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USE OF NUCLEAR PHYSICS IN RELATED FIELDS OF SCIENCE AND NATIONAL ECONOMY*

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IN accordance with the title of the paper, I shall attempt to describe very briefly the influence exerted and is still exerted by the "classical" nuclear physics on the scientific and technical progress of our society.

The rapid growth of our field of science during the last more than 20 years was determined by its tremendous military significance. But the influence of nuclear science and technology on the national economy and on human life is so varied and so large, that now peaceful applications of outstanding significance come to the forefront. This again attracts the interest of society in this field.

The development of nuclear science and technology is one of the heroic accomplishments of our nation. The truly heroic labor of our scientists, engineers, and workers has ensured the creation of atomic weapons within an exceptionally short time, under the difficult wartime and post-war conditions, and thereby guaranteed a peaceful life.

The contribution of the nuclear physicists is, of course, quite appreciable. They investigated all the physical processes that determine the success of the technical devices, and thus laid the ground work for both the defensive and peaceful atomic technology. The nuclear physicists performed and still perform most important tasks of planning and coordination of all the basic research in atomic technology.

The scientific and technical head of this entire grandiose state project was in his time I. V. Kurchatov, and it was precisely his talent of a scientist, his breadth of vision, and his remarkable human qualities which determined to a considerable degree the success of our country. Kurchatov made such a fundamental contribution, that not only the past but also the future of nuclear science and technology will for many years be connected with this truly historic personality.

In 1939, at the Khar'kov conference, Ya. B. Zel'dovich and Yu. B. Khariton reported on the conditions for the development of a chain reaction. It was clear even then that a chain reaction is possible in a system with enriched uranium. However, none of the participants sensed the close reality, and discussed only problems of measuring the decisive parameters—the cross sections of interaction and the numbers of the fission neutrons.

Before the war, work on nuclear physics expanded somewhat, particularly work on uranium fission, and G. N. Flerov and K. A. Petrzhak discovered spontaneous fission and measured some important cross sections; however, further progress in nuclear physics was interrupted by the war. All three of our nuclear centers, namely the Leningrad Radium Institute, the Leningrad Physicotechnical Institute, and the Khar'kov Physicotechnical Institute, were practically shut down.

In 1942, G. N. Flerov sent to the government a memo concerning the possibilities and significance of the chain reaction. This memo served as a "triggering mechanism," and soon a scientific organization, headed by I. V. Kurchatov, which was created and was able, owing to the decisive support of the party and of the government, to start the first graphite reactor as early as in 1946.

In 1943 the idea of heterogeneous arrangement of the uranium was advanced, and the main experiments on resonant absorption were performed. At approximately the same time I. I. Gurevich and I. Ya. Pomeranchuk developed the theory of resonance absorption.

The development proceeded with such intensity, at such an accelerated rate, that not only the necessary research was performed, but commercial reactors for the plutonium production, plants for separation of uranium isotopes, chemical plants, etc. were soon constructed.

The first stage of development of nuclear physics—the chain reaction—is characterized by the following steps:

1939—main facts, the Zel'dovich-Khariton theory.

1942—Flerov's memo.

1943–46—principles of reactor physics—experiment and theory.

1946—first graphite reactor.

1949—explosion of first atomic bomb.

Once the course of the chain reaction, its response to temperature changes, and the possibility of its control with the aid of delayed neutrons (which was essentially clear already in 1939) were understood, the idea immediately arose of the possibility of producing power reactors. However, it was possible to approach this possibility realistically only ten years later, in 1949, after experience with the operation of commercial reactors was accumulated.

The main ideas of the first atomic electric station were formulated by I. V. Kurchatov. Its implementation was assigned to Obninsk. These ideas were based on the experience of the first commercial reactors, and the atomic station was also graphite moderated and cooled with much hotter water. The first atomic electric station in the world was started in 1954 and is still in operation.

At the same time that work on this thermal-neutron atomic station began at the Institute of Atomic Energy, plans were initiated in Obninsk for fast-neutron reactors and with expanded fuel breeding (1948–1949). However, whereas thermal-neutron reactors were backed there was exact knowledge and commercial experience, only a likely hypothesis was known for fast-neutron reactors. A detailed study was made during these years of the physics of fast-neutron reactors, and further develop-

*Paper delivered at the session of the division of nuclear physics of the USSR Academy of Sciences, 5 October 1967.

Table I

Location	Designation	Electric power	Start of operation	Responsible physics institute
Obninsk	1st Atom. Elec. Sta.	5 MW	1954	IAÉ, FÉI
Siberia	"Siberian"	600 MW	1958	IAÉ
Icebreaker	"Lenin"	44 тыс. thous. hp	1959	IAÉ
Obninsk	TES-3	1,5 MW	1961	FÉI
Melekess	"Arbus"	0,5 MW	1963	FÉI
Novo-Voronezh	VVER-1	210 MW	1964	IAÉ
Beloyarsk	BAS-1	100 MW	1964	IAÉ
Moscow	"Romashka"	500 W	1964	FÉI
Melekess	VK-50	50 MW	1965	IAÉ
Beloyarsk	BAS-2	200 »	1967	IAÉ
Shevchenko	BN-350	150 MW, 120 000 M^3/day	1969—70	FÉI
Novo-Voronezh	VVER-2	400 MW »	1968	IAÉ
Bilibino	BATETs	2×12 MW, 2×25·10^6 kcal/hr	1970	FÉI

ment of reactor science and technology proceeded along two lines: the rapidly advancing line of thermal-neutron reactors, and the slightly gaining line of fast-neutron reactors.

The present-day status of our field of science can be characterized by the table of the constructed atomic electric stations and those now under construction (Table I) and by the list of experimental and experimental fast-neutron reactors other than to the commercial BN-350 reactor (Table II): BR-1, rated 100 W, constructed in 1954—55; BR-2, rated 100 kw, started in 1956; BR-5, rated 5000 kW, started in 1958; and an experimental test reactor, rated 60,000 kW (thermal), now under construction in Melekess and scheduled to be started in 1968. It should be noted that if we are successful in starting the BN-350 in Shevchenko on schedule, then this will be the first commercial fast-neutron reactor in the world.

Naturally, this technical development can and should occur as a result of intense work on the part of the physicists, who investigate the nuclear-physics processes in reactors with ever increasing detail and accuracy. By now the field of nuclear physics has become quite distinctly outlined, and is called reactor physics. It can be subdivided into two parts:

1. The study of elementary nuclear processes occurring in reactors, in the shields, etc: neutron scattering (elastic and inelastic), capture, fission, secondary neutrons (prompt and delayed), angular distribution of reactions, γ spectra, etc—in a wide range of neutron energies for all the natural and artificial isotopes used in reactors.

2. Study of the propagation of neutrons in fissioning and non-fissioning media, space-energy distributions of neutrons under conditions of complicated geometries, distributions of different nuclear reactions; study of the time evolution of the processes.

Owing to the efforts of various staffs, principally those of the Institute of Atomic Energy, the Institute of Experimental and theoretical physics, and the Physics and Power Engineering Institute, major results were obtained in this field and led to the contemporary development of atomic technology.

Table II. Experimental BR reactors

BR-1	1955	Obninsk
BR-2	1956	Obninsk
BR-5	1958	Obninsk
BR-60	1968	Melekess

I wish to recall that A. F. Ioffe regarded the organization of physicotechnical research in our country as one of the most important tasks. Numerous physicotechnical staffs were organized in the field of nuclear technology, as well as in many other fields, and the leading role was played and is still being played by the direct and indirect students of A. F. Ioffe.

It is impossible to list all the participants in this tremendous project, and I shall therefore confine myself only to the names of a few nuclear scientists of the older generation, who played a major role in the development of reactor physics. These, besides the already mentioned comrades, are Aleksandrov, Alikhanov, Blokhintsev, Bondarenko, Vladimirskii, Galanin, Groshev, Davidenko, Kazachkovskii, Kikoin, Krasin, Marchuk, Pevzner, Romanov, Spivak, Usachev, Feinberg, Frank, Fursov, Shapiro, and many others. Many names of major scientists from the younger generation have been appearing recently, thus evidencing healthy development. Thus approximately 200 persons took part in a 1966 conference on reactor physics.

In spite of the tremendous upsurge of work in this field, notice should be taken of the need for intensifying the work, since new problems and requirements arise continuously. Our knowledge of the cross sections or other parameters of the interaction of neutrons with nuclei, which should be measured with accuracy 1—2% in the entire energy range, is far from complete as yet.

For further development of research on nuclear physics, including the solutions of these problems, new installations are now being constructed and designed: a high-powered pulsed reactor in Dubna, an isochronous cyclotron and a charge-exchange electrostatic generator in Kiev and possibly also at the Institute for Atomic Energy, apparatus for neutron spectrometry on the Gatchinsk cyclotron, a powerful pulsed neutron generator in our own institute, etc. The installation of all this apparatus will reinforce and enhance the experimental technology of nuclear physics and also enable us to solve problems in reactor physics.

The reactor-physics calculation methods also call for improvement. In particular, it is necessary to improve the allowance for all the features of the behavior of the cross sections at different neutron energies, and it is necessary to develop more accurate and more effective methods for taking into account processes occurring under real geometry. The capacity of the elec-

tronic computers available to us is still insufficient; reactor problems encountered in practice are so complicated that the development of new methods that economize computer time are a serious necessity.

Insufficient knowledge of the constants of the interaction between neutrons and nuclei, and insufficient development of theory and capacity of the electronic computers, make it necessary for us to perform many expensive experiments and frequently make it necessary to operate with excessive "margins."

The great importance attached to nuclear physics has not only (perhaps, has not so much) helped develop that part of nuclear physics which is necessary for further extension and perfection of nuclear engineering, but has also made it possible to develop a new branch of nuclear physics, that of elementary particles, and to construct ever larger accelerators.

Work on thermonuclear reactions also is a consequence of the advances in nuclear physics.

Nuclear engineering, which made it possible to obtain powerful neutron fluxes in reactors and fluxes of charged particles in accelerators, turned out to exert a very strong influence on the development of various branches of science. The main role has been played in this case by the method of tracer atoms, the significance of which cannot be over-estimated. Its influence on science can be compared only with the invention of the microscope. It is impossible to present even a brief description of all the applications of nuclear engineering in various branches of science. We therefore confine ourselves to listing only some of the most noticeable ones:

1. Study of structures with the aid of neutrons—magnetic structures, organic and biologic molecules, defects in solids, etc.
2. Physics of radiation damage—a new branch of solid-state physics.
3. Energy transfer in liquids and solids.
4. Resonance scattering of gamma rays (Mossbauer effect)—a very subtle method with tremendous application capabilities.
5. Production of infralow temperatures with the aid of He^3.
6. Nuclear-physics research.
7. Activation analysis.
8. Geological and geochemical research.
9. Mechanisms of chemical reactions.
10. Biochemical reactions.
11. Different applications in biology, this being one of the most important trends.

Of course, it is easy to add many more applications to this list. In any case, it is clear that practically all branches of natural, technical, and even humanitarian sciences (history and archeology) are affected by nuclear science and technology.

What has nuclear science offered to engineering and what will it offer in the nearest future? The corresponding list is already quite impressive:

1. Isotopic instruments (the economic effect was 200 million rubles in 1963 and 250—300 million rubles in 1966).
2. Inspection of products by means of isotopic sources.
3. Sterilization of medical instruments and materials.
4. Conservation of fruit products.
5. Isotopes for diagnostics and therapy.
6. Explosions for excavation work (in the future).
7. Radiation chemistry—"sewing together," polymerization, etc. This will undoubtedly be one of the most important applications.
8. Water desalinization; this will be extensively used, since the need is great, and the thermal energy of large atomic electric stations will be cheap.
9. Power for outer space.
10. Power for transport.
11. Power for remote regions (small). Finally:
12. Large-scale power.

There is no doubt that the greatest influence on our living conditions will be exerted in the nearest future by atomic power, which I shall discuss in greater detail, and by radiation chemistry, which I shall not discuss.

Before proceeding to consider atomic power, the most important application of nuclear physics, I wish to note that the development of atomic engineering has also exerted a large indirect influence on technical progress, since it has required higher-grade materials, more perfect technologies, fault detection, new instruments, new materials, etc. All this has raised the overall technical level in several branches of our industry. In addition, atomic engineering has also exerted a strong stimulating action on the development of computation mathematics and computation engineering.

ATOMIC POWER FOR OUTER SPACE

I shall start the description of four trends of atomic power applications for outer space.

In the near future, it will be necessary to employ in outer space sufficiently powerful and long-lived sources of energy to perform various functions. Electric energy in space ships can be used to supply the instruments: for example, television and communication require airborne stations delivering tens and eventually even hundreds of kilowatts with a very long service life; electric energy is needed for the supply of ionic or plasma engines used to correct the trajectories (relatively low power) and to produce thrusts during flight (travel to planets, high power). Finally, a nuclear reactor can heat hydrogen to very high temperature, $\sim 3000^\circ K$, and produce propulsion thrust without the use of electricity.

Depending on the power and on the functions, we consider five types of apparatus for outer space:

1. Isotopic heaters for thermocouple batteries.
2. Reactors with thermocouple batteries.
3. Reactors with turbine generators.
4. Reactors with thermionic converters inside or outside the reactor.
5. Reactors for hydrogen jet engines.

On the basis of the published data, principally American and ours, we can estimate the existing and future outer-space power installations. Of course, such installations are used not only in outer space but also in other cases when prolonged autonomous operation is

necessary, for example, in various types of geophysical stations such as our "Beta-2."

Isotopic sources produce at present up to several dozen watts, and kilowatt sources will be feasible in the future. Reactor setups generate much larger power than isotopic ones, at the present approximately 500 W, but tens, hundreds, and even thousands of kilowatts are possible in the future.

The well-known reactor "Romashka" is a very interesting construction. It is a fast reactor using uranium dicarbide UC_2. The heat is transferred by conduction to the outer surface, to which the hot junctions of thermocouples are secured; the cold junctions give up the heat to a radiator. This reactor has operated well and is promising.

It should also be noted that the most promising, from the point of view of weight, are reactors with direct thermionic conversion inside the reactor fuel-element channels. In these reactors, the fuel elements themselves are the cathodes of the converter.

We have developed and tested successfully at our institute models of such channels in reactors. They operated well for a long time and produce approximately 2 W per cm^2 of cathode.

It is still a long way to the rocket reactor with thermionic converter for spaceborne stations, all the more since to obtain good weight characteristics it is necessary to increase the per unit power by a factor 5—10, but in time this will become quite feasible.

ATOMIC POWER FOR TRANSPORT

Of course, an atomic navy has been constructed, and this is the most important transport application of atomic power. However, from among the peaceful applications, the ice breaker "Lenin" is the most successful application of atomic engines for transport. The icebreaker makes good use of the advantages of atomic energy—there is no need to refuel. In the USA, under the influence of the success of our icebreaker, they are also getting ready to construct atomic icebreakers. Undoubtedly, atomic energy will also be introduced in the ordinary merchant marine as soon as the atomic power installations become cheaper.

If it becomes necessary in the future to construct engines for airplanes or dirigibles capable of carrying loads as far as desired without additional refueling, the engines for this purpose will likewise be atomic.

ATOMIC POWER FOR REMOTE LOCALITIES

This is perhaps a problem unique to our country. In northern and northeastern Siberia there are locations with very rich natural resources, where mines, residential settlements, and enterprises requiring electric energy and heat are being constructed. The transportation of fuel to such regions is so expensive that atomic stations of even small power become economically suitable. The first experimental small stations were constructed in Obninsk (TÉS-3) and in Melekess ("Arbus"). The first commercial station is being constructed in Bilibin on the Chukotsk peninsula (see the last line of Table I). It can be assumed that such stations, with larger or smaller ratings, will be widely used in our northern regions.

HIGH-POWER ATOMIC ENGINEERING

High-power atomic engineering is the most important application of atomic science and technology. Experience gained since the starting of the first atomic station in 1954, and experience in research and operation of many and various atomic electric stations, have demonstrated without any doubt the following:

1. The capital investment in large-scale atomic electric stations with power of approximately 1,000,000 kW per unit will amount to 100—150 rubles per installed kilowatt, i.e., not much different from the capital investment in coal stations.

2. The fuel component of the cost of electric energy for atomic stations is much lower than that for coal stations, since the heat-production capacity of uranium is larger by a factor 2×10^6, thus resulting in a much lower cost per calory.

These two circumstances assure us that the atomic electricity and atomic heat will be cheaper than those produced by coal, and consequently will be rapidly introduced.

Countries with developed atomic science and technology and with large commercial potentials are already constructing many atomic stations. Thus, in the USA, 20% of the electric stations on order in 1965 were atomic, and 50% in 1966. It is estimated that the USA will have by 1980 more than 120 million kW of installed atomic electric stations, since the greater part of the newly constructed stations will be atomic.

In our country we are also planning rapid development of atomic power and the construction of large atomic electric stations.

Reactors of various types are being constructed in different countries, depending on the local commercial-economic conditions and the accumulated experience, on the already made investments, on the availability of enriched uranium, etc. Thus, in the USA the development in the nearest future is based on water-water reactors, single-loop boiling water reactors and two-loop reactors without boiling in the reactor. In England, where experience on CO_2-cooled graphite reactors has been accumulated, an economic type of such a reactor has been developed. In our country we regard as economical water-water reactors, such as in the Novo-Voronezh station, and graphite reactors cooled with boiling water, similar to those used in the first atomic electric station in Obninsk. We are hoping to construct water-water reactor in Bulgaria, Hungary, and in East Germany.

There is no doubt that heavy-water reactors have the best physical qualities of all thermal-neutron reactors. They require less uranium than others and produce more plutonium than the others. However, the heavy-water reactor is the basic type only in Canada. The Institute of Experimental and Theoretical Physics, which has done much for the study of the physics of this reactor and its development, is helping in the construction of such a reactor in Czechoslovakia.

The rapidly developing construction of atomic electric stations has raised the question of the fuel resources. The situation is quite tight. The point is that thermal-neutron reactors are competitive only when the uranium cost is relatively low, not more than

Table III

Dollars per kilogram	Known resources, thous. tons	Possible resources, thous. tons	Total thous tons
11—22	682	681	1363
22—33	719	503	1222
33—66	429	$(1.1-11)\cdot10^3$	11000

Table IV

Type of reactor	Water	Heavy water	Gas-graphite	Fast neutrons
Uranium, thous. tons . . .	900	550	750	75

$20 per kilogram. There is relatively little such uranium, but there is very much uranium which can be obtained at a higher cost. The world's resources of uranium (without taking into account the expensive uranium from the ocean, where the resources are colossal) are estimated in Table III.

Specialists in the USA believe that at the existing rates of growth of atomic power, they have enough uranium for thermal-neutron reactors for apparently 15—20 years.

It is seen from the foregoing that the development of thermal-neutron reactors is an intermediate stage in the development of atomic power, and that it is expedient to start as soon as possible the construction of stations with fast-neutron reactors with extended fuel breeding, in which uranium is used highly economically and which are capable of employing the expensive uranium efficiently.

Fast-neutron reactors, owing to the advantageous neutron balance, can produce, using waste uranium-238 (waste from diffusion production and from plutonium reactors), approximately 1.4—1.6 times more plutonium than is being burned up in the reactor. This feature is the cause of all the remarkable qualities of fast-neutron reactors: production of new plutonium in the reactor, sufficient not only for further supply of this reactor but also for the construction of new reactors, the use of waste uranium, the use of very expensive uranium or plutonium, since more expensive plutonium is produced than is consumed, and the fuel cost is thus low for the same reason.

Experiments performed back in 1954 have already convinced us that the breeding coefficient of $Pu^{239}-U^{238}$ is very large. In 1955 we measured it with the BR-1 reactor and obtained 2.5 ± 0.2. This high value of the breeding coefficient has determined our physical and technical policy. We have decided that it is possible, at the expense of a slight loss in the breeding coefficient, to use ceramic PuO_2 and UO_2 fuel elements, which offer a very high temperature stability and ability of deep burnup of the plutonium and uranium. Our first experimental reactor BR-5, rated 5000 kW, was constructed with oxide elements and fulfilled all the expectations. The European countries have also changed over recently to the development of oxide-fuel elements for fast reactors. In the USA they have also greatly intensified work on oxide elements. The second resolution adopted by us for the BN-350, was to use not plutonium but uranium-235 in the first active zone of the reactor.

Finally, the third idea was the so-called mixed cycle, which made it possible to employ quite effectively the tremendous resources of thorium in the same fast reactors, without reconstructing them. Thus, extended breeding is obtained in fast neutron reactors, and consequently complete burnup of both the U-238 and thorium.

The foregoing circumstances make the fuel reserves for the fast-neutron reactors practically inexhaustible, particularly if account is taken also of the reserves in the ocean, from which British scientists promise to extract uranium at a cost of approximately $100 per kilogram.

If we take into account the fact that within 30 years there will be constructed atomic stations with a total rating of 400,000 MW (they are planning 800,000 MW in the USA), then the amount of uranium required for their construction and operation is tentatively shown in Table IV.

This table shows once more how important it is to introduce fast-neutron reactors as early as possible. The most important stage of this project is the starting of BN-350, which will provide us with a commercial experience, will demonstrate on a large scale the possibility of quiet operation of a fast reactor with sodium coolant, and will serve as the basis for further development and construction of larger stations.

In conclusion I emphasize once more the great influence of the development of nuclear physics on our living conditions. Abundant provision of cheap electricity and heat to humanity is an exceedingly powerful means for increasing national wealth. This alone will justify the efforts of the scientists and engineers.

It is not excluded that nuclear physics and nuclear power will also lead to other no less important applications. At any rate, it can be stated that the Soviet Union has competent nuclear physicists who have performed their duty and continue to develop science and technology successfully.

Translated by J. G. Adashko

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PROSPECTS OF SYNTHESIS OF NEW ISOTOPES AND ELEMENTS*

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NOWADAYS it is difficult to imagine that there are people anywhere in the world who do not know the significance of the word "radioactivity" or what radium is. Marie Sklodowska-Curie together with Pierre Curie gave humanity both the element and the concept.

The extensive and systematic investigation of natural and subsequently also of artificial radioactivity started with that great discovery. Indeed, this turned out to be an invaluable contribution to our concepts of the structure of matter and to our knowledge about the atomic nucleus.

Nuclear physics investigates the structure of both stable and radioactive nuclei. The larger the number of the various isotopes which have been investigated, the clearer a picture of the structure of nuclear matter is revealed. It is therefore natural to analyze how far we have progressed in this direction, how many isotopes have already been synthesized and investigated, and how many must still be obtained and investigated by experimenters in the future. An answer to this question can be obtained by considering Fig. 1. This figure shows the isotopes which have already been synthesized and the possible isotopes with various Z (Z is the number of protons in the nucleus) and N = A – Z (N is the number of neutrons in the nucleus and A is the mass number) which can apparently be studied in the future. Stable isotopes are marked by little black squares. About 1500 additional isotopes with around a hundred of them in the transuranium region were obtained by various methods in nuclear reactions after the Joliot-Curies discovered artificial radioactivity in 1934.

The scale of the diagram is so small that nuclear fission which determined the technological progress of the twentieth century left only small excursions on this isotope chart. The outer contour indicated by a continuous line marks the boundaries of the region of stability obtained on the basis of theoretical calculations. It is readily seen that the region of synthesized isotopes is very small compared with the region which remains to be filled. The estimated number of possible isotopes in this region is four to five thousand. This is considerably more than the number obtained so far.

Two questions arise: 1) what can one expect from an investigation of these isotopes and, consequently, should they be obtained? 2) can they be obtained?

In the opinion of the body of physicists and chemists working in Dubna, one should undoubtedly attempt to obtain these isotopes and investigate them. Synthesizing such isotopes as, say, calcium-70 or calcium-31, we have at our disposal nuclei with very unusual ratios of numbers of protons and neutrons (20p and 11n or

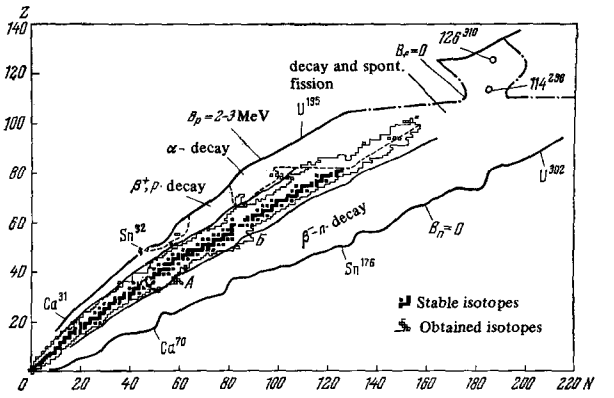

FIG. 1.

20p and 50n). In this case we can study nuclear matter in extremely unusual states. Such a methodological approach is very characteristic of physics in general. Thus, for example, investigators study the behavior of matter in strong magnetic fields, at very high pressures, under conditions of high electric fields, etc. From this point of view the study of nuclear matter when the ratio of Coulomb and nuclear forces is unusual will allow one to obtain very useful information about its properties. In this context one can understand the special interest in the study of far transuranium elements where both the Coulomb and nuclear forces are very great.

How can new isotopes be obtained? Attempts were made to solve this problem by many methods. In particular, underground nuclear explosions were used in the U.S.A. to obtain very heavy isotopes of transuranium elements. The essence of this method consists in the fact that in neutron fluxes of limitingly large density nuclei capture several neutrons one after another without having time to undergo beta decay. This makes it possible to obtain from the initial uranium-238 very heavy uranium isotopes which transform after several beta decays into further removed elements.

The first experiments were not specially intended for obtained heavy isotopes. The 100th element with a mass of 255 was discovered in 1952 as a result of an explosion (not underground but above ground) without a very large neutron flux. Starting from very general considerations, one could assume that if one were to obtain much larger fluxes and if one were to carry out a specially rapid chemical analysis, then this should lead to success in an attempt to advance to higher atomic numbers. Optimistic estimates indicated that one could thus obtain elements with a large value of Z. It was expected that one could then synthesize the 110th, 112th element, etc.

There are few instances in which so much effort was lost to reach a goal—the obtaining of large neutron fluxes and the chemical extraction of the trans-

*A lecture presented in Warsaw on the occasion of the celebration of the hundredth anniversary of the birth of M. Sklodowska-Curie (October, 1967).

uranium fraction, but scientists were inspired by the lofty task of penetrating into the region of long-lived isotopes of remote elements and we believe that everything possible was in general done. However, only the isotope of the 100th element with the mass 257 was successfully obtained by 1966, i.e., in the course of fourteen years this method resulted in no progress in Z and in all in two units of A. It does not appear to us that this indicates that the method is completely hopeless; there exist apparently some additional possibilities. It is seen, however, that there is a physical reason which has so far not made it possible to proceed by this method into the region of new elements.

A second method of synthesis of new nuclei whose development began in 1954 in the U.S.A. and in the U.S.S.R., apparently on the same conceptual basis, is an attempt to utilize heavy accelerated particles: carbon, oxygen, neon, and argon. In principle two procedures are possible in this case. First, pieces of nuclear matter, say five to seven neutrons together, may break off from the compound nucleus; thus instead of sequential capture the target nucleus can capture at once a whole complex of neutrons.

Reactions of this type were indeed investigated. Transfer of 5–8 neutrons was observed in Dubna. The cross section for such a process is small, although in this case we do not venture far from the region of stability. In order to penetrate into the region of instability (see Fig. 1), stable nuclei must be enriched with 40–50 neutrons. The cross section for such a process is so small that this method is of little promise even if heavier particles are used.

The second procedure consists in the fact that instead of a transfer process of neutron complexes one makes use of fusion reactions. Let us, for example, consider what one should obtain on bombarding lead-208 with neon-20. In this case the compound nucleus (uranium-228) will have an excitation of about 60 MeV. As a result it emits six neutrons and the light uranium-222 isotope is synthesized. This method yields neutron-deficient isotopes.

In particular, this method was used to synthesize proton emitting neutron-deficient isotopes. V. A. Karnaukhov and co-workers in Dubna, Bell in Canada, and subsequently also the American investigators R. Macfarlane, A. Paskanser, et al. succeeded in going a little outside the region of stability and nevertheless to observe about two dozen proton emitters.[1-3] On proceeding further into the region of neutron-deficient isotopes one should observe the two-proton radioactivity predicted by V. I. Gol'danskiĭ. This requires the emission of 15–20 neutrons. However, here a very strict law known to all who deal with synthesis of nuclei far from the stability region begins to operate. We would like to get away from this region as far as possible. At the same time, we utilize for this purpose nuclear processes which although they occur in 10^{-14} sec are in essence adiabatic. Therefore after the emission of 6–8 neutrons the probability of emission of neutrons by the nucleus decreases whereas the probability of fission of the nucleus of the emission of protons increases appreciably. In the case of neutron-deficient isotopes of medium masses the nucleus attempts to turn back and actually returns to the stability region emitting protons.

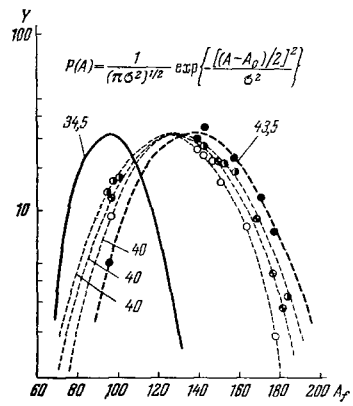

FIG. 2.

In the process of synthesis of transuranium elements there is a large probability of fission, as a result of which one obtains instead of a nucleus of the 100th element, for example, two nuclei with Z = 50. This indeed leads to the circumstance that in solving the problem of the synthesis of transuranium elements one must deal with catastrophically small cross sections. The latest experiments carried out in Dubna showed that whereas the cross section of the 102nd element of which six isotopes have been synthesized amounts to 10^{-9} barn, the cross section for the production of the 104th element is only 10^{-10} barn, and for the 105th element it is even smaller. All that can be done to increase the yield is to increase the intensity of the accelerated particles, or, instead of exposures of months, to carry out the experiment in the course of many years. Both of these methods are linear, whereas the decrease in the cross section is exponential. Therefore, in our opinion, the 105th element whose properties are at present being refined at Dubna will apparently be the last element that can be approached by this method.

A natural question is: is there a way out from the resulting situation? Analyzing the possibilities, we have reached the conclusion that nuclear fission is the main factor which makes the synthesis of new isotopes and elements difficult. Let us attempt to utilize a method sometimes used by experimenters—to make the interfering factor work to our advantage. We attempt to accomplish the synthesis of new elements by means of nuclear fission, increasing gradually the charge of the bombarding nucleus. The fission fragments will then also gradually increase their charge, and finally in the limiting case, say in the bombardment of uranium with uranium, one can obtain isotopes of remote transuranium elements, and not only transuranium ones, but at the same time also all the elements shown in Fig. 1. In addition this method is particularly promising for obtaining nuclei in isomer states of various types.

The idea appears sensible; however, one must carry out experiments which would indicate what is actually obtained, and how many isotopes of various elements are produced in the fission process. To this end Yu. Ts. Organesyan in conjunction with a group of chemists carried out during the past year in Dubna

systematic investigations of fission products of heavy nuclei under the action of multiply-charged ions. At first we turned to the work of 1956–1958 where comparatively light particles (carbon and nitrogen) were used to bombard uranium. A distribution curve with a maximum at Z = 50 was obtained in these investigations.

There arose the question of what would happen to the distribution curve when the charge of the incident particle is gradually increased. Undoubtedly, the maximum of the curve will be shifted, namely: a replacement of a particle with Z = 6 by a particle with Z = 22 (titanium instead of carbon) will lead to a compound nucleus with Z = 114, and fission into halves will yield Z = 57, i.e., a displacement of eight units will already have taken place. In addition, as V. M. Strutinskiĭ and co-workers showed, the spread of the distribution should increase.[4,5]

Figure 2 shows the distribution of fragments with respect to A for the case of uranium fission by a light particle with Z = 6 and by heavier particles with Z = 10 and Z = 18. The dashed curves show the dependence of the width of the distribution on the excitation energy. The experiment was carried out for several energies of the bombarding particles. A shift of the distribution maximum, an appreciable broadening of the curve, and a rather weak dependence on the energy of the incident particles are observed.

Experiments show that even when uranium is fissioned by neon this method of obtaining isotopes is appreciably more efficient than the usual method when fission is achieved by means of thermal neutrons. Inspite of the fact that in fission by thermal neutrons two peaks are obtained in the mass distribution of the fission fragments, the single peak of fragments in the fission of uranium by accelerated neon ions is so broad that for large A the isotope yield turns out to be larger by a factor of thousands and millions than in fission by neutrons (Fig. 3).

I recalled the fact that both transfer and fusion reactions are adiabatic processes. Therefore, synthesizing transuranium elements in nuclear fusion reactions with heavy ions, we obtain neutron-deficient isotopes lacking several—five, six and at times even more—particles. There is never any excess and the spread is very small. If, on the other hand, use is made of the fission process, then owing to the fact that

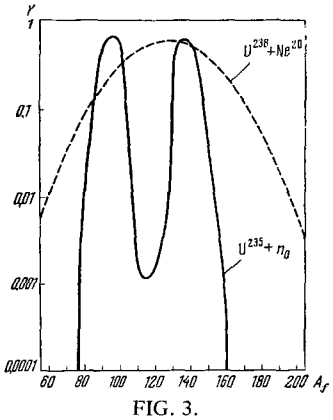

FIG. 3.

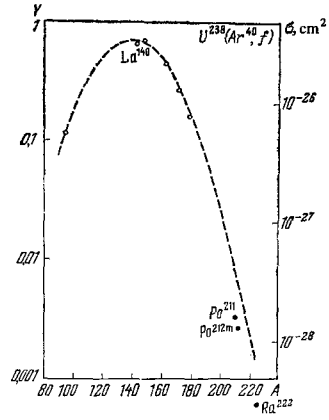

FIG. 4.

in this process there is a very complex distribution over excitation energies, the spread in A for given Z is also large. Of greatest interest perhaps is a recently obtained curve (Fig. 4). Bombarding uranium (Z = 92) with argon (Z = 18) we should have obtained a compound nucleus with Z = 110 and with fission into halves—nuclei with Z = 55. However, because of the spread in Z polonium and astatine (Z = 84, 86) were observed. This means that in this experiment we almost came close to the transuranium elements. Based on methods whose foundations were already laid many years ago by Marie Sklodowska-Curie, when polonium was first extracted from large quantities of ore, it has now been possible to study the A distribution for polonium on a large number of isotopes obtained in a uranium target bombarded with neon and argon ions.

The following figure (Fig. 5) depicts the cupola-like distribution of fission products for this case drawn in three dimensions in accordance with data from our experiments. Here the distribution in Z encompasses about 50 units and several dozens of isotopes are obtained for each given Z. Therefore, about 1000 isotopes are obtained even in an experiment in which we use comparatively light particles. There are no doubts that by accelerating heavier particles one can obtain many thousands of isotopes including isotopes of remote transuranium elements.

It has already been mentioned that it is essential to accelerate such particles as krypton, xenon, tungsten, and uranium. Special accelerator projects are at present being developed for this purpose all over the world; A. Ghiorso spoke of one of these in his lecture ("Synthesis of Transuranium Elements"). We at the JINR have chosen a way which differs somewhat from that followed by the U.S. physicists. At the present moment the ion source which operates in Dubna exceeds in its intensity of multiply-charged ions (with 7–8 charges) by a factor of 25 those obtained in the U.S. At the same time, not all the possibilities have so far been utilized in the sources. Our ion source was developed almost twenty years ago by L. A. Artsimovich and his co-workers for separating isotopes, and by changing its parameters but a little it was possible to obtain ions with 8–12 charges instead of singly-charged ions. We have full confidence that by making full use of the technology employed in plasma investigations we shall be able to obtain ions with 14–16

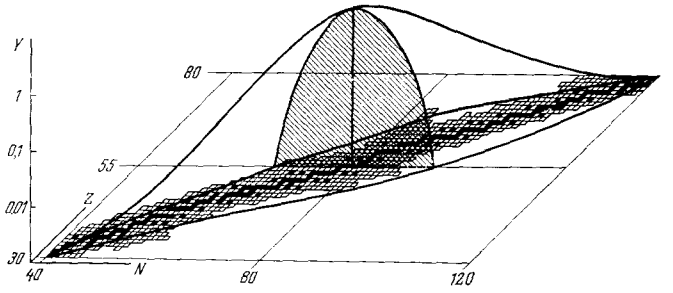

FIG. 5.

charges. Tungsten ions are being accelerated in the multiply-charged ion cyclotron of the JINR; true, so far only up to energies of about 100 MeV. Utilizing multiply charged tungsten (+10) and increasing the diameter of the device (but not as much as indicated in the lecture of A. Ghiorso), it will be possible to obtain tungsten and uranium ions with intensities of tens of microamperes and with the energies required for carrying out nuclear synthesis.

Investigations of ion sources reduce in essence to attempts to "drive" the largest power into a gas discharge. This is also done by those who are concerned with ion sources and controlled thermonuclear processes. It seems to us that here a new possibility has been discovered relatively recently. As a result of the development of laser technology it has been possible to obtain light beams of very high intensity. It suffices to say that a laser with an average power of 1 watt is equivalent to a pulsed source with a power of many hundreds of thousands of kilowatts. Naturally there appeared therefore thoughts of utilizing these gigantic powers for obtaining highly charged ions. The power of a laser is large, but the energy per quantum amounts in all to a few electron volts, and by means of these quanta one must detach from the atom electrons with binding energies of 100 and sometimes 1000 eV. Therefore, our attitude to the use of lasers was even as recently as a year ago not very serious; this was so up to the appearance of the first publications in which it was reported that ions with 8–10 and even 15 charges of such elements as calcium and iron are obtained as a result of irradiating metal plates with ultrapowerful lasers.

Apparently at such high powers there occurs something referred to by physicists as collective interaction with simultaneous absorption of a large number of light quanta, or some other processes take place which lead to electrical fields sufficient for the deep ionization of atoms. Therefore, along with further refinement of plasma sources, it is essential to develop laser sources.

If one considers the collective efforts in developing methods of accelerating the heaviest ions, then one will have in the first place to think about possible work directed towards the refinement of ion sources. The transuranium problem can serve as an example of such collective efforts in the solution of the most complex problems. Without entering into the fine details of the discussion of the chemistry of the 102nd element, I note that apparently the results of the American scientists substantially supplement our results based on gas chemistry. Of course, all this is far from what we should like to know about the 102nd element. The word " chemistry" includes both physico-chemical, electrochemical and many other properties, and it is essentially inexhaustible. The hope that we shall have a volume describing the properties of the 102nd element similar to the contents of Gmelin's handbook for other elements is, I believe, unfounded. But we can, say, determine the valence, which is also nominal. (It is well known that the valence depends on external conditions.) From this point of view it appears to me that gas chemistry—one of the basic methods of investigation used in our laboratory (the properties of both the 102nd and 104th element were studied by the method of gas chemistry)—represents already in itself a large step forward.[6,7]

There arises the question of the legitimacy of defining the physico-chemical properties of individual atoms. It should be said that when we began experiments on the chemistry of the 104th element we started from the premise that the chlorine compounds of the 104th element and the chlorides of hafnium will have analogous properties. Data on the temperature dependence of the vapor pressure for hafnium compounds were found in the textbooks. But how can one apply this concept to a single atom? A difficult situation resulted. It turned out, however, that an appropriate physical analogy exists for a single atom. If a single atom collides many times in an ion exchange column with a surface or settles on the resin and again escapes from it, then the number of adsorption and desorption acts is very large, and one introduces then instead of the vapor pressure the concept of the mean time during which this atom stays on the surface. This concept is valid and we have no doubt that the behavior of a single atom will coincide with the way in which a large complex of atoms would behave if there were no interaction between them. But the interaction need only be taken into account in weighable quantities; therefore, if we consider chemistry valid for hundreds of thousands of atoms, then it is just as valid for a single atom.

It appears to me that in this discussion, which will, I hope, still continue for a little while, this contrasting of chemistry and physics is very artificial. The fact is that if we deal with elements with live, say, millionth parts of a second then neither gas nor liquid chemistry will yield anything. At the same time, the nuclei will during those times capture K electrons and a study of the x rays will essentially yield as reliable data about Z as are, for example, obtained as a result of a chromatography study of the element.

Special consideration must also be given to the problem of the determination of the mass number of the new isotopes. In recent syntheses of short-lived nuclei, use has been made of so-called physical identification. According to these methods the mass numbers of the reaction products were identified, for example, from the excitation function of the given reaction, i.e., from the yield of the investigated product as a function of the energy of the bombarding particles. However, these methods of indirect identification do not always yield unambiguous results. A direct answer to the question regarding the mass number of an isotope can

be obtained by the use of a mass spectrometer or separator. However, this cannot be the usual variant of this instrument, but a rapidly operating one which permits one to work with very short-lived nuclei. As you well know, such instruments are at present constructed in a number of laboratories. Their main feature is that the products of nuclear reactions are rapidly separated from the target and rapidly transported to the ion source of a continuously operating mass separator. The detection of the decay of the separated isotopes is accomplished in the separator itself. Such a rapidly operating separator on line with a heavy-ion cyclotron is being constructed in Dubna.

It should be said that thus far the success of an experiment on the synthesis of isotopes is in many instances determined by the beam intensity, the isotope purity of the target, and the absence in it of impurities such as lead. Unfortunately, the first experiments on the synthesis of elements 102 and 103 did not satisfy these conditions, neither in the USA, nor in Sweden, nor in the Soviet Union. There were at that time no single-isotope targets and the obtained data could therefore be ascribed to this or that isotope. In particular, the isotope which was synthesized in the Swedish work "took on" in the course of a decade five values of the mass number from 251 to 255, and many years of work were required in Dubna[8] to synthesize and investigate the six isotopes of the 102nd element, in order to leave no room for ever new hypotheses of persistent authors.

The second circumstance also turned out to be important. During the initial stage of the experiments on heavy ions it was not clear that lead will be a very dangerous impurity. The yield of analogous alpha emitters for lead is larger by a factor of a million than the yield of the far transuranium elements obtained in irradiating plutonium, curium, or californium. Therefore the purification of targets of lead is absolutely essential. Since there is much lead in physical and chemical laboratories, this task proved to be very difficult. The laboratories are saturated with lead: soldering is done with lead solder, cables have lead jackets, shielding is made of lead, etc.

We have apparently succeeded in proving that the Swedish work did not deal with the 102nd element but with an irradiation product of lead, i.e., an isotope of the 88th element or a product of a stripping or fission reaction with $Z = 90$.

The work of synthesizing the 105th element also depends to a large extent on the purity of the target—only a limitingly small content of lead is admissible.

Another approach is to produce such conditions that even a single decay event is so reliable that it does not admit contradicting interpretations and that no background appears. In our work with the 105th element we are following both paths: on the one hand, we purify our elements of lead, and, on the other hand, we try to obtain a maximum of information per alpha decay, information that would absolutely exclude the possibility of the appearance of any interfering factors (the method of amplitude-time correlations).

The young participants in the work with the 105th element believed at one time that the work is complete. However, those complications which occurred with the 102nd element as well as the difficulties in the work concerning the 103rd element (our results conflict with what was published by American investigators in 1961), lead us to conclude that the investigation should be continued, inspite of the fact that the information about the 105th element which is at our disposal is more reliable than the data initially obtained for the 102nd and 103rd element.

I do not know whether I have succeeded in indicating the state of the problem at present and in the future. In the past there have apparently been very many hasty conclusions. This required an additional decade of work and it appears to me that we must now think more about the present and about the future. I have therefore not analyzed in detail the work of the Fifties and of the early Sixties.

If we are to recall the past, then only the remote past, namely the heroic efforts of Marie Sklodowska-Curie and Pierre Curie in their discoveries of the new elements. It should be mentioned that at that time they discovered new elements in the complete absence of data on their chemical properties, without application of any (from our point of view) complicated methods, but with a very exacting attitude towards their own results and a profound analysis of the obtained data. Therefore, in the work of the Curies there are essentially no instances similar to any extent to the situation that occurred with the discovery of the 102nd and 103 element, and which we hope shall not be repeated in the future.

In conclusion, allow me to express my hope that the problem of nuclear synthesis and of the investigation of numerous new elements and isotopes will be successfully solved by the joint efforts of scientists of the various countries.

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