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Teacher Lectures Given at UCRL During Summer of 1956

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Radiation Laboratory

TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

BERKELEY, CALIFORNIA

Manufactured in the United States of America

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Radiation Laboratory
University of California
Berkeley, California

PREFACE

In April of 1955 the Radiation Laboratory of the University of California sent out to 18 high schools in the Bay Area letters which said, in part, "The object of this program is to help science teachers achieve some practical knowledge and experience in nuclear science by working with some of our basic research groups in physics and chemistry. In this way we believe that we can assist these teachers in their efforts to make their students more aware of the nature of atomic energy and help to prepare them for the impact of atomic energy in their future."

The response was enthusiastic and 14 high school teachers were selected for the program. These teachers were assigned to various experimental groups at the Laboratory in Physics, Chemistry, and Biochemistry in the role of junior scientists to do whatever work was necessary with that group.

A series of lectures by senior staff members of the Laboratory was arranged for Tuesday and Thursday mornings. It was intended that each teacher should write up one or more of these talks and the whole should be made available to all. Editorial difficulties prevented completion of this phase of the program.

In general it was felt that the program was most worth while and successful. So much so, that it was repeated on a nearly doubled scale in 1956. The undersigned was asked to attend the lectures and write a series of notes on them.

The original order of the talks was determined by the availability of the speaker. The arrangement in these notes is an attempt to present general principles, equipment and techniques first, and special application afterward.

Each talk is an entity in itself so that there is some repetition and some variance in view point.

The first speaker (Dr. Roger W. Wallace) furnished his own extensive notes, and these have simply been incorporated into the series.

The second speaker (Dr. Warren Fenton Stubbins) made very extensive revisions and amplifications of this writer's briefer notes.

These notes are by no means verbatim reports. This author made up outlines and summaries of the rest of the talks and submitted them to the speakers. They carefully went over the notes, frequently revising or expanding sections. This cooperation was greatly appreciated and it is believed that as a result these reports are largely free from errors of fact. It is hoped they retain some of the stimulating flavor of the authoritative but impromptu original talks.

Glen W. Watson

The first meeting was held at 9 a.m. on Tuesday, June 19. Warren Fenton Stubbins introduced Dr. Donald Cooksey, Associate Director of the Radiation Laboratory, who welcomed the group. Dr. Cooksey explained that not only will the teachers actually assist briefly in carrying on the work of the Laboratory but also, it is hoped, they will absorb attitudes and techniques that will be reflected in increased competence and enthusiasm of the younger generation of science students.

Dr. Cooksey then gave a very brief summary of the history of the Laboratory. It is an outgrowth of the achievements and enthusiasm of Ernest O. Lawrence, who first came to the University of California at Berkeley in 1928. Soon afterward he got the fundamental idea of the cyclotron, for which he was awarded the Nobel Prize in 1939. The Radiation Laboratory was created in 1936 with Professor Lawrence as director to more effectively and intensively pursue investigations with that great tool. Outstanding and world-famous scientists are associate directors. The influence of the "Laboratory" is wide, deep, and continuing.

Roger W. Wallace then began a four-day series of lectures on "atomic" as distinguished from nuclear chemistry. At the end of his outline are brief comments on discussions during the "breaks."

TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

Radiation Laboratory
University of California
Berkeley, California

Chapter 1

ATOMIC PHYSICS

Roger W. Wallace

THE CHEMICAL FOUNDATIONS OF THE ATOMIC THEORY

By 1800 four laws governing the mass and volume relations between chemical compounds had been discovered. These laws led to the atomic and molecular hypotheses long before any experiments were conducted that measured the individual properties of atoms. These laws deal only with enormous numbers of atoms or molecules, and yet their form is a direct consequence of the individuality of atoms and molecules. The laws are:

1. The Law of Conservation of Mass - The total mass of a system is not affected by any chemical change within the system.

2. The Law of Definite Proportions - A particular chemical compound always contains the same elements combined in the same proportions by weight.

3. The Law of Multiple Proportions - If two elements combine to form more than one compound the different weights of one that combine with the same weight of the other are in the ratio of small whole numbers.

4. The Law of Reciprocal Proportions - The weights of two (or more) substances that react separately with identical weights of a third are also the weights that react with each other, or simple multiples of them.

From the above laws Dalton in 1803 introduced the Atomic Hypothesis that:

(A) Chemical elements are discrete and individual.

(B) All the atoms of an element are the same.

(C) Simple numerical relations exist between the numbers of atoms that combine into molecules.

Soon after this Avogadro introduced the Molecular Hypothesis in 1811, which states that equal volumes of gases contain equal numbers of molecules.

Somewhat after this Faraday drew the following two conclusions from his experiments with the passage of electricity through solutions:

(A) The weight of an element that is deposited by an electrical current while passing through a solution is proportional to the absolute electrical charge carried by this current through the solution.

(B) The weight of various elements deposited by the same charge is proportional to the chemical equivalent of these elements.

Faraday found that 96,000 amperes flowing for one second would deposit one chemical gram equivalent or mole of a monovalent element. From this number and the charge of one electron, which was measured many years later by Millikan, one can calculate the number of atoms in one mole of an element. This turns out to be 6×10^{23}, which is called Avogadro's Number, since he was the first to point out that each mole should contain equal numbers of molecules. All of the preceding information, plus a great deal of chemical data (with the exception of the more recently measured Avogadro's number), was available to Mendeléeff in 1869 when he suggested that the chemical elements could best be understood if arranged in a Periodic Table. He was drawn to this conclusion by the following facts:

(A) The chemical properties of the elements tend to repeat themselves in a periodic fashion when the elements are arranged in the order of their atomic weights.

(B) Similar elements either have approximately the same weight or have regularly increasing weights.

(C) The order of the atomic weights is also the order of the chemical valences.

(D) The common elements have small atomic weights and sharply defined chemical properties.

(E) The magnitudes of the atomic weights determine the chemical characteristics of the elements.

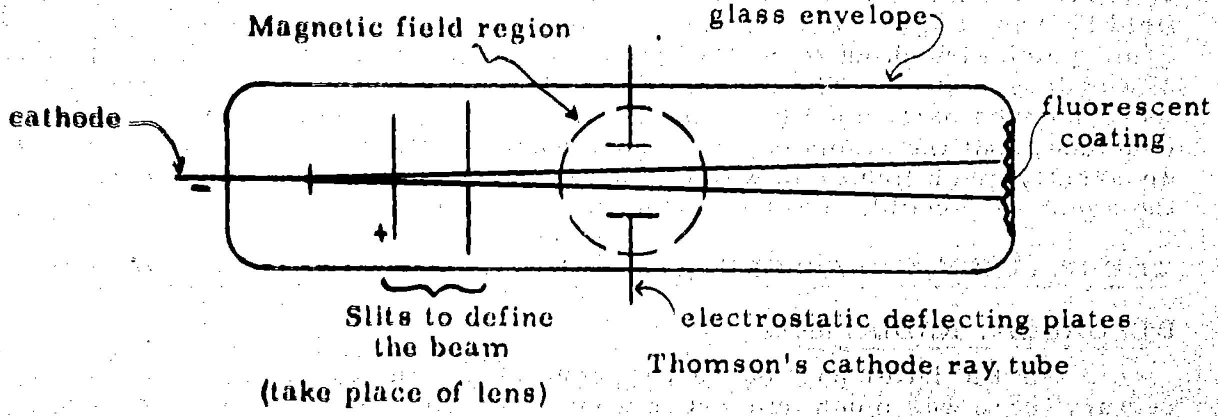
When the elements were arranged in the periodic table it became immediately possible to predict the existence of several elements that were then unknown--all of which have since either been found in nature or been produced artifically. The table also made it possible to check the accuracy of the atomic weights of adjacent elements and to make excellent predictions about the chemical properties of elements, which were yet to be discovered or were little known.

The proceding material forms the classical bases for the modern atomic theory and was understood and accepted by the latter part of the 19th century. At the close of the 19th century the atomic theory began to develop very rapidly, owing to the discovery within a few years of cathode rays, x-rays, the quantum theory, the special theory of relativity, and the photoelectric effect.

THE ELECTRON

Although the developments now to be described in some cases occurred simultaneously we will first consider the discovery of the electron.

Thomson in 1897 used an evacuated tube of the type shown schematically below (to demonstrate the properties of cathode rays which he eventually called electrons.)



Thomson's cathode ray tube

The negative electrode, or cathode, in the tube emits electrons which are accelerated toward a slit system that has a positive charge on it. Some of them pass through the slits in a narrow beam and strike the far end of the tube, which has a fluorescent surface. This tube is very similar to the modern television tube and all of Thomson's experiment could in principle be performed by anyone with his television set. He observed or demonstrated that:

(A) The cathode rays traveled in straight lines.

(B) They could penetrate a thin foil.

(C) They were negatively charged (as shown when they were allowed to strike an electrode).

(D) They were deflected toward the positively charged plate when the beam passed between metal plates on which there were opposite electrostatic charges.

(E) They were deflected on the arc of a circle when they passed through a magnetic field whose lines of force were perpendicular to their direction of motion.

(F) They carry with them a considerable amount of energy, since they easily heated whatever surface they fell on.

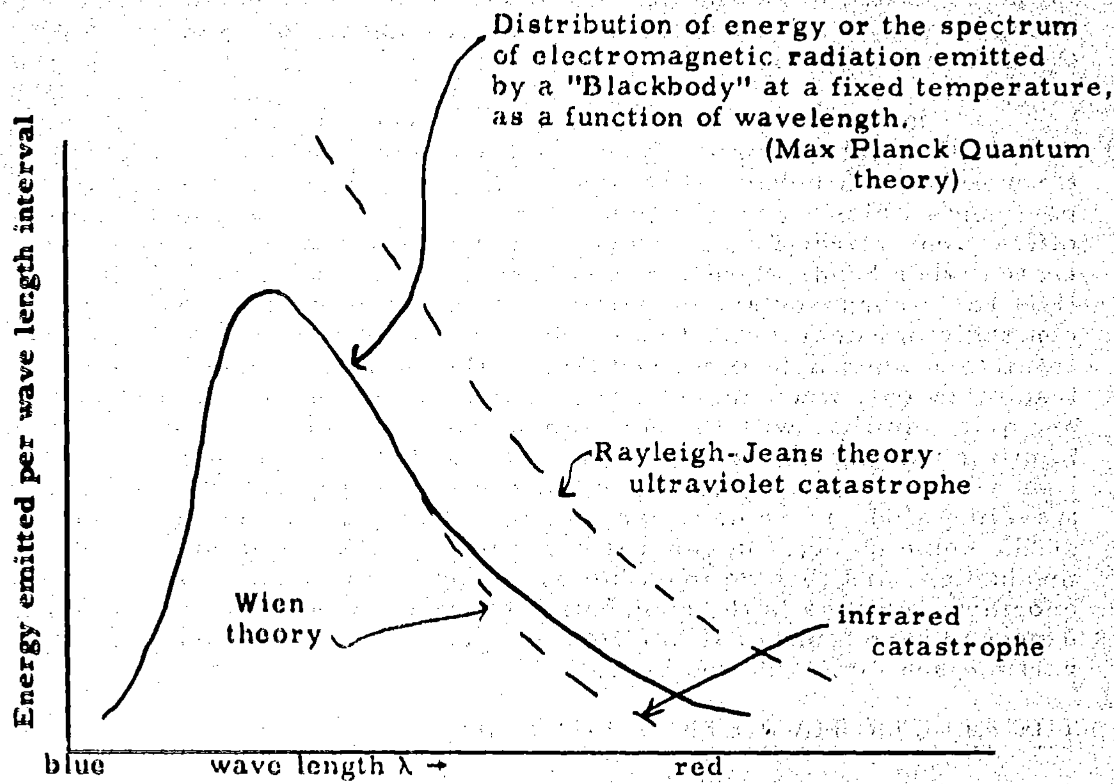
By passing the cathode rays through a region in which there was an electrical field pulling the cathode rays one way which was exactly balanced by a magnetic field pulling them in the other direction, he was able to measure their velocity. The electrical force eE = Hev, the magnetic force, where e is the charge on an electron, E is the electrostatic field, H is the magnetic field, and v is the velocity of the electron. Therefore, the velocity equal E/H, and he found this velocity was typically about 10% of the velocity of light. When he turned off the magnetic field and used only the electrical field he was able to measure the ratio of charge to mass for the cathode rays, e/m, which turned out to be 1800 times as large as the charge-to-mass ratio of a hydrogen atom. The charge of the electron was not known at the time that Thomson performed his experiment. From this experiment Thomson concluded that the atoms of the cathode were emitting electrons, which were apparently much lighter in weight than a hydrogen atom and which were probably the agent responsible for the conduction of electricity.

THE EMISSION AND ABSORPTION OF ELECTROMAGNETIC RADIATION

BLACKBODY RADIATION

In the latter part of the 19th century and the early part of the 20th century there was much interest in what is called by physicists Blackbody Radiation. Any body that is not at the same temperature as its surroundings tends to come to the temperature of its surroundings by means of energy transfer between it and its surroundings. This energy transfer takes place either by conduction, convection, or radiation. In the absence of air radiation is the only means available. Every body above the absolute zero of temperature is continuously receiving and emitting electromagnetic radiation, principally in the infrared region of the electromagnetic spectrum. In order to produce a region which is all at the same temperature and easily comes into equilibrium it is conventional to use a closed box with a small hole in it. This hole is said to represent a blackbody, since this hole appears to be completely black if the box is viewed from the outside when the box is at normal temperatures. If the box is heated it will eventually begin to emit visible light from the hole, which will become successively red, orange, and eventually white as the temperature increases. The spectral description of the light emitted from the hole is determined by the temperature of the inner walls of the box. This radiation is said to be the equilibrium radiation emitted by a body at the temperature of the walls.

The spectral distribution of this light (shown below) was difficult to explain theoretically until Planck in 1901 suggested that electromagnetic radiation must be emitted in discrete quanta rather than continuously as had formerly been expected. When Planck assumed that the energy of each quantum or photon of electromagnetic radiation was proportional to its frequency by the relation $E = h\nu$ he was able to completely explain the observed spectrum coming from the above-described hole in a box or blackbody. This discovery was the beginning of the Quantum Theory, which later developed into Quantum Mechanics.



Spectrum of Blackbody Radiation

The eventual implications of this theory are far reaching, and have affected every branch of physics, chemistry, and engineering. The constant h, which Planck introduced and which is named after him, has the units of erg seconds or energy multiplied by time. The frequency of the light emitted is equal to $\nu = c/\lambda$, where c is the velocity of light, equal to 3×10^{10} cm/sec, and λ is the wave length of the light in centimeters.

THE PHOTOELECTRIC EFFECT

The explanation of blackbody radiation accounted for the emission of electromagnetic radiation. However, the absorption of electromagnetic radiation was not explained until 1905--by Einstein, who received the Nobel Prize for it. When light falls on an object electrons are often emitted from its surface. It was found that the brightness or intensity of the light does not affect the energy of these electrons, but that the color of the light does. Even if light of an extremely low intensity strikes an object electrons are emitted immediately--rather than after a certain time has elapsed--before sufficient energy accumulates for the emission of an electron. This fact alone suggests that light probably consists of discrete particles, each having a characteristic energy, and that changes in the brightness or intensity of a beam of light change only in the number of such particles present. Einstein showed that the so-called photoelectric equation $E = h\nu - w$, where $E \equiv$ the energy of an emitted electron, $h\nu$ is the energy of an incident photon, and w is the so-called work function of the surface; w is a constant amount of energy which is subtracted from the kinetic energy of an electron as it passes through the surface.

One photon of light is all that is needed to emit one electron. It can be said that light is emitted and absorbed in quanta, but that in its propagation through space it behaves like a wave motion. There are many optical experiments which clearly demonstrate that light is a wave motion undergoing diffraction, refraction, scattering, interference, and such wavelike behavior. On the other hand, there are many experiments that clearly indicate that light has a corpuscular, or particle, or quantum nature. These two apparently contradictory characteristics of the behavior of light are not actually contradictory when light is viewed from a theoretical standpoint, but are contradictory only when considered by our own limited personal experience. We are quite familiar with the behavior of water waves and somewhat less familiar with the behavior of sound waves, but our detailed experience with light waves is actually quite limited since we never directly observe them traveling along as we do water waves, but only see their result as they strike some object. In general it can be said that we think in terms of classical mechanics, and that we must believe quantum mechanics because of its enormous success in the explanation of experiments, but that we must not expect to have a physical intuition for quantum behavior such that this wave-particle dualism exhibited by light.

THE ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum extends over at least sixteen orders of magnitude of wave length that have been investigated by physicists up to the present time.

Table I

Characteristics of electromagnetic radiation

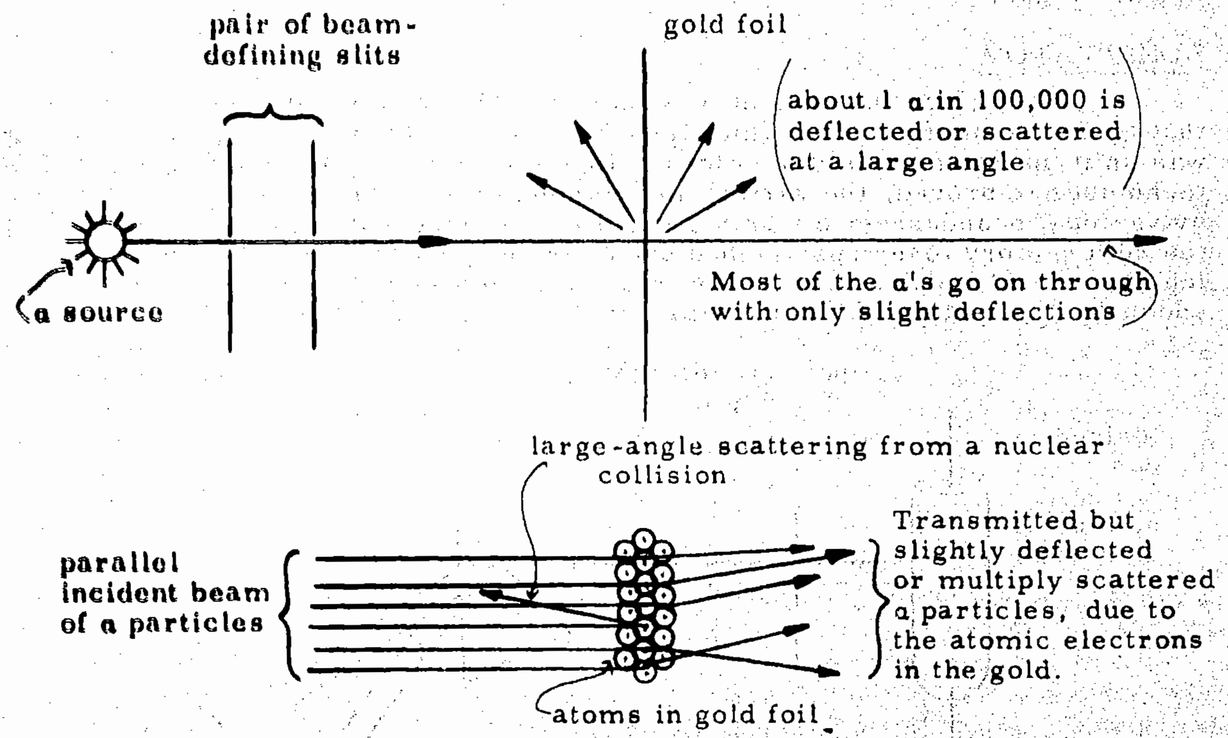
Type of radiation	Range of wavelength (cm)
Gamma rays	10^{-11} to 10^{-9}
X-rays	10^{-9} to 10^{-7}
Ultraviolet light	10^{-7} to 10^{-5}
Visible light	4×10^{-5} to 7×10^{5}
Infrared light	10^{-4} to 10^{-1}
Short radio waves	10^{-1} to 10^{+5}
Long radio waves	10^{+5} to 10^{+7}

All the above radiations travel at the same velocity and can be thought of as being emitted by accelerated charges. They all behave as photons whose energy is equal to $h\nu$. A naive picture of the emission of electromagnetic radiation can be had by considering that a charged electron is surrounded by an electric field and that if this electron's velocity is changed (i.e. it undergoes an acceleration) some of the electric field surrounding the electron will be shaken loose and will appear as electromagnetic radiation. This can be thought of as going on in the filament of a light bulb, where the electrons are shaken by the thermal agitation arising from the heating of the filament, or in a radio antenna, where the electrons are forced to move back and forth along the antenna by the voltages impressed on the antenna by the transmittor.

ATOMIC STRUCTURE

RUTHERFORD'S ATOM

Earlier works such as Thomson's had shown that atoms were composed of plus and minus charges, but the configurations assumed by these charges within the atom were not known. It was known that the negative charges were considerably lighter in weight than the positive charges and that the negative charges were responsible for electrical conduction in metals. In 1911 Rutherford and Geiger performed an experiment (as indicated in the sketch) in which he bombarded a thin gold foil with alpha particles, which were known to be the nuclei of helium gas atoms, and which had been discovered by earlier workers in radioactivity.



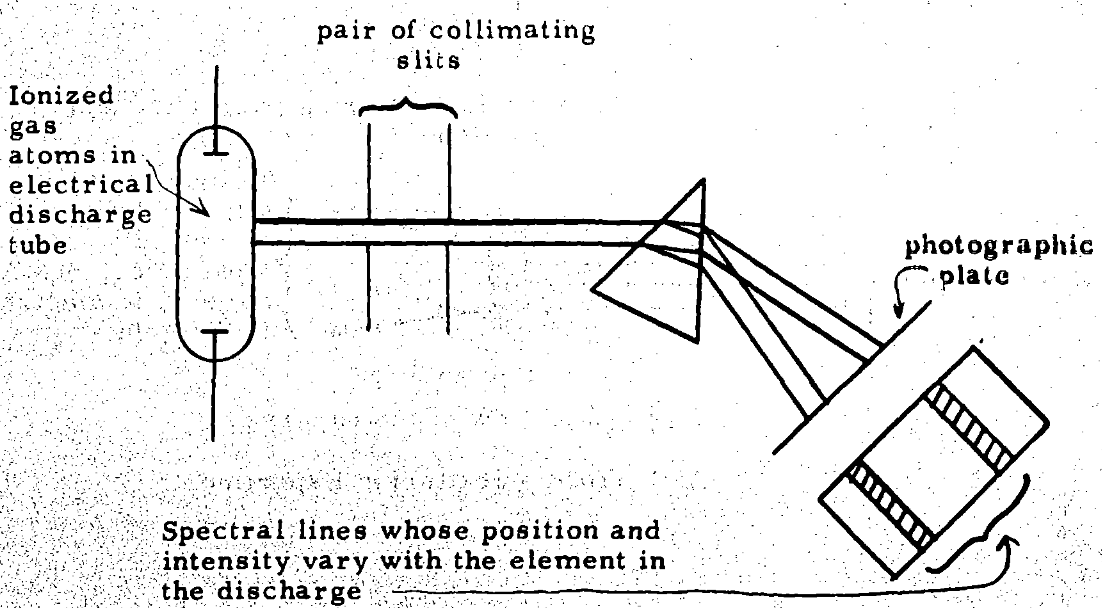
Large-scale view of the experiment

Rutherford's Scattering Experiment

For our purposes the incident alpha particles can be considered as heavy geometrical points moving at a high velocity through the gold foil. Most of the alpha particles went through the gold foil almost undeflected. About one in 100,000 were deflected or scattered at large angles, even up to 180°. It could be concluded from this experiment that very little of the foil was a solid barrier to the alpha particle, and that therefore the solid matter in the foil must have an area that is only a fraction of its total area. In addition, the solid matter must be quite heavy, or the large angles of particle recoil could not be explained. An alpha particle weighing almost 8,000 times as much as an electron could not bounce backward from a collision with an electron any more than a bowling ball would be expected to bounce back if rolled into a pile of ping-pong balls. Therefore, to account for a bowling ball's bouncing back when it hits a pile of ping-pong balls, there must be an occasional bowling ball hidden among the ping-pong balls in this large-scale analogy. Rutherford concluded that the atom of gold must be largely empty space occupied by electrons, and that the principal mass of the gold was concentrated in a region about 10^{-12} cm in diameter, which is called the nucleus. It had already been shown that the volume available to each gold atom was about 10^{-8} cm in diam., so that the gold must indeed be mostly empty space--as are all solids.

BOHR'S ATOM

Ever since the days of Newton in the 17th century it had been known that a thin beam of parallel white light when passed through a prism of glass was split up into a variety of colors called a spectrum. As experimental techniques improved, the variety and complexity of such spectra produced by various incandescent materials rapidly increased. By the beginning of the 20th century many spectra had been carefully measured and the wave lengths and intensities of their spectra lines recorded, but there was no adequate explanation of the structure or origin of these spectra.



Spectral lines whose position and intensity vary with the element in the discharge
Only two lines are shown for simplicity, frequently there are many lines present.

It was known that each element used as a source of light produced its own characteristic spectral pattern. In order to explain these complicated patterns Bohr suggested in 1913 that:

(A) The electrons, which are outside the nucleus, are circulating around it in stable circular orbits much in the fashion of the planets circulating around the sun.

(B) The angular momentum of an electron in such an orbit can only have certain discrete values equal to $n\hbar$, where $\hbar$ = h the Planck constant/2π, and n is an integer, 1, 2, 3, ... The angular momentum of an electron in an orbit is equal to the linear momentum of the electron (its mass times its velocity) multiplied by the radius of the orbit. This requirement is expressed as

$$mvr = \frac{nh}{2\pi} .$$

This "quantization" of angular momentum actually gives each electron an energy that is characteristic of its orbit, and the particular orbit occupied by an electron is determined by its principal quantum number "n."

(C) The spectral lines observed in the light emitted by an excited element are a result of the fact that light is emitted or absorbed as an electron makes a discrete jump from one of these orbits to another, and emits or absorbs a definite amount of energy which is the difference in the energy of the electron in each orbit.

The Bohr hypothesis is difficult to accept because the first postulate requires that an electron travel in a circular orbit without losing energy, which is inconsistent with "classical electrodynamics" which requires, as we have mentioned earlier, that an accelerated charge emit electromagnetic radiation. An electron traveling in a circle is being continuously accelerated toward the center, and yet obviously does not continue to lose energy by emitting radiation. This is another example of where physical intuition fails in the understanding of a quantum mechanical effect.

The quantization of angular momentum represented by the above equation can be viewed in another way, as suggested by de Broglie in 1925, if we consider that a moving particle has associated with it a wave length equal to h/mv, where h is the Planck constant and mv is the linear momentum of the particle. This suggestion is a counterpart of the particle-wave dualism of light applied to the elementary "solid" particles such as electrons and protons. If this momentum-wave relation is inserted in the momentum quantization of Bohr, it is found that there are n wave lengths of the electron around its circular orbit.

$$\lambda = \frac{h}{mv} \rightarrow mv\lambda = h \leftarrow \text{(divide by this equation)}$$

$$mvr = \frac{nh}{2\pi} , \text{ (angular momentum quantization)}$$

$$\frac{mvr}{mv\lambda} = \frac{nh}{2\pi h} , \longleftarrow \frac{\text{cancel}}{m, v, h}$$

$$n = \frac{2\pi r}{\lambda} = \frac{\text{circumference}}{\lambda} .$$

The electron can be thought of as a standing wave around its orbit. Standing waves on violin strings and piano strings do not appear to the unaided eye to travel, and by analogy the electron standing waves can perhaps be thought of as stationary, possibly explaining to our classical mechanical intuition why an accelerated electron traveling in a circular atomic orbit is stable and does not lose energy by radiation. If we combine the equilibrium equation for the forces acting on an electron in such an orbit with the angular momentum quantization and solve for the radius, we have

$$\text{electrical force} = \frac{e^2 Z}{r^2} \qquad \left\{ \begin{array}{l} \text{where Z is the number of positive} \\ \text{charges in the nucleus.} \end{array} \right.$$

The force necessary to produce the required radial acceleration to hold the electron in its orbit $= \dfrac{mv^2}{r}$.

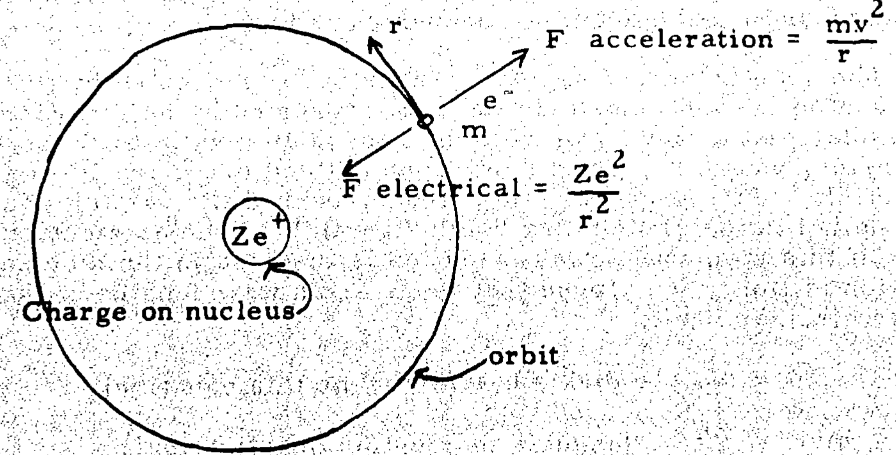
$$\frac{e^2 Z}{r^2} = \frac{mv^2}{r} \text{ , (multiply by r) } \quad \frac{e^2 Z}{r} = mv^2$$

$$mvr = m\hbar, \text{ (square this)}$$

$$r^2 = \frac{n^2 \hbar^2}{m^2 v^2} \text{ , } (\leftarrow \text{ substitute } mv^2)$$

$$r^2 = \frac{n^2 \hbar^2 r}{me^2 Z} \text{ , (multiply by } 1/r)$$

$$r = \frac{1}{mZ} \left(\frac{n\hbar}{e} \right)^2 \text{ , radius of the Bohr orbit,}$$



The energy of an electron in such a "Bohr orbit" is equal to the sum of its kinetic and potential energy, which is

$$W = T + V. \qquad T = \frac{1}{2} mv^2 = \frac{Ze^2}{2r} \quad \text{kinetic energy}$$

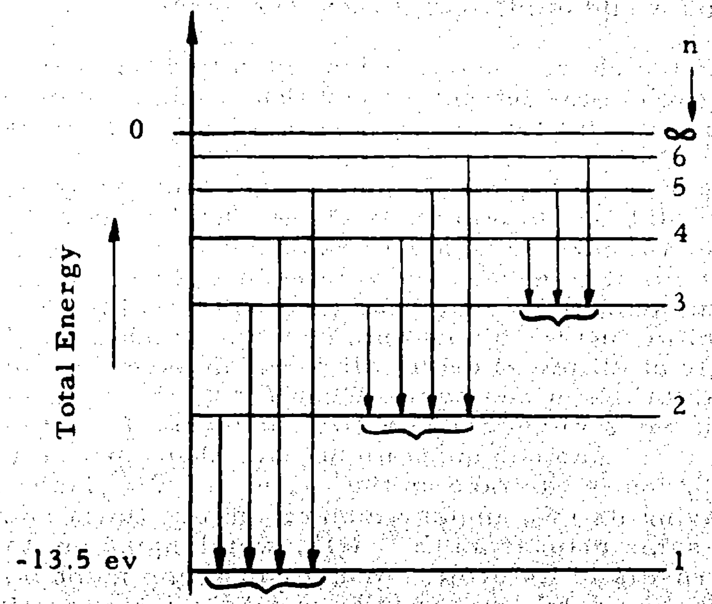
$$V = -\frac{Ze^2}{r} \quad \text{potential energy}$$

$$W = \frac{Ze^2}{2r} - \frac{Ze^2}{r} = -\frac{Ze^2}{2r}$$

The negative sign means the electron is bound in its orbit.

$$W = \frac{Ze^2 m}{2} \left(\frac{e^2}{n\hbar}\right)^2 = -\frac{mZ^2e^4}{2} \left(\frac{1}{n\hbar}\right)^2$$

The energy of a photon of light emitted by an excited atom is equal to the difference in energy of the electron in two orbits. The electron is said to jump from an orbit of higher energy to one of lower energy. The following diagram for a hydrogen atom illustrates this point.



The maximum energy that can be radiated is 13.5 electron volts when an electron falls from an outermost orbit where n is a large number down to the "ground state" where n is one. The relation $h\nu = w_1 - w_2$ gives the frequency of the emitted radiation. The energy of any radiation from a hydrogen atom is given by the following expression:

$$\Delta E = h\nu = W_1 - W_2 = -\frac{mZ^2e^4}{2\hbar^2}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) = \frac{me^4Z^2}{2\hbar^2}\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right),$$

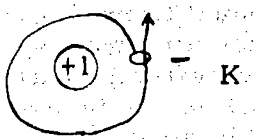
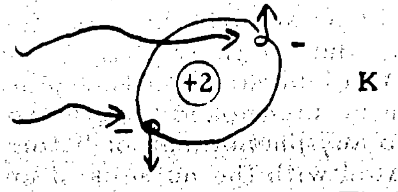
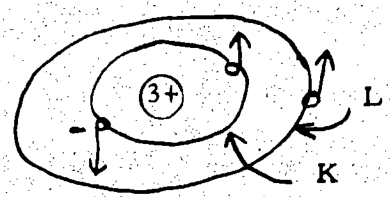
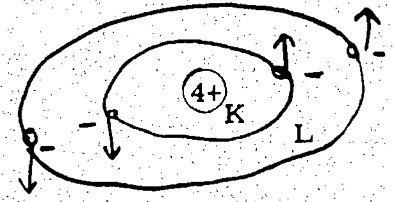
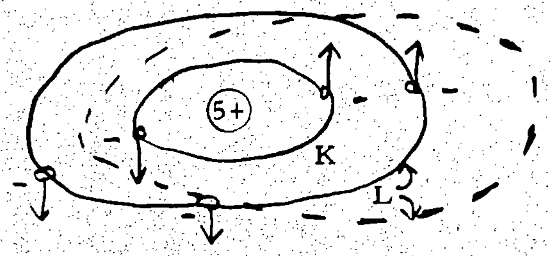
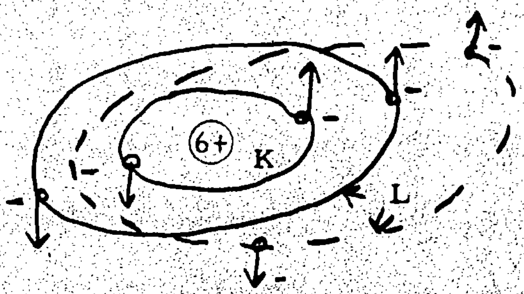
$$\Delta E = 1.09 \times 10^5 Z^2 \left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right) .$$

One atom can make only one jump or transition at a time. The many different spectral lines observed are the results of many atoms making a great variety of jumps in a short time. An atom can, in addition to emitting radiation in a spectral line, also absorb radiation in a spectral line. That is, if a continuous spectrum of light passes through a gas the atoms in the gas absorb light, leaving breaks in the continuous spectrum at exactly the wave lengths where the atoms would emit light if they were excited.

The letter n in the above considerations is called the principal quantum number, and each of the integer values that it can assume (1, 2, 3, . . .) defines a possible circular orbit for an electron in a hydrogenlike atom.

This picture served to explain the most important features of the hydrogen spectrum, but did not explain many of the fine details of this and other spectra. In order to make an adequate explanation of the observed complexity of the spectrum it is necessary to introduce three other quantum numbers. The quantum number ℓ, which can take on the values 0, 1, 2, . . . (n-1), is called the orbital angular momentum quantum number, and is associated with a family of elliptical orbits all of which have the same energy as a particular circular orbit defined by n. When $\ell = 0$, the orbit is circular; when $\ell = 1$, it has a slight eccentricity, and when $\ell = 2$ the eccentricity is larger; etc. Another quantum number that must be introduced is s, the spin of an electron; s can take on the values ± 1/2. Each electron can be thought of as having its own angular momentum due to its spin on its own axis, in much the same manner as the earth, which spins on its axis and at the same time travels in its orbit. Another quantum number, m, called the magnetic quantum number, can take on all the integer values between $+\ell$ and $-\ell$.

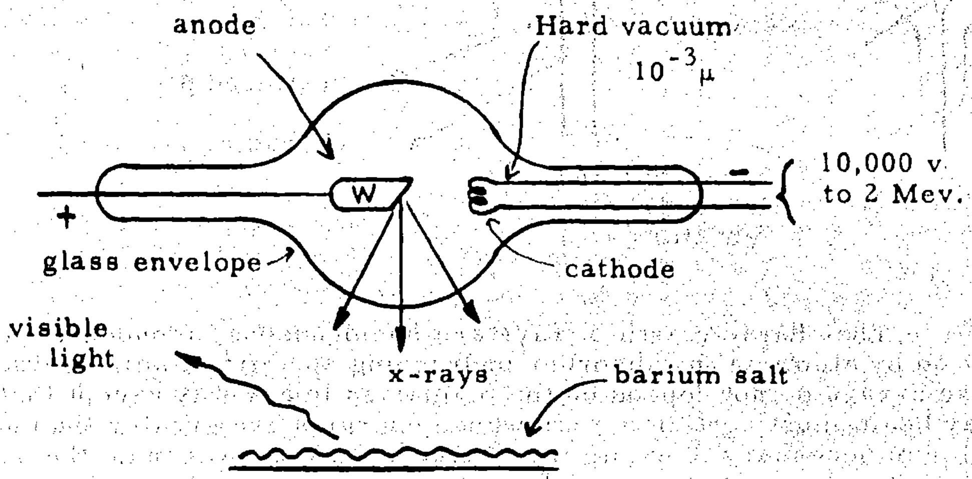
These four quantum numbers, n, ℓ, s, and m, by assuming values consistent with the selection rules mentioned (such as that s is allowed to be only + 1/2 or - 1/2) determine the orbits that are possible for an electron to take around a nucleus. For example, when n = 1, ℓ and m will both be 0, but s can be + 1/2 or - 1/2. This means that two electrons can circulate around a nucleus in an orbit where n = 1, as defined by the equation for the radius above. One of these electrons will have its spin pointed up and the other its spin pointing down. It is not possible for any other electrons to circulate in this particular orbit. This is called the Pauli Exclusion Principle. The atoms that are described by this picture are hydrogen and helium. When n is set equal to two, eight other orbits are possible, etc. The following table and schematic drawings show the situation in the first few elements of the periodic system. With certain complications (which we have not mentioned), this scheme can be extended to explain the atomic structure of all the elements, and can be made to account not only for the spectral distribution of light that they emit or absorb, but also for their chemical behavior in compounds and as ions, and for their physical behavior in solids, liquids, or gases. The complete elaboration of this picture is the entire subject of atomic physics. It might be mentioned that the widely used words "atomic energy" do not apply to any phenomena of "atomic physics," but actually apply to phenomena associated with the nucleus of an atom and not its external electrons.

		quantum nos.				orbit name
Atom	Z	n	ℓ	m	s	
H	1	1	0	0	+ 1/2	
He	2	1	0	0	+ 1/2	
		1	0	0	- 1/2	
Li	3	1	0	0	+ 1/2	
		1	0	0	- 1/2	
		2	0	0	+ 1/2	
Be	4	1	0	0	+ 1/2	
		1	0	0	- 1/2	
		2	0	0	+ 1/2	
		2	0	0	- 1/2	
B	5	1	0	0	+ 1/2	
		1	0	0	- 1/2	
		2	0	0	+ 1/2	
		2	0	0	- 1/2	
		2	1	0	+ 1/2	
C	6	1	0	0	+ 1/2	
		1	0	0	- 1/2	
		2	0	0	+ 1/2	
		2	0	0	- 1/2	
		2	1	0	+ 1/2	
		2	1	0	- 1/2	

X-RAYS

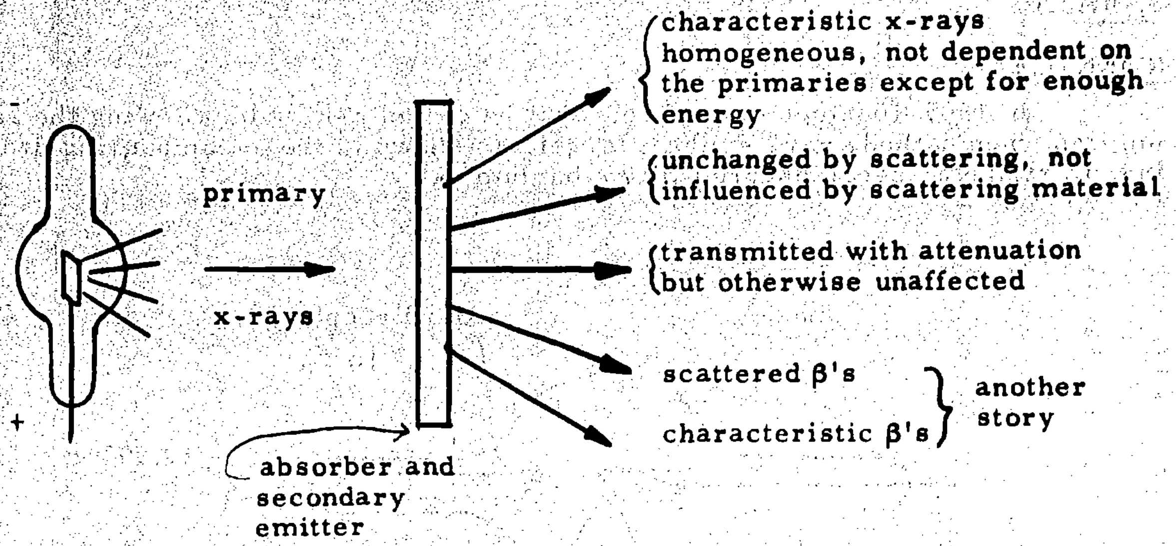
ROENTGEN

In 1895 Roentgen discovered what he called x-rays by allowing the rays emitted when cathode rays strike a target, as shown in the accompanying drawing, to strike a screen covered with a barium salt.



The barium salt is caused to fluoresce, allowing the x-rays to be observed. Roentgen found that opaque solids placed in the beam of x-rays absorb but do not completely eliminate them. He found that the x-rays blackened a photographic plate and caused a gas to conduct electricity, and he found that the x-rays traveled in a straight line and were not influenced by electric or magnetic fields. It is interesting to note that within a very few weeks from the time that Roentgen discovered x-rays they were being used all over the world for medical diagnosis in much the same way as they are used today. Later workers found that x-rays could indeed be reflected, refracted, and defracted just as light can be. X-rays differ from light only in that they have much shorter wave lengths than visible light.

Classical electrodynamics shows that a charged particle will emit radiation when it is accelerated or decelerated. The sudden stopping of an electron when it strikes a solid is the usual method for producing x-rays. X-rays differ in their penetrating ability, depending upon their particular energy. The energy of any one photon of x-rays is equal to $h\nu$, where $\nu = c/\lambda$, as is the case with light. When a beam of x-rays from a heterogeneous or nonmonochromatic source strikes a solid object, five different types of radiation are observed on the far side, as shown in the accompanying sketch.



The characteristic x-rays are homogeneous, monochromatic x-rays emitted by atoms in the absorber undergoing specific atomic orbital jumps. These x-rays do not depend on the primaries in any way except that the primary x-ray beam must contain x-rays whose energies are greater than a certain minimum necessary to excite the characteristic x-rays from the absorber. The scattered x-rays are merely primary x-rays which have been deflected but are not influenced by the scattering material. The transmitted x-rays are unaffected by the absorber and we will not discuss the two types of beta rays, other than to say that they are electrons which have been knocked out of the absorber.

SCATTERING OF X-RAYS

Atoms in an absorber struck by x-rays are accelerated by them, but the electrons in the target undergo much larger accelerations and are by far the most important source of reradiated x-rays. The electrons absorb energy from the x-rays and then, in being brought to rest in the absorber, reradiate this energy or scatter it. In light elements struck by moderately hard x-rays the incident and scattered x-rays differ only in their direction of travel. By classical electrodynamics it is possible to calculate the total energy scattered by a free electron from a plane parallel beam of incident x-rays, as given by the following expression:

$$I = \frac{8}{3}\pi\left(\frac{e^2}{mc^2}\right)^2 I_0 = \frac{8}{3} I_0 \pi r_0^2 \qquad I_0 = \text{incident energy per cm}^2$$

The expression $(e^2/mc^2)^2$ is called the classical radius of the electron and is equal to 2.8×10^{-13} cm, when the values of the electronic charge, electronic mass, and the velocity of light are substituted. If we solve the above equation for the ratio I/I_0 we have

$$\frac{I}{I_0} = \sigma_T = \frac{8}{3}\pi r_0^2 = 6.6 \times 10^{-25}\ \text{cm}^2 = 0.66 \text{ barns,}$$

the classical cross section for scattering by a free electron. This means that each electron has an effective area or "cross section" which it exhibits to an incident beam of x-rays. Any x-ray striking this area will be scattered from the incident beam. If we consider a thickness of material, dt, containing n atoms per cm^3, and each atom containing Z electrons, then the fractional attenuation of an incident beam of x-rays in passing through the thickness dt is given by

$$-\frac{dI}{I} = n\, Z\, \sigma\, dt.$$

If we wish to find the fractional loss of intensity as an x-ray beam passes through a thick absorber made up of many little layers each dt cm thick, we can integrate the above expression, getting

$$I = I_0\, e^{-nZ\sigma t},$$

where I_0 is the intensity of the incident x-ray beam and I is the intensity of the transmitted beam. This expression appears in many different physical situations and is characteristic of any process whereby an incident beam or stream of particles is attenuated "exponentially," as is the case with light, x-rays, infrared, ultraviolet, radio, and with particles undergoing nuclear collisions. This expression is frequently written

$$I = I_0\, e^{-\mu t} = I_0\, e^{-t/\lambda},$$

where μ is the linear absorption coefficient or λ is the mean free path. If our first expression is solved for Z we obtain

$$Z = \frac{1}{n\sigma t} \ln \frac{I}{I_0}.$$

Using this expression, the calculated value of σ, and the measured value of I/I_0, we can determine Z for an element that has been used as an absorber. This makes it possible to experimentally verify the atomic number of an element. It has been found by x-ray measurements of many elements that

$$nZ\sigma \cong 0.2\rho,$$

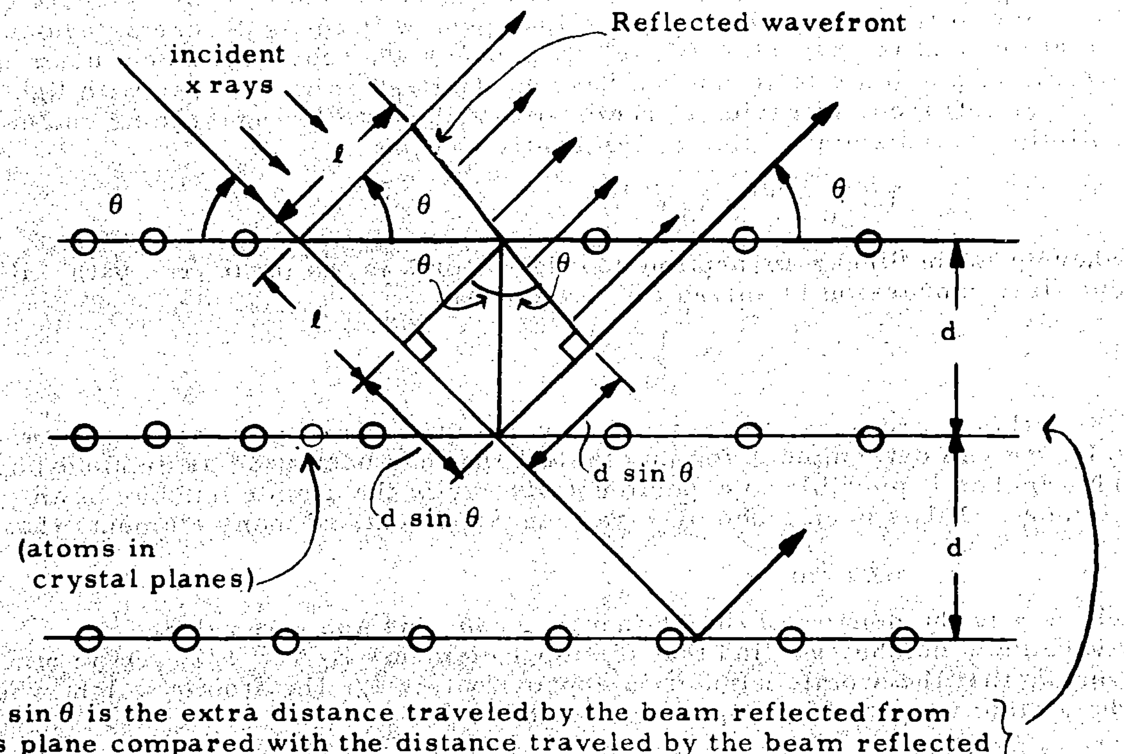
where ρ is the density of the element. From this and a knowledge of Avagadro's number we find that for most elements $Z/A \cong 1/2$. Or in other words, that the atomic number is approximately 1/2 the atomic weight when the atomic weight of hydrogen is taken to be 1.

DIFFRACTION OF X-RAYS

In 1912 von Laue showed that crystals could act as diffraction gratings for x-rays. In order for a wave motion to be diffracted by a periodic structure it is necessary that the wave length be somewhat shorter than the spacing of the structure, but not very much shorter. X-rays have wave lengths from about 10^{-8} to 10^{-9} cm, and crystals have spacings between their atomic planes of 10^{-7} to 10^{-8} cm.

If monochromatic x-rays fall on a crystal "lattice" at an angle of θ to the surface they will be reflected from each of many parallel layers of atoms. These reflected beams will all be parallel, and if it should happen that the angle θ has been chosen in such a way that the x-rays from each successive layer have been required to traverse an extra distance equal to one wave length then the reflected beams of x-rays will add "constructively," and the resulting reflected beam will be quite intense compared with the reflected beam observed at slightly different angles. The values of θ at which this particular reflection occurs are given by the following expression, which is derived from an examination of the accompanying sketch showing the extra path length traversed by the right-hand reflected beam which must be equal to an integer number of wave lengths, n.

$n\lambda = 2\, d \sin\theta$ = Bragg condition.



2 d sin θ is the extra distance traveled by the beam reflected from this plane compared with the distance traveled by the beam reflected from the top plane of atoms, and is equal to $n\lambda$.

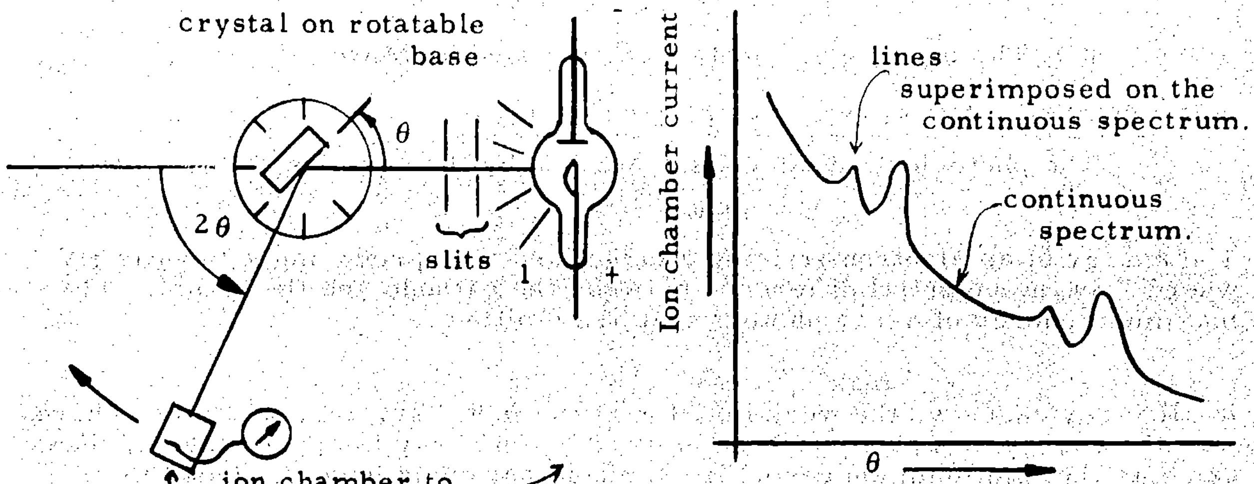
With a particular crystal, d is a constant. As n changes by integers from 1 to 2 to 3, etc., the incident x-rays are reflected by angles θ_n where

$$\theta_n = \sin^{-1}\left(\frac{n\lambda}{2d}\right).$$

These are called respectively first-order, second-order, etc. reflections.

X-RAY SPECTROSCOPY

A simple spectrometer can be made using a crystal in the manner just described, as shown below:



ion chamber to measure the x-ray intensity as crystal and ion chamber are rotated.

Note as the crystal rotates θ the ion chamber must rotate 2θ about the same axis.

The x-rays coming from the tube consist of a continuous spectrum. The lines in the spectrum change as the target material changes. The lines move to different angles but do not change in their relations to one another, as the crystal is changed, since the spacing of the crystal planes d is different for different crystals.

In 1913-1914 Moseley made x-ray tube targets of a great variety of elements. He measured the spectra arising from each and noted that there was an orderly shift of the characteristic lines in the x-ray spectrum from element to element. He concluded that:

(A) There must be a physical quantity that increases from one element to the next in the periodic system. This is Z, the atomic number.

(B) This quantity must be the total charge on the nucleus or the number of electrons around the nucleus.

(C) The atomic weight increases by about 2 from one element to the next.

(D) Since $Z \cong 1/2\,A$, then Z increases by 1 unit from one element to the next.

(E) The number of the place in Mendeleef's chart is the number of charges on a nucleus.

(F) The order of the atomic numbers Z is the same as the order of the atomic weights (except where it was already known that the weights disagreed with the order of the chemical properties).

(G) The missing elements were verified by Moseley.

RELATION OF THE PHOTO EFFECT TO X-RAYS

The photoelectric effect is described by the equation

$$E = h\nu - w.$$

The energy of an electron striking a target and thus producing x-rays is EV where V is the potential difference between the cathode and the target. The maximum energy of x-ray photons that are emitted is

$$E_{max} = h\nu_{max} = Ve.$$

In all x-ray cases w, the work function of the metal surface, is $\ll h\nu$. Therefore the energy of a photoelectron emitted by an x-ray is approximately the same as the minimum energy of an electron that could have produced that x-ray.

X-RAY SPECTRA

The several features of x-ray spectra are:

1. Continuous or bremsstrahlung spectrum due to electrons' being decelerated by the target without exciting any particular atomic level.

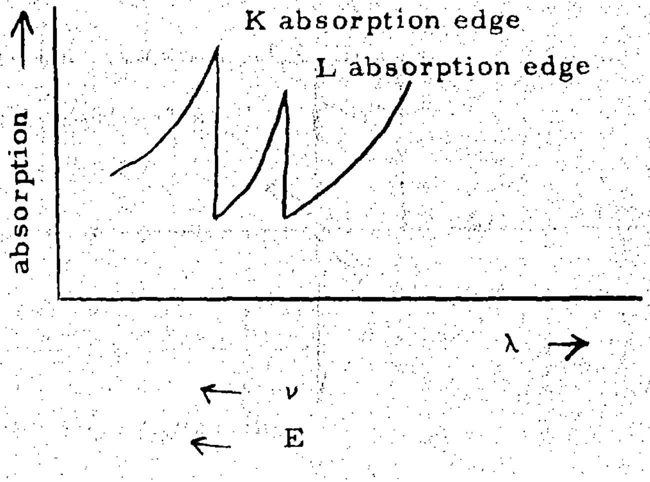
2. Line spectra due to a K or an L electron's being ejected and an outer electron then falling into this vacancy. In a heavy target these photons have much more energy than the hydrogen spectra had when an electron fell into the K orbit of hydrogen. This can be seen from the energy equation for an L-to-K jump,

$$\Delta E = h\nu = \frac{mZ^2e^4}{2\hbar^2}\left(\frac{1}{1^2} - \frac{1}{2^2}\right) = \frac{3}{8}\,\frac{me^4}{\hbar^2}\,(Z-1)^2$$

The (Z-1) is the effective charge of the nucleus with one K electron circulating around it as seen by an electron jumping into this K orbit and thus filling the K orbit. The large value of $(Z-1)^2$ accounts for the high energy of x-ray lines compared to optical lines.

3. There are no x-ray absorption lines because the orbits for some distance outside the K and L shells are filled, and the only place a K or L electron can be knocked by an x-ray is into the continuous or unbound energy region above the zero of energy in the energy-level diagram.

4. There are "absorption edges" in the x-ray absorption spectra, which occur at the energies where a K or L electron can be knocked completely out of an atom.



THE SPECIAL THEORY OF RELATIVITY

In 1905 Einstein proposed what is now called the Special Theory of Relativity. Although this "theory" has long since been tested so thoroughly that it is one of our best-founded sets of physical laws, it is still referred to as a theory. This set of principles and the Quantum Theory are the two principal developments of the 20th century. The word "special" refers to the limitation of the theory to constant velocities between the two observers who are usually involved in problems treated by the theory. If there is an acceleration between the two observers, then the Special Theory of Relativity does not treat the problems that arise, but the General Theory of Relativity (to which we will not refer) does treat them. Problems that involve gravitational fields and rotation are treated only by the General Theory.

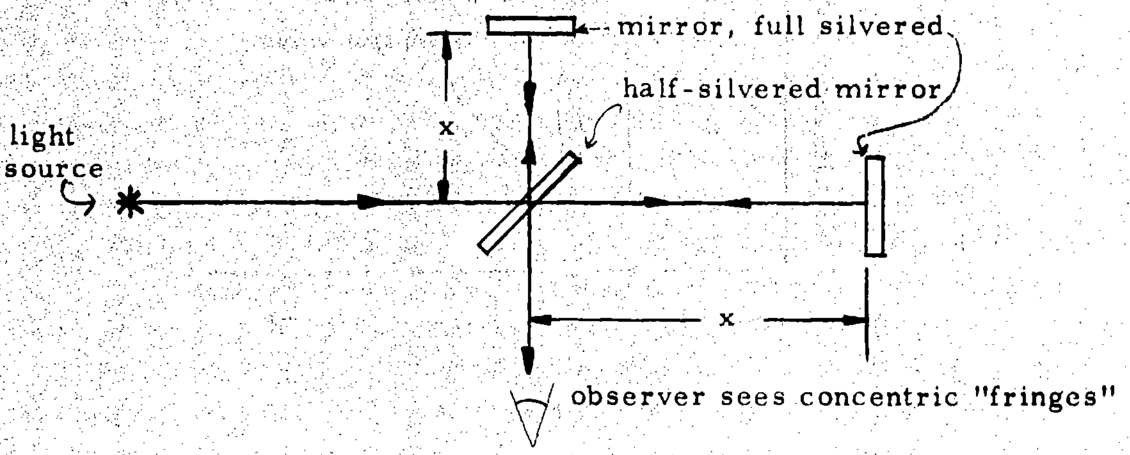
The Special Theory can be introduced by considering concepts of space, time, and simultaneity, or it can be introduced by considering the dilemmas of thought that were prevalent at the end of the 19th century. These were:

(1) The ether and the problem of absolute velocity.

(2) The invariant form of physical theories.

We will try the second approach.

Light waves would presumably need a medium in which to vibrate and be propagated. Light is known to pass through space that is devoid of matter. The ether that was suggested as the medium in which light vibrates and propagates, was said to be a weightless material permeating the entire universe. The ether was supposed to be stationary, whatever that means. The earth was supposed to move through it without disturbing it. By absolute velocity was meant the velocity relative to the ether. Michelson and Morley in 1897 performed an experiment to measure the velocity of the earth through this ether. Their experiment was done with an interferometer as shown below:



Interference fringes are seen by the observer, and a 90° rotation of the apparatus--moving one arm of the interferometer from its position parallel to the relative velocity of the earth and the ether to a position perpendicular to it--should have shifted the fringes by 1/3 of their width. A shift of 1/100 fringe could have been easily seen. More modern techniques have been sensitive enough to see a shift of 1/1000 of a fringe width. The velocity of the earth in its orbit is 30 km per second. The most refined versions of this important experiment have given a null result to within ± 1 km per sec. The negative result of the experiment made some suggest that the earth dragged the ether along, but there were few properties of the ether that were useful, and its experimental detection was apparently not possible, so it was abandoned. The conclusion that one is forced to by this and many other experiments is that all motion is relative and that there is no absolute velocity on frame of reference.

Einstein explained away the difficulties that had accumulated in mechanics and electrodynamics by the postulates of the Special Theory of Relativity and the conclusions that he and others have drawn from them. The postulates are:

(1) It is impossible to measure or detect the unaccelerated translatory motion of a system through free space or through any etherlike medium that might be assumed to pervade it.

(2) The velocity of light in free space is the same for all observers, independent of the relative velocity of the source of light and the observer.

The first law forces one to the conclusion that physical laws must be independent of the velocity of the system in which they describe events. If they were not, then their difference would define an absolute velocity. The second law is believed to be an experimental fact based on the Michelson and Morley experiment and on astronomical observations. The second law, plausible as it may seem, runs grossly contrary to our intuition. Consider, for example, a light pulse starting from a point P, and consider this event as recorded by observers stationed in two frames, one frame containing P at the origin, while the other frame moves relative to P with a velocity $\vec{v}$. Let the origins of the two frames coincide at the start of the pulse. According to the statement above, both observers must see the light wave propagating as a spherical wave centered at their respective origins! If we consider the position of the wavefront to be an event permitting description independently in space and in time, then this statement cannot be true. The independence of the velocity of light of the particular frame therefore requires a revision of the accustomed ideas of the possibility of specifying the position coordinates of an event referred to a particular frame; it requires specifying the time of the event by a "universal" time scale. The above paradox would not exist if there were no such universal time scale, and if the simultaneity of the wave-front passing through two points were an observation that was not independent of the frame of the observer. If such a disagreement as to the simultaneity of time of passage through a set of points were permitted to exist, then presumably a kinematics could be constructed in which a spherical light wave would be seen in both frames of reference.

Therefore, we are led to re-examine the concept of simultaneity. If we must abandon the existence of a universal time as not corresponding to reality, then we must establish a mechanism whereby simultaneity can be established in a given frame. This mechanism must be such that a measurement of the velocity of light in the particular frame using its time and distance scale must give c. This means that the only way in which simultaneity can be defined is by means of the velocity of light itself. This conclusion gives c a much more fundamental significance than just the velocity of propagation of electromagnetic waves; it introduces c into all the relations of physics. Among other things, the utilization of c as the defining element of simultaneity precludes the existence of the "ideal rigid body" of mechanics; if there were such a body, its ends would move simultaneously as observed by any frame and it would therefore be used as a means of establishing a "universal time," in violation of our former conclusions.

We therefore consider two instants of time t_1 and t_2 observed at two points x_1 and x_2 in a particular frame as simultaneous if

(a) a light wave emitted at the geometrically measured midpoint between x_1 and x_2 arrives at the time t_1 at x_1 and at the time t_2 at x_2, or if

(b) a light wave emitted at x_1 at the time t_1 arrives at x_2 at a time

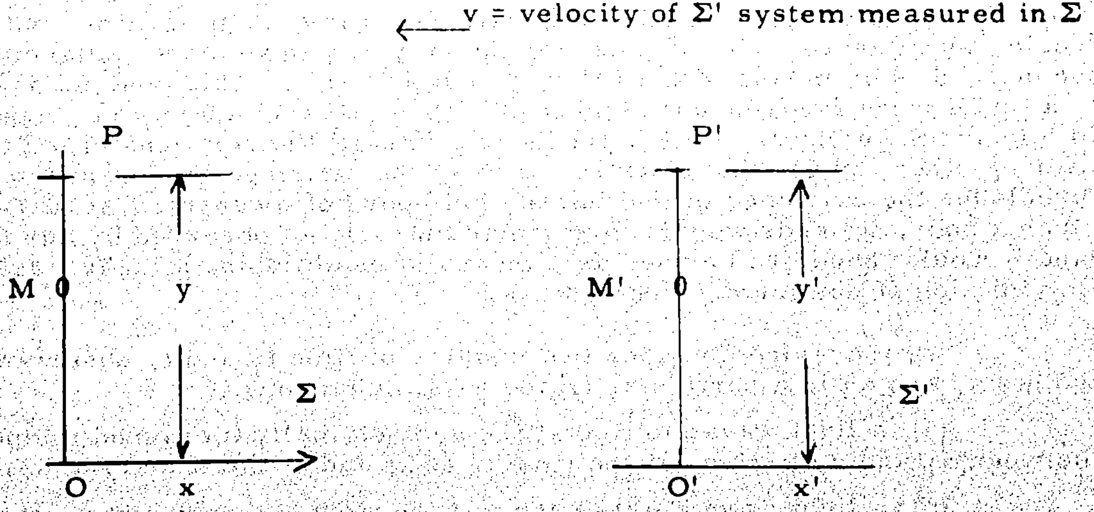
$$t_1 + \frac{x_2 - x_1}{c} = t_2 .$$

The first definition of simultaneity will automatically assure that a light pulse emitted at the origin will reach all equidistant points simultaneously and that the wave surface is therefore a sphere in a particular reference frame. Simultaneity of two events at two spatially separated points therefore does not have a significance independent of the frame. The relation of the time intervals observed by two different frames is therefore dependent on the spatial interval between the events; the Galilean* transformation, which transforms temporal intervals as observed by two frames independently of spatial coordinates, therefore cannot be in agreement with the simultaneity definition in terms of c. We must therefore attempt to derive the corresponding transformations from an (x, y, z; t) frame to a (x', y' z'; t') frame, which will supersede the Galilean transformation. Such a transformation must remain linear, to assure mathematical equivalence of all points in space and time, but the spatial and temporal coordinates need not transform independently.

The desired transformation gives the relation between the space-time coordinates of an arbitrary event (x, y, z; t) as observed in the Σ frame and the space-time coordinates (x', y', z'; t') as observed in the Σ' frame. This transformation must obey the postulates of special relativity for an event of any type. We shall therefore construct a set of "Gedanken-experiments,"** each of which will incorporate only one additional feature of the transformation in order to indicate how the basic postulates of relativity necessitate the nature of the transformation.

Experiment I - Comparison of parallel measuring sticks oriented perpendicular to their direction of relative motion.

Let us assume that it is possible to bring the frames Σ and Σ' of the figure below to relative rest and to adjust the two measuring sticks to equality.



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* Galilean transformation:

$x' = x - vt$

$y' = y$

$z' = z$

$t' = t$

** Thought experiments.

It is assumed explicity that the properties of a given body of specified structure are independent of its past history when observed in a frame where that body is at rest (called the "proper" frame*), it is therefore not essential whether the adjustment of lengths referred to is possible or not; it could for instance be specified that the length of each rod should be a given number of wave lengths of a specified spectral line measured in each frame.

Let the two systems approach each other so that the midpoints M and M' coincide. Let light signals be sent from O and P at the time when O and P coincide with the y' axis. Since OM' remains equal to PM' during the motion, O and P will appear to cross the y' axis simultaneously in both systems. We therefore conclude that along a direction perpendicular to the direction of relative motion simultaneity will be the same in both systems. Both observers can therefore compare the positions of the end markers at time of cross-over and arrive at the same result, since the time of observation for both ends is defined identically in both systems. Hence both observers would conclude either OP $\geqslant$ O'P', or O'P' $\geqslant$ OP; since both systems are fully equivalent as to their state of motion, an asymmetric solution would provide a means of determining absolute velocity, which is ruled out by the postulates. We therefore put

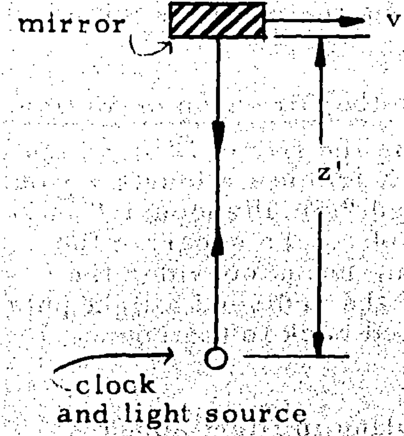
$$y' = y \tag{1}$$

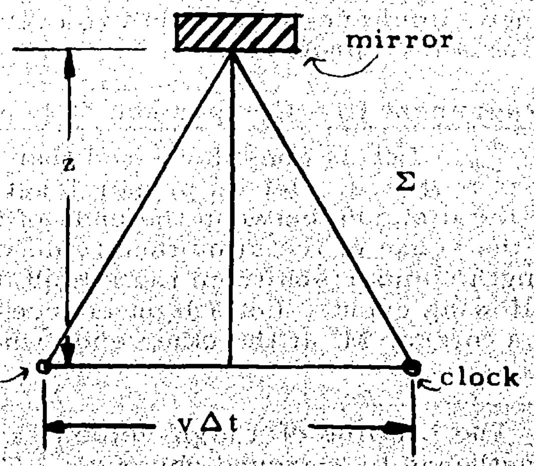
and, similarly,

$$z' = z, \tag{2}$$

Experiment II - Comparison of Clock Rates

In comparing clock rates among moving systems, we are faced with a fundamental difficulty: it is impossible to compare one clock in Σ with one clock in Σ', since they will not stay in coincidence; we must compare two clocks in Σ with one clock in Σ' and synchronize the two clocks in Σ by light signals. Consider that in Σ' at the clock position a light signal is emitted normal to $\vec{v}$ and reflected at a mirror normal to the z' axis at a distance z' from the clock and returned to the clock, as seen below:





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* The length of a rod when measured in a frame in which the rod is at rest is called its "proper length."

Σ' will define the time interval between the sending and receiving of the pulse as

$$\Delta t' = \frac{2z'}{c} \quad , \tag{3}$$

Σ can record the time interval Δt between the same events with two clocks spaced vΔt apart. Σ concludes therefore, since c is independent of frame,

$$c\Delta t = 2\sqrt{z^2 + \left(\frac{v\Delta t}{2}\right)^2} \quad , \tag{4}$$

$$\Delta t = \frac{2z}{c} \frac{1}{\sqrt{1-\beta^2}} \quad , \tag{5}$$

or, from (1) and (3),

$$\Delta t = \frac{\Delta t'}{\sqrt{1-\beta^2}} \quad (\Delta t' \text{ is the proper time interval}) \tag{6}$$

Note that the apparent asymmetry causes no paradox, since this is not a symmetrical situation; Δt' is the time interval between two events occurring at the same place in the Σ' frame. Although Δt' is called the "proper time interval" between the two events, Δt, on the other hand, is not a proper interval, since it is measured by two clocks at different places. A proper time interval, similar to a proper length discussed above, is a definite function of the physical nature of the clock: e. g., a particular radioactive decay constant or the natural frequency of a crystal of specified proper dimensions is a constant in the frame where such time intervals are observable at a single point; i. e. in a frame where such a "clock" is at rest.

Note therefore that Σ will find that his (not proper) time interval is longer than the proper time interval, measured in Σ'. This phenomenon is known as time dilation.* Σ' cannot judge the rate of the Σ clocks, but as we shall see later would consider them out of synchronism, which is reasonable since simultaneity between two events displaced along the x axis is not an invariant** property.

Experiment III - Comparison of Lengths Parallel to the Direction of Motion

Let us consider a rod that has a length x' in the frame Σ' in which it is at rest: i.e., let its proper length be x'. In the Σ frame its length x would be the distance between the ends of the rod measured "simultaneously" in Σ in the sense of the simultaneity definition in terms of c. To separate the length comparison from the simultaneity calculation, let us consider the following event. Let a light source S' at one end of the rod send a light pulse to a mirror M' at the other end, where it is reflected back to the source.

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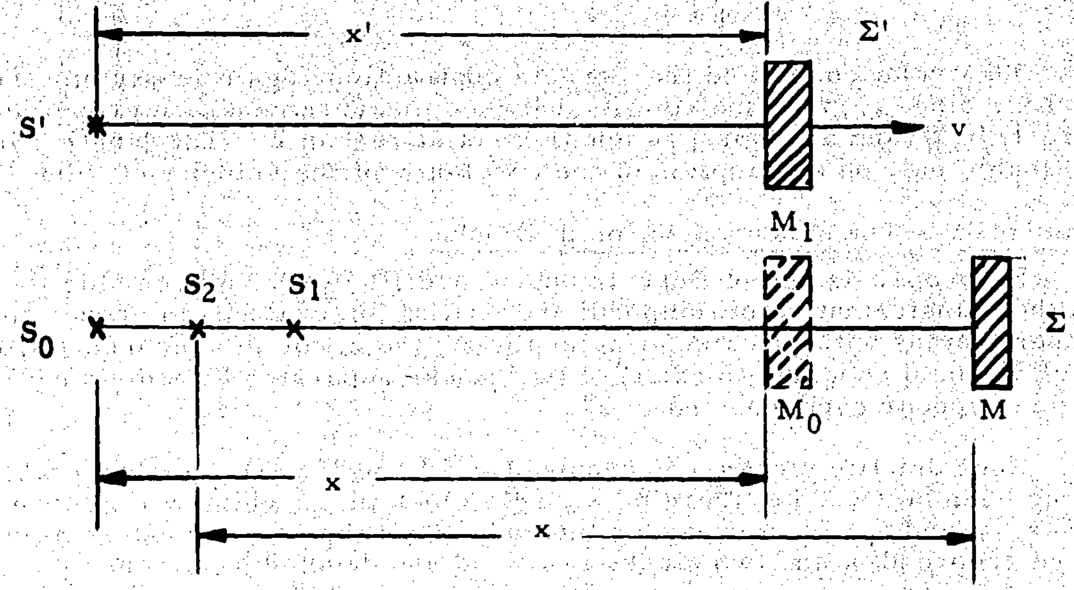
[*] The lifetime of a high-velocity meson disintegrating in flight appears lengthened to a ground observer. The lifetime in the proper (i. e., the meson's) frame is invariant.

[**] We shall use the word "invariant" to mean "independent of choice of inertial frame."



Let $\Delta t'$ be the time interval between the time of emission and the time of arrival of the signal. Note that $\Delta t'$ is a proper time interval, being observable with a single clock at one point. Evidently we have

$$\Delta t' = \frac{2x'}{c} \quad . \tag{7}$$

In Σ these same events appear to be more complicated. At the time of emission the source S' was at S_0 and the mirror M' at M_0. (This statement has unique meaning only when referred to Σ'.) At the time of reflection, the mirror M' has moved to M and the pulse returns to the source S' when it is at S_1. The time interval Δt is thus measured between the points S_0 and S_1 with two clocks (Δt is not proper) as in Experiment II. Equation (6) therefore applies here also. By definition, we mean by x the distance S_0M_0. Since M_0 has moved to M with velocity v while the light moved from S_0 to M with velocity c, we have

$$S_0M = x + \frac{v}{c} \; S_0M, \quad S_0M = \frac{x}{1-\beta} \tag{8}$$

and similarly, since the source has moved from S_2 to S_1 with velocity v (where $S_2M = x$) while the light has traveled from M to S_1 with velocity c,

$$MS_1 = x - \frac{v}{c} \; MS_1, \quad MS_1 = \frac{x}{1+\beta} \tag{9}$$

Hence we have

$$\Delta t = \frac{S_0M + MS_1}{c} = \frac{2x}{c(1-\beta^2)} \quad . \tag{10}$$

From (6) and (7), this becomes

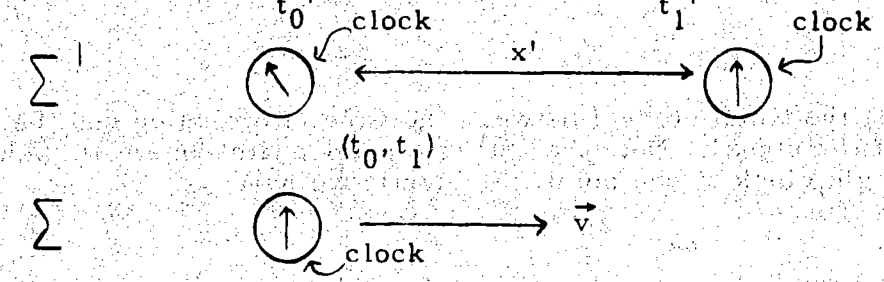
$$x = x' \sqrt{1-\beta^2} \quad . \tag{11}$$

This relation, called the Lorentz contraction, again is asymmetrical in x and x', since it gives the relation between measurement of a proper length x' (at rest) in Σ' and an improper length x not at rest in Σ. The length x in Σ was definable only on assumption of the constancy of the velocity of light.

Experiment IV - The Synchronization of Clocks

By proper design of Experiments II and III, we have been able to derive the transformation of temporal and spatial intervals from proper to nonproper frames without calculating explicitly the error in synchronization δ (which Σ would conclude to exist) of two clocks separated by a distance x' in Σ' which appear synchronized in Σ'.

Consider two clocks synchronized in Σ' and located a distance x' apart, as seen below. Let there be a single clock in Σ, which will record the times, t_0 and t_1, when it passes the ends of x'; the corresponding times in Σ' are recorded on the two clocks in Σ' and are denoted by t_0' and t_1'.



Since $t_1 - t_0$ is a proper time interval in Σ, we can apply (6) in reverse, giving

$$t_1' - t_0' = \frac{t_1 - t_0}{\sqrt{1-\beta^2}} \quad . \tag{12}$$

The observer on Σ could apply the dilation equation (6) to the rates of the individual clocks at the ends of x', but would conclude that they are out of step by an amount δ; i.e.:

$$t_1 - t_0 = \frac{t_1' - t_0' + \delta}{\sqrt{1-\beta^2}} \tag{13}$$

Both observers have to obtain the same value for the relative velocity v between the frames, since if one obtained either a larger or smaller value, the frames would not be equivalent. Hence

$$t_1' - t_0' = \frac{x'}{v} \quad , \tag{14}$$

$$t_1 - t_0 = \frac{x}{v}, \qquad (15)$$

but, since x' is a proper length in Σ', we obtain

$$x = x' \sqrt{1-\beta^2}. \qquad (11)$$

Combining Eqs. (13), (14), (15), and (11), we have

$$\delta = - \frac{x'\beta^2}{v} \quad . \qquad (18)$$

The negative sign indicates that in the opinion of Σ the leading clock (t_0') in Σ' should have indicated a larger time,* in order to make the elapsed time between t_0' and t_1' as observed by Σ smaller.

These four experiments have thus demonstrated four kinematic relations:

I. Distances transverse to the direction of motion are invariant.

II. A time interval Δt measured in a frame moving with velocity ±v relative to a frame in which the time interval Δτ between two events is proper (i.e., the two events occur at one place) is given by

$$\Delta t = \frac{\Delta\tau}{\sqrt{1-\beta^2}} \quad . \qquad (19)$$

III. The length Δx of a rod measured in a frame moving with velocity ±v relative to a frame in which the rod is at rest and has the proper length Δλ is given by

$$\Delta x = \Delta\lambda \sqrt{1-\beta^2} \quad , \qquad (20)$$

IV. Two clocks, synchronous in a given frame, and separated by a distance Δλ in that frame, appear to be out of synchronism as observed by a frame moving with a relative velocity -v to the clock frame, by an amount given by

$$\delta = - \frac{\Delta\lambda v}{c^2} \quad . \qquad (21)^*$$

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* The clock that is ahead (i.e., met first) is behind (in time).

THE LORENTZ CONTRACTION

The above thought experiments have led to kinematic relations that will now be combined into a general relation between the time and space coordinates of a particular event as observed from inertial frames in relative motion. This relation is called the Lorentz Contraction, and is given by the relations

$$x = \frac{x'+vt'}{\sqrt{1-\beta^2}}, \quad y = y', \quad z = z', \quad t = \frac{t'+\frac{x'v}{c^2}}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c} .$$

So far we have dealt with kinematics and no forces or masses were involved. In order to preserve the conservation of momentum we are forced by the above relations and others for the transformation of velocities to conclude that a mass moving relative to us must be increased by the relation

$$m = \frac{m_0}{\sqrt{1-\beta^2}} ,$$

where m_0 is the rest mass or the mass we would measure if the body were brought to rest.

Another direct result of the Lorentz transformations and the conservation of momentum is that the total energy of a body--that is, the sum of its "rest energy" and kinetic energy--is

$$E = mc^2,$$

where the rest energy is m_0c^2. It is this energy $E = mc^2$ that is conserved in any interaction. It is thus necessary to realize that each erg of energy has associated with it $1/c^2$ gram of mass. The chemical law of the conservation of mass and the First Law of Thermodynamics (the law of the conservation of energy of which we have not spoken) thus become one law.

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Material Developed in Discussion Following Lectures

In addition to explaining and expanding the outlined topics, Dr. Wallace gave a brief illustration of the technique of dimensional analysis, and in addition to the well known and widely used mks, cgs, and fps systems, mentioned one we hope is never widely adopted, wherein units are the chain, stone, and fortnight.

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After-lecture discussion topics included:

1. Conditions that determine whether a heated element gives its own or a continuous spectrum.

2. Coated lenses for reducing reflection. The same principle (application of a transparent layer 1/4 wave length thick) is the basis of the "dirty shirt" technique of coating ships with a rubber and iron-filing coat to minimize radar detection.

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The production of x-rays by components of television sets was discussed. The instructor pointed out that the glass of the picture tube was adequate shielding for the 17-kv tubes at present used on black and white sets. Color, with its higher voltages and metal target screens, might need reconsideration. He felt that indiscriminate use of fluoroscopes for "shoe fitting," particularly with children, was far more harmful. He also emphasized that radioactive decay of radon, everywhere (but fluctuatingly) present in the air, made isolated radiation counter readings subject to careful interpretation.

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TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

Radiation Laboratory
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Chapter 2

NUCLEAR PHYSICS

Warren Fenton Stubbins

UNITS AND DESCRIPTION OF THE NUCLEUS

There are several systems of units in use in the sciences. They are the cgs, mks, and fps. Nuclear physicists use almost exclusively the cgs (centimeter-gram-second) system. The electrical and magnetic fields and the strengths of charges are expressed in three systems of units also. These are the emu, esu, and practical systems. In computations the units must be adjusted to agree, i.e., be in one system only.

We shall encounter a number of natural constants and useful values of certain quantities, some of which arise by definition. A tabulation of a number of these is given below.

Review (and extension) of units

unit	mks	cgs	fps	atomic
(l) length	meter	cm	foot	
(m) mass	kilogram	gram	pound	atomic mass unit = amu
(t) time	second	second	second	
(F) force	newton	dyne	pound	
(E) work	joule	erg(dyne cm)	foot-pound	electron volt
power	watt(joules/sec)	watt	horsepower	

Approximate values for some well-established physical constants are:

Velocity of light	c	=	3×10^{10} cm/sec
Electronic charge	e	=	4.803×10^{-10} esu
Planck's constant	h	=	6.625×10^{-27} erg sec
Avogadro's constant	N_0	=	6.02×10^{23} per gram mole
Rest mass of electron	m	=	9.1×10^{-28} g = .51 Mev
1 atomic mass unit(amu) =	$\frac{1}{N_0}$	=	1.66×10^{-24} g = 931 Mev
Ratio mass electron/proton		=	1/1836
One electron volt	1 ev =		1.602×10^{-12} erg
One million ev = 1Mev,		=	1.602×10^{-6} erg

Einstein revealed much of the nature of nuclear physics in his study of special relativity, and the direct application of this theory is necessary in order to permit analysis and understanding of the observations of nuclear systems. Thus we note the following definitions of the energy content of a system and other quantities. We accept the premise that mass and energy are equivalent and are connected by the relation

$$E = Mc^2 \gamma = Mc^2 \frac{1}{\sqrt{1 - \beta^2}} = Mc^2 \frac{1}{\sqrt{1-(v/c)^2}} ,$$

where E is the total energy of the system, M is the rest mass of the particle, and v is its velocity; c is the velocity of light in a vacuum, a universal constant; $\beta = v/c$, the ratio of the particle velocity to the velocity of light, and γ are defined by the above equation. When the velocity of the particle is small compared with the velocity of light, the equation reduces to the classical, i.e., nonrelativistic, expression of our daily experience. For example, the value obtained when the velocity is zero is the rest mass in energy terms. The difference between the energy and the rest energy is the energy of motion, or what is called kinetic energy. Thus we define kinetic energy as the total energy less the rest energy. For a slow particle, $\beta << 1$, the kinetic energy by our definition becomes the classical

$$\frac{1}{2} Mv^2.$$

However, if the particle is not slow a serious error results if one uses the classical expression for kinetic energy. One may decide to consider a particle as relativistic when this error exceeds an arbitrarily chosen limit. As an example, for a particle with the velocity 1/10 the velocity of light, the total energy is about 0.5% greater than the rest energy. This increase is the kinetic energy of the particle. As the velocity increases the energy increases, and as the velocity nears the velocity of light the total energy increases without bound. For a particle with the velocity of light its total energy would be infinite, thus we conclude this velocity is not attainable by particles. In high-energy accelerators the energy of the particles may increase higher and higher, but the velocity only approaches the speed of light.

The linear momentum of a particle is defined as

$$p = Mv \frac{1}{\sqrt{1-v^2/c^2}} = Mv\gamma,$$

and a useful relation between the momentum, rest energy, and total energy is

$$E^2 = M^2c^4 + p^2c^2.$$

The simplest nuclei have masses of about 10^{-24} gram. An atomic mass unit--a useful unit of the masses of nuclei and atoms--is defined as 1/16 the mass of that isotope of oxygen having 16 nucleons. By this choice, 1 amu = 1.6599×10^{-24} gram, the masses of all other atoms are very close to integers when expressed in atomic mass units. In energy units 1 amu = 931 Mev. The atomic masses are determined by comparison in mass spectrographs, by dividing the total mass of a sample of a substance by the number of atoms in it; also by other means. A relation between the mass of a substance and the number of atoms in it is given by Avogadro's number whose numerical value is the reciprocal of the atomic mass unit.

Measurements of the sizes of the atom and of the nucleus have been made. The atomic size may be learned by x-ray examination of crystals, and nuclear sizes by scattering high-energy neutrons off the nucleus or by studying the theory of alpha decay. Atoms have a radius of about 10^{-8} cm and their nuclei about 10^{-13} cm. An interesting and revealing relation between the radius of a nucleus and the number of nucleons making up the nucleus is

$$r = r_0 A^{1/3},$$

where A is the number of nucleons and $r_0 = 1.5 \times 10^{-13}$ cm.

A picture of the distribution of nuclei in the most dense material, in a crystal, may be seen by expanding the nuclear size from its small actual size to the size of a baseball and allowing atomic dimensions to increase similarily. We thus find a 3-inch ball hung in space about every 3 miles in each direction. This wide spacing may make the diffusion of neutrons through matter a little more plausible, but because of the number of nuclei in matter (as reflected by Avogadro's number) a neutron can travel only a few centimeters through matter before a nuclear reaction occurs.

The density of nuclear matter may be calculated by dividing the mass of a nucleus by its volume. This is seen to be approximately 10^{14} grams per cubic centimeter, or about one billion tons per cubic inch.

It is necessary to define the terms "system" and "state of a system." For our purposes a system consists of the atomic and nuclear particles of interest prior to and after the nuclear process. These particles may be few, or even only one, before, and few or many afterwards. For example, a system of a decaying alpha emitter is initially the single nucleus and afterwards is the alpha particle and the recoiling residual nucleus. It may be initially a neutron and a uranium nucleus, and afterwards a number of free neutrons and several fission fragments. The state of a system is the description of the condition of each member of the system, including the energy, momentum, type of particle, charge, and other parameters.

Whether a system will undergo a nuclear reaction must be examined in the light of the principles of physics, once the state is known. Yet, if two charged particles of like charge are going to react nuclearly they must first come together. The electrical force that keeps them apart is Coulomb's force, and the particles must overcome the Coulomb barrier. This barrier may represent a considerable inhibition. Neutral particles, however, are not so hindered, and neutron-induced reactions are therefore of particular interest and application.

An atom consists of a nucleus and a system of negative electrons about it. The atom is neutral when the number of electrons is equal to the number of positive charges in the nucleus. An ionized atom is one from which one or more electrons have been removed, and is thus no longer neutral. The chemical properties of the atom are determined by the electrons surrounding the nucleus. The positive charge on the nucleus is formed by the protons contained in it. The other constituent is the neutrons. The protons and neutrons are both called nucleons, and their total number is called the mass number and is designated by A. The number of protons--equal to the number of electrons--is called the atomic number, and is designated by Z. The difference, A - Z, equals the number of neutrons and is called $n = A - Z$.

By the definition of the atomic mass unit, the actual mass of the nucleus is very close to the numerical value of A when the mass is expressed in mass units. One finds A by rounding the atomic mass to the nearest integer. For example, the mass of Al is 26.9899 amu, whereas its rounded value is 27. This is the number of nucleons in the aluminum nucleus. We may note this by writing Al^{27}. We know that aluminum has 13 electrons about it, so that the number of protons, Z, is 13, and thus 27 - 13 = 14 neutrons are also in the nucleus. We may denote this by ${}_{13}Al^{27}$, but we should observe that the 13 and the chemical name aluminum both mean the same. Thus we may not wish to write both.

Any nucleus is completely identified by specifying its A and Z. Its properties, however, must be learned by observation. Some nuclei (A, Z) are stable and found in nature, while others are radioactive, with various types of radiation. A radioactive nucleus is one that changes from one state to another spontaneously. For an initial collection of atoms with a particular nucleus its half life is the time required for half of the nuclei to have changed state. This time may be small or large. If it is so large as to be unmeasurable--say, something like 10^{17} years, we then say the nucleus is stable.

Any chemical element, i.e., of a given Z, may have several different values of A. These together are the isotopes of the chemical element; for example, the isotopes of carbon include C^{11}, C^{12}, C^{13}, C^{14}. Whereas the isotopes of a particular element act chemically very much alike, the isotopes differ greatly in the following respects.

(1) They have different masses.

(2) They vary in stability.

(3) They possess different nuclear properties:

 (a) if they are unstable, the characteristic radiations differ,

 (b) they have different probabilities of nuclear reactions (we say simply that their cross sections differ).

(4) The abundances of the stable ones found in nature differ.

For the isotopes that are radioactive, it is interesting to note that the differences between the types and characteristics of radiation permit each isotope to be identified by physical measurements of the half life, of energy, of radiation, etc. This fingerprint has been used to advantage in research and industrial applications.

Elements that have the same mass number A are called isobars. A given mass number includes different chemical elements, each of which has a different atomic mass although all are close to the same value. Isobars can be separated chemically and they each have different nuclear properties, including being stable or unstable and having different cross sections.

A major contrast between the realm of atomic and nuclear physics and the everyday physical world is the use of conservation principles in studying microscopic systems. Since each part of the system is of interest and may be accounted for, conservation rules are easily considered.

In nuclear reactions the following properties are conserved--i.e., the amount present before and after a reaction is the same:

1. Mass-energy (obeying $E = mc^2$)
2. The number of nucleons
3. Charge
4. Linear momentum (= $m v \gamma$)
5. Angular momentum (this the moment of linear momentum)
6. Statistics (Fermi-Dirac or Bose-Einstein)
7. Parity (not discussed, but it may be odd or even).

A particular nuclear reaction may be prohibited by nature because of not having these parameters conserved. The reactions observed experimentally are controlled or governed by the requirement for conservation. When these characteristic rules are resolved from the study of various reactions they are termed selection rules. Nuclear reaction equations can be balanced, similarily to chemical reactions equations, by requiring charge, number of nucleons, etc., to be conserved.

Stability of Nuclear Systems

A nucleus (A, Z) is composed of A - Z neutrons and Z protons. If we could unbuild the nucleus we would have this number of protons and neutrons. If the nucleus is to exist, the combination must be more stable than the separate parts. The energy holding the nucleus together is called the binding energy. Recalling that energy and mass are equivalent, we may also speak of the binding mass. To unbuild the nucleus one must add energy (mass). Thus we find the combined nucleons (the nucleus) less massive than its parts. All the energy required to unbuild the nucleus is the total binding energy, TBE. This may be computed by subtracting the mass of nucleus from the mass of all its nucleons when separate.

$$\mathrm{TBE} = ZM(\mathrm{proton}) + (A-Z)M(\mathrm{neutron}) - M(A,Z) \cdot$$

The greater the TBE the more stable is the nucleus, thus for a given (A) the less massive the nucleus the more stable it is. In these computations it is customary to express the masses in atomic mass units, which are available in tables, but we may use grams, or electron volts, if we wish.

Another concept of interest is the binding energy per nucleon. The average value of this may be formed by dividing the total building energy by the number of nucleons,

$$\frac{\mathrm{TBE}}{A} = \frac{+ ZM_p + (A-Z)M_n - M(A,Z)}{A}$$

This average is about 8 Mev. Figure 1 shows it plotted against the mass number. The heaviest elements have about 7.5 Mev TBE/nucleon, and the

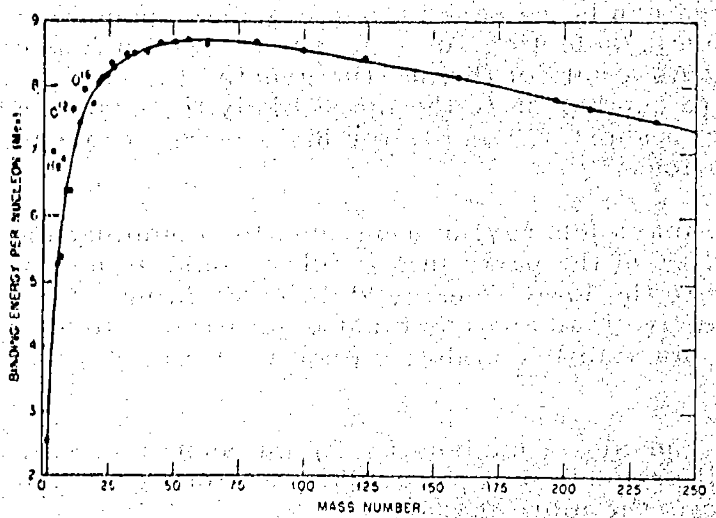


Fig. 1. Total binding energy per nucleon vs the mass number.

middle ones have about 8.5 Mev TBE/nucleon. If uranium fissions and becomes two middle elements, the energy available per nucleon is about 1 Mev. The total energy released in the fission of uranium is about 235 times this or just about 200 Mev. If hydrogen is combined to make helium, energy is also released, and this is about 7 Mev per nucleon. Thus we see the fission of hydrogen to helium is about seven times as productive of energy for each nucleon involved as the fission of uranium. The recent international conference on Peaceful Uses of Atomic Energy at Geneva in 1955 indicated that several nations are trying to tame the hydrogen bomb for constructive purposes.

We still must ask how we know a nuclear system is stable and under what conditions a nuclear reaction will take place. A necessary but not sufficient condition for a nuclear system to change its state spontaneously is that the energy of the new state be less than the energy of the initial state. Thus if energy can be released a nucleus may spontaneously change its state. However, selection rules govern the way it happens and may prohibit any change. As a rule of thumb, the greater the energy reduction from an initial state to another state the more likely the change will happen. That is, we expect a shorter half life for high-energy radiations than for low-energy radiations.

If the mass (energy) of a nucleus (or combination of nuclei) is larger than the masses of the parts into which it could divide, we suspect that it will transfer to the lower-energy state by dividing. On the other hand, if it is less massive than any combination of parts into which it may be divided, it is stable. Its stability is determined by a simple calculation of the masses involved.

If we consider a nucleus (A, Z) and subtract from its mass the masses of all products of a particular division, we learn whether the initial or final state is the more massive.

We must do this for each way it might divide, to have a complete format. The calculation is as follows:

$$M(A,Z) - [M(A_1Z_1) + M(A_2,Z_2) + \dots\dots] = Q,$$

where (A_1Z_1) represents one of the products.

If $Q < 0$ the system is stable and if $Q > 0$ the system is potentially unstable. For $Q < 0$ the reaction is termed endoergic and for $Q > 0$ it is exoergic. All spontaneous reactions are exoergic, i.e., release energy.

Consider the reaction

$$_0n^1 + {_5B^{10}} \rightarrow {_5B^{11*}} \rightarrow {_3Li^7} + {_2He^4} + Q,$$

where $_0n^1$ is a neutron, $_5B^{10}$ is a boron isotope, and $_5B^{11*}$ is an intermediate nucleus, called the compound nucleus, which exists for a very short time. Lithium and helium are the final products. Then we have

$M({}_0n^1)$	= 1.00893 amu,	$M({}_3Li^7)$	= 7.01822,
$M({}_5B^{10})$	= 10.01618,	$M({}_2He^4)$	= 4.00390,
	11.02511		11.02212

$$Q = M(\text{initial}) - M(\text{final}) = 0.00299 \text{ amu}$$

$$= 2.79 \text{ Mev.}$$

Since Q is positive, this energy is released in the reaction, which goes from left to right by itself. The energy released appears as kinetic energy of the Li and He. To make the reverse reaction one needs to add this energy, which may be done by accelerating an alpha particle, He^4, to sufficiently high energy (greater than Q alone) and allowing it to strike the lithium. This exoergic reaction is used for detecting neutrons.

Nuclear Systematics

A study of all the known nuclei reveals several systematic properties, which are clues in understanding the nature of nuclear forces and are a guide to many nuclear processes.

The first interesting fact is apparent when a graph of all the nuclei is made by plotting the number of neutrons vs the number of protons in each nucleus. This is shown in Fig. 2. The ratio of neutrons to protons starts at 1 to 1, and increases steadily to about 1.6 to 1.0. The graph also shows the line about which nuclei are found or can be produced. Any nucleus away from this line tends to move toward it, i.e., adjust its ratio of protons and neutrons by a radioactive decay. Those above the line decay so to have fewer neutrons and more protons. This process is negative beta decay. Those below the line exhibit positive beta decay. The increased number of neutrons in the heavier elements is expected because of the Coulomb repulsion between the protons. A lower-energy state can be achieved with an unequal number of neutrons and protons.

The relation between the radius of a nucleus and the number of nucleons in the nucleus is another interesting clue. Since we have

$$r = r_0 A^{1/3},$$

the volume of a nucleus,

$$V = 4/3\ \pi r^3 = 4/3\ \pi r_0^{\ 3} A,$$

is proportional to the mass number (the number of nucleons). If each nucleon attracted each other one in the nucleus we would expect the density of the nucleus to increase as the number of nucleons increases, since each additional one would be even more tightly bound. Because this is not observed we believe the nuclear forces to be short-ranged and the interaction

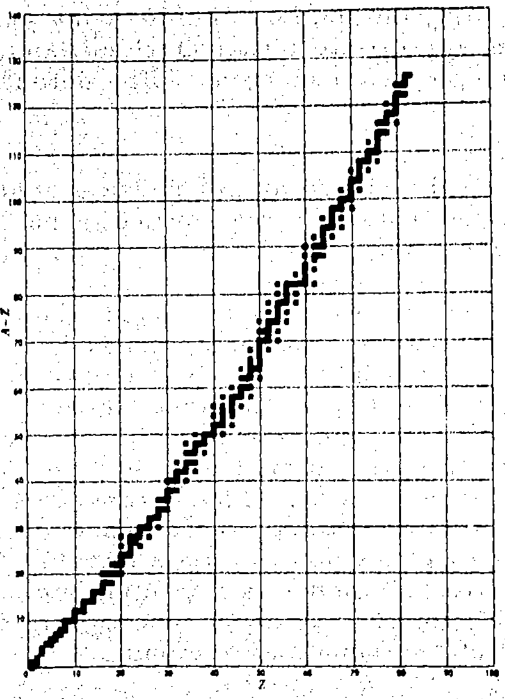


Fig. 2. Number of neutrons vs the number of protons by stable nuclei.

limited to adjacent nucleons. For nucleons on the surface of the nucleus the number of adjacent nucleons is fewer, and we expect and observe a surface effect; they are less tightly bound and tend to make the nucleus spherical to be as well bound as possible. This is analogous to a liquid drop formed by small droplets.

When grouping the stable nuclei found in nature according to the numbers of neutrons and protons (even or odd), we observe the numbers in each group.

Group		Designation	Number of stable nuclei
Z even	n even	even - even	163
Z even	n odd	even - odd	56
Z odd	n even	odd - even	50
Z odd	n odd	odd - odd	5

The nuclei that have an even number of protons or neutrons seem relatively stable (abundant), while those which have both even Z and n are more stable. The ones in which Z and n are odd are less stable. We conclude that the pairing of neutrons or protons separately increases the stability of the nucleus.

Another observation concerns the relative stability of some nuclei with respect to other. Those nuclei which have 8, 20, 50, 82, or 126 neutrons, or 8, 20, 50, or 82 protons are more stable, are more abundant, have more isotopes, are more tightly bound--and reflect this in their cross sections. This suggests that there is shell structure of nucleons in the nucleus analogous to the shells of electrons about the nucleus, but it is not as definite.

When the Coulomb repulsion between protons has been accounted for in the nucleus, the binding force between one proton and another (proton) is similar to that between two neutrons or between a neutron and a proton. We say nuclear forces are charge-independent. Three types of forces are known. They are gravitational, electrical, and specifically nuclear. The nucleus cannot be bound with only gravitational and electrical forces as we now know them.

The systematic variation of average binding energy per nucleon, TBE/A (discussed above), is also a useful observation.

These relations have been combined in developing a semiempirical mass formula, which makes an excellent prediction of the mass of any nucleus.

Radioactivity

The discovery of radioactivity and the subsequent experiments showed that the rates of decay and the types of radiation were independent of the atomic conditions in which the nucleus lived. Pressure, temperature, and the chemical combination of the atom made no changes. This was the clue that radioactivity was a nuclear, not an atomic property. The rate of radioactive decay is proportional to the number of atoms of the particular species, and each nucleus decays independently of each other nucleus. These facts may be combined in the following equation, which applies when one has a very large number of nuclei:

$$\frac{dN}{dt} = - \lambda N,$$

where N is the number of nuclei of the specific type present at the time t, $\frac{dN}{dt}$ is the rate of their radioactive decay, and λ is the proportional constant called the decay constant. The dimensions of λ are $\sec^{-1}$. This may be integrated to give

$$N = N_0 e^{-\lambda t},$$

where N_0 is the number present at the time $t = 0$ and e is the Naperian constant, $e = 2.718$.

The half life, $t_{1/2}$ may be formed by setting $N = (1/2) N_0$, which gives

$$t_{1/2} = \frac{0.693}{\lambda} \text{ sec.} = 0.693\ \tau \text{ sec}$$

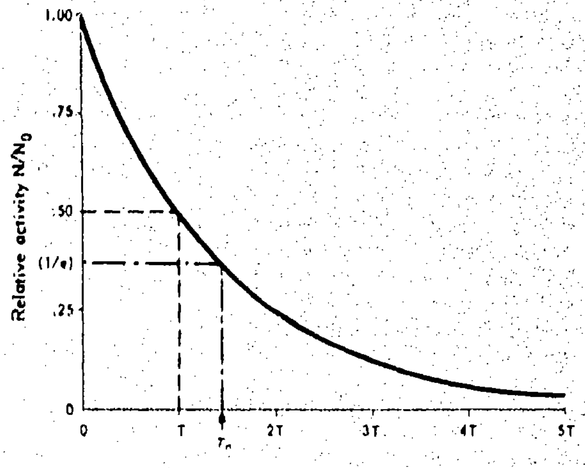
Because the rate of decay is proportional to the number of nuclei present,

$$\frac{dN}{dt} = -\lambda N,$$

one may plot the rate vs time. This is equivalent to plotting the number present vs time at a different scale. The curve is shown in Fig. 3. A more convenient presentation of the data is to plot the logarithm of the decay rate (or N) vs time. For a simple radioactive decay, the data fall on a straight line. See Fig. 4. One usually plots the data on semilog paper directly.

If two radioactive species are present in the sample being measured, a plot of the measured radioactivity on semilog paper gives a curving line (Fig. 5). This line is asymptotic to a straight line at very small and very large times. A subtraction of one asymptotic line from the curve gives the other straight line. The decay constants or half lives for each of the two decays may be easily determined. Note that one must subtract the numbers, not their logarithms.

When measuring radioactive samples that contain only an initial substance which decays into another radioactive substance or a chain of radioactive substances, one may observe the growth of the subsequent radiations. This is frequently termed mother-daughter growth. Eventually, if the mother



Elapsed time (in units of one half-life T).

Fig. 3. Relative activities vs time in units of half life.

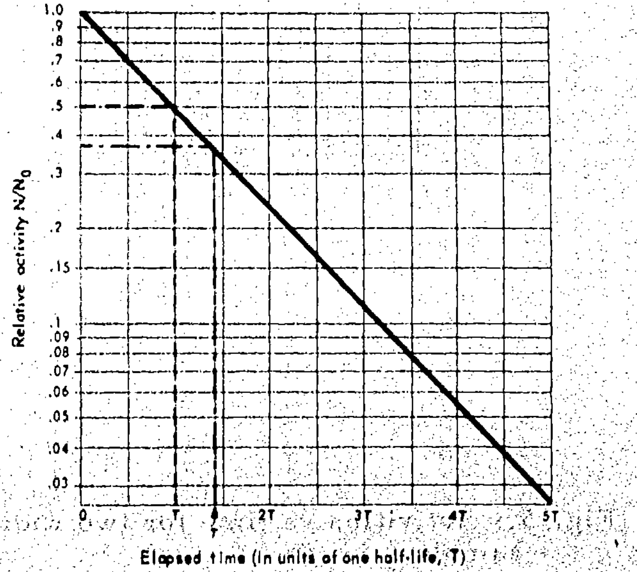


Fig. 4. Relative activities vs time in units of half life.

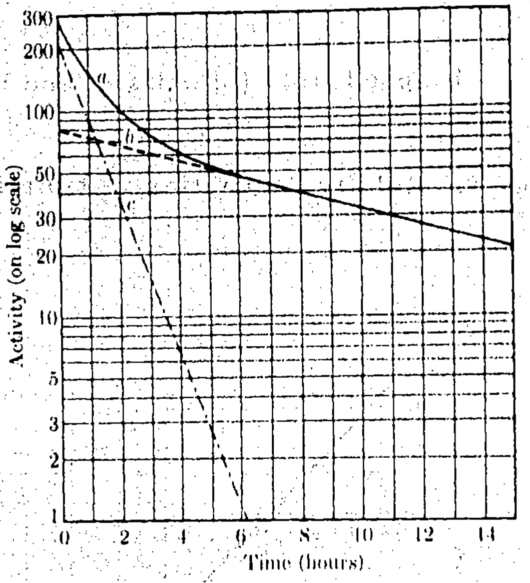


Fig. 5. Activities vs time for two radioactive species in the sample.

is long-lived, an equilibrium is established between the ratios of each substance. This is observed in the radioactive substances found on the earth which may have relatively short half lives all stemming from a very long-lived parent, which continues to replenish them. The growth rate of the daughter is used to find the half life of the very long-lived substance.

During constant production of radioisotopes in a reactor or accelerator, the loss by decay increases until eventually the loss rate is equal to the production rate. For example, after one half life of irradiation, one-half of all the radioactive nuclei that will ever be available are present. The next half life of irradiation increases the amount present to only 75% of the maximum, while the third half-life exposure builds to only 87.5%. For equal additional irradiation times a seriously diminishing return occurs.

Extremely short activities can be irradiated in a short time to maximum activity, but must be removed very quickly to be counted. One technique is to transfer the material from target to counter by a "rabbit," which works like a pneumatic change carrier in a department store. Another method is to have counters located so that the radioactive substance mounted on the periphery of a wheel is passed by them quickly after passing an irradiating beam. Electronic switching methods are also applied to this problem. Measurements of half lives as small as 10^{-3} sec are not difficult with these last two methods.

Two units of radiation are of interest. One, the curie, measures the rate of radioactive disintegration but says nothing about the energy, type of radiation, or hazard. One curie is 3.7×10^{10} disintegrations per second. This is approximately the number of disintegrations that occur in one gram of radium per second. For any sample, the strength in curies is obtained by

$$\text{Strength} = \frac{1}{3.7 \times 10^{10}} \lambda N,$$

where λ is the decay constant and N is the number of the specific radioactive nuclei in the sample.

N is computed by

$$N = \frac{N_0 \rho}{A} V$$

where N_0 is Avogadro's number, $N_0 = 6.023 \times 10^{23}$ atoms per mole; A is the mass number; ρ is the density in grams per cubic centimeter; and V is the volume of the sample in cc. A large decay constant λ means a high decay rate and correspondingly a short half life.

The roentgen measures the effect of radiation by indicating the amount of energy released by the radiation. The roentgen is defined for x-rays but is applied to all radiation. One roentgen is the exposure in which 83 ergs is released per gram of dry air. For biological tissue it is about 93 ergs per gram. The rate of exposure is given in roentgens per hour. Current AEC standards allow individual exposure of 300 milliroentgens in a week. Very few people accumulate this much.

Types of Radiation

Radioactivity, when discovered, was found to consist of three characteristic radiations. They were initially named α, β, and γ, and were later identified as a helium nucleus, a fast electron, and a photon, respectively. They differ greatly in their properties, the way they interact with matter, and the processes that govern their emission.

Alpha Particles

The longest-lived radioactive substances found in nature are the very heavy elements; these are alpha emitters. Shorter-lived nuclei that emit alpha particles have been produced artifically. The range of half lives is from 3×10^{-7} to 10^{10} years, or a factor of about 10^{17}, but it is surprising that the energies of the emitted alpha particles vary only by a factor of about 2, from 4 Mev to about 9 Mev. The higher the energy the shorter the half life, in accordance with our rule of thumb. Alpha emission is defined by the transition (A, Z) → (A-4, Z-2).

All alpha particles from one nucleus have almost the same energy, but some are accompanied by a gamma ray. The energy change from the initial nucleus to the final nucleus, i.e., the energy of the alpha particle and the gamma ray if it exists, corresponds to the change in the masses from the initial state to the final state. The nuclear change may be symbolized by the following diagram.

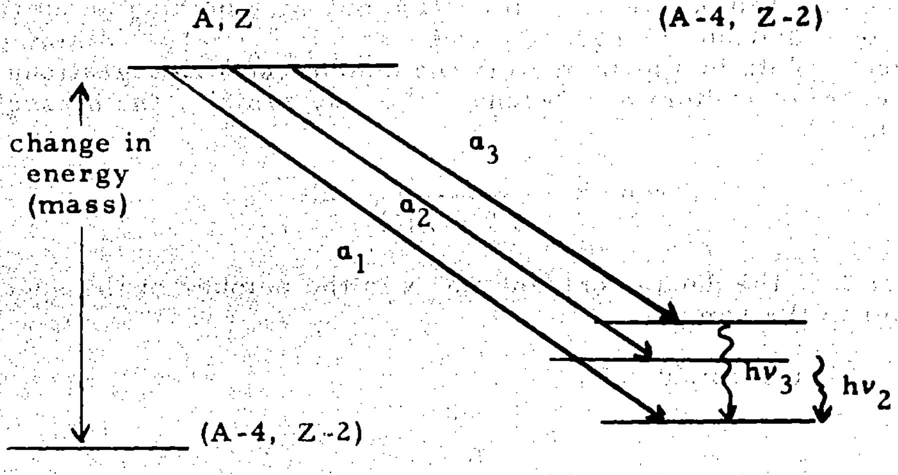


Fig. 6.

Experimentally the photon, $h\nu_3$, can be shown to be coincident with α_3 alone. The percentage of alphas by each path is the branching ratio. The several energy levels to which the alphas decay indicate a condition in the nucleus analogous to that in the atomic picture, in which quantized energy levels exist.

The strong dependence of half life upon alpha energy was explained by Gamow and independently by Condon and Gurney when they applied a quantum-mechanical analysis to the problem. The emission of alphas was viewed as a process of tunneling through the potential barrier, which would have kept an outside alpha particle from entering the nucleus. For a typical nucleus the analysis shows that a change of alpha energy from 6 Mev to 7 Mev would reduce the half life by a factor of a million. The nuclear radius is measured by this analysis, and the result corresponds to measurements by other means.

The nucleus is bound by being in a negative potential energy state while having a positive potential barrier about it. Figure 7 illustrates this.

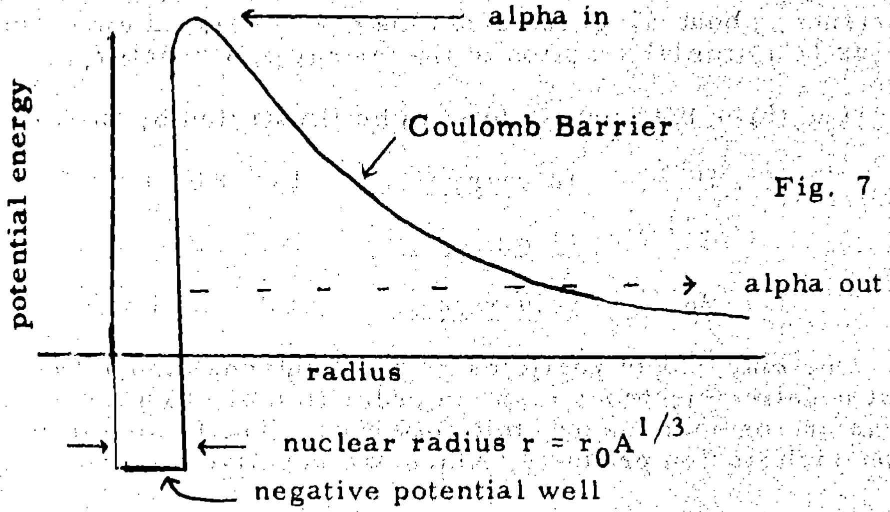


Fig. 7

Beta Particles

The nuclear transitions, which are called beta decay, are of three types.

(A, Z) → (A, Z+1)	negative electron or β^- decay
(A, Z) → (A, Z-1)	positron or β^+ decay
(A, Z) → (A, Z-1)	K capture

The nuclear charge is changed but the number of nucleons does not change, i.e., a proton becomes a neutron or vice versa.

The beta particles are emitted with large velocity and are therefore relativistic. When one plots the number of betas of a given energy vs their energy one is surprised. The curve is as shown in Fig. 8.

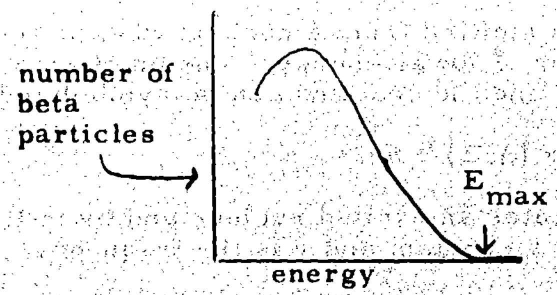


Fig. 8

The surprise comes from the fact that when one calculates the energy release from the mass changes, and gets $E_\beta$max, one measures a vanishingly small number of betas with that energy. One finds a continuous energy spectrum in contrast to the discrete one for alphas. Where has the other part of the energy gone? Also, are the other properties we expect to be conserved actually conserved in this process? We assume they are, and we account for the other part of the energy--the angular and linear momentum and the statistics--by accepting an additional particle as being involved in the decay. This particle is called the neutrino and designated by ν. Recent experiments at the Savannah River reactors have given additional evidence for these neutral particles that seldom react with matter. Roughly one-half of the energy of beta emission is carried off and lost through the neutrinos. This can represent a large amount of energy; for instance, about 5% of the sun's energy is carried away and not available to us, as is a similar fraction of the energy of a reactor.

The three beta processes can be illustrated by the following:

$$H^3 \xrightarrow{\text{12 years}} He^3 + \beta^- + \nu,$$

$$C^{11} \xrightarrow{\text{11 min}} B^{11} + \beta^+ + \nu,$$

$$Be^7 \xrightarrow{\text{52.9 days}} Li^7 - e^k + \nu.$$

One may expect particles rich in neutrons (above the stable ratio) to emit negative electrons or β^- in order to move to a more stable ratio, whereas proton-rich nuclei emit positrons. The fission of uranium produces neutron-rich fission products, which are negative electron emitters.

K capture occurs when a nucleus is in a state such that its energy can be lowered by the absorption of a negative electron. When one of the inner atomic electrons gets sufficiently close to the nucleus this process may occur. The result of K capture is the emission of an x-ray corresponding to a hole in the k shell of the new atom, i.e., (A, Z-1). Moseley's law enables us to know from which atom the x-ray came. This beta process does not result in any fast-moving electron's being emitted, just a photon of the characteristic wave length of the new nucleus. Capture from the other atomic shells is also possible, and occurs less frequently.

When a positron comes to rest it annihilates with a negative electron, producing a characteristic radiation, two gammas of 0.51 Mev in opposite directions. The presence of this radiation is a clue that positron emission is occurring.

Gamma Rays

Gamma rays are emitted from a nucleus when it reorganizes itself from one state to another of lower energy. The numbers and kinds of nucleons do not change, and the reaction can be symbolized as

$$(A, Z)^* \rightarrow (A, Z) + h\nu,$$

where the asterisk indicates an excited nucleus and $h\nu$ is the energy of the gamma ray; h is Planck's constant and ν is the frequency.

The gamma radiation carries the nucleus from its excited state toward the ground state. The excited state may have resulted from a previous radioactive decay, as we have seen. The gamma energies correspond to the quantized levels of the nucleus from which they come. The half lives of gamma emitters are in general very short, some as short as 10^{-14} second. The lifetime depends directly upon the amount of reorganization that must take place in the nucleus. The lifetime of the excited nucleus is proportional to the change in the internal angular momentum. For several units of angular momentum change the half lives become seconds, hours, days, or even years long. Nuclei that may be measured in both an excited and a ground state are called isomers.

The reorganization of the nucleus changes the distribution of charge, which leads to the emission of the electromagnetic energy in the form of a photon. This is parallel to the emission of electromagnetic energy from an accelerated electrical charge.

A process that is a gamma process but results in a beta's being emitted is called internal conversion. Internal conversion occurs when an electron of an inner shell of the atom perturbs the nucleus by being in the region of the nucleus. If energy can be released it may be transferred to the electron rather than coming out as a photon. The energy of the beta, E_β, is related to the gamma energy $h\nu$, as

$$E_\beta = h\nu - W,$$

where W is the energy required to remove the electron from its atomic shell. W is called the work function. In contrast to the betas from a beta emission, the internally converted betas have a discrete or quantized energy and can be identified by it. An x-ray also is produced when the hole in the atomic shell is filled.

The emission of gammas is governed by selection rules. These may prevent a nucleus from losing all its excited energy in one step, and a chain of gamma emissions may be required.

Interaction of Radiation with Matter

Each of the three types of radiation reacts differently as it passes through matter. Each interaction transfers energy from the radiation to the matter and results in ionization in the material. This ionization enables detectors to note the presence of the radiation and is the basis for most counters.

Heavy Charged Particles Going Through Matter

Heavy charged particles include the alpha particle, protons, deuterons, mesons, and fission products. Their interaction with matter is characterized by a very intense ionization in a relatively straight path, as these heavy particles brush the electrons off the atoms in their way. Infrequently the particles suffer a deflecting collision, which is caused by a nuclear encounter.

The intensity of ionization differs along the path as the particle's velocity changes. Figure 9 shows a Bragg curve for alpha particles. The intensity of ionization increases as the particles lose energy until a maximum is reached near the end of the path. The ionization per unit length drops rapidly as the particles come to a stop. The initial low ratio of ionization is caused by the short interaction time as the fast particles pass the atom of the material. As the particle slows down its interaction time becomes more favorable, at first, but finally its energy becomes too small to cause ionization. The energy is lost piecemeal, and measurements show that about 30 ev are required per ion pair that is produced. One can find the total number of ion pairs that will be produced by dividing the initial energy of the heavy particle by 30 ev.

A beam of heavy particles of a given energy will all have nearly the same range, since about the same number of ionizing interactions are required to stop them. This is seen in Fig. 10. One may define the range as the average path length of a given particle of a given energy.

The range and energy are directly related, and, in alpha emitters, the half life and energy are also related. Geiger and Nuttall found the relation between the range and the decay constant for the alpha emitters occurring in nature. This relation shows the strong dependence of half life and energy for alpha emitters.

Heavy charged particles of high velocity may be produced by accelerators as well as obtained from radioactive emitters, but their interaction is the same ionizing process. Thin metal sheets stop the non-relativistic heavy charged particles.

Electrons Going Through Matter

The light electron interacts in different ways as it speeds through matter. Electrons become relativistic at rather low energies so that a process in addition to ionization becomes important.

The ionization loss by electrons is important, but not characterized by the intense ionization and the straight lines of the heavy charged particles. Electrons are more lightly ionizing and are buffetted about as they encounter the atoms in their path. Thus their range is greater, but they tend to lose their initial direction rapidly.

As electrons are deflected by their encounter with matter, an acceleration (change in velocities) occurs. As they are charged particles, the acceleration causes them to lose energy by electromagnetic radiation. This is the source of x-rays, and for high-energy electrons this is known as bremsstrahlung. Thus we see that the energy loss of electrons gives rise to gamma rays. The bremsstrahlung loss exceeds the ionization loss when the electrons are very relativistic.

Gamma Ray Interacting with Matter

The interaction of gamma rays, and of their less energetic brothers, x-rays, with matter occurs in three ways; the photoelectric effect, the

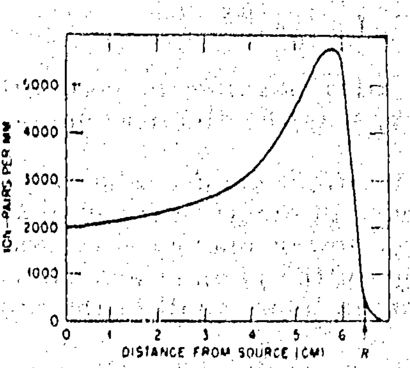


Fig. 9. Bragg Curve - the number of ion pairs per unit length vs the path length in matter.

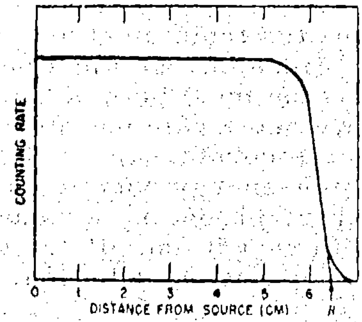


Fig. 10. Number of particles detected vs the path length in matter.

Compton effect, and pair production. Gamma rays go through matter with no continuous interactions, only discrete ones. For this reason the attenuation of gamma rays follows an exponential law,

$$I = I_0 e^{-\mu x} ,$$

where I is the intensity after passing through a thickness x of the material. I_0 is the initial intensity, μ is the absorption coefficient, and e = 2.718.

The photoelectric effect occurs when a gamma or x-ray interacts with an atom and removes an electron from an atomic shell. This process is most important for the lower-energy gammas, below 1 Mev, and increases abruptly when the energy of the gamma exactly equals the energy for removing an electron from an inner shell of the atom.

The Compton effect results when the gamma ray encounters a free electron, i.e., one not associated with an atom. The application of the rules of conservation of energy and momentum permits this problem to be solved to show that the gamma ray may lose a portion of its energy. The portion ranges from zero to 0.25 Mev for the greatest loss. The recoiling electron absorbs the energy lost by the gamma ray. This effect is important up to gamma energies of several Mev.

Pair production becomes possible when the gamma energy equals or exceeds twice the rest mass of the electron, i.e., gamma energies in excess of 1.02 Mev. A gamma ray may be converted into two electrons in the presence of a heavy nucleus. This is the interaction of most importance for high-energy gammas, i.e., above several Mev. The gamma energy in excess of the two rest masses is shared, not necessarily equally, by the electron pair and becomes their kinetic energy.

The production of matter from electromagnetic energy is governed by the conservation rules. Since charge must be conserved a positive electron and a negative electron must both be produced. Pair production was suggested by Dirac. We see a gamma interaction resulting in high-energy electrons, which is the counterpart of the production of bremsstrahlung by high-energy betas. In high-energy cosmic radiation each of these two interactions leads to the other, producing a "shower." As a positron member of the pair comes to rest it annihilates with a negative electron, making the characteristic annihilation radiation.

Cross Section

In all nuclear reactions one is interested in being able to say how probable the reaction is, i.e., under given conditions how frequently will the specific reaction occur? The measure of this probability is called the cross section.

The cross section may refer to all processes, when it is called total cross section, or it may refer to a particular process, and it is named to indicate that. For example, one refers to the cross section for fission, for scattering, etc. Specific cross sections are designated as $\sigma(n, f)$ for neutron-induced fission, $\sigma(\gamma, n)$ for photon production of neutrons, etc. Cross sections, total or specific, vary with the process, the energy of the bombarding particle, and the target nucleus.

The unit of cross section for a nucleus is a barn. One barn = 10^{-24} cm.^{2} The area of a nucleus as computed from the radius is about this size. Cross sections usually have values in the neighborhood of a barn with a range from a millibarn to 1000 barns. Some nuclear cross sections lie outside these values.

The cross section applying to the nucleus alone is called the microscopic cross section and is usually designated by σ. The microscopic cross section when multiplied by the number of nuclei per cubic centimeter of the substance gives the macroscopic cross section, designated by Σ.

$$\Sigma = \frac{N_0}{A} \rho\sigma$$

The reciprocal of the macroscopic cross section is the mean free path in the particular matter under the conditions implied by ρ, its density. N_0 is Avogadro's number and A the mass number.

Differential cross section is the term applied to the probability that a nuclear reaction will result in the particle's going out at an angle to the incident beam. Differential cross section is designated by

$\frac{d\sigma}{d\Omega}$ in which Ω is the solid angle into which particle is directed.
The integral of the differential cross section over all solid angles is the microscopic cross section for the process under study. The differential cross section gives added information about the nuclear structure and nuclear forces.

Accelerators

Particle accelerators have been developed to permit experiments to be performed with better control and with higher intensities than possible with radioactive materials. Further, acceleration of a wider variety of particles and to much greater energy than available in radioactive substances has allowed a great advance in the understanding of nature.

Accelerators may be classified and studied by their method of acceleration, the type of particles, the energy, the shape of the path of the particles in the accelerator, and other ways. All accelerators have two common features. Firstly, they accelerate only charged particles, and secondly, they must allow for two types of focusing.

The necessity for the particle to avoid a catastrophe, such as running into the walls of the accelerator, during the acceleration process requires the provision of spatial focusing. And the desire that the particle increase its energy requires that after a given time or distance the net energy shall have increased; this may be called energy focusing. Accelerators are ingenious devices for accomplishing these two types of focusing. They employ magnetic and (or) electrical fields, which may be static or changing, all chosen and controlled to accomplish the desired end.

TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

Radiation Laboratory
University of California
Berkeley, California

Chapter 3

A SURVEY OF TECHNIQUES IN HIGH-ENERGY NUCLEAR PHYSICS

Burton J. Moyer

Dr. Moyer has been with the laboratory since 1942. He lectures in Physics and is in charge of a group doing research where primary data are obtained by counters rather than with emulsions or cloud chambers or bubble chambers.

The Geiger counter is the best known to the man in the street, and is widely used here in the chemistry and health departments, but not in high-energy work because of the inherent 0.1-millisecond "dead time" after each discharge. The scintillation counter and Cerenkov counters are the chief detectors in the high-energy research field.

There are three parts to every scintillation counter:

1. the phosphor (or material that fluoresces),
2. the photosensitive device,
3. the amplifier.

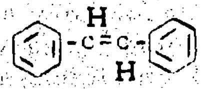
Rutherford used a primitive form of scintillator in his early work. The phosphor was zinc sulfide, but he relied on a darkened room and acuity of eyesight to detect the resulting light flashes.

The most common inorganic phosphor is sodium iodide, slightly contaminated--usually with thallium, although europium is sometimes used as the contaminant.

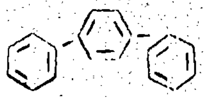
The "impurity centers" formed by the thallium atoms in the NaI crystal structure are able to absorb some of the energy of excitation of the crystal lattice produced by passage of swift charged particles, and to re-emit this absorbed energy as light in the visible region. The re-emitted light is negligibly absorbed by the NaI, since it is not related to energy levels of the crystal proper but rather to its impurity centers. This is not a molecular phenomenon, as is the scintillation of the organic phosphors, but is related to solid-state physics (see lecture by Dr. Kip on this topic).

This NaI (Tl) crystal has a rather long decay time during which it emits its photons, namely about 10^{-5} second. This makes it unsuitable for some high-energy work where sharp time resolution is needed, but it is very valuable in others. It is especially useful in locating radioactive iodine in the body and in gamma-ray spectroscopy. Its light output is linearly proportional to the energy absorbed. Since gamma photons result from transitions from excited to less excited or ground levels within the nucleus, a trained reader can analyze radioactive nuclei in this way. One commercial company (Harshaw) has succeeded in growing pure crystals of enormous size (as much as 6 in. diam. by 8 in. in length). It sells these properly packaged. This means they are sealed from the air (because they are deliquescent) and surrounded by white (not silvery) reflectors for maximum efficiency.

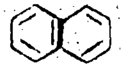
Where fast time resolution is needed (around 10^{-9} sec) organic phosphors are used. Materials used commonly are trans stilbene,



and terphenyl (p)



For slightly longer resolution times anthracene,



may be employed. At one time attempts were made to grow large crystals of these compounds; this was only partially successful. Then solutions in solvents such as xylene and toluene were used, but these have been almost entirely replaced by plastics, especially as with terphenyl in polystyrene. These plastics can be made of any shape, are locally made, and can be as large as 8 in. in diameter and 12 in. high. A small amount of spectrum-shifting material is usually included so that a larger percent of the emitted light comes in the visible range. By means of this plastic and associated electronics the entire signal can be received in 5×10^{-9} sec after the incident gamma ray. This is two thousand times as fast as the NaI(Tl) crystal.

The next part of a scintillator is the device that "sees" these brief feeble flashes and develops electrical signals from them. Such a device is called a photomultiplier tube. The actual photon-sensitive material is usually a cesium-antimony semiconductor properly evaporated onto the inside of a glass envelope. A focusing arrangement directs photoelectrons from this surface to the first of a cascade of dynodes, each of which gives a multiplication of about 4 or 5; there are 9 to 14 dynodes arranged either in a circular pattern or as a succession of "Venetian blinds" so that the over-all gain is one to one hundred million. The last stage goes to ground through a resistor and voltage pulses from that resistor are conducted by coaxial cable to amplifying and recording devices.

Roughly 2% to 3% of the energy dissipated by a swift charged particle in the phosphor is converted into light energy in the useful spectrum region. Five to 10% of the photons incident upon the photocathode yield electrons that enter the dynode system. A common high-energy event will release about 2 Mev energy per g per cm^2 target. This means a plastic 1 in. thick would "catch" 5 Mev of energy and convert it to 100,000 ev of light energy. In this range there are about 2.5 ev energy per photon so that would mean 40,000 photons, of which perhaps 1000 are collected by the photocathode. This yields, in turn, about 100 photoelectrons into the dynode system. Rutherford would doubtless be amazed at how his eye-strain method has been improved.

A fairly recent addition to detection devices is the Cerenkov counter. Fundamentally it depends on the fact that if a particle passes through a medium at a speed faster than the speed of light in that medium, it sets up a shock wave, which can be detected. An excellent analog is the passage of a boat through still water. It leaves a V trail (bow wave) behind it. The greater the speed the sharper the V, in accordance with the formula

$$\cos \theta = \frac{V}{v} = \frac{V}{\beta c} = \frac{1}{n\beta},$$

where

θ = the angle between light ray and particle path,

$\beta = \frac{v}{c}$,

V = velocity of light in the medium,

v = particle velocity,

n = refractive index,

c = speed of light.

In most experiments β is close to 1, so that $\cos \theta$ varies as $\frac{1}{n}$. If n is close to 1, (as it is in CO_2), θ is close to zero, or the wave front is nearly perpendicular to the advancing particle, so close that it can be focused by parabolic mirrors. For flint glass n = 1.59 and θ is about 51°.

It turns out that the frequencies in the wave front are continuous, with equal numbers of photons emitted per unit frequency interval throughout the spectrum, and that around 250 useful photons per cm result from a singly charged particle. This is much less than scintillation effects, but enough to be caught by photomultiplier tubes, and has the advantage that its duration is practically zero. By measuring the angle of aperture of the light cone, it is possible to determine the exact speed of the particle causing it, though this is possible only in very particular circumstances.

There are two kinds of cloud chambers--the older expansion type, which is intermittent in its action, and the more recently developed diffusion type, which provides a constantly sensitive volume. The whole trick is to create a volume which is somewhat, but not too greatly, supersaturated with vapor. Then passage of a charged particle becomes evident by the trail of drops it leaves behind due to condensation upon the ions formed along its path.

If a tiny transient drop forms in a region of supersaturation, there is a critical radius related to the degree of supersaturation above which it will grow, below which it will disappear. Electric effects accompanying a charged ion reduce this critical radius. It is necessary to avoid so high a degree of supersaturation as to allow random coalescence of molecules to grow into visible droplets, yet to provide sufficient supersaturation to produce growth of the vapor agglomerates forming about an ion.

In the expansion chamber the supersaturation is induced by cooling produced by a sudden increase of volume or reduction of pressure of the enclosed gas-vapor region.

The continuous cloud chamber has evaporating fluid (frequently methyl alcohol) at the top of a cylinder which is cooled at the bottom (usually with dry ice) trichloroethylene). Convection currents (downward) set up a gradient of saturation, and somewhere between top and bottom is a continuously sensitive region. The field can be cleared by electrostatic charges on a wire grid, and coincidence counters can be arranged to trigger a camera to photograph interesting events.

Dr. Moyer next showed application of these techniques to current laboratory experiments. In the antiproton experiment by Dr. Segrè and associates the setup was as shown in Fig. 1. (Description of antiproton setup.)

The high-velocity Bevatron beam produces a great variety of fragments at the target. The momentum-defining magnet is simply a bending magnet to put those with the same momentum in the same general path. These are focused by the quadrupole focusing magnet and brought out through the wall in a small well-defined beam where they hit a scintillation counter, the start of a timing device; the second scintillation counter is the other end of the timing device, and their output appears as associated pips on a cathode-ray'scope trace.

The rest of the device is a double check to guard against accidental coincidences. The first Cerenkov counter rejects any particle traveling at more than 78% of the speed of light (pions do this, antiprotons of the chosen momentum do not). Next comes a Cerenkov velocity-selection counter with a quartz radiator. The angle of the resulting shock wave confirms the speed of the particle, and the final scintillation counter is to make sure the triggering particle really came through the apparatus and was not caused by spurious external noise.

K-meson lifetimes are studied in the following manner. (See Fig. 2). High-velocity protons from the Bevatron impinge on the target. Some of the resulting mesons, which stream off at right angles, are bent and focused by magnets till a stream of uniform-momentum particles comes into the right side of the diagram. This stream contains many unwanted pions. The Cerenkov counter is set to "register" then but to pass K mesons, which register in scintillation counter No. 3. The K mesons are then slowed down by the wedge, so that they come to rest in scintillation counter No. C. Particles that go on and register in "2" are not K mesons. Therefore a

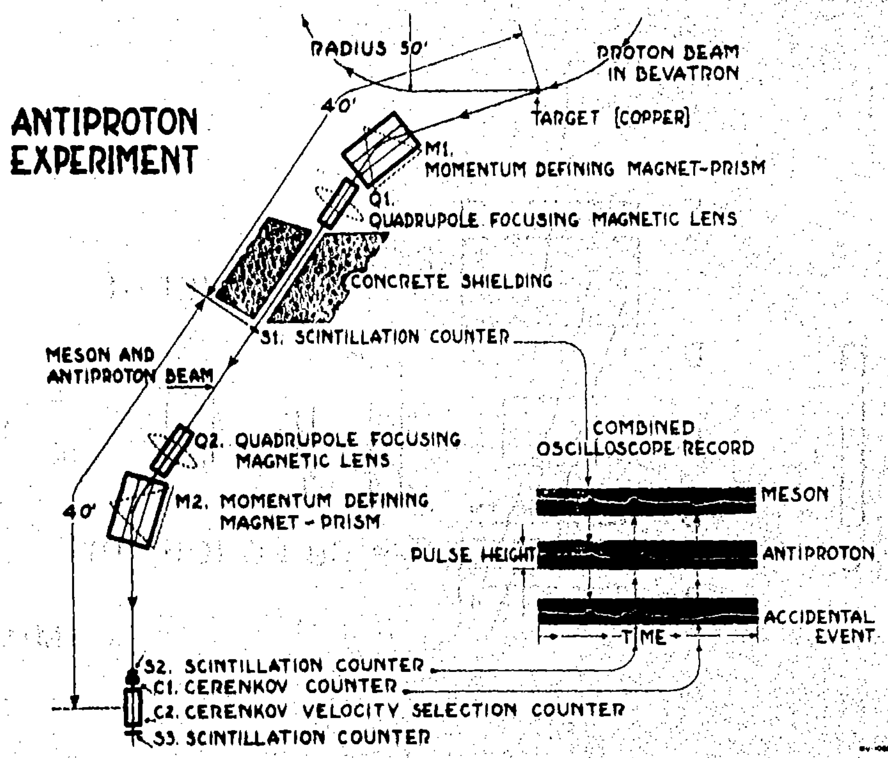

ANTIPROTON EXPERIMENT
RADIUS 50'
PROTON BEAM IN BEVATRON
40'
TARGET (COPPER)
M1. MOMENTUM DEFINING MAGNET-PRISM
Q1. QUADRUPOLE FOCUSING MAGNETIC LENS
CONCRETE SHIELDING
S1. SCINTILLATION COUNTER
MESON AND ANTIPROTON BEAM
COMBINED OSCILLOSCOPE RECORD
Q2. QUADRUPOLE FOCUSING MAGNETIC LENS
40'
M2. MOMENTUM DEFINING MAGNET - PRISM
MESON
PULSE HEIGHT
ANTIPROTON
ACCIDENTAL EVENT
TIME
S2. SCINTILLATION COUNTER
C1. CERENKOV COUNTER
C2. CERENKOV VELOCITY SELECTION COUNTER
S3. SCINTILLATION COUNTER

Fig. 1

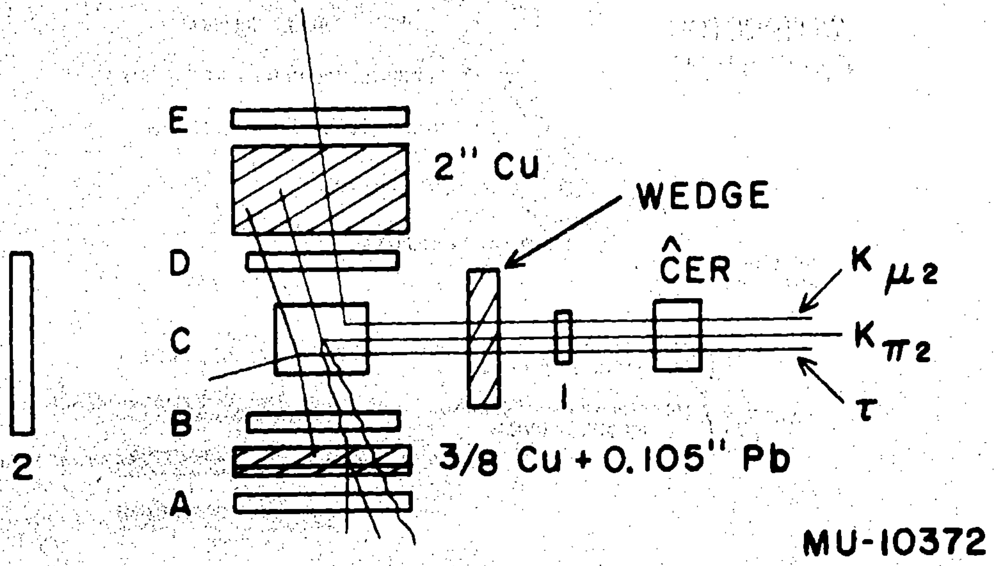


Fig. 2

particle that simultaneously gives no pulse in counter No. 1, a pulse in No. 3, a pulse in C, and no pulse in No. 2 is considered to be the desired K meson.

Decay products from C are then analyzed by counters A, B, D, E. Three modes of decay are known:

$K_{\mu 2}$, which breaks into a μ meson and a neutrino;

$K_{\pi 2}$, which breaks into a π^+ and π^0 meson;

τ, which gives three π mesons.

Strangely enough these all have nearly the same lifetime, namely 1.4×10^{-8} sec. This "lifetime degeneracy" is at present very perplexing.

In Fig. 3 is shown the device used to study θ^0 mesons (neutral K mesons). They decay into two neutral π mesons, which cannot be detected by counters, but the π mesons break into two high-energy gamma rays. These gamma rays pass through low-molecular-weight substances with little reaction (the antiscintillator), but they give copious pair production when incident upon lead, and the resulting electrons register in scintillator, also in the Cerenkov counter (which can be set to respond to electrons only), and finally in scintillator No. 2.

The entire array of counters and collimation can be moved so as to explore the yield of π^0-decay photons arising from regions in space near the target. The distribution in intensity of such photons indicates that the θ^0 mesons live between 1 and 2×10^{-10} second after escaping from the target in which they are produced.

Scintillation counters were an essential part of the triple-scattering polarization experiments by Chamberlain and his group. For further information see their report (Chapter 8).

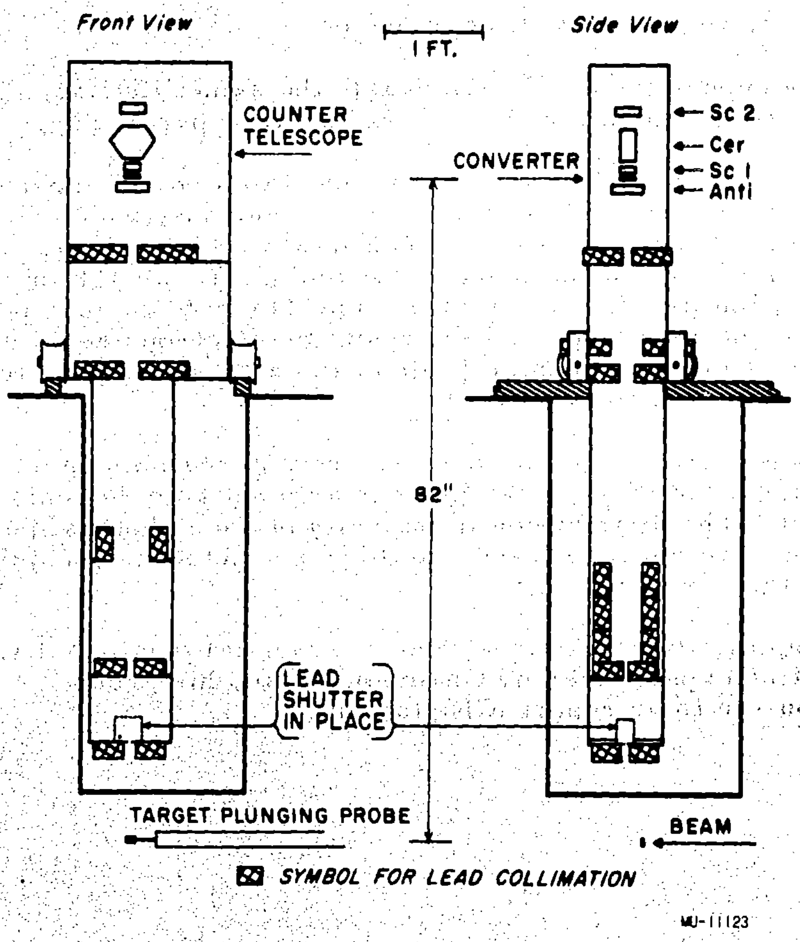

Front View
1 FT.
Side View
COUNTER TELESCOPE
CONVERTER
Sc 2
Cer
Sc 1
Anti
82"
LEAD SHUTTER IN PLACE
TARGET PLUNGING PROBE
BEAM
▨ SYMBOL FOR LEAD COLLIMATION
MU-11123

Fig. 3

TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

Radiation Laboratory
University of California
Berkeley, California

Chapter 4

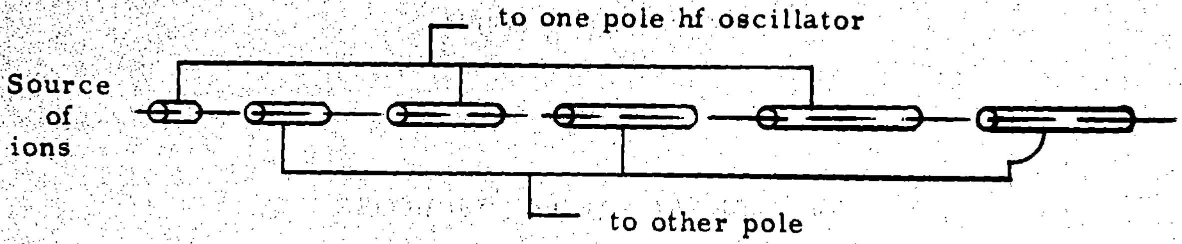
HIGH-ENERGY ACCELERATORS

David L. Judd

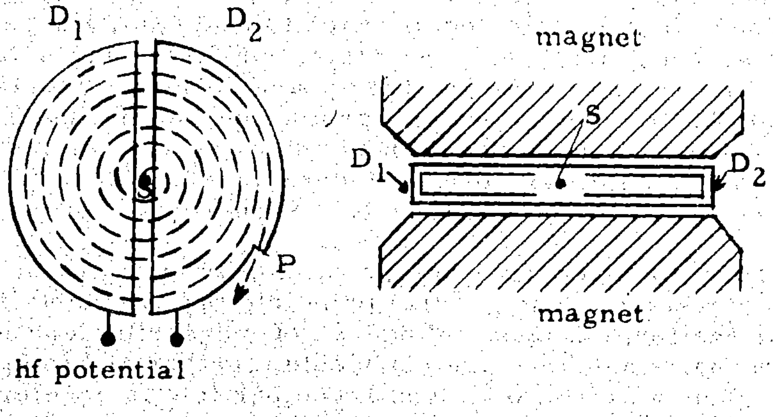
Dr. Thornton introduced Dr. Judd as head of the Theoretical Group at the laboratory. Dr. Judd had attended the recent high-energy acceleration conference at Geneva, and is generally regarded as a leader in theoretical work on accelerators in this country.

Dr. Judd said that the particles to be accelerated are electrons, protons, deuterons, tritons, alpha particles, and heavier ions. Alpha and beta rays from naturally radioactive substances are accelerated by natural processes and were the first to be used in experiments. Sir J. J. Thomson and others used electrostatic acceleration to find e/m, the ratio of charge to mass of electrons and ions. The desire for faster and more uniform ion beams led to the use of higher and higher accelerating voltages, obtained by the Cockcroft-Walton voltage multiplier and the Van deGraaff generator. The voltages obtainable by these "one-whack" devices are limited, by insulation breakdown, to a few million volts. Modern accelerators that exceed these energies work by timed repetitive boosts of energy.

The first such accelerator was the linear accelerator of Sloan and Lawrence at Berkeley. The general principle is a straight-line series of electrodes in the form of open cylinders, of increasing length but evenly spaced. Alternate members are connected together and to opposite poles of a high-frequency oscillator. A charged particle is accelerated when between electrodes; when it gets inside the electrode it feels no force and "drifts" while that electrode is of the reverse voltage. Because the field is properly synchronized with its acceleration, the particle gets to the end just in time to feel a pull from the next one. Thus if the potential difference is 1000 volts a series of 10 drift tubes could give a particle 10,000 ev of energy. The tubes have to be increasingly longer as the particle energy increases so that the time spent inside will be uniform. The experiments by Sloan and Lawrence were restricted to heavy slow-moving ions because at the time only relatively low-frequency oscillators were available. Our present proton linac operates at 200 megacycles, and Stanford has a linear electron accelerator operating at 3000 megacycles per sec.



In 1930 Professor E. O. Lawrence got the idea of using the same drift tube over and over. This was possible because the accelerated particle could be bent to re-enter by a magnetic field. The result is the basis of all present-day cyclotrons. Schematically, the arrangement is as follows.



The electrodes are two hollow flat semicircular boxes called dees (because of their shape). A glowing filament produces electrons which ionize some gas (hydrogen) as it enters the high vacuum chamber. The force on a moving ion resulting from its motion perpendicular to the magnetic field is a force perpendicular to both its velocity and the field; the magnitude of the force is

$$F = \frac{evB}{c} ,$$

where e = charge on particle (electrostatic units),
v = velocity of the particle,
B = magnetic field strength (electromagnetic units),
c = a constant (the speed of light) to adjust units.

The resulting path is a circle, so that the magnetic force must provide the centripetal force,

$$\frac{mv^2}{r} \; ;$$

therefore

$$\frac{evB}{c} = \frac{mv^2}{r} \text{ or } \frac{v}{r} = \frac{eB}{mc} \; .$$

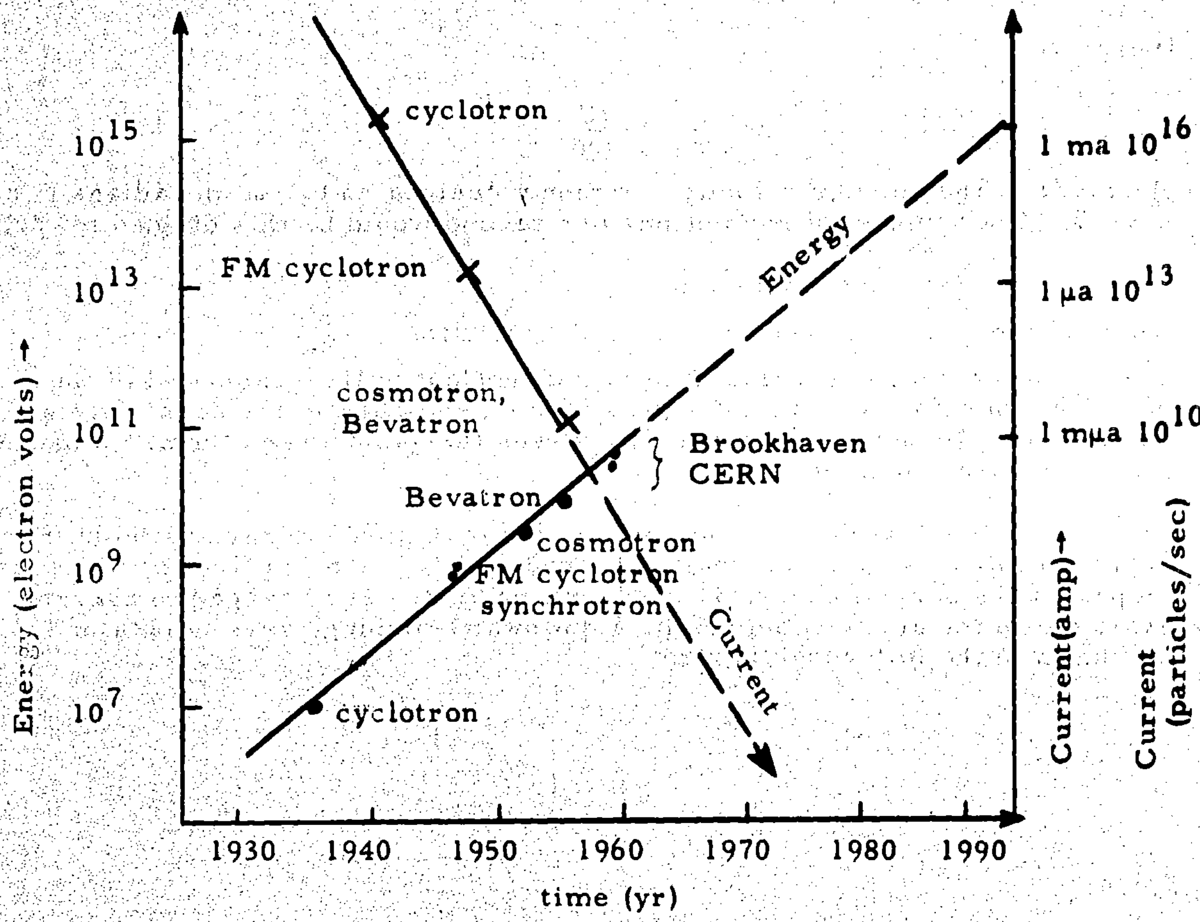
Here v/r is the angular velocity commonly designated by ω in radians per second. The number of revolutions per second would be this divided by 2π,

$$2\pi f = \omega = eB/mc,$$

and thus the time required for one-half revolution = $\frac{\pi mc}{Be}$.

This equation shows that this time is independent of the radius and of the velocity, therefore constant-frequency voltage applied to the dees gives a particle added energy every time it crosses the gap between them, no matter what size circle it is describing.

In a brief aside Dr. Judd plotted log maximum energy available from an accelerator vs calendar year and found nearly a straight line with upward slope. If the same abscissa is used, but ordinates are changed to current available in the accelerated beam, a downward-sloping curve is obtained, as shown in the following diagram.


Energy (electron volts) →
10^{15}
10^{13}
10^{11}
10^{9}
10^{7}
cyclotron
FM cyclotron
cosmotron,
Bevatron
Energy
Brookhaven
CERN
Bevatron
cosmotron
FM cyclotron
synchrotron
Current
cyclotron
1 ma 10^{16}
1 μa 10^{13}
1 mμa 10^{10}
Current(amp)→
Current
(particles/sec)
1930
1940
1950
1960
1970
1980
1990
time (yr)

Naive extrapolation indicates that we soon arrive at 10^{16} ev of energy at the rate of 1 or 2 particles per hr, somewhat less efficient than cosmic rays. There is room for doubt whether this is progress by any standard; the example serves to indicate the importance of maintaining high currents in future accelerators.

We now return to a consideration of the limits of the simple cyclotron. We have seen that the time of rotation is independent of radius and speed but does depend on mass. When speeds approach that of light the mass does not remain constant, but grows in the well-known relation

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}} ,$$

where m = actual or relativistic mass,

m_0 = rest mass,

v = velocity of the particle,

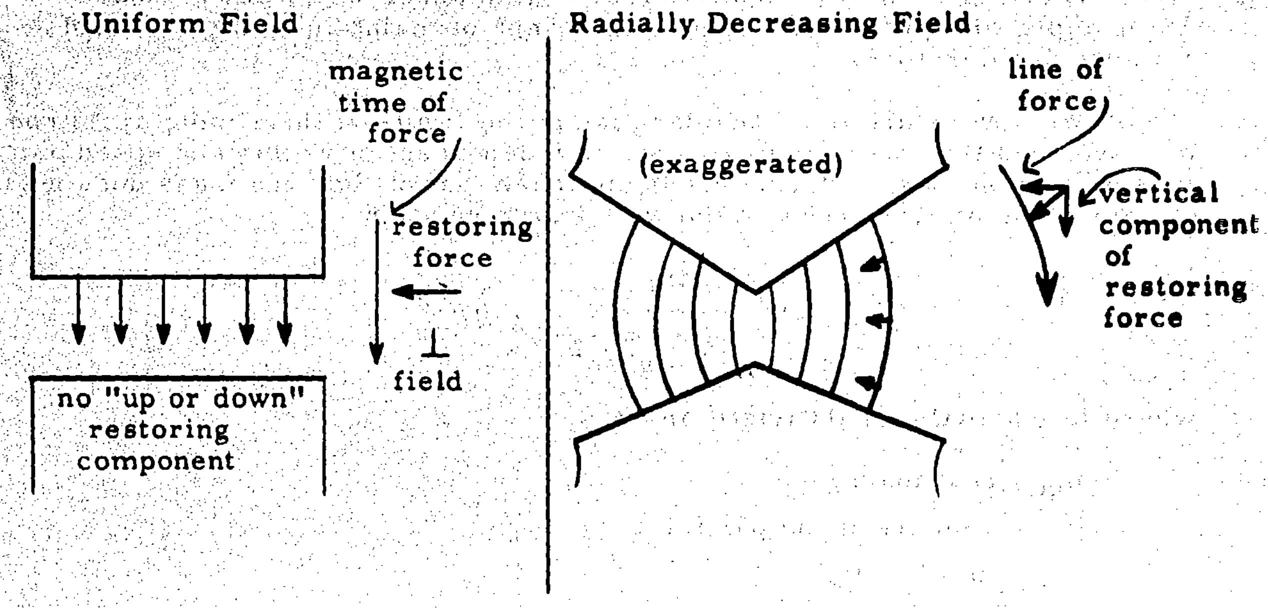
c = speed of light.

A quick look at our formula

$$t = \frac{\pi mc}{Be}$$

shows that as m increases in the numerator, the particles get behind the phase of the accelerating voltage. We should be able to compensate this phase slip by also increasing the magnetic field B. Unfortunately focusing requirements prevent this.

If a weight on a spring is disturbed by any force, it oscillates under the action of a restoring force. We should like to have the same kind of "stability" of particles rotating in their orbits. The uniform magnetic field provides a restoring force for radial displacements but none parallel to the magnetic field (z direction). To keep the particles in the median plane between the magnetic poles, it is necessary that the magnetic force have a restoring component toward that plane. This can be secured by making the field weaker as radius grows, as shown in the following diagram of cross sections of pole pieces.



In other words the pole shape necessary for focusing is exactly opposite to that needed to overcome relativity effects. Some of the key ideas that have developed in the advance of accelerator concepts may be listed as follows:

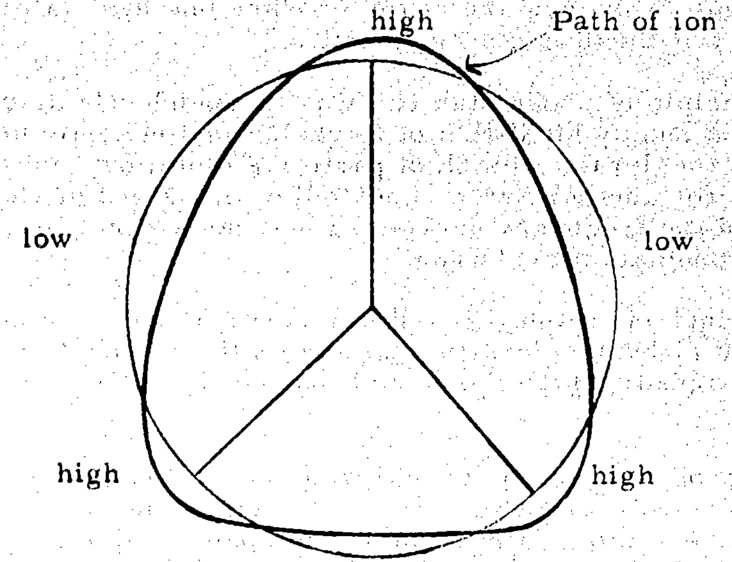
1. General cyclotron principle
2. Magnetic focusing
3. Phase compensation
4. Wedge field focusing (Thomas focusing)
5. Alternating-gradient focusing with pulsed magnetic fields
6. Alternating-gradient focusing with dc magnetic fields

(This is known as FFAG, standing for fixed field alternating gradient; both this and No. 5 are known as "strong focusing.")

7. Phase stability
8. Phase transition
9. Momentum compaction
10. Spiral-ridge focusing.

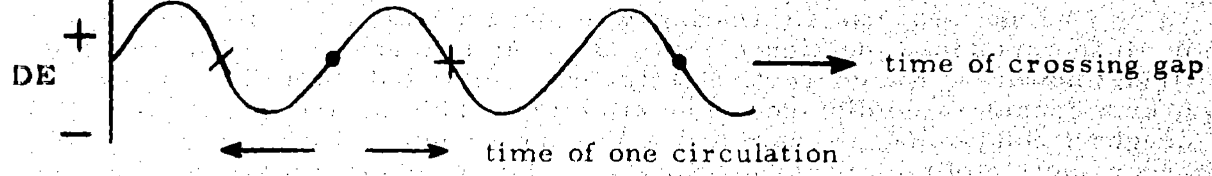
We have shown the incompatibility of the obvious type of magnetic focusing with relativistic mass change causing phase slip, but there is a more subtle type suggested by L. H. Thomas in 1938, and independently by Dr. E. M. McMillan of this laboratory in 1949. We have seen that a weakening outward field makes for vertical stability, but an outward strengthening field is needed for relativity compensation. By means of an azimuthally varying (instead of uniform) magnetic field it is possible to achieve both of these.

If the pole faces are made wedge-shaped, with alternating hills and valleys, the path of the ion departs from a circle and approaches that of a rounded polygon, as indicated.



Analysis shows that there is an average focusing effect toward the median plane. This can be combined with an over-all radially increasing field so as to compensate for the relativity effect. It is estimated that energies could be raised from 20 Mev to several hundred Mev by using this type of magnetic field.

The next topic discussed was phase stability. Suppose that in an ordinary cyclotron we have a particle circulating in such a phase, with respect to an accelerating gap with the proper radiofrequency voltage, that it neither gains nor loses energy. The gap crossings could be either at the crosses or dots on the diagram.



If the magnetic field and radiofrequency are held constant the particle energy will be held constant too, and this is a situation of equilibrium. The important question is: will the equilibrium be stable? If it is stable one may slowly change the frequency or the magnetic field or both so as to accelerate the particle, that is, to make ΔE positive on the average. This is analagous to accelerating a nearly full cup of coffee--initially at rest--by gently starting to carry it across the room, or to gently displacing the point of support of a pendulum initially at rest. The pendulum follows along and only small motions are induced. If it were unstable it would be as though one gently moved the support of an upside-down pendulum; this would of course produce a violent motion (the bob would fall). It turns out in this case that if the gap crossings are at the crosses one has stability, and that gap passages at the dots give instability.

This principle of phase stability was independently discovered by Veksler in Russia and by McMillan of Berkeley in 1945. By using this method one may accelerate a batch of particles from low to high energy and then go back for another batch repeatedly. If the magnetic field is held constant and the frequency decreased one has a synchrocyclotron or FM (frequency-modulated) cyclotron.

Our 184-inch operated that way for several years and gave 350-Mev protons with only 17 kv accelerating voltage on the dees. It has just been completely redesigned and it is expected that soon it will give 700-Mev protons.

The betatron or electron synchrotron has a doughnut-shaped magnetic field which is increased with time for each bunch. The frequency is held constant after the electrons attain nearly the speed of light. The electrons are pre-accelerated to as much as 1/2 that speed before injection and brought up nearly to that speed by betatron acceleration (which we do not have time to discuss). The growing magnetic field obtained by using 1/4 or 1/2 of a cycle of alternating current keeps the beam at approximately the same radius, and the electrons actually gain "weight" rather than velocity during most of the acceleration process.

A proton synchrotron utilizes the same principles, but both magnetic field and accelerating frequency are varied together during each batch. Our Bevatron has roughly a 110-foot diameter. The magnet weighs 10,000 tons and the vacuum chamber in which the protons travel is about 4 ft wide by 1 ft high. It produces 6-Bev protons. The "cosmotron" at Brookhaven is similar, with a top energy of 3 Bev.

We now discuss alternating-gradient focusing. The focusing effect in all the machines mentioned above has been secured by shaped magnetic fields; however, the corrective factor was small and had to be extended over a considerable distance to be effective. This means that the evacuated doughnut containing the beam had to be large compared with the ultimate cross section of the accelerated beam. This means that air gaps in magnetic circuits are large and the power needed grows rapidly with increasing size and energy of the accelerators.

Recent studies have shown that if the field, instead of being mildly corrective, is made violently alternately overcorrective and undercorrective the net result is a stronger focusing of the particle toward the desired orbit. This is known as "alternating-gradient focusing" or "strong focusing." Mathematically, this may be expressed by saying that the restoring force is represented by a second-order ordinary linear differential equation with a large periodic, instead of a small constant, restoring coefficient. An optical analogue is that a combination of alternate convex and concave lenses can be arranged so as to be converging.

The net result of this is that the beam never spreads more than a few inches from a circle whose radius is 250 feet or more, not unlike a garden hose wrapped around a house. This permits design of still more powerful accelerators with only moderate increase in weight, power requirements, etc., and plans to do this are going forward at Brookhaven, at CERN (Switzerland), and in Russia.

Dr. Judd then operated a device which was analogous to strong focusing. An upside-down pendulum (metronome ticker) is fundamentally unstable. Once it starts to fall it continues to do so with increasing speed; however, if the support of such a pendulum is vibrated up and down with a frequency that has a proper relation to the natural period of the pendulum, the whole becomes stable--the pendulum tends to remain upright. These motions were obtained by a small variable-speed motor operating a cam which gave an up and down motion to the base of the free-swinging, upside-down pendulum. Until the proper speed is obtained the pendulum must be restricted "by hand" to a nearly vertical position but at proper speeds the net focusing action takes over and manual support is no longer required. This may not prove that two wrongs make a right but it does prove that stability can come out of properly combining a violently stablilizing effect with a violently unstablilizing one--just as strong focusing produces a smooth restricted path from violent over-corrections.

This principle has also been applied to linear accelerators. Electric quadrupoles have been installed in the drift tubes of the Berkeley linac and their fields can be made to alternately focus and defocus the beams so that the net result is good focusing. This eliminates focusing grids, which were formerly needed but by their presence intercepted as much as 2/3 of the beam. Magnetic quadrupoles can be used also and will do the focusing in the Berkeley and Yale heavy-ion linacs and in other linacs now under design.

Lack of time prevented discussion of the remaining topics but the groups showed, by their spontaneous applause, their appreciation of the clear and understandable presentation of the fundamental principles of accelerator operation and improvement.

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Chapter 5

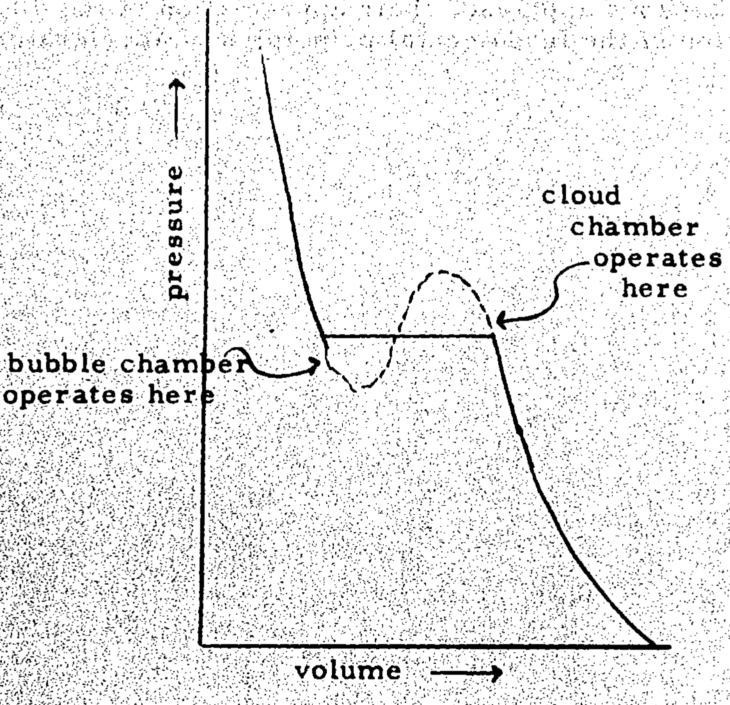
BUBBLE CHAMBERS

Don Gow

Mr. Gow first pointed out that there is little to be gained from breaking up atoms unless you have some way to examine the pieces. The machines to break the atom are spectacular and well known to the man in the street, but the detectors receive scant attention.

Historical methods of examining results of bombardment include Geiger counters, electroscope, scintillators, cloud chambers, and nuclear emulsions. The counters have good time resolution but very poor spatial resolution; photographic emulsions are at the other extreme--they show in detail <u>what</u> happened, but not <u>when</u>. The cloud chamber is in between, but as velocities and energies of projectiles increased it became more difficult to capture all interesting "events" in a chamber. Pressure chambers helped the situation somewhat, but they too soon ran into limitations.

Don Glaser of the University of Michigan made a comprehensive search for a better detector, and in 1952 came up with the fundamental idea behind bubble chambers.



An isothermal P-V curve for temperatures below critical is shown at the left. The cloud chamber uses the dotted extension at the right -- Glaser proposed and succeeded in using the dotted extension at the left as a medium that is sensitive to radiation.

Fig. 1

In other words he took advantage of the instability of superheated liquids against bubble formation in the same way as a Wilson cloud chamber utilizes the instability of super-cooled-vapors against droplet formations.

Dr. Glaser used diethyl ether as his liquid, and found that it could be held in a sensitive condition at 140°C and 20 atmospheres for periods up to 200 sec, although the average was around 60. Proximity to a Co^{60} source reduced this time almost to zero. He made his first report at a Washington meeting of American Physical Society Spring 1953, and members from this Laboratory who attended the meeting began experiments here immediately on their return.

Although ether has only 3 elements (C, H, O) instead of the many in photographic emulsion, some people in this laboratory felt that hydrogen would be best of all because it is a pure simple substance, and thus the target would always be uniquely known. Interpretation of nuclear events in a hydrogen chamber would be easier and more certain.

The first bubble chamber made here was all glass, about 1 by 0.75 in. The hydrogen was heated to about 29° K and kept under a pressure of 6.5 atmospheres, to prevent boiling. When expanded to a superheated condition it could be kept sensitive about 1 sec, which was plenty for satisfactory exposures.

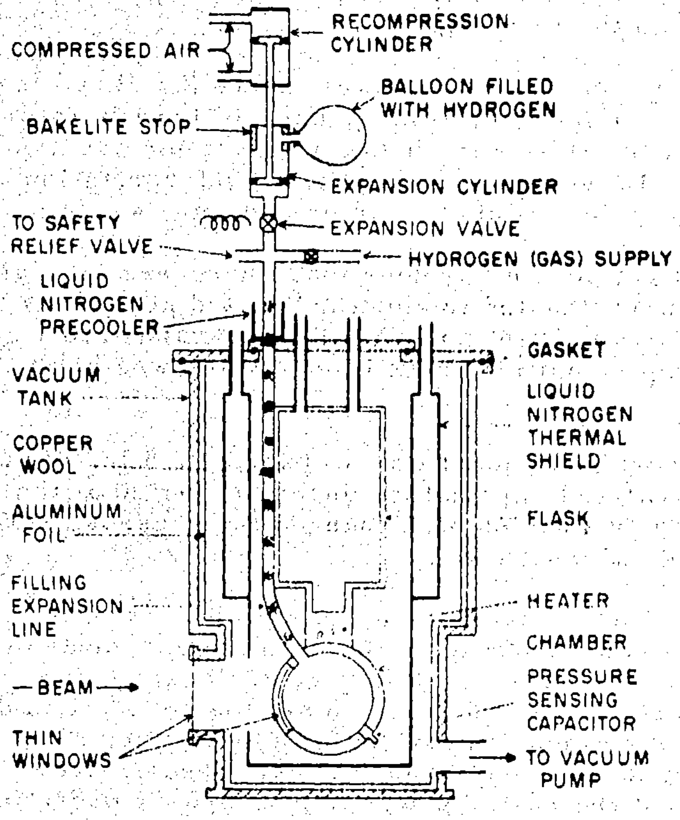
The next instrument was a chamber 2.5 in. in diameter, with metal walls. As expected, premature bubbling started at the metal-glass juncture, but the growth of wall bubbles changed the pressure slowly so that they did not interfere with operation.

The first chamber useful for physics was 4 in. in diameter and 2 in. in depth. Its general setup is shown in the accompanying diagram. (See Fig. 2.) It is reasonably self-explanatory except for the heater. The bubble chamber operates about 6° to 7° above the boiling liquid hydrogen in the flask. Heat exchange is provided by a connecting block of copper which is purposely made overconducting and has a heater installed in it. Automatic controls adjust the heater power to give proper operation.

The alternate expansion and compression during operation feeds heat into the chamber. This heat is dissipated by evaporating hydrogen--an undesirable waste. The waste can be minimized by fast recompression, so that the P-V "cycle" encloses a small instead of a large area.

The index of refraction for liquid hydrogen is around 1.08 -- only slightly more than the gas bubble. This means that the camera cannot be set perpendicular to the illumination, for the bubbles would not show up. It is necessary to so arrange it that the unrefracted light barely misses the camera, but the light refracted by a bubble just enters. This is achieved by a "Venetian blind." Bubbles appear as bright spots on a dark field.

The gasket for glass-metal contact was one of the most difficult problems to solve. Lead under spring load is the present solution, but the margin between lead-flow and glass-shatter pressures is uncomfortably narrow.


RECOMPRESSION CYLINDER
COMPRESSED AIR
BALLOON FILLED WITH HYDROGEN
BAKELITE STOP
EXPANSION CYLINDER
TO SAFETY RELIEF VALVE
EXPANSION VALVE
HYDROGEN (GAS) SUPPLY
LIQUID NITROGEN PRECOOLER
GASKET
VACUUM TANK
LIQUID NITROGEN THERMAL SHIELD
COPPER WOOL
ALUMINUM FOIL
FLASK
FILLING EXPANSION LINE
HEATER
CHAMBER
BEAM
PRESSURE SENSING CAPACITOR
THIN WINDOWS
TO VACUUM PUMP

MU-9466

Fig. 2

Two Helmholtz coils supply an adequate pulsed field of 15,000 gauss to aid in analysis of the tracks, but the resulting eddy currents make heating problems. The chamber is made of thin stainless steel to minimize this heating.

The present 10-inch chamber is a scaled-up version of the 4-in. one, with many improvements. A new recompression system has been used which has no rapidly moving pistons. The 10-in. will recompress within 30 milliseconds after expansion. This cuts heat losses and secures more uniform sensitivity throughout the chamber.

This bubble chamber is at present being used to study K^- mesons from the 6-Bev Bevatron beam. The unfiltered beam contains about one K meson to 50,000 π mesons, but filtering increases that to 1 in 1000. As a result, as high as one picture in 50 shows a K event. A typical plate is shown as Fig. 3. Here a K^- came in from the top, hit a proton, and formed a Σ^- and a π^+. Later the Σ^- decayed to a π^- + a neutron. The spirals are electron trails.

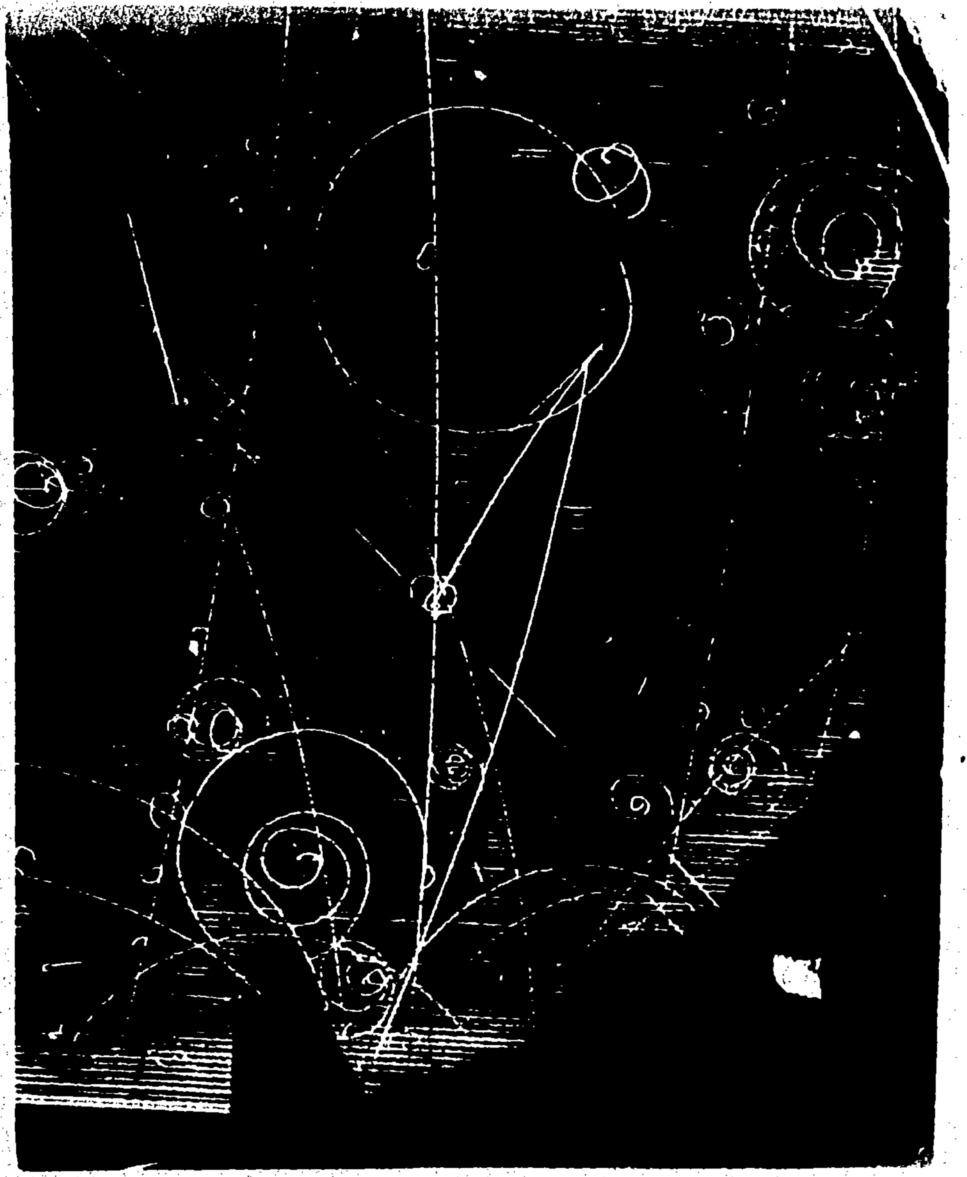
Plans are already well along for a larger chamber, tailor-made for a specific job. One of the most interesting kinds of events that is observed in very-high-energy processes is the disappearance and reappearance of charged particles. A typical reaction of this sort is

$$\pi^- + p^+ \rightarrow \theta^0 + \Lambda^0;$$

later the θ^0 decays to $\pi^+ + \pi^-$ and the Λ^0 to $p^+ + \pi^-$.

The delay interval is around 10^{-9} sec and it would be nice to have a chamber large enough for the entire sequence to take place within it. Figure 4 is an analysis of space requirements for the reaction above. Careful study of this and similar reactions has resulted in freezing the dimensions of the new chamber to be 72 in. long, 23 in. wide and 15 in. deep. The only hydrogen used will be in the bubble chamber itself. A refrigeration system replaces the cooling hydrogen. Design is well along and procurement of materials has started. Operation in 1957 is not overly optimistic. If the new chamber works as expected it is not unlikely that 10,000 interesting events per day will be recorded. Using present methods, a trained operator with a desk calculator can "analyze" an event in about two hours. Simple arithmetic shows that more than 2000 unavailable experts would be required to process the data.

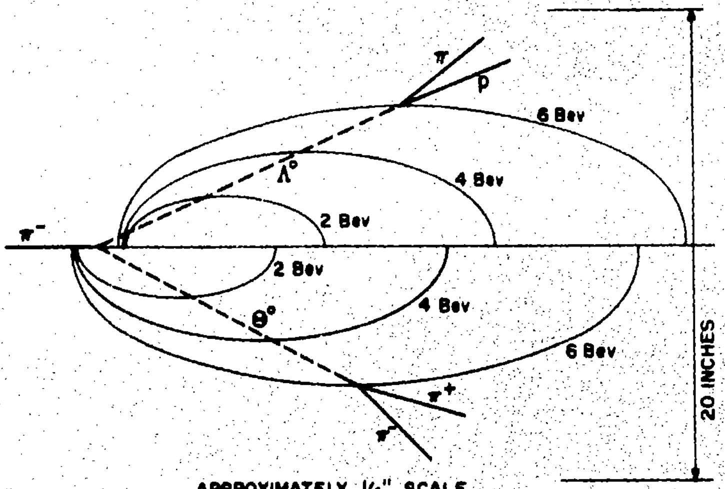
To prevent this pile-up, new machines are being developed. Humans will simply pick out by hand and eye the prints that look interesting. These will be fed to a precision reader, which is a sort of projection microscope. Data from this will be punched on IBM cards and these will be fed to a 650 computer, which can be programmed to give almost any information one might care to obtain. Corrections for nonuniform magnetic field and optical distortions can be made. Everything is automatic except the original curiosity and drive of the investigators.



ZN-1552

Fig. 3

DECAY CONTOURS FOR θ° & Λ°
FOR $\pi^- + p \rightarrow \theta^\circ + \Lambda^\circ$ FROM 2 TO 6 Bev



APPROXIMATELY 1/4" SCALE

MU-9902

Fig. 4

Mr. Gow closed with a list of credits both for leadership and for careful detailed construction and operation that has made progress in this new field so rapid and satisfying.

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Chapter 6

SOME TOPICS IN SOLID STATE

A. F. Kip

Dr. Kip explained that he got into the field of solid-state physics through the back door; that is to say, he was trained in microwaves, and that was associated with resonance studies with crystals.

His interest is in what makes a solid conduct or not. The range of naturally occurring resistivity is enormous, from 10^{-6} ohm per cm^3 for silver and copper to 10^{22} for materials like glass, sulfur, and quartz.

The theory of conductivity in metals is related to the theory of atomic structure, which is well established. Rigorous derivation requires acquaintance and facility with quantum mechanics, therefore we must rely mostly on analogies.

If a pendulum is attached to a horizontal taut wire and set in motion it vibrates with a definite period. If a second pendulum the same length is added at another point in the wire, the whole system vibrates with two different periods, which are higher or lower than the original, according to whether the two are in or out of phase. More pendulums make more periods, which are nevertheless restricted to a definite number and band of frequencies.

The foregoing picture gives the typical result that when similar oscillators--each of which has a single natural frequency alone--are coupled, the resulting system has more than one natural frequency. We compare this with the situation in solids.

Let us imagine a simple atom like lithium, having one electron, which is rather loosely bound. This electron at its lowest level (ground state) has a natural frequency (corresponding to a certain energy). If we bring another similar atom up close enough to it the electron has a choice of two unexcited levels. If several atoms are brought up the permitted levels become a band; each level, however, is still subject to the Pauli exclusion principle (which states that no more than one electron can occupy each possible energy state).

Thus we arrive at the conclusion there are "permitted" and "forbidden" energy levels or bands for electron movement within the body of macro quantities of elements. The relations between these bands determine whether the element is a conductor or an insulator. If the bands overlap then the electrons may be regarded as "free," and the element is a conductor. If the bands do not overlap, the element will still be a conductor if the top band is only partially filled, so that an electron can "move up" to a higher place within the band when subjected to an external field. This would be true for Group Ia elements. If the bands do not overlap and a band is "full", the element is an insulator, its specific resistivity being determined by the width of the "forbidden" band between that and the next "permitted" band.

The electron distribution of a normal insulator may be varied by the following means:

1. heat,
2. light,
3. introduction of impurities.

All of these are used. If the forbidden band is not too wide, then thermal energy may be sufficient to permit an electron to make the jump. This leaves an unfilled "hole" in the previously filled layer, which acts like a positively charged electron, so that the element becomes conducting. Gray tin, silicon, germanium, and tellurium act this way--they are known as intrinsic semiconductors.

A photon (bundle of light) may come into a metal with an energy determined by its frequency $h\nu$. If this energy is large it may be transferred to an electron which escapes entirely from the metal. This is the well-known photoelectric effect. If the energy transferred is not large enough to free the electron entirely it may still be great enough to permit the electron to cross a forbidden band, i.e., become conducting.

Germanium and silicon normally have four electrons in their outer shell and pair up like carbon in the diamond to form a stable tetrahedral configuration, except that the jump to the next permitted band is wide for carbon and narrow for Ge and Si. If very carefully regulated amounts of electron-surplus (n type) and electron-deficient (p type) impurities are added, a junction transistor results. (Details were not given.)

If, however, an electrostatic potential is applied to any of these semiconductors, a balance is set up in which we have $E e = m^* a$, where E is the applied emf, e is the charge on the electron, m is the apparent mass of the electron or hole, and a, of course, is the acceleration. Now, the effective mass m^* is not the true mass, and it would be helpful to find its value. This was done on this campus in 1952 by what is known as the cyclotron experiment. Germanium and silicon crystals (separately) were put in a microwave cavity oscillating at a fixed frequency. A variable magnetic field was applied. At some H there was absorption of energy according to the formula

$$\omega = \frac{eH}{m^* c}$$

where

ω = the angular velocity, m^* = the apparent mass,

e = the charge on the electron, c = the speed of light,

H = the magnetic field strength.

This gave a value for m^* roughly $\frac{1}{100}$ true rest mass, and is useful in further theoretical investigations involving crystal structure and wave mechanics.

Suggested Supplementary Material

Robert L. Sproull, Modern Physics (A Textbook for Engineers), John Wiley and Sons, Chapters 8 and 9, 1956.

John C. Slater, Modern Physics, McGraw-Hill, Chapter 10, 1955.

Modern Physics for the Engineer, A Symposium, Edited by Louis N. Ridenour, McGraw-Hill, Chapters 3 and 16, 1954.

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Chapter 7

THEORY OF NUCLEAR FORCES

Edward Teller

First we will briefly review the known physical properties of the nucleus, then examine proposed theories to explain these properties.

1. The nucleus has a radius of around 4 to 9 times 10^{-13} cm.

2. Its volume is proportional to the number of particles in it.

3. These particles consist of positively charged protons and neutrons without charge.

4. Each added nucleon is "bound in" with about 8 Mev of energy.

5. The "nuclear glue" or binding force that holds the nucleus together in spite of the repulsive Coulomb forces is unlike these forces in that it has only a short range (about 2×10^{-13} cm).

Bohr suggested a "liquid drop model," based on these facts, which had much to recommend it and was very useful in the early days of fission study. Dr. Teller feels, however, that continued adherence to that idea is now an actual hindrance to a true understanding of the nucleus.

A second model originally proposed independently in 1948 by M. G. Mayer and by Haxel, Jensen, and Suess indicates that there are definite shells of stability within the nucleus. Atoms having 28, 50, or 82 protons or neutrons (also 126 neutrons) are particularly stable. These are called "magic numbers." Lead 208 is doubly magic, as it has 82 neutrons and 126 protons. These magic-number elements may be compared in a way to the rare gases. A magic-number nucleus is unreactive and has a very low neutron-capture cross section. These shells are definite, but less sharply marked than are atomic shells. For instance it requires about 13 ev energy to ionize the first electron from a rare gas but only 4 to ionize the fast electron from the next higher element. The corresponding difference in the magic nuclei is a change from 9 Mev to 6 or 7 Mev.

In the nucleus there is a closer "coupling" between angular momenta due to spin and orbital motion than in the atom, where the electron experiences only a small "spin-orbit" force.

Also in the nucleus there is no strong central charged core that sets the main nuclear field. There is complete democracy; each nucleon contributes its own effect, and the resulting field is a composite of all. This leads to constant vibration-like small readjustments of the field which have been well studied by A. Bohr and Mottelson. Large field changes can be explained by individual nucleon excitations. Nuclear levels so derived help to systematize the growing field of nuclear spectroscopy.

The first step in a mathematically derived theory consistent with these known facts was taken by Yukawa in 1937. A rigorous development involves an extensive knowledge of quantum mechanics, but (Dr. Teller eliminated most of the mathematics from his talk; these notes eliminate even more, but will--we hope--give the feeling and "flavor" of the result.)

If a charged particle is snatched away with a high speed (but of course less than the speed of light), its field cannot keep up with it; therefore some is "abandoned" and the system adjusts itself to the new condition by emitting radiation of a characteristic frequency ν. The energy loss is quantized so that the following relation holds:

$$E = h\nu .$$

If the field has a finite range λ, then the frequency cannot be expected to be smaller than

$$\nu = \frac{c}{\lambda} .$$

Thus the particles have a minimum mass

$$E = \frac{hc}{\lambda} ,$$

which may be identified with the rest mass mc^2 of the quanta that are associated with the field. Thus if there is a short range λ there also will be a great quantum mass:

$$m = \frac{h}{\lambda c} .$$

Particles of such mass were found in cosmic rays soon after Yukawa's work, and hopes were high for a speedy solution of the nuclear puzzle. Unfortunately, when work was resumed after the war, it was found that these particles (called μ mesons) simply did not react with the nucleus. However, soon after this a new kind of meson, called the π meson, was found; these were artificially produced in this laboratory by bombarding matter with high-energy particles, and they did react with nuclei.

They reacted, but not in the right way to fit well any of the many theories advanced. Dr. Teller thinks he knows why and proceeded to tell us. He warned, however, that what he had said up to this point may or may not be true, but is widely known and generally accepted. What he tells us from now on is no more likely to be true; is less widely known; and where known, is not always accepted; therefore we believe at our own risk.

The first π mesons did not fit the theories; furthermore there were three kinds, with +, -, and zero electrical charge, and putting charged particles into a field theory introduces some complications. To make matters worse there are other kinds of mesons -- τ, θ, Σ, Λ, and Ξ, and probably lots more. Dr. Teller suggests that nuclear physics now has a similar position to that of chemistry 130 years ago. Chemists then knew there were more than the four elements (earth, air, fire and water) of the ancients, but had not yet decided on the temporarily permanent number 92. Which, or what combinations of these, are the nuclear glue?

Dr. Teller's answer is that none of the known mesons is the nuclear glue; there must be a simpler unit, one that is a simple scalar particle--that is to say, its field can be adequately described if you know only how many of them there are and what is the probability of finding one in a particular place in the nucleus. The chief trouble with such a particle is that it has not been found (but neither had Yukawa's at the time he suggested it). One reason is that it would have a very short life, probably not more than 10^{-14} second.

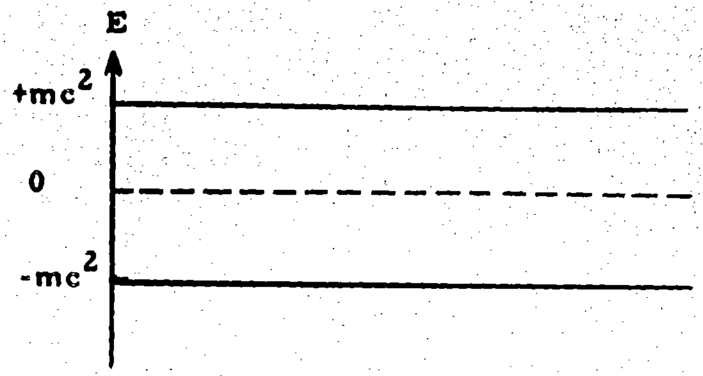
Dr. Teller is convinced that the nuclear glue is actually made up of two as yet undiscovered mesons. One of these mesons gives rise to an attractive force and leads to a nucleon (proton or neutron) mass, inside nuclear matter, of one-half the value for a free particle. The other meson gives rise to a repulsive force which prevents collapse of the nucleus. Changing the mass of a nucleon inside the nucleus affects the frequencies of light that nuclei will absorb, the ratio of neutrons to protons, the energy levels that will exist, and the scattering of neutrons and protons. Calculations of all these effects come closer to experiment than do theories based on the more usual assumptions.

Assuming the theory is true, we find some additional interesting results. A well-known formula in relativity is that the energy E of a particle is

$$\pm \sqrt{(mc^2)^2 + c^2p^2} \simeq \pm (mc^2 + \frac{p^2}{2m}),$$

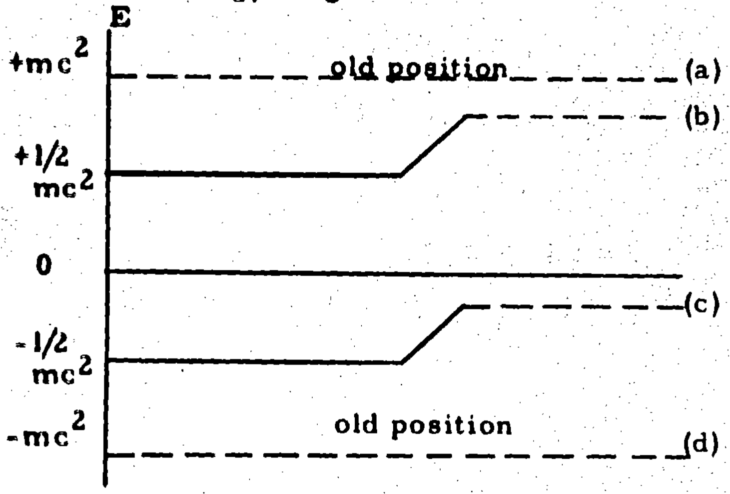
where m = mass, c = speed of light, p = momentum = mv, and v = velocity. In the early days it was customary to ignore the negative-energy solutions as being without meaning. However, Dirac suggested that these negative-energy solutions should correspond to antiparticles. These antiparticles behave like ordinary particles except that their charge is just the opposite.

Using the above relationship for the energy of a particle, we see that an energy-level diagram can be constructed.



For a free particle all energies greater than $+ mc^2$ are allowed, and for a free antiparticle all less than $-mc^2$ are possible.

If in the interior of a nucleus the particle now has only one-half its normal mass, the energy diagram "moves in" half way to zero.



In addition to having an "effective mass," the nucleon experiences a repulsive force due to the second type of meson. This repulsive force is similar to the usual Coulomb force; consequently, if it is repulsive for a proton it is attractive for an antiproton. Thus the resultant positions of the proton and antiproton energy levels are as shown by the dotted line (-----) in the second diagram.

The net result is that a nucleon moving in such a "nuclear glue" has its energy changed by an amount (a) - (b), whereas an antinucleon has its energy altered by an amount (c) - (d). This means that when an antiproton reacts with the nucleus, the cross sections should be much larger for the antiproton than for the proton.

During the discussion period attempts were made to get Dr. Teller to suggest specific experiments which would definitely prove or disprove his theory but he only smiled genially.

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Radiation Laboratory
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Chapter 8

NUCLEAR FORCES

Owen Chamberlain

Dr. Chamberlain had just returned from a conference on high-energy physics held in Moscow, U.S.S.R. He was one of three from this laboratory and 12 from the entire United States to be invited.

He gave a brief historical resumé of development of facts and theories about the nucleus. Early in 1911, Rutherford reported results on the scattering of alpha particles by gold and other foils. The relatively large number that scattered through a wide angle (some even up to 180°) could be accounted for only by assuming a highly charged small region of the atom considerably more massive than the α particle. His data would fit a repulsion or attraction equally well, but Thompson had shown that electrons (negative charges) existed in every atom; furthermore the atoms themselves are neutral. Therefore, Rutherford concluded the "nucleus" was positively charged, and all subsequent work has verified this. He drew the correct inference that the nucleus contained nearly all the mass of the atom.

This nucleus contains protons and neutrons only. Before the discovery of the neutron by Chadwick in 1932 some electrons were assigned to the nucleus. Theoreticians were unhappy because spin relations did not come out right in some atoms (deuterium for instance). Discovery of the neutron fixed that up.

The atomic weight of any isotope is slightly less than the sum of the weights of the nucleons making it up (by an amount known as the binding energy, which is around 6 to 8 Mev per nucleon, except in light-weight atoms).

Let us now compare and contrast the behavior of a complex atom and of a complex nucleus.

In an atom each additional electron added fits into a pretty definite orbit determined very largely by the large charge on the nucleus and influenced in only a minor way by neighboring electrons. In a nucleus one added nucleon is influenced more by its immediate neighbors than by the "central office."

In an atom added nuclear charge pulls the orbital electrons in close so that the diameters (and volumes) of heavy atoms differ little from and may even be less than those of lighter ones. However, by scattering experiments with protons, with fast neutrons, and even with electrons, it is found that the diameter of the nucleus does grow with added nucleons, closely approximating the formula $R = 1.3 \times 10^{-13} A^{1/3}$, where R is the radius in cm and A is the atomic number.

These facts led Bohr to suggest the liquid-drop model, in which the individual nucleons have much the same relation to one another as molecules in a drop of liquid argon. These attract one another with short-range forces, but repel one another at very close range because electron structures in atoms do not want to intermesh.

This model of the nucleus is substantiated by some facts but not others. Particularly this predicts that a disruption (short of fission or meson formation) should not differ greatly whether the projectile is neutron, proton or α particle provided that the same compound nucleus is formed when the projectile is absorbed. This is in keeping with work done in the laboratory in 1949 by Ghoshal.

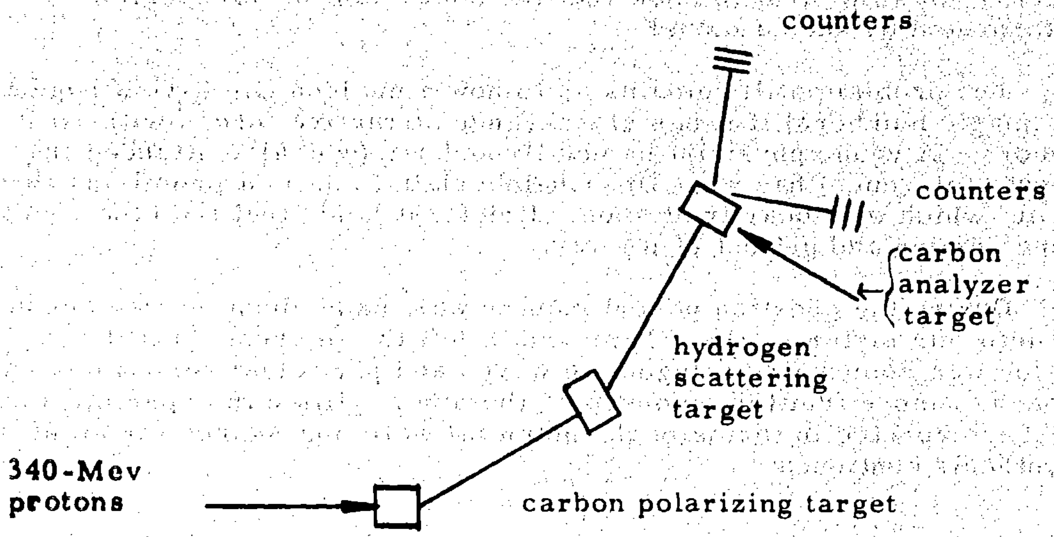
Originally there was no evidence for shell structure in the nucleus, but around 1950 M. Mayer in Chicago and Jensen in Germany found there was some evidence (higher binding energy) for such a configuration. (Dr. Chamberlain did not mention specific values but these nuclei have the "magic numbers" 2, 8, 20, 50, 82, protons or neutrons, also 132 neutrons.) The shell structure in nuclei is very much less prominent than it is in atoms.

When deuterons are bombarded by gamma rays nothing much happens till the energy reaches 2.225 Mev. Then protons and neutrons are ejected. This is the "binding energy," and by classical mechanics one would think it was also the depth of the potential "well." Quantum mechanics, however, puts the well much deeper, maybe 20 Mev.

Much work was done trying to determine the "shape" of this potential well, and it turned out to be a professional "yes man"--no matter what shape was suggested the data seemed to fit. This too-easy solution was shown by Blatt and Jackson at MIT to be due to the fact that with low energies the experiments were capable of determining only two parameters. In other words only the diameter and depth, not the shape, were given. This is known as the "effective range theory," and though it was disconcerting at first and increased mathematical difficulties, it means only that attention must be directed to higher-energy beams.

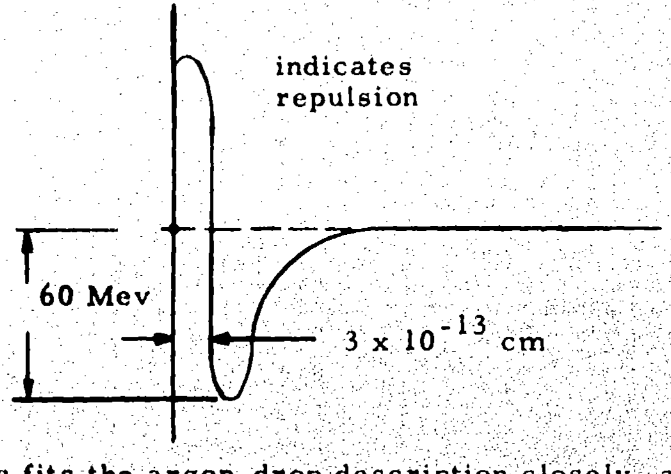
The difficulties here were that two different kinds of wells are needed, one for parallel-spin (triplet-state) protons, and one for antiparallel spin (singlet-state) protons--and originally all beams consisted of both kinds of protons. Work at the University of Rochester showed how to get a beam of polarized (same-spin) protons, and the method was used in this laboratory in the triple-scattering experiments.

The idea can be followed from the following diagram.



A 340-Mev beam of approximately 10^9 protons per sec is "polarized" by scattering from a carbon target; the left-hand spinning ones are directed to a hydrogen target and then again "analyzed" in another carbon block. By this time the flood of 10^9 protons per sec has been reduced to a trickle or one every thirty seconds or 3×10^{-2} per sec.

Now that we have a method of getting a unique projectile (polarized protons) we have a better chance of getting a unique answer as to the shape of the potential well. It is true that we still have no polarized target, therefore indirect means are used. (These were not explained in detail but it seems there is confidence in the conclusions.) The results for parallel spins is still ambiguous, but for antiparallel spin, results indicate a potential well something like the following.



Note that this indicates indifference at long range, with increasing attraction at approach, which reverses sharply and becomes repulsion at very close range.

This fits the argon-drop description closely, and is frequently known as the "hard core" model or theory.

Jastrow, a young physicist from The Institute of Advanced Study of Princeton, was the first to show that the data from these experiments could be interpreted by such a model.

The problem still remains as to how a nucleon can have a regular orbit (magic numbers) if it has close-range attractive forces with all its neighbors. A young physicist named Brueckner (who also attended the Moscow conference) has what Dr. Chamberlain feels is a promising theory about it, which may bear fruit soon. Briefly it holds that the other nucleons see one coming and get out of its way.

During the question period inquiry was made about where mesons fitted into this picture. Dr. Chamberlain left the impression that the situation was somewhat analogous to waves and particles; sometimes one approach is more fruitful, sometimes the other. His own experiments can be best interpreted in terms of the potential well, but search for an over-all synthesis continues.

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Chapter 9

NUCLEAR ENERGY LEVELS

Isadore Perlman

Dr. Perlman has been part of a group working for several years on radiochemistry of the elements, especially the transuranium elements. The purpose is to learn the chemistry of some elements in particular and the constitution of the nucleus in general.

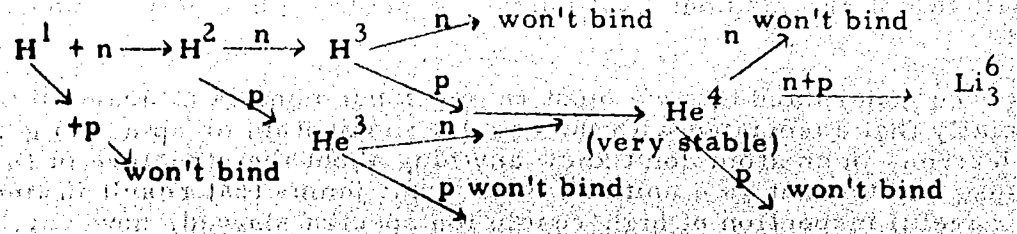
The nucleus is known to contain two kinds of particles, neutrons and protons, and is usually considered to be spherical; but it is definitely not a "bag of marbles." The forces that hold the nucleus together are not at present understood to the extent that one can predict from these "first principles" the detailed structure of complex nuclei, but it is possible to learn a lot about the behavior of the nucleus without knowing its structure.

Dr. Perlman reviewed very briefly what is known about the nucleus.

1. Its radius is between 10^{-12} and 10^{-13} cm and varies as $A^{1/3}$, where A = mass number.

2. The forces that hold it together are short-range, and they "saturate" (are not cumulative).

3. It contains neutrons and protons and in the creation of stable nuclei these prefer to pair with each other, as shown by the following representation of what will and will not stick together.



Many nuclei are stable in the sense that neutrons and protons are actually bound, but unstable in the sense that a conversion of a proton to a neutron or vice versa (β-instability) will produce a more stable structure. In the above examples H^3 is a bound nuclear structure but it is slightly unstable with respect to He^3, to which it decays by conversion of a neutron to a proton with the emission of a β^- particle (electron).

Including H^2 and Li^6, there are only 4 β-stable nuclei that have odd numbers of both protons and neutrons, and all of these are among the light elements, in which it is possible to have equal numbers of neutrons and protons. There are more than 160 stable nuclei that have even numbers of both neutrons and protons (even-even nuclei), about 50 that have even protons and odd neutrons (even-odd), and about 50 with odd protons and even neutrons (odd-even).

Incidentally, the peculiar interconversion of protons and neutrons that is the essence of β radioactivity bears the implication that these are two forms of the same fundamental particle, called the nucleon. A β-stable nucleus is simply one that is in a lower energy state than its neighbors with the same mass number. An example of a β^--unstable nucleus is P^{32}, which is much used as a tracer for the element phosphorus:

$${}_{15}P^{32} \xrightarrow{\beta^-} {}_{16}S^{32} .$$

Two other interesting examples are

$$K^{40} \xrightarrow[10^9\text{ yrs}]{\beta^-} Ca^{40} + 1.3\text{ Mev},$$

$$Na^{24} \xrightarrow[14\text{ hr}]{\beta^-} Mg^{24} + 1.3\text{ Mev}.$$

Both of these release about the same amount of energy in the β particle, yet the half life of one is about 1 billion years and the other only 14 hours. How come?

To understand this we must review fundamentals of quantum numbers, especially that associated with the angular momentum or spin. In general, the electrons in an atom don't know anything about the structure of the nucleus, and treat it as a unit and make orbit jumps that result in line spectra. Very careful inspection of high-resolution spectra showed, however, that these "lines" were really bundles of small lines; in other words, there was a hyperfine structure. This is caused by the small effect of nuclear spin upon the electronic energy levels. The nuclear spin can be oriented in a number of different ways, producing slightly different electronic energy states. The unit of nuclear spin is $h/2\pi$, and if the spin of a particular nucleus has I such units, this results in a hyperfine multiplicity of 2 I+1; that is, a spectral line is split into that many components. The analysis of the hyperfine structure is one of the important methods of determining nuclear spin.

It turns out that all nuclei with even numbers of both neutrons and protons have zero spin for the lowest energy state. This means that the nucleons pair in such a way as to cancel the spins of the individual particles. It should further be pointed out that the spins of individual nucleons are always half-integral values of $h/2\pi$, so that all nuclei with an odd number of total nucleons have half-integral spins and those with even numbers are integral or zero.

Now let us return to the cases of the β-decay lifetimes of K^{40} and Na^{24}. In general a nucleus doesn't want to change angular momentum or spin in going from one state to another, and this accounts for the variation in half life with the same energy change. The K^{40} is hindered by a large spin change, the Na^{24} is not. In particular, K^{40} has a spin of 4 units and can decay only to the ground state of Ca^{40}, which has spin zero; but Na^{24}, which has spin 4, can decay to an excited state of Mg^{24}, which also has spin 4. If K^{40} could reach a spin-4 state of Ca^{40} it also would decay quickly, but none is available.

It has just been mentioned that Na^{24} decays to a spin-4 state of Mg^{24}, which is an excited state. This state then drops to the ground state by γ-ray emission. How do we know that the excited state has spin 4? It cannot be measured by the method mentioned because it only lasts for perhaps 10^{-10} to 10^{-12} second. There are other ways. We know that Mg^{24} ground state has spin zero, and by indirect means it is often possible to build upon this and deduce spins of excited states. One of these methods is to measure properties of the γ-ray transition, such as the internal conversion coefficient, which is the ratio of transitions that involve the ejection of an orbital electron to those in which the γ ray itself is emitted. The theory of internal conversion tells us what the spin change is. Other properties of γ radiation can also be used to get this information.

So far we have considered spin changes to explain differences in β-decay lifetimes. They also influence γ-emission lifetimes and all other nuclear processes. Gamma emission, which is usually extremely rapid, can be greatly retarded by large spin changes, and where these lifetimes enter the measurable range we call the long-lived upper state and the lower state nuclear isomers. There is a more general interest in assigning spins to nuclear states. This has to do with the problem of nuclear configurations. Just as electrons fill into the atoms in a regular sequence giving periodic properties to the elements, so there appears to be a systematic build-up of nuclear systems, and we would like to arrive at an understanding of it. Each nuclear state is characterized by a particular configuration, and the spin is one of the important properties that give insight into the nature of the configuration.

Perhaps the first definite point of entry in this general problem came from the recognition of certain "magic numbers," which signify numbers of neutrons and protons that result in extraordinary nuclear stability. These have some analogy to the closed shells in atomic structure. Outside of the lightest elements, these magic numbers are 28, 50, 82, 126. The trick was to fill in quantum states in some regular sequence to arrive at breaks in the sequence precisely at these numbers, and particularly to have the spins corresponding to these states come out right. Other nuclear properties, including "parity" (not dealt with here), must also conform. This is a crude description of what the shell theory attempts to do--and has so far accomplished with remarkable success.

In spite of its successes the shell or independent-particle theory breaks down in explaining many details. Apparently the nucleus is approximately spherical at these closed shells but departs widely from it elsewhere; this becomes more evident with larger nuclei, where it is possible for both neutrons and protons to depart widely from the "magic numbers." It can become either long (like a football) or flat (like a pumpkin). These deformations perturb the single-particle states and result in some radical changes not predictable from shell theory. In some cases best results come from treating the nucleus as a whole, not unlike a liquid drop. Its collective behavior can be described in terms of surface oscillations or elastic vibrations superimposed upon particle behavior, and much theoretical work has been done along these lines.

As in so many phases of chemistry and physics, a higher synthesis with predictions verifiable in the laboratory is still to come.

During the question period Dr. Perlman told very briefly of his own present research, which is concerned with analysis of alpha disintegration of heavy elements to determine various energy levels within those nuclei. Accompanying gamma rays provide a valuable check on the results.

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Chapter 10

UNSTABLE PARTICLES

Edwin M. McMillan

An unstable particle was defined as one which, left alone in space, would break down into something else. This does not include particles that react with other particles. It is easier to list stable particles and then say all others are unstable; stable particles are as follows:

	Symbol	Name
1.	γ (gamma)	photon
2.	e^-	negative electron
3.	e^+	positron
4.	p (or p^+)	proton
5.	$\tilde{p}$ (or p^-)	antiproton
6.	ν (nu)	neutrino
7.	$\tilde{\nu}$	antineutrino (probably exists)

The uninitiated will be surprised at finding the positron and antiproton in this list, since anyone who knows anything at all about them knows they are ordinarily very short-lived. However, this is because they react with other particles always present; they do not disintegrate of themselves, hence they are stable by our definition.

The first of the unstable particles is the neutron (particle No. 8) some readers will think this is wrongly placed, for do not nuclei containing neutrons last indefinitely? The point is that in nuclei the neutrons are stabilized by the binding energy of their association with protons. Free neutrons undergo β decay, with a half life of around 20 minutes, according to the equation

$$n \rightarrow p + e^- + \nu.$$

This reaction releases around 3/4 Mev of kinetic energy, hence it is spontaneous and the neutron is unstable.

Most of the above eight particles (7 stable and 1 unstable) were well known and characterized by 1935. Since then particles of a second class, known as mesons, have been studied. They were first predicted on theoretical grounds, then found in cosmic-ray studies, and can now be produced in the laboratory with the energies available in the larger cyclotrons. Mountaineers have been replaced by chair-sitters, but the quantity and quality of the data improve.

The first mesons studied were discovered in the cosmic rays. They are now called μ(mu) mesons and have an average life of 2.15×10^{-6} sec. (It is customary to express radioactive decays in terms of the half life--that is, the time for any activity to diminish to 1/2 its original value.) Meson decays are expressed in terms of the average life, which turns out to be the time for activity to go to 1/e of its original value. Half life is usually indicated by τ(tau), but that can be confused with tau mesons, so we will use t_{ave} and $t_{1/2}$; $t_{ave} = 1.443\, t_{1/2}$. It should be mentioned that 10^{-6} sec is a very long time in the nuclear world.

Powell and his co-workers in England soon showed that μ mesons had parents called π mesons, which were children of the original cosmic rays, which consisted of high-speed protons. These facts can be summarized in the following equations.

$$\left.\begin{array}{ll} 9. & \mu^+ \rightarrow e^+ + \nu + \nu \\ 10. & \mu^- \rightarrow e^- + \nu + \nu \end{array}\right\} \quad t_{ave} \cong 10^{-6} \text{ sec}$$

$$\left.\begin{array}{ll} 11. & \pi^+ \rightarrow \mu^+ + \nu \\ 12. & \pi^- \rightarrow \mu^- + \nu \end{array}\right\} \quad t_{ave} \cong 10^{-8} \text{ sec}$$

$$13. \quad \pi^0 \rightarrow \gamma + \gamma \qquad t \cong \begin{array}{c}\text{very short,} \\ \text{may be}\end{array} \; 10^{-14} \text{ sec}$$

In the laboratory all three kinds of π mesons may be made by bombarding any matter with any high-energy particles. Actually the Laboratory used 390-Mev α particles and 345-Mev protons on carbon targets. Note that the end products are neutrinos, electrons, and kinetic energy.

We now leave the field of "well known" and "fairly well known" to enter that of vaguely known or suspected. These are called "strange particles." [In an aside Dr. McMillan said they were no stranger than any others, just newer. As a matter of fact, to him the strangest of all is the neutrino.] These too were first discovered in cosmic rays, but can now be created in the laboratory by the Bevatron and similar machines (the cyclotron does not furnish enough energy.)

The first of these are the K mesons. They have a mass of roughly 1/2 the proton and an average life of around 10^{-8} sec. Originally there were several kinds of K mesons, and the situation was so confused that considerable effort and ingenuity were applied to "undiscovering" some of the brood. This was successful in the conclusion that the same species could decay in different ways. (Roman letters are used to designate classes of particles, Greek letters are used to designate fairly well-established individual particles.) Some relationships are shown in the chart.

14. $\tau^+ \rightarrow \pi^+ + \pi^+ + \pi^-$

15. $\tau^- \rightarrow \pi^- + \pi^- + \pi^+$

16. $\theta^+ \rightarrow \pi^+ + \pi^0$
$\quad\searrow \mu^+ + \nu$
$\quad\searrow e^+ + \nu$

17. $\theta^- \rightarrow \pi^- + \pi^0$
$\quad\searrow \mu^- + \nu$
$\quad\searrow e^- + \nu$

18. $\theta^0 \rightarrow \pi^+ + \pi^-$
$\quad\searrow \pi^0 + \pi^0$

all of these are K mesons.

All the zero-charge particles have a shorter average life than the plus or minus ones.

The second class of "strange particles" is the hyperons. They are heavier than protons and probably are actually composite, consisting of a neutron or a proton plus "something stuck on." Their "family tree" appears as follows.

19. $\Lambda^0 \rightarrow p + \pi^+$
$\quad\searrow n + \pi^0$

20. $\Sigma^+ \rightarrow n + \pi^+$
$\quad\searrow p + \pi^0$

21. $\Sigma^- \rightarrow n + \pi^-$

22. Ξ^- (cascade particle) $\rightarrow \Lambda^0 + \pi^-$.

We see that our total number of primary particles has grown to 22, of which only 7 are stable. Can we make a unified coherent whole out of them? Not yet. Mathematical treatment leads to equations nobody can solve, but we do have some working rules.

1. A particle is unstable (metastable is probably a better word) only if it can change into something else <u>and release kinetic energy</u>.

2. In all reactions energy (or the mass equivalent of energy) is conserved.

3. Charge is always conserved.

4. Linear momentum is always conserved.

5. Angular momentum is always conserved.

6. Parity is always conserved. (This has no classical analogue, but has to do with the symmetry of the wave function.)

These rules have stood the test of time, and a new one is offered tentatively.

7. "Strangeness," a new quantum number invented by Gell-Mann, does not change, or at least only reluctantly (delays things from 10^{-20} to 10^{-8} sec.) A corollary is that "strange particles" are always created in pairs. (For instance, if a particle of strangeness +1 and a particle of strangeness -1 are created simultaneously, the total strangeness produced is zero.) This substantiates findings at Brookhaven and elsewhere. A table of strangeness is appended.

Strangeness:	-2	-1	0	+1
Particles:	Ξ	K^-	p	K^+
		K(?)	n	K^0(?)
		Σ^+	π	
		Σ^-	μ	
		Λ^0	e	
			ν	
			γ	

The appearance of K^0 in both - and + columns is not an error. It has a dual nature.

[During the question period it was brought out that primary data for all these theories come from cloud-chamber tracks, photographic emulsion tracks, and ionization and scintillation counters.]

Some of the nuclear emulsion pictures show successive and delayed stars. This can be accounted for by the inclusion of a Λ^0 particle in a nucleus that later "explodes" and gives short-lived unusual nuclei such as hydrogen-4 and helium-5.

[The writer feels that Dr. McMillan's speech has negated Rule 7 and some of the "strangeness" of this front line of physical inquiry has been annihilated and replaced by at least a "speaking acquaintance," even if not by a true understanding.]

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Chapter 11

ANTIPARTICLES

Emilio Segrè

Dr. Segrè was introduced by Dr. Stubbins as one who had contributed much and continuously to nuclear research. His early work was in Italy, where he was associated with Fermi. He has been Professor of Physics at UC since 1946 and has recently returned from the Moscow conference on high-energy physics.

Dr. Segrè said that antiparticles were first suggested in 1928 as a result of Dirac's relativistic wave theory of the electron. As a starting point of this theory he used the relativistic expression for the energy of an electron,

$$E^2 = m_0^2 c^4 + c^2 p^2,$$

where E = the energy of the electron,

m_0 = rest mass,

c = speed of light,

p = momentum of the electron.

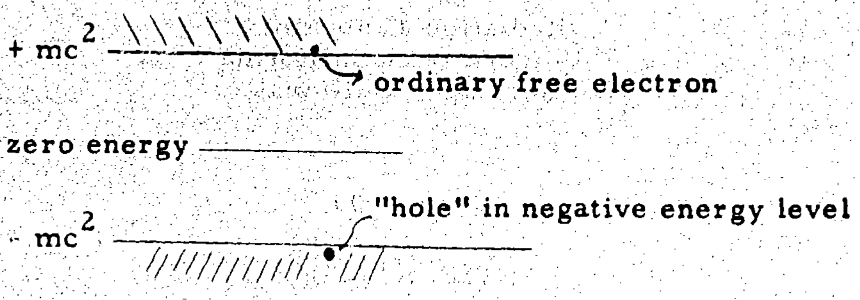
Solving for E, we get

$$e = \pm \sqrt{m_0^2 c^4 + c^2 p^2}.$$

In classical mechanics we could just "throw away" the negative value as meaningless, but it was an essential part of the relativistic quantum treatment. This means that there must be a negative state of energy, and a positively charged particle with other properties similar to those of an electron. Early attempts to identify the proton with this particle showed that the proton had much too great a mass.

The theory proved so useful and accurate in predicting spin (mechanical and magnetic moment in the correct ratio) and the fine structure of spectral lines of hydrogen, that it could not be "laughed off."

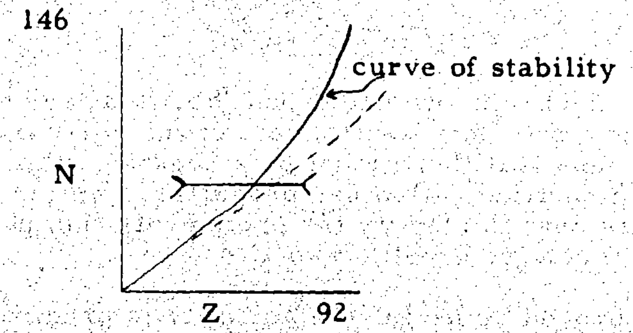
In 1932 C. D. Anderson at CalTech found a track in film used in cosmic-ray studies that could only have been made by a particle with the properties postulated by Dirac. He named it positron; it is really the first of the antiparticles, an antielectron. Dirac's ideas are illustrated by the following diagram.



Dirac suggested that the reason transitions to and from this negative continuum were not ordinarily noticed was that all energy levels in it were already filled and transitions were forbidden by Pauli's exclusion principle. However, if slightly more than the energy equivalent of two electron masses (> 1 Mev) were to impinge on matter, it might be possible to move an electron from the negative to the positive realm. The "hole" left would then act like a positron. Its existence would be short-lived because it would soon be filled by one of the readily available electrons in "normal matter. The original amount of energy would then be radiated.

Now, we actually do have "pair production' and its reverse, annihilation, in keeping with these energy requirements, though some people are reluctant to admit the existence of this never-never land of negative energy.

The most convenient way to get positrons is not from pair productions but from suitable radioactive elements. There is a well-known curve of stability for atoms obtained by plotting N (the number of neutrons) vs Z, the number of protons. It starts out in a 1-to-1 ratio, but goes to about 1.6 to 1 for uranium. Elements off the line to the left (too many neutrons) achieve stability by emitting electrons (changing neutrons into protons). Elements off line to the right do the reverse, as shown in this diagram.



Sodium-22 is a good source of positrons because it decays as follows

$$Na^{22} \xrightarrow{2.6\ yr} Na^{23}\ \beta^{+}$$

Let us list some properties of the normal particles and antiparticles;

1. Mass -- same.
2. Charge -- opposite.
3. Magnetic moment -- opposite.
4. Spin -- same.
5. Generated in pairs.
6. Annihilated in pairs.
7. Stability in vacuum -- same.

After Anderson's discovery of the antielectron, a thorough search was made for other antiparticles, especially the antiproton, but efforts were in vain for 25 years. A creation energy of more than 2 mc^2 shows that if two protons were moving with equal speed toward each other each would have to have an energy in excess of 1 Bev, but if one were standing still the other would need about 6 Bev energy, because some would be transferred to center-of-mass momentum and only the remainder would be available for pair creation.

Man-made energies in this range became available only with completion of the Berkeley Bevatron, and the search was taken up with renewed zest. Identification of the particle, if produced, depends on Properties 1, 2, and 7 listed above. The mass would be the same, the charge opposite, and the inherent stability infinite. Stability should not be confused with reactivity; the half life of the antiproton is infinite in vacuum but about 10^{-7} sec under conditions of the laboratory experiment.

Any bombardment that could conceivably produce antiprotons would at the same time make a great many mesons, so that an elaborate "filtering" process is necessary. The charge could be used to separate it from all positively charged particles and its momentum would cause it to curve in a magnetic field differently from all other momenta. Finally, its mass would give it a different velocity from all other particles having the same momentum and thus it could be uniquely determined.

The separated antiprotons were allowed to impinge on nuclear emulsions, and on development these showed a few stars, the total energy of which exceeded the incident particle--proof that an additional nucleon had been annihilated.

Thus the long search has ended, but as usual in scientific works it arouses more questions than it settles. Dr. Segrè is absolutely convinced that there must be an antineutron. Because of its lack of charge it will be harder to find--the methods will depend on elimination--but plans are already under way here at the laboratory for an experiment to find it. So now we have complete symmetry of ordinary particles and antiparticles. Is there really an antiworld somewhere, or is it just a mathematical trick? And if there is an antiworld, what will happen when it touches our "real" world? Will there be terrific annihilation of matter and creation of energy, or will the first energy blow the masses apart and stop the reaction? And how did the worlds get separated in the first place? As Dr. Segrè said, we have now passed from the realm of science into that of speculation.

TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

Radiation Laboratory
University of California
Berkeley, California

Chapter 12

THE TRANSURANIUM ELEMENTS

Glenn T. Seaborg

Dr. Seaborg received his doctorate at Berkeley in 1937 and has been associated with the University ever since, except for an interlude with the Metallurgical Project at Chicago during World War II. He was awarded the Nobel rize in 1951 and since then has continued to be an active worker and inspiring leader in studies of the transuranium elements.

Dr. Seaborg listed the transuranic elements, gave a very brief history of them, and discussed their production and detection. The elements, with their histories, are:

Element 93 - Neptunium (Np) was so named because it is the first element after uranium, just as Neptune is the first planet beyond Uranus. It was discovered by E.M. McMillan and P. H. Abelson in 1942 as a result of bombarding uranium with neutrons from the Berkeley 60-inch cyclotron.

Element 94 - Plutonium (Pu) -The name, derived from Pluto, results from a continuation of the planet system. The element was discovered in the Berkeley Radiation Laboratory by bombarding uranium with deuterons.

Element 95 - Americium (Am)- Since there are no more known planets lying beyond Pluto, a new method of naming was needed. About this time it was pointed out that these transuranium elements have properties very similar to those whose atomic weights are 32 less. (See Fig. 1.) The name indicates analogy with element 63 (95-32) called europium.

Element 96 - Curium (Cm) - Curium is analogous to gadolinium, element 64, (96-32) named after J. Gadolin, the great Finnish investigator of the rare earth elements. Similarly curium is named after the great French workers in radioactivity, Pierre and Marie Curie.

Element 97 - Berkelium (Bk) - This is pronounced Berk'lium, not Ber ke'lium, and was named to honor the city of Berkeley in the same manner as its homolog terbium honors the Swedish town of Ytterby.

Element 98 - Californium (Cf) - The homolog of californium is dysprasium which means hard to get. Analogies were abandoned in naming this element and the state and university of discovery were honored.

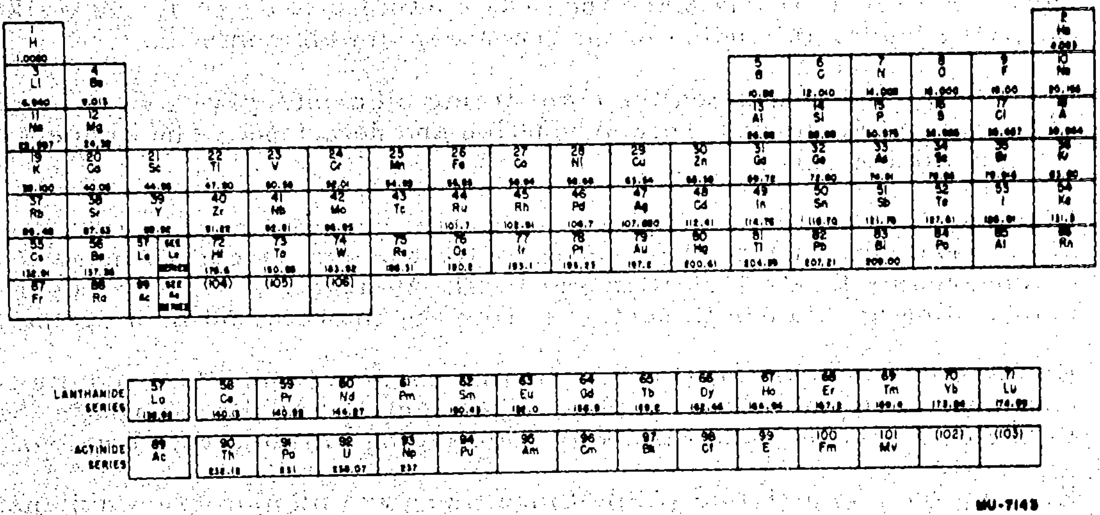
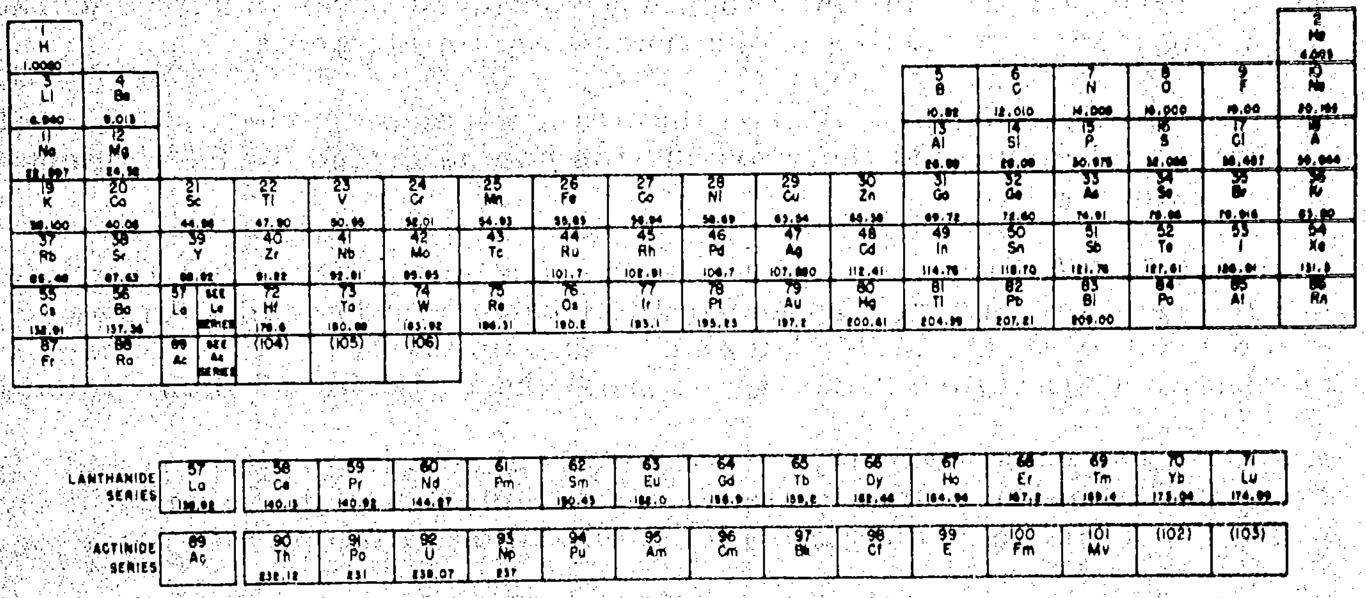

1 H 1.0080
2 He
3 Li
4 Be 9.013
5 B
6 C 12.010
7 N
8 O
9 F 19.00
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 A
19 K
20 Ca 40.08
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga 69.72
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru 101.7
45 Rh
46 Pd 106.7
47 Ag
48 Cd 112.41
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe 131.3
55 Cs
56 Ba 137.36
57 La
SEE La SERIES
72 Hf
73 Ta
74 W 183.92
75 Re
76 Os 190.2
77 Ir 193.1
78 Pt
79 Au 197.2
80 Hg 200.61
81 Tl
82 Pb 207.21
83 Bi 209.00
84 Po
85 At
86 Rn
87 Fr
88 Ra
89 Ac
SEE Ac SERIES
(104)
(105)
(106)
LANTHANIDE SERIES
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
ACTINIDE SERIES
89 Ac
90 Th
91 Pa
92 U 238.07
93 Np 237
94 Pu
95 Am
96 Cm
97 Bk
98 Cf
99 E
100 Fm
101 Mv
(102)
(103)
MU-7143

Fig. 1



1 H 1.0080																	2 He 4.003
3 Li 6.940	4 Be 9.013											5 B 10.82	6 C 12.010	7 N 14.008	8 O 16.000	9 F 19.00	10 Ne 20.183
11 Na 22.997	12 Mg 24.32											13 Al 26.98	14 Si 28.09	15 P 30.975	16 S 32.066	17 Cl 35.457	18 A 39.944
19 K 39.100	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.93	26 Fe 55.85	27 Co 58.94	28 Ni 58.69	29 Cu 63.54	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.91	34 Se 78.96	35 Br 79.916	36 Kr 83.80
37 Rb 85.48	38 Sr 87.63	39 Y 88.92	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	47 Ag 107.880	48 Cd 112.41	49 In 114.76	50 Sn 118.70	51 Sb 121.76	52 Te 127.61	53 I 126.91	54 Xe 131.3
55 Cs 132.91	56 Ba 137.36	57 La SEE La SERIES	72 Hf 178.6	73 Ta 180.88	74 W 183.92	75 Re 186.31	76 Os 190.2	77 Ir 193.1	78 Pt 195.23	79 Au 197.2	80 Hg 200.61	81 Tl 204.39	82 Pb 207.21	83 Bi 209.00	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac SEE Ac SERIES	(104)	(105)	(106)												

LANTHANIDE SERIES	57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 Pm	62 Sm 150.43	63 Eu 152.0	64 Gd 156.9	65 Tb 159.2	66 Dy 162.46	67 Ho 164.94	68 Er 167.2	69 Tm 169.4	70 Yb 173.04	71 Lu 174.99
ACTINIDE SERIES	89 Ac	90 Th 232.12	91 Pa 231	92 U 238.07	93 Np 237	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 E	100 Fm	101 Mv	(102)	(103)

MU-7145

Fig. 1

Element 99 - Einsteinium (E) - This element was named to honor the distinguished scientist, Albert Einstein, who died about the time of the discovery of this element.

Element 100 - Fermium (Fm) - The name is a memorial to the great worker in nuclear reactions, Enrico Fermi, who died at an early age soon after the discovery of this element.

Element 101 - Mendelevium (Mv) - This name honors Dimitri Mendeleev, the originator of the periodic table. Incidentally the adoption of this name helped establish friendly international relations at the Geneva Conference.

All of these are α radioactive, some are β^- instable, and some change by K capture, which is equivalent to being β^+ emitters. Spontaneous fission becomes increasingly important with atomic weight. In fact it is the determining factor in the half life of fermium. The rate of α decay also increases with increasing atomic weight. At present the definition of an element says it must have unique chemical properties. Extrapolation of half life indicates that by the time element 104 is reached it will have such a short half life that we will not have time to perform chemical operations. We can, however, probably identify nuclear properties such as decay rates, energies of resulting particles, wave length of resulting x- and γ-rays, etc. for another four atomic numbers. So once again the "end" of the periodic table is in sight. Element 103 should finish filling the 5f shell, so 104 would be like hafnium, 105 like tantalum, etc. This arrangement is shown in Fig. 1.

It is the ability to predict accurately the properties of these new elements that makes their discovery possible. Originally working with the rare earths was most tedious. Sometimes years of fractional crystallizations were needed and, even then, products were not spectrographically pure. This situation was improved during the war by the discovery of suitable ion-exchange columns. The technique of ion exchange involves the adsorption of a mixture of ions on an ion-exchange resin followed by selective elution from the resin. The generalized equations for adsorption of actinides and lanthanides on cation ion-exchange resins are

$$M^{+3} + 3\,NH_4R \rightarrow MR_3 + 3\,NH_4^+$$

followed by

$$MR_3 + 4\,NH_4A \rightarrow MA_4^- + 3\,NH_4R + NH_4^+,$$

where M^{+3} stands for any trivalent lanthanide or actinide, R is the fixed polymer part of the resin, and A is a monovalent anion. As the solution moves down the column these two reactions alternate and each "M" proceeds at a slightly different rate. Thus bands or zones of the different ions are formed in the column. An example of exchange resins is Dowex-50, a cation exchanger which was used in these transuranium experiments. It is a synthetic polymer containing free sulfonic acid groups.

Complexing agents such as chloride, citrate, and the recently employed alpha hydroxy isobutyrate ion are used as eluants. The rare earths are eluted in reverse order of their atomic numbers. Very clean separations can be obtained with impurities as low as one part per million. With the actinides similar reactions occur. Although the amounts are too small to weigh, the elements can be located by the radioactivity of the solutions. To illustrate, californium was made by bombarding curium with high-energy helium ions. Because of the analogy of californium to dysprosium, predictions were made that it would appear in the 26th drop from the exchange column. These predictions were exactly substantiated.

In making mendelevium a special technique of "bombarding from the rear" with 41-Mev helium ions was evolved. Only the transmuted element had a forward motion which separated it from the unchanged einsteinium. This simplified purification and preparation of the counting sample.

Only the first four transuranium elements have been made in weighable amounts, and of these only plutonium has been made in more than gram lots. Five thousand atoms sufficed for the identification of californium. An aggregate of one hundred atoms was enough to identify curium and one lone atom was all the mendelevium identified at one time. This was done 15 times before it was announced to the world. It could be identified because it spontaneously fissions, thereby releasing unmistakably large amounts of energy.

Elements 99 and 100 were first found in 1942 in the debris from the "Mike" thermonuclear explosion at Eniwetok. Uranium-238 must have captured 15 to 17 neutrons and then undergone 7 or 8 β^- decays to end up with what is now known as einsteinium and fermium.

The most hopeful method of obtaining transplutonium elements is by bombardment with heavy ions in the range from carbon to, perhaps, argon. The newest building at the UCRL houses a large linear accelerator designed expressly for heavy-ion bombardments. With a very versatile front end, this accelerator can provide a great variety of projectiles. It is hoped the accelerator will be in operation before the end of the current year.

During the discussion period the inevitable question was asked - What good is the production of these infinitesimal amounts of elements, aside from the fun of doing it? The answer, definite and detailed, is:

1. It has given us a better understanding of atomic structure.
2. It has straightened out arrangements of the periodic table.
3. From it we have learned much about radioactivity.
4. From it we have learned about nuclear structure.
5. From it we have learned more about fission with all its potentialities for constructive use.

The resounding applause at the end indicated that the group appreciated this "capsule course" on the actinides and was confident that under such leadership we would make continued progress in this important field of research.

For further details see:

Glenn T. Seaborg, Comprehensive Inorganic Chemistry, Sneed, Maynard, Brested, eds., D. Van Nostrand, 1953, Vol. 1, p. 161-223.

TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

Radiation Laboratory
University of California
Berkeley, California

Chapter 13

ROCKETS

W. M. Brobeck

Dr. Thornton introduced Mr. Brobeck as Chief Engineer of the Laboratory, whose ability is evidenced by many of our large machines, especially the Bevatron. His present interest is rockets, and his friends laughingly tell him his Bevatron will never get off the ground.

There is a program studying nuclear propulsion of rockets at the Laboratory, but no more will be said about that phase.

Rockets are propelled by emitting a material formerly carried by the rocket. They are self-sufficient; they do not react with or depend on their surroundings for either power or steering. They are chiefly of military value, their peacetime uses being restricted to distress calls, and celebrations.

Rockets were known in China as early as 1232. The fuel was gunpowder. They were widely used during the Middle Ages but were superseded by guns because of the gun's greater accuracy, especially after helical cuts in the barrel were invented to give spin to the projectile.

During World War II, rockets, both large and small, were again widely used. The chief value of small rockets is that they have no launching recoil or kickback, and the launching device itself is light and simple.

The rocket (bazooka), plus shaped charges, made it possible for a foot soldier to carry the equivalent of a 3-inch gun capable of knocking out a tank. Rockets can be fired from airplanes without interfering with their maneuverability.

In the last months of World War II the Germans brought long-distance rockets (the V-2) to a state of perfection never previously approached. Before the war many Germans were avid rocket fans and had an active amateur club; purely for amusement they learned to make rockets that could rise to 1/4 mile or better. When Hitler came to power this was used as the core of military developments that were almost too successful. In World War I the "Big Bertha," which shelled Paris from 80 miles away had only 25 lb of explosive in the head, whereas the V2's contained a ton or 80 times that, and they had a 200-mile range with an angular accuracy comparable to best artillery results. Before launching, the rockets weighed 13 tons, and contained much delicate mechanism. After preliminary tests, 4300 of these were launched; this was a violent death throe of a dying regime, but a remarkable technical achievement.

Werner von Braun, who directed this technical excellence, is now working in the United States.

All three United States military services have active rocket development plans. It is presumed our former allies are equally interested.

One method of classification of rockets is by intended use.

1. Sounding (comparable to ocean depth sounding). This includes:
   a. Some 40 V-2's captured at the end of the war and launched from White Sands Proving Ground, N. M.
   b. The Aerobee
   c. The Viking

2. Surface to Surface.
   a. Corporal
   b. Redstone
   c. Atlas
   probably half a dozen more.

3. Surface to Air
   a. Terrier
   b. Nike
   There are several Nike installations around the country--including one in the Bay Area. The missiles are guided by radar and the necessary ground equipment is intricate and extensive, containing probably more than a million and a half parts.

4. Air to Air

Most of these are like the bazooka--not guided. Germany worked on some guided by a wire from plane to rocket, unreeling as the projectile accelerated. This system has the advantage that it cannot be jammed or interfered with by the enemy.

5. Ship to Submarine

An apparatus used in all these categories except surface-to-surface is a "homing device." The "lure" can be mechanical vibration (submarines and ships) or a magnetic field (steel in submarines and ships), heat (infrared rays from hot engines), or just the ability to reflect radar waves. All radar devices, however, are subject to jamming.

6. Satellite

The well-publicized satellite to be launched during the International Geophysical Year (1957) will be boosted into its orbit by rockets.

7. JATO

Heavy planes on short runways become airborne quicker with the help of rockets; this is known as jet-assisted take-off (JATO.)

That covers the history, and the present and the projected uses, and leads to discussion of the general principles of operation.

The fundamental principle involved in rocket propulsion is Newton's third law of motion which states for every action there is an equal and opposite reaction. Practically this simplifies to ejecting mass in small particles at high velocity (the higher the better), with the reaction pushing a containing shell (the rocket with pay load) in the opposite direction.

A rocket is characterized by its specific impulse, which is defined as follows:

$$I_{sp} = \frac{\text{pounds thrust}}{\text{pounds propellant per sec}} = \frac{\text{Velocity of Jet}}{\text{acceleration due to gravity}}$$

$$I_{sp} = \frac{V_J}{g} \quad \text{or } V_J = I_{sp} g.$$

An approximate formula (increasingly correct as range increases) is

$$V_R = V_J \ln \frac{M_1}{M_2} \quad ,$$

where V_R = Velocity of rocket
V_J = Velocity of Jet
M_1 = initial or take-off mass
M_2 = weight after propellant is consumed ("dry weight").
Obviously $(M_1 - M_2)$ = weight of propellant.

For typical liquid propellants, $I_{sp} = 200$ sec and the corresponding jet velocity is 200 g or 6440 feet/sec.

From 3/4 to 9/10 of present-day rockets consist of propellant.

For a 200-mile range a velocity of 5600 ft/sec must be achieved soon after launching.

For the satellite, which is supposed to have an orbit about 100 miles out from the earth's surface, an initial speed of

26,000 ft/sec or

5 mi/sec or

18,000 mi/hr will be necessary.

This is roughly 20 times the speed of today's fastest manned airplanes.

The "escape velocity" is about 37,000 ft/sec. At that speed the trajectory changes from an ellipse to a hyperbola and the projectile will not return to earth.

All the long-range rockets use up their fuel early in their path and "coast" from then on like an artillery shell, and thus merit the name of ballistic missiles.

Small rockets use solid propellant because it is easier to handle and store. Some materials used include picric acidand T.N.T.

All large rockets use liquid propellant consisting of fuel which may be gasoline, alcohol hydrazine, ammonia aniline or ethylene diamine, and oxidant which may be liquid oxygen, 70% hydrogen peroxide or nitric acid. The V-2's used alcohol and liquid oxygen.

The problem is to get a rapid smooth reaction (combustion or decomposition rather than detonation) when it is wanted and not before. This requires extraordinary purity of chemicals and care in engineering. Let us use the formulas and data already given to see what mass ratios are necessary for a 200-mile flight. We have

$$V_R = V_J \ln \frac{M_1}{M_2}, \qquad V_J = I_{sp}\, g.$$

For a 200-mile range V_R must equal 5600

$$5600 = 200 \cdot 32.2 \ln \frac{M_1}{M_2}$$

$$\text{or } \ln \frac{M_1}{M_2} = \frac{5600}{6440}$$

$$\text{or } \frac{M_1}{M_2} = e^{\frac{5600}{6440}}$$

$$\text{or } \frac{M_1}{M_2} = e^{\frac{7}{8}} = (2.718)^{7/8} = \text{approx } 2.4.$$

The original formula was only approximate, and corrections for air pressure, pull of gravity, etc., show that 3.2 is more nearly correct for an actual case. This means that $(M_1 - M_2)/M_1$ or 70% of the original weight must be propellant.

Following the same reasoning for the satellite gives

$$\frac{M_1}{M_2} = e^{\frac{26,000}{6440}} = e^{4.^{+}} = \sim 56,$$

or $(M_1 - M_2)/M$ or 98.2% of the satellite rocket must be propellant.

This looks rather discouraging, but the difficulty can be overcome by making a multistage rocket. If each stage had a ratio of 3.8, the over-all ratio would be $(3.8)^3$ or 56 to 1, which is possible. However, if the pay load is to be 1/4 of the dry weight and the final satellite weighs 25 lb, calculations show that original ground weight would need to be

$4^3 \times 56 \times 25 \cong$ 90,000 pounds. Obviously freight rates to a satellite will be higher than pony express charges were.

A rocket is inherently unstable in that it is pushed rather than pulled, therefore the steering mechanism must be delicate and reliable. As long as the path is through air, fins may be adjusted, but above the atmosphere the only control is by changing the angle of the emergent jet. This, in turn, requires propellant, therefore all steering must be done early in the flight.

Another problem is prevention of burning up (like a meteor) when the rocket re-enters the earth's atmosphere. This means resistant materials in the first place or saving part of the fuel for retarding action at the end of the flight. Obviously the problem is challenging from every point of view, including the financial one.

Mr. Brobeck then allowed himself some brief speculations about space travel, but warned that any consistent reader of current "space" literature was already 'way ahead of him.

He compared the "figure eight" round trip to the moon with the pontoon bridge of space stations, and felt that the latter was more "practical" if such a word belongs in this discussion at all.

If the question arises as to why one should care to visit the moon, two answers are

(1) for prestige,

(2) to see what the other side looks like.

In the absence of pari-mutuel facilities he is offering odds that the other side of the moon looks very much like this side. He mentioned the possibility of using the "space stations" as television relay posts so that the Russians could also look at Milton Berle, but did not say whether he thought that would ease or heighten world tensions. Particles shot off by radioactive materials could in principle be had for rocket propulsion. The attainable thrust is extremely low, however, so that such a rocket could not leave the surface of the earth. Once in a satellite orbit, however, any thrust would produce an acceleration, so that such a system might be considered for travel in interplanetary space.

During the question period it was brought out that jet temperatures in the V-2 were around 6000°F.

A five-stage rocket could probably reach escape velocity.

Since the jet doesn't need to push against anything except the rest of the rocket, the thrust is independent of any velocity it already has - thus the velocity of the rocket can and does exceed that of the propelling jet.

Further details may be found in the following references.

Bibliography

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John Humphries, Rockets and Guided Missiles, McMillan, 1956.

Seifert, Mills, and Summerfield in Amer. J. Phys. 15, 1 (1947). (This includes a section on nuclear rockets).

TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

Radiation Laboratory
University of California
Berkeley, California

Chapter 14

PHOTOSYNTHESIS

Melvin Calvin

Dr. Calvin has been with the University of California since 1937 and has been director of the Bio-Organic Division of the Radiation Laboratory since 1946. Although nothing can replace the satisfaction of hearing an expert discuss with enthusiasm his own work, it is a fact that much of the material he covered is available as listed later in this paper. Therefore this report merely summarizes some of the high points.

The importance of photosynthesis is obvious to those with any scientific training at all. Not only does our present food supply depend on it, but the energy of our fossil fuels, coal and ore, are in a very real sense sunshine solidified via photosynthesis. The energy conversion is very efficient (30 to 60%), so we would very much like to know how the plant does it.

Originally only C^{11} with a half life of 20 min was available for the studies, but now large quantities of C^{14} with a half life of 5000 years is available from nuclear reactors, and that is being used in current studies.

Dr. Calvin showed a 16-min colored sound movied titled "The Riddle of Photosynthesis" (produced by The Handel Film Corp., 6926 Melrose Avenue, Hollywood 38, California). It showed the techniques of growing, killing, and analyzing algae. Chromatographic methods are shown here. Dr. Calvin was careful to explain solemnly that though the "spots" appeared promptly on the developed chromatogram the accompanying names required as long as 4 years' development. The substance of his talk is in the attached report.

The question or "heckle" period brought out some interesting discussions.

Dr. Calvin confirmed that it is possible to make glucose today entirely synthetically--but at a prohibitive cost (probably two or three thousand dollars per gram).

The mechanism whereby energy changes water into molecular oxygen and "active" hydrogen is not understood. Incidentally, the use of radioactive hydrogen has little value, because it exchanges for regular hydrogen too readily. So far there is no satisfactory radioactive oxygen. O^{17} has been used and its progress can be followed by nuclear resonance methods. If O^{18} is used it can be followed by mass spectroscopic methods, but that requires much work and pains. As a chemist, Dr. Calvin thinks the physicists should provide a satisfactory radioactive oxygen - it would make this study easier.

There is a hint that this "photolysis" may be analogous to the action of semiconductors, but no good evidence yet.

There is definite interest in the idea of using photosynthesis, not to make food, but to restore oxygen to used-up air in submarines and in similar situations.

Dr. Calvin feels that aside from satisfaction at finding "what makes it tick," studies of photosynthesis will be most valuable in redirecting rather than bypassing it. For example, if the percent sugar in beets can be increased or the protein content of soy beans be improved, that will repay in economic worth the time and money spent on the problem.

THE PHOTOSYNTHETIC CYCLE

Melvin Calvin and J. A. Bassham

Radiation Laboratory and Department of Chemistry
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Berkeley, California

Photosynthesis is usually defined as the biochemical reaction

$$CO_2 + H_2O \xrightarrow{nh\nu} (CH_2O)_x + O_2 .$$

This represents the conversion of carbon dioxide and water to carbohydrate and oxygen by green plants in the light. The reaction is separated both chronologically and chemically into two parts: the photolysis of water,

$$H_2O \xrightarrow{nh\nu} 2[H] + 1/2\, O_2 ,$$

and the reduction of carbon dioxide,

$$CO_2 + 4[H] \longrightarrow CH_2O + H_2O .$$

Each of these two reactions represents a complex series of reactions with many steps. The term [H] is used to denote reducing agents generated in the photochemical decomposition of water. These reducing agents probably undergo several transformations before they are used in the reduction of carbon dioxide.

The reactions involved in the reduction of carbon dioxide have been studied and the results of these studies have been reported in a series of papers on "The Path of Carbon in Photosynthesis."1),2),3)

The radioactive carbon isotope, C^{14}, was used throughout this investigation. To a lesser extent, radioactive phosphorus, P^{32}, was also employed.

As a result of this work, it is now possible to write the complete path of carbon reduction in photosynthesis, with all intermediates and enzymatic reactions, from carbon dioxide to sucrose. The study of carbon reduction and its relation to respiratory transformations of carbon compounds has provided evidence regarding the nature of the reactions involved in the decomposition of water and the formation of the primary reducing agents and other energy-rich compounds required for carbon reduction.

FIRST PRODUCTS

The methods used in studying the path of carbon in photosynthesis are here described briefly. In nearly all cases the initial condition is an actively photosynthesizing plant in which photosynthesis has been maintained long enough to establish a "steady state." In this steady-state condition the concentrations of various intermediate compounds in the pathway from carbon dioxide to sucrose are constant. The plants commonly used in these experiments are the unicellular green algae, Chlorella or Scenedesmus, but leaves of higher plants are sometimes used.

In the first type of experiment to be discussed, $C^{14}O_2$ is added to the unlabeled CO_2 that the plant has been using. After a measured short period of photosynthesis with $C^{14}O_2$, the plant is killed by sudden treatment with boiling ethanol. All enzymatic processes are thereby quickly halted. Extracts of the plant material are made, concentrated, and then analyzed by two-dimensional paper chromatography and radioautography. The techniques of two-dimensional chromatography and radioautography of plant extracts labeled with C^{14} have been described earlier,1) as well as the identification of the numerous labeled compounds.1),4),5),6),7) The radioautographs obtained from experiments of 10-seconds and 60-seconds photosynthesis with $C^{14}O_2$ are shown in Figs. 1 and 2. The 60-second experiment illustrates the importance of various sugar phosphates and acid phosphates in carbon reduction. The 10-second experiment shows the predominance of phosphoglyceric acid at short times. If the percentage of C^{14} in phosphoglyceric acid (PGA) of the total C^{14} incorporated during photosynthesis for various short periods of time is extrapolated to zero time, it is found that at zero time all the C^{14} should be in phosphoglyceric acid. This compound is therefore identified as the first compound into which carbon dioxide is incorporated in photosynthesis.

Fig. 3 shows the distribution of the labeled carbon in the three carbon atoms of the glyceric acid obtained from the phosphoglyceric acid in a 15-second experiment. Half of the C^{14} is in the carboxyl group and the other half is divided equally between the other two carbon atoms. From the same experiment some hexose (fructose and glucose) was obtained and degraded. The distribution of carbon in the two 3-carbon halves of the hexose was found to be very much the same as it is in the three carbons of glyceric acid. This result immediately suggests that the six-carbon piece is made from the two three's by joining the two carboxyl carbon atoms. This is simply a reversal of the well-known aldolase split of fructose diphosphate in the glycolytic sequence, a part of which is shown in Fig. 4. Here the phosphoglyceric acid is reduced with the hydrogen from the photochemical reaction to phosphoglyceraldehyde, which is then isomerized to form dihydroxyacetone phosphate (DHAP). Condensation of phosphoglyceraldehyde with DHAP then results in formation of the hexose, fructose-1,6-diphosphate. Thus, the two carbon atoms which were originally carboxyl-carbon atoms finally fall in the middle of the hexose chain. It is quite clear that there must be some compound that accepts the carbon dioxide to form the glyceric acid. Furthermore, that compound must be regenerated from the PGA (phosphoglyceric acid), triose phosphates, and hexose phosphates, or some other compound formed from them. It is thus evident that there is a cyclic process involved in the reduction of carbon dioxide.

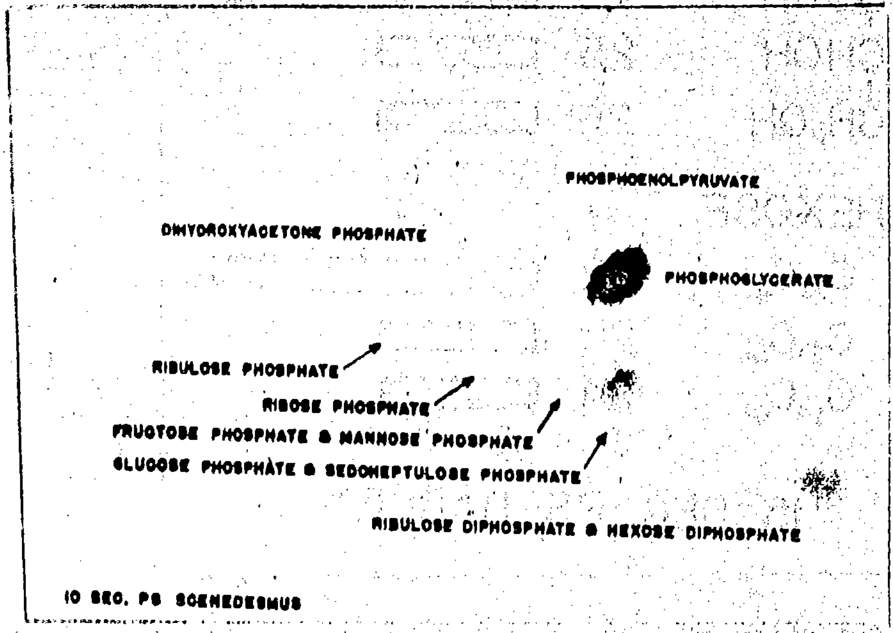


Fig. 1 - Chromatogram of extract from algae, indicating uptake of radiocarbon during photosynthesis (10 seconds).

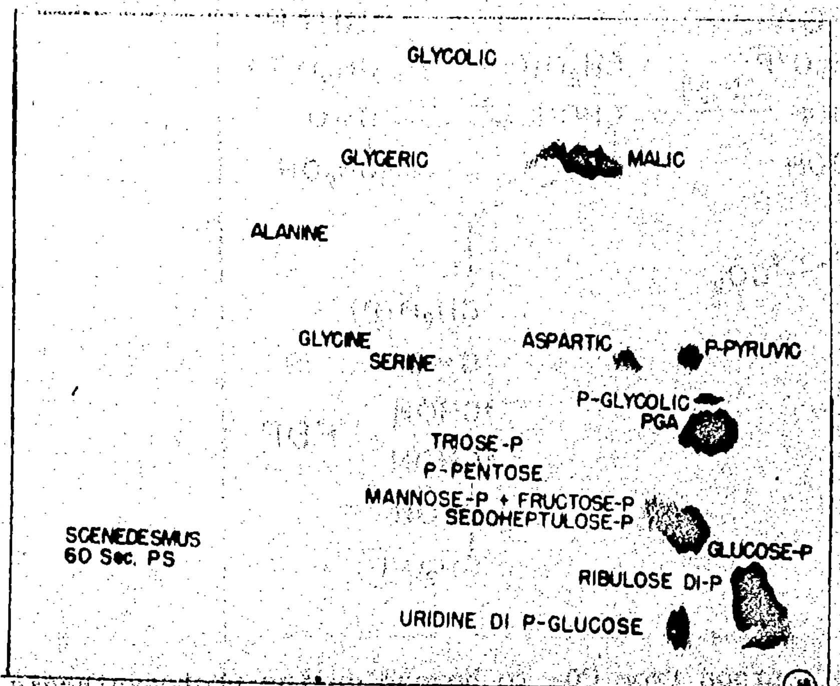


Fig. 2 - Chromatogram of extract from algae indicating uptake of radiocarbon during photosynthesis (60 seconds).

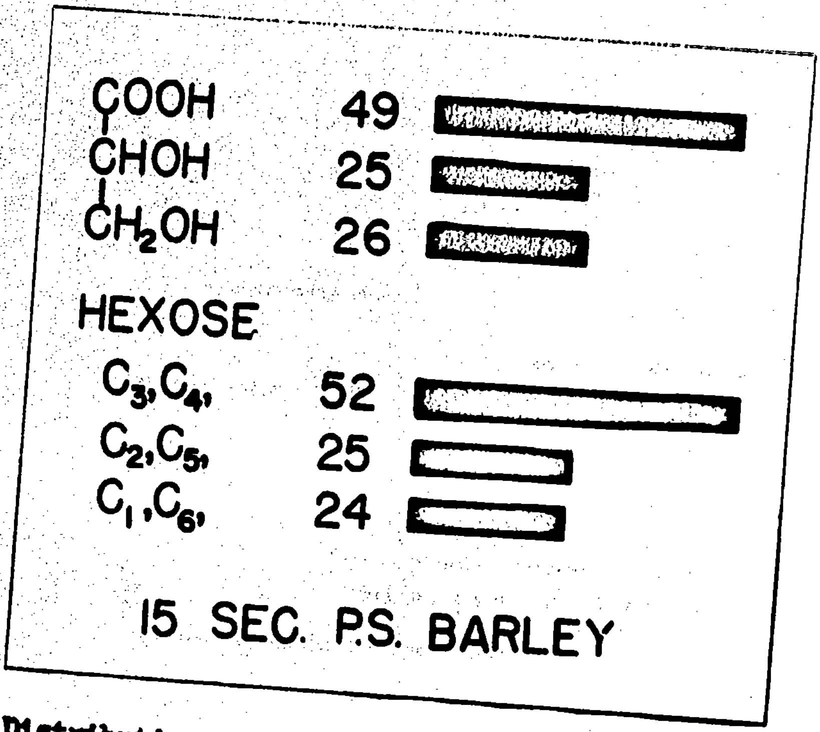


Fig. 3 - Distribution of labeled carbon in photosynthesis experiments

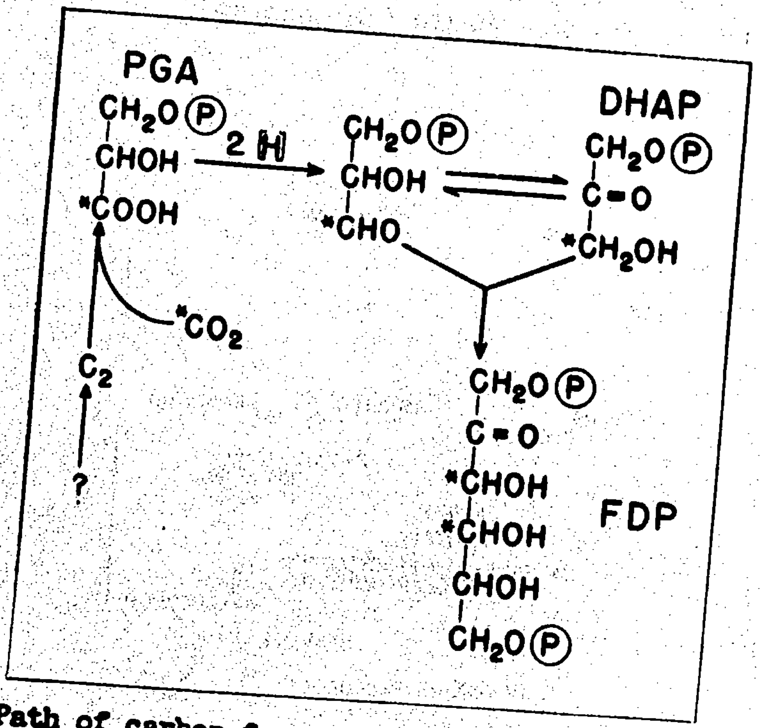


Fig. 4 - Path of carbon from CO_2 to hexose during photosynthesis

Before considering the nature of this cyclic process it is of interest to mention the steps leading from fructose diphosphate to the final product of photosynthesis, sucrose. These steps were identified after the intermediate compounds were isolated by paper chromatography and radioautography. Fig. 5 shows the relationship that was found. Here are shown the phosphoglyceric acid, fructose diphosphate, and the various transformations that lead ultimately to glucose-1-phosphate. This compound reacts with uridine triphosphate, to make uridine diphosphoglucose. Uridine diphosphoglucose (UDPG) is found on the paper, with the glucose moiety labeled after very short $C^{14}O_2$ exposures. UDPG can then react in one of two ways: either with fructose-1-phosphate to form sucrose phosphate which then is phosphatased to sucrose, or directly with free fructose to form sucrose in one operation. However, since one seldom finds any free labeled fructose, the first of these alternatives appears to be the major pathway for green leaves. An enzyme performing the reaction

$$\text{UDPG} + \text{fructose phosphate} \longrightarrow \text{sucrose phosphate}$$

has recently been prepared in a partially purified state by Leloir in Argentina. Fig. 6 shows the structural formula for the UDPG and its reaction with fructose-1-phosphate. This reaction gives uridine diphosphate and sucrose phosphate with the phosphate on the No. 1 carbon atom of the fructose moiety. The phosphate is then removed to give sucrose. This appears to be the common route to sucrose and is therefore one of the major synthetic reactions in agriculture, since sucrose provides the substrate for a wide variety of other transformations.

C_5 and C_7 Sugars

We now return to the problem of cyclic regeneration of the carbon dioxide acceptor. The roles of PGA, triose phosphates, hexose phosphates, UDPG, and sucrose have already been identified. Of the compounds labeled by short periods of photosynthesis, there were left only the seven- and five-carbon sugar phosphates. These were sedoheptulose-7-phosphate (SMP), ribose-4-phosphate (RMP), ribulose-5-phosphate (RuMP) and ribulose diphosphate (RuDP).

An attempt was made to determine the order of occurrence of these compounds by the same technique as was used to identify PGA as the first product of CO_2 fixation.

Since the reactions of carbon reduction are so rapid, a flow system was designed to obtain sufficiently short periods of exposure to $C^{14}O_2$ to permit observation of the relative rates of labeling of the various sugar phosphates.3) The system used is shown in Fig. 7. A suspension of algae was forced by means of a pump from a transparent tank through a length of transparent tubing into boiling methanol. An aqueous solution of $C^{14}O_2$ was injected at a constant rate into the tubing. The time of exposure of the algae to $C^{14}O_2$ was determined by the rate of flow of algae through the tubing and the length of tubing between the point of injection and the killing with methanol. In this way exposure times ranging from 1 to 20 seconds were obtained. When the radioactivity found in each of the sugar phosphates was extrapolated to zero time of exposure, however, no choice could be made between the pentose, hexose, and heptose phosphates. It appeared that all were formed at the same time. It was necessary, therefore, to turn to degradation studies of these various sugar phosphates labeled in the very short exposures.

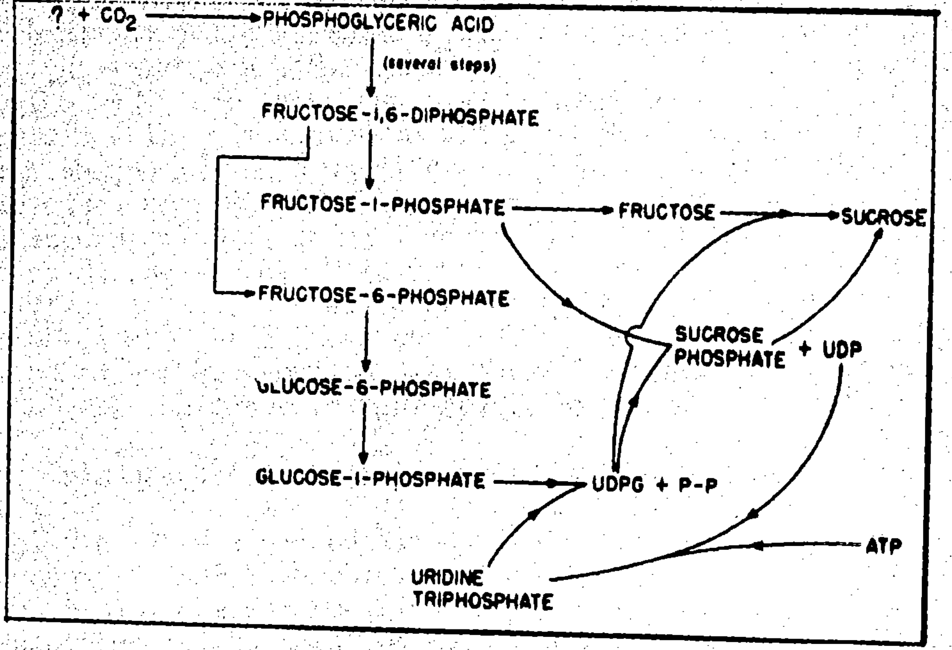


Fig. 5 - Proposed mechanism for formation of sucrose with uridine diphosphoglucose

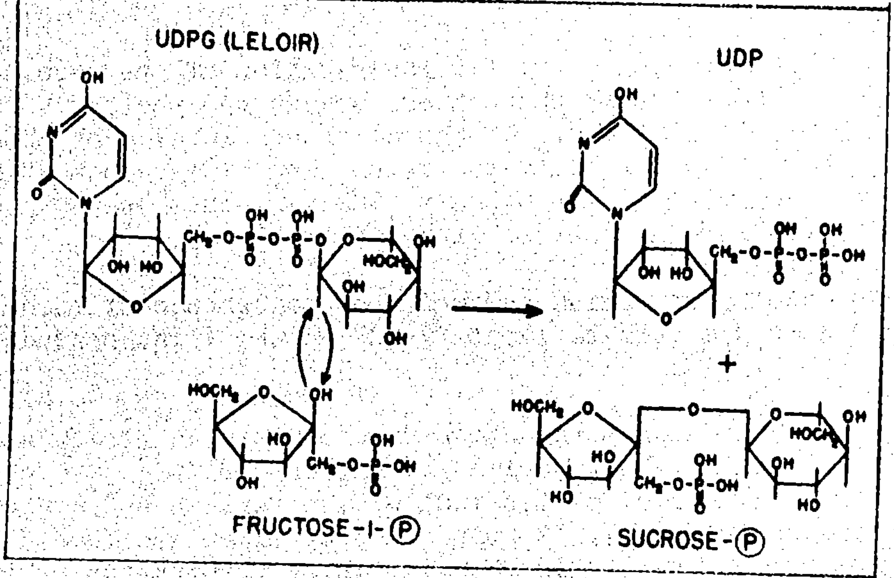


Fig. 6 - Uridine diphosphoglucose reaction with fructose phosphate

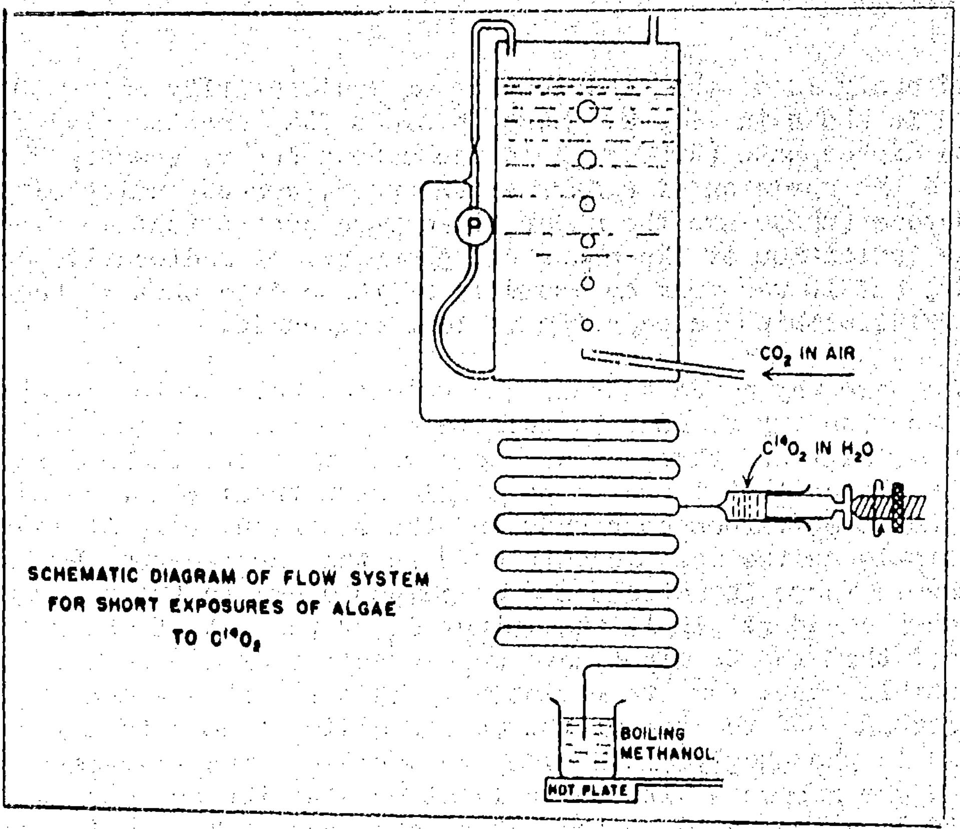


Fig. 7 - Schematic diagram of flow system for short exposures of algae to $C^{14}O_2$

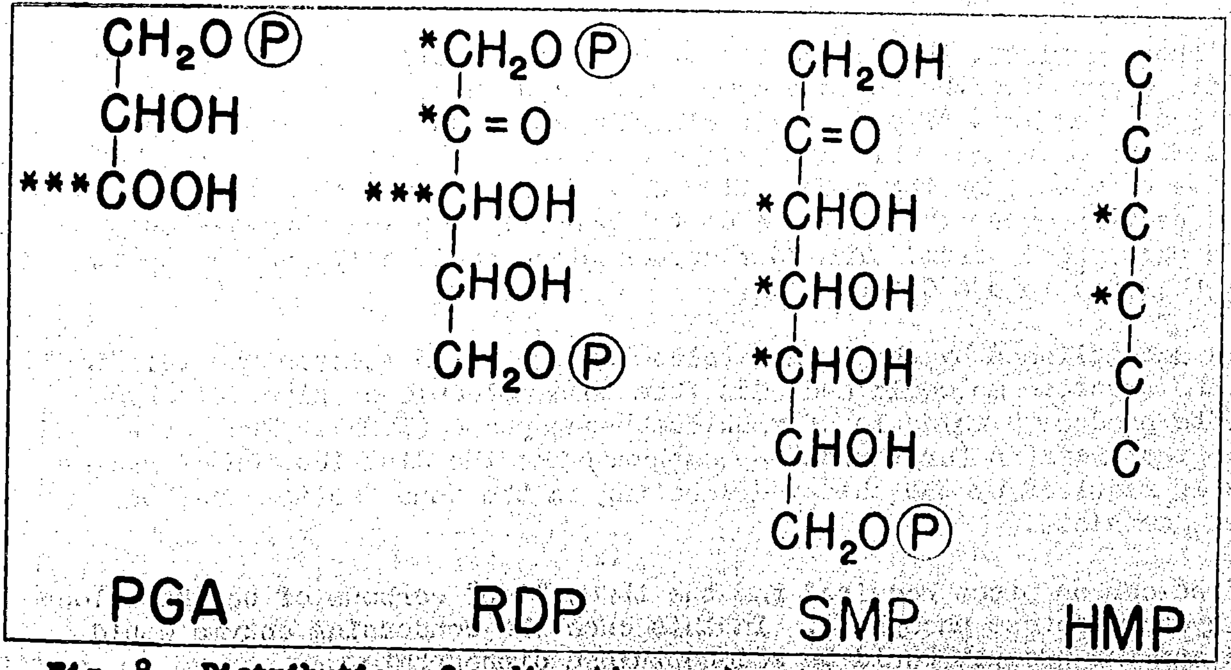


Fig. 8 - Distribution of radioactive carbon in certain sugars

A detailed analysis of the distribution of radioactivity among the carbons of these sugars is shown in Fig. 8. Here, besides PGA, are the five-carbon sugar, ribulose diphosphate (RuDP); the seven-carbon sugar, sedoheptulose phosphate (SMP); and the skeleton of a six-carbon sugar, corresponding either to glucose or fructose (these are the major six-carbon sugars that we find). The stars give some indication of the order of appearance of radioactive carbon in these compounds, and it was from an analysis of these data that it became possible to deduce relationships between the various compounds.

In much the same way as we deduced the relation between the three-carbon PGA and the six-carbon sugars we were able to deduce the relationships between the five-, seven-, six- and three-carbon compounds that are shown here. It is quite clear at a glance that there is no simple structural relationship between the five- and the seven-carbon compounds and the other sugars. At least, there is nothing as simple as the relationship between the three-carbon PGA and the six-carbon hexose. There is no sequence of carbon atoms in the C_5 or C_7 sugars that could be considered as simply the intact C_3 or the intact C_6, respectively. Until we realized that the C_5 might have more than one origin we were not able to deduce a possible route for its formation. This route is shown in Figure 9. By taking two carbons off the top of the C_7 and adding them onto a three-carbon piece labeled as is phosphoglyceraldehyde, we would get two five-carbon pieces - one ribulose and one ribose - with their labeling distributed as shown. The average of their labeling would be the actual one found. This evidence, therefore, indicates that the origin of the ribose and ribulose phosphates is in a transketolase reaction of the sedoheptulose phosphate with the triose phosphate to give the two pentose phosphates. These can be interconverted by suitable isomerization. Thus, the pentoses are formed from heptose and triose.

As was shown earlier, the hexose is formed from two trioses. The question then remains: where does the heptose come from? And here, again, a similar detailed analysis was made of the carbon distribution within the heptose molecule as a function of time. This analysis led to the realization that the heptose must have been made by the combination of a four-carbon with a three-carbon piece. The question arose then: where do the properly labeled four-carbon and three-carbon pieces come from? The four-carbon piece could only come by splitting the C_6 (hexose) into a C_4 and a C_2.

This is accomplished by the transketolase enzyme which removes the two "top" atoms from the fructose molecule and adds them to a molecule of glyceraldehyde-3-phosphate to produce a molecule of ribulose-5-phosphate (RuMP). The four-carbon piece that remains (erythrose-4-phosphate) has the distribution of radiocarbon that is required by the observed labeling in the four "bottom" carbon atoms of sedoheptulose.

The three-carbon piece required for the three "top" carbons of sedoheptulose might be dihydroxyacetone phosphate. In this case the condensing enzyme would be aldolase and the product would be sedoheptulose diphosphate.

Alternately, the three-carbon piece might be obtained by the splitting of hexose by the enzyme transaldolase, which would transfer the three top atoms of fructose-6-phosphate to the four-carbon piece (erythrose phosphate) formed from the four bottom atoms of another fructose molecule. In this case the product would be sedoheptulose-7-phosphate.

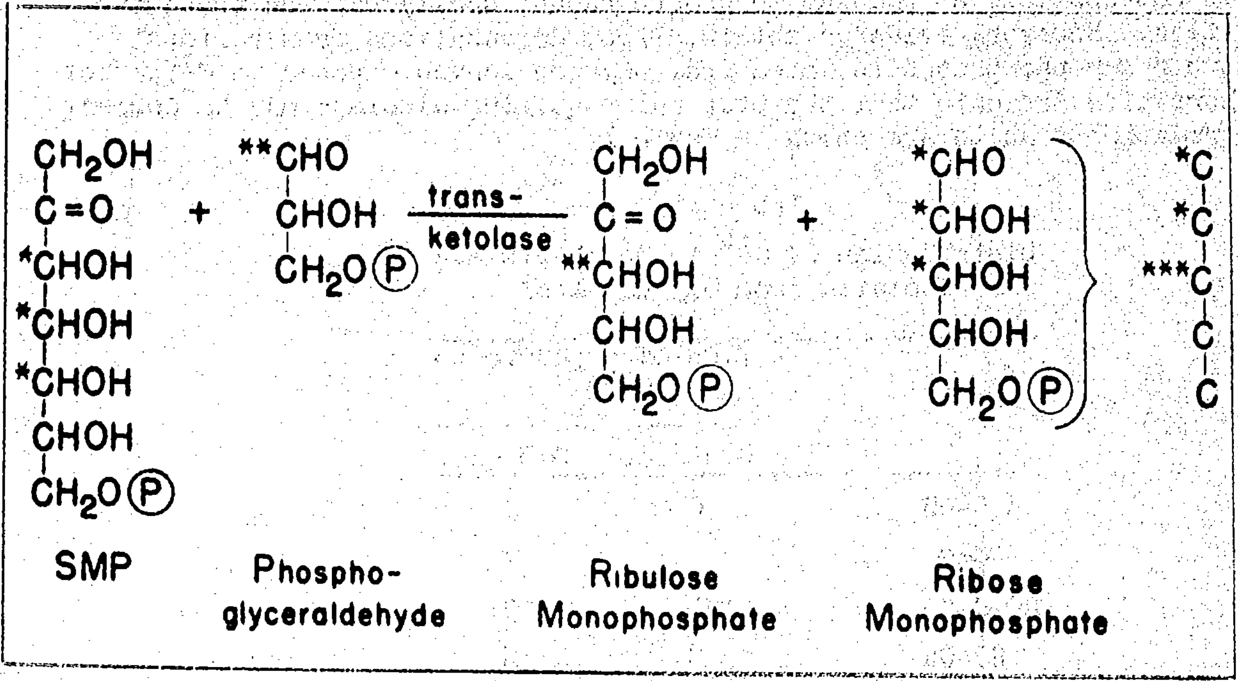


Fig. 9 - Formation of 5-carbon sugars from sedoheptulose phosphate

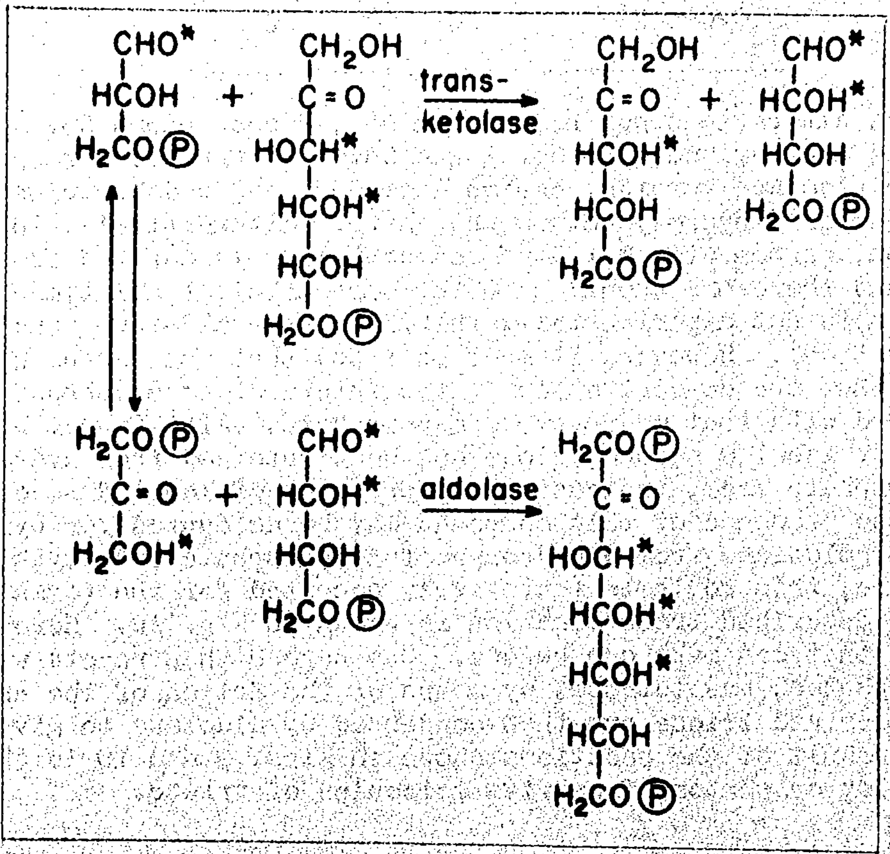


Fig. 10 - Formation of a heptose from triose and hexose

It is not possible at present to choose unequivocally between these two possibilities. However, evidence obtained from degradations from various radioactive sugar phosphates isolated from soybean leaves exposed to $C^{14}O_2$ for a very short time indicate that the proposal requiring aldolase may be correct. These degradation results are shown in Table I.

Table I
Distribution of C^{14} in Sedoheptulose
Isolated from Soybean Leaf

	Time of exposure to $C^{14}O_2$	
	0.4 sec.	0.8 sec.
H_2C-OH	0	2
$C=O$	0	2
$HO-C-H$	33	39
$HC-OH$	8	18
$HC-OH$	49	38
$HC-OH$	0	2
$H_2C-OPO_3H^-$	0	2

In either of the alternate sugar rearrangements, carbon atoms No. 4 and No. 5 of sedoheptulose are derived from No. 3 and No. 4 of fructose, respectively. However, in the aldolase version, carbon atom No. 3 of sedoheptulose is derived from carbon No. 1 of dihydroxyacetone phosphate. Alternatively, in the transaldolase version, carbon atom No. 3 of sedoheptulose is derived from carbon No. 3 of fructose and therefore should have the same label at all times. Since the latter condition is not experimentally fulfilled, the aldolase reaction appears to be the correct one. However, it must be noted that this argument rests on the assumption that the concentration of the intermediate erythrose phosphate is small compared with that of fructose-6-phosphate. Also it may be noted that a small amount of labeled sedoheptulose has been obtained from hydrolysis of the sugar diphosphate area, indicating the presence of labeled sedoheptulose diphosphate. The presence of this compound may be accounted for by assuming its formation by aldolase from dihydroxyacetone phosphate and erythrose phosphate. Therefore, this route is tentatively accepted for the formation of sedoheptulose. The described transformation is shown in Fig. 10. Here are shown the two trioses that can make one hexose. One hexose then reacts with another triose to give pentose and tetrose, by means of the action of the enzyme transketolase. Tetrose and triose are then condensed by aldolase to give sedoheptulose. The net result of the reactions shown in Figs. 9 and 10 is the formation of three molecules of pentose from five molecules of triose.

Identification of CO_2 Acceptor

All the results thus far were obtained with the first type of experiment, in which $C^{14}O_2$ was added to plants for a very short period (1 to 60 seconds) before the plants were killed. A second type of experiment was used for the identification of the CO_2 acceptor. In this case once again the starting condition was an actively photosynthesizing algae suspension in "steady-state" condition. In addition, the intermediate compounds were "saturated" with C^{14}. This was accomplished by leaving the plants in contact with an atmosphere of C^{14}-labeled CO_2, maintained at constant specific activity and CO_2 pressure, for more than an hour prior to the start of the experiment. Under this condition, the concentration of each labeled intermediate compound can be determined from the radiocarbon found in that compound on subsequent analysis by chromatography and radioautography.

After this initial C^{14}-saturated steady state was obtained, aliquots of the algal suspension were taken at frequent intervals for analysis. Then some environmental condition such as light was suddenly changed. Aliquots of the algae were taken every two or three seconds for about a minute, and then at less frequent intervals. Analysis of these aliquots showed the way in which the concentrations of the various intermediates varied as a result of the environmental change.

In the first such study2) the light was turned off. It was found that the concentration of PGA increased very rapidly while that of ribulose diphosphate (RuDP) decreased rapidly. The results of a later, somewhat more refined, experiment are shown in Fig. 11.8) Here it is seen that the concentration of RuDP decreases to below a detectable amount (<1% of its initial value) in about 30 seconds. These changes in concentrations can be accounted for if we assume the following: the reduction of PGA to triose and the formation of RuDP are reactions requiring light; RuDP is converted to PGA via a carboxylation reaction that does not require light.

These relations are shown in Fig. 12. PGA is reduced to triose phosphate (at the sugar level); the triose phosphate then undergoes a series of rearrangements, such as the ones described earlier, through the hexose, pentose, and heptose, back again to the ribulose-5-phosphate. This is all at the sugar level of oxidation and requires very little energy for its operation. There is then some light requirement for the formation of RuDP from RuMP. The reduction of PGA requires both reducing power, reduced triphosphopyridine nucleotide (TPNH), and adenosine triphosphate (ATP), while the formation of RuDP from RuMP requires ATP, as will be seen later. Both these cofactors are produced at the required rate only when the light is on. Thus, when the light is turned off the rate of formation of RuDP and the rate of reduction of PGA decrease but the rate of carboxylation of RuDP to form PGA continues unaffected except by the concentration of RuDP.

From the above scheme it was possible to predict the result if the light were left on but the CO_2 pressure were suddenly decreased. In that event, the carboxylation of RuDP to form PGA should decrease but the formation of RuDP and the reduction of PGA should be unaffected. Consequently the concentration of RuDP should rise while that of PGA should fall. This experiment was performed9) and the expected result, shown in Fig. 13, was obtained. When the CO_2 pressure

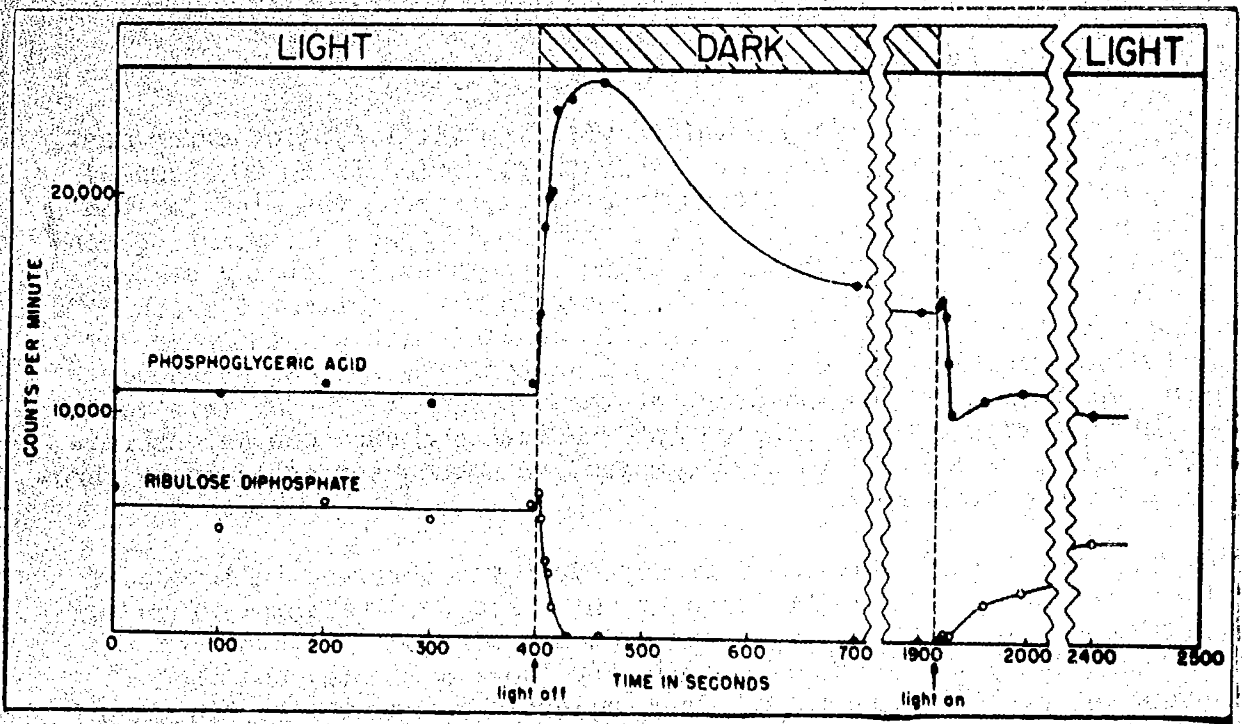


Fig. 11 - Light-dark transients in PGA and RuDP concentrations

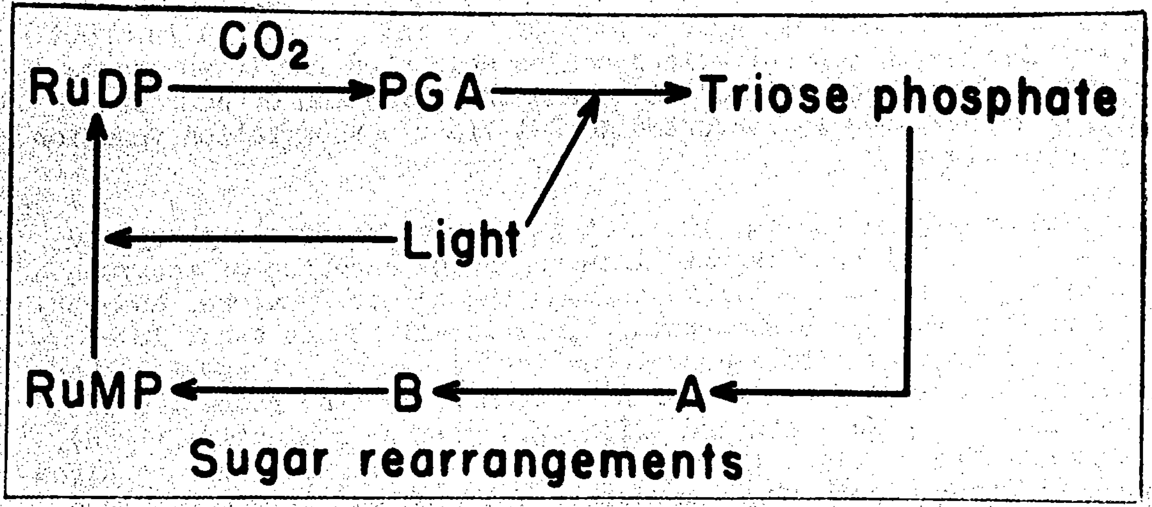


Fig. 12 - Suggested cyclic scheme for relationships in photosynthesis

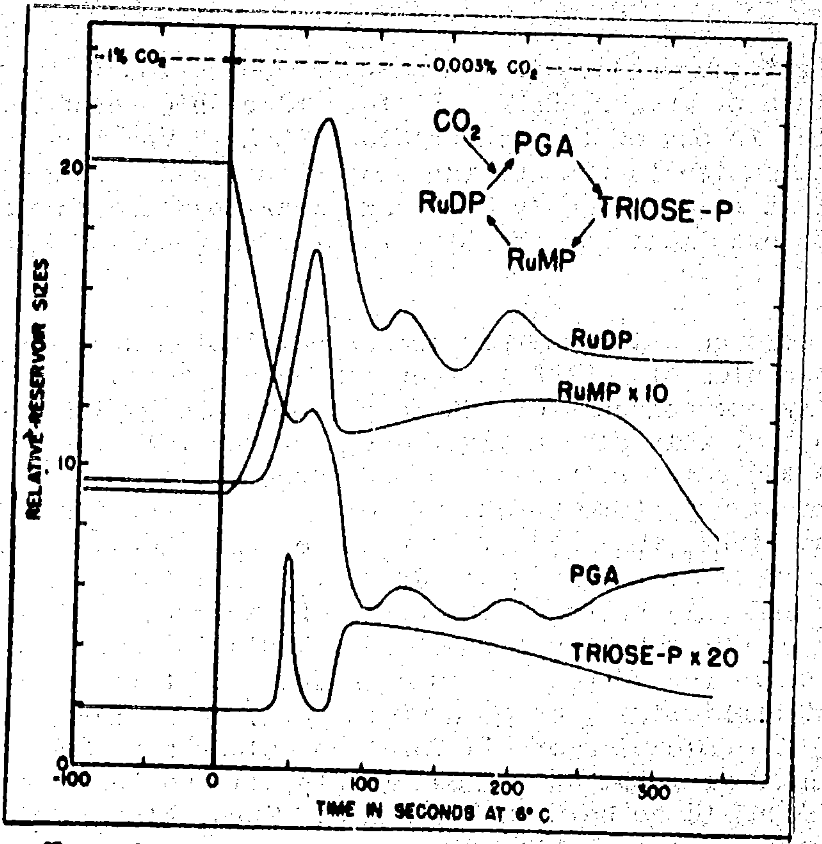


Fig. 13 - Transients in the regenerative cycle

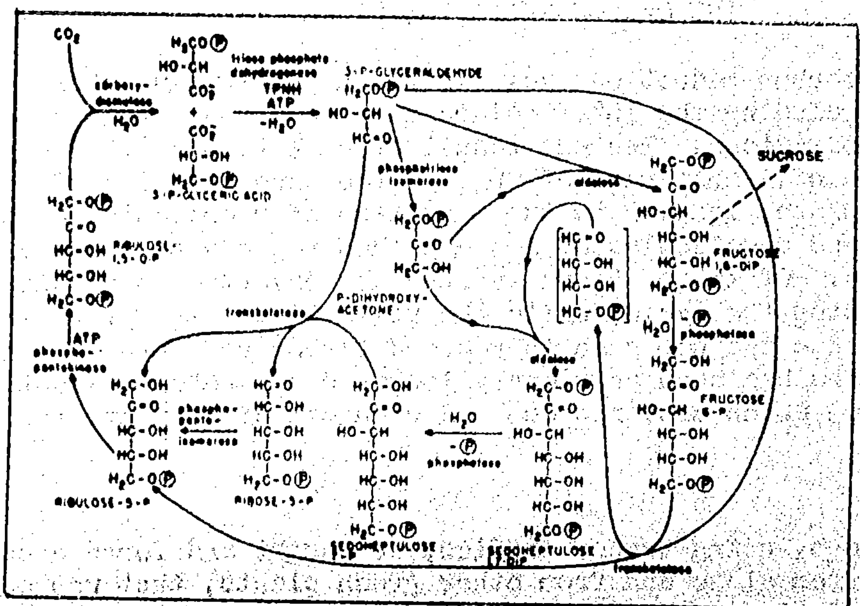


Fig. 14 - The complete photosynthetic carbon cycle

is decreased, the first compound to increase in concentration is RuDP and the second is its immediate precursor, RuMP. Last to rise in concentration is triose phosphate which is one of the precursors of RuMP. The first compound to decrease in concentration is PGA and the second is its immediate product, triose phosphate. Next to decrease is RuMP, and last to decrease is RuDP. These changes provide excellent confirmation for the proposal of the cyclic system.

There remained some question whether the carboxylation of a molecule of RuDP produced two molecules of PGA or whether some other reaction might occur *in vitro* in which only one molecule of PGA is produced along with a molecule of triose. In order to test this alternative, a rather careful experiment was performed[8] in which the rate of increase of PGA when the light was turned off was compared with the steady-state uptake of CO_2. During the first few seconds after turning off the light, the rate of increase of PGA should approximately equal the rate of its formation during steady-state conditions, provided reduction of PGA could be suddenly halted. The ratio of molecules of PGA increase per second/molecules of CO_2 taken up per second should indicate the number of molecules of PGA actually formed per molecule of CO_2. If this ratio experimentally approached 2 at short times, or even exceeded 1, we would have evidence for the formation of two molecules of PGA for each molecule of RuDP carboxylated. The ratio was calculated from the data shown in Fig. 11 and the measured CO_2 entry rate, and was found to be between 1.5 and 2. Thus, kinetic *in vitro* evidence is provided for the carboxylation reaction

$$\text{RuDP} + CO_2 + H_2O \longrightarrow 2\ \text{PGA}.$$

THE CARBON-REDUCTION CYCLE

The complete carbon-reduction cycle is shown in Fig. 14. Here are shown all the details, including the intermediate compounds and enzymes required for the various transformations. The net result of each turn of the complete cycle is the introduction of 3 molecules of CO_2 and the carboxylation of 3 molecules of ribulose diphosphate, leading to the formation of 6 molecules of phosphoglyceric acid. These 6 molecules of PGA are then reduced to provide 6 molecules of triose phosphate. Of these, 5 are eventually converted to ribulose diphosphate, thus completing the cycle, while the sixth finds its way ultimately into sucrose and represents the net gain in reduced carbon per turn of the cycle. All the enzymes shown had been previously isolated separately except for the carboxylation enzyme which converts CO_2 and ribulose diphosphate to PGA.

Carboxydismutase

About a year ago, using tracer studies, we sought and found a cell-free preparation, both from algae and from other green plants, that was capable of catalyzing the production of PGA specifically from ribulose diphosphate (RuDP) and sodium bicarbonate. The RuDP used in these experiments was isolated by chromatography from green-plant extracts. The technique was to expose the RuDP and the enzyme preparation to $NaHC^{14}O_3$ and show that carboxyl-labeled PGA was formed (Fig. 15). The traces of malic, citric, and aspartic acids and alanine formed indicate the presence in the preparation of some Krebs-cycle enzymes which could convert some of the PGA initially formed to other compounds.

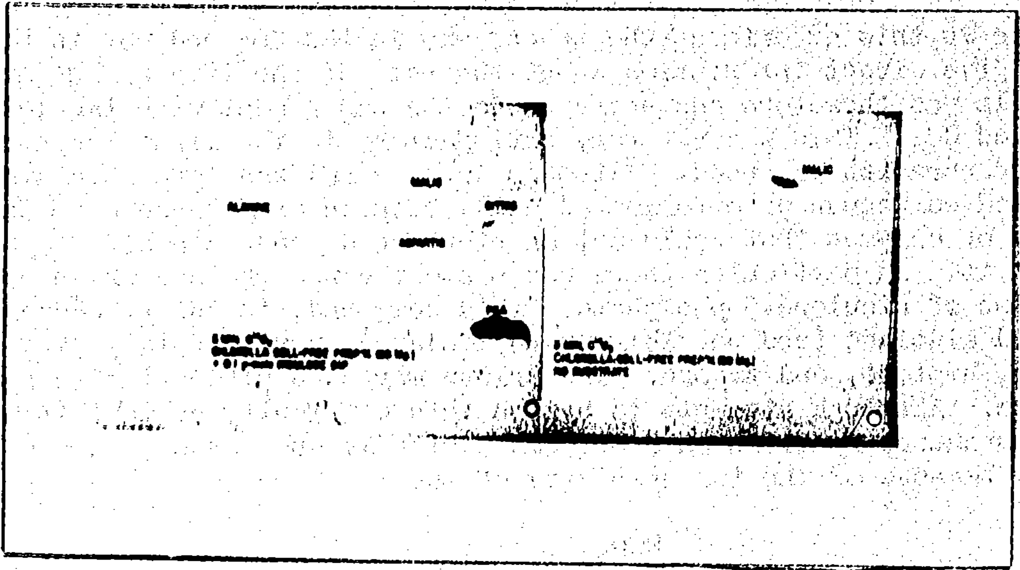


Fig. 15 - Chromatograms indicating formation of carboxyl-labeled PGA

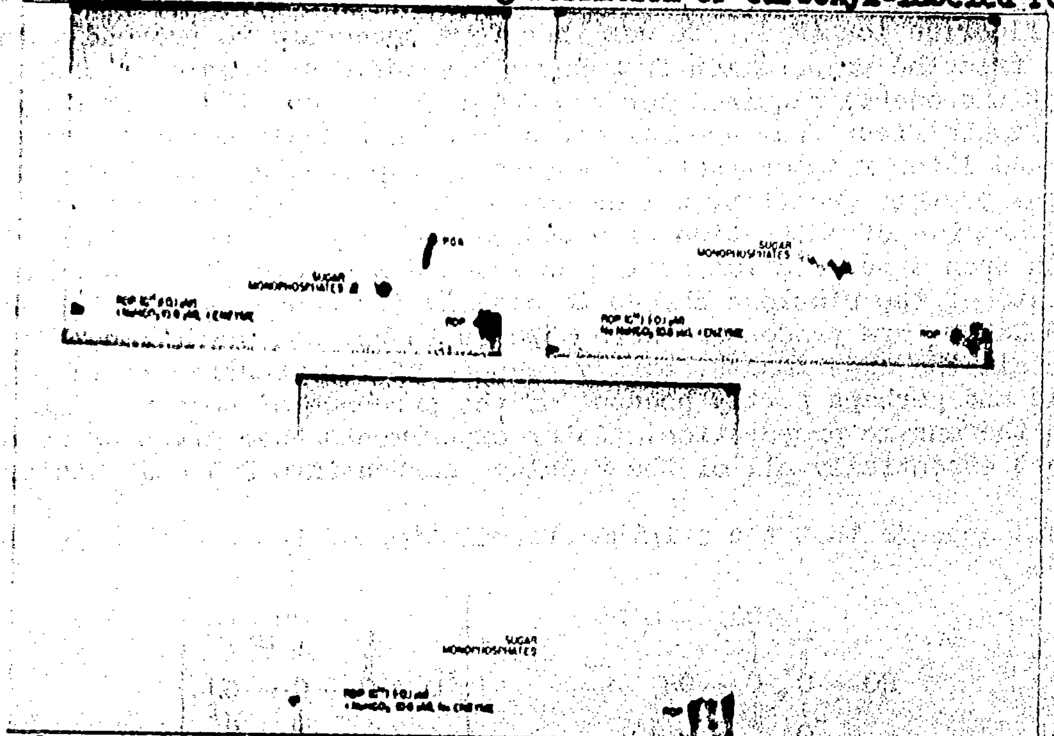


Fig. 16 - Chromatograms showing effect of enzyme action on ribulose diphosphate.

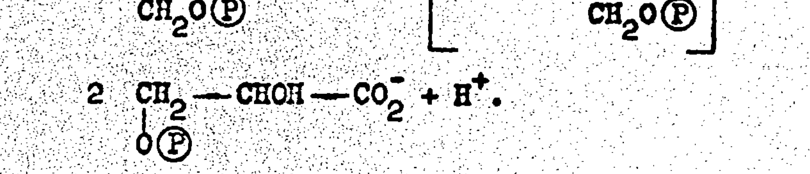
Indeed, upon longer exposure (> three minutes) to these crude preparations, much of the PGA was converted. The formation of a little labeled malic acid in the absence of substrate (RuDP) indicates the presence of pyruvic acid and malic enzyme.

Because in this experiment the tracer was in the CO_2 and not in the RuDP, it did not give direct information about the fate of the five carbon atoms of ribulose. It was therefore necessary to do the experiment with labeled RuDP and unlabeled CO_2. This was not very satisfactory in the first instance when the crude preparation was used. Although labeled PGA was formed, a good many other labeled compounds were formed as well, because of the presence in the preparation of enzymes that could act on ribulose diphosphate and compounds formed from it. In particular there was present a phosphatase which permitted the formation of ribulose-5-phosphate. This compound, in the presence of transketolase and aldolase (and possibly transaldolase), would rapidly find its way into hexose, heptose, and triose. The triose may have given rise to some PGA by oxidation. Although attempts to bypass this difficulty by inhibiting the initial phosphatase reaction on RuDP were partially successful, they were not conclusive, because of the insensitivity of the

$$\text{RuDP} \xrightarrow{\text{HCO}_3^-} \text{PGA}$$

system to fluoride ion (F^-). It was therefore necessary to proceed with the attempt to free the preparation from any other enzymes capable of acting upon RuDP except the one(s) required for the PGA-forming reaction (from CO_2). This was accomplished first from neutral extracts of New Zealand spinach (Tetragonia expansa), and later from extracts of sonically ruptured algae. The enzyme appears in the protein fraction, salted out of neutral extracts, between approximately 0.3 and 0.4 of saturation with $(NH_4)_2SO_4$. The results of an early experiment with such a preparation acting on labeled RuDP are shown in Fig. 16.[10] Here the fate of the ribulose carbon is clearly its conversion to PGA when both enzyme and $NaHCO_3$ are present. There appears to be some sugar monophosphate present in all the experiments, partly because of its presence in the original RuDP sample and perhaps partly because of the presence of some residual phosphatase in the enzyme preparation. Later experiments have given preparations that convert essentially all of the ribulose carbon into PGA and nothing else.

It thus appears that the original formulation of the reaction is at least a likely one,



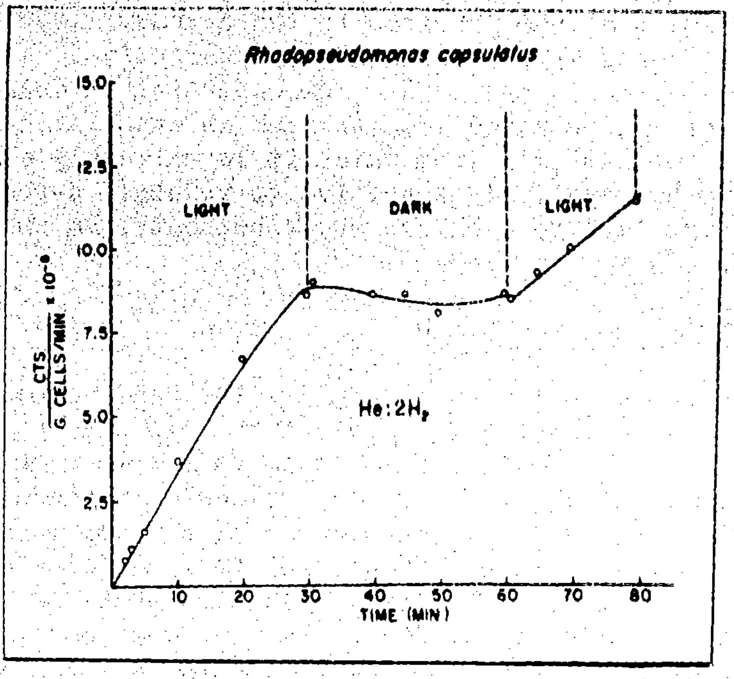


Fig. 17 - Photoreduction of CO_2 by purple bacteria

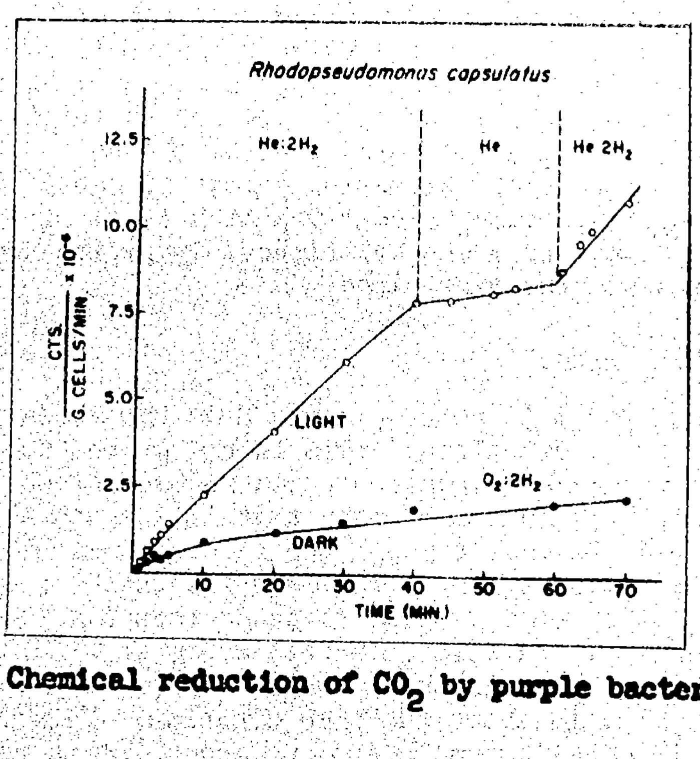


Fig. 18 - Chemical reduction of CO_2 by purple bacteria

Because the carboxylation reaction takes place at the expense of the oxidation of carbon atom No. 3 of the ribulose to the carboxyl level, the name "carboxydismutase" suggests itself as uniquely descriptive. It is interesting to note that the enzyme is not readily demonstrated in animal tissues (rat liver), and that it can be obtained from spinach in association with the highly organized intact chloroplasts,[11] from which it is extremely easily separated. It does not appear to be especially sensitive to vereene, o-phenanthroline, or cyanide, but it is sensitive to p-chloromercuribenzoate, an inhibition that is reversed by cysteine.

Chemical Requirements to Run the Cycle

We now have the cycle in its details (Fig. 14), and we now know precisely what reagents are required to make the cycle turn. It can be seen that the requirement for the reduction of a PGA molecule to a triose is one molecule of triphosphopyridine nucleotide (TPNH) and one molecule of adenosine triphosphate (ATP). The only other energy requirement comes at the point of conversion of RuMP to RuDP, where another molecule of ATP is used. A calculation of energetic compounds needed per CO_2 molecule entering will show that the net requirement for the reduction of one molecule of CO_2 to the carbohydrate level is four equivalents of reducing agent, or four electrons, and three molecules of ATP. The four electrons are supplied by two molecules of TPNH. All these required cofactors must be made ultimately by the light through the conversion of the electromagentic energy in some way. It must be emphasized that in this requirement for reducing carbon there is no particular requirement for a photochemical reaction other than the production of the two reagents. If we could supply those two things from some other source than the photochemical reaction, we should be able to make this whole sequence of operations function. We have reason to believe that this is indeed being done by the use of the required collection of enzymes. But a suitable situation exists in nature also. The situation is such that we must have simultaneously a high level of this particular reducing agent - which we now know can be triphosphopyridine nucleotide (TPN) - and ATP at the same time and the same place.

Running the Cycle Without Light

There is one known system in nature, aside from the green plants, in which that situation occurs. This situation exists in one of the photosynthetic purple bacteria that does not make oxygen, but does reduce carbon dioxide with molecular hydrogen. Figs. 17 and 18[12] show that it is possible to have the reduction of CO_2 take place either through the agency of light or through the agency of a chemical oxidation system. The organism is the purple bacterium, *Rhodopseudomonas capsulatus*. The initial slope corresponds to the reduction of carbon dioxide in the light. In this case both hydrogen - as the reducing agent - and light are required. As soon as the light is turned off, the reduction of carbon dioxide stops. Fig. 18 shows the same organism. This is a dark fixation. Here it is exposed only to helium and hydrogen, and there is an initial fixation which immediately saturates and stops. When oxygen is then admitted to the system, the fixation again continues in the same way as it does with light. The intermediates in the dark are very much the same as in the light. The hydrogen presumably provides the reducing power that is needed. The oxygen is required to oxidize some of that hydrogen to make ATP, and the two together can make the carbon dioxide cycle function. This suggests that a prime function of the light, in this case where hydrogen is the reducing agent, is to supply the oxidizing agent necessary for the production of the required ATP.

Quantum Requirements

In order to estimate what a minimum quantum requirement for photosynthesis may be, on the basis of the information we have so far accumulated about the detailed chemistry of the process, at least one assumption is necessary. This is related to the mode of interaction of electromagnetic radiation and matter. It is that a single quantum can excite not more than a single electron. Another assumption about the behavior of the excited electron is required, namely, that it does not by some chemical (or physical) dismutation process give rise to more than one equivalent of reducing power at the potential of TPNH. And if that is the case, inspection of the requirements mentioned above allows one to predict what the minimum quantum requirement for such an operation would be. Four electrons are needed for the reduction, and three molecules of ATP.

Something about the various ways in which ATP can be produced is already known. For example, during the transfer of two electrons from DPNH to an atom of oxygen, two or three molecules of ATP can be produced. Therefore, one can suppose that when all the energy for the operation of this cycle comes from light, the minimum quantum requirement must be six or seven. That is, four electrons are needed for the reduction and two or three more for the three molecules of ATP that are required. However, it should be possible to find conditions under which the quantum requirement for the reduction of CO_2 and the evolution of oxygen would be as little as four, provided there were some other source besides the light for the three molecules of ATP. These conditions have been realized.13) The quantum-requirement determination was carried out by use of an apparatus in which one could measure directly, without any ambiguity, the production of oxygen by a direct measurement of a unique quality of the oxygen, paramagnetism, rather than merely by a gas pressure. Also it was possible to measure directly the amount of carbon dioxide absorbed by measuring a property of the CO_2 in the gas phase, in this case its infrared spectrum.

As a result of these measurements, it was found that the quantum requirement ranged experimentally from 7.4 at high light intensities, where photosynthesis exceeded respiration by a factor of 12, to 4.9 at low light intensities, where photosynthesis and respiration were nearly equal. At zero light intensity the value of the quantum requirement extrapolated to four.14) This result indicates that some of the ATP requirement of photosynthesis can be met by reactions of respiration which produce ATP but that the four electrons of reducing agent must be supplied by the light reaction or, with special organisms, by externally-supplied reducing agents.

QUANTUM CONVERSION

So far only the reduction of carbon has been considered. Since this seems to be quite a separate system from the oxygen-evolution reaction, it might appear that one should not expect to learn much about the photoproduction of the electrons and the ATP from studying the carbon reduction. But there must be a connection between the two. By suitable observations it is possible to see at least one point at which the carbon-reduction cycle makes contact directly with the photochemical apparatus. This is shown in Fig. 19. Here the cycle is

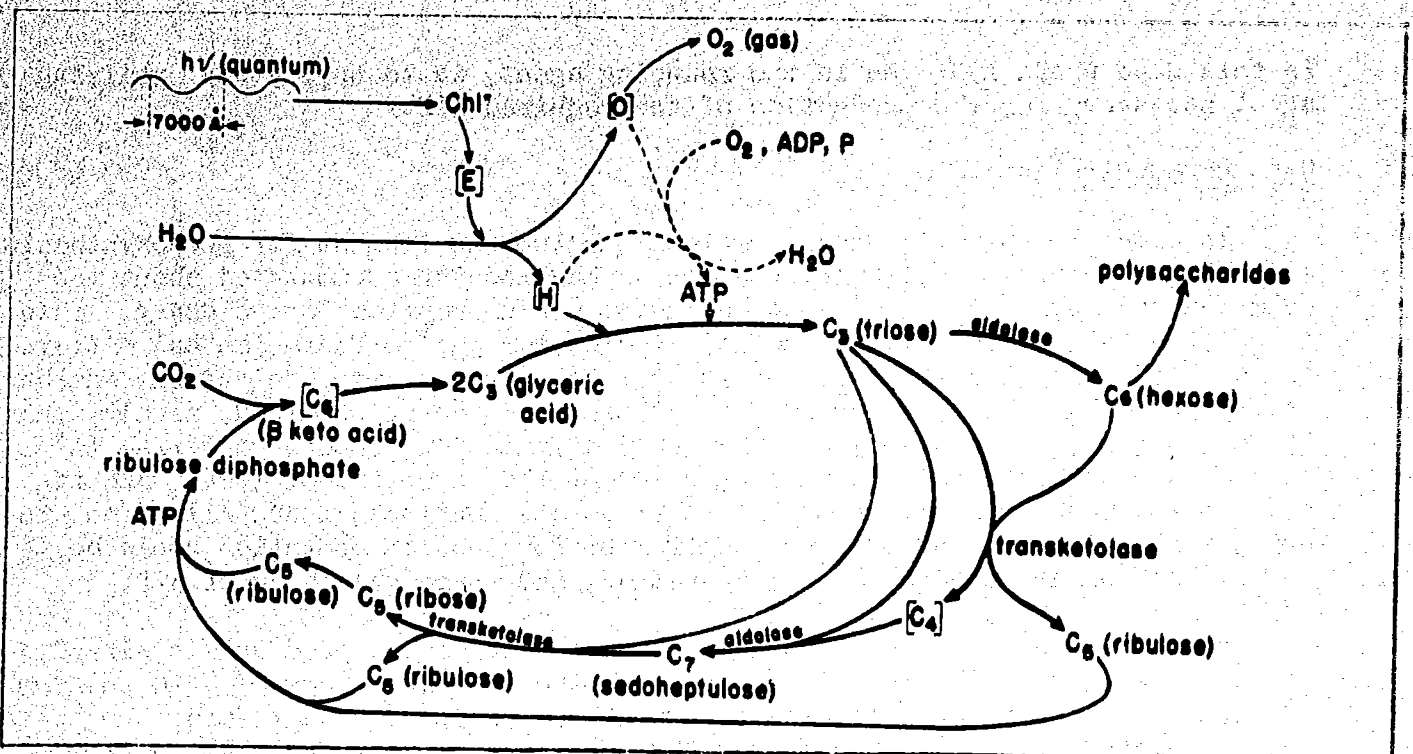


Fig. 19 - Proposed cycle for carbon reduction in photosynthesis

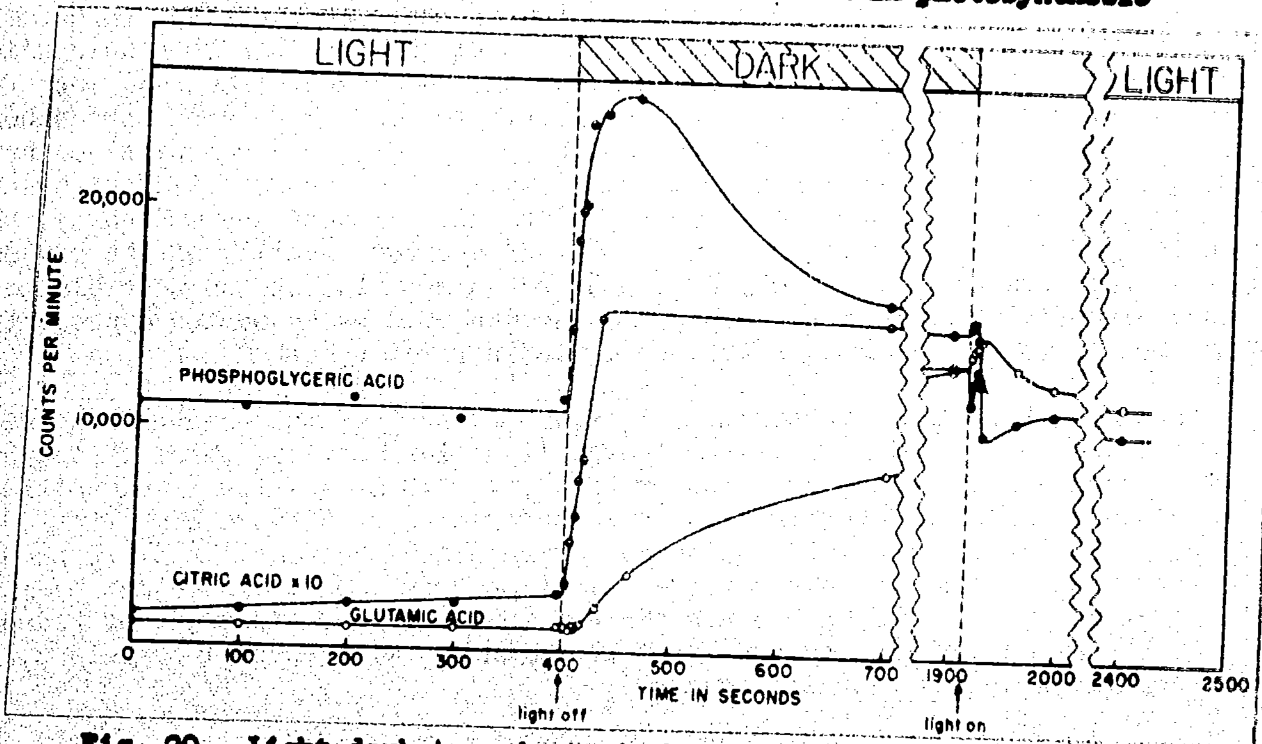


Fig. 20 - Light-dark transients in PGA, citric acid and glutamic acid concentrations

show again. The quantum is first absorbed by chlorophyll and converts water into something that makes a reducing agent [H] and some oxidizing agent [O]. The reducing agent can reduce the glyceric acid to triose. Some of the reducing agent must be used to make ATP, with oxygen or the intermediates on the way to oxygen, because that is necessary for the cycle to run. What we wish to consider now is this point of contact, [H], between the photochemical apparatus and the carbon cycle and what information about the quantum conversion we can gain from this study.

Light Inhibition of TCA-Cycle Incorporation

An experiment was carried out in which a steady state was examined and the changes induced by a sudden change of conditions were observed. Fig. 20 shows the result of this experiment. Here is the same type of experiment as before, but with the examination directed toward different substances. Attention is focused on glutamic acid and citric acid, and it will be seen that while the light is on, the rate of formation of radioactive glutamic acid and radioactive citric acid is quite low. But immediately after the light is turned off, the rate of formation of these labeled acids is increased manyfold. Glutamic and citric acids are two compounds very closely related to the respiratory cycle known as the Krebs cycle, and Fig. 21 describes in schematic terms the metabolic relationships leading to the experimental facts we have just seen. Here is shown the photosynthetic cycle and the Krebs (tricarboxylic acid) cycle. The glutamic acid and citric acid are in or related to the Krebs cycle. The photosynthetic cycle does not contain either glutamic or citric acid but does form PGA and sugars. Eventually these direct products of the photosynthetic cycle have to become carbohydrates, proteins, and fats, and ultimately they will get back into the tricarboxylic acid cycle. That is the major route in the light. But immediately after the light is turned off a direct connection between the two cycles is apparently made which allows the PGA to be transformed directly into the compounds of the tricarboxylic acid cycle. Fig. 22 shows the details of that mechanism. Carbon can enter the tricarboxylic acid cycle via acetyl Coenzyme A, condensing with oxalacetic acid to give citric acid, thence continuing around this cycle and via a side reaction to glutamic acid. The question is: how is glyceric acid converted to acetyl Coenzyme A? This must happen rapidly in the dark, but not very rapidly in the light. Fortunately we have some idea how acetyl-CoA may be formed from glyceric acid, and Fig. 22 shows this. The glyceric acid is dephosphorylated to form pyruvic acid; the pyruvic acid then reacts with an enzyme system, of which thioctic acid is a coenzyme, to form acetyl-thioctic acid and carbon dioxide. The acetyl-thioctic acid then undergoes a thiol ester interchange with CoA to form reduced thioctic acid and acetyl-CoA, which then goes on into the citric acid cycle, Fig. 23.16)

How does light affect these reactions? The conversion of PGA to citric acid provides for the entrance of carbon into the tricarboxylic acid cycle, and if somehow this pathway is closed by reduction of the level of the disulfide, the rate of transfer of radioactive carbon from the photosynthetic cycle to the citric acid cycle will be reduced. This suggests that the light shifts the equilibrium from the disulfide to the dithiol form of thioctic acid by inducing reaction with something other than pyruvic acid, perhaps ultimately water. In the dark, oxidation converts the dithiol form to the disulfide, which can again catalyze the oxidation of pyruvic acid to CO_2 and acety-CoA. This system is like a valve that is closed by light, and that controls the flow of carbon from

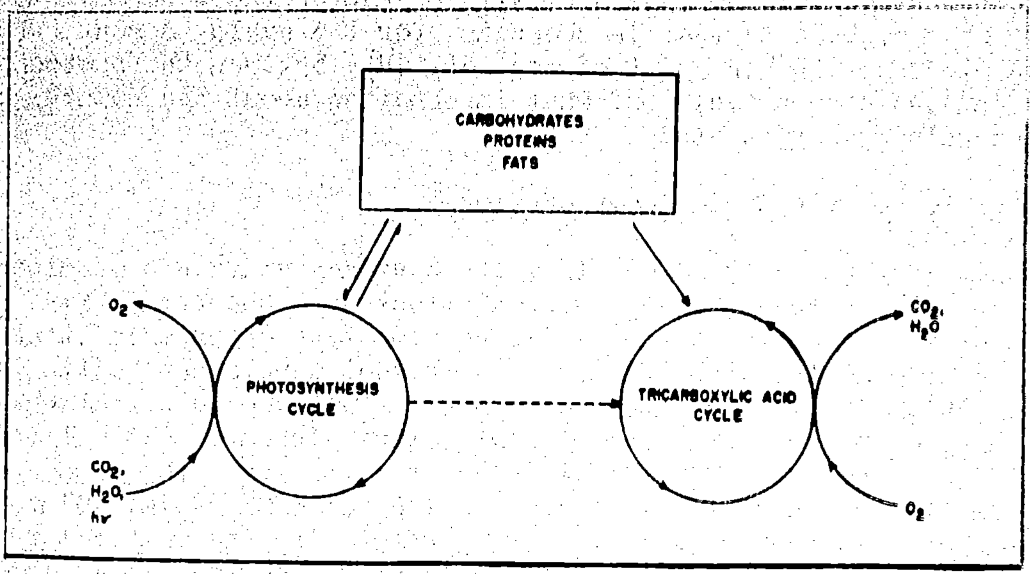


Fig. 21 - Schematic relationships between the photosynthetic cycle, the tricarboxylic acid cycle, and storage products in the plant

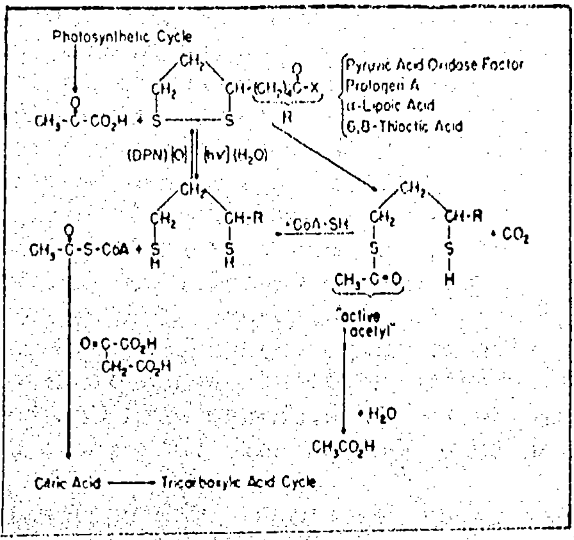


Fig. 22 - Mechanism of photochemical control of the relationships between the photosynthesis cycle and the tricarboxylic acid cycle

the photosynthetic cycle directly into the tricarboxylic acid cycle. It suggests further that the disulfide may be closely allied to, if not identical with, the electron acceptor from the photochemical act. Actually a number of experiments have been performed that indicate that this may be so.[17),18),19)]

The proposed relations between the photosynthetic carbon reduction cycle, the photochemical reactions, and the Krebs cycle are shown in Fig. 23. It is suggested that the required ATP is generated by reactions coupled with the oxidation of TPNH or DPNH through the cytochrome system.

It can be seen that the use of radioactive elements, employed as tracers, have made possible the elucidation of the path of carbon reduction in photosynthesis. In addition, information gained from the study of the path of carbon in photosynthesis and its relation to reactions of respiration has provided the basis for proposals regarding the energy transport from the primary photochemical act.

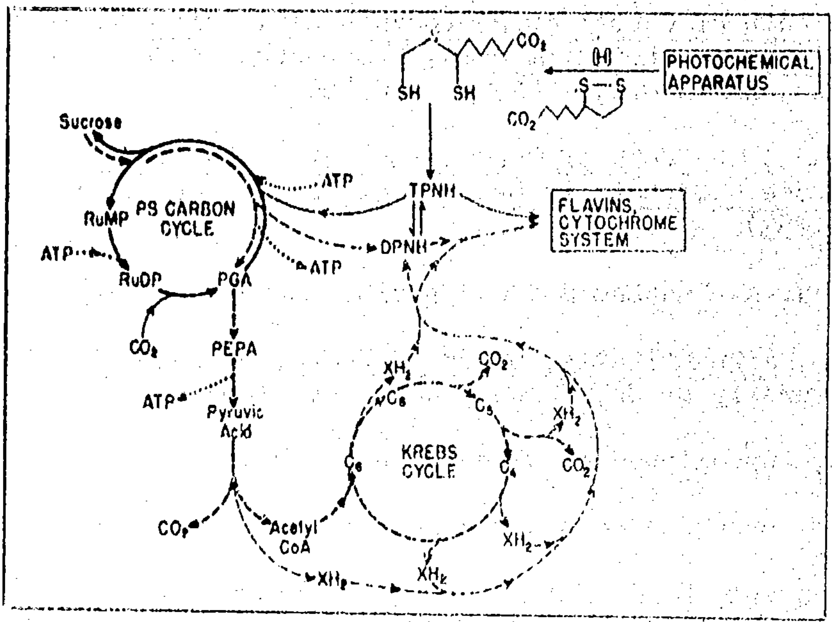


Fig. 23 - Diagram of the suggested nature of the photochemical apparatus and its relationship to other functions

- - - - Oxidative, or respiratory, pathways
——— Reductive, or photosynthetic, pathways

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TEACHER LECTURES GIVEN AT UCRL DURING SUMMER OF 1956

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Chapter 15

MEDICAL AND BIOLOGICAL APPLICATIONS OF RADIATION

C. A. Tobias

Dr. Stubbins introduced Dr. Tobias as "the man who paid for running the cyclotron much of the time." Dr. Tobias immediately disclaimed any such credit, declared he was only the agent for interesting research, and expressed sincere thanks and appreciation to the individuals, private foundations, and government agencies who really do pay the bills.

He gave details of the rapid growth of and increasing interest in his field of biological and medical physics. In 1941 there were four people at the laboratory interested in those topics. Since the war there have been 65 graduate students working in this field, about 40 of them at Donner Laboratory. All graduates have interesting and well-paying jobs. The demand is steadily increasing, and it is probable that a society will be formed with regular meetings and reports to encourage broader and deeper work in this field. More than half of recent Nobel Prize winners in biology have been in the field of biological physics. Both the tools and concepts of physics have found increased use in biology and medicine.

He then told of the applications of radioactivity to cancer research. The use of radioactive isotopes (iodine and phosphorous) enables one to follow the course of these elements through the body and thus compare the action of normal with diseased tissue, so that frequently the source of malfunction can be first located and then treated. Originally the radioelements were observed by means of fluoroscopes and photographs, but there is increasing use of television cameras.

One important branch of cancer research is connected with breast cancer. Approximately 5% of all adult females in the United States have it at some time during their life, and some 20,000 per year die from it. It is especially painful and malignant with younger women. Life expectancy is less than three years when it is untreated.

Dr. Tobias feels that the general course of cancer is now fairly well understood, though there is not complete agreement among all workers in the field. In general there are three factors that contribute to the disease.

1. Some carcinogenic chemical (there are more than 1000) or irritation or radiation starts it.

2. There are some inheritance factors involved (but their effect was not discussed).

3. There is a hormonal contribution from various glands. These glands excrete growth elements into the blood stream, and if their contribution can be stopped or nullified, the malignancy, though started, will not grow and may even regress for a time.

To understand the theory behind the treatment it is necessary to study Fig. 1. The body has a built-in control system of maintaining equilibrium conditions, based on feedback principles. Its operation is quite similar to that of a thermostat for maintaining constant temperature.

If a carcinogenic agent affects some of the breast cells, they are unable to perform their usual functions, and send out a call for increased growth factors. The pituitary notifies the ovaries via FSH (follicle-stimulating hormone), and the ovaries then relay the orders to the breast cells via their own hormone, estrogen, and the cells grow. The result, however, is like a thirsty man drinking sea water--he only gets thirstier. In other words, the malignancy grows. Cutting off the message from the ovarian tissue stops the growth. This can be achieved by surgical removal of the ovaries or by administration of a countermanding message (androsterone). Both these methods have been used, and following them the rate of growth definitely decreased for a time.

In less than a year, however, the pituitary discovers that its message is not getting through, so by way of ACTH it orders the adrenals to supply the "lack" and they start making estrogen, which they send to the breast, and the cancer grows again. The next step was to remove the adrenals. The patient can be kept alive by administration of cortisone. Again this turned out to be only temporarily effective, therefore some cases that were beyond all other help have been treated by removing the pituitary itself. Of course a lot of preliminary work was done with rats, dogs, and monkeys.

Here is where the cyclotron comes into use. There are only a very few doctors with sufficient confidence and skill to operate on the pituitary. X-rays and ordinary radioactive substances produce intolerable skin-burning effects or spread too greatly in their action. A stream of 190-Mev deuterons or 340-Mev protons can be collimated to a thin pencil not more than 1 mm in diameter.

These can penetrate flesh up to 30 cm. Therefore if the head can be rotated in the right position in the beam, the desired treatment can be applied at the vertex of a cone, giving much greater intensity there than elsewhere.

It is well known that the ionizing (and therefore tissue-killing) effect is greatest near the end of a trajectory's path. This fact is commonly illustrated by the Bragg curve. If this effect could be utilized it would

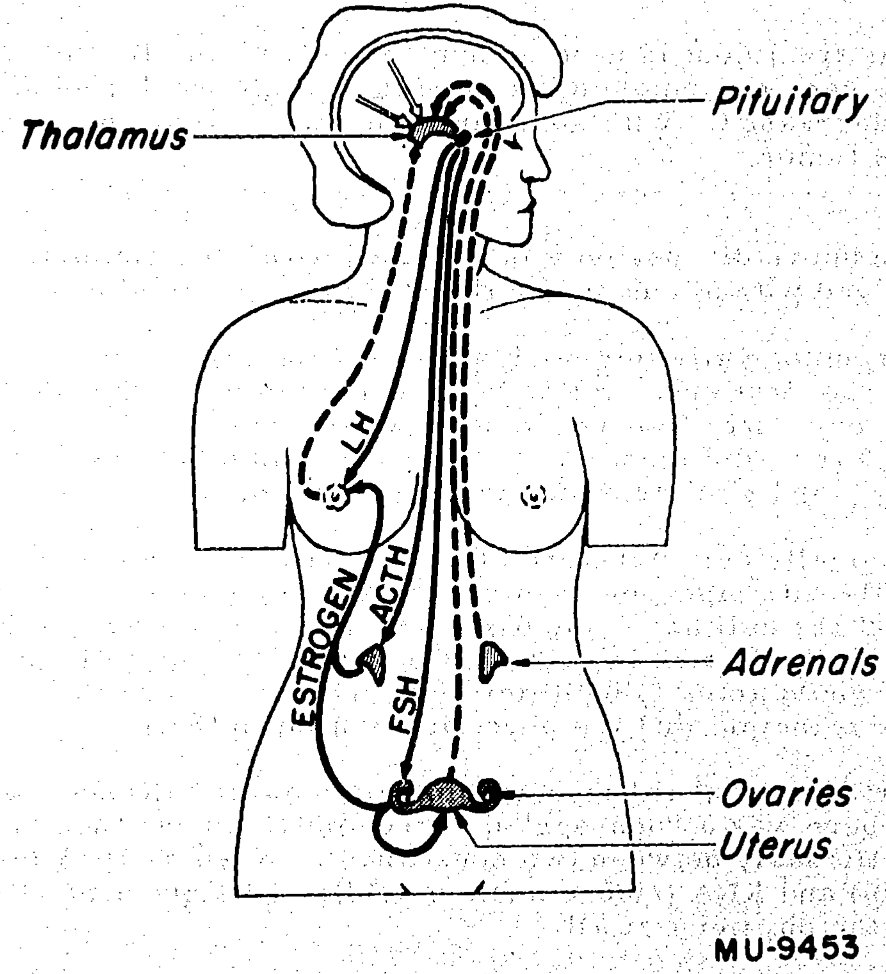
Pituitary
Thalamus
LH
ACTH
ESTROGEN
FSH
Adrenals
Ovaries
Uterus
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Fig. 1

further increase the relative intensity at the target, but so far a workable technique for this has not been devised. However, deep and safe therapy is now possible by the methods indicated.

Moreover, the actual treatments are short and can be done by well-trained technicians. There are four places in the world with cyclotrons adequate for this kind of work. They are: the Radiation Laboratory at Berkeley, the Argonne Laboratory near Chicago, a laboratory at Liverpool, England and a laboratory at Uppsala, Sweden.

The general arrangement of treatment is shown in Fig. 2 and Fig. 3.

This treatment is used on humans only when all other methods fail. There have been no complete recoveries, but the rate of growth has been markedly decreased. With some animals there has been a complete melting away of the tumor.

The above discussion was received with such enthusiasm that Dr. Tobias obliged with an encore on the study of cell division.

Chronologically this study preceded the cancer studies and was in fact one of the first problems to be investigated by the Biophysics Group at the Laboratory. Dr. Tobias did not develop rigorously the mathematical treatment, but he did mention certain parallelism between cell structure and division, and similar topics on the atomic or nuclear level.

Originally cell structure and division were studied by carefully observing cells with high-power microscopes. Of course a great deal was learned, but the cell has many parts and division takes place by stages and there is a 5% fluctuation in cell division time, so that cells that appeared to be alike would actually be different. In other words, there is a built-in uncertainty principle (but the physicist is used to that).

Furthermore, although all biologists agreed that cell division was periodic, there was a "hen-egg" disagreement, among them about cause and effect, particularly between two constituents known as DNA (desoxyribose nucleic acid) and RNA (ribose nucleic acid). This question of priority did not bother the physicist at all.

He was able to plot the growth and decay fluctuations of each compound and then consider them as different phase relations of a single wave train. Fourier analysis, permits resolution of complicated wave patterns into a series of sine waves. This mathematical tool was employed by the physicist in analysis of the above problem.

Not only in the theoretical treatment, but also in the laboratory work, we find many analogies between simple cells and atoms. Dr. Tobias worked with unicellular yeast cells called haploids. These are of two different sexes, which may be compared to protons and neutrons. Each form can asexually reproduce its own kind, but also they can unite and produce a diploid with

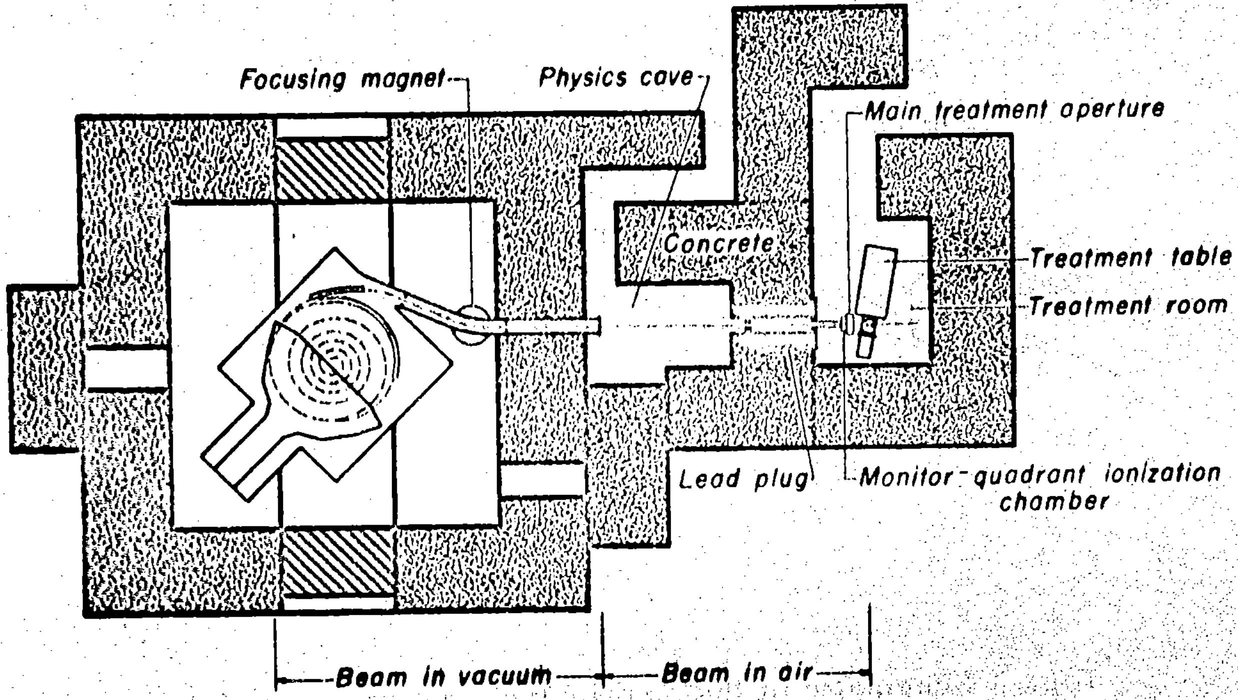

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Fig. 2. General layout of the 184-inch cyclotron and treatment rooms (not to scale). The deflected beam passes through a room for physics experimentation and arrives at the treatment room beyond.

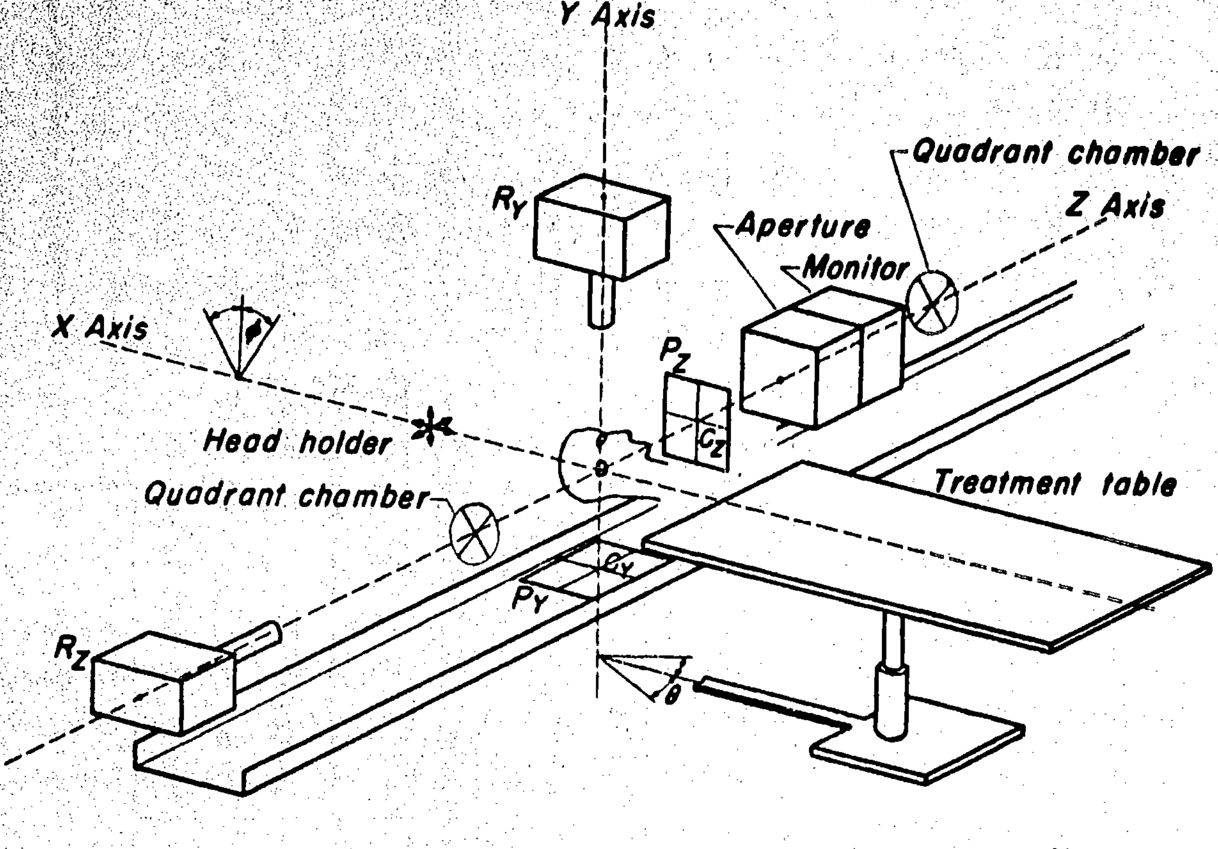

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Fig. 3. Schematic of the positioning, alignment, and rotation of the human head. The optical treatment bench is aligned with the beam, while the patient lies on an adjustable table at some predetermined treatment angle. This angle is changed in 7.5° intervals on different treatment days. The head of the patient is held rigidly by a mask. Position of the head is checked by a lateral, horizontal diagnostic x-ray, taken by an x-ray machine rigidly mounted on the treatment bench. The sella turcica is aligned by moving set screws in the X (longitudinal) and Y (vertical directions, until the center of the sella and the cross hairs marking the beam position are coincident.

With the vertical x-ray machine, mounted above the treatment plane, one obtains a frontal diagnostic picture. The patient's head is moved by set screws in the Z direction until the center of his sella coincides with the center of rotation of the head rotator, as marked by cross hairs.

Rotation of the head occurs around the longitudinal axis of the body (X); rotational limits of ± 30° or ± 35° are easily tolerated.

two genetic components. This might be compared to deuterium. These can again unite to make tetraploids, which might be compared to helium, or they can beget their own kind, or can be made to revert back to two haploids.

In the experiments, haploids and diploids were irradiated with x-rays, deuterons, or protons, etc. The dosage was plotted against the percentage of surviving cells and it was found that the diploids were much more resistant than haploids. To make a theoretical curve fit these survival facts, it was necessary to assume that each genetic "unit" had several "sites" and that these must be damaged in pairs in the diploids to inhibit growth.

When diploids are irradiated, some die and some live, but those that live have inherited recessive effects, and if their progeny are again irradiated the lethal effect is greater than for normal ones. This effect can be calculated by probability methods, and predictions agree well with laboratory results.

It has been found, however, that the recessive effect is not always permanent; after several generations cells may outgrow it and even become more resistant to further radiation than untreated cells. The rate of recovery depends on temperature and other environmental factors. This treatment seems to bring out hidden genetic factors in the cell, possibly giving time for the chromosomes in the cell to rearrange.

There is here an analogy with radioactive transformations. An atom will not voluntarily depart from its stable ground state, but if external energy kicks it into a metastable condition then transitions from that to other, originally forbidden, states are possible. Thus the new strain is not really the same as the original diploid.

Now the cells of the human body are diploids, and cancer growth is an unwanted but new, more viable cell growth. If we understand cell division in diploid yeast cells it gives us hope in other fields. In studies using these single cells, controls of all kinds are easier and measurement of results more certain than with more complex organisms. Dr. Tobias feels sure that in understanding--and therefore controlling--cell growth, biophysical application of the methods and ideas first used at the atomic level will be fruitful.

Greater detail and further development of these ideas is found in the following references.

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Chapter 16

EMPLOYMENT OPPORTUNITIES

Kenneth Simpson

Dr. Simpson has been a philosopher, physicist, and teacher; he is at present director of professional personnel for the laboratory, in charge of employing professional people both here and at Livermore.

Dr. Simpson called attention to the paradoxical situation that whereas the need, demand, and remuneration for scientists, particularly physicists and engineers, is increasing, the supply is diminishing. One set of published statistics states that in 1890 about 90% of high school students had a course in physics, but in 1952 only 6% did. This is not as big a drop as appears, since only 4% of all students went to high school in 1890 and in 1952 21% went.

Some of the probable reasons for this drop are

1. "progressive" education methods,
2. general tendency to antirationalism,
3. general lack of enthusiasm for "hard" subjects,
4. long training period (7 to 8 years for a Ph. D.),
5. poor pay (a lessening deterrent),
6. lack of special training and enthusiasm of <u>some</u> high school teachers.

The contrast between our dip and Russia's rise in science training worries some people. It is estimated that this year science graduates will number about 25,000 here, and double that in Russia. Fluctuations in the number of graduates in physics from American colleges are shown below.

Year	Bachelors	Masters	Ph. Ds.
1930	1100		
war	500		
1950	3700	400	100
1956	2600	800	600

Formerly small colleges contributed a disproportionate share of science majors, but this differential is disappearing. Emphasis varies greatly in state institutions. Santa Barbara, with 2000 students, has only 20 majoring in physics, but at Riverside 100 out of 800 are physics majors.

Dr. Simpson believes it is very important to get students interested in science early, certainly before freshman college age, and preferably early in the high school course. The subject matter of physics now is so difficult, complex, and voluminous that a late start is a serious handicap. The most productive years in research and discovery are the late 20's and early 30's. This is in contrast with executive and managerial capacity, which matures much later. Dr. Simpson feels that mathematics and science as contrasted with philosophy, can profitably be studied much earlier than is common here. This is being done in Russia, with the result that their bachelor students are comparable to our Ph.D's.

There is no dearth of potential material for these needed jobs. Reliable analysis indicates that less than 1/4 of the people who could succeed at physics study it.

There are about 5 times as many jobs available to physics graduates today as in 1920, and the number is increasing, especially for those with bachelor's degrees only. Moreover, there are increasing opportunities to continue education on the job. These are "fringe benefits" now necessary to get and hold the needed personnel.

The very real nature of the shortage is shown in a tabulation of starting monthly salary schedules, (below), which represents a cross section of 50,000 firms who use scientists.

Subject	year	Bachelor	Ph. D.
Physics	1948	275	450
Physics	1955	400	610
Physics	1956	476	750
Chemistry	1956	440	670
Math	1956	460	750
Management	1956	365	
Finance	1956	334	
Agriculture	1956	325	

It is estimated that the promotional cost of hiring a professional man is close to $2000.

About $3.75 billion was spent for research in the United States in 1952. About 2% of that was by universities, 25% directly by business; much of that came indirectly from the government, and the rest directly from the government. More money has been spent on research in the last eight years than in all previous history. Even if this large government spending should be curtailed, industries with an eye on the future would cut their research last of all, for it is now considered a necessity, not a luxury. Its long term returns are better than for any other investment.

During the discussion it was repeated that the greatest demand is for physicists, engineers, and mathematicians, with chemistry running a close second. There is no shortage of biologists--at least the nonmathematical, nature-study kind--and good recent law graduates can be hired for $300 per month.

Dr. Simpson was against compulsory science courses, and did not feel that just making the courses harder would improve the output. He did urge, though, that students be told of the increasing need and be given early opportunity to sample these fields--always intellectually, and now also financially, rewarding.

This work was done under the auspices of the U. S. Atomic Energy Commission.

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