IN COMMEMORATION OF THE EIGHTIETH ANNIVERSARY OF THE FIRST ARTIFICIAL NUCLEAR REACTION REALIZATION

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In 1919, a distinguished English physicist Earnest Rutherford was the first to observe the nuclear reaction.

To explain remarkable results of preliminary experiments on α-particle scattering by air and metal sheets, which he conducted together with G. Geiger and D. Mardsen, Rutherford put forward in 1911 a new model of atom - the nuclear model. According to this model, in the centre of the atom there is a positively charged nucleus of a very small size (of about 10^{-12} ... 10^{-13} cm). Around the nucleus, at a distance of about 10^{-8} cm from it, electrons rotate in circular orbits. A great strength of nuclei in nonradioactive elements suggests the conclusion that the nuclei can be caused to undergo fission only under an extremely energetic external action, i.e., the particles entering into the nuclear reaction must be brought together within the distance where the nuclear forces are in operation (about 10^{-13} cm). In the case of charged particle interaction, this approach is impeded by Coulomb repulsion forces reaching significant values at such small distances.

In the Rutherford experiment, nitrogen nuclei were bombarded with 7.7 MeV α-particles emitted by polonium. (The potential barrier of nitrogen nucleus for the α-particle is 3.5 MeV). The fluorescent screen, examined with a microscope, showed the scintillations although α -particles could not have reached it through the aluminum foil placed in front of the screen. Rutherford then suggested that the scintillations observed were due to highly penetrating particles that arose in nitrogen under the action of α-particle bombardment.

Magnetic deflection experiments have shown these particles to be protons, their path in the air makes up to 40 cm. The whole nuclear reaction can be written as

$${}_7N^{14} + {}_2He^4 \rightarrow ({}_9F^{18}) \rightarrow {}_8O^{17} + {}_1H^1 - 1.26 \text{ MeV}.$$

The transformation of the nitrogen nucleus under the impact of α-particles was confirmed by the photographs taken in the Wilson chamber (1925, P. Blackett). They clearly demonstrated both the existence of the proton and the possibility of artificial transmutation of elements. Among a great many photos of α-particle tracks in nitrogen there were certain single cases observed, where the α-particle track ended with a "fork", i.e., two new tracks were formed: one, a long and thin track belonging to the proton, and the other, thick track belonging to the oxygen nucleus ${}_8O^{17}$ that underwent recoil. The "forks" were observed in eight cases out of the total number of about 500000 photos of α-particle tracks in nitrogen. In the mentioned transformation of the nitrogen nucleus, an energy of 1.26 MeV is absorbed. This is the energy of nuclear reaction (nuclear transformation) equal to the difference between intranuclear energies of particles existent before the reaction (${}_7N^{14}$ ${}_2He^4$) and of the particles appearing after the reaction (${}_8O^{17}$ ${}_1H^1$). The negative sign at 1.26 MeV means the energy absorption in the reaction (endothermic reaction).

Over ten thousand other nuclear reactions have been investigated since Rutherford's discovery. So, what is the aim of studying nuclear reactions? Firstly, nuclear reactions give the basic information on the structure of nuclei and the nature of nuclear forces, since in the microworld the particle or the nucleus cannot be "looked at" because of the presence of quantum mechanisms. Secondly, the study of nuclear reactions is of great practical importance, namely, for the use of intranuclear energy and for production of radioactive isotopes.

The artificial transmutation of elements accomplished at the expense of natural radioactivity has given a powerful impetus to development of accelerator engineering.

It is, of course, of interest to artificially accelerate particles to such energies that they could be able, on collisions, to induce nuclear transformations. The most attractive feature of such a device is the particle beam energy, as this significantly enhances the nuclear reaction yield. Indeed, the total α-emission from 1g of radium makes up $3.7 \cdot 10^{10}$ α-particles per second, while a beam of doubly charged ions at a 1 μA current strength presents a flux of particles carrying $3.125 \cdot 10^{12}$ ions/sec through a very moderate area. Another advantage of the accelerating device over a natural source of fast particles consists in its controllability, in the possibility of varying at will a sort of accelerated particles and their finite energy. As early as in 1932, the first nuclear reaction excited by artificially accelerated particles was accomplished at the Rutherford laboratory by Cockroft and Walton, who used a 700 kV cascade tube. The phenomenon discovered in this experiment, namely, the fission of lithium by protons, was also of particular interest because as a result of the use of protons rather than helium ions, as was the case in Rutherford et al.'s experiments, Cockroft and Walton first attained the reaction of the second type, i.e., the (p,α)-type reaction. In October of the same year, Sinel'nikov, Lejpunsky, Val'ter and Latyshev at the Ukrainian Physical-Technical Institute also caused lithium to undergo fission by protons:

$${}_3Li^7 + {}_1H^1 \rightarrow ({}_4Be^8) \rightarrow {}_2He^4 + {}_2He^4 + 17.3 \text{ MeV}.$$

The potential barrier height for protons was half as large as that for alpha-particles. As a result, the (p, b) reactions take place at lower energies. The reaction proceeds to release an energy of 17.3 MeV (exothermic reaction).

From this time onwards a period of extremely intense use of accelerators for various investigations in the field of nuclear physics sets in. The most important discoveries of the period from 1932 to 1934, namely, the discovery of the neutron and the discovery of artificial radioactivity, were made with the help of natural fast-particle sources. However, a wide use of these discoveries was made possible only owing to the presence of accelerators in service today. The production of heavy hydrogen (deuterium) by Urey in 1932 by distillation of liquid hydrogen, and the development of the method of "heavy water" (D_2O) concentration by electrolysis on a substantial scale gave the possibility to obtain deuterium and to use it in ion sources. This has added to the number of nuclear projectiles provided by accelerators one more, extremely valuable projectile - the deuteron, i.e., a singly charged deuterium ion consisting of the proton and the neutron. One of the important properties of fast deuterons is their ability of exciting (d,n)-type reactions characterized in a number of cases by their very large cross section (${}_4Be^9(d,n){}_5B^{10}$, ${}_3Li^7(d,n){}_4Be^*$). This makes it possible, if needed, to transform the accelerating device into a neutron source overwhelmingly more powerful than the sources using radium and polonium.

The bombardment of deuterons by deuterons gives rise to tritium nuclei, i.e., the hydrogen isotope of mass 3, which the scientists failed to find in heavy water. Tritium is radioactive.

An important advantage for nuclear structure investigations belongs to high-energy electrons. The interaction between electron and the nucleus is electromagnetic and can be calculated to a high accuracy. In 1955, Hofstadter et al. demonstrated in their experiments on 100-550 MeV electron scattering by protons that the charge and current distributions in the proton had a spatial extent of about 1F (10^{-13} cm).

Among a great variety of elementary particles, the neutron occupies nearly the same exclusive position in nuclear physics as the electron does in electronics. Owing to its electric neutrality, the neutron of any energy easily penetrates the nucleus and causes various nuclear transformations to occur. It is for this reason that the nuclear reactions induced by neutrons have played an enormous part in the development of nuclear physics. The same reason accounts for the involvement of neutron physics in numerous and, perhaps, most important applications of nuclear physics in other sciences and engineering.

After the discovery of neutron-induced fission reaction by Gann and Stressman in 1938, the burning up of nuclear fuel in nuclear reactors has become one of the actual ways of organic fuel replacement. The first NPP with a power of 5 MW was put into operation in 1954. The commissioning of the first NPP has initiated the development of nuclear power engineering.

Only three isotopes that can be used as a nuclear fuel or as a raw material for fuel production occur in nature. These are the isotopes of uranium and thorium: ${}_{92}U^{235}$, ${}_{92}U^{238}$, ${}_{90}Th^{232}$. The last two isotopes give no chain reaction, but they can be reprocessed through the radiative capture reaction (n,γ) into the isotopes which can enter into the following chain reactions:

$$n + {}_{92}U^{238} \rightarrow {}_{92}U^{239} \xrightarrow[\beta^-]{} {}_{93}Np^{239} \xrightarrow[\beta^-]{} {}_{94}Pu^{239}$$

$$n + {}_{90}Th^{232} \rightarrow {}_{90}Th^{233} \xrightarrow[\beta^-]{} {}_{91}Pa^{233} \xrightarrow[\beta^-]{} {}_{92}U^{233}$$

These two reactions have opened up a real possibility for nuclear fuel breeding in the progress of chain reaction.

The earth's crust comprises thorium several times as much as uranium. The natural thorium practically consists of one-type isotope ${}_{90}Th^{232}$, while the natural uranium mainly consists of the ${}_{92}U^{238}$ isotope and of the ${}_{92}U^{235}$ isotope to the extent of 0.7% only. In view of this, the method proposed by Rubbia to produce nuclear fuel (${}_{92}U^{233}$ isotope) from thorium by the use of intense pulsed neutron sources with high-power proton accelerators as the basis appears to be very attractive. The proton beam energy must be ≥ 1 GeV, and the beam intensity must be ≤ 1A. The advantage of electronuclear breeding over breeder reactors consists in the fact that practically no transuranium elements are produced in the process. Besides, owing to high proton beam intensity, during neutron generation by targets, the device can be operated at subcritical conditions and this increases the safety of its operation.