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Atomic Energy

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Noted for his work on ultra-high speed centrifuges and on the separation of isotopes, Dr. Jesse Wakefield Beams worked on the separation of uranium isotopes for the Manhattan project during the recent war. Besides his work on the centrifuges and separation of isotopes, Dr. Beams has written numerous articles on the measurement of very short time intervals, the electro-optical Kerr effect, and the methods of accelerating ions to high velocities by moving electric fields.

It has long been known that all material substances are composed of atoms. Each atom in turn is made up of a positively charged nucleus surrounded by negatively charged electrons. The positive electrical charge on the nucleus is always an integral multiple of the electrical charge on the nucleus of the hydrogen atom or proton while the electron and proton possess charges of equal magnitude but of opposite sign. The absolute value of this charge is 4.80×10^{-10} esu and is the elementary charge from which all electrical charges in nature are built. The number of these elementary charges on the nuclei of the elements found in nature increases from one for hydrogen to 92 for uranium and is called the atomic number Z. Since the atoms of most substances in their normal state are uncharged, the number of electrons surrounding the nucleus is obviously equal to its atomic number. The Z electrons around the nucleus determine the chemical properties of the element so the atomic number Z also may be used to distinguish the various chemical elements. The exact arrangement of the electrons around the nucleus can not be accurately described without the use of the rather formidable mathematical language of Wave Mechanics and Quantum Theory, but for the present purpose it is sufficient to follow the original ideas of Rutherford and Bohr and to think of the electrons revolving about the nucleus in orbits somewhat analagous to the way in which the planets revolve around the sun. Like the orbits of the planets around the sun, some of the electron orbits pass comparatively close to the nucleus while others lie considerably further away. The average distance being the order of magnitude of 10^{-8} cm. Small as this distance may seem, it is roughly 10,000 times larger than the radius of the nucleus (10^{-12} cm) or the electron (2×10^{-13} cm) so that practically all of the volume occupied by matter actually is made up of empty space! Although the size of the electron is very roughly the same as that of the nucleus, practically all of the mass of the atom resides in the nucleus. The mass of the proton (hydrogen nucleus) is approximately 1.67×10^{-24} gms or about 1840 times larger than the rest mass of the electron (9.1×10^{-28} gms) while the mass of the uranium 238 nucleus (3.9×10^{-22} gms) is over 400 thousand times greater than the rest mass of the electron. Before the experimental technique for determining the masses of individual atoms was worked out a scale of atomic weight measurements was developed based upon the relative combining weights of the elements in their chemical reactions. This scale is still in use mostly by chemists. Oxygen was taken as standard on this scale and arbitrarily assigned the value of 16.00. This value turned out to be one-half the weight in grams of 22.4 liters (NTP) of oxygen (O_2) gas. Thus 16 grams of oxygen contains 6.02×10^{23} atoms. On this atomic weight scale hydrogen has the value 1.00785, helium 4.002 and uranium 238.17.

At the present time, it is believed that the electron is an elementary or fundamental particle in the sense that it has not been possible to subdivide it experimentally. On the other hand, with the possible exception of the proton (outside the nucleus) the nuclei are not fundamental particles, as they are split into fragments when hit by the proper atomic projectile. As a result of a large amount of experimental evidence, it is generally believed that most of the masses of the nuclei are made up of protons and neutrons. The neutron (outside the nucleus) is apparently a fundamental uncharged particle having a mass almost the same as that of the proton (1.675×10^{-24} gms or 1.0089 atomic weight units). On this view, the mass of any nucleus should be nearly (but not exactly) an integral multiple of the masses of the proton and neutron while the positive electrical charge on the nucleus or its atomic number Z should be determined by the number of protons in the nucleus since the neutrons have no charge. It often happens that two or more nuclei possess the same number of protons but different numbers of neutrons. When this occurs the resulting atoms have the same atomic number Z and hence the same chemical properties, but different masses. These different atomic species of the same chemical element are called isotopes. It is interesting to note that oxygen has three isotopes, one of which has an abundance of 99.6 percent. This isotope is assigned the atomic weight of exactly 16 on the physical scale. The atomic weights on this physical scale and those on the chemical scale are in the ratio of 1.000272 to 1.

About one-half century ago, the French physicist, H. Becquerel, discovered that several uranium salts were continuously emitting an invisible radiation capable of penetrating thin layers of opaque material. Subsequently, as a result of the efforts of a large number of investigators, led principally by Lord Rutherford and P. and Mme. Curie, this effect was found to result from the spontaneous explosions of the nuclei of the atoms and was given the name of natural radioactivity. This phenomenon of natural radioactivity was found to be confined to elements with very high atomic weights (with the exception of potassium, caesium and rubidium, which are weakly radioactive) and to three families of atoms headed by uranium 238, uranium 235 and thorium 232. When these radioactive atoms explode, they may give off so-called gamma, beta or alpha rays. The alpha rays are composed of helium nuclei usually with energies of several million electron volts, the beta rays are high energy electrons and the gamma rays are penetrating photons or very high frequency light waves. When an alpha ray is emitted from a nucleus the atomic number drops by two units and the mass by 4 atomic weight units so that a new and lighter element is formed. When an electron is emitted the atomic number is increased by one while the mass changes only by a comparatively small amount. The emission of the gamma ray on the other hand does not change the atomic number and the same element remains. The rate of disintegration of the element is constant and characteristic of the nucleus itself. It is interesting to note that all of the elements in the three radioactive families continue to disintegrate until the stable element lead (atomic number 82) is formed. However, the stable end products of the families headed by uranium 238, uranium 235, and thorium 232 are the lead isotopes with atomic weights of 206, 207 and 208 respectively. Since the rates of disintegration of the elements are a constant characteristic of the nuclei and are accurately known, the "age" of the radioactive mineral deposits can be determined by a proper isotopic analysis of the lead present and a measure of the helium content of the rocks.

At the end of World War I, Rutherford first succeeded in producing nuclear disintegration artifically in the lighter elements. He bombarded nitrogen with alpha particles from a deposit of radium C having energies of well over 5 million electron volts and produced oxygen and hydrogen. Following up this discovery Rutherford and Chadwick succeeded in disintegrating all of the elements from boron to potassium with the exception of carbon and oxygen, with he high speed alpha particles emitted by the naturally radioactive elements. The disintegration of these elements by the high energy alpha particles greatly stimulated the development of laboratory methods for producing other high energy particles. As a result, in 1930, Cockroft and Walton first succeeded in disintegrating lithium with 300,000 volt protons. At about this same time, the cyclotron was invented by Professor E. O. Lawrence, and other methods of accelerating particles such as the Van de Graff generator were developed in laboratories all over the world. With these great advances in technique, it was found that practically all of the elements could be disintegrated if the proper projectiles were hurled with enough energy into the nuclei. Professor Lawrence found that the deuteron (single charged nucleus of the hydrogen isotope of mass 2) was a particularly effective projectile when accelerated to several million electron volts energy. In a large number of the disintegrations neutrons are emitted from the nucleus. Since these neutrons have no electrical charge, they are not strongly repelled by the charged nuclei so that they easily can penetrate them. Sometimes instead of producing disintegration, the projectile attaches itself to the nucleus. This is a rather common occurence when the neutron is the bombarding particle. In this case, the atomic number remains the same and the atomic mass is increased, i.e., a heavier isotope of the same element is formed. Sometimes instead of the disintegration taking place immediately, the resulting element becomes radioactive. This is called induced radioactivity and is often produced by the capture of a neutron by the nucleus.

It will be recalled that when a chemical reaction takes place, heat is usually absorbed or given out by the reaction, i.e., we say the reaction is endothermic or exothermic. This is also true for the case of a nuclear reaction. For example, when 1 gram of hydrogen and 8 grams of oxygen unite chemically to form water about 34,000 calories are given out while the nuclear reaction of

1 gram of hydrogen and 7 grams of lithium to form helium releases about 5 billion calories. The question naturally arises how does this enormous energy released in nuclear reactions originate. The answer to this question is found in the theory of relativity which shows that energy and mass are equivalent and the energy released in nuclear reactions results from a disappearance of mass.

In 1905 Einstein showed that $E=MC^2$ where E is the energy, M the mass and C the velocity of light. Since that time, this relation has been amply confirmed by experiment. Because of the very large value of C^2 (9×10^{20} cm^2/sec^2) the energy released by a small mass is enormous. For example, the complete conversion of 1 gram of mass to energy releases 9×10^{20} ergs or 25 million kilowatt hours. However, in the actual nuclear reaction only a very small portion of the mass is converted into energy except in special cases similar to the combination of a positive and negative electron to form a million volt gamma ray photon. The next question which naturally arises is whether or not this atomic energy released in atomic reactions can be used in a practical way. The answer to this question was unresolved until 1939 when Hahn and Strassman discovered the phenomenon known as nuclear fission.

This phenomenon of nuclear fission occurs when some of the heavier elements such as uranium or thorium are bombarded with neutrons. When a neutron strikes, say the uranium 235 nucleus, instead of disintegrating into another heavy element and a proton, neutron, alpha particle, electron or positron, it splits into two elements each with roughly half the atomic number of the uranium 235 with the release of about 165 million electron volts of energy. This represents an enormous release of energy since the bombarding neutron which produces the disintegration was subsequently found to have only very low or thermal (1/40 volt) energy. For example, one pound of uranium undergoing fission would release about 10 million kilowatt hours of energy or 100 thousand dollars worth of power at the rate of 1 cent per kilowatt hour if it all could be utilized without loss. This striking discovery of nuclear fission naturally stimulated nuclear physicists everywhere to subject the phenomenon to rigorous experimental and theoretical investigation. As a result of this activity it was soon learned that, in addition to the fission of uranium 235 with low energy neutrons, it required high energy (order of 1 million volts) neutrons to produce fission in uranium 238, thorium 232 and in protactinium 231. In investigating a nuclear reaction such as fission, it is necessary to know the cross section S, which the nucleus presents to the bombarding particle in the process as well as the energies and masses involved. This cross section S, or target area, is not necessarily determined by the dimensions of the colliding nuclear particles and may have different values depending upon the particular process occurring. In other words, the cross section indicates the probability of the particular nuclear reaction, i.e., with a S of 10^{-23} cm^2 the reaction is 10 times more probable (or occurs 10 times more often) than if the S was 10^{-24} cm^2. In the case of uranium 235 it was found that not only did very low energy neutrons produce fission, but the cross section S for the process was strikingly large which rendered it quite probable. Also in addition to the large fission fragments, it was reported that from one to three neutrons were emitted per fission. Consequently, if the uranium 235 were pure enough, a chain reaction should start, i.e., each fission process would release enough neutrons to produce more than one additional fission. However, in natural uranium only about 0.71 per cent is uranium 235, the remainder being made up of 0.006 percent uranium 234 and 99.28 percent uranium 238. Furthermore, resonance absorption by uranium 238 for neutrons was found which would capture an important fraction of the higher energy (order of 1 million volts) neutrons released by fission of uranium 235 and thus prevent a chain reaction. Two methods were immediately suggested for resolving the problem. The first method was to purify the isotope 235 by some process of isotopic separation and the other, due to Fermi, was to make use of a substance known as a moderator which could prevent the high energy fission neutrons from being absorbed by the uranium 238. It was suggested that this moderator should be a light element which upon collision with a neutron would not capture it but would collide elastically and thus absorb only a portion of its energy at each collision. If the amount of energy absorbed at each collision is large in comparison with the energy ranges in which the fission neutrons are captured by uranium 238, then the resonance absorption of the neutrons by uranium 238 may be made small enough to allow a sufficient number of neutrons to reach low enough energies and thus produce the requisite additional fission of uranium 235 to give a chain reaction; i.e., if the neutrons produced in each fission of uranium 235 can produce one or more further fissions before they are captured

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by uranium 238 or by the moderator, then a chain reaction occurs. Clearly another factor which enters is the size of the reacting pile of uranium and moderator. If the pile of uranium is too small the neutrons can leak out before they have a chance to produce additional fission and thus are lost. This effect can be somewhat reduced by surrounding the pile of uranium with a material with which the neutrons can collide and be knocked back into the pile. However, for each particular arrangement a critical size of pile is required. At about this time war had started in Europe and since either of the above schemes might lead to a bomb or power plant of military value, the scientists on their own volition and the various governments stopped publication of the results of practically all researches in this field until the atomic bomb dropped on Hiroshima and the subsequent release of the Smyth Report by the War Department Aug. 12, 1945. This report traces the enormous amount of research and developments carried out by the OSRD, the Manhattan District, the Navy and others in producing the chain reaction apparently by both as well as a combination of the above mentioned methods. Space here does not permit even a brief review of the progress made in the five years of the scientific news blackout, so reference should be made to the Smyth Report for this. However, it should be noted that several successful methods were developed for separating the isotopes of uranium and several moderators were found which successfully avoided undesirable capture of the fission neutrons by uranium 238. Also, in Professor Lawrence's laboratory in California, experiments were carried out which showed that, in some cases when uranium 238 absorbed a neutron, it started a reaction which ended up with a new element of atomic weight 239 and atomic number 94. This element was called plutonium and was found to undergo fission with low energy neutrons with the release of large amounts of energy. Consequently, by the proper arrangement of moderators and uranium (enriched and unenriched with uranium 235), known as a pile, it is possible to generate large quantities of heat by the fission process in both uranium 235 and plutonium 239. In this process both uranium 235 and 238 are used up and many new fission products are formed. Obviously such a pile furnishes a vast amount of heat energy as well as an extremely strong source of neutrons.

Judging from the results of reports released by the government, the atomic power plant may become a most promising way of generating energy for industrial use. Statements have been made by responsible investigators that it already might compete with coal commercially in the production of heat in isolated regions. According to Professor J. M. Cork's recent excellent text book on Radioactivity and Nuclear Physics, a very large supply of fissionable materials (uranium and thorium deposits) probably exist which, if properly used, should provide the whole world with ample power for many generations yet to come. Although undoubtedly the government has much information that has not been released, it is a good guess that the production of nuclear energy is today in a comparable stage of infancy with the electrical industry at the time of Faraday and Henry, or the automobile industry at the beginning of the present century. It is almost a certainty, if disastrous war can be avoided, that scientific and technical ingenuity eventually will transform the nuclear power plant into a great boon to all mankind. In addition to this direct use of nuclear power the by-products of the atomic plant already are being used in many types of physical, chemical, biological and medical researches.

It may be of interest briefly to mention the great natural atomic power plant to which we are all indebted for our present existence. It has long been a puzzling question as to how the sun maintains its constant temperature. Calculations show that if no heat were generated within the sun, its temperature would fall about 15°C per year due to the enormous amount of heat radiated into space. Since no such lowering of temperature has been observed, the heat must be generated in some way within the sun. From a knowledge of conditions existing on the sun together with extrapolations to conditions far below its surface, Bethe and others have devised various nuclear reactions which might take place at the proper rate to account for the generation of the sun's energy. These nuclear reactions in the sun apparently are not nuclear fission reactions, but take place between the lighter elements. They are believed to include the formation of helium from hydrogen by a cyclic process involving carbon, nitrogen and oxygen. The presence of such great atomic power plants in nature, such as the sun and stars in which the common lighter elements are having their mass turned into heat at a steady rate, presents a great challenge to the future nuclear physicists. The magnitude of this challenge looms all the more enormous when it is

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realized how little is really understood about the nucleus at the present time. Strange and undetermined forces apparently exist in the nucleus and even the theory of mechanics which has been so successful outside the nucleus evidently does not apply inside, at least in its present form. Such important questions as to why we have an elementary unit of charge such as the electron or why energy is always emitted or absorbed in multiples of $h\nu$, etc., are still unanswered. We believe that at least some of the cosmic rays which bombard the earth from outer space have energies thousands of times greater than could be obtained by the complete disintegration of any known atom. These cosmic rays, upon colliding with the elements in our atmosphere sometimes cause them to burst into a great many fragments, etc. Evidently, the path is mostly unknown and, no doubt, full of pitfalls, but the goal is great.

Finally, before closing, it might be appropriate in an engineering magazine such as this, to hazard a brief guess concerning the possible effect of the new atomic power development on scientific and engineering education in the University. Certainly in the next decade or so, if we are to have successful atomic power plants coming into general use, university graduates must be properly trained to direct their operation. The potential dangers inherent in the operation of such powerful sources of energy as atomic piles will require at least for some time to come, the highest technically trained personnel possible and such personnel cannot be found in sufficient quantity outside the universities. The University of Virginia together with several other southern universities already have very wisely taken a lead in establishing the Oak Ridge Institute of Nuclear Studies at Oak Ridge, Tennessee for the above purposes. In the near future, it should be possible for a limited number of properly qualified and acceptable students or faculty members at Virginia to take advantage of the most excellent facilities at Oak Ridge to carry out researches in the fields of natural science, engineering and medicine.

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