Nuclear power for mechanical engineers

by Ralph W Arboe

A THESIS Submitted to the Graduate Faculty In partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at Montana State College
Montana State University

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This thesis was written to be used as a text for M E. 508, Atomic Power Engineering and consists of declassified material released by the Atomic Energy Commission, as well as this student's original ideas end presentation. The presentation is on a level for a graduate student. All of the complicated mathematics and physics have been eliminated and only a straight-forward engineering approach presented.

The introduction starts with the basic concept of the atom and its structure. Also in the introduction are a table of definitions and conversion tables for converting energy, mass and charge units. The brief review in the introduction is then used as a background for the remainder of the thesis.

The discussion then turns to a brief history of the findings of radioactivity, isotopes, isomers, artificial radioactivity, nuclear reactions, neutrons and positrons. Nuclear energy is explained and the type of reactions needed to produce energy by means of nuclear reaction and fission.

Separation of isotopes and the detection of radiation must be understood before a useful reactor may be designed. The types of reactors are discussed showing the advantages of one type over the other.

In conclusion all of the aforementioned material is compiled to use nuclear power for industrial uses. Nuclear power is put to use in aircraft, power stations, locomotives, industrial processes and heating. Calculations show the amount of nuclear fuel required in comparison to coal and oil, as well as a cost comparison.

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Abstract

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INTRODUCTION

ANOTHER LOOK INTO THE ATOM

Before the turn of the century (1880-90), the Physicists were content to believe that nothing new could be found and that they had explained every phenomenon. The future technical outlook appeared as if all experimental and research work would have to be along the lines of already existing theories. This belief did not last long, because a series of discoveries starting with Wilhelm Roentgen's discovery of X-rays in 1895, Henri Becquerel's discovery of natural radioactivity in 1896, also the work of the Curie's, J.J. Thomson, Max Planck, Rutherford and Soddy, Einstein, Bohr, Aston, Compton, Chadwick, the Joliot's, Fermi and Oppenheimer, with the final result being the Atomic Bomb. (The above mentioned scientists and their work will be discussed in the following pages.)

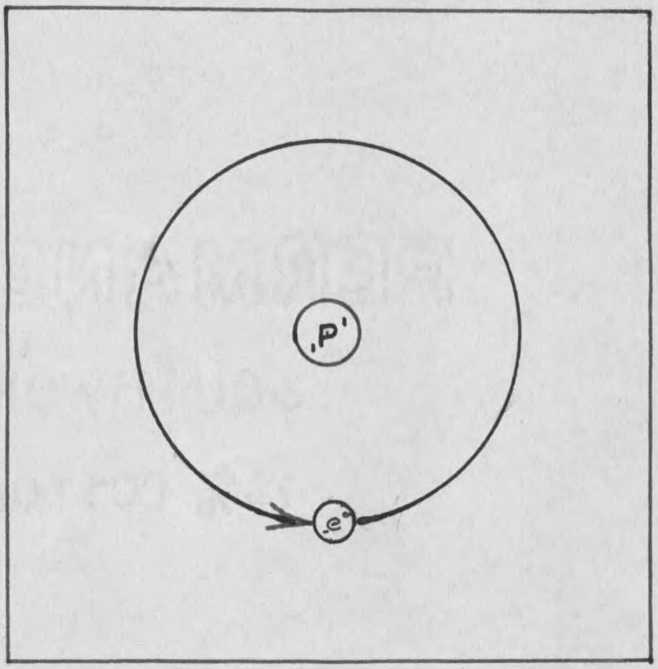

Figure 1 The Hydrogen Atom

Before continuing with our discussion let us examine the present concept of the atom. According to the present concept every atom consists of a small heavy nucleus approximately 10^{-12} cm in diameter surrounded by a large empty region 10^{-8} cm in diameter[1] in which electrons move somewhat like the planets about the sun. The nucleus having a positive charge (the amount depending on the individual atom) which is counterbalanced by an equivalent negative charge of the electrons (or electron). The mass of one electron is 2.01×10^{-30} lbs. or 9.1066×10^{-28} gms. Because of these awkward units the physicists have used another unit for the mass of these small particles, being the atomic mass unit (1 amu = 1.66×10^{-24} gms) which is based on the most abundant isotope[2] of oxygen having a mass of 16 atomic mass units.[3]

In examination of the smallest and simplest of the atoms, the hydrogen atom, we find that its simplicity is drawn from the fact that it has only one electron. As a result it needs only one positive charge in its nucleus (See Figure 1). The hydrogen atom has an atomic number (Z) of one, the next atom in sequence is the helium atom with an atomic number of two.

The helium atom has two electrons and two positively charged particles in its nucleus and therefore its weight should be twice that of the hydrogen atom. Referring to the mass of the hydrogen atom 1.00813 atomic mass units and the helium atom 4.003 atomic mass units we can see

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1 It is interesting to note that the diameter of the electron orbits is 10,000 times the diameter of the nucleus, and that all matter is made of atoms but only a very small volume of the atom is comprised of the nucleus and electrons, the rest of the volume being empty.

2 Isotopes will be discussed later.

3 In chemistry the mass is slightly larger. This is because the unit is established by assigning the value 16.000 not to the predominant $_8O^{16}$ isotope, but to oxygen as it occurs in nature. The ratio of the mass of an object on the physical scale to its mass on the chemical scale is 1.00027.

that the mass ratio is approximately four and not two as we assumed. (At the present time the physicists have accurately determined the masses of the atoms and various isotopes). Our assumption was erroneous and there must be something else in the nucleus besides these two positively charged particles (protons). The other particles were found to be neutrons,[4] a particle with no charge and a mass approximately that of the proton.

Therefore, the helium nucleus is made of two protons and two neutrons with two electrons moving in their orbits (Figure 2). The helium atom has an atomic number of two, an atomic mass number of four, and atomic weight of 4.003 amu. For future reference the atomic number, atomic mass number, and atomic weight will be designated by the symbols Z, A and M respectively.

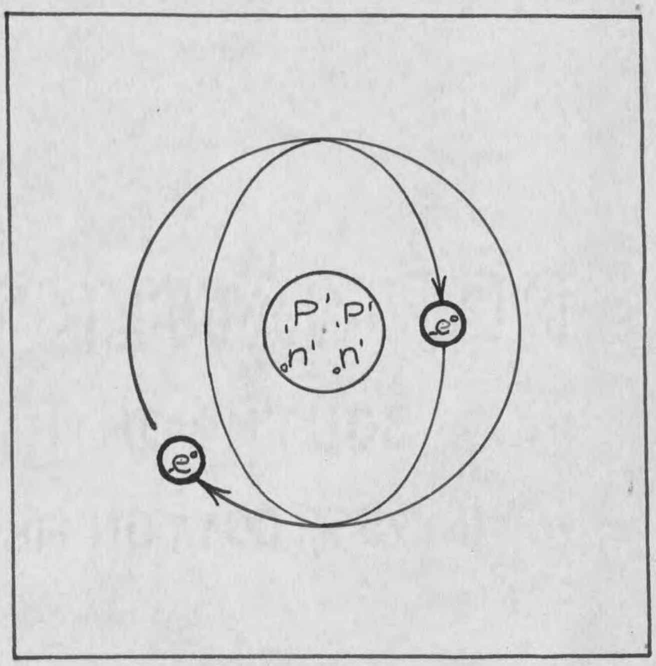

Figure 2 The Helium Atom

The atomic number (Z) is the number of positive charges in the nucleus. It determines the number of electrons in the extra-nuclear structure, and this in turn determines the chemical properties of the atom.

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[4] The discovery of the neutron will be discussed in detail later.

Thus all the atoms of a given chemical element have the same atomic number, and conversely all atoms having the same atomic number are atoms of the same element regardless of possible differences in their nuclear structure. The electrons in an atom arrange themselves in successive shells according to well-established laws. Optical spectra arise from disturbances in the outer parts of this electron structure; X-rays arise from the disturbances of the electrons close to the nucleus.

If we go back to a fundamental law of physics, Coulomb's Law of Force between electrically charged particles,

$$F = \frac{q_1 \ q_2}{kr^2} \qquad (1)$$

where F is the force in dynes, q_1 and q_2 charge on particles 1 and 2 in coulombs, r distance between particles in cm and k is the dielectric constant. The significance of this law is to calculate the force between charged particles, whether they have the like or opposite charges. As we already know, like charges repel each other and opposite charges attract. The nucleus of the helium atom is comprised of two protons and two neutrons. The charge on a proton is plus 4.805×10^{-10} stat-coulombs. There are two protons both having a positive charge, therefore, from Coulomb's Law, there must be a force of repulsion.

A present anolagy is that there are two types of opposing forces in the nucleus, those of attraction and those of repulsion. The electrostatic force of repulsion, (long range force) is due to the like charges of the protons. This force may be fairly large; it has been calculated that two grams of protons placed at opposite poles of the earth would repel each other with a force of 26 tons. The forces of attraction in the nucleus, called nuclear forces (short range forces) exceed even the electrostatic forces. These forces of attraction exist between protons, between neutrons and between protons and neutrons. These forces are not predominate except at very close range. If we were to graph these two forces against the distance (r) between the charged particles, the long range force would decrease exponentially from a distance of approximately $3x10^{-12}$ cm to where the force approaches zero at a distance of infinity. The short range forces are only in effect up to approximately $3x10^{-12}$ cm. (Figure 3). The height of the curve x is generally referred to as the potential barriet; any positive charged particle moving toward a nucleus must have sufficient energy to overcome this potential barrier to enter the nucleus. But neutrons have no charge and are not effected by this long range electrostatic force, therefore, a neutron moving in the direction of a nucleus will not have to overcome this potential barrier and may move directly within range of the nuclear

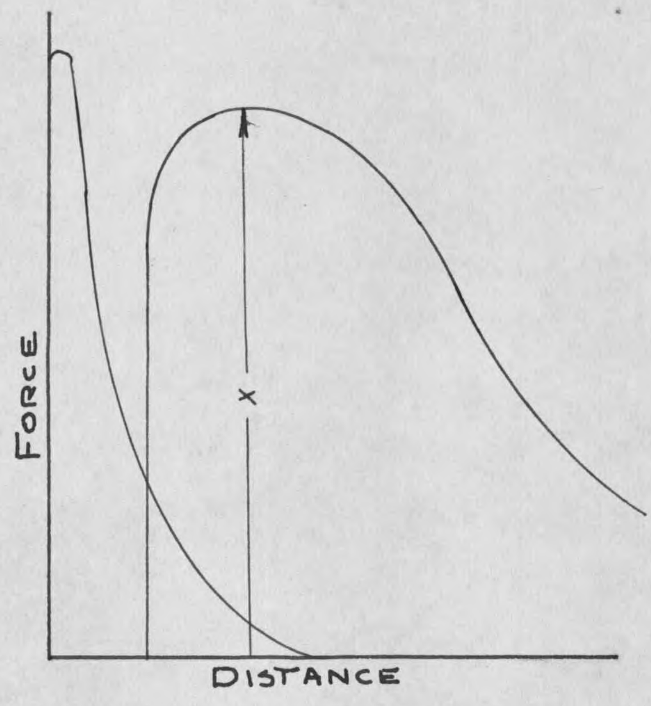

Figure 3 Comparison of Electrostatic Forces to Nuclear Forces as plotted against Distance

forces of attraction (this is the secret to nuclear energy and will be referred to at frequent intervals). However, these short range forces reach a point of saturation depending on the individual nucleus. Two hydrogen atoms attract each other very strongly to form a hydrogen molecule (H_2) and then attract no additional atoms, also two protons and two neutrons tend to unite into the helium nucleus with comparable saturation effects.

An isotope of uranium $_{92}U^{235}$ will have in its nucleus 92 protons and 143 neutrons but let us examine the forces acting on these particles. The uranium atom has an atomic number of 92 and an atomic weight of 238.07. The force on a proton in the center of the nucleus is the nuclear force of attraction for any of its adjacent particles (other protons or neutrons, short range forces). But a proton on the outside surface of the nucleus is in contact with less neutrons and protons, and a proton on the opposite side of the uranium nucleus may be beyond the short range and be in the range for the electrostatic forces of repulsion. Taking this into consideration it can be seen that some of these heavier atoms, although stable, may be disrupted very easily; an example of what may happen is easily shown by taking a drop of water and letting it fall from some high point (the gravitational force acting on the drop will be, $F = mg$). The drop will split into two halves.

So far this discussion has two main purposes, first to give a very brief resume of the atom (for a more detailed discussion see any college physics text) and second to give the reader several new things to think about.

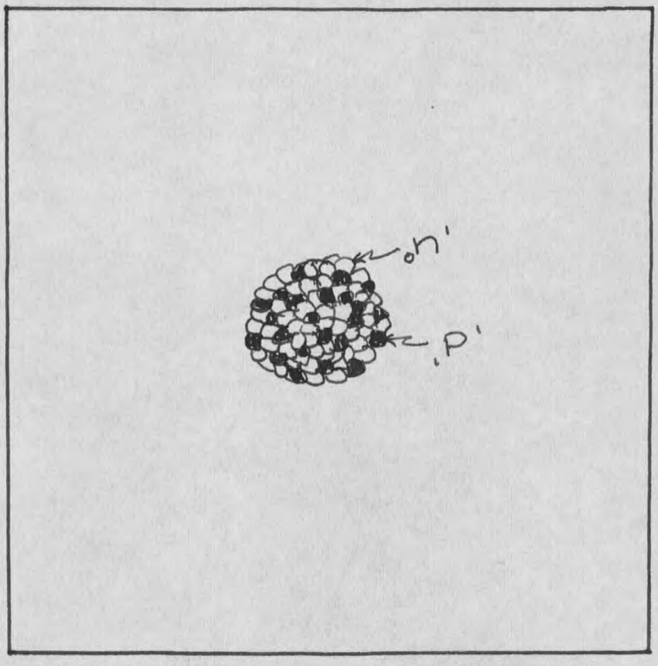

Figure 4 A Typical Heavy Atom (U)
showing the Protons and Neutrons

The presentation is only complete enough for a Mechanical Engineer's first study in nuclear power and not intended for a study in nuclear physics. Before going further I believe several definitions and tables should be presented.

TABLE I

Particle	Symbol	Weight (amu)	Change in Stat-Coulombs
Electron	$_{-}e^{0}$	.00055	-4.803×10^{-10}
Proton	$_{1}H^{1}$	1.00758	$+4.803 \times 10^{-10}$
Neutron	$_{0}n^{1}$	1.00893	0
Deuteron	$_{1}H^{2}$	2.01418	$+4.803 \times 10^{-10}$
Alpha	$_{2}He^{4}$	4.00276	$+9.606 \times 10^{-10}$
Neutrino		0	0
Positron	$_{+}e^{0}$	.00055	$+4.803 \times 10^{-10}$
Meson		Approx. .1 & .16	$\pm 4.803 \times 10^{-10}$

BASIC DEFINITIONS

Alpha rays - A stream of alpha particles.

Alpha particle - the nucleus of the helium atom ($_{2}He^{4}$).

Atom Smashers - devices used to accelerate charged particles to a sufficient energy for nuclear reactions.

Artificial radioactivity - radioactive nuclei produced by means of bombarding stable nuclei with various particles.

Barn - a unit used in measuring cross-section and equal to 10^{-24} cm ^{2}/ nucleus.

Beta particles - negatively charged high speed electrons.

Beta rays - a stream of beta particles.

Binding Energy - the amount of energy required to break a nucleus into the fundamental particles (neutrons and protons).

Compound Nucleus - a nucleus believed to exist instantaneously during nuclear reactions.

Critical Size - the size for which the production of free neutrons by fission is just equal to their loss by escape and non-fission capture.

Cross-Section - the probability that an incident particle will cause a nuclear reaction with a nucleus.

Deuteron - a positively charged particle comprised of one proton and one neutron, being the nucleus of the rare isotope of hydrogen ($_1H^2$), the isotope that combines with oxygen to produce heavy water, mass of 2.01418 amu.

Electrometer - an instrument for measuring an electric current.

Enriched Piles - the use of partially separated uranium, i.e., the U^{235} isotope in greater abundance than that of uranium as it occurs in nature.

Factor-K - the ratio of the number reoccurring fission neutrons to the number of incident neutrons.

Fission - the process whereby a nucleus, generally a very heavy nucleus, splits into two lighter nuclei. The reaction differs from radioactivity in the fact that there are two product nuclei and not just one product nuclei and a particle.

Flux - neutron density, number of fissions occurring per second per unit volume.

Gamma rays - electromagnetic radiations, similar to X-rays.

Half-life - the time required for a radioactive substance to decrease its mass by one half.

Ionization - the process whereby an atom, which generally of neutral charge, becomes charged because of the loss of one or more of its planetary electrons. Ionization may be caused by light, X-rays or any charged particle and the ionized atom becomes an ion.

Isobars - atoms of the same mass number (A) but of different atomic numbers, these are atoms of different elements, but have the same number of nucleons.

Isomers - nuclei which are identical in mass numbers and in atomic number but have different radioactive properties.

Isotope - atoms of different weights (mass numbers, A), but of the same atomic number (Z). Different isotopes of the same atom cannot be differentiated by chemical means because they have identical chemical behavior, the only difference being their masses.

K-election capture- this process occurs in place of the emission of a positron during the radioactive decay of a nucleus. Actually the nucleus will capture an electron from the K shell, thus forming a product nucleus of an atom in the excited state, it will then return to the normal state by the emission of X-rays.

Meson - a particle with either positive or negative charge found in cosmic rays and having a mass of approximately 200 times that of the electron.

Neutrino- still a theoretical prediction, not proven experimentally as yet, though there is experimental evidence for belief in their existence (the physicists cannot account for a very small amount of energy or mass during several nuclear reactions and the neutrino is a means of balancing their equations).

Neutrons- nucleons with zero charge having a mass of 1.00893 amu.

Nucleons- the particles comprising the nucleus, protons and neutrons, generally referred as the total number of particles in the nucleus.

Positron- a charged particle with electron mass and charge except the charge is positive.

Proton - positively charged nucleon having a mass of 1.00758 amu, is also the nucleus of the hydrogen atom ($_1H^1$).

Radioactivity- occurs naturally in unstable atoms which emit alpha, beta (and), or gamma rays, thereby changing to some other element. (The change depends on the type of emission.

Resonance Energy- the energy of a bombarding particle for which a nucleus is exceptionally reactive. For instance the resonance energy for the absorbtion of a neutron by U^{238} is 38 ev.

Spectrograph- the mass spectrograph is a precision instrument used in measuring the masses of isotopes.

Thermal Neutrons- neutrons of very low energy.

Transmutation- the changing of one nucleus to the nucleus of another. Generally pertaining to nuclear reactions.

Transuranic- elements of atomic number greater than 92, for instance plutonium and neptunium.

Wilson Cloud Chamber - an instrument used in visibly showing the paths of charged particles.

ENERGY UNITS

The energy of an electron traveling at a velocity of (3×10^{8} cm/sec) would be

$$E = \frac{1}{2} mv^2.$$

$$E = (\tfrac{1}{2}) (9.1066 \times 10^{-28}) (3 \times 10^{8})^2$$

$$= 40.9 \times 10^{-12} \text{ ergs}$$

$$= (40.9 \times 10^{-12}) (2.78 \times 10^{-14})$$

$$= 1.138 \times 10^{-24} \text{ Kw-hrs.}$$

$$= (1.138 \times 10^{-24}) (3413)$$

$$= 3.885 \times 10^{-21} \text{ BTU}$$

The basic study will be with very light particles, and as shown above our conventional units (Kw-hrs, BTU) are too large for this study. Therefore, we must use energy units that are very small. The electron volt can be used to advantage in cases of this nature. One electron volt is the energy of one electron as it passes through a potential difference of one volt. With relation to Kw-hrs there are 2.25×10^{25} electron volts in one Kw-hr.

$$E = (1.138 \times 10^{-24}) (2.25 \times 10^{-25})$$

$$= 25.6 \text{ ev.}$$

The proton whose mass is 1840 times as great as the electron the energy units used will be Mev (Million electron volts).

The following conversion table will prove useful for energy units.

TABLE II

MULTIPLY	BY	TO OBTAIN
Mev	1.07×10^{-3}	amu
	1.60×10^{-6}	ergs
	3183×10^{-14}	Gm. Cal.
	4.45×10^{-20}	Kw-hrs.
	1.52×10^{-16}	BTU
Amu	9.31×10^{2}	Mev
	1.49×10^{-3}	ergs
	3.56×10^{-11}	Gm. Cal.
	4.15×10^{-17}	Kw-hrs.
	1.417×10^{-13}	BTU
Ergs	6.71×10^{2}	amu
	6.24×10^{5}	Mev
	2.39×10^{-8}	Gm. Cal.
	2.78×10^{-14}	Kw-hrs.
	9.49×10^{-11}	BTU

MULTIPLY	BY	TO OBTAIN
Gm. Cal.	2.81×10^{10}	amu
	2.62×10^{13}	Mev
	4.18×10^{7}	ergs
	1.16×10^{-6}	Kw-hrs.
	3.96×10^{-3}	BTU
Kw-hrs.	2.41×10^{16}	amu
	2.25×10^{19}	Mev
	3.60×10^{13}	ergs
	8.60×10^{5}	Gm. Cal.
	3.413×10^{3}	BTU
BTU	7.06×10^{12}	amu
	6.62×10^{15}	Mev
	1.054×10^{10}	ergs
	2.53×10^{2}	Gm. Cal.
	2.93×10^{-4}	Kw-hrs.

Table II shows only the conversion of energy units. For units of electric charge mass, etc. refer to Tables III and IV.

TABLE III

MULTIPLY	BY	TO OBTAIN
Statcoulombs (esu)	$1/3 \times 10^{-10}$	Abcoulombs (emu)
Statcoulombs (esu)	$1/3 \times 10^{-9}$	Coulombs
Coulombs	3×10^{9}	Statcoulombs (esu)
Coulombs	0.1	Abcoulombs (emu)
Volts	1/300	Statvolts (esu)
Volts	10^{8}	Abvolts (emu)
Statvolts (esu)	300	Volts
Statvolts (esu)	3×10^{10}	Abvolts (emu)
Abvolts (emu)	10^{-8}	Volts
Abampere (emu)	10	Amperes
Ampere	0.1	Abampere
Statvolts/cm	1	Dynes/esu (field)
Volts/cm	300	Dynes/esu
Electron-volts	1.074×10^{-9}	Amu (Phys.)

TABLE IV

Electron charge	$= 4.803 \times 10^{-10}$ statcoulombs
	$= 1.602 \times 10^{-19}$ coulombs
	$= 1.602 \times 10^{-20}$ abcoulombs
Electron, charge/mass	$= 1.7592 \times 10^{7}$ abs emu/gm.

Electron, rest mass.	$= 9.1066 \times 10^{-28}$ gm.
	$= 5.4862 \times 10^{-4}$ amu (phys.)
	$= 5.4847 \times 10^{-4}$ amu (chem.)
Electron volts	$= 10^{-6}$ Mev
	$= 1.161 \times 10^{-6}$ deg. (ags)
	$= 1.768 \times 10^{4}$ gm.
	$= 1.768 \times 10^{-33}$ gm.
Amu	$= 1.65993 \times 10^{-24}$ gm.
Velocity of light	$= 2.99776 \times 10^{10}$ cm/sec.

After examination of Tables II and IV it is interesting to note that there are conversion factors for converting mass units to energy units, and vice versa, this is the basis of the energy from nuclear reactions. The name, Atomic Power, has been misused because actually the energy comes from the nucleus and not the atom, this test will refer to it as a nuclear power. This first came about when non-technical men wrote the original publicity directly after the first bomb was dropped on Japan.

As Mechanical Engineers, we are interested in the power available from the nucleus, how it may be obtained, and in what form it exists. Therefore, this text will eliminate the complicated nuclear physics behind this new type of power and only touche the more important issues. This text's primary purpose is to present basic material for Mechanical Engineers so they will be able to discuss intelligently and have a working knowledge of nuclear power. The following material is presented at a level for seniors or graduate students in Mechanical Engineering and reviews their background in nuclear physics and features some of the uses of nuclear energy as directly related to Mechanical Engineering problems. For a more detailed discussion on the subject of nuclear physics there are numerous texts, but they are beyond the scope of our study and are intended for a student majoring in physics. As Mechanical Engineers we are interested primarily in using this energy for our power plants, steam generation, heating and gas turbines.

RADIOACTIVITY

In 1895 William Roentgen, a German physicist, discovered some new invisible rays with very deep penetrating properties which he called X-rays. This discovery came about while using a Crookes tube, the rays emitted passed through a variety of things, including his own flesh. For when he placed his hand in the path of these rays a clear outline of the bones of his hand could be seen on a fluorescent screen. A series of experiments showed these rays easily passed through substances of low density but were stopped by very dense

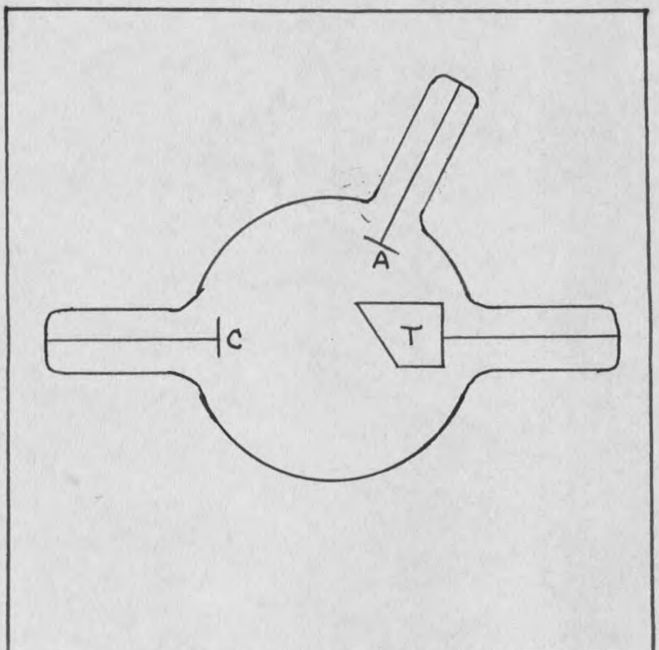

Figure 5 Typical X-ray tube showing position of Anode, Cathode and Target in Vacuum Tube

elements such as lead. The use of photographic plates also played a prominent part in the detection of X-rays. Figure 5 shows a schematic sketch of a typical X-ray tube. X-rays are produced, in this tube, by the bombardment of the target (T) by high speed electrons. A difference in potential (V) between the cathode (C) and the anode (A) cause the electrons emitted from the heated cathode to have an energy in ergs of

$$E = Ve \qquad (2)$$

E will be in ergs if V is in statvolts (esu) and e the charge on one electron in statcoulombs (esu, 4.803×10^{-10}), see Tables I, III, and IV. The X-rays produced by these high speed electrons bombarding the target will have a frequency as calculated by the equation:

$$E = h\nu \qquad (3)$$

E again being in ergs, h Planck constant (6.624×10^{-27} erg-sec.) and ν the frequency of the produced X-rays in cycles per second. The wave length of these waves may be calculated from the equation:

$$\lambda = \frac{C}{\nu} \qquad (4)$$

λ being the wave length in cm, C the velocity of light in cm/sec., and ν the frequency in cycles per second. Under certain conditions it may be necessary to calculate the velocity of the initial electrons by means of the equation:

$$E = \tfrac{1}{2}mv^2 \qquad (5)$$

E again in ergs, m mass in grams, and v in cm/sec. Combining equations (2) and (5):

$$Ve = \tfrac{1}{2}mv^2$$

$$\text{or} \quad v^2 = \frac{2Ve}{m}$$

$$v = \sqrt{\frac{2Ve}{m}}$$

As the velocity (v) of the electrons approaches the speed of light (see Table IV), the law of relativity, as derived by Einstein must be taken into consideration to determine the mass of the electron at its high speed. The equation for changing rest mass, taking into consideration the inertia at velocity v is:

$$m = \frac{m_o}{\sqrt{1 - \frac{v^2}{C^2}}} \qquad (6)$$

where m_o is the rest mass in grams, v the velocity of the particle in cm/sec., C the velocity of light in cm/sec., m being the corrected mass. For a more detailed discussion of the elementary physics equations consult and study any College Physics text.

Example No. 1. An X-ray tube has a difference in potential of 300 volts between the cathode and anode. Find the energy of the electrons in ergs, the electrons velocity and the frequency of the X-rays.

$$V = \frac{300 \text{ Volts}}{300 \text{ Volts/Stat-Volts}} = 1 \text{ Statvolt}$$

From equation (2)

$$E = Ve = (1)(4.803 \times 10^{-10})$$

$$= 4.803 \times 10^{-10} \text{ ergs.}$$

From equation (5)

$$E = \tfrac{1}{2}mv^2$$

$$v^2 = \frac{2E}{m} = \frac{(2)(4.803 \times 10^{-10})}{(9.1066 \times 10^{-28})}$$

$$v = 1.023 \times 10^9 \text{ cm/sec.}$$

but we did not insert the relativity correction for the mass.

Equation (6)

$$m = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{9.1066 \times 10^{-28}}{\sqrt{1 - \frac{(1.023 \times 10^9)^2}{(3 \times 10^{10})^2}}}$$

$$= \frac{9.1066 \times 10^{-28}}{\sqrt{1 - .00116}} = \frac{9.1066 \times 10^{-28}}{.9998}$$

$$= 9.10662 \times 10^{-28} \text{ gms.}$$

The difference in this case is negligible. For future work we may say that the relativity correction need not be inserted unless the velocity of the particle is greater than 10% of the velocity of light.

From equation (3)

$$E = h\nu$$

$$\nu = \frac{E}{h} = \frac{4.803 \times 10^{-10}}{6.624 \times 10^{-27}}$$

$$= 7.255 \times 10^{16} \text{ cycles/sec.}$$

we may further calculate the wave length of these rays.

From Equation (4)

$$\lambda = \frac{c}{\nu} \quad \frac{3 \times 10^{10}}{7.255 \times 10^{16}}$$

$$= .413 \times 10^{-6}$$

$$= 41.3 \text{ Å}$$

where one Ångstrom unit (Å) = 10^{-8} cm.

RADIOACTIVITY. Within a year after Roetgen's discovery of X-rays, the French scientist, Antione Henri Becquerel, while examining various substances for possible fluorescent and phosphorescent effects, found uranium, its various minerals, and compounds emitted invisible radiation capable of affecting photographic plates and ionization of the air. Becquerel then found that several of the other heavier elements have this same behavior and no matter what he did to these substances he could not change this property which he then called radioactivity. He tried compounding uranium with various elements and even running experiments with powered uranium which lead him to believe that this property (radioactivity) must come from the atoms of uranium. Shortly after this time Sir Ernest Rutherford, a British physicist, carried on experiments to determine the penetrating properties of these invisible rays and found them to be of two types. One type was easily stopped by a thin aluminum foil which Rutherford called alpha rays and the other was stopped by aluminum sheet which he called beta rays. Later he found a third type of radiation which had very deep penetrating properties and reacted similarly to Roentgen's X-rays but were finally called gamma rays.

Rutherford used an electrical method to study these radiations based upon the ionization produced by the radiation in its passage through a gas (his later work, of a similar type, caused one of the first nuclear reactions). Professor Pierre Curie and his wife Mme. Curie using a similar method showed that the amount of activity of any uranium compound varied directly with the amount of uranium in the compound, thus showing that this activity must come from the atoms themselves.

The Curies then carried on a series of experiments with all available chemical materials to obtain further evidence of the existence of radioactivity in other substances. In 1898, G. C. Schmidt as well as Mme. Curie found the element Thorium to exhibit radioactive properties both emitting the alpha rays. While experimenting with various uranium-bearing ores and minerals, the Curies found these unrefined uranium minerals exhibited greater radioactivity than the refined uranium metal they had produced in their laboratory. This lead to the belief that there must be another radioactive element present in these minerals that has greater activity than pure uranium. After careful study the Curies were able to separate this new radioactive element with bismuth. Its properties were similar to bismuth except for radioactivity. Mme. Curie then named this element after her native home Poland, which she called Polonium in 1898. The Curies with several colaborators discovered and named radium. Work was also done to determine the atomic weight of radium which was found to be 226. In 1899, Debierne discovered another radioactive element which he called actinium. Several scientists were working in all parts of the world on these newly discovered radioactive elements as to their atomic weights, chemical and physical properties. It is interesting to note that every new element had already been determined by Mendelieff's periodic table in approximately 1865. Mendelieff's periodic table had the elements arranged in periods, starting with the lightest element, hydrogen, and that at certain regular intervals elements would appear with similar properties (bismuth and polonium; radium and barium). All of these new elements fell in an open space in this periodic table. Today's Periodic

Chart of the atoms, as designed by Henry D. Hubbard (National Bureau of Standards), shows how all the known elements fall into periods.

By 1903, Rutherford and Soddy in England had studied the emanations from radioactive materials and had formed a theory of radioactive disintegration. As previously mentioned, the invisible rays emitted by radioactive materials were shown to be of three types and named alpha, beta and gamma. Rutherford found these three types by their penetrating powers and was further established by means of letting these radiations pass through an electromagnetic field, Figure 6. This proved that the alpha rays were of a positive charge, that the beta rays had a negative charge and the gamma rays were of a neutral charge. Upon further study, Rutherford and Soddy found that when a radioactive atom emits an alpha particle, its mass decreases by four times the weight of a hydrogen atom and its positive charge decreases by two, thus forming a new element of two less atomic numbers. This also lead to the fact that alpha rays consisted of a series of alpha particles and that an alpha particle is actually thenucleus of the helium atom (two protons

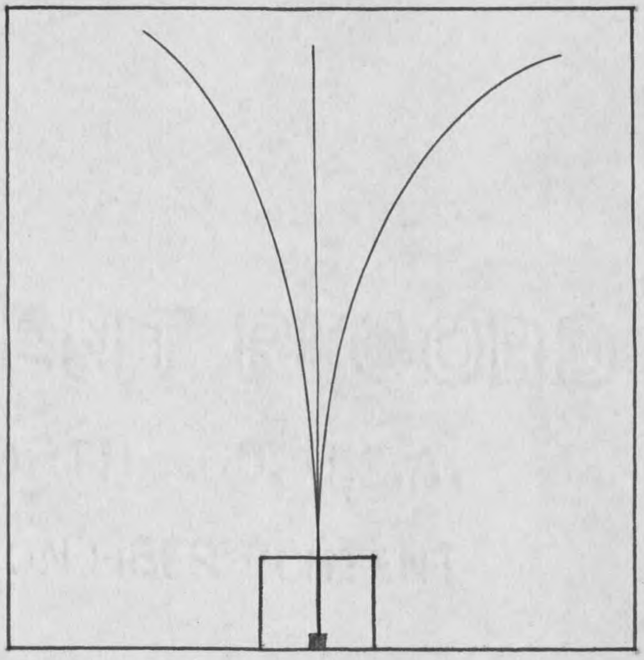

Figure 6 Paths of Alpha, Beta and Gamma Rays in an Electromagnetic Field

and two neutrons). However, when a beta particle was emitted from a radioactive atom, its mass is practically unchanged but the positive charge in the nucleus is increased by one. This fact and that bets rays were negative helped prove that these rays consisted of very small particles (beta particles) which were essentially electrons. Figure 7 shows graphically the changes that take place during radioactivity. Gamma rays as they occur during radioactivity are found only in connection with beta rays and are never found alone. For this reason we will call radioactive materials either alpha of beta emitters except for several cases that may emit both (these will be discussed later).

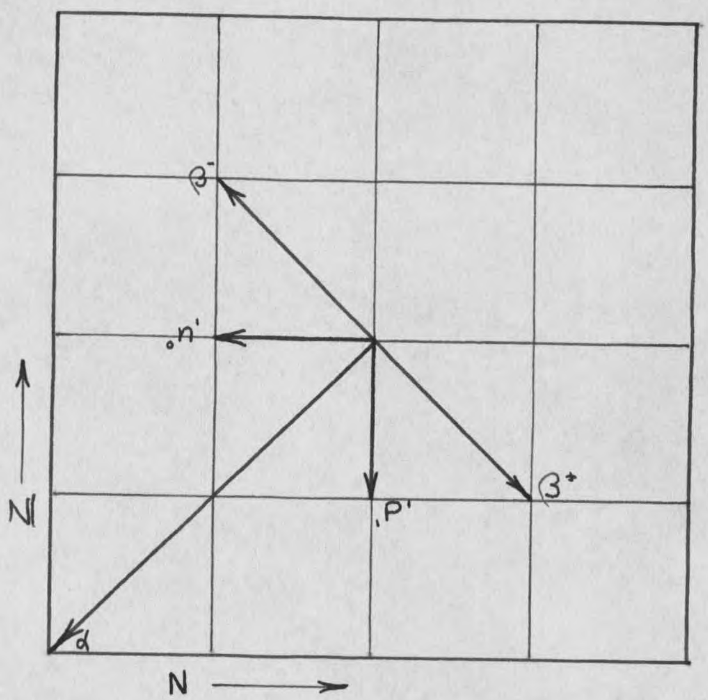

Figure 7 Radioactive Emissions

Rutherford and Soddy also found several radioactive series to exist in nature, i.e., uranium emits an alpha particle and becomes thorium, which is also radioactive, etc., until a stable atom is formed. There are four series as shown in Figures 9, 10, 11, and 12. Figure 13 shows the uranium-radium series graphed.

The Neptunium Series (Figure 12) is one that existed in nature but its members had short enough half-lives that they long since have disappeared during the two-billion year history of the earth. This series is called the Neptunium Series because this element is the longest-lived of the Series.

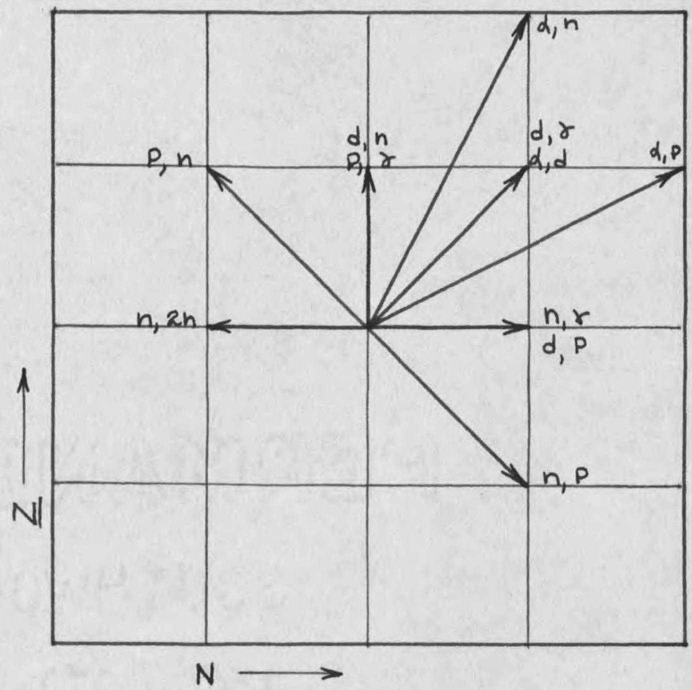

Figure 8 Nuclear Reactions

It is now known that various elements emit alpha or beta particles. The Curies found Polonium to be more active than uranium, this also holds true for all other radioactive elements each one having its own rate of emitting alpha or beta particles. The rate of emission is generally in terms of half-life of the material, the half-life being the time required for half the number of atoms to change by emitting alpha or beta particles. The number of particles emitted per unit time is inversely proportional to the half-life. Taking one gram of a radioactive element the emissions may be counted and the half-life determined, but if we were to separate one atom from this original gram the time elapsed before emission could not be predetermined because this emission is haphazard and the exact time when each atom is going to change

URANIUM-RADIUM SERIES

ELEMENT	MASS Number	ATOMIC Number	RADIATION	HALF-LIFE
Uranium (Uranium I)........	238	92	a	4.55×10^{9} yrs
Thorium (Uranium X_1).......	234	90	β^-	24.1 days
Protactinium (Uranium X_2)..	234	91	β^-	1.14 minutes
Protactinium (Uranium Z) ..	234	91	β^-	6.7 hours
Uranium (Uranium II).......	234	92	a	2.3×10^{5} yrs
Thorium (Ionium)...........	230	90	a	8.225×10^{4} yrs
Radium.....................	226	88	a	1590 years
Radon......................	222	86	a	3.825 days
Polonium (Radium A)........	218	84	a	3.05 minutes
Lead (Radium B)............	214	82	β^-	26.8 minutes
Bismuth (Radium C).........	214	83	a, β^-	19.72 minutes
Polonium (Radium C").......	214	84	a	1.5×10^{-4} sec.
Thallium (Radium C").......	210	81	β^-	1.32 minutes
Lead (Radium D)............	210	82	β^-	22.2 years
Bismuth (Radium E).........	210	83	β^-	4.97 days
Polonium (Radium F)........	210	84	a	139.5 days
Lead (Radium G)............	206	82	Stable	

Figure 9

(Courtesy of Westinghouse Electric Corp.)

THORIUM SERIES

ELEMENT	MASS Number	ATOMIC Number	RADIATION	HALF-LIFE
Thorium	232	90	a	1.389 x 10^{10} years (longest)
Radium (Mesothorium I).....	228	88	β^-	6.7 years
Actinium (Mesothorium 2)..	228	89	β^-	6.13 hours
Thorium (Radiothorium)....	228	90	a	1.90 years
Radium (Thorium X)........	224	88	a	3.64 days
Radon (Thoron)............	220	86	a	54.50 seconds
Polonium (Thorium A)......	216	84	a	0.145 seconds
Lead (Thorium B)..........	212	82	β^-	10.6 hours
Bismuth (Thorium C).......	212	83	a, β^-	60.6 minutes
Polonium (Thorium C").....	212	84	a	3 x 10^{-7} sec. (shortest)
Thallium (Thorium C")....	208	81	β^-	311 minutes
Lead (Thorium D)..........	208	82	Stable	

Figure 10

Note: The traditional names for the disintegration products are given in parentheses. These names were assigned before the products were adequately identified, and they do not, in general, correctly name the element of which the disintegration product is an isotope.

(Courtesy of Westinghouse Electric Corporation)

ACTINIUM SERIES

ELEMENT	MASS Number	ATOMIC Number	RADIATION	HALF-LIFE
Uranium (Actinium U)......	235	92	a	7.13×10^{8} yrs
Thorium (Uranium Y).......	231	90	β^-	24.64 hours
Protactinium	231	91	a	3.2×10^{4} yrs
Actinium	227	89	a, β^-	13.4 yrs
Thorium (Radioactinium)...	227	90	a	18.9 days
Francium (Actinium K).....	223	87	β^-	21 minutes
Radium (Actinium X).......	223	88	a	11.2 days
Radon (Actinon)...........	219	86	a	3.92 seconds
Polonium (Actinium A).....	215	84	a	2.1×10^{-3} sec.
Lead (Actinium B).........	211	82	β^-	36.0 minutes
Bismuth (Actinium C)......	211	83	a, β^-	2.16 minutes
Polonium (Actinium C").....	211	84	a	2×10^{-3} sec.
Thallium (Actinium C").....	207	81	β^-	4.71 minutes
Lead (Actinium D).........	207	82	Stable	

Figure 11

Note: The traditional names for the disintegration products are given in parentheses. These names were assigned before the products were adequately identified, and they do not, in general, correctly name the element of which the disintegration product is an isotope.

(Courtesy of Westinghouse Electric Corporation).

NEPTUNIUM SERIES

ELEMENT	MASS Number	ATOMIC Number	RADIATION	HALF-LIFE
Plutonium	241	94	β^-	Relatively long
Americium	241	95	a	500 years
Neptunium	237	93	a	2.25×10^6 years
Protactinium........	233	91	β^-	27.4 days
Uranium.............	233	92	a	1.63×10^5 years
Thorium.............	229	90	a	7×10^3 years
Radium..............	225	88	β^-	14.8 days
Actinium............	225	89	a	10 days
Francium............	221	87	a	4.8 minutes
Astatine............	217	85	a	1.8×10^{-2} second
Bismuth.............	213	83	a, β^-	47 minutes
Polonium............	213	84	a	4.4×10^{-6} second
Thallium............	209	81	β^-	1 hour
Lead................	209	82	β^-	3.3 hours
Bismuth.............	209	83	Stable	

Figure 12

Named the Neptunium Series because of the long half-life of Neptunium. The other elements in the series include the new "man-made" elements americium (No. 95) and uranium-233, as well as the recently identified elements, astatine (No. 85) and the francium (No. 87). The series differs from the three found in nature in having an end product other than lead. The final stable product of the neptunium series is bismuth-209.

(Courtesy of Westinghouse Electric Corporation)

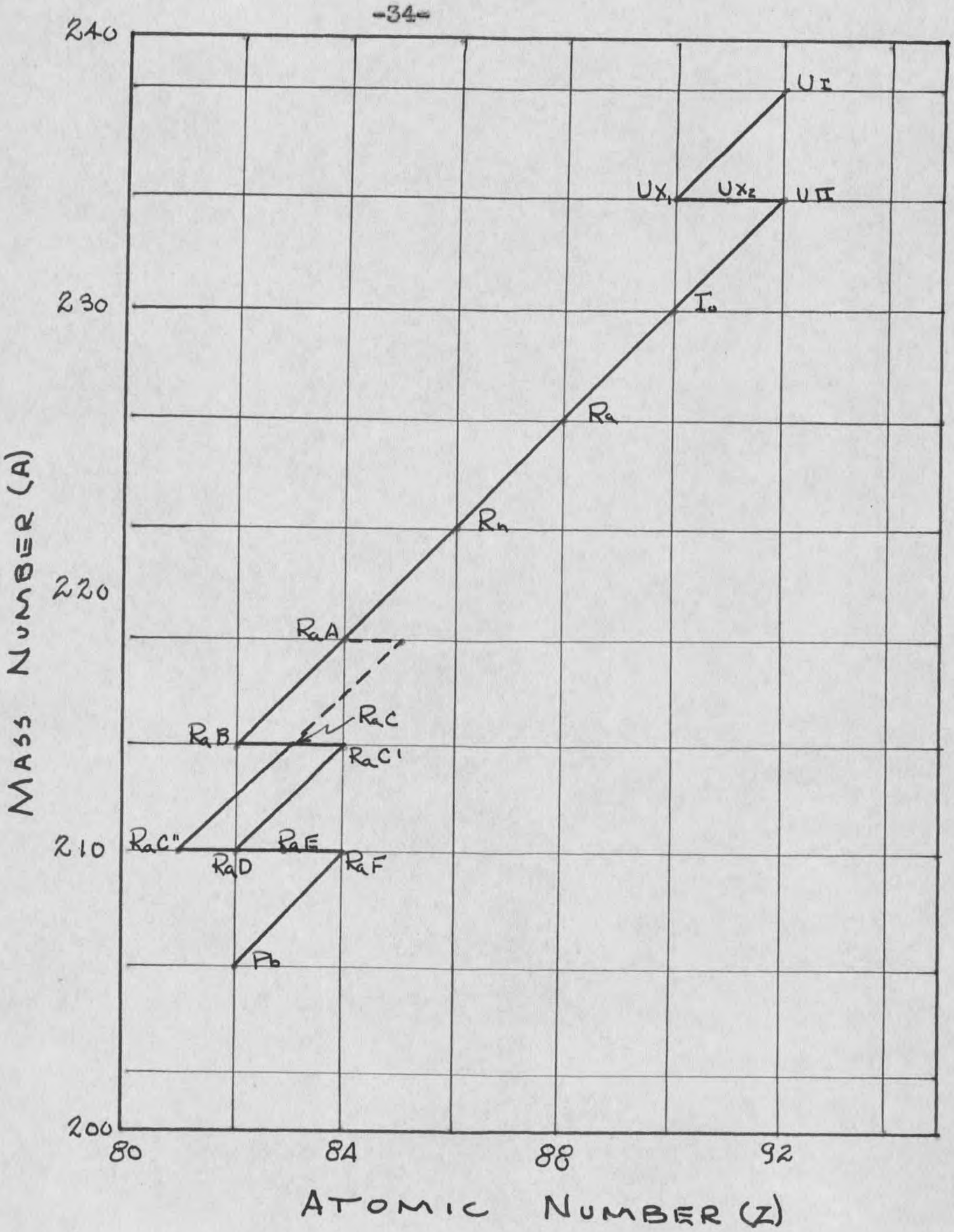

Figure 13 Uranium Series, plotting Mass Number against Atomic Number

is somewhat of a quantum secret. Also the rate of radioactive disintegration is independent of all physical and chemical conditions. Take a sufficient number of radioactive atoms of any one element and during a small interval of time, dt, there will be a certain number of atoms disintegrating, dN; if the number of atoms present at time t and δ is the disintegration factor, which varies with each radioactive element. The following relation exists:

$$-dN = \delta N dt \qquad (7)$$

Separating Variables

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

Integrating

$$\text{Log } N = -\delta t + \text{Log } c \qquad (7a)$$

C being the constant of integration, to evaluate, when t = 0, $N_i = C$, where N_i is the initial number of atoms:

$$\text{Log } N = -\delta t = \text{Log } N_i \qquad (7b)$$

$$N = N_i e^{-\delta t} \qquad (8)$$

Equation (8) shows that the number of atoms present at any time t disintegrates exponentially. The number of atoms present is a direct relation of the mass of the atoms therefore equation (8) may also be written:

$$M = M_i e^{-\delta t} \qquad (8a)$$

where M is the mass remaining after time t and M_i the initial mass when t = 0. Taking equation (7b) and substituting $\frac{N_i}{2}$ for N and T for t, the capital (T) must be the time required for one-half of the initial number of atoms to disintegrate, therefore being the half-life:

$$\mathrm{Log}\ \frac{N_i}{2} = -\delta T + \mathrm{Log}\ N_i$$

$$T = \mathrm{Log}\ 2 = 0.693$$

$$T = \frac{0.693}{\delta} \qquad (9)$$

Under certain conditions the average lifetime of a radioactive atom may be desired which will be denoted by T_a and found by integrating the product tdN over the limits of from o to N_i and dividing by N_i.

$$T_a = \frac{\int_o^{N_i} t\,dN}{N_i}$$

from equation (8) by differentiating:

$$dN = -N_i\ \delta e^{-\delta t}\ dt$$

combining the two above equations (from page 35):

$$T_a = \frac{-N_i \int_\infty^o t\,\delta e^{-\delta t}\ dt}{N_i} = \int_o^\infty t\,\delta e^{-\delta t}\ dt$$

by means of integration by parts:

$$T_a = \delta\left[\frac{-te^{-t\delta}}{\delta} + \frac{e^{-\delta t}}{\ }\ dt\right]_o^\infty$$

$$= \delta\left[\frac{-te^{-t\delta}}{\delta} - \frac{e^{-t\delta}}{\delta^2}\right]_o^\infty$$

$$= \delta\left(\frac{1}{\delta^2}\right)$$

$$= \frac{1}{\delta} \qquad (10)$$

Taking equations (9) and (10) and equating the half-life may be put in terms of the average life:

$$T = 0.693\ T_a \qquad (11)$$

Figure 14 shows equation (8) plotted with N as the ordinate, also showing the points of half-life and average life. One method in determining the half-life of radioactive elements is by means of counting the number of emissions per unit time and then graphing this activity against time. The slope of the curve will be δ, and using equation (9) the half-life may be readily calculated. The counting of emissions may be achieved by means of a Geiger Counter which will be discussed in detail later.

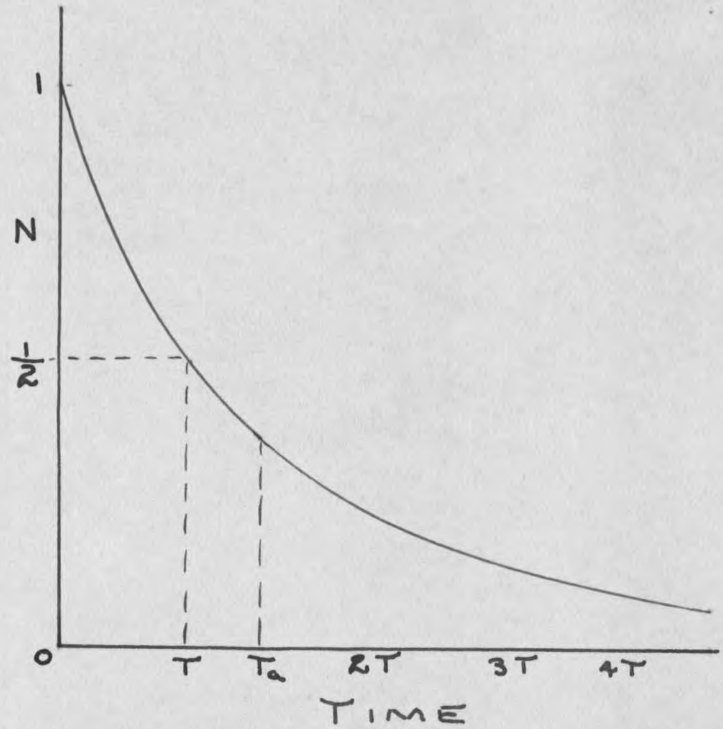

Figure 14 Equation (8), plotting N against Time showing the points of Half-life and T_a

Example No. 2. A radioactive element emitting beta particles was placed within range of a Geiger Counter. Emissions were counted at intervals of one minute and the following counts were tabulated after making corrections for background readings: 626, 508, 416, 354, 290, 240, 198, 164, 133, 111, 90, 76, 63, 52, 43, Calculate the disintegration constant and the half-life.

Using equation (7b)

$$\text{Log } N = -\delta t + \text{Log } N_1 \qquad (7b)$$

May be written:

$$\text{Log } N = -\delta t$$

Because we are only interested in calculating δ, which is the slope of an activity (log N) time curve, the term Log N_1 will only shift this curve and not effect its slope.

Figure 15 shows the curve of Log N plotted against time. The slope of this curve will be calculated by:

$$\text{Slope} = \delta = \frac{\Delta \text{Log } N}{\Delta T}$$

$$= \frac{5.87 - 4.14}{13 - 4} = \frac{1.73}{9} \quad \text{(Values taken from graph)}$$

$$= .192$$

For half-life:

$$T = \frac{.693}{\delta} \qquad (9)$$

$$= \frac{.693}{.192}$$

$$T = 3.61 \text{ minutes}$$

ISOTOPES:

Figures 9, 10, and 11 showing tables of the Uranium-Radium, Thorium, and Actinium series have one thing in common and that being that they end with stable lead. The Atomic weight of lead had already been established as 207.21 amu but the lead found in connection with the Uranium-Radium series had an atomic weight of approximately 206. At first there seemed to be some experimental error but trial after trial proved the same result. The atomic weight of the lead from the Thorium series was found to

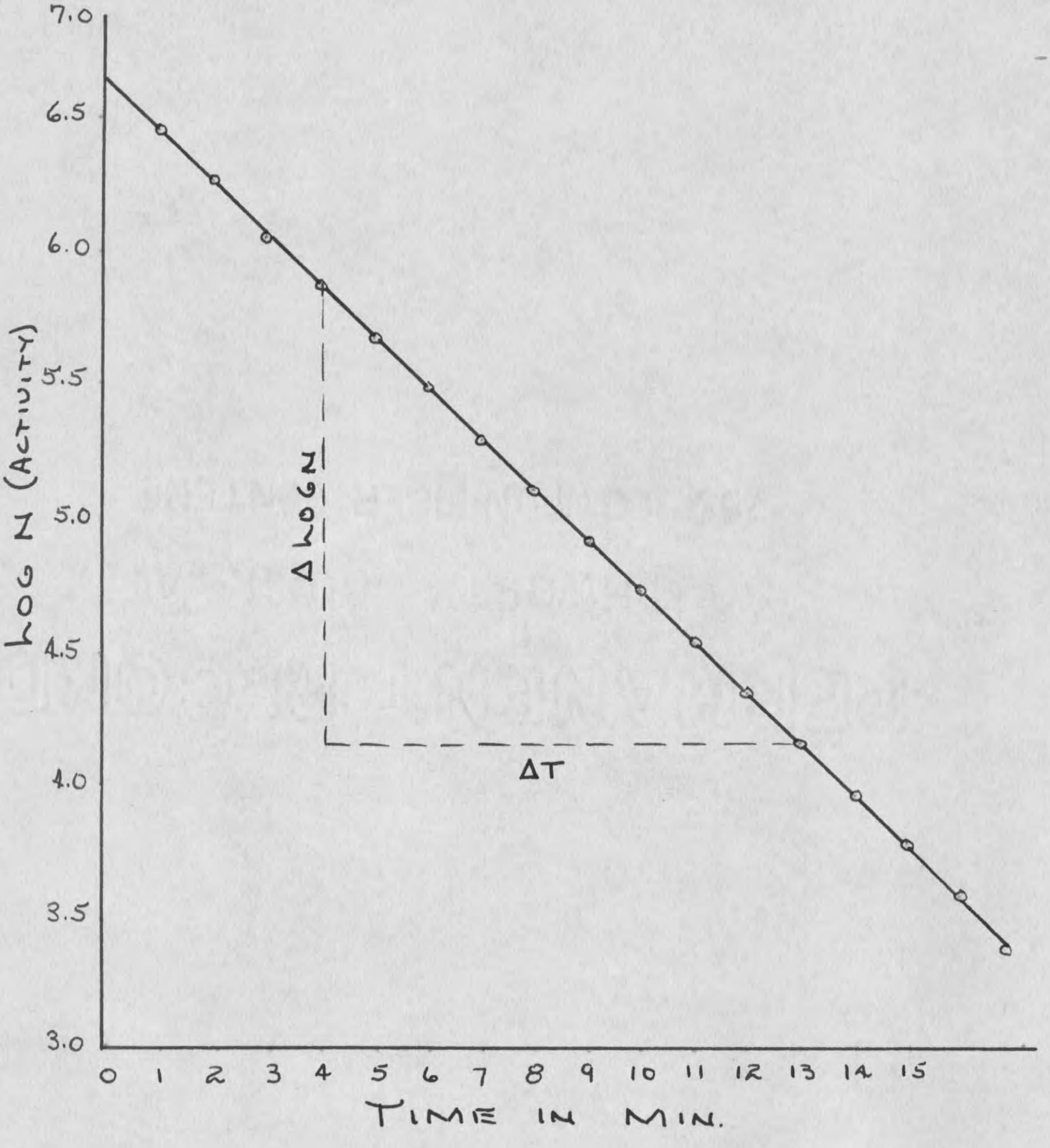

Figure 15 Graph for Example No. 2

be approximately 208, and the lead from the Actinium series was found to be approximately 207. The lead from the Actinium series seemed to be the only one that agreed with the already established atomic weight of lead.

Further experiments and study showed that normal lead was comprised of three different atoms, their chemical properties being identical, the only difference being their mass. This mass difference is taken advantage of when separating these different atoms. The different atoms of one element were named isotopes and much later a fourth isotope of lead was discovered having an atomic mass number of 204.

It has now been shown most known elements have at least two isotopes. Lead has four with the following percentages:

204	1.5%
206	23.6%
207	22.6%
208	52.3%

Lead has an atomic number (Z) of 82, meaning its nucleus has 82 protons with 82 planetary electrons, and 204 minus 82 or 122 neutrons for the lightest isotope of lead and 124, 125 and 126 neutrons for the other three isotopes. This difference in the number of neutrons accounts for the difference in the masses of isotopes of one element, while the same atomic number of the isotopes of any one element accounts for the identical chemical properties. Isotopes of the various elements will be denoted by ${}_{82}Pb^{206}$ where Pb is the symbol for the element, the number at the lower left is the atomic (Z) and the number at the upper right is the mass number (A).

ISOMERS:

From Figures 9 and 13 in the Uranium-Radium Series, there is a single line of disintegration until Bismuth (Radium C) is reached. At this point the radiation may be either Alpha or Beta particles. In the case of Alpha emission, Thallium (Radium C") is formed while when beta emission occurs, Polonium (Radium C) is formed. However, the distribution of the emission from Bismuth (Radium C) is only 0.04% Alpha particles and 99.96% Beta particles. When dual emissions occur from one isotope, they are known as isomers.

SECULAR EQUILIBRIUM:

Again in the Uranium-Radium Series, uranium ($_{92}U^{238}$) emits an alpha particle with a long half-life of 4.55 x 10^9 years to form Thorium ($_{90}Th^{234}$) which has a short half-life of 24.1 days. In cases of this nature, the rate of emission from the uranium may be considered constant and the amount of thorium builds up to steady amount where the same amount of thorium disintegrates as is formed by the activity of the uranium. When this takes place the product is said to be in secular equilibrium and the following equations hold true:

Where δ_U, N_U - uranium

δ_T, N_T - thorium

$-dN_T$ - rate at which thorium disintegrates

dN_U - rate at which uranium disintegrates or which thorium accumulates

or

$$\frac{dN_T}{dt} = dN_U - dN_T$$

substituting equation (7)

$$-dN = \delta N dt \qquad (7)$$

$$\frac{dN_T}{dt} = \delta_U N_U - \delta_T N_T \qquad (12)$$

If secular equilibrium exists N_U is considered constant

$$\frac{dN_T}{\delta_U N_U - \delta_T N_T} = dt$$

Multiplying both sides by $-\delta_T$

$$\frac{-\delta_T \, dN_T}{\delta_U N_U - \delta_T N_T} = -\delta_T \, dt$$

Integrating

$$\text{Log} \, (\delta_U N_U - \delta_T N_T) = -\delta_T t + \text{Log} \, C$$

$$\delta_U N_U - \delta_T N_T = Ce^{-\delta_T t}$$

Solving for the constant of integration C

When $t = 0, \; N_T = 0$

or $\delta_U N_U - 0 = C \times 1$

$$C = \delta_U N_U$$

$$\delta_U N_U - \delta_T N_T = \delta_U N_U e^{-\delta_T t}$$

$$\delta_U N_U - \delta_U N_U e^{-\delta_T t} = \delta_T N_T$$

$$N_T = \frac{\delta_U}{\delta_T} N_U \left(1 - e^{-\delta_T t} \right) \qquad (13)$$

As t approaches infinity

$$e^{-\delta_T t} = 0$$

$$t \longrightarrow \infty$$

$$N_T = \frac{\delta_U}{\delta_T} N_U$$

Using the half-life equation (9)

$$T = \frac{0.693}{\delta} \qquad (9)$$

$$\frac{N_T}{N_U} = \frac{\delta_U}{\delta_T} = \frac{T_T}{T_U} \qquad (14)$$

Example No. 3. In the Uranium-Radium Series, ${}_{92}U^{238}$ disintegrates through a series of radioactive elements to ${}_{82}Pb^{206}$. Where a uranium ore is found, the ratio of the amount of lead present with respect to the amount of uranium is 100 grams to 1000 grams respectively.

Calculate the length of time the uranium has been in existence and the radium present per 1000 grams of uranium.

From table on Figure 9

Half-life of Uranium - 4.55×10^9 years

Half-life of Radium - 1590 years

$$N = N_i e^{-\delta t} \qquad (8)$$

$$\delta = \frac{.693}{T} = \frac{.693}{4.55 \times 10^9}$$

The initial number of atoms (N_i) of uranium must take into consideration the loss in mass of the particles emitted.

$$N_i = 1000 + 100\,\frac{238}{206} = 1115.6 \text{ grams}$$

$$N = 1000$$

$$e^{\delta t} = \frac{1115.6}{1000} = 1.1156$$

$$t = \frac{(\text{Log } 1.1156)(4.55 \times 10^9)}{(.693)}$$

$$= 7.17 \times 10^8 \text{ years}$$

The amount of radium present under conditions of secular equilibrium

$$\frac{T_r}{T_u} = \frac{M_r}{1000}$$

$$M_r = \frac{1590 \times 1000}{4.55 \times 10^9}$$

$$= 3.49 \times 10^{-3} \text{ grams}$$

Radioactive disintegration will be written in equilibrium form for the remaining portion of our study. Taking the disintegration of uranium into thorium by the emission of an alpha may be written:

$$_{92}U^{238} \longrightarrow {}_{90}Th^{234} + {}_{2}He^{4}$$

where $_2He^4$ is the nucleus of the helium isotope having the mass number four. Equations of this type will be written for the nuclei of the atoms neglecting the planetary electrons.

NUCLEAR REACTIONS AND ARTIFICIAL RADIOACTIVITY

In 1919 Sir Ernest Rutherford used the knowledge of Radioactivity to perform a series of experiments. His thoughts were to use these atomic "bullets" from radioactive substances and observe their reactions when bombarding other nuclei. But first he wanted to study the range of alpha particles in air so as to be able to deal with his other work more easily. One of the main reasons for this work was to be able to understand more about the atom as to its construction, which lead to our present day concept (as discussed previously).

Using a closed chamber for his work Rutherford found that while measuring the range of alpha particles in air there would be an amount of hydrogen present. This seemed very strange, so he then tried nitrogen in place of air and again hydrogen was found. No explanation could be given at that time and further experiments showed that when the air or nitrogen was replaced by several other gases such as oxygen, carbon dioxide or carbon monoxide no hydrogen was found. Therefore the hydrogen formed must have some relationship with the alpha particles and the nitrogen nuclei (or atoms). Later the Wilson Cloud Chamber showed this reaction to be the absorbtion of the alpha particles by the nitrogen nucleus with the formation of a proton and a much heavier particle. Remembering that the proton is the hydrogen nucleus ($_1H^1$). (The use of the Wilson Cloud Chamber will be discussed in detail later). The complete reaction may be written in equation form as follows:

$$_2He^4 + {_7N^{14}} \longrightarrow ({_9F^{18}}) \longrightarrow {_8O^{17}} + {_1H^1}$$

the flourine is known as the compound nucleus. There is not any proof of its existence but is believed to exist for a very short period of time. The $_7N^{14}$ and the $_8O^{17}$ are known as the reacting and product nuclei respectively. Nuclear reactions of this type are also written in a more concise method, for the same equation as above:

$$N^{14}\ (\alpha, p) O^{17}$$

In using this condensed method of writing a nuclear reaction, the subscripts may be omitted because the chemical symbol establishes the value of Z. The symbols inside the parentheses designate in order the incident and ejected particles, but they are not the chemical symbols used in the longer method. A proton is designated by the letter p instead of $_1H^1$. The other symbols used to represent the incident and ejected particles are:

n - neutron

d - deuteron

α - alpha particle

γ - gamma rays

This being the first time that nuclei of one element were converted into nuclei of another. It might be said that this change was the dream of scientists in the past. This change also brought about numerous experiments by new scientists. The majority of this new work was in the form of bombardment with all the known particles on the lighter elements. The bombardment of beryllium, boron and lithium by alpha particles emitted a very penetrating ray. At first this radiation was thought to be gamma radiation although it was more penetrating than any gamma rays known, and the details of experimental results were very different and difficult to interpret on this basis. The next important contribution was reported in 1932 by Irene Curie and F. Joliot in Paris. They showed that if this unknown radiation fell on paraffin or any other hydrogen-containing compound it emitted protons of very high energy. This was not in itself inconsistent with the assumed gamma ray nature of this new radiation, but detailed quantitative analysis of the data became increasingly difficult to reconcile with such an hypothesis. Finally (later in 1932) J. Chadwick, in England, performed a series of experiments showing that the gamma ray hypothesis was untenable. He suggested that the new radiation consisted of uncharged particles of approximately the mass of the proton, and he performed a series of experiments verifying his suggestion. Such uncharged particles are now called neutrons.

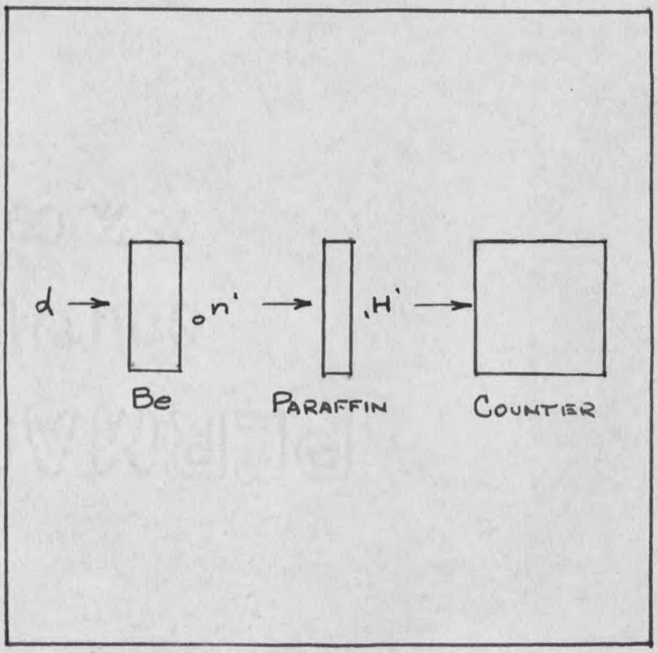

Figure 16 Schematic Drawing of Chadwick's Experiment for the Discovery of the Neutron

A brief history of the experiments leading to the discovery of the neutron would start with the original gamma ray hypothesis.

$$_4Be^9 + _2He^4 \rightarrow (_6C^{13}) \rightarrow _6C^{13} + \gamma$$

Calculations made by Bothe and Becker (1930) showed that the gamma ray protons to have an energy of approximately 6.8 Mev when absorbed in lead. In the Curie-Joliot experiments the assumed gamma rays ejected protons when bombarded into paraffin with an energy of 5.5 Mev (See Figure 16). Other experiments showed the energy to range from 15 to 90 Mev using the conservation of mass, energy and momentum. This inconsistency lead to further study, which showed that omitting the paraffin (Figure 16) the counts were relatively small, then using a thin lead sheet only decreased the number of counts slightly. But when the paraffin is inserted the number of counts increases greatly. The explanation for this is that the paraffin when bombarded by these uncharged particles (neutrons) ejects protons which have a charge and may be counted. When the paraffin was replaced by lead the reason for any counts at all is that the neutrons will collide with parts of the counter and eject nuclei which cause the counts. When the lead is removed and the neutrons move directly into the counter the approximate number of counts are taken showing that these high energy neutrons are not stopped by thin sheets of lead. This is just the opposite as would occur if this radiation were gamma rays. Chadwick then measured the velocity of the ejected protons from paraffin and then used nitrogen to replace the paraffin and measured the velocity of the nitrogen nuclei after the collision. Using the conservation of energy and equation (5)

$$\frac{1}{2} MV^2 + 0 = \frac{1}{2}mv^2 + \frac{1}{2} M(V-v)^2$$

Where M and V are the mass and velocity of the neutron before collision, m and v the mass and velocity of the proton, or nitrogen, nuclei after the collision. Taking the velocity of the proton and nitrogen as zero before collision,

$$MV^2 = mv^2 + M(V^2 - 2Vv + v^2)$$

$$2MV = v(M + m)$$

$$\frac{v}{V} = \frac{2M}{M + m}$$

the velocities Chadwick found were

$$v_H = 3.3 \times 10^9 \text{ cm/sec. for the proton}$$

$$v_N = 4.7 \times 10^8 \text{ cm/sec. for the nitrogen}$$

taking the two experiments and combining in one equation

$$\frac{v_H}{v_N} = \frac{M + m_N}{M + m_H}$$

where m_H and m_N are the masses of the proton (hydrogen) and nitrogen respectively. Taking nitrogen as being fourteen times the mass of the proton ($14\ m_H = m_N$)

$$M = 1.16 \text{ amu}$$

After more careful and detailed experiments this value for the mass of the neutron was changed to our present value of 1.00893 amu.

The most important property of the neutron is the fact that it has no charge, which is the main reason for the delay in its discovery. This also makes them very penetrating, it is impossible to observe then directly and makes them very important as agents in nuclear change. An atom in its normal state is also uncharged, but it is ten thousand times larger than a neutron and consists of a complex system of negatively charged electrons widely spaced around a positively charged nucleus. Charged particles (such as protons, electrons, or alpha particles) and electromagnetic radiations (gamma rays) lose energy passing through matter. They exert electric forces which ionize atoms of the material through which they pass. (It is such ionization processes that make the air electrically conducting in the path of electric sparks and lightning flashes). The energy taken up in ionization equals the energy lost by the charged particles, which slows down, or by the gamma ray, which is absorbed. The neutron, however, is unaffected by such forces; it is affected only by the short-range force, i.e., a force that comes into play when the neutron comes very close to an atomic nucleus. This is the kind of force that holds a nucleus together in spite of the mutual repulsion of the positive charges within it. Consequently a free neutron goes on its way unchecked until it makes a "head on" collision with an atomic nucleus. Since nuclei are very small, such collisions occur but rarely, and the neutron travels a long way before colliding. In the case of a collision of the "elastic" type, the ordinary laws of momentum apply as they do in the elastic collision of billiard balls. If the nucleus that is struck is heavy, it acquires relatively little speed, but if it is a proton, which is approximately equal in mass to the neutron, it is projected forward with a large fraction of the original speed of the neutron, which is itself correspondingly slowed. Secondary projectiles resulting from these collisions may be detected, for they are charged and produce ionization. The uncharged nature of the neutron makes it not only difficult to detect but hard to control. Charged particles can be accelerated, decelerated, or deflected by electric or magnetic fields which have no affect of neutrons. Furthermore, free neutrons can be obtained only from nuclear disintegrations; there is no natural supply. The only means we have of controlling free neutrons is to put nuclei in their way so that they will be slowed and deflected or absorbed by collisions. As we shall see, these effects are of the greatest practical importance. Further experiments showed that the bombardment of a series of elements by alpha particles emitted neutrons. All of these elements being in the first two rows of the Periodic Chart (aluminum, argon, beryllium, boron, flourine, lithium, magnesium, nitrogen, phosphorus, and sodium).

THE POSITRON

In about 1910, Victor F. Hess found the existence of a penetrating radiation from sources outside the earth called cosmic rays. At first these rays were considered similar to gamma rays, but because of their greater penetration to have a shorter wave length. Later electrostatic and electromagnetic experiments proved the rays to be composed of charged particles. In 1932, C. D. Anderson, at the California Institute of Technology, using cloud chamber experiments found that a portion of these charged particles had the same mass as that of an electron. This new particle also has the charge of an electron but is positive and are now called positrons. Also in cosmic rays particles have been found with electronic charge but masses from 200-300 times that of the electron which are called meson (Table I).

1932 also brought forth another discovery, by H. C. Urey, F. G. Brickwedde, and G. M. Murphy found that hydrogen had an isotope of mass number 2, present in natural hydrogen to one part in 5000. Because of its special importance this heavy species of hydrogen is given a name of its own, deuterium, and the corresponding nucleus is called the deuteron. The deuteron is not a fundamental particle being made of one proton and one neutron.

Curie and Joliot in 1934 while bombarding various light elements with alpha particles with the emission of neutrons found that the product nucleus continued to emit radiations even after the source of alpha particles had been removed. Further study showed this radiation to be positrons and the intensity of the radiation was shown to decrease exponentially with time, the same as natural radioactive substances. Using this decrease in radiation Curie and Joliot were able to calculate the half-lives of these artificially produced radioactive substances. They found that the alpha particle bombardment of aluminum, boron and magnesium performed this phenomena with half-lives of 3.25 minutes, 14 minutes and 2.5 minutes respectively. Shown in equation form

$${}_{13}Al^{27} + {}_{2}He^{4} \longrightarrow ({}_{15}P^{31}) \longrightarrow {}_{15}P^{30} + {}_{0}n^{1}$$

$${}_{15}P^{30} \longrightarrow {}_{14}Si^{30} + {}_{+}e^{0} \qquad T = 3.25 \text{ min.}$$

Where ${}_{+}e^{0}$ is the symbol used for the positron showing the positive charge and the zero mass number, the reactions from the boron and magnesium being of the same type as shown for the aluminum. Several other unstable isotopes that emit positrons have since been found (${}_{13}Al^{26}$, ${}_{11}Na^{22}$, ${}_{9}F^{17}$,

$_{17}Cl^{34}$). At this time nuclear physics was well on its way, and at the present time radioactive isotopes have been produced of practically all the known elements. Typical examples are shown in Table V. Note that in the neutron induced reaction with $_6C^{12}$ (Table V) the product nucleus is $_6C^{11}$ which emits a positron plus two neutrons. These two neutrons may in turn bombard another $_6C^{12}$ starting the reaction again with two neutrons as its result, thus causing a continuous action or chain reaction. This chain reaction is necessary in order to produce a continuous supply of power as we will see later.

With the production of radioactive isotopes great advances are being made in the fields of medicine, agriculture and engineering. For instance radioactive calcium may be fed to animals and then later the radiation from the various bones of the animal may be measured showing the distribution of the original calcium. Similarly fertilizer made with radioactive phosphorus will show the distribution in plant life. As Mechanical Engineers we will be interested in wear caused from friction in internal combustion engines. Work has been performed on piston rings which were made radioactive and then inserted in an engine. After several hundred hours of operation the oil is drained from the engine and examined for radioactive radiation. From this, calculations can show the amount of wear the piston rings have undergone. This is one of the many Mechanical Engineering uses of radioactive isotopes. Table VI shows a list of commercially used radioactive isotopes.

The forming of these radioactive isotopes stimulated similar experiments all over the world. In particular, E. Fermi reasoned that neutrons, because of their lack of charge, should be effective in penetrating nuclei; especially those nuclei of high atomic number which strongly repel protons and alpha particles. He was able to verify his prediction almost immediately. Finding that the nucleus of the bombarded atom captured the neutron and that there was thus produced an unstable nucleus which then achieved atability by emitting an electron. The several differences that exist between natural and artificial radioactivity are that positrons are never emitted from natural sources while alpha particles are very rare from artificial radioactivity. Also artificial radioactivity under certain conditions undergoes K-electron capture. Instead of the nucleus emitting a positron, it may capture an electron from the extra nuclear part of the atom, generally from the K shell of electrons. With this there are several changes the electron now in the nucleus combines with a proton to form a neutron, thereby increasing the atomic number by one, also an X-ray is emitted by this process. But careful calculations show that the law of momentum is not satisfied, therefore the physicist contends there is another very small particle emitted called the neutrino (Table I). The neutrino is still a theoretical prediction. As yet this particle has not been experimentally verified, though there is experimental evidence for belief in its existence.

TABLE V

TYPE	TYPICAL REACTION	PARTICLE EMITTED
	PROTON INDUCED	
p,	${}_{6}C^{12} + {}_{1}H^{1} \rightarrow ({}_{7}N^{13}) \rightarrow {}_{7}N^{13} + \gamma$	${}_{+}e^{0}$
p,	${}_{4}Be^{9} + {}_{1}H^{1} \rightarrow ({}_{5}B^{10}) \rightarrow {}_{5}B^{9} + {}_{0}n^{1}$	${}_{+}e^{0}$
p,	${}_{9}F^{19} + {}_{1}H^{1} \rightarrow ({}_{10}Ne^{20}) \rightarrow {}_{8}O^{16} + {}_{2}He^{4}$	None
p, d	${}_{4}Be^{9} + {}_{1}H^{1} \rightarrow ({}_{5}B^{10}) \rightarrow {}_{4}Be^{8} + {}_{1}H^{2}$	${}_{-}e^{0}$
	NEUTRON INDUCED	
n,	${}_{48}Cd^{113} + {}_{0}n^{1} \rightarrow ({}_{48}Cd^{114}) \rightarrow {}_{48}Cd^{114} + \gamma$	None
n, p	${}_{7}N^{14} + {}_{0}n^{1} \rightarrow ({}_{7}N^{15}) \rightarrow {}_{6}C^{14} + {}_{1}H^{1}$	${}_{-}e^{0}$
n,	${}_{8}O^{16} + {}_{0}n^{1} \rightarrow ({}_{8}O^{17}) \rightarrow {}_{6}C^{13} + {}_{2}He^{4}$	${}_{-}e^{0}$
n, 2n	${}_{6}C^{12} + {}_{0}n^{1} \rightarrow ({}_{6}C^{13}) \rightarrow {}_{6}C^{11} + 2\,{}_{0}n^{1}$	${}_{+}e^{0}$
	ALPHA PARTICLE INDUCED	
, p	${}_{7}N^{14} + {}_{2}He^{4} \rightarrow ({}_{9}F^{18}) \rightarrow {}_{8}O^{17} + {}_{1}H^{1}$	None
, n	${}_{5}B^{10} + {}_{2}He^{4} \rightarrow ({}_{7}N^{14}) \rightarrow {}_{7}N^{13} + {}_{0}n^{1}$	${}_{+}e^{0}$
	DEUTERON INDUCED	
d, p	${}_{11}Na^{23} + {}_{1}H^{2} \rightarrow ({}_{12}Mg^{25}) \rightarrow {}_{11}Na^{24} + {}_{1}H^{1}$	${}_{-}e^{0}$
d, n	${}_{6}C^{12} + {}_{1}H^{2} \rightarrow ({}_{7}N^{14}) \rightarrow {}_{7}N^{13} + {}_{0}n^{1}$	${}_{+}e^{0}$
d,	${}_{8}O^{16} + {}_{1}H^{2} \rightarrow ({}_{9}F^{18}) \rightarrow {}_{7}N^{14} + {}_{2}He^{4}$	None

TABLE VI

USEFUL RADIOACTIVE ISOTOPES

Element	Isotope	Half-Life	Radiation	Typical Uses
Calcium	$_{20}Ca^{45}$	180 days	β^-, γ	Research on fertilizers, bone formation.
Carbon	$_{6}C^{14}$	4700 years	β^-	Study of photosynthesis, plant physiology, carbohydrate utilization in animals.
Chlorine	$_{17}Cl^{36}$	10^5 years	β^-, β^+, K	Research on the physiology of plants and animals.
Gold	$_{79}Au^{198}$	2.7 days	β^-, γ	Treatment of leukemia.
Iodine	$_{53}I^{130}$	12.6 hours	β^-, γ	Treatment of thyroid cancer and hyperthyroidism.
Iodine	$_{53}I^{131}$	8.0 days	β^-, γ	
Iron	$_{26}Fe^{55}$	4 years	K	Study of anemia, disease of plants, blood circulation.
Phosphorus	$_{15}P^{32}$	14.30 days	β^-	Treatment of leukemia (including lymphocarcoma and Hodgkin's disease), polycythemia vera, skin cancer. Study of blood circulation and metabolism.
Potassium	$_{19}K^{42}$	12.4 hours	β^-, γ	Research on diseases of the heart and nervous system.
Sodium	$_{11}Na^{24}$	14.8 hours	β^-, γ	Study of blood circulation, cell function, congestive heart failures.
Sulfur	$_{16}S^{35}$	87.1 days	β^-	Research on plant physiology, proteins.

NUCLEAR ENERGY

In the basic courses of chemistry and physics there are two basic principles which govern all the reactions. The first--that matter can be neither created nor destroyed but only altered in form which has lead to the principle known as the law of conservation of mass. The second--that energy can be neither created nor destroyed but only altered in form, which is known as the law of conservation of energy. These two principles have constantly guided and disciplined the development and application of science. For all practical purposes they were unaltered and separate until this past decade. For most practical purposes they are still so, but it is now known that they are, in fact, two phases of a single principle for we have discovered that energy may sometimes be converted into matter and matter into energy. Specifically, such a conversion is observed in the phenomenon of nuclear fission of uranium which is the basis for nuclear power.

RELATIVITY:

In the development of the theory of relativity it was shown that the inertial mass of a moving body increases as its velocity increases (Equation 6). This implies an equivalence between an increase in energy of motion of a body, i.e., its kinetic energy, and an increase in its mass. To most practical physicists and engineers this appeared a mathematical fiction of no practical importance. Even Einstein could hardly have foreseen the present applications, but as early as 1905 he did clearly state that mass and energy were equivalent and suggested that proof of this equivalence might be found by the study of radioactive substances. He concluded that the amount of energy, E in ergs, equivalent to a mass, m in grams, was given by the equation

$$E = mc^2 \qquad (15)$$

where c is the velocity of light in cm/sec. It is interesting to note that Einstein's work was accomplished and published in Germany (1905) but the physicists and militarists at that time could not foresee a use for energy formed from matter. Equation (15) shows that one kilogram (2.2 pounds) of matter, if converted entirely into energy, could give 25 billion kilowatt hours of energy. This is equal to the energy that would be generated by the total electric power industry in the United States (as of 1939) running for approximately two months. Compare this fantastic figure with the 8.5 kilowatt hours of heat energy which may be produced by burning an equal amount of coal.

The extreme size of this conversion figure was interesting in several respects. In the first place, it explained why the equivalence of mass and energy was never observed in ordinary chemical combustion. We now believe that the heat given off in such a combustion has mass associated with it, but this mass is so small that it cannot be detected by the most sensitive balances available (it is of the order of a few billionths of a gram per mole). In the second place, it was made clear that no appreciable quantities of matter were being converted into energy in any familiar terrestrial processes, since no such large sources of energy were known. Therefore we may say that the conversion of matter to energy has been taking place in numerous Mechanical Engineering phenomenon but until recently we were unaware of its existence.

BINDING ENERGY:

In the discussion previously, the energy of the particles was purposely eliminated until this time when mass and energy conversion can be discussed in detail. Also the discussion has been of stable and unstable nuclei made up of assemblages of protons and neutrons held together by nuclear forces. It is a general principle of physics that work must be done on a stable system to break it up. Thus, if an assemblage of neutrons and protons is stable, energy must be supplied to separate its constituent particles. If energy and mass are really equivalent, then the total mass of a stable nucleus should be less than the total mass of the separate protons and neutrons that go to make it up. This mass difference, then, should be equivalent to the energy required to disrupt the nucleus completely, which is called the binding energy. It has been previously mentioned that the masses of all nuclei were approximately whole numbers. It is the small differences from whole numbers that are significant.

From the introduction we found that the nucleus of the helium atom (alpha particle) is composed of two protons and two neutrons having a mass number of four. If this nucleus were pulled apart and the weight of its parts carefully taken the following would be found--

$$_2He^4 \text{ (the nucleus before taken apart)} = 4.00276 \text{ amu}$$

if one neutron is taken from the nucleus leaving $_2He^3$.

$$_2He^3 \ (3.01589) + {_0n^1} \ (1.00893) = 4.02482 \text{ amu}$$

if the nucleus is split in two, leaving two nuclei of one proton and one neutron each (deuteron).

$$_1H^2 \ (2.01418) + {_1H^2} \ (2.01418) = 4.02836$$

If the nucleus were divided into its basic particles.

$$2\,{}_1H^1\ (2 \times 1.00758) + 2\,{}_0N^1\ (2 \times 1.00893) = 4.03302 \text{ amu}$$

Examining the total masses of the original nucleus and also after being pulled apart in various segments. When the alpha particle exists the mass is is the least and should be the most stable of the four catagories shown above because there is a tendency in nature for the nucleons to find the catagory of least mass and least energy. From this it would appear that any of the other three groups would have a tendency to transform into this one of lowest mass but as we know there are millions of ${}_2He^3$ and deuterons in nature which seem very stable and contended. The answer to this question is that deuterons and ${}_2He^3$ are the nuclei of atoms and are surrounded by a free atom or one chemically combined. The electrons forming a strong electrostatic field of repulsion to one another and even if ionized the nucleus itself also has an electrostatic force of repulsion except when two nuclei come to within 10^{-12} cm. apart then the short-range forces react.

Again examining the mass we find the mass of the alpha particle 4.00276 amu while dividing into the basic particles the total mass is 4.03302 amu; expressed by means of an equation

$${}_2He^4 = {}_1H^1 + {}_1H^1 + {}_0n^1 + {}_0n^1$$

$$4.00276 = 4.03302$$

The lawwof conservation of mass does not hold true but previously it has been shown that mass and energy are interchangeable, therefore the mass difference must have been in the form of energy. 4.03302 minus 4.00276 equals 0.03026 amu

$$0.03026 \text{ amu} \times 931 \text{ Mev/amu} = 27.95 \text{ Mev}$$

This mass difference being converted into energy now shows the amount of energy required to pull apart the helium nucleus into protons and neutrons or may be stated as its Binding Energy. This energy of 27.95 Mev is the energy per nucleus or 2.7×10^{19} ergs per gram molecule of helium. In units more familiar to the engineer, this means that to break up the nuclei of all the helium atoms in a gram of helium would require 1.62×10^{11} gram calories or 190,000 kilowatt hours. Conversely, if free protons and neutrons could be assembled into helium nuclei, this energy would be released. Evidently it is worth explaining the possibility of getting energy by combining protons and neutrons or by transmuting one kind of nucleus into another.

By means of the mass spectrograph, F. W. Aston and others were able to determine the masses of the isotopes of many elements. From this and later work the binding energies of these isotopes has been accurately calculated. This binding energy, B is the difference between the true nuclear mass, M and the sum of the masses of all the protons and neutrons in the nucleus. That is,

$$B = (ZM_p + NM_n) - M$$

where M_p and M_n are the masses of the proton and neutron respectively, Z is the number of protons, $N = A - Z$ is the number of neutrons, and M is the true mass of the nucleus. Quite often this energy is in terms of B/A the binding energy per particle. Figure 17 shows this binding energy per particle (B/A) plotted against the mass number (A). The graph shows that, apart from fluctuations in light nuclei, the general trend of the binding

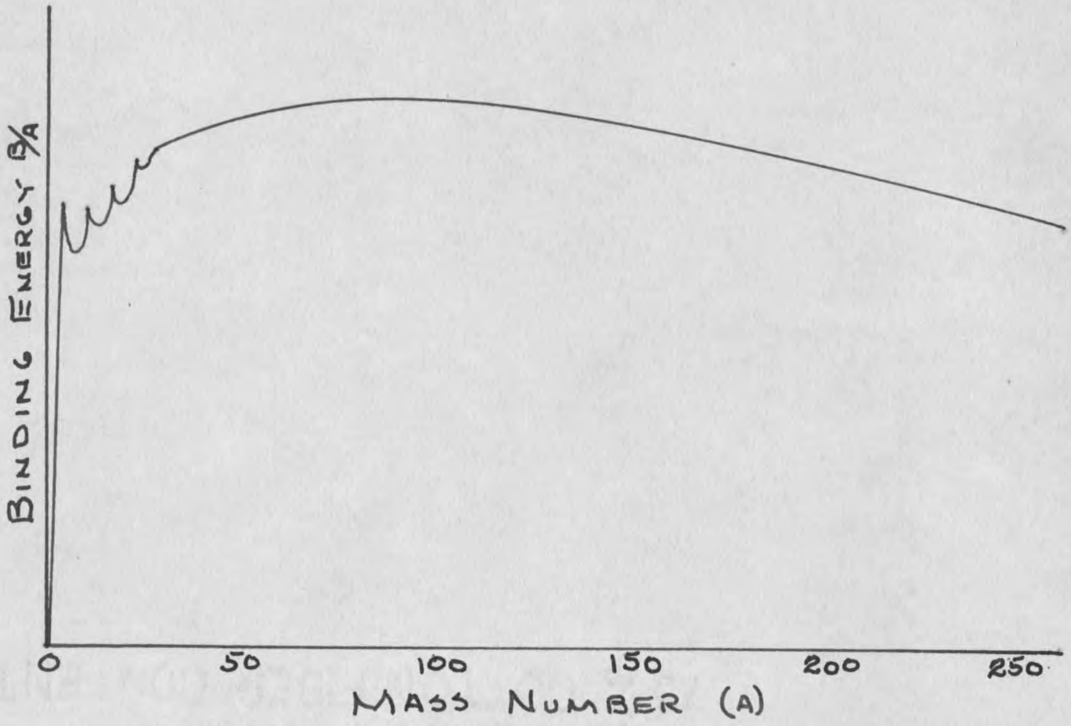

Figure 17 The Binding Energy per particle (B/A) plotted against the Mass Number (A)

energy per particle is to increase rapidly to a flat maximum around A = 60 (nickel) and then decrease again gradually. Evidently the nuclei in the middle of the periodic table, nuclei of mass numbers 40 to 100, are the most strongly bound. Any nuclear reaction where the particles in the resultant nuclei are more strongly bound that the particles in the initial nuclei will release energy. Thus, in general, energy may be gained by combining light nuclei to form heavier ones (i.e., nuclei in the meium range) or by breaking very heavy ones into two or three smaller fragments. However, not all of the lighter elements may be used to the best advantage as is sometimes shown in connection with their packing

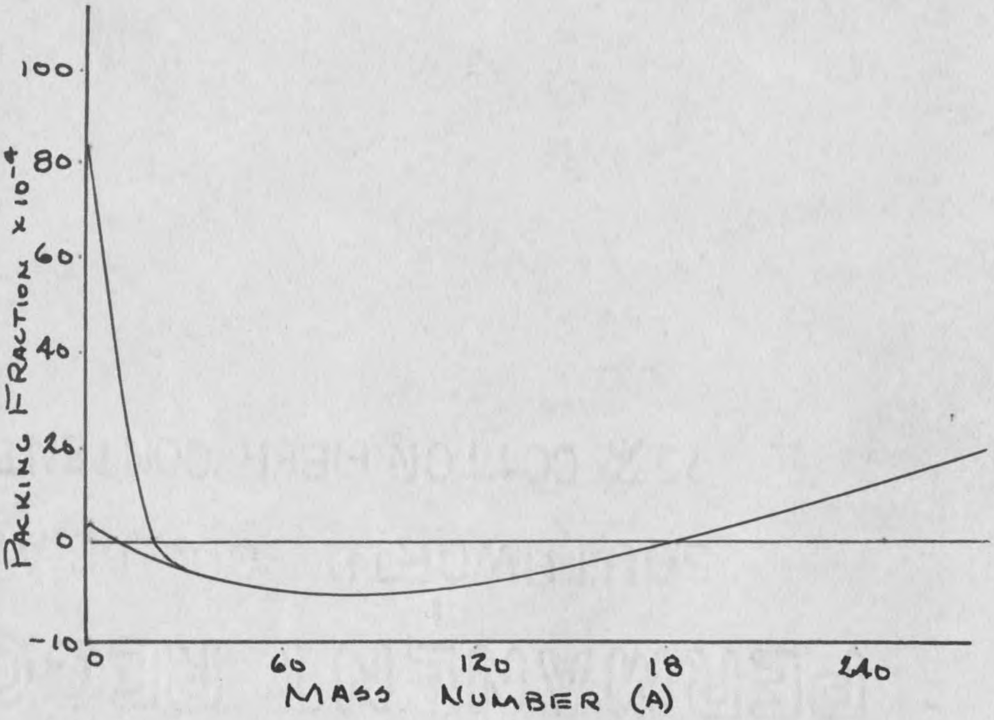

Figure 18 Packing Fraction plotted against mass number
showing positive and negative values

fraction.

Packing Fraction

It has been previously mentioned that the actual masses (amu) of all the isotopes varies slightly from whole numbers, their mass number (A). The isotopes with mass numbers from 1 to 20 (or 21) have atomic masses (M) that are slightly greater than their mass number. From mass number of 20 to 168 the atomic mass is slightly less than the mass number and above 168 the atomic mass again becomes greater. Various sources of atomic masses will sometimes use packing fraction or the mass defect per elementary particle in the nucleus. That is

$$P = \frac{M - A}{A}$$

where P is the packing fraction and M - A is the mass defect or the mass difference from a whole number which will cause the packing fraction to be negative when using mass numbers of 20 to 168. Figure 18 also shows that for the lighter nuclei two curves must be used to satisfy all the isotopes.

Rutherford's work in 1919 on artificial nuclear disintegration, has previously been mentioned, and was followed by many similar and more advanced experiments. High voltage apparatus used to accelerate particles was replacing natural sources of alpha particles from radioactive substances. The energy at which an alpha particle is emitted from radioactive sources vary with the various atoms, for instance, the alpha particle from radon has a velocity of 1.63×10^9 cm/sec. while an alpha particle from thorium C has a velocity of 1.71×10^9 cm/sec. This difference does not seem to be very great but we must remember that this is the velocity and from equation (5) $E = \frac{1}{2}mv^2$ shows that the energy varies directly as the square of the velocity which will cause a greater difference in the energy. In 1932, J. D. Cockcroft and E. T. S. Walton bombarded a target of lithium with protons of 700 kilovolts energy and found that alpha particles were ejected. In equation form

$$_3Li^7 + _1H^1 \rightarrow (_4Be^8) \rightarrow _2He^4 + _2He^4$$

Taking the masses of the nuclei and particles in the above equation we find

$$7.01816 + 1.00813 = 4.00386 + 4.00386$$

Adding $\quad 8.02629 = 8.00772$ amu

As can be seen the left hand side (initial) of the reaction is heavier than the right hand side, therefore something must be added to balance this equation. 8.02629 minus 8.00772 equals .01857 amu; this mass has disappeared in the reaction and if converted to energy units equals

$$.01858 \text{ amu} \times 931 = 17.298 \text{ Mev.}$$

Experiments have shown that the two alpha particles emitted each have an energy of approximately 8.62 Mev or a total of 17.24 Mev which compares favorably with our calculated value 17.298 Mev. However this is taking the initial energy of the proton ($_1H^1$) as being negligible. It should also be noted that the masses used in the above calculations were those of the atoms, not just the nuclei. This is satisfactory because there is an equal number of electrons on each side of the reaction therefore actually cancelling out their masses.

The energy released during this reaction (17.298 Mev) may be converted into more frequently used engineering units.

$$17.298 \times 4.45 \times 10^{-20} = 76.98 \times 10^{-20} \text{ Kw-hr/atom}$$

$$\frac{76.98 \times 10^{-20}}{7.01816 \times 1.66 \times 10^{-24}} = 66,200 \text{ Kw-hr/gram}$$

from this can be seen the energy released per atom and also the energy per gram showing a source of nuclear power. But examining the source of this power (energy) we find that for each reaction to take place a proton is required that will bombard the nucleus of a lithium atom. Not all protons will cause such a reaction, the remainder just passing by all the lithium nuclei. The number of protons required per lithium atom will be discussed under cross-section in the following paragraph. This probability could well be in the neighborhood of 1 to 1,000,000 which shows the enormous supply of protons required to keep a steady supply of energy. However at this time it can be foreseen that the most practical method for continuous energy would be to have a reaction where the initial particle is the same as one (or more) of the ejected particles. For instance in Table V,

$$_6C^{12} + {_0n^1} \rightarrow ({_6C^{13}}) \rightarrow {_6C^{11}} + 2{_0n^1}$$

where one neutron bombards a $_6C^{12}$ nucleus and there are two neutrons ejected which may bombard more $_6C^{12}$ nuclei causing a continuous reaction (chain reaction). However, this reaction cannot be used because energy is absorbed not released, but it does show the type of reaction needed.

CROSS-SECTION

As mentioned in the above paragraph, not all particles that move in the direction of a nucleus cause a reaction. This probability varies widely with the various particles, nuclei, and their kinetic energy. But instead of complex probability relationships, the interactions between projectile particles and nuclei are expressed very simply in terms of nuclear cross-section. The centers of the atoms in a very thin foil can be considered as points evenly distributed over a plane. The center of an atomic projectile striking this plane has geometrically a definite probability of passing within a certain distance (r) of one of these points. If there are n atomic centers in an area A of the plane, this probability is $n r^2/A$, which is simply the ratio of the aggregate area of circles of radius r drawn around the points of the whole area. Let us consider these atoms (of area A) to be thin steel targets with a small impenetrable centers and for the projectiles let us use several calibers of guns. A 50 caliber shell would indicate that the cross-section of the target was just the diameter of the small impenetrable center while a bee bee gun would show the cross-section to be the full area of the target. However, in the case of particles and nuclei, sometimes (in the case of neutrons) the slower particles may have a larger cross-section to certain nuclei. Actually we would say that we were measuring the equivalent stopping cross-section of the nuclei. For example, the probability that an alpha particle striking a beryllium target will produce a neutron can be expressed as the equivalent cross-section of beryllium for this type of reaction. From the previous discussions we saw the long and short range forces and how they reacted with charged and uncharged particles. The cross-section of a nuclei also varies depending on the charge of the projected particle, i.e., the alpha particle has twice the positive charge of the proton while the neutron is neutral.

For all practical purposes in computing cross-section the impinging particles are taken as having a negligible diameter. The technical definition of cross-section for any nuclear reaction is therefore:

$$\frac{\text{number of processes occuring}}{\text{number of incident particles}} = (\text{number of target nuclei per cm}^2)(\text{nuclear cross-section in cm}^2)$$

this equation is for cross-section per nucleus. In many cases, the number of particles emitted or scattered in nuclear processes is not measured directly; one merely measures the attenuation produced in a parallel beam of incident particles by the interposition of a known thickness of a particular material. The cross-section obtained in this way is called the total cross-section and is usually denoted by σ.

Previously the diameter of a nucleus was said to be in the neighborhood of 10^{-12} cm. We might therefore expect the cross-sections for nuclear reactions to be approximately 10^{-24} cm^2. For this reason the nuclear physicist has taken the area of 10^{-24} cm^2 equal to one barn (1 barn = 10^{-24} cm^2/nucleus). For example, slow neutrons absorbed by the (n,) reaction the cross-section in some cases is as much as 1000 x 10^{-24} cm^2, while the cross-sections for transmutations by gamma-ray ( ) absorbtion are in the neighborhood of .001 x 10^{-24} cm^2 (.001 barns).

On the previous pages it was shown that a great amount of energy was released when lithium ($_3Li^7$) is bombarded with protons. But the difficulties are in producing the highspeed protons and in controlling the energy produced. As the experiments we have been talking about have been done with very small quantities of materials, large enough in numbers of atoms, to be sure, but in terms of ordinary masses infinitesimal--not tons or pounds or grams, but fractions of micrograms. The amount of energy used up in the experiment was always far greater than the amount generated by the nuclear reaction. Compare this energy with common sources of power, chemical reactions (combustion of coal or oil), sunlight and waterpower. Combustion releases energy as the result of rearrangements of the outer electronic structures of the atoms. Combustion is always self-propagating; thus lighting a fire with a match releases enough heat to ignite the neighboring fuel, which releases more heat which ignites more fuel, and so on. In the nuclear reactions that we have described this is not generally true; neither the energy released nor the new particles formed are sufficient to maintain the reaction. However nuclear energy for industrial and military purposes was publicized as early as 1930 by Prof. Arthur H. Compton, Nobel prize winner, in the Hearst newspapers. Soon after Compton's article the University of Chicago installed a huge atom smasher with all steel discs weighing over 164,000 pounds each, and containing more than four miles of copper wire placed between the discs to form a giant magnet. At Chicago, the gold nucleus was split, thus forming two other nuclei.

SOLAR ENERGY:

In 1940 Hans Bethe at Cormell University worked out a theory of the nuclear process that gives energy to the sun. Using the fact that astrophysical evidence shows the most abundant type of nucleus present in the stars (and sun) is the proton. There are two types of reactions that occur depending solely on the temperature. When the temperature is above about 15 million degrees, as it is in the sun, the following reaction takes place--four hydrogen atoms change into one helium with carbon as a catalyst.

$${}_1H^1 + {}_6C^{12} \rightarrow {}_7N^{13}$$

$${}_7N^{13} \rightarrow {}_6C^{13} + {}_{+}e^{0}$$

$${}_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14}$$

$${}_7N^{14} + {}_1H^1 \rightarrow {}_8P^{15}$$

$$_8P^{15} \rightarrow {}_7N^{15} + {}_+e^0$$

$$_7N^{15} + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4$$

The $_6C^{12}$ atom, which acts as the catalyst reappears in the final products to be used again. Any $_6C^{12}$ atom that enters the reaction will emerge again as pure carbon only after about 5 million years. The two positions ($_+e^0$) emitted will combine almost immediately with neighboring beta particles, and the masses of the particles completely disappears to form two gamma rays per positron reactions. The sun is converting its mass into energy at a rate of about 4 million tons per second. But the sun is so huge that it will require a billion and a half years for it to lose only 0.01% of its mass. In this process (solar) of changing protons to helium there is released only about one part in 125 of the mass of the proton. This mass reappears in the form of radiant heat. The earth being 93,000,000 miles away from the sun, intercepts only two parts in one billion of the sun's energy.

In the cooler stars, below 15 million degrees, a direct conversion of protons into helium appears to give the stars its energy. This is the reaction that occurs on the greater majority of stars. This reaction being the source of a star's light but very little energy beyond this reaches the earth and occurs as the following equation shows:

$$_1H^1 + {}_1H^1 \rightarrow ({}_2He^2) \rightarrow {}_1H^2 + {}_+e^0$$

and is followed by two additional proton reactions to form a helium nuclei (alpha particle)

$$_1H^2 + {}_1H^1 \rightarrow {}_2He^3$$

$$_{2}He^{3} + _{1}H^{1} \rightarrow (_{3}Li^{4}) \rightarrow _{2}He^{4} + _{+}e^{0}$$

and again the positrons will be anialated after coming into contact with two electrons forming two gamma rays.

This may be a good time to calculate the amount of energy released when a positron combines with an electron to form two gamma rays, written in equation form,

$$_{+}e^{0} + _{-}e^{0} \rightarrow h\nu + h\nu$$

h being the energy in a gamma ray. The mass of the positron and electron is .00055 amu each and the gamma rays having zero mass their energy must be

$$M = 2 \times .00055 \text{ amu} = .0011 \text{ amu}$$

$$E = .0011 \times 931$$

$$= 1.0241 \text{ Mev (total energy in gamma rays)}$$

Going back to the equations of the reactions of the energy released by the sun we find an ideal situation for a continuous reaction. However, if this same train of reactions were performed in a laboratory here on earth we would find that the energy required to produce protons that would carry on such a reaction would be greater than the energy released. On the sun temperatures of up to 40 million degrees are reached being the reason for the reaction occuring. Therefore we are back where we started, without a reaction that is self-sustaining and will release large amounts of energy.

Thus far we have discussed several sources of nuclear energy none of which were suitable for a continuous source of nuclear power.

Figure 18 shows a graph of the packing fractions against mass numbers of all the isotopes. Noting on this curve that mass numbers from 1 - 20 and from 190 - 240 have packing fractions greater than zero and the mass numbers of from 20 - 190 have packing fractions of less than zero. This should indicate that if one of the heavier elements, above a mass number of 190, were split in half a great amount of energy would be released due to the maximum loss in mass. The problem now being the process used to split this atom. If protons, electrons or any charged particles were used for bombardment they must have a very great amount of energy to overcome the electrostatic forces of repulsion in such a large atom. The larger the atom the greater the number of protons and electrons which are the charged particles causing the electrostatic forces. Therefore the neutron seemed to be the answer because it is not affected by the electrostatic forces and may have very little energy (thermal neutrons) with a great amount of penetrating power. The neutron also seemed to be the answer because of the possibility of a chain reaction. This possibility was formulated because the heavier atoms have greater percentage of neutrons per proton than the atoms in the middle range. Therefore if one of the heavier nuclei (atoms) are split in half by means of neutron bombardment there should be an excess of neutrons in the product nuclei which may be emitted thus allowing a chain reaction. Suppose the ${}_{92}U^{238}$ nucleus is broken exactly in half; then, neglecting the mass of the incident neutron, we have two nuclei of atomic number 46 and mass number 119 (${}_{46}Pd^{119}$). But the heaviest stable isotope of palladium (Z = 46) has a mass number of only 110. Therefore to reach stability each of these imaginary new nuclei must eject nine neutrons, becoming $_{46}Pd^{100}$ nuclei, or four neutrons in each nucleus must convert themselves to protons by emitting electrons thereby forming stable tin nuclei of mass number 119 and atomic number 50 ($_{50}Sn^{119}$) or a combination of such ejections and conversions must occur to give some other pair of stable nuclei.

Fermi and his colleagues, in 1934, bombarded uranium with neutrons but their results were misinterpreted and proved puzzling. The puzzling part being the product nuclei formed emitted four beta rays of different half-life periods, while it is known that uranium is radioactive but emits an alpha particle. Careful chemical examination showed that one of the product nuclei has similar properties (chemical homologue) of manganese. Referring to the Periodic Chart of the atoms an element of atomic number 93 would be in the same column as manganese. Other chemical examinations showed that none of the nuclei in the range of atomic numbers from 86 - 92 could possibly be present. Chemical examinations of this nature are extremely difficult because of the micro study nature, i.e., only a minute amount available. However, it was not until 1940 after the works of Bohr, Frisch, Meitner, Hahn, Stassmann, Joliot and Fermi were known and discussed that the existence of transuranic elements were definitely established. The transuranic elements now known are of atomic numbers 93 - 96. U^{238} was then bombarded by thermal neutrons and the following reactions are suggested:

$$_{92}U^{238} + {}_0n^1 \rightarrow ({}_{92}U^{239}) \rightarrow {}_{92}U^{239} + \gamma$$

the product nuclei being an unstable isotope of uranium with a half-life of 23 minutes, with the following reaction occuring:

$$_{92}U^{239} \rightarrow {}_{93}Np^{239} + {}_{-}e^{o}$$

Np being one of the newly found transuranic elements of atomic number 93, which was named neptunium. This neptunium isotope is also unstable with a half-life of 2.2 days, with the following reaction occuring:

$$_{93}Np \rightarrow {}_{94}Pu^{239} + {}_{-}e^{o}$$

Pu is the transuranic element plutonium atomic number 94. This isotope is an alpha particle emitted with a half-life of 24,000 years

$$_{94}Pu^{239} \rightarrow {}_{92}U^{235} + {}_{2}He^{4}$$

This series of reactions are not a source of nuclear power but plutonium will warrant mentioning later. The original thermal neutron has a resonance energy of 38 ev. Resonance energy being the energy of the bombarding particle for which a nucleus (U^{238}) is exceptionally reactive.

Changing the energy of the incident neutron another isotope of neptunium was found, with the following reactions occuring:

$$_{92}U^{238} + {}_{o}n^{1} \rightarrow ({}_{92}U^{239}) \rightarrow {}_{92}U^{237} + {}_{o}n^{1} + {}_{o}n^{1}$$

$$_{92}U^{237} \rightarrow {}_{93}Np^{237} + {}_{-}e^{o}$$

$$_{93}Np^{237} \rightarrow {}_{91}Pa^{233} + {}_{2}He^{4}$$

the half-lives of the Np and Pa being 6.8 days and 2.25×10^{6} years respectively. Then another beta emission occurs

$$_{91}Pa^{233} \rightarrow {}_{92}U^{233} + {}_{-}e^{0}$$

With a half-life of 27.4 days.

In the above reactions it has been shown that two different reactions occur, depending entirely upon the energy of the incident neutron. A tabulation of the reaction that may occur when bombarding U^{238} with neutrons of any energy. The reactions will fall into several groups as shown in Table VI.

TABLE VI

Neutron Energy in ev	
Below .5	Low degree of absorbtion for Pu^{239}
0.5 - 50	High degree of absorbtion for Pu^{239}
50 - 100	Moderate absorbtion for Pu^{239}
100 - 1,000,000	Low absorbtion to yield Pu^{239} or U^{233}
Over 1,000,000	Fissions

The fact that U^{238} fissions when bombarded by high energy neutrons is shown in Table VI, (Fission is the reaction where one nucleus is broken down into two lighter nuclei, sometimes referred to as atom smashing. This differs from previous discussed reactions where the result was a nucleus and a particle). The reason that this fission is not considered as a source of nuclear power is that the neutrons must be of very high energy.

In 1940 uranium was bombarded by deuterons in the laboratory of Seaborg, McMillan, Wahl and Kennedy which formed another isotope of plutonium

$$_{92}U^{238} + {_1}H^2 \rightarrow ({_{93}}Np^{240}) \rightarrow {_{93}}Np^{238} + {_0}n^1 + {_0}n^1$$

$$_{93}Np^{238} \rightarrow {_{94}}Pu^{238} + {_{-}}e^0$$

$$_{94}Pu^{238} \rightarrow {_{92}}U^{234} + {_2}He^4$$

The $_{93}Np^{238}$ and $_{94}Pu^{238}$ having half-lives of 2.5 days and 50 years respectively. Note that the two plutonium isotopes formed have extremely long half-lives, Pu^{239} 24,000 years and Pu^{238} 50 years, which aided in their detection. The question may now occur why all this just to produce some plutonium, the answer is Pu^{239} fissions when bombarded by neutrons of <u>any</u> energy, being the ideal isotope as a source of nuclear energy. The next question being isn't there any natural supply of plutonium instead of forming these micro amounts. For our use of nuclear power or a nuclear bomb, greater amounts of plutonium will be needed. A natural source of uranium, pitchblinde ore was examined as to a possible source of plutonium. But the amount of plutonium present was very minute and not a practical source. Therefore the only alternative was to produce plutonium on a production basis by means of nuclear reactions, which will be discussed in full later.

Observing the uranium atom we find three isotopes present U^{234}, U^{235}, U^{238} the relative abundance percent being 0.00518%, 0.719% and 99.274% respectively. We have already seen the reaction of U^{238} with neutrons but further study showed that U^{235} is fissionable when bombarded by neutrons of any energy similarly as Pu^{239}. The U^{234} isotope may be eliminated from this discussion because of its scarcity. Therefore we can consider the uranium atoms, as produced or found in nature, being 1 part U^{235} isotope to 139 parts U^{238} isotope. The remaining problem being to separate the two isotopes. In the case of chemical compounds (NaCl) there are several methods of separating the difference in their chemical behavior. But separating two isotopes of the same element, chemical means cannot be used because the isotopes are chemically identical. There is only one property that exists which is different, this being their masses. However, even their masses only differ slightly, a ratio of 235 to 238. This separation now being a problem for the physicists and engineers to solve. Prior to 1940 isotopes had been separated in laboratories by means of spectrographs but only several atoms of each isotope being produced. The discussion of isotope separation will be discussed in full later.

NUCLEAR FISSION OF U^{235}:

In the previous paragraph it was mentioned that U^{235} was fissionable with neutrons of any energy. But it was shown that U^{238} reacted differently when bombarded by neutrons of different energies so does U^{235} except that the only difference being the fission products (that is, fission always occurs but the nuclei formed and the number of neutrons, electrons, etc., emitted vary). Examining one of the possible fission reactions from U^{235} using thermal neutrons of approximately .03 ev we found:

$$ {}_0n^1 + {}_{92}U^{235} \rightarrow ({}_{92}U^{236}) \rightarrow {}_{54}Xe^{139} + {}_{38}Sr^{95} + {}_0n^1 + {}_0n^1 $$

the xenon and strontium isotopes are unstable beta emitters with half-lives of 41 seconds and 2 minutes respectively. This above reaction splits into two branches, let us follow the xenon branch first.

$$_{54}Xe^{139} \longrightarrow {}_{55}Cs^{139} + {}_{-}e^{o}$$

this isotope of caesium is also unstable and emits a beta particle with a half-life of 7 minutes to produce a barium isotope.

$$_{55}Cs^{139} \longrightarrow {}_{56}Ba^{139} + {}_{-}e^{o}$$

the half-life of the barium being 86 minutes

$$_{56}Ba^{139} \longrightarrow {}_{57}La^{139} + {}_{-}e^{o} + \gamma$$

the lanthanium isotope being stable ending this branch. It may be noted that there is a series of isobars $_{54}Xe^{139}$, $_{55}Cs^{139}$, $_{56}Ba^{139}$ and $_{57}La^{139}$, that is, isotopes with the same mass number (139) but having different atomic numbers. Now second, let us follow the strontium branch

$$_{38}Sr^{95} \longrightarrow {}_{39}Y^{95} + {}_{-}e^{o}$$

the half-life of yttrium being 11.5 hours to form

$$_{39}Y^{95} \longrightarrow {}_{40}Zr^{95} + {}_{-}e^{o} + \gamma$$

the half-life of the zirconium being 65 days

$$_{40}Zr^{95} \longrightarrow {}_{41}Nb^{95} + {}_{-}e^{o}$$

the columbium having isomers with two half-lives of 35 days and 90 hours the longer emitting a gamma ray

$$_{41}Nb^{95} \longrightarrow {}_{42}Mo^{95} + {}_{-}e^{0} + \gamma$$

The complete reaction may be written

$$_{0}n^{1} + {}_{92}U^{235} \rightarrow ({}_{92}U^{236}) \longrightarrow {}_{57}La^{139} + {}_{42}Mo^{95} + 2\,{}_{0}n^{1} + 7\,{}_{-}e^{0} + 3\gamma$$

However, it must be remembered that this is only one of many of the fission reactions occuring when U^{235} fissions from neutrons. A general equation may be written for all the possible reactions as follows:

$$_{0}n^{1} + {}_{92}U^{235} \longrightarrow ({}_{92}U^{236}) \rightarrow X^{90-105} + Y^{130-150} + {}_{-}e^{0} + {}_{0}n^{1}$$

This equation shows the two final product nuclei of fission as X and Y with mass numbers in the ranges of 90-115 and 130-150. (The average number of neutrons emitted during the fission of U^{235} is 2.3 high energy neutrons). Which means then that the product nuclei will generally (always) be in these two ranges as shown in the graph on Figure 19. The graph of Figure 19 being fission yield (%) plotted against mass numbers (A). The most important characteristics of the yield-mass are, the definition of the fission nuclei into these two pronounced groups (heavy and light). Over 19% of the fissions fall in the mass range of 83-105 and 129-151. The most probable masses are 95 and 139 being the situation used in the proceeding example. No satisfactory theoretical explanations for this asymmetric nature of the fission process has yet to be offered.

Example No. 4

U^{235} has a packing fraction of 5.4×10^{-4} amu. Upon fission, one set of the products is thought to consist of Ba^{138} and $_{36}Kr$ with an emission of 13 neutrons.

a) Write the equation for this reaction neglecting the incident neutron.

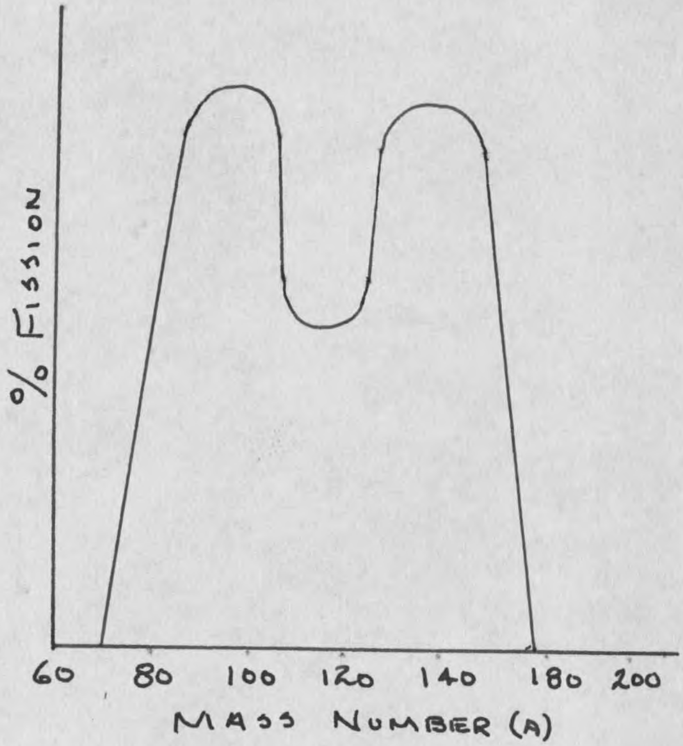

Figure 19 Percent Fission Products from U^{235}

$$_{92}U^{235} \quad {}_{56}Ba^{138} + {}_{36}Kr^{84} + 13\,{}_{0}n^{1}$$

b) Find the atomic weight of U^{235}

$$P = \frac{M - A}{A} = \frac{M - 235}{235} = 5.4 \times 10^{-4}$$

$$M - 235 = 0.1269$$

$$M = 235.1269$$

c) The Ba has an atomic weight of 137.9162 amu while Kr has packing fraction of -8.56×10^{-4} amu. Find the amount of mass that disappears in each fission process.

$$\frac{M - 84}{84} = 8.56 \times 10^{-4}$$

$M = 83.9281$ amu (for Kr)

$235.1269 = 137.9162 + 83.9281 + 13(1.00893) + Q$

$Q = .166534$ amu

d) Find the energy in Kw-hr for one pound of U^{235} to completely fission in the above process.

$$\text{Kw-hr} = \frac{453.6 \times .1665 \times 4.15 \times 10^{-17}}{235.1269 \times 1.66 \times 10^{-24}} = 8.04 \times 10^{6} \text{ Kw-hr}$$

To clarify the last equation it may be best to use dimensional analysis.

$$\text{Kw-hr} = \frac{\text{gms/lb} \times \text{amu/atom} \times \text{Kw-hr/amu}}{\text{amu/atom} \times \text{gms/amu}}$$

The above example showed a mass deficit of .166534 amu which may be converted to Mev per atom

$$.166534 \times .931 = 157 \text{ Mev/atom}$$

this value of 157 Mev is rather low; the average energy released per atom during fission of U^{235} is approximately 200 Mev.

By 1940 the following information on fission was known internationally (most of the following has been previously mentioned):

a) Uranium, thorium and protactinium when bombarded by neutrons sometimes split into approximately equal fragments, and that these fragments were isotopes of elements in the middle of the periodic table, ranging from selenium to lanthanium.

b) Most of these fissions fragments were unstable, decaying radioactively by successive emission of beta particles through a series of elements to various stable forms.

c) These fission fragments have very great kinetic energy.

d) That fission of thorium and protactinium was caused by high energy