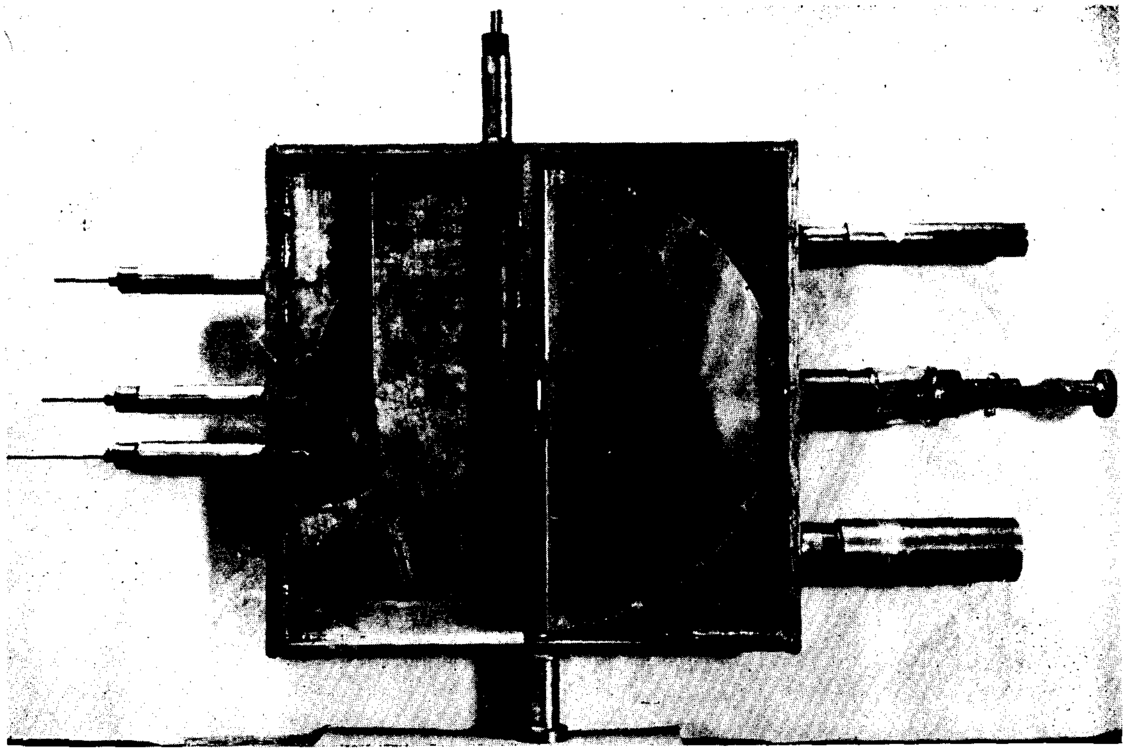


Fig. 13. One of the early models of the cyclotron vacuum chamber with the lid removed so as to show the accelerating mechanism. Only the one Dee on the right was used, the accelerating gap being between it and a grounded bar across the center. The deflector and target chamber are on the left. This simple 11-inch diameter model was the first to produce a useful proton beam, finally attaining protons with 1.25 Mev of energy.

repeated. All that is necessary is that the magnetic field be kept on constantly so that the particle will revolve properly and that each time the particle emerges from a Dee, the electrical field be in the proper direction to give the particle an acceleration. The particle will spiral outward because, as it gains speed, it has more centrifugal force. The length of path taken between successive transversals of an accelerating gap increases as the particle moves outward. It can be shown, however, that the speed of the particle increases at such a rate that the time of travel between accelerations will be constant; that is, it takes the same time to go around a small semicircle slowly as to go around a large semicircle fast. This allows one to make the plus and minus alternations applied to the Dees have a constant frequency. A constant stream of particles may thus be kept in the process of acceleration from the center out, because those near the center are being accelerated synchronously with those farther out.

In a practical case the frequency of oscillation of the Dees is about ten million cycles per second. The voltage difference between the Dees depends on the cyclotron and its operating conditions, but is of the order of one hundred thousand volts, *i.e.*, oscillations of the order of from plus to minus fifty thousand volts on each Dee. There is little difficulty experienced in controlling voltages of these values inside a good vacuum such as is maintained in the chamber. Another reason for obtaining a high vacuum in the accelerating chamber is to avoid having air molecules present with which the accelerated particles could collide and lose energy. With the degree of vacuum achieved (the order of a hundred millionth of an atmosphere) a particle being accelerated rarely encounters an air molecule. Suppose that a particle receives a full one hundred thousand volt push in

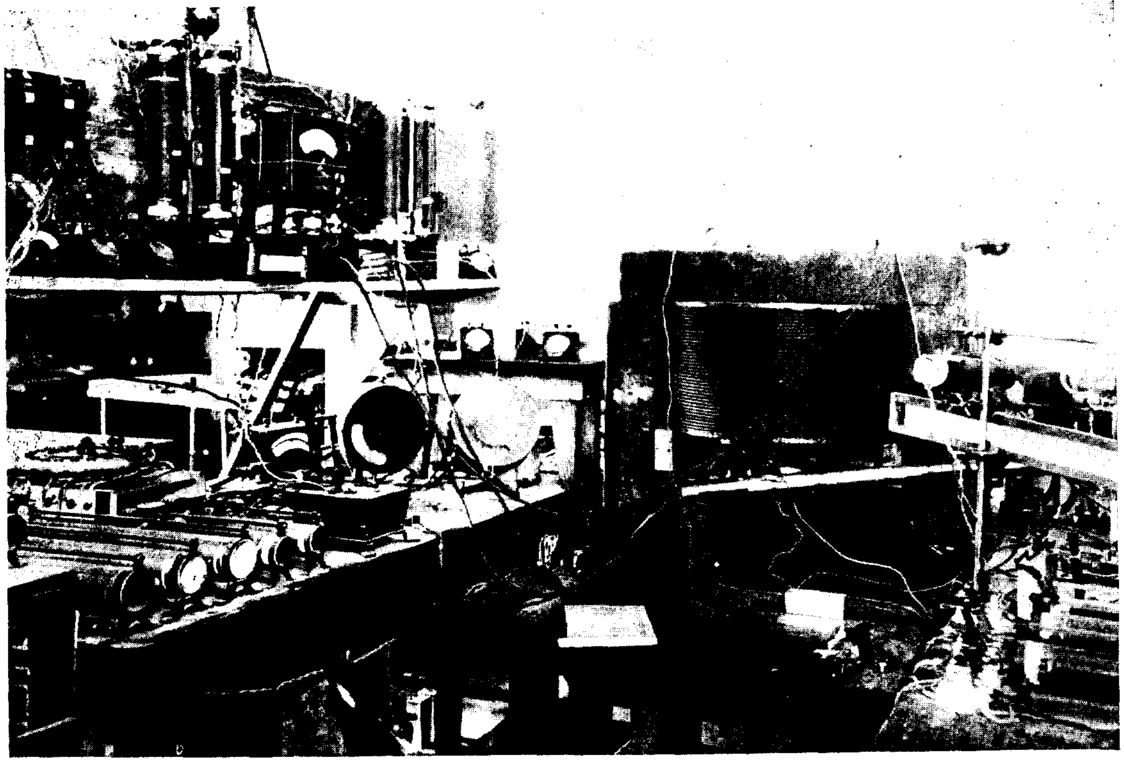


Fig. 14. The first cyclotron to produce a useful high energy beam of particles. This model was developed in 1931 and used in 1932 for producing transmutations with protons having over one million electron-volts. The magnet on the right, weighing about a *ton*, had 11-inch diameter poles. It made use of the chamber of Figure 13. Previously, in 1930, a smaller model having magnet poles and a chamber 4 inches in diameter was used in demonstrating that ions could be accelerated synchronously by the cyclotron principle.

its first acceleration and comes around a semicircle at the proper time to be again accelerated. It will then obtain another one hundred thousand volt acceleration, and will have a total of two hundred thousand electron-volts of energy.[3] At the next acceleration it will then acquire another one hundred thousand volt push and be up to an energy of three hundred thousand electron-volts, etc., so that by the time it has crossed the gap one hundred times, that is, fifty complete revolutions, it will have a total energy the same as though it had been given a single ten million volt push. It is thus evident that by means of the cyclotron, particles can be accelerated to very high voltages through the use of readily obtainable intermediate voltages.

In order to bombard targets with the accelerated particles, a probe containing the target material can be introduced into the gap between the Dees near the periphery where particles reach their highest voltage (internal target method), or one can pull on the particles where they come out from the Dee by means of an attracting negative plate, called a deflector, placed alongside the Dee, so that they will be deflected away from the Dees to an external target.

Figure 13 shows the vacuum chamber part, with lid removed, of the first cyclotron to produce a beam of accelerated particles. The chamber is a metal box 12 inches square and only about three-fourths of an inch deep inside. Only a single Dee was used, the other Dee being in effect the

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[3] A volt is a unit of electrical potential, or potential difference, while an electron-volt is a unit of energy, namely, the energy that an electron (or proton, which also has the same amount of charge) gains in falling

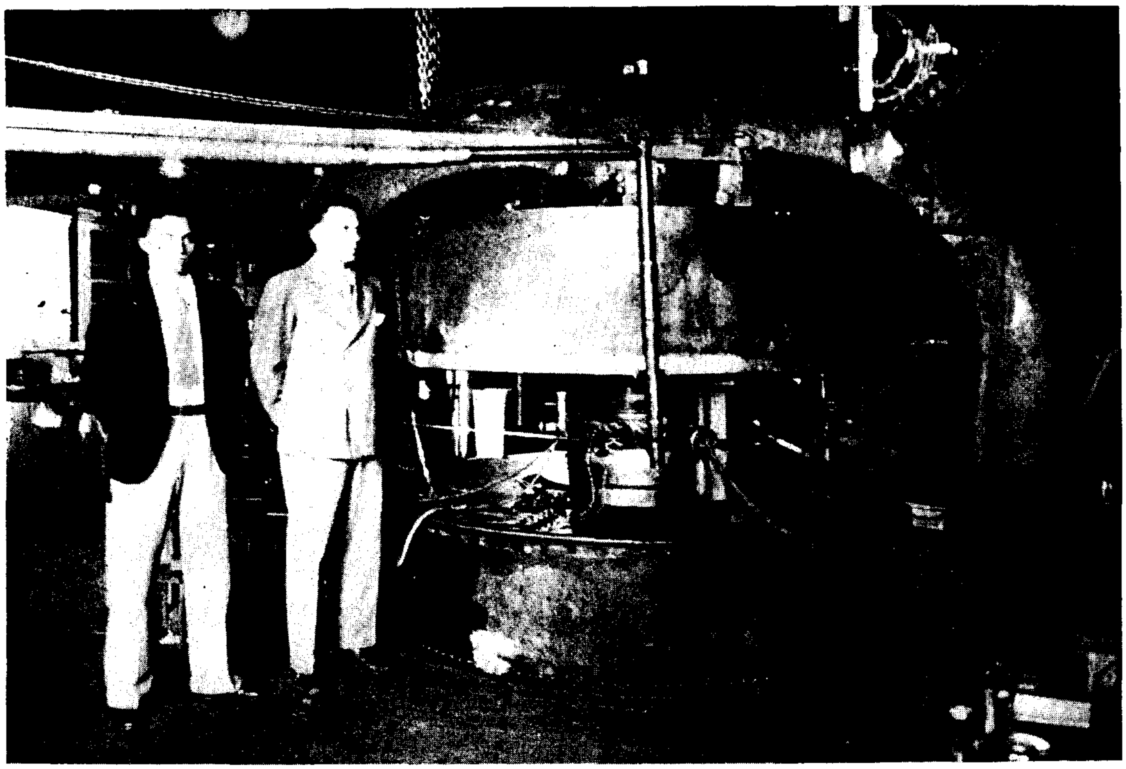

Fig. 15. The second cyclotron as it was in 1933. Prof. Ernest O. Lawrence, inventor of the cyclotron, is standing nearest the magnet and next to him is Dr. M. Stanley Livingston, who aided greatly in the early development. The 80-ton magnet was fitted first with only 27-inch poles and equipped as a cyclotron in 1931 and 1932. It was in successful operation in 1932 at energies over 2 Mev. By 1936, just before it was changed to a 37-inch cyclotron, it had produced intense beams of deuterons with energies up to 6.2 Mev.

vacuum chamber. The Dee was insulated to stand the radiofrequency voltage used (roughly 4 kv.) by the small glass insulator on the right. The accelerating gap is the space between the Dee and the grounded bar (containing a slot for the particles to go through) which is across the middle of the chamber. A small deflector and bombarding chamber are seen on the left. This chamber was placed between the 11-inch diameter poles of the one-ton magnet shown on the right of Figure 14. With this first cyclotron protons with energies somewhat over a million electron-volts were obtained and transmutations of several light elements were produced. The principle of the cyclotron was conceived late in 1930, the above 11-inch diameter apparatus was built in 1931, and in 1932 transmutations were achieved with it.

In the period between 1931 and 1932, an 80-ton magnet, designed for spark quenching in telegraphy but made obsolete by the advent of radio-tube transmission, was rescued from a scrap heap and made into a cyclotron. The magnet has a core for poles 45 inches in diameter but for the early trials was set up with poles to take only a 27-inch diameter chamber. In Figure 15, the 27-inch cyclotron (the size of a cyclotron is arbitrarily given by the diameter of its vacuum chamber) is seen in its early stages. Beside it are Dr. E. O. Lawrence, inventor, and Dr. M. S. Livingston, who aided in its development. The first beams obtained were protons having energies of less than two million electron-volts. In 1934 after deuterium became available, it was possible to accelerate deuterons, and by 1935 the 27-inch cyclotron was developing deuterons with energies of 4 Mev. In 1936 the diameter of the poles was increased to 37 inches and an improved vacuum chamber was installed

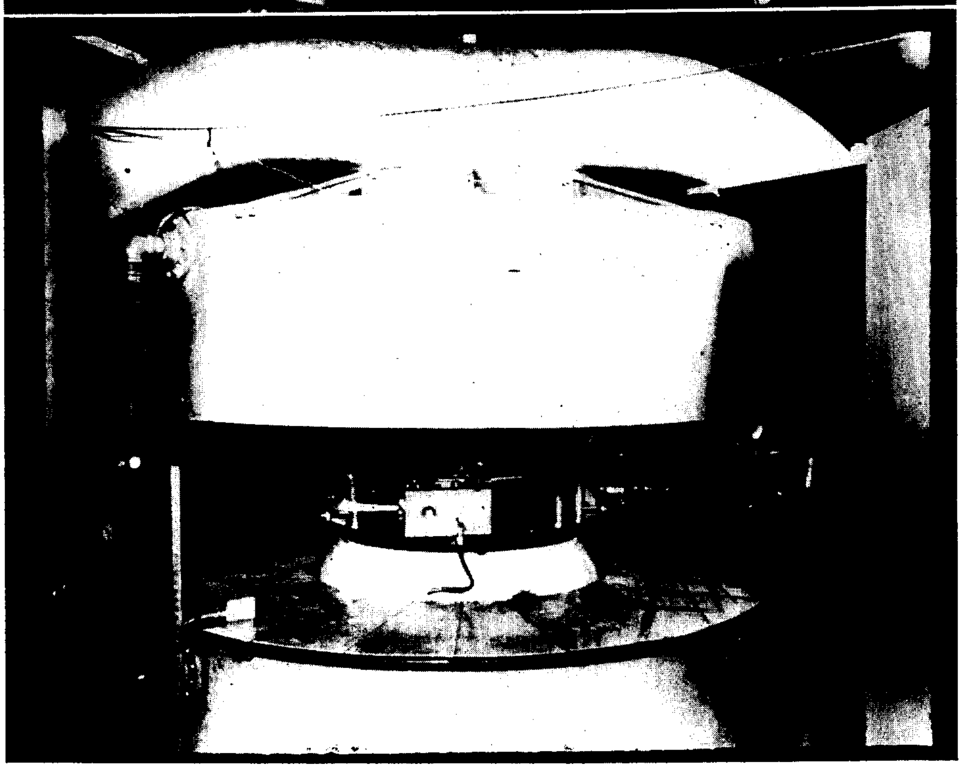

Fig. 16 (above). A view of the 37-inch diameter Dee chamber first used in 1936. The 2-inch thick steel lid is removed to show the Dees with the accelerating gap between them. The deflector plate can also be seen alongside the Dee on the left. In the foreground are the supports which hold the Dees insulated from the surrounding chamber. On the left is the manifold through which the chamber is evacuated.

Fig. 17 (below). A view of the 37-inch cyclotron while it was shooting a beam of deuterons with an energy of 8 Mev out into the air. The beam going through the air produced the bright

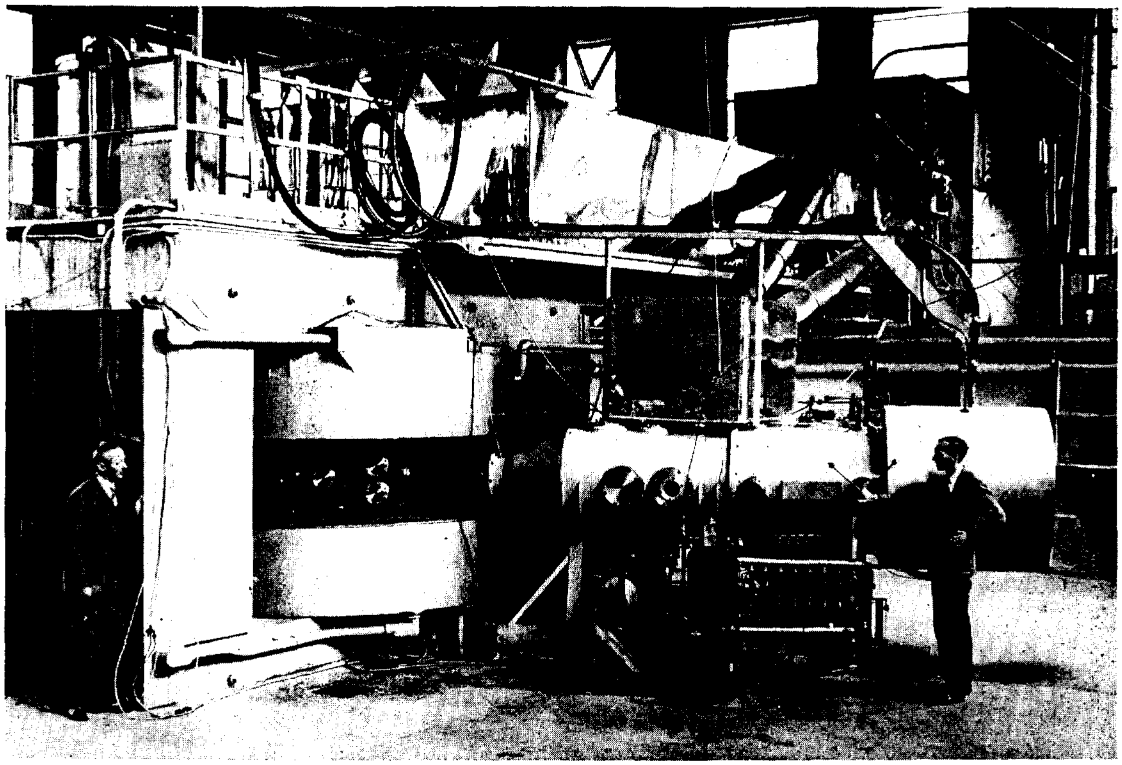

Fig. 18. Photograph of the 60-inch medical cyclotron of the W. H. Crocker Laboratory in the fall of 1939, just before it was enclosed by large shields for radiation protection. Dr. Donald Cooksey, Assistant Director of the Radiation Laboratory, is standing on the left at the west end of the 200-ton magnet. Dr. Kenneth Green, on the right, is standing by the west one of the two large parallel Dee-supports that extend out to the right. The deflector voltage is led in internally through the west Dee-support to the deflector alongside the west Dee. The extension on the end of this support alongside Dr. Green is a housing for the deflector voltage lead.

(Fig. 16). Beams of deuterons with energies up to 8 Mev were soon obtained and used regularly for physical and biological experimentation. The current of the bombarding beam was increased from millionths of a microampere in the first work to hundreds of microamperes in the later work. Figure 16 is a picture of the vacuum chamber of the 37-inch cyclotron with the top cover removed so that one can see the two Dees and other internal parts. The Dees are insulated from the surrounding tank and supported by the two large glass insulators shown in the foreground. Beside the Dee at the left is a curved plate, the deflector, which, when charged negatively, pulls on the passing beam and deflects it toward the target bombarding region. Figure 17 shows this vacuum chamber in place in the 37-inch cyclotron, with a beam of deuterons issuing from it. For this picture a thin aluminum foil was placed at the end of the bombardment chamber instead of a target, so that the deuteron beam could penetrate into the air and yet permit maintenance of the vacuum in the chamber. Because the beam consists of high-speed charged particles, ionization and excitation of the atoms and molecules in the air are produced all along its path and a bluish-purple glow is seen as a result of the light given out when the excited atoms and molecules return to normal. The beam of 8 Mev deuterons is able to penetrate through about a foot of air before thus losing all its energy. In the photograph it appears as a short bright streak extending out of the

streak, approximately a foot long, seen issuing to the left from the target chamber in the center of the apparatus. One of the surrounding radiation shields, a tank of water 3 feet thick, was pulled back to obtain this picture.

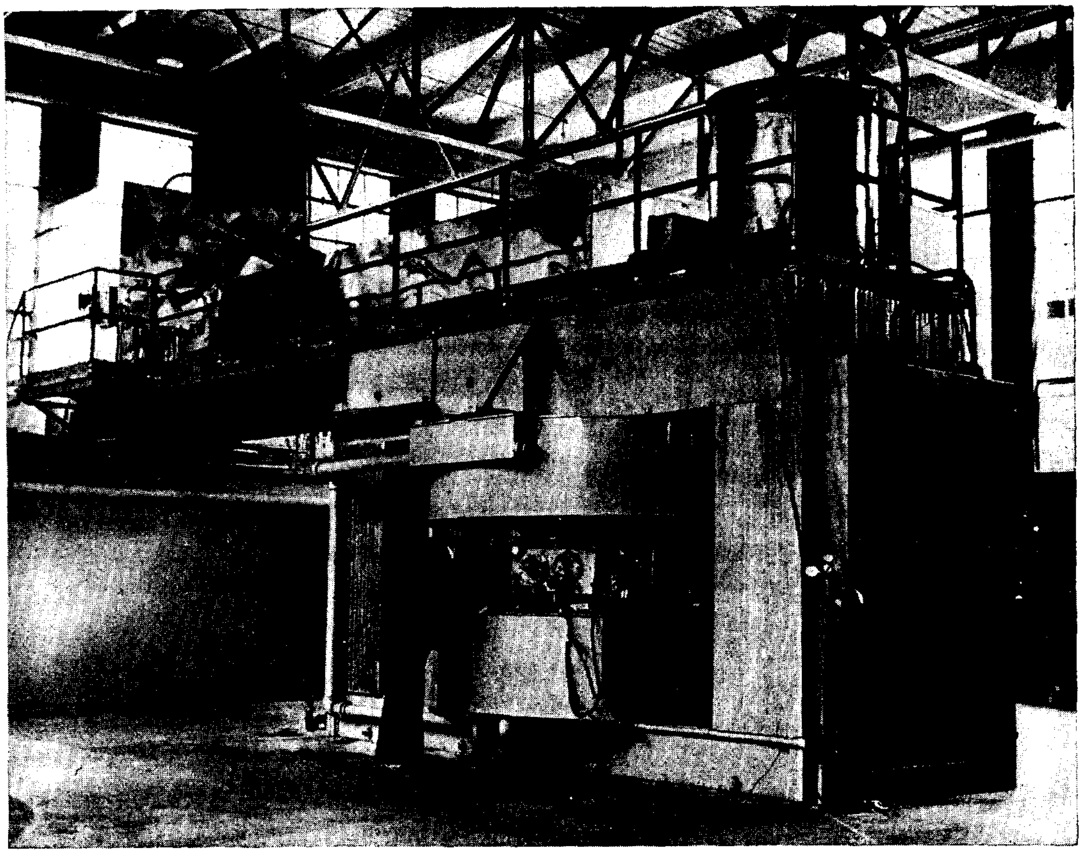

Fig. 19. View of the 60-inch cyclotron from the bombardment chamber side. The bombardment chamber is seen at the edge of the Dee chamber between the coils of the magnet. The radiofrequency oscillators for supplying power to the Dees are in the metal house at the left above the cyclotron, while the D.C. voltage supply for the deflector is in the tank above at the right.

target chamber. Figure 20 is a close-up of a more energetic deuteron beam.

So successful was the 37-inch cyclotron in its production of induced radioelements and neutron radiation, and so useful were these in physical and biological experiments, that in 1937 a larger cyclotron was planned especially for biological and medical use. Construction was started late in 1937, and by June 1939, beams of deuterons were obtained with energies twice as great as those obtained previously. Figure 18 shows the completed 60-inch medical cyclotron of the W. H. Crocker Laboratory before it was surrounded by thick radiation shielding. Dr. Donald Cooksey,[4] who is standing on the left, is at the west end of the large electromagnet, which was fabricated from 190 tons of steel. The yoke of this magnet is rectangular, roughly 15 feet long, 12 feet high, and 6 feet wide. One pole of the magnet is attached inside the yoke to the center of the upper part, and the other pole is attached directly below on the lower part, leaving a gap between them in which the vacuum chamber is placed. Although the poles are actually 6 feet in diameter, they are tapered near the gap to 60 inches, making this a 60-inch cyclotron, whereas it is potentially 12 inches larger. It was not made larger when built, in order not to make the cyclotron too great an extrapolation over the 37-inch one. Around the poles are the large doughnut-shaped tanks containing the coils or windings of 30 tons of copper strip through which a strong D.C. current is

[4] Most of the photographs of cyclotron apparatus were taken by Dr. Cooksey, Assistant Director of the Radiation Laboratory. The author is grateful for permission to use them.

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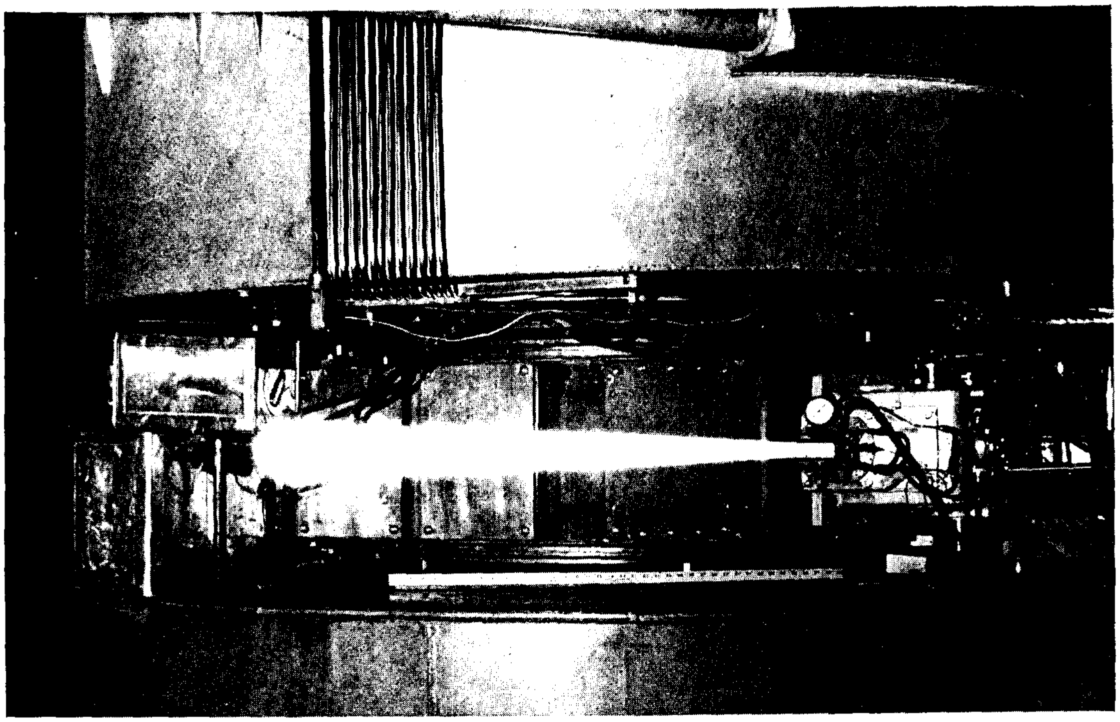

Fig. 20. A close-up view between the magnet coil tanks of the 60-inch cyclotron, showing the approximately 5-foot-long glow produced in the air when a 16-Mev beam of deuterons is let out of the target chamber on the right. A thin aluminum foil, through which the deuterons easily penetrate and yet which will maintain a vacuum in the chamber, is used in place of an ordinary thick target. The beam flares at the end of its travel because when the deuterons slow down they scatter more easily and ionize more heavily.

passed to create the magnetic flux. The vacuum chamber in the center between the poles has sidewalls of brass or other non-magnetic materials, so that the magnetic field does not suffer an abrupt change near the sides of the chamber. The large tubes extending horizontally to the right, where Dr. Kenneth Green is standing, are called Dee-stems and are the means developed especially to support the large Dees for this cyclotron. (The Dee stem on the east side is hardly visible in this picture, but it is parallel to the west one which Dr. Green is touching.) The voltage between the Dees goes as high as 200,000 volts in this cyclotron and the radiofrequency power needed to make them alternate is about 75 kilowatts. For such power and voltage, the type of glass insulating supports used on the smaller 37-inch cyclotron was not feasible. The Dee-stem arrangement eliminates the use of Dee insulators by feeding the radiofrequency power to the Dees by a coaxial line system. The metal house appearing above the cyclotron on the mezzanine contains the 200-kw. capacity radiofrequency generator. The power is fed from the oscillators to the Dee-stems along two transmission lines with coaxial shielding, seen in the photograph as the two long cylinders coming down at a slant from the oscillator housing. In this cyclotron the deflector is surrounded by, but insulated from, a special shield attached to the side of the Dee so that the deflector does not have radiofrequency currents induced in it, an improvement over former designs. The approximately 100,000-volt negative D.C. potential applied to the deflector is led down from a voltage supply on top of the magnet along the black shock-proof cable, to an internal lead through the west Dee-stem, and to the deflector inside its special radiofrequency shield. The other auxiliary equipment is for the purpose of producing

evacuated before opening the gate to the main chamber.

Such great intensities of neutrons and gamma rays are emitted during operation of the cyclotron that it is imperative to provide adequate radiation protection for persons who spend much time in the environment. If no shielding at all were provided around the 60-inch cyclotron, persons could not work eight hours daily and receive a daily dose of radiation within the limits of safety unless they were hundreds of meters away. While distance is a worth-while protective factor, it is in itself alone obviously impracticable and must be supplemented by shielding around the cyclotron. The first consideration in providing shielding is to absorb the fast neutrons which are able to penetrate through great thicknesses of material. Since a hydrogen nucleus, as a consequence of having a mass about equal to that of a proton, recoils much more than any heavier nucleus when hit by a fast neutron, a material rich in hydrogen is the most effective in taking energy away from fast neutrons. In a material containing only heavy nuclei, a neutron may bounce from nucleus to nucleus without causing the nuclei to recoil enough to rob the neutron of much of its energy. Consequently, lead and concrete, although the most efficient and economical absorbers for gamma rays, are not practical as shielding materials for fast neutrons, while water or paraffin, which are inefficient absorbers of gamma rays, are the most practical absorbers for fast neutrons. To take care of both the gamma and neutron radiation, a combination of heavy and hydrogenous absorbers is thus desirable. To obtain a sufficient reduction in the neutron intensity from

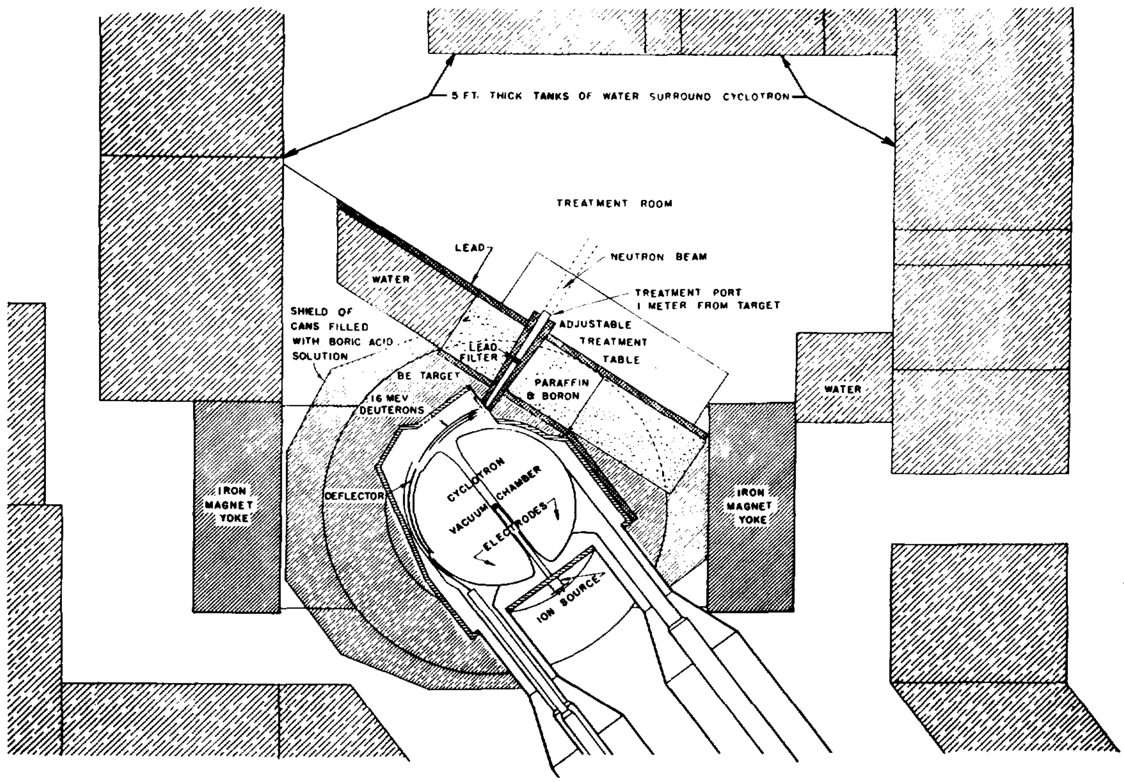

Fig. 22. A horizontal cross-section of the 60-inch cyclotron, showing the shielding arrangements for using fast neutrons in the treatment of neoplasms and for protecting the personnel of the laboratory from the penetrating radiations emitted during nuclear bombardments. The internal arrangement of the cyclotron, including the method of supporting the Dees and the deflector, is also outlined.

the 60-inch cyclotron a 5-foot thickness of water shielding around the cyclotron was desirable. This was accomplished by using tanks full of water. It was found that the region over the top of, as well as the entrances into, the cyclotron needed to be covered to prevent scattering of radiation out through those openings. The cyclotron is consequently no longer open to view, as in Figures 18 and 19, but is completely inside an igloo of water tanks, somewhat as shown in Figure 21. Since the latter picture was taken, the early and expedient practice of using 5-gallon cans full of water to cover over the roof has been abandoned as unsuitable for a permanent installation and the roof is now covered with tanks of water 4 feet deep. These large shields of water surrounding the cyclotron, which are a prime necessity for reduction of the neutron intensity, are also effective, because of their great mass, in removing most of the accompanying gamma radiation. Fortunately, also, the tons of steel and copper inherent in the cyclotron magnet are a considerable further shielding factor. In addition, lead, paraffin, water, and other absorbers fill up the space between the magnet coils directly around the target and vacuum chamber. The operating personnel are protected from the small amount of penetrating radiation which gets through or leaks out of all this shielding around the cyclotron by being behind over 18 inches of concrete wall.

A cross-section horizontally through the middle of the cyclotron and the surrounding water tanks is shown in Figure 22. This also shows the arrangement used in defining a beam of neutron radiation for the treatment of patients with neoplasms. The 16 Mev deuterons, which are used to produce the neutrons, are shown being drawn away from the Dee by a deflector and shooting into a target placed at the periphery of the vacuum chamber. For producing the most abundant quantity of neutron rays this target is made of beryllium. The region all around the vacuum chamber is filled with shields of neutron energy reducers, such as water or paraffin. The neutrons lose energy by making collisions in these hydrogenous materials until they become what are called "slow" or thermal energy neutrons, that is, neutrons that bounce around through the material with only the energy of thermal agitation of the atoms they encounter. The final resting place of a neutron must be inside of some nucleus, for neutrons do not exist free in nature. Neutrons are most readily absorbed into nuclei when they are going most slowly (they thus spend more time in which to be caught in a transit through a nucleus). Final absorption of the slow neutrons is best accomplished by boron nuclei, for these have a tremendous factor of absorption for slow neutrons, and in the absorption process no gamma radiation is emitted as is the case for some other neutron absorbers. Accordingly, borax is dispersed throughout the paraffin shields and dissolved in the water in the patient shield region. Shields of lead are also properly arranged to take out gamma rays. A channel of a desired cross-section is opened through the shields so that the neutron rays can come down the channel and be directed against the region of the patient to be treated. A filter of lead 3 cm. thick is put in the channel to suppress

TABLE I

Radioelement	Half-life	Reaction	Yield 8 Mev	Yield 16 Mev	Yield 100 Mev Estimated
$_{11}Na^{24}$	15 hours	Na (d in, p out)	2,000	10,000	350,000
$_{15}P^{32}$	14.2 days	P (d in, p out)	30	200	7,000
$_{26}Fe^{59}$	47 days	Fe (d in, p out)	0.005	0.03	1
$_{53}I^{131}$	8 days	Te (d in, n out)	1	20	1,000

Yield expressed in microcuries per micro-ampere-hour of deuterons. d = deuteron, p = proton, n = neutron.

gamma rays directly from the target. The patient is aligned by means of a movable bed and other supports. The surrounding 5-foot-thick water tanks, which shield workers in other parts of the laboratory, also form the walls of the treatment room.

THE GIANT CYCLOTRON

As the energies of bombarding particles have been pushed higher, greater yields of radioelements have been obtained and in addition many new processes have been discovered. The enhanced yields of several radioelements obtained with increased energy of the bombarding deuterons are shown in Table I. The values for 8 and 16 Mev deuterons were obtained from 37-inch and 60-inch cyclotron data. The values for 100 Mev deuterons are estimated by extrapolation of known yields, using approximations for the factors of penetration into targets and into nuclei. The attainment of one hundred million electron-volt deuterons should result in much greater yields of radioactive elements. This, however, is not the major reason for wanting to obtain greater bombarding energies, for in previous experience each time the energy of bombardments has been materially increased, new phenomena and new processes have been observed. Also, one would like to find out more about the forces that hold nuclei together. According to the latest theories, nuclear forces are somehow associated with particles, first observed in cosmic ray phenomena, called mesotrons, which may have plus or minus charges like electrons but which are about a hundred or more times heavier than the latter. It is thought that the liberation or formation of these particles requires the expenditure of energies of around one hundred to two hundred million electron-volts. It is possible that with bombarding energies of over 100 Mev sufficient energy may be supplied to nuclei to affect the mesotron

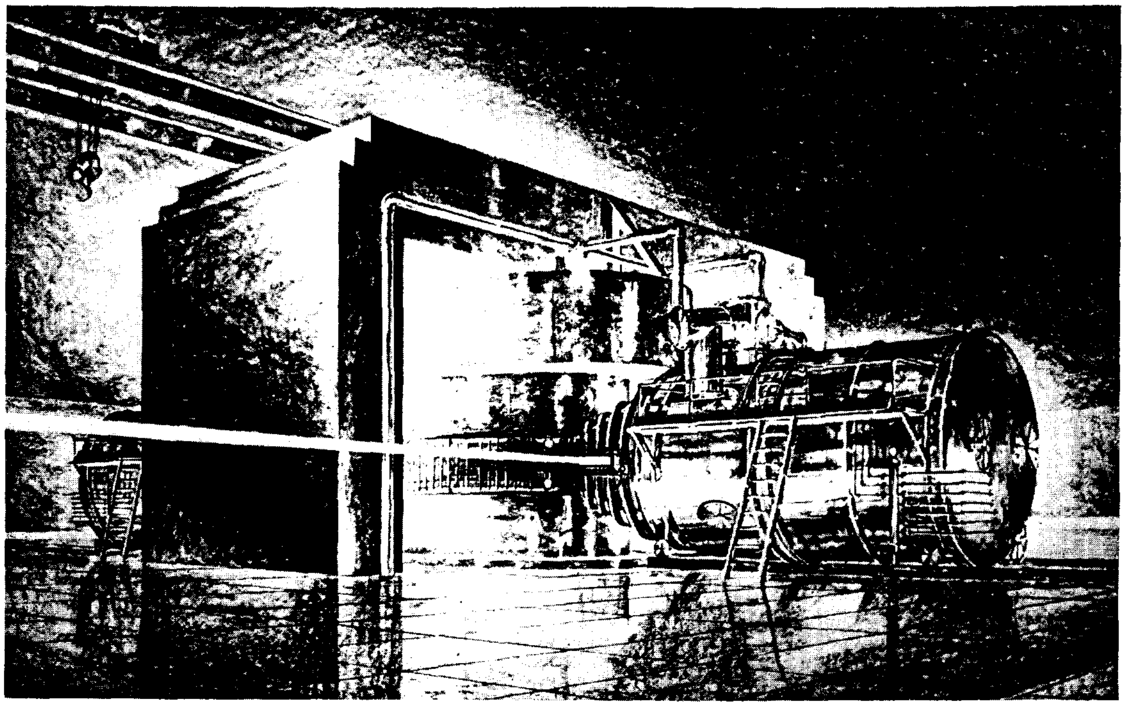

Fig. 23. An artist's conception of the giant cyclotron with a beam of 100 Mev deuterons issuing from it. The beam, illustrated on the left, would streak 140 feet through the air. The magnet has much the same design as used for smaller cyclotrons, but the Dee chamber and Dee support structures are a departure in design. The Dee supports are the large tanks coming out diametrically opposed from the Dee chamber instead of parallel and on the same side, as in former cyclotrons.

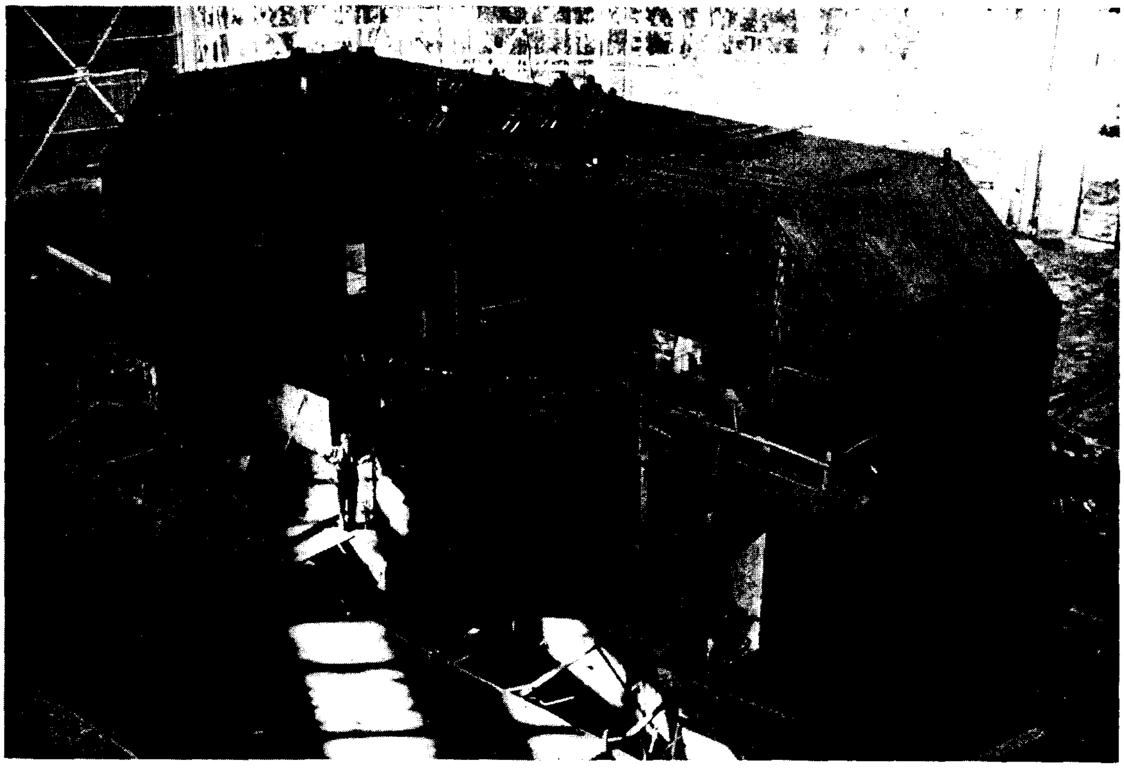

Fig. 24. The magnet for the giant 184-inch cyclotron shown in the process of construction early in 1942. It is 56 feet long, 30 feet high, and about 15 feet wide. It was fabricated from 3,700 tons of steel plate, mostly 2 inches thick, bolted together and welded. The construction of the magnet in laminations of plates had no purpose magnetically but was the simplest way to fabricate such a structure. With the 300 tons of copper coils needed to energize it, the magnet will weigh 4,000 tons, the world's largest. The size of the 184-inch diameter poles can be judged from the figures of the men standing nearby. The deuterons will have to start at the center and spiral all the way out to the edge of a chamber of this diameter in the process of acquiring their great energy.

forces and thereby yield knowledge of the nuclear binding forces.

A still further reason, and the most exciting one, for wishing to obtain higher bombarding energies is to investigate the possibilities of what is popularly called "atomic energy," that is, the energy that is released when nuclei disintegrate. Einstein was the first to point out that there is an equivalence between mass and energy, that in atomic and nuclear reactions mass may disappear and in its place energy will appear. One of the first verifications of this equivalence of mass and energy was in the disintegration of lithium, already illustrated in Figure 6, in which lithium plus a proton divides into two alpha particles. The mass of two alpha particles, as well as the masses of lithium and a proton, can be measured very accurately. It was observed that the mass of two alpha particles is much less than that of lithium plus a proton and that the difference was just the right amount to explain the large amount of energy acquired by the alpha particles during this process. According to Einstein's hypothesis, the energy released is equal to the mass multiplied by the square of the velocity of light. The square of the velocity of light is, indeed, a very large number, 9×10^{20}, so that even the disappearance of a small amount of mass results in considerable energy. Conversion of a gram of mass into energy would result in more than two million kilowatt hours. Radium, which is continually disintegrating and which is undergoing a sequence of disintegrations in which mass is being lost, gives out enough energy to heat its own weight of water to the boiling point every hour. With the attainment of more information about nuclear

Fig. 25. The giant cyclotron laboratory, 165 feet in diameter and 90 feet high, on a hilltop directly above the campus of the University of California, where ten years earlier the first cyclotron was born. The Golden Gate Bridge is visible in the background across the Bay.

forces or the discovery of new nuclear processes, the tremendous energies locked in the nuclei of atoms may some day be tapped for practical use.

With these points in mind, that is, (1) increased yields of radioelements, (2) new processes and phenomena to be discovered, (3) further knowledge of nuclear structure, and (4) possibility of atomic power, plans were conceived for a giant cyclotron to produce deuterons with bombarding energies of one hundred million electron-volts or greater. Figure 23 is an artist's conception of how such a cyclotron might look. If the beam of 100 Mev deuterons were to be let out of this cyclotron into the air, as illustrated by the bright streak shooting out to the left, it would travel a distance of 140 feet; thus a door would be needed in the surrounding building to let the beam through.

Preliminary ideas and hopes for a giant cyclotron arose in 1939. Through the support of a large grant by the Rockefeller Foundation, actual plans were laid in early 1940 and construction was started later that year. About three years were to be required for completion. Figure 24 shows the giant magnet for this cyclotron under construction, its size being indicated by a comparison with the men standing inside the yoke near the bottom pole. Since the diameter of the pole is 184 inches (about 15 feet), this is designated a 184-inch cyclotron. The steel required for the magnet was about 4,000 tons and the copper used in the coils to energize the magnet weighs 300 tons; that is, the copper alone weighs much more than the weight of the present 60-inch medical cyclotron. The yoke of the magnet is 56 feet long, 30 feet high, and 184 inches wide. It is the largest electromagnet known.

This huge electromagnet is housed in a building, 165 feet in diameter, shown in Figure 25 on its site overlooking the Golden Gate. This structure was made, perhaps, larger than necessary to allow for any large shielding tanks within the building or any unforeseen large-scale experiments. The building was put on the crest of a hill so that there would be no nearby habitation. This also permits the possibility of having the control house over the brow of the hill in a tunnel, putting a hundred feet of earth or more for radiation shielding between the operators and the cyclotron. A closer control house will be possible if the radiation produced proves to be absorbed chiefly by feasible thicknesses (say 25 feet) of water tanks. The building is a large dome-shaped structure which gives it the appearance of an observatory. Also, the size is somewhat the same as that needed for the giant telescope. It is an interesting commentary on the extent to which man is investigating his universe that in one instance he builds a huge observatory and instrument to look out into the vast realms of space at things millions and millions of times larger than himself, whereas in another he constructs a giant laboratory and apparatus for the purpose of looking into the most infinitesimal realms, millions and millions of times smaller than he.

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