THE RELEASE OF ATOMIC ENERGY*

By Prof. M. L. OLIPHANT, F.R.S.

University of Birmingham

APPROXIMATELY fifty years ago the French scientific worker Bequerel discovered that certain minerals containing uranium possessed the property of producing energy in small amounts spontaneously, and apparently continuously. The Curies showed that the active substance responsible for this radioactivity in uranium minerals was not uranium itself, but was a small admixture of the rare element radium, which they were able to isolate. The activity of this concentrated material was so great that a mass of a gram of one of its salts maintained itself permanently several degrees hotter than its surroundings.

The disentangling of the complicated series of changes through which radium passes on its way to become lead was due almost entirely to Rutherford and his colleagues. Rutherford's youthful enthusiasm in Montreal was devoted to radioactivity. Nuclear physics, which he created, remained his one real interest throughout his life. The great advances in our understanding of this complex, submicroscopic subject, which has culminated in the atomic bomb, were all due to him and to that enthusiasm which he communicated to all who worked with him. It is interesting to notice that progress in this subject, which until now has been of purely academic interest, has been greater than in many branches of physics which are much more straightforward, but to which no Rutherford has devoted his genius.

Rutherford and his school established that the energy changes associated with radioactive transformations were very large in comparison with the energies associated with chemical change. It is customary in atomic physics to measure energies in terms of the energy acquired by an electron in falling through a potential of 1 volt—the 'electron-volt'. The energy associated with the motion of molecules is only 1 electron-volt for each 10,000° in absolute temperature, so that even in the surface of the sun, the average energy of atoms is less than 1 eV. The energy given out per atom of carbon (coal) burnt in oxygen is about 4 eV. The energy emitted by atoms as visible light is a few electron volts. In contrast with these the energy associated with radioactive change is millions of electron-volts. Indeed, inside the nucleus it is common to employ as the unit of energy 1 MeV. Realization that changes in the nuclei of atoms were accompanied by energy emission or absorption millions of times greater than are available in chemical reactions led at once to speculation about the possibility that this energy might one day be released for the use of mankind. Rutherford was always sceptical about this possibility, but success has come eight years after his death.

Rutherford and Soddy showed that the radioactive change which resulted in the emission of charged particles from the nucleus produced also a change in the chemical nature of the atom—the substance was spontaneously transmuted. There followed those brilliant researches, so simple in concept and so far-reaching in their results, by Rutherford and his collaborators, on the scattering of α-particles by matter. Thus he initiated the modern method of nuclear research, the bombardment of elements by

high-speed particles. The first fruit of this study of scattering was the formulation, with Bohr, of the nuclear model of the atom. The second was the discovery in 1919 of the artificial transmutation of matter—the transmutation of nitrogen into oxygen by bombardment with α-particles.

Since that time nuclear physics has followed almost as a matter of course. It was in Rutherford's laboratory that atomic transformation with artificially accelerated particles was first achieved by Cockcroft and Walton in 1932, and there, in the same year, Chadwick discovered the neutron. These two discoveries led to spectacular advances, especially because the method of artificial transmutation gave large yields of neutrons.

The absence of electric charge rendered these new neutral particles very efficient agents with which to penetrate inside the nucleus, and Fermi showed that they produced transformations in the majority of the elements. It was the unsatisfactory nature of Fermi's conclusions about the reactions produced in uranium which led Hahn to make a detailed study of the products by chemical methods. Hahn, at one time a pupil of Rutherford, proved that the uranium nucleus, after absorption of a neutron, sometimes underwent a complete splitting into two single elements, so discovering the unexpected phenomenon of nuclear fission.

With this brief history in front of us, can we doubt that the modern release of nuclear energy is almost wholly the fruit of Rutherford's genius ?

Bohr has given a simple and satisfactory qualitative picture of what happens when a neutron invades a nucleus. With Wheeler he has developed a model based upon the fact that the interactions between particles inside the nucleus, which he regards as made up of protons and neutrons, are so strong that an incoming particle must react with them all, that is, with the nucleus as a whole. This is in direct contrast with the action of a moving charged particle on the outer electronic structure of the atom, where, because of the loose interaction between them, individual electrons are excited to higher states, or are removed completely from the atom. In a nuclear collision which imparts energy to the struck nucleus the whole of the energy is shared among the particles, or in other words the nucleus is 'heated'. Because there are a finite number of particles in the nucleus there will exist well-defined energy levels for small or moderate excitations; but for an added energy of several million volts the system of levels will have crowded to a continuum.

For small excitation there may exist resonance levels for capture of neutrons; that is, over a restricted energy range, depending on the 'width' of the levels, the probability of capture may be extremely high as compared with that for energies on either side of these particular bands. If the energy of the neutron is large, or if the continuum of energy levels occurs for low energies, the probability of capture will not depend strongly on the kinetic energy of the neutron but will fall off slowly with increase of energy.

These models of neutron capture can be illustrated by the differences between the behaviour of the two isotopes of uranium, ^{238}U and ^{235}U.

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The probability of capture by ^{238}U is vanishingly small for slow neutrons except for a pronounced resonance at neutron energy of about 38 eV. Capture of neutrons into this energy band produces a nucleus of mass 239. This isotope of uranium is unstable, emitting a beta-particle and transforming into an element of atomic number 93, or 'neptunium'. Neptunium itself is unstable and transforms, by emission of a further beta-particle, into element 94, or 'plutonium'.

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U \xrightarrow{e^-} ^{239}_{93}Np \xrightarrow{e^-} ^{239}_{94}Pu.$$
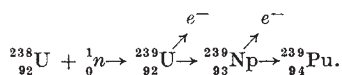
Plutonium is a comparatively stable substance. It is radioactive, emitting alpha-particles and transforming to $^{235}_{92}U$, with a half-period of a few tens of thousands of years.

$$^{239}_{94}Pu \longrightarrow ^{215}_{92}U + ^{4}_{2}He + energy.$$
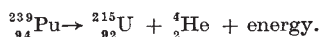
Neptunium and plutonium do not exist on earth because they are too short-lived to have survived, and there is no natural process by which appreciable quantities can be formed in uranium.

Uranium of mass 238 captures neutrons of energy greater than about 1 MeV., the neutron entering into the region of continuous energy levels. Bohr's picture of the process is then :

The uranium nucleus captures a neutron and becomes very 'hot'. The oscillations of the heated drop result in conditions which in a very short time lead to a splitting of the nucleus into two parts, the parts separating with tremendous energy. This is the phenomenon of nuclear fission, which was discovered by Hahn and verified by Meitner and Frisch. The break-up does not take place always in the same way and the relative masses of the products vary over a wide range, with a maximum probability that the ratio of the masses is about 2 : 3.

The energy with which the fission products separate is about 180 MeV. This energy is produced because the products together have a mass less than that of the original 'hot' composite nucleus, the mass ΔM which disappears being transformed into kinetic energy in accordance with Einstein's relation, $W = \Delta M . C^2$, where C is the velocity of light.

Uranium-235 differs from uranium-238 in that it is raised to a high enough state of excitation to undergo fission by the entry of a neutron of any energy. The probability of fission of ^{235}U for slow neutrons is large, varying with increasing energy inversely as the velocity.

Plutonium behaves in a very similar way, under-going fission after capture of a neutron of any energy.

Thorium, like ^{238}U, undergoes fission as a result of the absorption of fast neutrons only.

In all cases the products of fission are themselves radioactive, emitting one or more beta-particles before becoming stable elements.

This simplified picture of the fission process is not complete. There are secondary products of fission, just as there is spray produced when a liquid drop is pulled apart, or dust when a stone is shattered. Joliot and his co-workers showed, shortly before the War, that these secondary products are neutrons, there being on the average more than two neutrons liberated per fission, the neutrons being ejected with an average energy of a little less than 1 MeV. This observation rendered it immediately obvious that a chain process was possible, since these neutrons could cause fission in other uranium nuclei. Provided the difficulty of competitive absorption of neutrons by ^{238}U could be overcome, it was clear that there existed the possibility of power production and of an atomic bomb. The problem reduced to one of technology and of the evaluation of the exact conditions under which chain reactions actually occurred.

Suppose we imagine a mass of pure uranium metal and try to understand what would happen to the neutrons liberated in a fission process occurring near the centre of the mass. The neutrons are not fast enough on the average to initiate fission of ^{238}U. The isotope ^{235}U is present in natural uranium only to the extent of 0.7 per cent—approximately 1 part in 140 of the metal. Consequently the probability of collision between these neutrons and ^{235}U is much smaller than for collisions with ^{238}U. The neutrons have a long free path, and unless the mass of metal is large they will escape from the exterior before they can produce fission in fresh ^{235}U nuclei. If the mass is very large and is extremely pure, so that the life-time of neutrons is long because they are not captured by other substances, collision with uranium nuclei will reduce the energy slowly. The energy lost in a single collision is very small because of the large mass difference, and the neutrons will therefore hang about for a long time in any given energy state. The probability of capture into the resonance level of ^{238}U thus becomes large. There is likely, therefore, to be too great a loss of neutrons by absorption which does not lead to fission, for a chain reaction to be produced in a mass of uranium metal, however large, though this is not quite certain.

Two methods have been devised to ensure that a chain reaction will take place in a finite mass of uranium.

The first is to slow down the neutrons very rapidly by collision with some material such as heavy water (deuterium) or graphite (carbon) so that the chance of resonance capture by ^{238}U is reduced, and the probability of fission of ^{235}U is increased. Heavy water or graphite is used because neither captures neutrons readily, as does ordinary water. This gives a system operating on neutrons of thermal energy or there-abouts, and is probably the best procedure for power production.

The second method is to concentrate the ^{235}U so that the fast fission neutrons have a proper chance of producing a chain reaction directly ; or alterna-tively to prepare plutonium in quantity by first operating a slow-neutron reacting system. Such a fast-neutron chain reaction gives an extremely rapid multiplication of fissions and proceeds at a super-explosive rate—the atomic bomb.

The slow-neutron chain is best achieved with ordinary uranium metal by the use of graphite as a 'moderator' to slow down the fission neutrons. The arrangement used is a so-called 'heterogeneous pile', consisting of some tens of tons of uranium rods or slugs disposed in a calculated 'lattice' throughout a mass of some hundreds of tons of graphite, which is just a dense form of carbon. Fission neutrons which escape from one of the rods, in which there is a very

small chance of capture, pass into the graphite where, by successive collisions, they lose energy rapidly. The chance that they encounter a ^{238}U nucleus before they are slowed to energies below the resonance level is greatly reduced, and when the neutrons do diffuse to a uranium rod again they are readily captured by the ^{235}U and give rise to further fissions.

For the slow-neutron chain reaction to take place, the size of the system must be greater than a critical size, where the escape of neutrons from the surface is not greater than the rate of production. Some of the neutrons produced in fission are delayed, that is, they are emitted only after an interval of as much as one second. This means that for a system which is only just above critical size the exponential increase in the rate of fissions takes place rather slowly. By inserting into the pile rods of a material like boron or cadmium, which absorbs slow neutrons readily, the multiplication can be prevented altogether. Slow withdrawal of these rods allows the reaction to begin, and there is then plenty of time to reinsert them if the multiplication rises too rapidly. Adjustment of the rods can be carried out automatically by use of equipment like a thermostat, which sets the position of the absorbing rods so that the system runs continuously at any desired energy level.

The critical size of the system obviously depends upon the precise arrangement of the uranium and graphite and upon whether the surroundings reflect back any of the neutrons which escape from the surface. The fission energy is degenerated by collisions into heat, and the rods become hot. This heat may be extracted by cooling the rods, either by blowing gas such as air, hydrogen or helium, past them, or by surrounding them with a concentric tube through which water flows.

Unfortunately, uranium is very active chemically, and in particular it is very easily oxidized by contact with air or water. To prevent this the uranium rods or slugs must be coated with a layer of resistant metal which is in good thermal contact, but which does not absorb neutrons appreciably. There are very few metals which fulfil these conditions, and aluminium is the only one which has been applied in practice. It is necessary to keep the temperature of the air or water in contact with pure aluminium below about 100° C. in order that corrosion of the aluminium itself should not occur. Hence, at the present time, energy can be extracted only at temperatures of about 100° C., which is much too low for the operation of an efficient heat engine. The coating on the rods serves also to keep the products of fission from escaping into the cooling air or water. The fission products, which are highly radioactive, must be kept out of the machinery, pumps, etc., which have to be serviced, and must not be allowed to pollute the air or streams of water. The amount of heat which may be extracted from uranium rods or slugs is limited also by the low heat conductivity of the metal.

The size of the pile required to obtain a reacting system is obviously very large—how large can be judged from the fact that the first such system was built up on a squash court. The pile itself must be surrounded by coatings of graphite alone, to reflect back neutrons, and the whole enclosed in absorbing walls of concrete to prevent the escape of harmful radiations. Elaborate precautions are necessary to prevent accident. Materials inside the pile become so strongly radioactive that methods of handling them from a distance become essential, and all

chemical operations on the uranium removed from the system have to be carried out in such a way as to prevent injury to the operatives by radiations from the accumulated fission products. Notwithstanding all these difficulties, piles have been operated at power levels of hundreds of thousands of kilowatts for months at a time.

The size of a reacting system can be reduced greatly by using uranium in which the concentration of the ^{235}U has been increased by partial separation of the isotopes or by adding another fissile element, for example, plutonium, to the metal.

Not all the neutrons in the pile escape capture by ^{238}U. There is a continuous production of plutonium, the concentration of which grows until it is destroyed as fast as it is formed. This plutonium, being chemically different from the uranium, can be separated from it by chemical methods. By suitable choice of the lattice the production of plutonium can be given an optimum value. This is the method used for producing plutonium in quantity. The rate of production of the element turns out to be about 1 kgm. per day for each million kilowatts of heat energy released. All this energy is dissipated at present to heat the Colombia River !

The possibility of using nuclear energy for industrial purposes clearly depends upon the solution of engineering and metallurgical problems of extraction of the heat at a temperature high enough for the efficient operation of heat-engines. There remains the question of the economics of the process as compared with the burning of coal or oil.

We have seen that because ^{235}U or plutonium undergoes fission for neutrons of any energy, a mass of such material which is large enough will develop an explosive chain reaction through the direct multiplication of the fission neutrons. Plutonium for the purpose can be produced in large 'piles', or ^{235}U may be separated from natural uranium by one of the processes, such as diffusion of a gaseous compound of uranium through a membrane, or by means of large mass-spectrographs, which have proved successful in the laboratory. Whether we require plutonium or ^{235}U, the plant is extremely large, complex and costly.

The critical size of a fast-neutron reacting system is far smaller than that of a slow-neutron system with ordinary uranium metal. The critical radius for a sphere of the material will clearly be of the order of magnitude of the free path of a fission neutron for capture by a fresh fissile nucleus, and this is of the order of 10 cm. The critical mass must then be of the order of 10–30 kgm. The critical mass will depend on the shape and the nature of the surroundings. A mass of fissile material which is smaller than the critical mass for the particular shape is perfectly stable. If two such masses are brought rapidly together the composite structure may be several times the critical mass, and if a neutron source is then activated inside the system the whole will immediately react violently. The time of passage of a fast neutron across the mass of fissile material is about 10^{-8} sec., so that in a microsecond or two the number of fissions will have multiplied to a stage where the temperature has risen to tens of millions of degrees and the pressure will have reached tens of millions of atmospheres. The glowing mass is far brighter than the sun itself and the radiation sears and scorches everything upon which it falls. The blast created by the expansion of the heated gases gives the great destructive effect.