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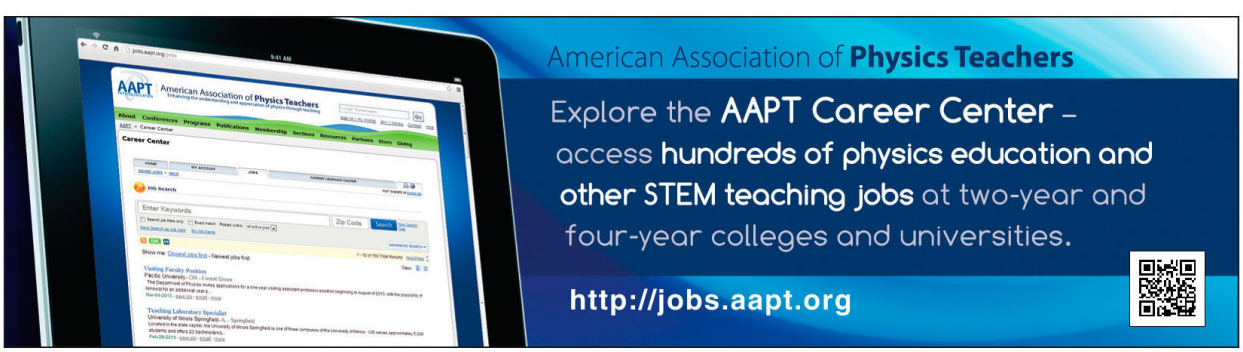

Equation (10) with $x_0 = 1$ is to be compared with Wall's Eq. (31)[2] and with James and Guth's Eq. (6.12)[3].

Even for small extensions of an elastomer the elastic force is not proportional to the elongation, as would be the case if Hooke's law applied. As a matter of fact, the general law, Eq. (9), yields a sigmoid curve, which is typical of rubber and other elastomers. Successful applications[3] of this law to natural and synthetic rubbers lend support to the belief that the foregoing analysis is essentially correct. It should be noted, however, that for vulcanized and filled samples the effective chain lengths are reduced by introducing the concept of fix-points. These have the effect of decreasing the number of links per chain and, therefore, of increasing the q-value of the sample. Consequently, the sample becomes more rigid and less resilient.

From the general law for elastomers it is immediately evident that a larger force must be applied at elevated temperatures to produce the same amount of elongation as at room temperature. In other words, an elastomer behaves as though its effective Young's modulus were increased by a rise in temperature. This conclusion is in agreement with the well-known thermoelastic properties of rubber. For quantitative applications, ordinary thermal expansion must be taken into account.[6]

The elasticity of animal tissues has long been recognized to be much like that of rubber.[7] An extension of the foregoing analysis to cylindrical tubes with elastomeric walls yields a pressure-volume relation that describes fairly well experimental results on the human aorta.[8] Furthermore, systems manifesting superposed elastic and viscous behavior have been studied in terms of the present theory.[9] The general law for an ideal elastomer has been employed in a variety of problems with marked success.

[6] S. L. Dart and E. Guth, *J. Chem. Physics* **13**, 28 (1945).
[7] C. S. Roy, *Foster's J. Physiol.* **3**, 125 (1880).
[8] A. L. King, to be published in *J. App. Physics* **17** (1946).
[9] A. V. Tobolsky and R. D. Andrews, *J. Chem. Physics* **13**, 3 (1945).

A Brief Account of the Physics of the Atomic Bomb

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THE atomic bomb comes as a climax to an era in physics which may be said to have started about 50 years ago with the discovery of radioactivity by Becquerel. Underlying the theory of the release of atomic energy is the principle of the equivalence of mass and energy, $E = mc^2$, discovered by Einstein in 1905. During the early 1930's the rate at which fundamental discoveries were made in physics was considerably accelerated. Thus in 1932 Cockroft and Walton effected the first artificial transmutation; Chadwick discovered the neutron, and Anderson the positron; Urey, Brickwedde and Murphy discovered deuterium; and the cyclotron and Van de Graaff machines were first developed. Artificial radioactivity was discovered by Curie and Joliot in 1933.

It was in 1934 that Fermi and his collaborators bombarded uranium with neutrons in the hope of producing the transuranic elements of atomic numbers 93 and higher. Prior to this, these investigators had shown that nearly all elements could be made radioactive by bombardment with neutrons. The problem of identifying the products resulting from the bombardment of uranium by neutrons was by no means an easy one, for not only is the chemistry difficult but the amounts of the substances produced are extremely small. An account of the experiments of Fermi and others is contained in an article by Turner[1] on "Nuclear Fission."

The problem of producing transuranic elements was of course very exciting, and many physicists and chemists turned their attention to it as will be seen by looking at the long list of references given in the article by Turner. A

[1] L. A. Turner, *Rev. Mod. Physics* **12**, 1 (1940).

quotation from this article shows how the apparently contradictory results of different workers were finally explained:

> In a second paper [Hahn and Strassmann, January 1939] they gave the details of a most beautiful and thorough set of experiments which showed beyond a doubt that both "Ra III" and "Ra IV" were actually isotopes of barium rather than of radium. Further, the 15-min and the ~4 hr "Ra's" obtained from bombarded thorium were likewise shown to be isotopes of barium.

This was a type of disintegration previously unknown in nuclear physics; for now, in place of relatively light particles being ejected from an activated nucleus, the activated uranium and thorium nuclei had broken apart into comparatively heavy particles, one of which was identified as barium. The excitement which this discovery produced may be judged from the fact that nearly 100 papers on the subject were published in 1939.

As is well known, the name *fission* was given to this phenomenon of the breakup of the uranium or thorium nucleus. Later it was shown that protoactinium could also show fission. The work in 1939 demonstrated that there was an enormous release of energy at fission—about 200 Mev per atom of uranium; that there were about 30 fission products associated with fission, barium being one of them; that these fission products were radioactive; that neutrons were also ejected on fission. Bohr and Wheeler[2] showed theoretically that the two important isotopes $_{92}U^{238}$ and $_{92}U^{235}$ behaved very differently towards fission and that it was the 235 isotope, having a relative abundance of 1 part in 140, which was primarily responsible for the fission phenomenon.

All this information appeared to some physicists to be of considerable importance to a world at war. The neutrons which are ejected at fission might perhaps be used to induce further fission and this in turn additional neutrons, thus producing a self-sustaining atomic chain reaction with an enormous release of energy. In other words, an atomic bomb might be possible. The British physicists, too, felt that a military weapon of vital importance might be based on the phenomenon of fission. Even with the war pressing them as it was in 1940, research in this field was carried on in the British Isles. Fears were heightened when it was discovered that Germany was pursuing research in nuclear fission.

After it was decided to investigate further the possibility of the atomic bomb, nuclear physics became a secret field of investigation. As is well known, two official reports have recently been published on the work accomplished during the war.[3,4] These documents represent the official release of information at present and, though a great amount of information is still secret, the interested reader will find it profitable to read them.

Bohr and Wheeler[2] predicted theoretically, and it was later confirmed experimentally, that the more common isotope of uranium, $_{92}U^{238}$, undergoes fission only when bombarded with high energy neutrons, and this to a relatively small extent; on the other hand, that the rarer isotope, $_{92}U^{235}$, would not only undergo fission to a small extent with high energy neutrons but also to a considerable extent with low energy, or thermal, neutrons. These qualitative statements concerning the relative extent of fission are expressed quantitatively in terms of cross section for fission, but their actual values still remain in the realm of secrecy. Another point of difference in the two isotopes is that $_{92}U^{238}$ can absorb neutrons of a "resonance" energy without undergoing fission. This resonance energy lies in the region above the thermal energies: from 1/40 to about 1000 ev. The probability of this kind of nonfission absorption in $_{92}U^{238}$ is very high. As was found by the Radiation Laboratory at the University of California, this nonfission absorption gives rise to the transuranic elements neptunium, atomic number 93, and plutonium, atomic number 94, through two successive beta-particle emissions as shown by the equations:

$$_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} + \text{gamma-rays},$$

$$_{92}U^{239} \xrightarrow[23\ \text{min}]{} {}_{93}Np^{239} + {}_{-1}e^{0},$$

$$_{93}Np^{239} \xrightarrow[2.3\ \text{da}]{} {}_{94}Pu^{239} + {}_{-1}e^{0} + \text{gamma-rays}.$$

[2] N. Bohr and J. A. Wheeler, *Physical Rev.* **56**, 426 (1939).

[3] H. D. Smyth, *A general account of the development of methods of using atomic energy for military purposes under the auspices of the United States Government, 1940–1945* (Princeton Univ. Press); also, *Rev. Mod. Physics* **17**, 351 (1945).

[4] *Britain and the atomic bomb* (British Information Service, 1336 New York Ave., NW, Washington 5, D. C.); also, *Rev. Mod. Physics* **17**, 472 (1945).

The 23 min and 2.3 da are the half-life times of the radioactive elements. Plutonium, $_{94}Pu^{239}$, does emit alpha-particles and so decays to $_{92}U^{235}$, but the rate of emission is so slow that plutonium is in effect a stable element. As regards fission, plutonium is very similar to the rarer isotope of uranium, $_{92}U^{235}$.

With this information available the policy committee in charge of the atomic-bomb project had to investigate the various means of obtaining rapidly either $_{92}U^{235}$ or $_{94}Pu^{239}$, or both, in quantities sufficient to make bombs. A great deal of attention was paid to the possible methods of separating $_{92}U^{235}$ from the natural material. This was by no means an easy task; a brief discussion of it will be given later.

First, a few of the problems involved in producing plutonium must be considered. This task was undertaken under the direction of A. H. Compton, as Director of the Metallurgical Laboratory of the University of Chicago, with E. Fermi, of Columbia University, and E. Wigner, of Princeton University, in charge of the experimental and theoretical work, respectively. To produce plutonium, neutrons must be absorbed by $_{92}U^{238}$. As was previously stated, this absorption takes place at neutron energies between approximately 1/40 and 1000 ev. The neutrons available for this resonance absorption must come from those released at fission, which come off with energies of the order of 1 Mev. Also, if this reaction is to be self-sustaining, at least one of the neutrons released from fission of each uranium atom must, after being slowed down to thermal energies, remain to produce fission in another uranium atom. Thus, if the reaction is to be self-sustaining, the reproduction factor, denoted by k, must be unity or greater.

As has just been mentioned, there must be some means for slowing down the fission neutrons to thermal energies. This slowing down may be accomplished by allowing the neutrons to collide with light atoms—the lighter the better, since the neutron mass is almost the same as that of the hydrogen atom. Thus, the elements at the beginning of the periodic table are the most effective in slowing down—in acting as "moderators"—for the neutrons. To get the reproduction factor k up to unity, so that a chain reaction may take place, these moderators must not absorb neutrons. This requirement rules out hydrogen, lithium, and boron as moderators. Deuterium and beryllium were ruled out because of their unavailability; helium was ruled out because it is a gas and forms no compounds. Thus the most suitable moderator material was carbon, in the form of graphite blocks. This graphite had to be considerably purer than the usual commercial types.

The chain-reacting system used consisted of blocks of uranium or uranium oxide placed at some distance from one another in a lattice arrangement among the blocks of graphite. This was referred to as "a graphite pile," or simply as a "pile." In determining what geometric arrangement of uranium and graphite would produce the best value for k (greater than unity), it was not necessary to attempt to build a chain-reacting pile; instead, experiments could be made on a smaller unit called an "exponential" pile. In this unit a neutron source, radium-beryllium, was placed at the base of the uranium-graphite pile, and the thermal neutron intensity at various points in the pile was determined by measuring the activity of foils of some suitable material such as indium placed at these points. Since the neutron intensity decreases exponentially with increasing vertical distance from the neutron source, the piles were called exponential piles.

With the materials available, and with a particular geometric arrangement, Fermi reported a value of 0.87 for k in the fall of 1941. A lattice structure of graphite and uranium in the form of a cube about 8 ft on a side was used. The importance of a lattice structure lies in the fact that it reduces nonfission capture in $_{92}U^{238}$. Unless this is done the value of k would be too small for a chain reaction to take place. By July 1942 the value of the reproduction factor as calculated from the exponential pile experiments had exceeded unity; actually it was 1.007.

Before proceeding with a discussion of the chain-reacting pile, we shall briefly discuss the energy release and also the theory of a pile. The energy released on fission may be accounted for by the difference in the masses of the activated uranium nucleus and of the fission products into which the uranium nucleus splits. An approximate value of the energy given out may be obtained from the mass defects of the atoms in-

volved; it is calculated from the packing fraction curve. The packing fraction f of an atom is defined by the equation

$$f=(M-A)/A, \quad (1)$$

where M, is the isotopic mass of the atom and A is the mass number, that is, the total number of protons and neutrons in the nucleus of the atom. If M_0 is the mass of the nucleus before fission, and M_1, M_2 are the nuclear masses of the fission products, then by Einstein's mass-energy relationship the energy ΔE released on fission is

$$\Delta E=c^2(M_0-M_1-M_2).$$

Introducing packing fractions from Eq. (1), we have

$$\Delta E=K[A_0(1+f_0)-A_1(1+f_1)-A_2(1+f_2)],$$

where f_0, f_1, f_2 are the packing fractions of the atoms of mass numbers M_0, M_1, M_2, respectively, and K is a conversion factor which, if ΔE is to be in terms of 1 Mev, is approximately equal to 931. Since A_0, the mass number of the activated uranium nucleus, must be equal to the sum of A_1 and A_2, the mass numbers of the fission products, it follows that

$$\Delta E=K(A_0f_0-A_1f_1-A_2f_2).$$

Though the fission of every uranium atom does not give rise to the same two kinds of atoms, the fission products lie in two groups, a heavy one of atomic number ranging from 127 to 154, and a light one whose atomic number lies between 83 and 115; nevertheless, for these atoms the packing fractions are negative and approximately the same. Using as an example, $A_1=140$ and $A_2=96$ and using the packing fraction for these atoms and for uranium such as may be found approximately in the form of a curve in many textbooks,[5] one finds that the release of energy for each fissionable atom is approximately 200 Mev.

For the heavy elements such as uranium, the mass number A is much larger than twice the atomic number Z; that is, there are many more neutrons than protons in uranium. On the other hand, for stable atoms near the middle of the periodic table, A is approximately equal to $2Z$. Thus, when the uranium nucleus divides, it cannot break down into two stable atoms. For instance, if one of the fission products is $_{56}Ba^{140}$, which is a stable isotope of barium, the other would have to be of atomic number 36 and atomic mass 96. The heaviest isotope of krypton, $Z=36$, has a mass of 86. Hence to attain stability there must be ejected from this latter nucleus a total of ten neutrons and electrons since the ejection of an electron is equivalent to the transformation of a neutron into a proton. The fission process then is accompanied by the emission of neutrons as well as by the production of highly beta-radioactive substances.

Now let us consider the theory of a chain-reacting pile by considering the life cycle of neutrons in a pile. Suppose at the start there are N high energy fission neutrons released in the graphite-uranium pile. On the average the energy of these N neutrons is above the threshold energy for producing fast fission in $_{92}U^{238}$ but, by collision with atoms of uranium and carbon, their energy is diminished and reaches the threshold value. Fission can be produced by some fast neutrons, and the original number N is increased by a small factor ϵ, which is called the *fast-fission effect*, or *fast multiplication factor*. The energy of the $N\epsilon$ neutrons is further reduced as the neutrons diffuse through the carbon and the resonance-energy capture region is reached. This neutron capture is taken into account by multiplying the number $N\epsilon$ of neutrons by a factor p, called the *resonance escape probability*, which is less than unity. The resonance escape probability is the probability that a given neutron starting with energy above the resonance region will reach thermal energy without capture in $_{92}U^{238}$. Thus of the original N high-energy neutrons there are $N\epsilon p$ neutrons that attain thermal energy.

Not all these neutrons are absorbed by the uranium since some are absorbed by the graphite and any other substance in the pile. There is a certain probability that a thermal neutron will be absorbed in the uranium, and this is expressed by a factor f called the *thermal utilization factor*. Thus there are $N\epsilon pf$ thermal neutrons absorbed in the uranium. Each thermal neutron absorbed by the uranium produces on the average η high energy fission neutrons. The final result is that

[5] Richtmeyer and Kennard, *Introduction to modern physics* (McGraw-Hill), p. 590.

$N\epsilon pf\eta$ high energy neutrons are produced. If this number exceeds the original N, or if the quantity $\epsilon pf\eta$ is greater than unity, a self-sustaining chain reaction can take place. This assumes that there is no loss of neutrons by escape from the pile, which would be the case only if the pile were of infinite size. If k_∞ is the value of the reproduction factor for a pile of infinite size, then $k_\infty = \epsilon pf\eta$.

The critical size of a pile is that for which the production of free neutrons by fission is just equal to their loss by escape and nonfission capture. If the size is smaller than the critical size, no chain reaction can take place. In other words, k is less than unity for this pile,

We have already stated that in the exponential experiments a value for k greater than unity was obtained in the summer of 1942. By the fall of that year enough graphite, uranium oxide, and uranium metal were available to justify the construction of a self-sustaining pile. Since only 6 tons of pure uranium metal were available, the remaining lattice spaces had to be filled with the oxide. Instruments such as ionization chambers and Geiger counters filled with BF_3 or air were used to measure the neutron density and gamma-ray intensity as the pile was being constructed. Movable control rods made of cadmium metal and boron steel, both of which strongly absorb neutrons, were inserted in the pile so that the neutron density could be changed. Pushing in the control rods diminished the neutron density and lowered the value of the reproduction factor k. The pile began to operate on December 2, 1942 at a power of $\frac{1}{2}$ w. This was the first self-sustaining atomic chain reaction known to man! The power was then increased to 200 w but, since these experiments were being performed in a city, it was decided for reasons of safety not to increase the power further and the pile was dismantled. Early in 1943 a somewhat larger pile was built—the Argonne plant, just outside the city of Chicago. A 1000-kw air-cooled experimental pile was built at Clinton, Tennessee. These served as pilot plants for testing materials and processes for the production plant at Richland, Washington.

Once the uranium had been in a pile for a suitable time it had to be taken out and chemically treated for the extraction of the plutonium. In the Richland pile, which operated at a high and secret power level, the uranium blocks were enclosed in tight aluminum cases and placed in long aluminum cylinders through which water flowed for cooling. Since the activated uranium contained all the fission products, each of which was highly radioactive, the chemical separations were by no means easy.

In the early days when plans were being made, it was decided to investigate as many means as possible for obtaining the rare isotope $_{92}U^{235}$ from natural uranium. Altogether, four methods for the separation of $_{92}U^{235}$ were considered, namely, gaseous diffusion, centrifugation, thermal diffusion, and the electromagnetic method. Only a pilot plant was built using centrifuges. Work on gaseous diffusion was begun at Columbia University in 1940 under H. C. Urey and J. R. Dunning. The principle of operation is that in a mixture of two gases of molecular weights M_1 and M_2, respectively, the two components would diffuse through a porous barrier into an evacuated space at different rates.

Let us consider the gas, uranium hexafluoride, the two components of which, $U^{235}F_6$, $U^{238}F_6$, with molecular weights of 349 and 352, respectively, diffuse at different rates. In the ideal case the rates of diffusion are inversely proportional to the square roots of the molecular weights. If a small quantity of uranium hexafluoride diffuses through a porous barrier, the diffusate is enriched in $U^{235}F_6$ by a factor of $(352/349)^{\frac{1}{2}}$, or 1.0043. For an ordinary sample of uranium the relative concentrations of the 235 and 238 isotopes is 1 to 140. If a relative concentration of 9 to 1 is desired, there has to be an enrichment factor of 9×140, or 1260. If the ideal enrichment factor on passing once through a single barrier is 1.0043, then it can be seen that there must be a considerable number of multiple-stage recycling diffusion units in order to reach the relative concentration of 9 to 1. A large production plant covering several acres and working on the gaseous diffusion principle was built at Clinton, Tennessee.

The other method of isotope separation which proved successful was the electromagnetic one for which E. O. Lawrence, of the University of California, was responsible. In this method the ions of the uranium isotopes are accelerated in an electric field, and the beam is bent by a magnetic

field so that the 235 isotope is brought to a focus at a different place from the 238 isotope, as in the electromagnetic spectrograph. If the limiting slits in the apparatus are narrow, the enrichment factor will be high but the yield will be small. A large number of production units were put into operation at Clinton, Tennessee. This was the first of the methods to produce the 235 isotope in quantity. By starting with uranium which was already enriched somewhat in the 235 isotope, the yield is considerably increased. As stated in the Smyth report, "an electromagnetic unit that could produce one gram a day of 40 percent pure U-235 from natural uranium could produce two grams a day of 80 percent U-235 if the concentration of U-235 in the feed material was twice the natural concentration (1.4 percent instead of 0.7 percent)." Owing largely to the work of P. H. Abelson, of the Naval Research Laboratory, a thermal diffusion[6] plant was set up and operated for the purpose of supplying enriched feed material to the electromagnetic separator. This increased the production rate of $_{92}U^{235}$ considerably.

The purpose of all this work during wartime was to forge the powerful weapon which has come to be known as the atomic bomb. This work was placed in the charge of J. R. Oppenheimer, of the University of California, and was eventually located at Los Alamos near Santa Fe, New Mexico. What is needed in a bomb is a sudden release of energy. An atomic bomb has to be so constructed that a large fraction of the uranium nuclei undergo fission before the materials composing the bomb become appreciably separated. Separation of the uranium would mean that neutrons would escape, and thus the chain reaction would stop before all the fissionable material was consumed. Fission in this case must be caused by fast neutrons, for the time duration of the chain reaction, if it is to be efficient, must be extremely small. Just as in the huge graphite-uranium pile, where graphite was used on the outside as a neutron reflector to reduce the critical size of the pile, so a reflector may be used to reduce the critical size of the bomb. In the latter case the reflector, known as a "tamper," is also useful in reducing the rate of expansion of the bomb by virtue of its inertia.

Unless the amount of U^{235} or of Pu^{235} used in the bomb is larger than the critical amount, no chain reaction takes place; and when the amount is larger than the critical amount, the chain reaction spontaneously takes place, for there are always a few neutrons available to initiate the reaction. The detonation of the bomb would then appear to be effected by bringing subcritical amounts of the fissionable material into sudden and intimate contact. It should be mentioned that a chain reaction cannot be produced in a block of pure uranium metal, no matter how large, because the resonance or nonfission capture of neutrons in $_{92}U^{238}$ is relatively large. The actual construction of the bomb is still veiled in secrecy, as is the efficiency of the bomb.

An article of this kind can touch only on the high points of the atomic bomb. It has been suggested that 30 volumes be devoted to the report of the work of the Metallurgical Laboratory at the University of Chicago alone. This gives some idea of the encyclopedic nature of an account of the whole project.

By making and using an atomic bomb, physicists have created a new problem in the world. Mankind has to decide what to do with this enormously destructive weapon. Since nuclear energies are of the order of millions of electron volts while chemical energies are of the order of a few electron volts, it follows that this weapon is approximately a million times as potent as the usual type of explosive weapon. Mankind will have to make the choice of either world cooperation of an effective kind or of partial world annihilation. Without effective world cooperation scientists may find themselves involved in an armament race in nuclear physics. Scientists have created this weapon and have a moral obligation to see that their work is used for the betterment of civilization.

[6] Brief descriptions of this process are given in reference 3 and in Pollard and Davidson, *Applied nuclear physics* (Wiley), p. 180.