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# ATOM FOR PEACE

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ATOM FOR PEACE

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# ATOMIC ENERGY—A POWERFUL TOOL OF TECHNICAL PROGRESS

All matter is composed of atoms. According to contemporary ideas, an atom of any element is made up of a positively charged nucleus around which negatively charged electrons revolve. The central part of the atom—the nucleus—is composed of protons and neutrons. Although the nucleus is tens of thousands of times smaller than the atom itself, yet it comprises over 99.95% of the atomic mass. The density of the nuclear matter is extraordinarily high: one cubic centimetre of the matter of the atomic nucleus would weigh approximately one hundred million tons. It follows that the mass, and hence the energy of the atom, are concentrated mainly in its nucleus.

Atomic energy is the energy released in the different transformations taking place in the atomic nucleus.

Various kinds of nuclear transformations are known. In some the nucleus ejects one or more particles (neutrons, protons, deuterons, $\alpha$-particles) or quanta of $\gamma$-rays, which makes the newly formed nucleus differ from the original one (in mass or charge) by not more than several integers. Nuclear transformations of this type were first observed at the close of the last century, when radioactivity was discovered. Later, in 1919, such transformations were induced artificially.

The energy produced in nuclear transformations is millions of times greater than that evolved in chemical transformations (combustion, oxidation, etc.) of the same atom. The naturally radioactive elements, however, are highly dispersed in nature, and their extraction from the ores is a laborious and costly process. In addition, the rate of disintegration of the most widespread of these elements is extremely small, so that the amount of energy liberated in unit time is insignificant. When such transformations are effected artificially, then in many cases the energy liberated by each nucleus is considerably greater than the energy of the particle inducing the transformation; however, due to the extremely small probability of a nucleus capturing a particle, the energy spent for accelerating these particles would be many times greater than the amount of energy thereby produced. Hence, this kind of nuclear transformation cannot be utilized for the generation of energy.

The power industry has recourse to another type of nuclear transformation which was discovered towards the close of the 1930's: the fission of uranium and thorium nuclei induced by neutrons.

As a result of such a reaction a nucleus of uranium (or thorium) splits into two fragments of slightly different charges and masses. These repel each other and fly off in opposite directions with very great velocities. When these fragments collide with the atoms of the medium in which fission takes place their kinetic energy is transformed into the thermal energy of the atoms of the medium.

Such a transformation of atomic energy into thermal energy takes place in the so-called nuclear reactors or piles. The amount of energy evolved in this process considerably exceeds (tenfold and more) the amount evolved when a naturally radioactive atomic nucleus disintegrates. (The complete fission of 1 kg of uranium leads to the liberation of energy equivalent to the heat of combustion of about 2,000 tons of high-grade anthracite coal.) But most essential of all—in each act of fission for every neutron absorbed, two or more neutrons are emitted. This permits of making the reaction self-sustaining, i.e., of producing a chain reaction, and hence of considerably increasing the amount of energy obtainable. Although in actual conditions only a portion of the matter participating in the process is utilized, nevertheless, the energy which can be obtained is considerable. About 80% of this energy is transformed into heat. The remaining 20% is produced in the form of so-called nuclear or radioactive radiations.

There also exists another type of nuclear transformation based on the synthesis, or "fusion", of the simplest nuclei of light elements (hydrogen, for example) into more complex nuclei (helium). The amount of energy released in such a transformation is many times greater than that produced in the fission of an equal amount (by weight) of uranium or thorium. This type of reaction seems very promising for the power industry, for in this manner it may be possible to obtain energy from the light elements, such as hydrogen, which are abundant in nature, whereas uranium and thorium are comparatively rare.

The necessary condition for the reaction of fusion is a high temperature (from several millions to hundreds of millions of degrees). It is extremely difficult to produce such temperatures under controlled conditions. Until now this has been achieved only under uncontrolled conditions (in the hydrogen bomb). One of the most important goals of modern physics is to find ways and means of producing such high and controlled temperatures. Work in this direction is being pursued in a number of countries. In the U.S.S.R. a temperature of the order of millions of degrees has been produced by means of a high power electrical discharge (up to two million amp) in hydrogen, deuterium and other gases. This is the first time such a temperature has been achieved in laboratory conditions. At such a temperature the gas exists in the form of a "plasma," i.e., it consists of electrons and "bare" atomic nuclei, stripped of their electronic shells. Although neutrons and high-energy X-rays were observed in these experiments, nevertheless, this is not sufficient proof that nuclear fusion takes place in the plasma, for its temperature is not high enough.

Several years ago Soviet scientists proved theoretically the possibility of a reaction of fusion in liquid hydrogen at low temperatures. Such a reaction takes place with the participation of so-called mesoprotons. These are minute particles of matter resembling the hydrogen atom, in which the electron revolving about the nucleus (proton) has been replaced by a negatively charged $\mu$-meson. Such a reaction was recently effected experimentally and confirmed the predictions of the theory. It appears, however, that this reaction is not suitable for the production of energy. The probability of the process is extremely small, and inasmuch as during the extremely short life-time (two-millionths of a second) of the μ-meson it succeeds in bringing about only one or two fusion reactions, the "efficiency" of the reaction is negative. It is slightly probable that a minute particle may be found with a considerably longer life-time (of some hours) which will be able to play the part of catalyst similar to the μ-meson. In such a case this reaction may prove to be of practical significance. Other ways of bringing about the reaction of fusion may be found. The problem is at present being studied in a number of countries.

To date only one nuclear reaction—the fission of the nuclei of the heavy elements (uranium and thorium) — is of practical significance for obtaining industrial power. In a controlled and large-scale fission reaction a huge amount of energy is released, accompanied by large amounts of penetrating radiation and by the production of radioactive isotopes. Nuclear radiations are generated and numerous radioactive isotopes are produced also by special machines called accelerators of elementary particles. Due to the efforts of scientists, engineers and various other specialists, the energy, radiations and isotopes thus produced are now being utilized in industry, agriculture, medicine and science.

Atomic energy is of immense significance as a new source of industrial power. The world demand for power is huge. According to the data of the Geneva Scientific-Technical Conference, the annual consumption of energy per capita in the leading industrial countries today comprises from 23 to 54 megawatt-hours; 80% of this energy is obtained from coal, oil and gas (about 1.7 billion tons of anthracite coal are at present consumed annually), and the demand is rapidly increasing. According to the same source, the production of electrical energy will double in the next ten years and increase tenfold in the course of 33 years. It is forecast that by 2000 A. D. the world consumption of energy will be approximately trebled.

The production of hydroelectrical energy, which to date supplies only 1.5% of the total demand, will greatly increase by that time: nevertheless, according to preliminary calculations, it will satisfy no more than 15% of the total demand. If the increased demand for energy is to be supplied by organic fuels it will be necessary to burn 7-8 billion tons of anthracite coal annually. The fuel resources of a number of countries are, however, already on the wane; the extraction of coal is becoming more difficult and more costly.

In contrast, the cost of atomic energy will decrease with technological progress, while the supplies of uranium and thorium are great. The amount of energy available from the known deposits of these elements is many times greater than that obtainable from all the other sources now utilized.

In addition, atomic energy has other important advantages. One of the main advantages is the high energy content of nuclear "fuel" as compared with all other types of fuel. This will make it possible to utilize atomic energy in districts far away from sources of uranium or thorium, since the cost of transportation of atomic "fuel" will be comparatively low.

In view of this advantage means are being sought of utilizing atomic energy for propulsion, particularly on ships and airplanes.

An important practical result achieved by the U.S.S.R in the utilization of atomic energy was the construction and opening in June 1954 of the first atomic power station in the world with a capacity of 5,000 kilowatts. The experience obtained with this station has made it possible to undertake the design and construction of larger stations (400-600 thousand kilowatts) and of atomic motors for propulsion. In 1956-1960 the U.S.S.R. plans to build five experimental atomic electric power stations with a total capacity of 2,000-2,500 megawatts, primarily in regions lacking their own fuel base. In addition, several experimental atomic installations with a capacity of 50,000 kilowatts each are being planned. The main aim of this plan is to obtain experience in the industrial exploitation of atomic power stations, to choose the most economically advantageous type of reactor and to study many other problems of importance for the future of atomic power.

Other countries have also begun the construction of atomic power stations. An especially extensive program is planned and being carried out in Britain whose power supplies are small. In 1956 Britain put into operation an experimental atomic power station at Calder Hall with a capacity of 70 megawatts.

Britain's first industrial atomic power station with a capacity of 275 megawatts is being built at Berkeley; it should begin functioning by the spring of 1960. A second atomic power station of 300 megawatts is under construction at Bradwell (work was begun on it in January 1956); and a third of 320 megawatts at Hunterston. It was recently announced that by 1965 Britain plans to have 16-19 atomic power stations delivering a total output of about 6,000-7,500 megawatts.

All of Britain's atomic power stations—those in operation, under construction and being planned—have gas-cooled graphite-moderated reactors. This road of development of atomic power is quite specific and may prove not to be the most economically advantageous.

Other countries are building atomic power stations on a far smaller scale. For example, the U.S.A. plans to build by 1960 six large and a number of small atomic power stations with a total output of 800 megawatts. France proposes to have atomic power stations of approximately the same capacity by 1965. Western Germany, Belgium, Holland and a number of other countries are also planning to build atomic power stations.

Work is under way on a wide scale to find means of utilizing atomic energy for propulsion. The U.S.S.R. has built an atomic-powered ice-breaker of 16,000 tons displacement, 134 m long and 27.6 m wide. The ice-breaker is equipped with a nuclear reactor furnishing 44,000 hp. This permits the ice-breaker to develop a speed of 18 knots (in open water). It is able to plow through frozen seas thus making it possible to open regular communication along the Northern Sea Route.

A number of countries are sponsoring work on the development and construction of various kinds of ships (commercial, passenger, tankers, etc.), as well as atomic-powered locomotives, airplanes and other means of transport.

Great possibilities have been opened by the utilization of radioactive isotopes and nuclear (radioactive) radiations, which are being widely applied in the U.S.S.R. The directives of the 20th Congress of the Communist Party of the Soviet Union envisage further extension of the use of radioactive isotopes and radiations in industry, agriculture and science.

The investigations of recent years have mapped out quite a number of fields for which the application of radioactive radiations and isotopes is undoubtedly important and highly promising.

The applications of nuclear radiations are based on their specific ability to strongly affect matter, living organisms and processes, and to be fairly weakly absorbed by matter. This makes it possible with their aid to bring about processes which would not take place under ordinary conditions; to obtain new, more stable materials; to stimulate desirable processes and to suppress undesirable ones; to see what goes on beyond walls opaque to light rays, etc.

Radioactive isotopes may be utilized as a source of nuclear radiations. Like the stable isotopes, they can be used as "tracer" atoms. This last-mentioned application has opened up unusually great possibilities to science. In a number of instances the results thus achieved have proved to be of fundamental importance. The potential possibilities of the method of tracer atoms are enormous and have still to be investigated.

The applications of atomic energy are varied and manifold. We do not as yet foresee all the possibilities which they open up. Many possible trends of development are still in their early stages or have yet to be explored.

The present book aims to give some idea of the principal ways in which atomic energy, radioactive isotopes and radiations are being applied today in industry, agriculture and science. The book does not treat questions of the technology of nuclear "fuel" or structural materials used in atomic power installations, as being of specific interest.

Mankind has taken only the first steps on the road to the peaceful application of atomic energy. However, the achievements to date indicate that atomic energy is a powerful tool of technical progress. The speediest and fullest utilization of this new source of power is thus in the interests of humanity.

There is no doubt that atomic energy would find considerably wider application were its use for military purposes forbidden. Hence, the prohibition of the atomic and hydrogen bombs, which the Soviet Union is so persistently striving to achieve, would significantly further the development of the productive forces of mankind.

E. MOROZ

# ACCELERATORS OF CHARGED PARTICLES

The atomic nucleus is investigated by means of intricate apparatus, among the most important of which are accelerators of charged particles. In designing such accelerators one must take into consideration the velocity dependence of the mass of the moving particles, the quantum nature of light and numerous other phenomena with which engineers have heretofore had no dealings. Specialists in nuclear physics and vacuum engineering, electrical and radio engineers, chemists and representatives of a number of other professions take part in the operation of such installations.

Accelerators serve to increase the kinetic energy of electrons, α-particles, protons, deuterons, and other charged particles. Such fast-moving particles help us to penetrate into the secrets of the atomic nucleus and to understand the nature and laws of nuclear reactions.

Fast particles are encountered in nature in the form of α- and β-rays and cosmic radiation. The maximum energy of the α- and β-rays usually does not exceed 10 million eV; while the mean energy of the cosmic radiation equals several billion electron-volts.

The fast-moving particles emitted by the radioactive elements cannot be utilized in many experiments because of their energy insufficiency; the cosmic radiation is inconvenient because it consists of a haphazard mixture of different particles flying with the most varied velocities in all directions. In addition, the intensity of the natural sources of fast particles is exceedingly small, which also makes it difficult to use them in many experiments. In view of all these reasons a search for methods of artificially accelerating charged particles was started back in the 1930's. The progress of nuclear physics and the rise of the atomic power industry are to a large extent due to the development of accelerators of charged particles.

## METHODS OF ACCELERATION

The earliest method proposed was that of direct acceleration: the charged particles were sent through a tube to the ends of which a high voltage was applied. With an apparatus of this type in 1932 the English physicists J. Cockcroft and E. Walton were the first to effect a nuclear reaction accompanied by the emission of energy: this was the splitting of the lithium nucleus by protons accelerated to an energy of 0.7 million eV.

The method of direct acceleration is used in specialized X-ray apparatus, in impulse generators and in the Van de Graaff generator invented in 1930. The maximum energy of the particles attainable in such installations does not exceed several million electron-volts. Such a limit is due to the circumstance that too large a potential difference applied to the ends of the accelerating tube leads to sparking and breakdown of the apparatus.

At present the method of direct acceleration is frequently used for preliminary acceleration of particles going then into more powerful installations.

A number of other methods of acceleration of particles have also been worked out. One of these—the induction method—is used in betatrons (fig. 1)—accelerators of electrons, which produce artificial $\beta$-rays (the betatron is not suitable for accelerating heavy particles). This apparatus consists of an a-c electromagnet with a doughnut-shaped chamber set up between its poles. A circular electric field (a rotational field) which serves to accelerate the electrons is induced in the chamber with the rapid increase of the magnetic field in it.

Air, which hinders the motion of the fast-moving particles, is evacuated from the chamber by powerful pumps, so that the pressure in the chamber does not exceed some billionths of a fraction of the atmospheric pressure. However, even at such high evacuation each cubic centimetre of the volume of the chamber still contains tens of billions of atoms of different gases. When the charged particles collide with these atoms they are deviated from their theoretically prescribed orbits. For this reason special measures must be taken in all accelerators to guarantee the stability of motion of the particles and keep them from "wandering off their path".

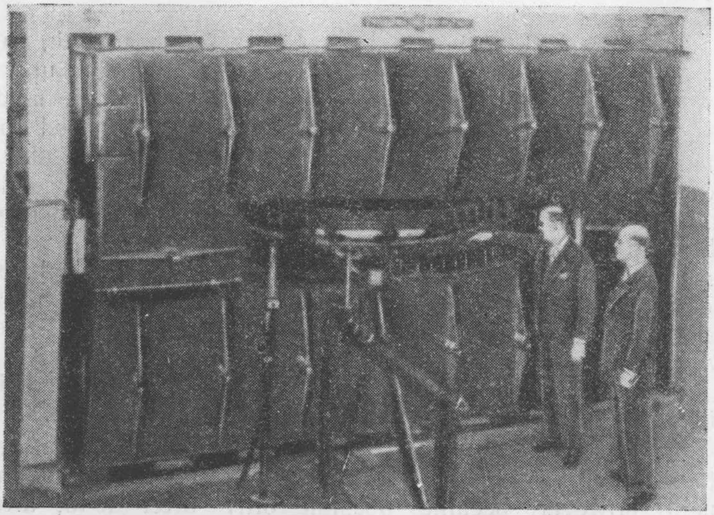

Fig. 1. General view of the betatron

We may note that R. Wideroe, the inventor of the betatron, did not have a sufficiently well worked out theory of the apparatus, and the machine which he built in 1927 did not function properly. Only in 1940 did D. Kerst succeed in building a satisfactory installation of this type.

Considerable credit for the development of the theory of the betatron is due to the American scientists D. Kerst and R. Serber and to the Soviet scientist I. Terletski.

Induction accelerators are widely employed.

If a target in the form of a metal plate is placed inside the chamber of an induction accelerator, the high-speed electrons incident upon it give rise to a directed beam of hard $\gamma$-radiation which penetrates more deeply into matter than the $\gamma$-rays of radioactive elements, to say nothing of ordinary X-rays. These hard rays are used to test large metallic details, as well as for biological and medical investigations.

The betatron is a very effective accelerator when the electrons are to be given comparatively low energies, say of the order of 20-50 million eV. There exist, however, induction accelerators which furnish electrons of far greater energies.

The Soviet physicists D. Ivanenko, I. Pomeranchuk, and L. Arzimovich have shown in their works that the upper limit of the energy of the electrons obtainable in the betatron is close to 300-400 million eV and is determined by their electromagnetic radiation. At an energy of about 100 million eV electrons moving in a magnetic field begin to emit a bright glow, which consumes part of the energy obtained from the field and necessary for normal acceleration. As a result of this loss of energy, the electrons begin to move along a spiral, instead of a circular path, making ever smaller turns until they impinge on the inner wall of the vacuum chamber.

The defects of the betatron have been overcome in linear and especially in circular resonance accelerators.

Back in 1924 the Swedish scientist G. Ising proposed the principle of the linear accelerator. Its practical development, however, became possible only after 1945, after the appearance of radar and powerful u. h. f. generators and generators of waves of the centimetre range. The largest linear accelerator is 70 metres long and produces electrons with an energy of 600 million eV. These machines have no need of superhigh voltages, and this is their chief advantage over installations working on the principle of direct acceleration. The particles move along a rectilinear path passing through many successive accelerating intervals (created by a rapidly alternating electric field), in which their energy increases.

Linear accelerators of electrons up to 15 million eV are being employed in industry and medicine. Accelerators of electrons of higher energies, as well as proton accelerators, are used to investigate the atomic nucleus. Fairly large linear accelerators of protons do not yet exist.

Linear accelerators are also utilized to pre-accelerate electrons or protons which then go into more powerful installations for further acceleration.

All the above-mentioned accelerators are of importance for scientific research and in industry. The most important

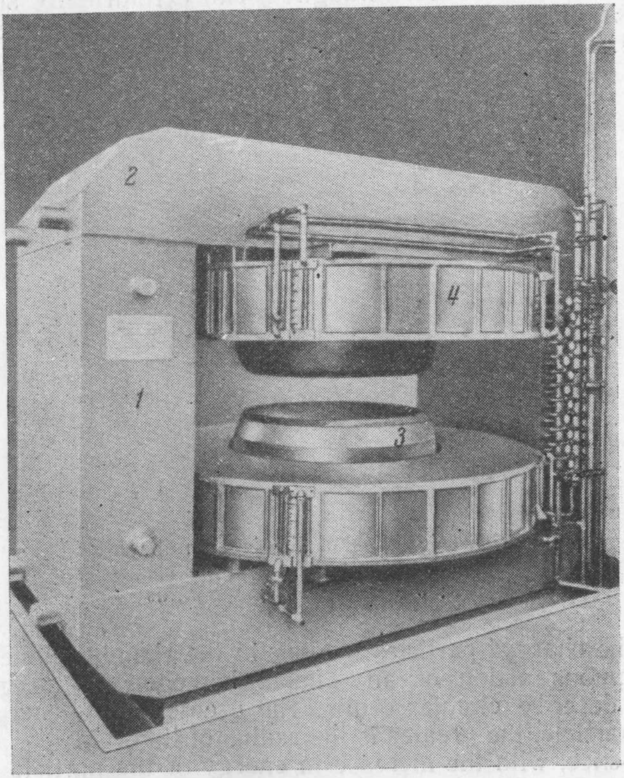


Fig. 2. Cyclotron electromagnet: *1* — vertical yoke; *2* — horizontal yoke; *3* — pole of magnet; *4* — exciting coil

role in scientific research to date, however, is played by circular resonance accelerators, in which the particles passing repeatedly through the same accelerating interval increase their energy. The first such machine—the cyclotron—was built in the early 1930's in the U.S.A. by a group of physicists under the leadership of E. Lawrence.

In the cyclotron the particles are accelerated in a vacuum chamber, the vertical walls of which are made of non-magnetic material. A vacuum of up to $10^{-5}$ mm Hg is kept up in the chamber which is situated in the gap between the poles of a d-c electromagnet. The cylindrically shaped poles of the electromagnet usually have a diameter of 0.5-1.5 m, while the height of the gap is 20-50 cm (fig. 2).

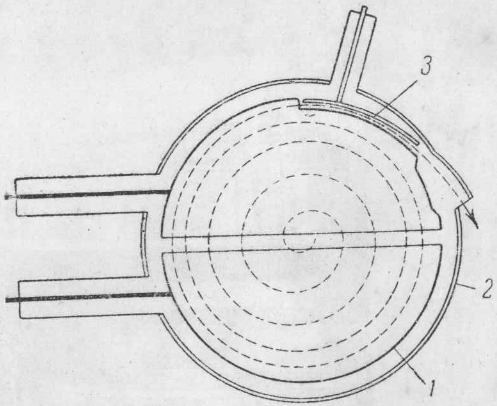


Fig. 3. Trajectories of the ions in the cyclotron chamber: *1* — dee; *2* — chamber; *3* — extracting apparatus

The charged particles moving in the chamber under the continuous action of an almost homogeneous magnetic field describe circular orbits. The greater the energy of the particle, the greater is the radius of its orbit.

Hence, with the increase in energy of the particle as it passes through the accelerating interval, the radius of its circular orbit increases. The entire trajectory of the particle resembles an expanding spiral.

The operation scheme of the cyclotron is illustrated in fig. 3. Acceleration takes place in the gap between two metallic electrodes, called dees *1*, to which a rapidly alternating voltage is applied.

In form the dees resemble the two halves of a round box cut through its diameter. The dees are set up inside the vacuum chamber *2* so that they do not touch its walls.