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ATOMIC AND MOLECULAR ENERGIES[1]

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The period of modern physics, which began with Roentgen's discovery of x-rays just fifty years ago, is unique in the history of science. Never before have so many fundamental discoveries been made in the span of half a century. Never since Copernicus have scientists been compelled so thoroughly to admit the limitations of even their basic ideas and adopt new modes of thought in order to comprehend essentially new phenomena. Since the recognition of this aspect of modern physics may well serve as a valuable guide in our search for a proper attitude towards the difficult political problem which has recently been created by atomic scientists, it will be stressed in the present discussion.

The exploration of atomic and molecular structure has been the primary concern of physicists during the last fifty years, and a major part of their efforts have been directed towards the study of atomic and molecular energies. The concept of energy, now regarded as basic and indispensable in every one of the natural sciences, took shape very slowly in mechanics which, next to descriptive astronomy, is the oldest part of physical science. In classical mechanics the energy concept is not absolutely essential, and it is derived from other concepts which are regarded as more fundamental. Only in the formulation of mechanics given by Hamilton about a hundred years ago does the idea of energy play a central role.

In the early part of the nineteenth century the desire to improve the steam engine led to various efforts to understand the nature of heat and to discover the relation between heat and mechanical work. In the eighteen forties Mayer and Helmholtz in Germany, Colding in Denmark, and Joule in England, independently arrived at the principle of the conservation of energy.

It may be of interest to note that the first to formulate this principle, Robert Mayer, was led to his discovery by a biological observation. When serving as a ship's doctor he noticed, at the harbor of Surabaya in 1840, that the venous blood of the Javanese is almost as bright red as the artèrial blood. This, he assumed, is because a smaller amount of oxidation is required to maintain the body temperature in the tropics than in colder climates. Two years later he announced the law of the conservation of energy but had great difficulty in getting his paper published and did not live to see his ideas accepted.

The principle of the conservation of energy claims that in all the changes which occur in nature there is something that remains constant, the energy. If energy of one kind disappears an equivalent amount of other forms of energy makes its appearance. Thus, when a gas is compressed at constant temperature, an amount of heat flows away from it which is equal to the work of compression. If the gas is prevented from giving off heat, its temperature goes up when it is compressed, and its so-called internal energy is increased by an amount equal to the work done. The study of the internal energy and the closely related heat content of substances, and of the changes occurring in these quantities with changes in temperature, volume, state of aggregation, chemical composition, and so on, has become a very important field of research.

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When the concept of energy is extended to new phenomena, the procedure is always to search for a quantity which makes its appearance when energy of known forms disappears. Thus the definition of energy depends essentially upon the law of the conservation of energy. For a long time it was believed that all forms of energy are mechanical in nature; in particular, the internal energy of a body was regarded as mechanical energy of the randomly moving molecules of which the body was believed to be composed.

However, as the study of the electromagnetic phenomena progressed, it was found that the principle of the conservation of energy could be upheld only by assuming that energy resides in the space surrounding electrically charged bodies. It was also found necessary to ascribe momentum to the electromagnetic field, even in empty space. When a charged particle moves with constant velocity the energy in the field simply moves along with the particle. However, classical theory predicts that when the velocity of the particle varies electromagnetic energy should be radiated with the speed of light. It is perhaps clear that the application of the ideas of energy and momentum to the electromagnetic phenomena required a renunciation of the intuitive character of these concepts which now took on a broader meaning and ceased to be purely mechanical concepts.

The theory of relativity led to a revision of classical mechanics and to a modified expression for the kinetic energy of a moving body. Moreover, by combining the conservation laws for energy and momentum with the principle of relativity, Einstein was led to the startling conclusion that all energy has inertia, or mass, which can be computed by dividing the energy by the square of the speed of light. Since this is a very large number, nine followed by twenty zeros if cgs units are used, the mass associated with ordinary amounts of energy is usually far too small to be detected.

But if all energy has mass, the question naturally arises whether all mass is not a manifestation of energy. If that were true even a small amount of mass would represent an enormous amount of energy; for to convert mass into energy we would have to multiply by nine followed by twenty zeros. Thus, one pound of any material would represent a latent energy of over ten billion kilowatt-hours.

Einstein's theory does not tell how to transform mass into energy nor even claim that such transformation is possible. Rather, it states that if any process exists in which mass is substantially reduced, then the latent energy represented by the lost mass will make its appearance as other forms of energy. When Einstein published his purely theoretical paper forty years ago no means of effecting such a release of energy was in sight. However, his bold idea stirred the imagination of physicists and guided them to remarkable discoveries, the most recent of which is now shaking the world.

The old conception that all matter is made up of a huge number of minute particles became a scientific hypothesis at the beginning of the nineteenth century in the hands of the English physician, John Dalton. While many physicists, especially those who were under the influence of Kant's philosophy, still clung to the view that matter is a continuum, Dalton's assumption that chemical compounds are composed of molecules, which in turn are made up of atoms, led to great advances in chemistry. Curiously enough, towards the end of the nineteenth century many chemists, led by Ostwald, were ready to drop the atomistic view as one which was not absolutely indispensable and which could never be verified experimentally. However, by this time the idea had taken hold among physicists, and they were already carrying out experiments which not only established the existence of atoms beyond any doubt but even gave information about still smaller particles of which the atoms are built up.

The first subatomic particle, the electron or quantum of negative electricity, was discovered by J. J. Thomson in 1897. Immediately afterwards

Lorentz, through his explanation of the magneto-optic effect discovered a year previously by Zeeman, obtained strong evidence for the belief that electrons vibrating inside the atoms are responsible for the emission and absorption of light. However, all attempts to account for the spectra emitted by the elements, on the basis of classical mechanics and electrodynamics, failed. Similarly, Rayleigh's formula for the intensity distribution in the continuous spectrum emitted by a black body, which agreed very closely with the experimental data at long wavelengths, failed completely at short wavelengths. No flaw could be found in Rayleigh's derivation. Thus, it became apparent that atomic phenomena are not governed by the laws of classical physics, which had been regarded by physicists and certain philosophers as having universal validity.

The gradual renunciation of many of the basic ideas of classical physics, and the successful search for new principles leading to an understanding of the atomic phenomena, began in the year 1900 when the German physicist, Max Planck, in order to obtain a formula for the intensity distribution in the black-body radiation, reluctantly made the radical assumption that atoms do not emit or absorb electro-magnetic energy continuously but intermittently, in quanta which are proportional to the frequency.

Since the black-body radiation depends only upon the temperature but not at all upon the chemical composition of the black body, Planck's theory could give no information about the structure of atoms. However, in 1911 Rutherford discovered that the entire positive charge and practically all the mass of an atom are concentrated in a nucleus having a diameter about ten-thousand times as small as the over-all diameter of the atom. Two years later Niels Bohr, making even greater departures from classical physics than had Planck, created his famous quantum theory of atomic structure and spectral lines. This theory was extremely fruitful for more than a decade and led to a remarkably detailed knowledge of the systems of electrons which surround the nuclei of the different chemical elements. In spite of the many successes of the Bohr theory, it gradually became clear that even this theory was not radical enough. However, by 1927, Heisenberg, de Broglie, Schrödinger, Bohr, and others had succeeded in working out a new theory, the so-called quantum mechanics, which provides an adequate basis for the understanding of practically all of the known atomic and molecular phenomena. The difficulty which most people experience in grasping this theory is caused by the fact that it requires them to give up some of the ideals which classical physics strove to attain and to learn to use such concepts as energy and momentum in a strange new manner.

As first realized by Bohr, an atom or a molecule can exist more or less permanently only in certain states which are characterized by definite energy values. An atom in a state of high energy may spontaneously undergo a transition to a stationary state of lower energy. In this process, which cannot be subdivided and hence cannot be described in detail, a rearrangement occurs in the motions of the electrons revolving around the nucleus, and electromagnetic radiation is emitted having a frequency which is proportional to the difference between the energies in the initial and the final state. If an atom in the lower energy state is illuminated by light of this same frequency the reverse transition may occur, i.e., light energy may be absorbed and the atom raised to the higher energy level. Thus, when the frequencies emitted or absorbed by a substance are measured by means of a spectrometer, it is possible to determine the energy values in which its atoms or molecules can exist. In some cases thousands of energy levels have been measured.

When an atom is known to be in a given stationary state, no description in terms of time can be given of the electron within the atom. Any observation of the time when an electron inside an atom passes a certain position would throw the atom over into another stationary state. Thus, it is impossible in principle to follow the path of an electron inside an atom. We must therefore shape our thinking about atoms in such a manner that we are not led to form intuitive pictures about the electronic motions. Furthermore, since any observation of an electron in an atom leads to a break in the causal chain, we are forced to forego a causal description and be satisfied with statistical laws for the atomic phenomena.

Under these circumstances it is remarkable that the principles of the conservation of energy and momentum have been found to hold for all known atomic processes. Several times during the development of the atomic theory phenomena have been discovered which seemed to violate the conservation laws, but further investigation always led to the validation of these laws. It should be pointed out, however, that to uphold the principles of the conservation of energy and momentum it has been necessary to create the idea of light quanta, or photons, and to assume the existence of a particle, the so-called neutrino, which is not directly observable.

Except for the lowest, most-stable state, the energy values of atoms and molecules in stationary states are not absolutely sharp. Rather, the width of an energy level is proportional to the probability that the atom will spontaneously jump to any of the lower energy levels in unit time. This follows directly from Heisenberg's famous uncertainty principle.

The energies that we have referred to here are the kinetic and potential energies of the electrons and, in case of molecules, the energies associated with vibrations and rotations of the molecule. The forces involved are essentially the electrostatic attractions between electrons and nuclei and the mutual repulsions between electrons and between nuclei. These are also the forces which bind atoms together to form molecules and bind molecules together in liquids or solids. These statements should not be taken too literally; for, in quantum theory, energy is a basic concept and the idea of force is not used. Moreover, the potential- and kinetic-energy functions are used in a purely formal manner, and many aspects of atomic or molecular energy, such as the so-called exchange or resonance energy which plays an important role in present-day theoretical chemistry, have no counterparts in classical physics. The strangeness of the quantum theory, from the classical point of view, should not surprise us; for the very existence of stable atoms and molecules with well-defined properties is entirely incomprehensible on the basis of classical ideas.

From spectroscopic measurement of atomic and molecular energies much important information can be derived about the structure of atoms and molecules, about the energy required to break up molecules in different ways, about the energy liberated in chemical reactions, and so on. If a sufficient number of the lower energy values are known for a molecule, and if it is known how many stationary states correspond to each of these energy values, it is possible to compute not only the internal energy of the compound in the gaseous state but also the entropy. This important quantity, which measures the degree of disorder, can be used to determine the direction in which a given process, such as a chemical reaction, can go under given circumstances.

A couple of examples will indicate the magnitude of the energy values which we have to deal with. A silver atom has 47 electrons. It requires only 7.6 electron volts to remove the very outermost electron from the atom, but it takes 25,000 electron volts to pull out one of the two electrons which are closest to the nucleus. By an electron volt is meant the energy acquired by an electron when it falls through a potential difference of one volt.

When one molecule of methane unites with two molecules of oxygen in a gas furnace 9.2 electron volts of energy are liberated. When no electronic rearrangements are involved in the processes, the energy changes are much smaller. Thus, the spacing between the vibrational energy values of molecules is usually of the order of a tenth of an electron volt or less. The energy values corresponding to different states of rotation lie even closer together, the spacing being usually less than a ten thousandth of an electron volt.

The processes which occur in nature can be roughly divided into those which involve the electrons revolving around atomic nuclei and those which involve changes in the nuclei. All optical and chemical processes, and most other known phenomena, are electronic in nature. These processes can be more or less readily influenced by varying the temperature, the pressure, or other experimental conditions. On the other hand, the radioactive phenomena, which were discovered and studied by Becquerel, the Curies, Rutherford, and others, are associated with processes going on inside the nuclei of the heaviest atoms. For a long time all attempts at influencing or controlling these processes were of no avail. The reason for this, as well as for the failure of the alchemists, is that atomic nuclei are vastly more stable than the electronic structures surrounding them. To disturb or break up a nucleus the most violent means are required.

The first to succeed in changing the nucleus of an atom was Rutherford who, in 1919, bombarded nitrogen with α-particules and changed it to oxygen and hydrogen. More recently, especially after the invention of the cyclotron and other devices for producing streams of hydrogen, deuterium, or helium nuclei having kinetic energies of several million electron volts, many other artificial transmutations of elements have been accomplished. In many cases it has been possible to measure both the change in mass produced and the energy released in the nuclear reaction, and in all such cases Einstein's principle of the equivalence of mass and energy has been verified.

In 1930 Bothe and Becker in Germany discovered that when beryllium is bombarded with α-particles from polonium some very penetrating rays are emitted. Somewhat later Irene Curie and her husband, Joliot, found that when these new rays fall on matter containing hydrogen, protons (hydrogen nuclei) are ejected with enormous speeds. Chadwick, in England, repeated these experiments and, in 1932, was able to prove that the penetrating rays discovered by Bothe and Becker consist of an entirely new kind of particle which has about the same mass as a proton but no electric charge.

The discovery of this new particle, which Chadwick called the neutron, had tremendous consequences. Immediately after Chadwick's discovery it was suggested by Iwanenko and by Heisenberg that all atomic nuclei are built up of neutrons and protons, and this view has received general acceptance.

The extremely large binding energy which holds the neutrons and protons together is a kind of energy never before recognized by man. Heisenberg and Majorana assumed that the peculiar saturation character of the forces between neutrons and protons is connected with a transfer of the charge and the spin from the proton to the neutron and back again. Thus, each particle is assumed to be alternatingly proton and neutron, or the proton and the neutron are regarded as two different states of a single elementary particle, sometimes called the nucleon.

The Japanese physicist Yukawa conceived of a different kind of transformation of a proton into a neutron and predicted that a new kind of particle, having a mass intermediate between the mass of an electron and that of a proton, should be ejected in the process. Such a particle, the so-called mesotron, was shortly afterwards found in cosmic rays. According to Yukawa, it is related to the field of nucleons in much the same way as the light quantum or photon is related to the electromagnetic field.

In 1934 Fermi, then in Italy, reported a series of experiments in which a large number of the chemical elements were bombarded with neutrons. Since a neutron has no electric charge, it is not repelled by an atomic nucleus and hence can pass right into it, thus forming a new nucleus which usually is radioactive. A large number of such manmade radioactive forms of the common elements have been made, and they are beginning to find important uses in chemical and biological research and in medicine.

In the nineteen thirties a large amount of information was obtained about atomic nuclei. In particular, the energies in the various stationary states were determined for a number of nuclei. Whereas the spacing of the lowest *electronic* energy levels of an atom is a few electron volts, the spacing between the lowest *nuclear* energy levels are of the order of one million electron volts. A theory which provides a general understanding of nuclear structure and energy levels was given by Bohr.

In 1939 a remarkable new phenomenon, the so-called fission, was discovered. Fermi and others had bombarded uranium with neutrons and had obtained complicated results which they were unable to explain satisfactorily. Late in 1938 Hahn and Strassman in Germany identified one of the reaction products as a radioactive form of barium. Lise Meitner and Frisch immediately concluded on the basis of Bohr's theory that the barium must have been produced by a splitting, or *fission*, of the uranium atom in two nearly equal parts. This idea was brought to America by Bohr in January 1939 and shortly after his arrival was verified at Columbia University, at the Carnegie Institution, at the University of California, and at Johns Hopkins, as well as in Copenhagen and Paris.

It was predicted and verified that about two hundred million electron volts of energy is released when a uranium atom undergoes fission. This can be understood from a consideration of the atomic masses of the various chemical elements. The elements of intermediate atomic mass are the most stable, as shown by the fact that for them the difference between the sum of the masses of the neutrons and protons making up their nuclei and the nuclear mass is greater than for the very light elements and for the very heavy elements. In fact, for elements like barium the mass of the nucleus is about one-percent less than the sum of the masses of the separated nuclear particles. For uranium, on the other hand, because of the greater effect of the repulsion between the protons within the nucleus, the nuclear mass is only nine-tenths of one percent smaller than the mass of the neutrons and protons separately. Thus, when a uranium nucleus breaks up into two more-or-less-equal fragments, about one-tenth of one percent of the mass disappears. This is converted into kinetic energy of the fragments. A simple calculation shows that if it were possible to cause all the atoms in one pound of uranium to undergo fission, about ten million kilowatt-hours of energy would be released.

When it was found that two or three neutrons are ejected in the fission process, the question immediately arose whether it might not be possible to produce a self-perpetuating chain of fission processes and thus release this tremendous amount of energy.

It was soon realized that the ordinary form of uranium, of atomic mass 238, would not be suitable for such a chain reaction, since it does not undergo fission when bombarded with slow neutrons. It was believed, however, that a chain reaction might be set up in the rare uranium isotope of mass 235. It was suggested also that a new element, now called plutonium, which is formed by neutron bombardment of uranium-238, might be suitable.

As you know, Fermi and other refugees from Hitler's and Mussolini's Europe succeeded in persuading the Federal Government to back researches on the production of uranium-235 and plutonium and on the explosive release of nuclear energy by fission. For some time this work was carried on on a modest scale, but after a nuclear chain reaction had been actually produced, by the end of 1942, the project assumed gigantic proportions. You are all familiar with the climactic outcome.

I shall not attempt to sketch this most amazing chapter in the history of science and technology. I have chosen, rather, to outline the background or setting for this truly Promethean feat. I hope to have made clear that nuclear energy is totally different in nature and in magnitude from any other form of energy ever known to man. I have outlined the rise of the idea of energy which originated in classical mechanics and, after several revisions, became one of our most fundamental scientific concepts. We have seen that our present understanding and mastery of the atomic phenomena have been gained only because scientists have been willing to admit the limitations of even their most basic concepts and to learn to use old ideas in new and strange ways. The development of science cannot be separated from the creation and critical testing of concepts and the emergence and growth of new modes of thought.

In conclusion, let us briefly touch upon the staggering social and political implications of the discovery of nuclear energy and means of releasing it. Never before has man held in his hand such tremendous power for good or evil. Never have we as a nation had a greater responsibility thrust upon us. What use do we intend to make of our power to release nuclear energy? This is the real secret of the atomic bomb. It is the question, above all other questions, which haunts the world today. It is a question which all of us must struggle with, since we are a democratic nation. The welfare and future of all mankind may depend upon the answer we give.

In considering this question we must realize that we are only at the beginning of the atomic age. The bombs dropped on Japan were hardly more than a few-percent efficient. More-efficient uranium and plutonium bombs will probably be developed soon. Moreover, we must reckon with the possibility that entirely new ways of releasing nuclear energy may be found. If it should become possible some day to change hydrogen into helium by processes similar to those which maintain the temperature of the sun, we should not only get ten times as much energy per pound of matter reacting but our source of energy would be one of the most abundant elements. Even in this case energy would be released only by packing neutrons and protons closer together. If it should ever become possible to annihilate these particles, as negative and positive electrons can be annihilated, the energy released would be a thousand times greater than in the present atomic bomb.

Research in nuclear physics is being pursued with renewed effort in many countries. No one can predict where the next advance in the release of nuclear energy will be made. Several other countries have sufficient resources to make atomic bombs, and if we continue to make them, some of these countries will feel forced to do likewise. Within a few years, at the most, we shall not be in sole possession of this means of mass destruction.

The possibility of using nuclear energy for constructive, peaceful purposes seems very promising. If properly exploited, this new source of energy could contribute to the attainment of an economy of plenty and thus to the elimination of major causes of war and internal strife. We need not fear that our petroleum industry would suffer from such a development. On the contrary, it would be to the advantage of the oil industry and Oklahoma if our oil should come to be used primarily as a source of chemicals.

In addition to providing power, the controlled release of nuclear energy from uranium fission would furnish a large number of radioactive by-products which would not only be of the greatest value for nuclear research but would undoubtedly find important uses in chemistry, biology, and medicine.

But any discussion of peacetime use of nuclear energy is futile as long as the world lives in deadly fear of the atomic bomb. The urgent problem of how to control this terrible weapon is a political rather than a scientific problem. Nevertheless, the scientists who discovered and found the means of releasing nuclear energy must share in the responsibility for its solution. Fortunately, they have succeeded in making their voices heard and in injecting some measure of realism into the public discussion. As you know, they are practically unanimous in claiming that, because of the enormous advantage which the atomic bomb gives the aggressor and the impossibility of providing an effective defense against it, some kind of international supervision of the use of atomic energy, coupled with freedom of inquiry and free dissemination of scientific knowledge, is needed to guard against the danger of sudden atomic war. To devise and agree upon such a system of control will require a partial renunciation of the idea of national sovereignty. It will also require radical changes in our thinking about world affairs. If the atomic scientists are right, and I believe they are, we are facing a situation not unlike that which has preceded every great advance in science. Whenever basically new facts have come to light, it has always been necessary, before they could be understood and mastered, to give up old ideas and to learn, painfully, to think in new ways. Only thus has our insight into the atomic processes been gained, and only by a similar renunciation of old ideas in the political realm and a commitment to new modes of thought may we avert the threat of the atom bomb and clear the way for constructive use of atomic energy. It is the duty of all of us to participate in this fateful search for new bearings in a changed world.