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FIFTIETH ANNIVERSARY OF THE A. F. IOFFE PHYSICOTECHNICAL INSTITUTE, USSR ACADEMY OF SCIENCES (LENINGRAD)

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1. ORGANIZATION OF THE INSTITUTE. THE LENINGRAD SCHOOL OF PHYSICS

THE celebration of the 50th anniversary of the Soviet State has been reflected, in particular, in the numerous articles and entire publications devoted to the development of physics in this country [1-3]. The exceptional significance of the role played in the history of Soviet physics by the Physicotechnical Institute of the USSR Academy of Sciences can be readily grasped from even a cursory examination of this jubilee material. Now, in 1968, the A. F. Ioffe Physicotechnical Institute (FTI) is celebrating its 50th anniversary of existence.

The significance of the FTI as a forge for the cadres of Soviet physics is graphically demonstrated by the fact that the leading scientific institutes of the Soviet Union are now headed by scientists whose activities had commenced at the Physicotechnical Institute of the USSR Academy of Sciences and who have been for years inseparably connected with it. And indeed, the P. N. Lebedev Physics Institute of the USSR Academy of Sciences, is directed by D. V. Skobel'tsyn; the Institute of Physics Problems of the USSR Academy of Sciences, by P. L. Kapitza; the I. V. Kurchatov Institute of Atomic Energy, by A. P. Aleksandrov; the Institute of Chemical Physics of the USSR Academy of Sciences, by N. N. Semenov; the Institute of Theoretical and Experimental Physics, by A. I. Alikhanov; the Institute of Solid State Physics of the USSR Academy of Sciences, by G. V. Kurdyumov; the Institute of Biophysics of the USSR Academy of Sciences, by G. M. Grank. In Leningrad, the Physicotechnical Institute—this first fruit of the science-organizing activities of A. F. Ioffe (and now bearing his name) and the Institute of Semiconductors of the USSR Academy of Sciences, which was the last of the 15 institutes organized by Abram Fedorovich Ioffe, are headed by V. M. Tuchkevich and A. R. Regal', respectively. The list of these products of the Leningrad school of Ioffe could be still further enlarged if we consider the identities of the scientists heading the activities of physics institutes in other cities in this nation.

Space does not permit a sufficiently complete review of all the stages of development of the FTI and all the research projects carried out in it. Below we shall dwell on the traditional research orientations of the FTI, as well as on two new orientations (plasma physics and astrophysics); all this will be preceded by a general introduction that includes a concise review of the prerevolutionary state of physics in Petersburg.

Physics in pre-revolutionary Russia was chiefly confined to the universities. In Petersburg it was represented by O. D. Khvol'son and I. I. Borgman. These scientists have more than once been written about; it is known that they did not succeed in creating a physics school in Petersburg. The most gifted students graduating from the Petersburg (and Moscow) universities were assigned for advanced training abroad, chiefly in Germany (we will name, e.g.) P. N. Lebedev, D. S. Rozhdestvenskiĭ, L. I. Mandel'shtam, D. A. Rozhanskiĭ, A. F. Ioffe, N. N. Andreev).

Khvol'son and Borgman have accomplished much for our native physics. O. D. Khvol'son penned a multivolume work outlining a course in general physics which for three decades had been a major textbook not only in this country but also abroad. S. I. Vavilov had termed him "a consummate chronicler of physics"; in his 1909 lecture in Salzburg the young Einstein mentioned "the superb textbook by Khvol'son, published in 1902," and cited from it.[4] It is worth noting that Enrico Fermi studied Khvol'son's books.[5] As for his authority in contemporary Russia, it can be gleaned from the unwritten rule that had existed at the time: any young physicist who started out his career as an educator made a special trip to Petersburg in order to present himself to Khvol'son.[6] I. I. Borgman also enjoyed fame even beyond Russia's borders (incidentally, both Khvol'son and Borgman had been invited to take part in a festschrift in honor of Boltzmann's 60th birthday and had their articles published in it[7]).

Being adherents of classical physics, Khvol'son and Borgman were unable to head in Russian the work to develop modern physics initiated by the labors of Einstein and Planck. According to the testimony of Torichan Pavlovich Kravets, "during the first decade of this century three men had been working especially hard to unify the Petersburg physicists. One of them was P. S. Ehrenfest (in Russia Ehrenfest was called Pavel Sigizmundovich—V. F.), who can be credited with truly extraordinary accomplishments in unifying the Russian Petersburg physicists and igniting in them the flame of interest (which at the time was feebly represented) in theoretical physics".[8] The two others named by Kravets were Abram Fedorovich Ioffe and Dmitriĭ Sergeevich Rozhdestvenskiĭ. Ehrenfest organized in Petersburg a seminar on the new physics, which once every two weeks was held in his apartment. The participants in this seminar were the young physics instructors Ioffe, Rozhdestvenskiĭ, K. K. Baumgart, L. D. Isakov, the mathematicians A. A. Fridman, Ya. D. Tamarkin and others, and also the physics students Yu. A. Krutkov, V. R. Bursian, V. M. Chulanovskiĭ, G. G. Veikhardt, and certain others. The university professors did not vist this seminar.

Of the young scientists named above the most well-known at the time was Ioffe, who had undergone excellent training in Munich with Roentgen and, on joining the

Directorate of the State Physicotechnical Roentgenological Institute and P. S. Ehrenfest (September 1924, at main enterance of the Institute). Left to right: I. V. Obreimov, N. N. Semenov, P. S. Erenfest, A. F. Ioffe, A. A. Chernyshev. (Published the first time)

Polytechnical Institute in the capacity of a senior laboratory worker* at the Department of Physics (headed by Professor V. V. Skobel'tsyn), began to develop there his experimental research into the mechanical and electrical properties of crystals. It is conceivable that his decision to experimentally investigate the photoelectric effect may have been influenced by Ehrenfest, with whom Ioffe was linked by close ties of friendship. Ioffe published his findings in an article which gained broad publicity and which not only confirmed Millikan's experimental data on the measurement of the elementary electrical charge (on which doubt had been cast in a series of subsequent studies by Ehrenfest) but also at the same time experimentally demonstrated the quantum nature of the photoelectric effect.[9]

This work, complemented by measurements of the magnetic field and of the magnetic effect of cathode rays (the existence of these effects had at one time been denied by Hertz) was presented by Ioffe as his Master's dissertation and was brilliantly defended in 1913. It opened the way toward a professorial appointment and in the same year Ioffe became Extraordinary Professor at the Department of Physics of the Polytechnical Institute.

Along with it, in the same years, Ioffe published works of a theroetical nature which showed that Einstein's hypothesis of the existence of "atoms of light" (quanta) and of their absorption by Planck resonators of corresponding frequency leads to the spectral formula of Wien rather than Planck and that the derivation of this formula requires acceptance of the theory of the existence of "light molecules"—formations having an energy that is the multiple of $h\nu$ ($2h\nu$, $3h\nu$, etc.).

*Now this title corresponds to "assistant."

This work[10] also has not remained unnoticed. Albert Einstein wrote about Ioffe in his letter to Ehrenfest (February 1912): "I don't doubt Ioffe's ability (Faehigkeit)," probably in reply to a letter in which Ehrenfest highly lauded the work[10] of his Petersburg friend.*

It was precisely within the walls of the Polytechnical Institute, after World War I had begun, in the spring of 1916, that Ioffe's seminar, with its historic consequences to the future Soviet physics, had begun to be held. He enlisted the participation in that seminar of not only young students of the Polytechnical Institute and his co-workers (Kapitza, Ya. G. Dorfman, N. I. Dobronravov, K. F. Nesturkh, M. V. Kirpicheva, Ya. G. Shmidt) but also the University upperclassmen P. I. Lukirskiĭ, N. N. Semenov, and Ya. I. Frenkel'.

The advances made by physics, and the revolution which had shaken its very foundations and which was associated with the experimental and theoretical discoveries made at the turn of the century, convincingly demonstrated that physics was fated to play an exceptional role in the development of technology. This raised the problem of freeing physics from its academic ivory tower in which the slogan of "science for science's sake" had been traditionally followed and separation from engineering and industry was a matter of pride. At the same time, it was becoming clear that physics with its new ideas, methods and tools could contribute to the progress of allied domains of knowledge and particularly of medicine. Speaking of these last prospects we refer primarily to the discovery of x-rays and radioactivity, therapeutic and diagnostic potential of

*I am indebted to the Albert Einstein Fund (Director: Otto Nathan) for permission to publish this excerpt.

which had quickly been grasped by scientists.

In Russia the one man who understood this best was Mikhail Isaevich Nemenov, who had worked in the Women's Medical Institute and founded as far back as in 1913 the All-Russian Society of Roentgenologists and Radiologists. It was roughly at that time, too, that he began to advocate the founding of an institute in which research into x-rays could be centered. However, his initiative collided with the wall of inertia and indifference characteristic of the officialdom of the ministries of Tsarist Russia, and the commencement of World War I seemed to bury completely this idea.

The October revolution altered from the ground up the entire way of life of Russia and, in particular, it unlocked completely new vistas for the development of science in this country. This was due to the foresight of the head of the Soviet Government, Vladimir Il'ich Lenin, and his closest advisers, mainly Anatoliĭ Vasil'evich Lunacharskiĭ, who headed the People's Commissariat of Enlightenment. It is thus not surprising that the Government entirely supported the initiative of the progressively minded Russian intelligentsia for the advancement of science in this country. In Petrograd this initiative was taken, in particular, by Nemenov, Ioffe, and Rozhdestvenskiĭ. In 1918, that year of the hardest trial for the young republic, Nemenov turned to Lunacharskiĭ for support of the idea of founding the new institute and, on recalling his encounter with him many years later,[11] he expressed his amazement at Lunacharskiĭ's immediate grasp of the problem and his zealous promise to support this initiative in every way and contribute to translating it into reality. Nemenov considered it expedient to organize not only research into the medical effects of x-rays and the rays of radium but also purely physical (from his standpoint, applied physical) research intended to throw a bridge between the characteristics of radiation and its biological effect. Along with this, he intended to organize the production of x-ray equipment in this country. In those years there existed two suitable figures for heading the work to implement these plans in Russia: Petr Petrovich Lazarev, a well-known physicist, disciple and inheritor of the mantle of P. N. Lebedev (Nemenov was drawn to him by his interest in biophysics: Lazarev was essentially the first Russian biophysicist, who moreover had a medical background) and Abram Fedorovich Ioffe, the nation's greatest specialist in x-rays. Lazarev could not be a candidate as he was occupied with organizing a new institute in Moscow. Ioffe, on the other hand, responded affirmatively to Nemenov's proposal and undertook to organize the Physicotechnial Division of the future institute. In addition, plans existed to incorporate in the institute's structure a medicobiological division (M. I. Nemenov) and a radiological division (L. S. Kolovrat-Chervinskiĭ).

The present-day Physicotechnical Institute, which bears the name of A. I. Ioffe, dates its existence from 23 September 1918. On that day, as evidenced by the minutes of the meeting of the Little Oblast Commission for Enlightenment, its meeting was opened at 4:45 PM. The nine matters listed on the agenda (and all decided upon within half an hour: the meeting was adjourned at 5:15) of the commission included listening to the "paper by Comrade Lunacharskiĭ concerning the State Roentgenological and Radiological Institute"; the commission resolved to "entrust Professor Ioffe with working out the plan for the Physicotechnical and Radiological Divisions of the State Roentgenological and Radiological Institute."[12]

A book by M. S. Sominskiĭ[13] traces in detail all the principal stages of the founding of the Physicotechnical Institute. To put it briefly, at first the new institute was conceived as an annex, so to speak, of the Women's Medical Institute; this was desired primarily by its director (B. V. Vvedenskiĭ). The organizers of the institute, and chiefly M. I. Nemenov, had a different idea. This led to fairly sharp disagreements. Hence, Ioffe, who took a relatively neutral position toward this conflict, became the first president of the institute—according to the institute's charters each division heads should successively be appointed president), on 24 October 1918. It must be admitted that quite rapidly contradictions had arisen between the Medicobiological and Physicotechnical Divisions. The reason was that Ioffe thought it expedient to broaden the scope of activities of his Division beyond the framework of the interests and goals that had been specified by Nemenov when outlining the future subdivisions of the institute. In this dispute each party was right in its own way but this, to be sure, did not lessen the tension. The difficulty was compounded because the Medicobiological Institute was housed on the Petrograd side, on a street named after Roentgen, while the Physicotechnical Institute was for the time being based in Lesnyy, at the Polytechnical Institute, on the premises of the Laboratory of General Physics graciously provided by V. V. Skobel'tsyn.

Mikhail Petrovich Kristi, quondam head of the Department of Scientific Establishments and Educational Institutions supervising the activities of the Institute, attempted to establish at least a "hollow truce," but when these attempts had failed, he decided to separate the two divisions into two autonomous institutes in order to prevent "a real fray." A corresponding decree was adopted on 29 November 1921 and the Physicotechnical Division commenced its legitimate independent existence under the name of the State Physicotechnical Roentgenological Institute.

Who then laid the cornerstone for the Division (and soon afterward, the Institute)? The originators were primarily the aforementioned participants in Ioffe's seminar, as well as, next, part of the physicists who had attended Ehrenfest's seminar and chiefly Yu. A. Krutkov and V. R. Bursian (the other part rallied around Rozhdestvenskiĭ at the Optical Institute). Lastly, Ioffe recruited for work at the Institute the most progressive-minded—in both the scientific and the political planes—representatives of engineering, mainly from the Polytechnical Institute. It was thence, too, from the Physics and Mechanics Department organized in 1919, that the Institute was complemented with capable young people who began to work in the laboratory starting with the first courses (this was the case with A. I. Alikhanov, A. F. Val'ter, G. A. Grinberg, Ya. G. Dorfman, I. K. Kikoin, V. N. Kondrat'ev, G. V. Kurdyumov, N. N. Mirolyubov, B. Ya. Pines, Yu. B. Khariton, A. I. Shal'nikov, L. V. Shubnikov, and many others).

Ioffe's closest assistants in his work to organize the Institute were his deputies ("president's comrades")

N. N. Semenov, A. A. Chernyshev and, somewhat later, I. V. Obreimov. This was difficult and generally unrewarding work: young scientists in the prime of their creative vigor and talent had to waste their time and effort and even risked nervous exhaustion by attending to supply problems instead of instensely pursuing physics within the walls of the laboratories provided to them, among their own students who by then had begun to appear. That period was characterized by the then 26 years old Semenov in his letter of 25 March 1922 to his friend P. L. Kapitza, who at the time was working under Rutherford:* ". . . Consider what science in Russia is like at present, what is its position and whether it has many energetic members who bear up steadfastly under the difficulties. The position of physics is particularly bad, because it has only begun to come into life in Russia. . . . Where can genuine physics be born. . . , Russian physics only because it will be in Russia and hence it will make it possible to enlist Russian efforts in the field of unified international science? Of course, here, in Petrograd, and the nest of experimental physics should be the Physicotechnical Institute. However inexperienced and numerically few we may be, it is here and only here [in Petrograd] that experimental physics can develop. But its development requires a favorable ambient, instruments, facilities, shops, an adequate staff. That is why the administrative side of the affairs of our Institute seems to be so important, and that is why I believe that the greater part of energy must be devoted to it. . . . It may be that I am exaggerating, but I believe that the organizational death of our Institute would retard the development of physics in Russia for tens of years.

"We have a second and just as important problem but for its solution your resources are greater than all ours. I am referring to the training of physicists, not chatterboxes and idlers but genuine scientists—systematic, persistent, familiar with equipment and techniques, who view science not only as a gratification but also in a business-like manner. . . . But such a corporation of scientists is at present being created very slowly. If the present situation is compared with the situation that had existed in the era of Petrushevskiĭ and Borgman, the progress is obvious. Abram Fedorovich [Ioffe] has played a vital role in training a few disciples—us—who, in our turn, must be concerned for training new cadres. . . . This task is feasible only if an entire team of us works here, since scientific teamwork, intellectual vigor are highly instructive. . . .

"I do not attach so much importance to our work. My belief is that it need not be creatively outstanding so long as we can pave the way for the coming generation which will create a genuine, living Russian science replete with discoveries and inventions. Because I believe, after all, that science, and any other field of endeavor for that matter, is moved not by individuals but by society, even by the entire nation. As for the task of the individual, it is to blaze trails, to help translate into reality the potential contained in the nation."

It was Ioffe's invaluable contribution that, within the walls of the Institute he organized, he created a genuinely creative atmosphere. Its fundamental premise was that Ioffe himself was a man of great and independent talent with wide-ranging interests in physics. Another important quality of Ioffe was that, in the eyes of his (mostly young) colleagues, he was a paragon of moral excellence. Recently N. N. Semenov wrote: "His example shows what a happy old age can be attained by a scientist if his passion for science does not wilt, if he has succeeded in winning the love and esteem of his disciples, if from his very first steps in science only the torch of truth alone has been illuminating his path, if the will o' the wisp of personal gain, vanity, arrogance and envy do not sidetrack him from the path of service to science and thus to his nation."[14]

The third fortunate personal quality of Ioffe was his unique intuition, his ability to predict the orientation of development of science at a time when it still existed at the wellsprings of that orientation. Another and no less important manifestation of this intuition was his ability to sense and assess talent in young scientific workers, to encourage this talent and provide the conditions for its maturing and consolidation. It was the combination of these qualities that had made Ioffe the head of a scientific school of his own, and the role of that school was played by the entire staff of the Institute, which was infused with new cadres of young scientists. Under these conditions, the young people were susceptible to the occasionally intangible, gentle and beneficial influence of their elder work comrades. A. I. Shal'nikov, a representative of the school of Ioffe, the school of the Physicotechnical Institute, once observed in a private conversation that Ioffe's disciples in this country are "everyone and no one." "Everyone," because every major Soviet physicist who had joined science during the 1920s—1940s, including even those who had not worked in the Physicotechnical Institute, has exposed himself to Ioffe's influence, whether by attending the seminars skillfully conducted by him or by taking part in the congresses and conferences which he had organized and headed or by confiding in him or in his closest associates his plans and hopes, sharing with him his doubts and failures. "No one," or more exactly "almost no one," because the number of immediate associates of Ioffe who had worked in his own laboratory has always been very small. Here the comments of Petr Nikolaevich Lebedev may be apposite. When people spoke to him about his contribution to the rise of the Moscow school, which is rightfully associated with his name, he answered with the jesting remark that "he had not a single disciple, and he elucidated it by saying that he did not teach talented people, as these became valuable persons thanks to their own talent; he was wasting his effort, time and nerves on ungifted people, and those anyway turned out to be worthless."[15] When they associate themselves with some one or other scientific school, and particularly with the school of Ioffe, our greatest scientists do not mean at all daily instruction but an atmosphere of creative zeal, enthusiasm, and goodwill even though combined with severe criticism. It is not for nothing that the "pure" theoreticians Ya. I. Frenkel', L. D. Landau, and B. I. Davydov, who had joined physics in the 1920s—1930s, also consider themselves his disciples. This is a manifestation of the esteem and gratitude to the man

*I wish to express my sincere gratitude to N. N. Semenov and P. L. Kapitza for permission to cite these excerpts.

(and the staff) who had encouraged the young scientist and guided his first steps toward science.

This feeling of esteem grows if it is recalled that Ioffe parted with the best of his disciples and associates once he saw that the experience they acquired in directing laboratories enabled them to head even larger staffs of scientists both in Leningrad and in the other cities of this nation which during the first few five-year-plan periods had been experiencing a particularly acute shortage of scientists.

II. RESEARCH INTO THE MECHANICAL PROPERTIES OF SOLIDS

At the time when the Institute was being organized and its future name considered, the decision to call it a Roentgenological Institute was dictated not only by the wish to honor that scientist, still alive at the time, who had discovered x-rays. That name also corresponded to the intended thematics of the Institute where x-rays were to serve both as an object of research and as a tool with the aid of which Ioffe and his associates planned to investigate the mechanical properties of crystals. This possibility, as is known, was discovered barely five years prior to the establishment of the Institute, in 1913, owing to a discovery by Laue, Friedrich, and Knipping which had occurred literally before the eyes of Ioffe who at the time had been working (for two summer months) in Munich. The first scientific achievements of the Institute were associated precisely with research into the radiography of crystals. On observing the variation in the Lane diffraction pattern of a crystal under a load, Ioffe decided to investigate the dynamics of the process of plastic deformation. The system of diffraction spots projected onto a fluorescent screen underwent variation in time; the spots turned into elongated bands, reflecting the processes occurring in the specimen—its fragmentation into blocks. This study was carried out by Ioffe and M. V. Kirpicheva;* the variation in the diffraction pattern was termed asterism. The photographs of the x-ray patterns of a rock salt crystal, fixing the stages of the process of this fragmentation, obtained by Ioffe and Kirpicheva, were reproduced in literally every monograph in the world devoted to crystal structure.

Another major accomplishment was the discovery of the discontinuous nature of deformation. This phenomenon, arising at temperatures exceeding a certain critical value, is accompanied by a characteristic sound resembling the ticking of a clock. No matter how small the load may be and hence also no matter how slow the process of deformation may be, it occurs in "micron" jumps which take place at a fixed frequency over a prolonged interval of time. Originally (in 1924) this phenomenon was studied in zinc monocrystals (for which the aforementioned critical temperature is below room temperature) by Ioffe and P. S. Ehrenfest. This research was continued during 1927—1928 by M. V. Klassen-Neklyudova who, working with rock salt, aluminum, and brass investigated the temperature dependence of this effect, and particularly the behavior of loaded specimens of rock salt in the neighborhood of its melting point, etc. The theory attributing the discontinuous course of deformation to recrystallization, which lowers the elastic limit of the specimens, and to subsequent hardening, was developed by N. N. Davydenkov who also, in collaboration with I. N. Mirolyubov, showed that even at a deformation rate of the order of 1 mm per month (!) the deformation occurs in jumps.

During the years preceding the discovery of dislocations, a major contribution to understanding the process of plastic deformation was made by the studies of A. V. Stepanov. He found that the process of the plastic deformation of rock salt is accompanied by a very acute (10^{10}-fold) increase in its electrical conductivity. A similar change occurs, as had already been known then, with transition of the salt from solid to liquid state. Stepanov attributed this to the deformation-energy-induced heating of the narrow zone adjoining the slip planes. This heating is accompanied by dissociation of atoms which, in its turn, is responsible for the increase in electrical conductivity.

We shall not describe in detail all these studies, as they are among the best-known to have been carried out within the walls of the Physicotechnical Institute. Taken together, they are a complex whole unified by the idea of creating a picture of the behavior of real crystals, a picture that should, in particular, reconcile the glaring contradiction between the theoretical (derived by M. Born during World War I) and experimental values of strength and other characteristics of crystalline solids. The development of macroscopic theories of the real crystals reduced to elucidating the role of surface imperfections—cracks producing a catastrophic effect on strength. Theories of the role of these cracks, in the neighborhood of which local overstresses arise during loading of the specimen, were proposed in 1920 by Griffith. In the studies by Ioffe and his associates these theories were most completely elaborated and conclusively confirmed experimentally. In effective experiments Ioffe and Levitskaya demonstrated the decisive role of cracks (defects), whose elimination from the surface, as occasionally accomplished in the course of experiment, resulted in a multiple increase (by two orders of magnitude) in strength. In the world literature this work of Ioffe and his associated received broad recognition and the corresponding complex of phenomena began to be termed the Ioffe effect. Note that Griffith, when proposing his theory of cracks and their role, did not raise the question of their origin: in his calculations he assumed their existence and shape (a more or less elongated ellipsoid) to be specified. Further basic and experimental research into these problems at the Physicotechnical Institute was successfully undertaken by I. V. Obreimov, B. Ya. Pines, and G. Kh. Gorovits. The first considerations concerning the kinetics and atomic mechanism of crack-formation were formulated in the 1930s by A. V. Stepanov. He proposed the experimentally confirmed (using ionic crystals as an example) postulate that the rise of foci of fracture in a specimen under load occurs in the process of plastic deformation which always to some degree precedes fracture itself. This view of Stepanov has now become commonly adopted.[16, 17]

*L. S. Termen took part in the development of observation methods and adjustment of apparatus. Somewhat later the collaboration of M. A. Levitskaya also was invited.

The success of the entire cycle of studies mentioned above was largely due to the felicitous selection of the "main material." Most experiments in those years were carried out with rock salt, whose theoretical ultimate strength was known. Moreover, its translucence made it possible to employ optical methods of recording the observational results. This refers primarily to the method developed by I. V. Obreimov and L. V. Shubnikov (observation of plastic deformation in polarized light whose ability to pass through the specimen depended on the latter's deformation). The conclusions derived from the experiments with rock salt were also extended to the case of metallic solids.

The further development of the work on the macroscopic picture of the real crystal is associated with the studies by A. P. Aleksandrov and S. N. Zhurkov[18] of brittle strength and the so-called scale factor. It was shown that the strength of a specimen (quartz and glass filaments) unambiguously correlates with its cross sectional area, increasing—under a given load—with decrease of that area. The observed anomalously high strength was attributed to the decrease in the probability that on the surface of the specimen there may arise a dangerous, i.e. catastrophically growing crack cleaving it in half. This phenomenon was observed not only for thin filaments but also, though not as explicitly, for "thicker" specimens having a one-millimeter cross section.

The microscopic picture of real crystals is currently associated with "Frenkel' defects" a particular case of which is the "Schottky defects." Frenkel' introduced the concept of "internal evaporation" consisting in that an atom (or ion), owing to fluctuations of its thermal motion, which increase in intensity with rise in temperature, abandons "its" site and occupies a space in the "interstitial lattice." From that moment on, the resultant vacant space—the hole—and the atom in the interstice (the so-called Frenkel' pair) begin their independent existence in the crystal, moving within it and decisively affecting the processes of diffusion, self-diffusion, and viscosity.

Another study of the microscopic theory of real crystals, also carried out by Ya. I. Frenkel' (in collaboration with T. A. Kontorova), is associated with dislocations, whose concept was introduced in 1934 by Taylor who at the time also pointed to their role in the mechanical properties of solids and particularly in plastic deformation. Frenkel' and Kontorova investigated a one-dimensional model of a moving dislocation, while Taylor confined himself to a consideration of fixed dislocations. The movement of such a linear dislocation was associated with a definite minimal energy (energy of shear-formation) which must be transmitted to a dislocation in order to "evict" it from its location. Thus the magnitude of this energy must be a yardstick of nonplasticity, hardness of the substance. And indeed an unambiguous correspondence was established between its theoretical value and the hardness of materials measured by some method or other (e.g. by the Brinell test).

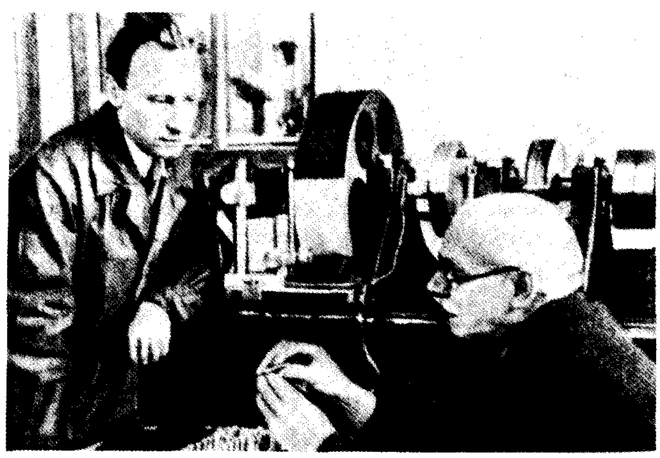
During the 1930s Stepanov carried out a series of important studies. He discovered the phenomenon of the electrization of ionic crystals during plastic deformation, i.e. fixed the occurrence of charges at their faces—the "Stepanov effect," now described in terms of charged dislocations. In another study he linked the process of shear-formation to the rise and development—under the action of an applied load—of "shear nuclei," whose formation could be stimulated by scratching, nicking or otherwise damaging the surface of specimens. It was established that the growth of shear nuclei commences under stresses equaling the elastic limit.

All the studies of the mechanical properties of solids enumerated above had a direct bearing on the needs of industry. Relations with industry were handled at the Physicotechnical Institute in a most direct manner by N. N. Davidenkov and G. V. Kurdyumov. To Davidenkov as well as to E. M. Shevandin and others we are indebted for studies of the cold brittleness of ferrous metals—a special type of fracture occurring under shock loads at relatively low temperatures. Their names also are associated with a large-scale project for equipping plant laboratories with up-to-date machines and instruments for the testing of materials as well as with the development and practical introduction of new methods of these tests at the plants. Kurdyumov during the 1930s carried out (partially at the Dnepropetrovsk Physicotechnical Institute of which he was head) important studies of the structure of martensite and of the phase transformations of steel, which made it possible to obtain metals with desired properties by deliberately selecting specific regimes of heat treatment.

Along with the study of the mechanical properties of crystals, during the last decade prior to World War II, amorphous materials were intensively investigated from the same standpoint at the Physicotechnical Institute (P. P. Kobeko, A. P. Aleksandrov, S. E. Bresler, S. N. Zhurkov, M. I. Kornfel'd, Yu. S. Lazurkin, and their co-workers), as were also fluids (V. K. Frederiks, M. I. Kornfel'd, E. V. Kuvshinskiĭ, N. I. Shishkin, and others).

During the war the research by specialists on the mechanical properties of materials at the Institute was placed in the service of national defense (F. F. Vitman, V. L. Kuprienko, M. I. Kornfel'd, L. M. Shestopalov, and others; for a time this category of defense work was under the direction of I. V. Kurchatov).

The problems of the strength and plasticity of crystalline bodies remain in the focus of attention of a large



F. F. Vitman (left) and N. N. Davidenkov number of the Institute's laboratories (the laboratories of S. N. Zhurkov, A. V. Stepanov, V. A. Stepanov, and L. M. Shestopalov).

Our exposition of that work will begin with the studies conducted under the direction of S. N. Zhurkov. In the course of this research it was shown that the very concept of ultimate strength is essentially fictitious and should be superseded by the concept of a completely unambiguous dependence existing between the load on the specimen (σ), the time the specimen can withstand that load without fracturing (τ), and the temperature at which the corresponding experiment is performed (T). This dependence is of an exponential nature:

$$\tau = \tau_0 \exp [-(U_0 - \gamma\sigma)/kT],$$

where τ_0, U_0, and γ are constants characteristic of a given material.*

Thus, any load (inclusive of the specimen's own weight) is essentially critical and, given sufficient time, causes fracture of the specimen. In this the role played by load is the same as that played by a constant electrical field in phenomena of field emission: in both cases a substantial decrease in the potential barrier occurs. It is worth noting the correspondence between the experimentally established and theoretically substantiated formula for "life under load" and the relations describing various kinds of activation processes (e.g. such processes as the flowability of fluids and solids).

It is known that fluctuations of thermal motion, imparting to some or other atom a sufficiently large energy, cause the disruption of interatomic bonds. In an unloaded specimen at moderate temperatures an equilibrium sets in between these processes of disruption and recovery of bonds. The application of a load sharply upsets this equilibrium in favor of the disruption of bonds. Let us emphasize that this disruption itself is caused by fluctuations of thermal motion and not by the load.

All these considerations, formulated in the Laboratory of the Physics of Strength of the Physicotechnical Institute, have found experimental proof in a series of studies conducted with the aid of modern techniques and equipment for experiments in physics. Research into an enormous variety of materials, including metals, ionic crystals, and polymers (as well as building materials such as concrete, lumber, paper, etc.) completely confirmed the formula for material life. Moreover, it can be stated that so far not a single material has been found whose behavior under load cannot be described by this formula.

In the case of polymers all the stages of the fracture process are traced by direct observations. The fact of decrease in bonding energy due to the application of a load can be established from the variation in the absorption spectrum in the infrared region (I. I. Novak). The gradual accumulation in specimens (caprone and natural silk) of free radicals, associated with the thermal fluctuation disruption of bonds has been directly recorded by the EPR method (É. V. Tomashevskiĭ). The bonds most susceptible to this disruption could then also be identified. In a loaded polymer this disruption is observed with the aid of mass-spectometric methods (V. R. Regel'): in the course of the test the mass spectrum of the products diffusing from the interior of the polymer (monomer links and their fragments) is analyzed. This phenomenon was termed mechanical degradation. It turned out that the composition of the products of mechanical degradation is the same as that of the products of thermal degradation, which intensively occurs at higher temperatures (it may be said that the application of a load effectively raises the temperature of the specimen by lowering the potential barrier). Lastly, with the aid of x-ray diffraction methods (A. I. Slutsker) it proved possible to locate the sites of intense evolution of the process of the disruption of bonds and directly trace the dynamics of the genesis and development of fracture cracks in the volume of the specimen, beginning with dimensions of the order of several tens of Angstroms and ending with the dimensions that precede fracture and can be determined with an optical microscope.

At present similar research into every stage of the process of disruption of bonds is under way on crystalline objects and particularly on metals.

For a number of recent years A. V. Stepanov, O. V. Klayvin, S. P. Nikanorov and their associates have been investigating the behavior of elastic constants of alkali-halide materials and elucidating their temperature course at temperatures almost at their melting points. The researches into plasticity and strength which are being conducted in the region of the temperatures of liquid helium are interesting not only from the standpoint of theory (here the results are obtained in "pure form," i.e. without being affected by thermal motion) but also from the standpoint of their practical application to the development of space technology. The needs of that technology have also stimulated to a large degree high-temperature research into elastic constants.

It has already been mentioned that a number of studies of physical strength was carried out at the Physicotechnical Institute on glass rods and fibers (filaments). In recent years research into the mechanical properties of glass has been successfully developing under the direction of F. F. Vitman. Now, however, it is being carried out on "large-scale" objects such as sheet silicate glass, which is a most widely used material in the national economy. This work provided yet another proof of the optimistic conclusion drawn by Ioffe as far back as in the 1920s concerning the possibility of attaining the theoretical values of the strength of the structural elements and components directly used in industry.*

In the course of this research Vitman as well as V. P. Pukh, G. S. Pugachev, and others, on etching the glass surface (i.e., by means of an operation that had

*τ_0 equals approximately 10^{-13} sec, i.e. it equals the period of oscillations of an atom about its equilibrium position in the lattice, while the quantity U_0, also determined experimentally from the above formula, proves to be with satisfactory accuracy equal to the binding energy of the atom in the material concerned (whether a metal or a polymer).

*At the Physicotechnical Institute this was accomplished with sheet glass as the example. But an analogous situation exists regarding the so-called metal whiskers (which, incidentally, were first obtained and investigated in the USSR at the Physicotechnical Institute, in A. V. Stepanov's laboratory). In the Soviet Union specimens of steels having a strength of the order of 350 kg/mm^2 have already been obtained under laboratory conditions.

been employed even earlier during research into the "Ioffe effect"), succeeded in obtaining specimens of sheet glass having a strength as high as 250 kg/mm^2 in air and even 500 kg/mm^2 in vacuo. It turned out, however, that following its storage in normally dust-laden air this glass loses its high-strength properties. The reason for this lies, as has been shown, in the incidence of microscopic particles of abrasive materials onto the surface of the glass. If a dust particle of this kind happens to enter the zone of direct contact between that surface and a load source (steel ball, in the experiments), foci of fracture of the surface will arise in the presence of stresses as insignificant as 10 g. A major stride on the path toward the introduction of high-strength glass into industry was the establishment of the possibility of prolonged preservation of its strength properties by coating its surface with a thin (of the order of 10μ) polymer film.

Note that while for metal "whiskers" the high level of the strength of is due to the perfection and defect-free nature of crystal structure, in the case of high-strength glasses it is due, as is known, to their saturation with various sorts of defects. In this sense, glass, which lacks a crystalline structure, may be regarded as an "ideally defective" material in which, in particular, dislocations do not arise. It is this that, according to the theories developed by Vitman and his associates, accounts for the fact that glass, when not in the neighborhood of its softening point (and in the absence of microcracks and cavities), is characterized by such a high strength.

Another example of the research under way at the Physicotechnical Institute which has direct bearing on the needs of industry is the techniques of obtaining a wide variety of products and specific physicochemical properties directly from the melt, developed in the laboratory of A. V. Stepanov.[19] These techniques are used to obtain rolled strip of semiconductor materials such as germanium, which ultimately may make it possible to dispense with the labor-consuming and costly process of the metallurgical processing of germanium ingots, which entails considerable economic losses.

A major place in the research into the mechanical properties of materials being conducted at the Physicotechnical Institute is occupied by the study of their behavior under high loading rates. The work on these problems, which in recent years have been extremely topical, is being carried out (as a continuation of prewar research by N. N. Davidenkov and F. F. Vitman) by V. A. Stepanov and N. A. Zlatin and their co-workers. At present impact rates have been markedly increased, reaching as much as 1000 m/sec and more. V. A. Stepanov, while investigating the motion of rigid bodies at such rates in plastic media, established a relationship between the resistance forces and the shape and properties of the medium as well as the velocity. A similar study was carried out for the case of motion in granular media and polymers. Vitman, Zlatin and their associates have worked out a theory of the modeling of processes of high-speed collisions between solids which makes it possible to obtain data pertaining to velocities of the order of 10^4 m/sec (which are inaccessible to direct investigation in laboratory conditions). This series of studies significantly affected the development of a new orientation in engineering physics—the dynamics of solids.

In concluding this section, it should be mentioned that the success of the researches recapitulated above was constantly assisted by close contact between experimenters and theoreticians. In recent years the problems of strength and plastic deformation have been considered in the theoretical studies by A. I. Gubanov, A. N. Orlov and their associates.

III. SEMICONDUCTOR PHYSICS

The role of the Physicotechnical Institute in the organization and rise of the entire Soviet physics is particularly explicitly reflected in the development of semiconductor research. Ioffe, to whom belongs the credit for initiating this research, was prepared for it by his entire prior scientific activity. As far back as at the beginning of this century, while working for Roentgen in Munich, he had demonstrated on quartz and certain other materials the relativity of the concept of the "insulator" and carried out his first studies of the intrinsic photoelectric effect. On examining his classical works on the electrical conduction of pure—for that time—crystals, one can readily perceive the inevitability of Ioffe's becoming later interested in semiconductors. In his experiments, already carried out within the walls of Polytechnical Institute (1916) on specimens of ammonium alum and cuprous oxide, Ioffe unambiguously linked the scatter of values of electrical conduction to the presence of all sorts of impurities in these specimens. By using purification techniques he succeeded in reducing electrical conduction.

The conduct of this research within the walls of the Physicotechnical Institute in the 1930s was stimulated by studies carried out both in the USSR and abroad. At that time it turned out that the distinctive processes occurring at the interface between metal needlepoints and various sorts of materials,* which had been observed as far back as late in the last century, are not simply amusing effects but can have a definite technical application. This refers to O. V. Losev's studies of the carborundum (CSi) detector, carried out at the Nizhegorod Radiolaboratory. Losev showed (1922) that this detector can generate radio-frequency oscillations and, somewhat later, he also had investigated the glow of the surrounding zone accompanying the passage of current through a contact (what is now known as recombination glow) as well as the formation of a photo-electromotive force on illumination of the contact.

Similar research was also intensively pursued in the 1920s abroad (the rectifier effect of cuprous oxide—Grondall and Geiger, 1924; the first selenium and cuprox (cuprous-oxide) rectifiers to be industrially manufac-

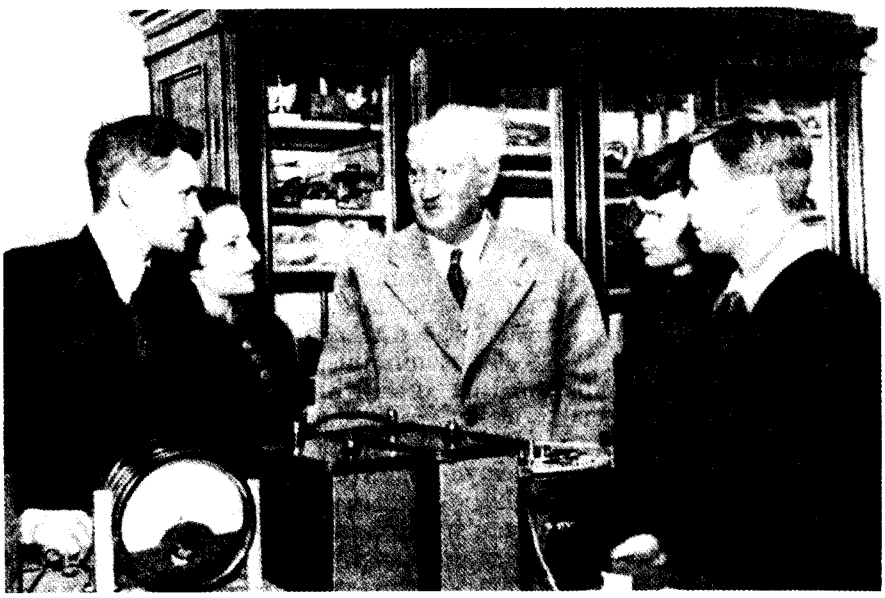
*Now we term these materials semiconductors; this term is comparatively recent: it is not listed in Teknicheskaya entsiklopediya (Encyclopedia of Technology), published in the USSR in the late 1920s and early 1930s. Volume VI of Malaya Sovetskaya entsiklopediya (Little Soviet Encyclopedia) contains just three lines concerning semiconductors: "Semiconductors—appellation of substances which conduct electricity poorly, e.g.:wood, cotton." Thus the 19th century investigators who had worked with semiconductors resemble to some extent Molière's hero who did not suspect that he had been speaking prose all his life.

tured, in 1927; the cuprous-oxide photocell, 1930). But while the spread of semiconductor devices of the Losev detector generator type—the "crystadyne"—into radio engineering was halted by the vigorous development of electron tubes in the late 1920s, which had continued without competition until the end of the 1940s, the research into the rectifier effect and the photoelectric effect, initiated in the 1920s—1930s, has continued to be intensively pursued both abroad and in this country. In fact, it became predominant in the agenda of the Physicotechnical Institute.* It was carried out, of course, along with research into purely physical processes in semiconductors: kinetic effects (electrical conductivity, galvanomagnetic effects, thermoelectricity) and into their energy spectra.

The introduction of semiconductor studies into the plans of the Physicotechnical Institute exemplifies the manner in which Ioffe was able to enlist large groups of scientists for work on research projects. After a group of co-workers at the Physicotechnical Institute had rapidly familiarized themselves with the new problems and began to carry out investigations of their own (A. N. Arsen'eva, A. K. Val'ter, V. P. Zhuze, B. V. Kurchatov, I. V. Kurchatov, D. N. Nasledov, K. D. Sinel'nikov), the first semiconductor conference was held in September 1931. It was attended by representatives of scientific and plant circles; the co-workers of the Physicotechnical Institute presented a number of review papers and reported on their first results. With his characteristic skill, Ioffe organized a discussion in the course of which the possibilities for carrying out the pertinent research in various cities in the nation and its future geography were elucidated, the problem of coordinating the research being carried out by the corresponding institutions was resolved, and able young people to be provided with the necessary support were identified. The Physicotechnical Institute not only undertook the research into semiconductor physics but also applied research projects for preparing the production and industrial introduction of semiconductor devices. However, the division of these projects into "physical" and "applied" was very arbitrary, as we shall have occasion to mention somewhat later.

The Institute's theoreticians also joined in the work on this problem. Among them M. P. Bronshteĭn should primarily be named. In 1932 he (in collaboration with A. N. Arsen'eva) had published a review[20] incorporating Bronshteĭn's own findings on the theory of kinetic phenomena in semiconductors (calculation of thermomagnetic and thermoelectrical coefficients, electrical conductivity, Hall constant). Note that the credit for the theory of the tensor of the effective mass of conduction electrons belongs precisely to Bronshteĭn. The publication of the above review played a major role in advancing the research being conducted in this country.

A no smaller role was played by Ioffe's monograph, Elektronnyye poluprovodniki (Electronic Semiconductors),[21] which soon afterward was published abroad as well. Then also there was a third review, written in 1940 by B. I. Davydov and I. M. Shmushkevich[22] which even now is often cited in textbooks and monographs. This review includes the basic projects carried out at the Physicotechnical Institute (in particular, the studies by the authors as well as by N. L. Pisarenko concerning



A. F. Ioffe among young co-workers of Physicotechnical Institute (2 October 1940). Left to right: Yu. A. Dunaev, É. Ya. Zandberg, A. F. Ioffe, N. S. Shishkin, A. R. Regel'

*In 1931 the Physicotechnical Institute consisted of seven groups (including Biophysics and Theoretical Physics). The Energetics Group, headed by Ioffe, contained, the "Fifth Brigade" – "Semiconductors." This was the first mention of semiconductors in the names of the Institute's subdivisions.

the theory of thermoelectric phenomena in semiconductors).

Reviews[20-22] as well as the semiconductor seminars held at the Physicotechnical Institute and also the convened semiconductor conferences, were instrumental in working out the language in which the properties of semiconductors are even now being discussed and investigated. Thus, the very concept of "hole conduction" was formulated at the Physicotechnical Institute. The treatment of the processes of electrical conduction (and their theory) in terms of holes in the filled band of the energy spectrum is to be credited to the British physicist A. Wilson and to Bronshteĭn. The same processes were described by Ya. I. Frenkel' in the spirit of the hole mechanism of electrical conduction of solids (and fluids) extended to the case of the motion of an electron in an electrical field away from one ("electropositive") lattice site or hole regarded as a positive charge toward another, and of the return motion of the hole in the opposite direction.

The studies carried out by the Institute's experimenters demonstrated the role of (donor and acceptor) impurities in electrical conduction, and the contribution of these impurities, which is essential at relatively low temperatures, was isolated from the contribution of natural conduction. This work was carried out by B. V. Kurchatov and V. P. Zhuze on cuprous oxide. In the case of thallium sulfide and lead sulfide it was shown that the same conductor may display either hole conduction or electron conduction, depending on the nature of the impurity.

Considerable interest was aroused by the discovery of the photoelectromagnetic effect by I. K. Kikoin and M. M. Noskov (also on cuprous oxide) who discovered the attendant rise of an electromotive force on illuminated specimens placed in a magnetic field.

Research into the electrical properties of semiconductors was performed by Ioffe's associates such as: B. M. Gokhberg, E. D. Devyatkova, Yu. A. Dunaev, V. P. Zhuze, B. T. Kolomiets, B. V. Kurchatov, Yu. P. Maslakovets, D. N. Nasledov, M. S. Sominskiĭ, V. M. Tuchkevich, P. V. Sharavskiĭ and others. Ioffe himself, in collaboration with A. V. Ioffe, devoted a great deal of time to the study of photoelectric phenomena in semiconductors. This resulted in establishing proportionality between the number of absorbed photons and the number of carriers that they formed—in earlier experiments this proportionality had been masked by reflection of light from surface and by other effects. Another study resulted in the discovery of the "negative photoelectric effect," i.e. of the decrease of conduction in fields exceeding a certain critical limit.

A major role in the preparations for the industrial production of photocells was played by the work of B. T. Kolomiets. He had succeeded in collaboration with Yu. P. Maslakovets in achieving a record (for that time) efficiency (1.1%) of the conversion of sunlight to the energy of electrical current. As is justly pointed out in the article[23], this work "was of great moral significance. It showed that the photoelectric properties of semiconductors indeed harbor great possibilities and that the optimistic appraisal of these possibilities that had once been provided by Ioffe rests on a solid foundation."*

In concluding this survey of the prewar work of the Physicotechnical Institute mention should be made of the results obtained in the theory and practice of semiconductor rectifiers. The original variant of this theory was proposed in a work by Ioffe and Ya. I. Frenkel' in which the description of unipolar conduction was based on the mechanism of the tunneling of electrons across the potential barrier formed at the metal-semiconductor contact interface. This idea, while fortified by detailed calculations, could not account for all the aspects of the rectification effect. Yet it is interesting to note that the tunnel effect in rectification processes found its embodiment in the tunnel diode discovered by Esaki in the late 1950s. † As applied to cuprous-oxide rectifiers, the corresponding diffusion theory was developed by B. S. Davydov, D. I. Blokhintsev, and S. I. Pekar'.

The credit for the introduction of the semiconductor devices developed in the Physicotechnical Institute (cuprous-oxide and selenium rectifiers, photocells and photoresistors) belongs to the following co-workers of the Institute: Yu. A. Dunaev, B. V. Kurchatov, B. T. Kolomiets, A. Z. Levenzon, V. I. Tuchkevich, and P. V. Sharavskiĭ.

As early as in the prewar years Maslakovets had developed thermoelectric lead-sulfide generators with an efficiency of the order of 3%. During and after the war the efforts of Ioffe and his closest associates were focused on translating into reality the possibilities of semiconductors pertaining to these problems. It is known, for example, that the thermogenerators developed at the Physicotechnical Institute served as a power source for many partisan radio transmitters.

In 1952 Ioffe organized the Laboratory of Semiconductors under the Physicomathematical Division of the USSR Academy of Sciences, and a large number of coworkers from his division joined the staff of that laboratory. The interests of this laboratory, as well as of the Institute of Semiconductors that was established on its basis in 1954, have chiefly been focused on research into thermoelectric effects and their engineering applications along with research into general problems of physics.

At the same time, as is known, in the late 1940s, following the publication of the famous works of Shockley, Bardeen, and Brattain, a major jump occurred in the development of semiconductor research. With the discovery of carrier injection effects, with the development of the theory of p-n junctions and the reexamination on this basis of the previously accumulated experimental facts concerning the rectifier effect and, lastly, with the development of transistors, it became

*This foundation, as is known, has been still further strengthened now that germanium and silicon solar batteries have been developed at the Physicotechnical Institute by V. M. Tuchkevich and associates. Present-day silicon solar energy converters have an efficiency of the order of 15 % (in the USSR they were developed by A. P. Landsman and V. S. Vavilov). To be sure, their high cost as yet does not make it possible to completely exploit their potential

† In his first publication [24] L. Esaki directly refers to the word of Soviet authors and to the somewhat later publications by Wilson and Nordheim.

clear that a new scientific discipline, namely, semiconductor radiophysics, was taking form. It was also obvious that industry must readjust itself to the mass production of semiconductor devices. This also raised the problem of developing semiconductor metallurgy (a new phrase even appeared: "materials of semiconductor purity"). Selenium and cuprous oxide became superceded by germanium and, in the long run, silicon.

It was exactly this complex of problems associated with semiconductor radiophysics, with the research on new semiconductor materials and with the investigation of photoelectric effects in these materials, that was taken up by an initially small group of co-workers of the Physicotechnical Institute (V. M. Tuchkevich, B. T. Kolomiets, D. N. Nasledov, S. M. Ryvkin).

Already in the mid-1950s semiconductor research at the Institute began to be vigorously pursued and the number of scientific research co-workers engaged in this research increased to such an extent that now the Physicotechnical Institute is rightfully considered one of the nation's largest scientific establishments working on semiconductors. It had succeeded in achieving this position owing to an interdisciplinary—in the spirit of the Institute's traditions—approach to the solution of the problem such that its technological outcome was a natural continuation of thorough study of the physical effects underlying the performance of semiconductor devices, and their development logically led to the discovery of new effects. It was exactly this uniting of physics and technology into a single alloy whose components are difficult to isolate that had been intended by Ioffe as far back as in the distant 1920s; it had found its reflection in the very name of the Physicotechnical Institute.

The problem of germanium semiconductor devices at the Physicotechnical Institute began to be actively considered by V. M. Tuchkevich as far back as in 1951. At that time a number of the nation's institutes faced the problem of developing the first Soviet transistors. The work carried out at the Physicotechnical Institute was a very important factor in solving the problem of overcoming the lag of our industry in this respect. During 1952—1953 Tuchkevich, A. I. Uvarov and their associates developed the first Soviet junction-type germanium diodes and worked out their production technology. The success of this work was due not only to the aforementioned traditions and the prior "semiconductor knowhow" of the Institute but also to the fact that in the course of that research special attention was devoted to germanium. It was used to construct the devices not in that far-from-perfect form in which the Physicotechnical Institute received it from outside organizations, but as obtained directly in the Institute's own laboratories by means of the purification and subsequent growing of monocrystals.

During 1953—1954, on the basis of the considerable experience gained in working with germanium, monocrystalline silicon was studied at the same laboratory and, again for the first time in the USSR, on its basis the first silicon radio-engineering diodes were developed. Along with this, the processes of diffusion were investigated and a diffusion technology for doping large-sized monocrystalline specimens with impurities was worked out, along with the ensuing possibility of developing heavy-current rectifiers. At that time, the collaboration of a number of major branch institutes was rapidly enlisted for research on semiconductor radio-engineering devices. This as well as the considerable demand of the national economy for heavy-current rectifiers,* and the essentially already well-developed technology of their production, caused the Institute to decide to develop high-power rectifiers. From the very beginning the Physicotechnical Institute has been occupying the dominant position in this field in the USSR. The high-power rectifiers which it has developed and transmitted for series production surpassed in their indicators (maximum permissible voltage and current) their foreign counterparts.

In addition to the uncontrolled rectifiers the laboratory of V. M. Tuchkevich has investigated and explored the properties of multi-layer p-n-p-n structures. Their great potential was pointed out as far back as in 1950 by W. Shockley but it was only in the early 1960s that this idea was translated into reality abroad and in this country. At the same time, the possibilities of the devices operating on the basis of these structures (thyristors) are extremely broad and the functions they fulfill exceptionally varied: above all they serve as a means of regulating (without energy loss) current and voltage as well as of "transforming" direct current (i.e., regulating its voltage), smoothly converting the frequency of alternating current, converting direct to alternating current, and of course rectification. Thyristors can also be used as valve devices having an operating speed measurable in fractions of a microsecond. To assess the significance of all this work, note that industry at present is manufacturing millions of rectifiers on the basis of the technology worked out by the Physicotechnical Institute, and the economic effect of their introduction during the five-year period beginning in 1965 will have reached 500 million rubles according to the calculations of the Institute of Economics of the USSR Academy of Sciences.[26]

Longtime research into complex structures with p-n junctions as well as into the development of their production technology and the introduction of silicon power rectifiers into commercial production was rewarded in 1966 with the Lenin Prize (V. M. Tuchkevich, V. E. Chelnokov, I. V. Grekhov, V. N. Shuman and a group of workers from the plant manufacturing these devices).

The selection and synthesis of new semiconductor materials are clearly of tremendous scientific and practical interest. These problems also have been lying in the focus of unflagging attention of the Physicotechnical Institute. In October 1950 the Seventh All-Union Conference on the Properties of Semiconductors—the first postwar conference of its kind[27, 28]—was held in Kiev and the papers, albeit—still numerically few, on new semiconducting substances were presented at it. The study by A. R. Regel' and associates[29] dealt with the temperature dependance of the resistivity of an intermetallic compound of the $A_{III}B_{V}$ type—InSb; the authors' attention to this compound was attracted by N. A. Goryunova, who assumed that indium antimonide must

*The operation of electrical rail transport and urban rapid transit as well as electrometallurgy and the charging of capacitor batteries all require direct current. More than 20% of electric power in this country is consumed in the form of direct current.[25]

display semiconducting properties and particularly the characteristic temperature dependence of electrical conduction. At the same conference Goryunova and A. P. Obukhov reported on the results of studies demonstrating that gray tin also is a semiconductor and that compounds of the $A_{III}B_V$ type (InSb, CdTe) proved to be isomorphic with respect to it. The experiments described in[29] confirmed Goryunova's assumption and laid the foundation for a series of studies of the compounds $A_{III}B_V$ (as well as of the more complex ternary compounds) synthesized during subsequent years at the semiconductor laboratories of the Physicotechnical Institute.

The advantages associated with the zone structure of $A_{III}B_V$ compounds (considerable width of forbidden band, making it possible to develop devices operating at high temperatures, considerable carrier mobility* were translated into reality in the studies carried out at the laboratory of D. N. Nasledov.

At present the compounds of the $A_{III}B_V$ type have been used at the Physicotechnical Institute as the basis for developing all the "classical" semiconductor devices with p-n junctions—diodes (power and radio-engineering) and triodes, solar cells, infrared radiation sensors, etc. In the course of this work a number of new effects has been discovered.

Of the compounds in this group the most interesting proved to be gallium arsenide. It was the first semiconductor on which the narrowing of the emission line during passage of a current through the crystal, i.e. the laser effect, was discovered in the Physicotechnical Institute in 1962. This substantiated the possibility of developing a semiconductor laser** and made it possible to recommend an active substance for this purpose. This project, carried out at the Institute by A. A. Rogachev, S. M. Ryvkin, D. N. Nasledov and B. B. Tsarenkov, and at the Physics Institute of the USSR Academy of Sciences by N. G. Basov, B. M. Vul and associates, was awarded the Lenin Prize in 1964. The production technology of gallium arsenide lasers was worked out with the direct participation of the Physicotechnical Institute. On the basis of gallium phosphide (GaP), D. N. Nasledov, B. B. Tsarenkov and associates have developed in 1967 sources of incoherent emission characterized by a great rapidity of action (10^{-9} sec) in the region of green light and having an efficiency of ~15%. This opens broad vistas for their application in high-speed computers, in monitoring of satellite-borne instruments, and for other purposes.

We note another important group of semiconductor materials which also was discovered at the Physicotechnical Institute in the mid-1950s by B. T. Kolomiets and N. A. Goryunova; they are at present being succesfully investigated in the laboratory of Kolomiets. This refers to chalcogenide glasses. Studies of these glasses confirm the assumption (first put forward by Ioffe) that the energy spectrum of a substance is decisively affected by the short-range order of its atoms. On the other hand, the combination within one substance of the properties of transparency (characteristic of glass) with a broad range of electrical properties inherent in semiconductors, offers great opportunities for practical application. We note that a number of studies of the theory of amorphous semiconductors has been carried out at the Physicotechnical Institute by A. I. Gubanov.[30]

In 1953 S. M. Ryvkin and V. M. Tuchkevich developed and introduced into production electron-hole photodiodes—converters of luminous energy into electrical energy, which, while displaying an enormous sensitivity that is hundreds of times as high as the sensitivity of vacuum photocells, were inferior to the latter in inertia. Longtime research on low-inertia photodiodes has led Ryvkin, O. A. Matveev, D. V. Strokan and associates to develop (in 1966) photodiodes with a time constant of 10^{-10} sec (to appreciate this scale, note that the use of these photodiodes makes it possible, in particular, to determine the shape of nanosecond pulses obtained from solid-state lasers). Low-inertia germanium and silicon photodiodes of a special design can record nuclear radiation: α particles, neutrons, protons, electrons, and γ quanta. In the case of γ quanta the germanium counters at the same time represent γ spectrometers which, while displaying a resolving power which is close to that of magnetic spectrometers, advantageously differ from the latter by their small dimensions such as are characteristic of semiconductors. A semiconductor spectrometric detector of α particles based on cadmium telluride can record α particles at room temperature. Counters which can not only record the signal but also amplify it internally (so that the signal per incident particle reaches ten volts) are being investigated.

High-sensitivity photoelectric sensors with an adjustable region of spectral sensitivity have been developed by V. M. Tuchkevich, Zh. I. Alferov and associates in the course of their studies of heterojunctions between various compounds of the $A_{III}B_V$ type.

These junctions are produced by means of epitaxial techniques which are being intensively developed in various laboratories. Stimulated emission has been observed in the multilayer heterostructures obtained by means of these techniques; on the basis of these structures, high-frequency diodes designed for inverse voltages of as much as 1000 V, with a switching time of the order of 10^{-8} sec, have been developed.

In this exposition of the research done in recent years attention has been chiefly focused on its applied nature. We shall complete this chapter with a survey of the results obtained during research into excitons (whose instrumental applications are just beginning to outline themselves), which have played a great role in the complex of work on solid-state physics.

The foundation of this research was laid nearly forty years ago in the now classical work of Ya. I. Frenkel'.[31] Basing himself on the analogy with absorption of light of frequency ν by a gas whose first polarization potential of the atoms is $V_i > h\nu/e$, i.e. on the analogy with absorption accompanied only by excitation of atoms, Frenkel' extended the theory to the case of current-free absorption of light by solid dielectrics; he introduced the concept of an excitation wave propagating

*Thus GaAs has a 1.4-eV forbidden band. The electron mobility in the perfect InSb crystal obtained at the laboratory of D. N. Nasledov was 10^6 cm^2/V-sec and the impurity concentration was of the order of 10^{12} cm^{-3}. For its time (1956) this was the purest semiconductor ever.

† By now lasers based on a large number of compounds of the $A_{III}B_V$ group—GaAs, GaSb, InSb, InAs, etc. are already in use.

through a crystal that had absorbed a photon, and, in the spirit of the principles of quantum mechanics, he compared it to a corresponding particle which he termed the exciton. This theory was thoroughly elaborated quantitatively by Frenkel' and in the 1930's it served as the foundation for research by a large group of theoreticians—Mott, Wannier, Peierls, Slater, and others. In the subsequent years the exciton theory was intensively developed in the USSR (by A. S. Davydov, S. I. Pekar', A. I. Ansel'm, and others).

It took almost twenty years, however, before excitons were accepted by experimental solid-state physics; afterward, though, they became a useful tool of that physics, accounting for a large number of phenomena and serving as the basis for modern solid-state spectroscopy.[32] It is worth noting that these first experimental studies were carried out chiefly at the Physicotechnical Institute. They were initiated with a series of studies by V. P. Zhuze and S. M. Ryvkin dealing with the features of the photoconductivity of cuprous oxide. The existence of a temperature dependence of the photocurrent and its exponential nature demonstrated that light causes the electrons to enter the conduction band from impurity levels to which they are flung by thermal motion from their own band. At the same time, the absorption of light occurring at the edge of that latter band is too great to be attributed to the comparatively few acceptor impurities. The authors were able to resolve this contradiction by proposing the existence of the following mechanism of light absorption. Light quanta, on being absorbed, form excitons (current-free absorption) which, on moving through the crystal and colliding with the acceptor impurities present therein (ionized F-nuclei, to use the terminology of S. I. Pekar') are caused by "exciton impact of the second kind" to transmit their energy to the impurity electron, thus transferring that electron to the conduction band. The mechanism thus proposed also provides an explanation for the fact that at low temperatures, when electrons are absent at impurity levels, no photoconductivity is observed, as well as for the fact that photoconductivity decreases in magnitude with increase in the perfection of crystal structure.

The classical and still continuing studies of E. F. Gross and his school, devoted to the optical properties of excitons, date from 1950. On the basis of the theoretical studies by Ya. I. Frenkel' and the aforementioned works of Khuze and Ryvkin (as well as of the works of V. E. Lashkarev in the USSR and D. Apker in the United States) which had presented indirect proof of the existence of the exciton, Gross posed the problem of finding a direct proof of that existence. He succeeded in accomplishing this in a 1951 project, carried out in collaboration with N. A. Karryev,[33] dealing with the investigation of the absorption of light and Cu_2O at low temperatures, which led to the discovery of the hydrogen-like spectrum of the exciton—a formation consisting of a hole and an electron linked by Coulomb forces of attraction. Subsequent studies (by Gross, B. P. Zakharchenya, A. A. Kaplyanskiĭ, and others) led to the discovery of Stark and Zeeman effects in the exciton spectrum and the identification of the ionization of excitons and of their annihilation with emission of light of a specific frequency corresponding to "exciton absorption frequencies" observed in the luminescence spectrum. The exciton spectrum also proved to be sensitive to unidirectional elastic deformations of crystals: they counteract the degeneration of energy states and thus, along with the Zeeman and Stark effects, they represent an additional piezospectroscopic method for investigating the band structure.

It was shown that the spectral photosensitivity curves of a number of crystals (CdS, HgI_2 and Cu_2O) display special features—maxima and minima, at frequencies corresponding to the exciton absorption lines. This could be directly explained by the exciton mechanism of absorption and was a direct proof of the motion of the exciton from the place of its formation until its encounter with an impurity center.

In 1966 the work on excitons by Gross, Zakharchenya, and Kaplyanskiĭ was awarded the Lenin Prize, which they received jointly with the Kiev group of physicists (A. S. Davydov, A. V. Prikhot'ko, and others).

It is worth noting that most recently at some places (particularly at the Physics Institute of the USSR Academy of Sciences (N. G. Basov and associates)) the pertinent research already accomplished has by now assured the feasibility of technological applications of the work on excitons. At the Physicotechnical Institute Gross, B. S. Razbirin and associates in 1967 had also discovered that the excitation of CdSe crystals at low temperatures by a high-energy high-density electron beam is accompanied by the rise of coherent emission of free excitons corresponding to their annihilation on lattice oscillations with emission of a photon and a phonon.[34] The accomplishment of generation on free excitons (i.e., the development of an exciton laser) is definitely feasible, since their accumulation within a definite energy range is basically not limited by the Pauli principle.

4. NUCLEAR PHYSICS

We shall begin our survey of the achievements of the Physicotechnical Institute in nuclear physics by mentioning that it was precisely in that Institute, in 1924, that D. V. Skobel'tsyn had investigated in detail the Compton-effect recoil electrons and confirmed the validity of the theories of the corpuscular properties of γ quanta (and at that time these properties had still been doubted). He carried out these studies with the aid of a Wilson chamber and they served as a basis for a series of important investigations which Skobel'tsyn had performed on this—at the time practically unique—installation. Thus he was the first to obtain the tracks of cosmic "ultra-β-particles" in a Wilson chamber (placed in a magnetic field*). In that field (of the order of 2000 Gauss) these tracks did not deviate, which implied that their energy exceeded tens of MeV. Moreover, Skobel'tsyn obtained photographs of two and three (and in a 1932 study, four) charged particles originating from a common center, i.e., this had resulted in the discovery of an effect which, following subsequent studies by Blackett and Occhialini, had been termed showers

*Studies of α particles in a Wilson chamber placed in a magnetic field of 43,000 Gauss were first carried out by P. L. Kapitza (cf. for example, [34a]).

formed by high-energy cosmic-ray particles.*

But nuclear research was properly expanded only after 1932, a year that is famous in the history of nuclear physics and marked by three outstanding discoveries. On 27 February the British journal Nature published a communication by Chadwick stating that the radiation arising during the bombardment of beryllium with α particles (a problem about which Bothe and Becker as well as the spouses Joliot-Curie had been racking their brains) is attributable to new particles—neutrons. This was followed by Anderson's discovery of the positron on (or "negatron" as he had originally termed it) on 2 August, while Cockroft and Walton, having accelerated protons in a 600 kV field, accomplished a nuclear reaction with lithium.

In the late 1932 Ioffe ordered the organization within the Institute of a special nuclear research group which included I. V. Kurchatov, D. V. Skobel'tsyn and others as well as, among the theoreticians, M. P. Bronshteĭn and D. D. Ivanenko. Within a year this group turned into an entire autonomous division of the Institute which in 1934 had included the laboratories of D. V. Skobel'tsyn, A. I. Alikhanov, L. A. Artsimovich, and I. V. Kurchatov (head of the division).

Among the studies by the co-workers of that division we will name in chronological orders the first publications by D. D. Ivanenko. Immediately following the discovery of the neutron he suggested the now apparently simple and logical hypothesis that neutrons are part of atomic nuclei (the credit for the detailed elaboration of the neutron theory belongs to Heisenberg, who refers to the note by Ivanenko published in Nature of 28 May 1932). Ivanenko noted that if a spin of 1/2 is ascribed to the neutron, the "nitrogen catastrophe" is by the same token eliminated. Let us recall that Razetti's work on the spectra of the N_2 molecule had shown that the nuclei of nitrogen are Bose particles. At the same time, the electron-proton model, according to which the N nucleus includes 14 protons and 7 electrons, implied that this nucleus must obey Fermi statistics. Until the discovery of the neutron attempts had been made to resolve this contradiction by stating that the electrons in the nucleus "lose" their characteristic free-state spin. The β-decay effect seemed to confirm this idea, since it confirmed the presence of electrons in the nucleus. Even earlier, however (in 1930), Ivanenko and V. A. Ambartsumyan stated the methodologically important remark that conclusions on nuclear electrons should not be inferred from β decay, just as the emission of a photon by an excited atom does not signify that the photon had been its component part.

I. V. Kurchatov in 1932, when he had already been working at the Physicotechnical Institute for 5 years, gained wide fame by his works on ferroelectricity, which he carried out in collaboration with P. P. Kobeko and a number of associates (B. V. Kurchatov, G. Ya. Shchepkin, and others). Already then, at a time when Kurchatov was heading a small collective of co-workers, he had begun to display his outstanding organizational talent and magnificent qualities of leadership, such as were clearly formulated by I. N. Golovin as follows: "ability to direct others without injury to their self-respect."[35]

The first major accomplishment in nuclear physics that had been made by I. V. Kurchatov, B. V. Kurchatov, L. I. Rusinov, and L. V. Mysovskiĭ was the discovery of the phenomenon of nuclear isomerism, explainable in terms of the existence (in bromine, on which this phenomenon was discovered at the Physicotechnical Institute) of excited metastable states of nuclei (Weizsaecker's interpretation).

An important series of studies of β decay and searches for the neutrino was carried out at the Physicotechnical Institute in the 1930s. The brothers Alikhanov and M. S. Kozodaev discovered the electron-positron pair production effect in the process of the internal conversion of excited nuclei (this research was being simultaneously carried out by another triumvirate of physicists: Chadwick, Blackett, and Occhialini). The experiments of A. I. Leĭpunskiĭ, who engaged in the study of the recoil nuclei of the radioactive carbon nucleus, provided the first convincing proofs of the reality of existence of the neutrino.[36] The works of A. I. Alikhanov, A. I. Alikhan'yan and L. A. Artsimovich demonstrated the exact observance of the laws of momentum conservation in the processes of positron annihilation.

In February 1936 Niels Bohr had formulated his theory of the compound nucleus; he pointed out that the energy introduced into the nucleus during the absorption of a neutron will be distributed between its nucleons. Elaborating his ideas, Ya. I. Frenkel' in the same year proposed using the principles of statistical physics to describe the nuclei of heavy elements (having a large number of nucleons). He was the first to introduce the concept of the nucleus temperature and he drew an analogy between, say, the processes of the emission and capture of neutrons and "evaporation" and "condensation." On the basis of these simple theories Frenkel' calculated the lifetime (probability of particle evaporation) of the excited nucleus, which proved to be in good agreement with experimental data.

The last prewar cycle of research to have been carried out at the Physicotechnical Institute or to have been stimulated by other research conducted there was associated with neutron physics, on which I. V. Kurchatov had been working for a number of years. At the Physicotechnical Institute, as in the world's other scientific institutions, the exceptional importance of the discovery by Hahn and Strassmann of the neutron-induced fission of uranium was immediately appreciated. Following the study by O. Frisch and L. Meitner,[37] Ya. I. Frenkel' published his electrocapillary theory of the splitting of heavy nuclei by slow neutrons[38] in which, on the basis of an analogy between a nucleus and a drop of charged fluid and on using the data of the Rayleigh theory of capillary waves, formulas for estimating fission processes were derived. These formulas implied, among other things, as spelled out in Frenkel's article,[38] the possibility of the spontaneous fission of uranium and thorium and derived the corresponding energy condition. Frenkel', however, assumed that fission of this kind oc-

*Note that cosmic ray research is being currently continued at the Physicotechnical Institute by N. S. Ivanova and associates. She is investigating the charge spectra of cosmic rays and the nuclear reactions they cause. Recent studies have been carried out by the method of exposing stacks of photoemulsion plates on artificial earth satellites.

curs only for elements with $Z \geq 93$, and he attributed the implication, ensuing from his own theory, of the possibility of spontaneous decay of uranium to the roughness of his calculations. An exact and complete theory of electrocapillary fission was somewhat later developed by Bohr and Wheeler[39] who, incidentally, also estimated the half-life of the process of spontaneous fission of uranium.

It was precisely within the walls of the Physicotechnical Institute, in the classical study by G. N. Flerov and K. A. Petrzhak,[40] that the spontaneous fission of uranium was experimentally established. It can be probably stated that this was the last major discovery in nuclear physics that had been accomplished with the aid of comparatively elementary and inexpensive equipment. Lastly, the concluding chord in prewar work "to assault the atomic nucleus" (by analogy with the title of a small book by A. K. Val'ter, a co-worker of the Institute,[41] published in the early 1930s) was the work of Ya. B. Zel'dovich and Yu. B. Khariton, co-workers of the Institute of Chemical Physics (a daughter institute and nearest neighbor of the Physicotechnical Institute). That work showed that enriching uranium with its light isotope makes possible a chain reaction accompanied by liberation of energy. The results of this work and a review of other pertinent research were generalized in a series of two articles published in Usp. Fiz. Nauk in 1940.[42] The second article of that series, written for the journal by the same authors, had even specified the numerical value of the critical mass of uranium. But the publication of that article was halted by the war and subsequently all the research into the problem of uranium entered a new and decisive stage.

The heroic "uranium era" had already found its first chroniclers and we now know that Kurchatov himself, and practically all the scientists whom he had mobilized for the solution of the "uranium problem," belonged to the school of the Physicotechnical Institute and worked in its laboratories (not necessarily nuclear). From this standpoint, the contribution of the Physicotechnical Institute and its services to the nation are known and cannot be overestimated. But usually therewith ends the appraisal of the Institute's role.

Actually, however, it is worth noting that in the second half of the 1940s the Institute was charged with highly important problems of research into the separation of isotopes—at first of heavy and later of light elements as well; this concerned the development of principles for their large-scale industrial production. A large group of the Institute's co-workers headed by B. P. Konstantinov, who had tested out the known methods and worked on new methods, was mobilized for the solution of these problems. Strenuous labors commencing as early as in the beginning of the 1950s led to the construction of appropriate industrial shops. This construction was completed in record-breaking time and the nation's atomic power industry was provided with high-quality low-cost raw materials. Kurchatov described as follows the results of these activities in his conversation with co-workers the Institute: "When we started this work, there were no light isotopes, there was only the problem of obtaining them; now this problem no longer exists and the isotopes are available." The complex of research into isotope separation was awarded the 1953 State Prize (A. P. Votinov, K. V. Donskoĭ, N. I. Ionov, N. Yu. Lagunov, G. Ya. Ryskin) and the 1958 Lenin Prize (B. P. Konstantinov and B. A. Gaev).

To the Physicotechnical Institute also belongs considerable credit for assuring the development of accelerator engineering. A small cyclotron was built and put into operation as far back as in 1934 in Kurchatov's laboratory by his co-worker M. A. Eremeev. The diameter of its pole pieces was 25 cm, with the protons accelerated to energies of the order of 1 MeV (recall that the first cyclotron of Lawrence himself, operating in California, was of roughly the same dimensions: diameter 28 cm, proton energy 1.22 MeV). The "little cyclotron" of Kurchatov's laboratory was the first swallow of the summer; in 1937 Kurchatov himself and A. I. Alikhanov took a direct part in putting into operation Europe's first cyclotron being built in the Radium Institute by a group headed by D. G. Alkhazov. At roughly the same time, the work to design the cyclotron of the Physicotechnical Institute was commenced (I. V. Kurchatov, A. I. Alikhanov, L. M. Nemenov, Ya. L.

A. F. Ioffe, I. V. Kurchatov, P. L. Kapitza

Khurgin, P. Ya. Glazunov). The history of that cyclotron is very dramatic. On 22 September 1939 its foundation was laid, and the erection of its pavilion was completed in early summer of 1941; the particle beam was scheduled to be obtained on 1 January 1942. On 22 June 1941 Pravda published a report on the progress of the final stage of this construction project. But the war interfered with the plans of the scientists and the construction had to be suspended. However, the blueprints of that cyclotron, for which L. M. Nemenov traveled to the besieged Leningrad in 1943, were transmitted to Moscow and utilized to start the cyclotron of the Laboratory No. 2 (the laboratory of I. V. Kurchatov).

In January 1945 the Government decided that the work on the construction of the cyclotron of the Physicotechnical Institute should be completed, and as early as in 1946 this cyclotron was put into operation. It was precisely this cyclotron that was used to obtain the first microportions of plutonium which had played an essential role in working out a number of technological processes associated with the development of the atomic industry. It was also used, in collaboration with Kurchatov's co-workers, to measure the neutron cross sections of transuranium elements.[43]

In 1947–1948 the Physicotechnical Institute was the site of a cycle of research projects culminating in the construction, on the basis of the cyclotron, of the first synchrocyclotron in the USSR (D. G. Alkhazov, D. M. Kaminker, and others) with a deuteron energy of 22 MeV and a beam current of the order of 0.2 μA.

The exponentially growing rate of development of accelerator engineering seemed to make the Institute's cyclotron something of a museum exhibit, a relic. Actually, however, it has been (and still is being) used to carry out important research into the Coulomb excitation of atomic nuclei. This research, which received universal recognition, originates from the early 1950s when K. A. Ter-Martirosyan, a co-worker of the Theoretical Division of the Institute, developed the theory of the Coulomb excitation of nuclei by electrons and heavy charged particles. He showed that for calculations of the cross section of the process, the trajectory of the "exciting" particle can be described in the classical language, and derived formulas which made it possible to relate the nuclear level excitation cross section to the lifetime of that level. Ter-Martirosyan's work served as the basis for a number of both theoretical studies (in particular, more precise quantum-mechanical calculations showing the validity of his semiclassical method of calculation) and experimental studies. It was shown that the use of heavy ions affords special advantages for research into the Coulomb excitation of short-lived (with $\tau < 10^{-13}$ sec) levels; then, primarily, the process cross section increases and moreover, the interaction between the target nuclei and light bombarding particles is accompanied by competing interaction processes which interfere with exact measurement of the cross section of the sought process.

In 1955 work was begun (D. G. Alkhazov, I. Kh. Lemberg, A. P. Grinberg, and others) to adapt the cyclotron of the Physicotechnical Institute to the acceleration of heavy multiply charged ions such as He, B, C, N, O, Ne and Ar with a charge of as much as 7^+ in the case of Ar. The development and use of special quadrupole magnetic lenses made it possible to substantially enhance the intensity of the ion beam (at ion energies of 10–65 MeV the currents on the target ranged from 5×10^{-6} to 5×10^{-11} A, depending on the type and charge of the ion.

The Physicotechnical Institute rightfully occupies a universally recognized dominant position in the worldwide research into Coulomb excitation. The data, obtained in the process of research, on the lifetimes of the excited states of many tens of nuclei made it possible to verify the existing theories of the structure of nuclei, described by various nuclear models.

The work on Coulomb excitation is characteristic of the Physicotechnical Institute, where problems of nuclear spectroscopy have long and successfully been investigated. This orientation was linked for many years with the name of L. I. Rusinov and subsequently of V. M. Kel'man, who for a number of years had headed the corresponding Laboratory of Nuclear Spectroscopy at the Institute. In that laboratory several perfect types of β-spectrometers had been developed.

Basic research into atomic nuclei in the postwar years was successfully conducted by L. A. Sliv and associates. It included the examination of various models of the nucleus as a system of strongly interacting particles. In the course of this research, and on the basis of the resulting simplifying assumptions concerning the nature of the forces binding the nucleons, the shell model and the optical model had been interpreted, as was the spectrum of quasiparticle excitations. It was shown that as the number of nucleons increases (in excess of the occupied shells), transition of nuclei to states with static deformation and a rotational spectrum takes place.

Another series of studies by L. A. Sliv associated with nuclear spectroscopy pertained to the calculation of the coefficients of internal conversion of γ rays on atomic electrons, since these parameters are sensitive to the spin and parity of nuclear levels.

The highly accurately calculated internal conversion coefficients for the K^-, L_1^-, L_2^- ... shells of the atoms were presented in corresponding tables[44] which are widely used in every nuclear laboratory in the world.

During 1951–1953 a synchrotron for electron energies of the order of 100 MeV was built at the Physicotechnical Institute under the direction of A. P. Komar. This synchrotron assured γ-ray intensities from the internal target reaching as much as 10^{10} MeV/sec-cm^2 at a distance of 1 m from the target, and it produced γ rays of high monochromaticity and was used to carry out important research into photonuclear reactions.

In 1959, on Kurchatov's initiative, the Physicotechnical Institute began the construction of a new type of proton synchrocyclotron designed for energies as high as 1 GeV. It was built under the direction of D. G. Alkhazov. In 1968 this proton accelerator, the world's largest in its class, was used to obtain a beam of the designed energy and intensity. The construction and adjustments of the synchrocyclotron were accompanied by the development, in the Institute's Laboratory of High-energy Physics (A. P. Komar), of apparatus designed for use in the course of the scheduled research into strong and weak interactions, high-energy nuclear reactions, etc. In particular, it has built liquid-hydrogen bubble chambers, a heavy-fluid bubble chamber equipped with a holographic system for information recording (i.e., for analysis of particle tracks), numerous variants of spark chambers, etc.

But while the physics research associated with this powerful synchrocyclotron is still barely in the planning stage, there already exists another giant physics apparatus—the nuclear reactor of the Physicotechnical Institute—which makes possible an intense conduct of this research, justifying the effort and expense invested in its construction. The initiative for its construction is to be credited to L. I. Rusinov (1954), who headed a large group of scientists and engineers who had modernized a commercial VVR-S (water-moderated water-cooled) reactor to increase its designed capacity and maximum neutron flux. By the end of 1959 the physical startup of this reactor, which at the time was the best research reactor in the Soviet Union, had been accomplished. Subsequently the capacity of the reactor was raised to 16 MW and the neutron flux, to 10^{14} $cm^{-2}sec^{-1}$, on improving all of its operating characteristics. The modernized reactor of the Physicotechnical Institute served as a model for perfecting the VVR-S reactors received by the scientific institutions of the USSR and a number of socialist countries.

In 1965 V. M. Lobashov initiated a series of studies intended to verify the nonconservation of parity during γ transitions of nuclei. The existence of an impurity represented by a weak nucleon-nucleon interaction in the strong interaction—an impurity that does not conserve P-parity—was implied by the theory of the universal (V − A) interaction.[45] The experimental detection of this extremely tiny effect presented an exceptionally great difficulty, which was first surmounted in Lobashov's studies (as well as in the studies by Abov et al.[46]). This success was due to the use of resonance devices which made it possible to isolate and accumulate a small periodic signal as a result of which the accuracy of measurements could be increased by two-three orders of magnitude. On investigating the decay of unpolarized Ta^{185} and Lu^{175} nuclei Lobashov and his associates measured the circular polarization of γ quanta and estimated the relative amplitude of weak interaction (the mixing factor) which proved to equal several 10^{-7} units. The fundamental significance of this finding is universally recognized.

The cycle of research performed by O. I. Sumbaev and associates in the same laboratory is close to the studies mentioned immediately above in accuracy of investigation of effects and in elegance of the methods (chiefly nuclear) employed, even though their studies do not directly pertain to the domain of nuclear physics. This refers to the measurement of the energy displacements of the internal ($K\alpha_1$) electron levels in the atoms of both light (as had been accomplished even earlier) and heavy (with $34 < Z < 74$) elements) (accomplished for the first time). These displacements (termed chemical shifts) are, as is known, due to the fact that when an investigated atom enters a chemical compound, its corresponding level becomes influenced (displaced) by its partner-atom, causing a redistribution of the density of valence and inner electrons. The apparatus developed made accessible to measurements a record-breaking region of relative level shifts lying within the limits of $10^{-7} < \Delta E/E < 10^{-5}$, i.e., it made possible the detection of shifts of the order of tenths of an eV in the presence of energies of tens of keV. It turned out that the magnitude of the shift of internal levels remains roughly constant over a broad range of the values of Z. The detailed investigation of the chemical shift effect made it possible to establish previously unknown valence structures of a large number of metals. The method developed by Sumbaev also allows the investigation of allotropic transformations in metals and alloys; it opens broad vistas for further research.

Along with the chemical shift an isotopic shift (simultaneously discovered by Boehm in the United States) also was observed; it represents yet another possibility for investigating the structure of atomic nuclei.

V. THEORETICAL PHYSICS AT THE PHYSICOTECHNICAL INSTITUTE

The first co-workers of the Physicotechnical Division of the new Institute included two theoreticians: Yu. A. Krutkov and V. R. Bursian. Bursian soon headed the "Theoretical Physics Group" (the small number of co-workers did not warrant considering a separate division). By that time Krutkov had also gained fame by his studies of statistical mechanics and quantum theory; it was precisely his first years at the Physicotechnical Institute that are associated with his studies of adiabatic invariants. But Krutkov's principal field of activity remained the University [of Leningrad] and his sojourn at the Physicotechnical Institute, though fruitful, was not long. Bursian worked at the Institute for more than ten years, for a long time in the capacity of its Scientific Secretary. Throughout that time he had been working in the domain of x-ray physics, thermodynamics, and electronics. He solved the problem of the passage of current in electron tubes with allowance for the space charge and Maxwellian velocity distribution of the electrons, and he also investigated the electron drift in a space without an electrical field (this last study, carried out in collaboration with V. I. Pavlov, proved to be highly important to the development of klystron theory).

In 1921 Ya. I. Frenkel' joined the Institute and the activity of the Theoretical Physics Division of the Institute (formally organized in 1930 with Frenkel' as its head) is chiefly linked with his name.

What has been said earlier about "everyone and no one" being students of Ioffe applies even more so to Frenkel': among the theoreticians of the 1920s—1940s his disciples were "everyone and no one." Everyone, because there was no one equal to Frenkel' in the breadth of his research (although, generally speaking, such a breadth is inherent in major theoretical physicists to a much greater extent than in equally eminent experimenters). Everyone because, moreover, he was the author of the first Soviet set of texts on theoretical physics.* And no one, or more exactly almost no one, because he had very few immediate associates. This

*This refers to Teoreticheskaya mekhanika (Theoretical Mechanics) (successive editions published in 1925, 1935, 1940), Elektrodinamika (Electrodynamics) (1926, 1928, 1934-35, 1956), Volnovaya mekhanika (Wave Mechanics) (1929, 1932, 1933, 1934, 1936), and Statisticheskaya fizika (Statistical Physics) (1933, 1948, 1957) last circumstances largely stemmed from the fact that Frenkel' did not work out the general methods of theoretical physics whose application to a broad range of particular problems by various people usually warrants classifying these people as the disciples or followers of the author of the method concerned. His strength lay in his being a unique "idea generator," and it was not possible to teach any one the art of "generation" of this kind.

The nature of Frenkel's talent ideally suited the Physicotechnical Institute with its broad research scope, and we already had occasion to mention some of his studies while discussing individual research orientations at the Institute.

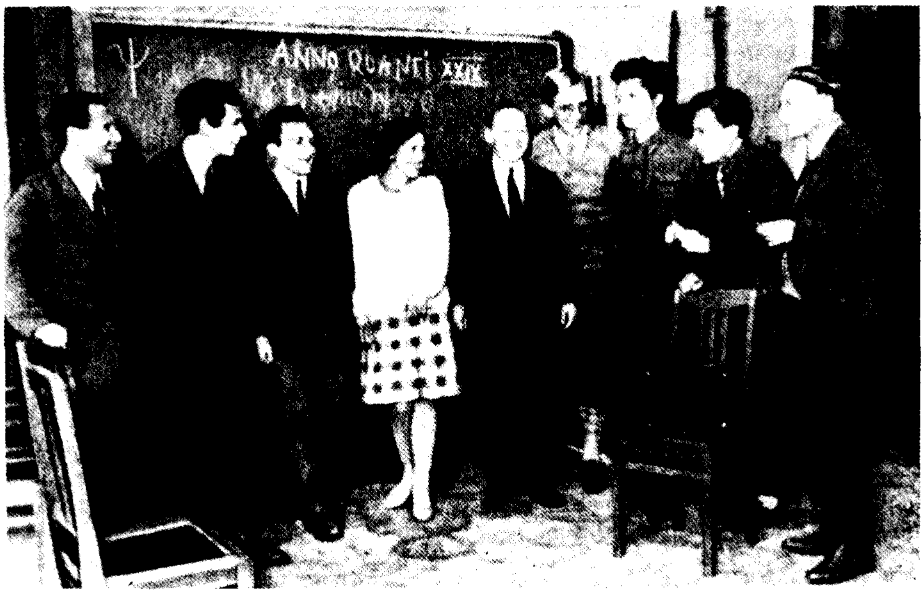
Of the works on general problems of theoretical physics mention should be made of Frenkel's studies of classical electrodynamics.[47] In the mid-1920s he developed the theory of the point electron, whose starting premise was the concept of the fictitiousness of the problem of electron "stability." He had, further, refined the relativistic theory of the spinning electron whose concept was introduced by Uhlenbeck and Goudsmit. The simple observation that the motion of the magnetic moment of the electron must be associated with the rise of an electrical field prompted Frenkel' to describe the spinning electron by means of an antisymmetric tensor whose components are both the magnetic and the electrical moments of the electron. Note, lastly, that Frenkel's ideas of the relationship between the field and charged particles as well as on retarding and advanced potentials in classical electrodynamics provided Feynman with one of the major premises for his theory of quantum electrodynamics, as he directly points out both in his original works[48] and in his Nobel speech[49]. Paying due tribute to the corresponding works of Frenkel', Feynman proposed applying the appellation of "Frenkel' fields" in classical electrodynamics to, first, the "natural" field generated by a given electron and, second, the "external" field to which all the other electrons contribute—it is precisely the latter field that acts on the given electron.

It was within the walls of the Physicotechnical Institute that L. D. Landau commenced his life work in 1926 as a postgraduate student under Frenkel'. The very first work of the 19-year Landau is rightly regarded as a major contribution to the development of quantum mechanics that had been worked out by then by de Broglie, Schroedinger, Heisenberg and Born. This first work of Landau (1927) introduced the concept of the density matrix, making possible the description of quantum-mechanical systems which cannot be described in terms of wave functions (i.e. systems with which a "complete experiment" has not been performed). The language of the density matrix has become firmly rooted in present-day quantum mechanics. Landau also carried out (in collaboration with R. Peierls) important fundamental studies of the quantum mechanics of photons. Their 1930 study showed that it is not possible to speak of the localization of a photon in conventional space (as distinct from momentum space) within the confines of a region smaller than the photon wavelength, and hence also the concept of probability density in this plane is meaningless (this quantity assumes both positive and negative values). Another work by the same authors (1931) showed that the relativistic generalization of the uncertainty relation $\Delta E \cdot \Delta t > h$ leads to more stringent limitations on the possibilities of momentum measurement—to a new type of uncertainty relation.

For a number of years (1924—1934) V. A. Fock was a co-worker of the Theoretical Physics Division of the Physicotechnical Institute. That period also was associated with his greatest and well-known accomplishments pertaining to the relativistic generalization of Schrödinger's equation, the theory of functionals and second quantization, as well as with his development (in 1930) of the methods of quantum-mechanical description of the many-electron system (the Hartree-Fock method). To be sure, it must be stated that in addition to working at the Physicotechnical Institute Fock was at the same time also working in the Leningrad University and Optics Institute, so that both these institutions also have a claim to being the sites of these studies by Fock (particularly of his research into the n-body system in quantum mechanics).

An even greater role was played by the research performed at the Theoretical Physics Division of the Physicotechnical Institute on the application of the general principles of quantum mechanics to the solution of its particular problems (part of this research is reflected in other sections of this article). As far back as in 1924 Frenkel', on the basis of the concepts of Bohr's quantum theory, provided an explanation for the so-called "specific heat catastrophe" (i.e., the fact that free electrons of a metal do not contribute to its total specific heat). He had subsequently refined this study by using the de Broglie relation to describe electron motion, which made possible a new interpretation of resistance as a distinctive effect associated with the wave nature of electrons and resembling the scattering of light in turbid media, with impurities and density fluctuations playing the role of inhomogeneities from which the electron waves get scattered. The simultaneously published study by Sommerfeld, who described the free electron gas in terms of the recently developed Fermi-Dirac statistics provided a more complete description for all these effects but, unlike Frenkel's work, it implied, e.g., anomalously high values of the free-path length.

Even more important results were obtained within the walls of the Physicotechnical Institute in developing the quantum theory of magnetic phenomena. Here mention should primarily be made of Frenkel's study of ferromagnetism, which provided an explanation of this effect on the basis of theories of exchange interaction (introduced by Heisenberg when constructing the theory of the helium atom) and of the associated additional energy. A more refined theory of ferromagnetism was published by Heisenberg several months later in the same year 1928. In 1930 Landau quantized the motion of electrons in magnetic fields and developed his theory of the diamagnetism of free electrons which implied that electron gas displays not only paramagnetic susceptibility (Pauli, 1927) but also diamagnetic susceptibility—"Landau diamagnetism," which in fields of low intensity equals one-third of spin paramagnetism. Simultaneously Landau showed that at low temperatures the susceptibility of electron gas periodically varies with variation in the magnetic field. The corresponding effect was later discovered by De Haas and Van Alphen and bears their



Theory Seminar. Left to right: L. É. Gurevich, L. D. Landau, L. V. Rozenkevich, A. N. Arsen'eva, Ya. I. Frenkel', G. A. Gamow, M. V. Machinskiĭ, D. D. Ivanenko, G. A. Mandel' (1929)

name.

In the same year 1930 Ya. G. Dorfman and Ya. I. Frenkel' carried out an important study of the domain structure of ferromagnetics, which clarified the cause of the division of a ferromagnetic into domains, attributing it to a unique interplay of conventional magnetic and quantum (exchange) forces; it was shown that the domain dimensions depend on the body dimensions—a fact corroborated by experimental data. A detailed theory of the domain structure of ferromagnetic bodies allowing for the anisotropy energy was developed in 1935 by Landau and E. M. Lifshitz in the Ukrainian Physicotechnical Institute in Khar'kov. Dorfman also has carried out studies directly relevant to those above (theoretical and experimental), pertaining to ferromagnetic and paramagnetic resonances whose significance was with special clarity demonstrated by subsequent works of Soviet and foreign physicists—Van Vleck, G. V. Skortskiĭ and, particularly, E. K. Zavoiskiĭ. The principal researches carried out at the Theoretical Physics Division of the Physicotechnical Institute during 1930s—1940s pertained to semiconductor problems, nuclear physics, and high polymers, in accordance with the new scope of research commenced during these years.

Beginning with the mid-1950s the Theoretical Division of the Institute entered on a period of rapid expansion. A major role in this process was played by I. M. Shmushkevich, K. A. Ter-Martirosyan and also L. A. Sliv and A. Z. Dolginov. Their scientific interests, which were centered on problems of nuclear physics, theory of elementary particles, and high-energy physics, largely predetermined the topics of research being carried out by a large group of young co-workers active in the Sector of the Theory of the Atomic Nucleus (I. M. Shmushkevich). Along with this the Sector of Applied Theoretical Physics (A. I. Gubanov) was organized during these years, as was somewhat later the Sector of Solid-state Theory (L. É. Gurevich). Subsequently the number of sectors within the Division continued to grow (owing to separation of the Sector of the Theory of the Atomic Nucleus).

For a number of recent years the Institute's Basic Research Division has been intensively pursuing research into the physics of high energies and elementary particles. As is known, it is precisely this domain of modern theoretical physics that represents its farthest frontier.

At the Physicotechnical Institute a fairly numerous staff of theoreticians is concerned with problems of the physics of high energies and elementary particles. The greatest accomplishments in this domain have been achieved in the work on the asymptotic behavior of scattering amplitudes in the presence of high energies and complex moments. The principles of the theory of complex angular momenta developed by V. N. Gribov stimulated an entire series of studies in this domain, in which the theoreticians of both the Physicotechnical Institute and other research centers in the USSR and abroad are currently engaging. In this domain of physics the Physicotechnical Institute is rightfully considered one of the few leading institutions in the Soviet Union (and throughout the world for that matter).

A number of studies carried out at the Institute pertains to research into the symmetry of elementary particle interactions, which was initiated in the mid-1950s, at a time when I. M. Shmushkevich developed the extremely simple method of deriving isotopic relations between the cross sections of various reactions (with the participation of nucleons and mesons), a method which is highly effective in the examination of reactions with multiple particle production. As early as in the beginning of the 1960s interesting research into the symmetry of strong interactions has been conducted at the Institute (V. M. Shekhter) and most recently, following the appearance of the hypothesis (of Gell-Mann and Zweig) of the existence of quarks, this model was used as a basis for examining the problem of hadron scattering and obtaining data on the ratio of the total meson-nucleon and nucleon-nucleon scattering cross sections.

Let us also mention yet another cycle of studies (also having a history of more than ten years) which have been markedly developed and have received broad recognition: this concerns the work on reactions with the participation of three strongly interacting particles. The case of their resonance interaction was considered in the well-known study by K. A. Ter-Martirosyan and G. V. Skornyakov from the standpoint of "classical quantum mechanics" (1956) and it led to the derivation and solution of integral equations describing the scattering of a neutron by a deuteron. This solution was refined in a later study by G. S. Danilov (1962). V. N. Gribov investigated the reaction of the formation of three particles (also at low energies, near the reaction threshold) on the basis of theories of the analytic properties of reaction amplitudes. A. A. Ansel'm and I. T. Dyatlov have also been successfully working in this direction.

Unfortunately, not all of these studies can be described tersely in the layman's language; hence we will confine ourself here essentially to presenting a list of the problems on which the Institute's theoreticians are working in this domain.

A traditional orientation of research at the Theoretical Division of the Physicotechnical Institute is the study of the general problems of statistics and physical kinetics. The Division has been intensively expanding research into the kinetic theory of condensed systems and problems of phase transformations (Ya. I. Frenkel'), substantiation of statistical physics (B. I. Davydov, Yu. N. Obraztsov), theory of Brownian motion (B. I. Davydov), kinetics of chemical reactions (V. R. Bursian, L. É. Gurevich, O. M. Todes, S. V. Izmaĭlov), theory of kinetic phenomena in semiconductors (A. I. Ansel'm, M. P. Bronshteĭn, B. I. Davydov, N. L. Pisarenko, K. S. Shifrin, I. M. Shmushkevich).

We shall dwell in some detail on certain studies performed in this extensive domain during postwar years. In 1946 L. É. Gurevich (at the time working in the Leningrad State University) showed that a distinctive effect of the dragging of electrons by the phonon flux ("phonon wind") must occur in the processes of heat conduction in solids and that the corresponding thermal e.m.f. in metals, and especially in semiconductors, can markedly exceed in magnitude the thermal e.m.f. due to the direct action of a temperature gradient on the electrons. The idea of "dragging" and the calculations performed in the course of its realization accounted for a large number of the anomalies so characteristic of thermoelectric effects. Gurevich's work served as the point of departure for an entire avalanche of studies, both theoretical and experimental. In particular, as Gurevich and his associates had shown, the dragging effects also are significant in phenomena of electrical conduction. Further, it was shown that the dragging of electrons by phonons (as well as the reverse effect) occurs also in a number of astrophysical processes.

In 1960 O. V. Konstantinov and V. I. Perel' predicted the possibility of the propagation of electromagnetic waves of the radio range (subsequently termed helicons) in metals placed in a magnetic field, thus also refuting the previously unshakable idea that a metal represents, apart from the skin layer, an impermeable screen to electromagnetic waves. This effect, despite the high concentration of free electrons characteristic of metals, occurs within a broad range of wavelengths exceeding a certain critical limit. The reason for the presence of this boundary (given a specific intensity of the magnetic field) is that collisionless cyclotron damping can occur only if the velocity of electrons in resonance interaction with the electromagnetic waves exceeds (in the presence of an above-critical wavelength) that maximally possible value which corresponds to the Fermi surface. This does not mean, however, that the metal will completely transmit the above-critical wavelengths. The studies by V. G. Skobov (Physicotechnical Institute) and É. A. Kaner (Institute of Radio Engineering and Electronics, Ukrainian Academy of Sciences) showed that in most metals placed in a magnetic field the damping of helicons is due to a distinctive mechanism. It can be illustratively represented as magnetic Landau damping, i.e., as the acceleration of electrons by moving magnetic mirrors. The latter are formed when the longitudinal component of the magnetic field of the wave combines additively with the constant field (this also is an example of a distinctive Fermi micromodel of the acceleration of cosmic particles). Another important question that was resolved in these studies is related to the existence of a quantum effect of giant oscillations of wave absorption.* The effects mentioned above were discovered by direct experiments. As often happens, the newly discovered effect evolved from an object of investigation into a distinctive tool of investigation—in this case a tool for the investigation of high-frequency volume effects in metals.

Closely adjoining to the research in theoretical physics is also the research in mathematical physics; the boundary line between these two is highly conditional, as is strikingly exemplified by G. A. Grinberg, who headed the research in mathematical physics ever since the first few years of existence of the Physicotechnical Institute and who is now its oldest co-worker. At first the group for mathematical physics was part of the Theoretical Division, but as of 1945 it was segregated into a division of its own, headed by Grinberg. Grinberg's first studies (in the 1920s) dealt with the application of the ideas of the relativity theory to problems of the theory of elasticity and hydrodynamics; his approach to these problems reflected the fact that he had studied under A. A. Fridman. The vigorous development of radio engineering and particularly of microwave engineering in the 1930s was reflected in Grinberg's pioneering works on the theory of high-frequency diodes, triodes, and magnetrons. Early in the 1940s he developed the general theory of the focusing effect of magnetic and electrostatic fields which would necessarily assure a specified trajectory of charged particles. These works played a major role in the development of television tubes. Other important studies also pertain-

*The presence of giant oscillations of the absorption of sound in metals was established earlier in the works of V. G. Skobov, V. L. Gurevich and Yu. A. Firsov.

ing to radiophysics were Grinberg's investigations of the propagation of electromagnetic waves in inhomogeneous media and of the theory of shore refraction. His associates also had been working in this field. The prewar studies of diffraction theory by M. I. Kontorovich and N. N. Lebedev, in which the method of integral transforms which now bears their name was developed, still are widely known.

During the postwar years, too, diffraction problems remained in the focus of the attention of the Division, as did the theory of integral transforms (G. A. Grinberg, N. N. Lebedev, I. P. Skal'skaya, and Ya. S. Uflyand). The general form of this theory of integral transforms in the region where its applicability to problems of mathematical physics is concerned was developed by Grinberg.

Most recently the Division's co-workers have been concentrating their efforts on the solution of urgent problems of magnetohydrodynamics (Ya. S. Uflyand and others) and plasma physics with applications to astrophysics (Yu. V. Vandakurov). N. N. Lebedev obtained a number of important results in the special functions theory. Grinberg has carried out important studies of problems with "moving boundaries" (as classically exemplified by the well-known Stefan problem of the freezing of a liquid or by the drawing of crystalline specimens from a melt). Problems of this kind could be solved even earlier but only owing to a lucky "guess." Grinberg proposed a general method for their solution allowing for the various physical conditions occurring at the moving boundary (of liquid and solid phases in the instances named above). Moreover, he showed that the method developed in his works can be successfully also used for the solution of static bivariate equations of mathematical physics with the role of time being played by one of the variables and the equivalent of the "moving boundary" being represented by a curve on which the conventional (static) boundary conditions are specified.

VI. PLASMA PHYSICS AND ASTROPHYSICS

We have described above the results of research conducted in directions traditional of the Physicotechnical Institute. The Institute also has the tradition of skill in reorienting large teams of co-workers to research in new and increasingly topical domains of physics. Recent years demonstrated the expediency of this scientific policy, as strikingly exemplified by the inclusion into the Institute's program of the problems of plasma physics and astrophysics, accomplished on the initiative of B. P. Konstantinov who had headed the Physicotechnical Institute for more than ten years (from 1957 to 1967).

The postwar years have been marked by the dynamic development of not only high-energy physics but also astrophysics, biophysics, and plasma physics. It is precisely in these fields that the most fundamental discoveries have been made or are expected in the future. In the case of plasma physics, moreover, significant "high-energy" applications associated with the accomplishment of controlled thermonuclear reactions have been obtained or are expected.

Ever since the late 1950s and early 1960, the Physicotechnical Institute has been expanding its research in all these orientations. We will dwell in more detail on the research into plasma physics and astrophysics.

Plasma research was commenced at the Institute in 1958 in connection with the expansion of research into controlled thermonuclear fusion in the USSR. In that year the combined effort of the Efremov Scientific Research Institute of Electrophysics Equipment and the Physicotechnical Institute resulted in organizing the work with the large toroidal apparatus "Al'fa," the largest of its kind in the world at the time. The Physicotechnical Institute undertook to develop the methods of diagnostics of hot plasma. During that period the problem of measuring the high-temperature plasma was highly urgent: the available information on plasma parameters in various systems was of a highly contradictory nature. The complexity of measurements in plasma of this kind is associated with the need to develop contactless methods of measurement, since the introduction of measuring elements into the plasma interior inevitably results in its cooling. To emphasize the importance of diagnostic research, one may cite the now classical example of incorrect interpretation of data obtained on the British Zeta apparatus, which led to an unjustifiably high estimate of plasma temperature. On the basis of this estimate it was erroneously concluded that the achievement of energetically advantageous thermonuclear reactions was a matter of several years.

The possibility of a rapid switching of the Physicotechnical Institute to research into the problem of thermonuclear fusion was largely due to the circumstance that studies into the processes of atomic collisions had long been successfully developed at the Institute.* Many data on the ion-atom collision cross sections were obtained by V. M. Dukel'skiĭ, N. V. Fedorenko, and their associates. These data greatly affected the entire research program, chiefly in connection with the problems of plasma injection and energy loss.

The problem of contactless plasma measurements was solved at the Physicotechnical Institute in three directions. N. V. Fedorenko, V. V. Afrosimov and their associates were the first in the world to develop (on the basis of B. P. Konstantinov's idea) a method for measurements of hot plasma based on the analysis of the rapid neutral particles emitted by that plasma—the so-called method of "passive diagnostics." The idea of this method is that since neutral particles arise in the plasma owing to processes of resonance charge exchange with ions, which occurs practically without a change in the energy of each of the interacting particles, the energy spectrum of the neutral particles emerging from the plasma reproduces faithfully the spectrum of the plasma ions. At present this method is the only way of determining the energy distribution of hot plasma ions, and it has become widely used. The same group of investigators also has developed "active corpuscular diagnostics" based on the sounding of plasma with fast neutral particles. The attenuation of their beam provides information on ion concentration and electron temperature.

The second orientation of diagnostic research of this kind was based on the interaction between microwaves

*This research was commenced as farback as in the 1920s by N. N. Semenov, V. N. Kondrat'ev and others.

and plasma. The Physicotechnical Institute had proposed and translated into reality a radar ranging method for determining the spatial density of plasma. A similar method was widely used as far back as in the 1930s in ionosphere research. The application of this method to laboratory plasma research required, first, transition to much higher frequencies (owing to a difference of many orders of magnitude in the charged particle densities). Second, owing to the fact that the volumes of laboratory plasma were, on the other hand, many orders of magnitude smaller (again compared with the ionosphere), it was necessary to switch from pulse-echo radar ranging to phase radar ranging. The plasma radar ranging method developed at the Physicotechnical Institute (B. P. Konstantinov, V. E. Golant and associates) has become widely used in research on various plasma installations. In particular, it has been used to investigate diffusion in decomposing plasma, adiabatic compression, etc.

The Physicotechnical Institute was also the site of the development of a method for determining the parameters of plasma present in a metal chamber from its noise emission in the microwave range, as well as of the development of corresponding apparatus, and it also was there that a method for analyzing plasma by using microwave scattering was proposed and tested (M. M. Larionov and others). It was there also that the newly discovered open cylindrical resonators were first used for plasma research (V. E. Golant, N. I. Vinogradov and others). By the same token it proved possible to markedly expand the range of measurable concentrations and to largely eliminate the limitations imposed on the dimensions of the investigated plasma in the resonator method.

An important orientation of diagnostic research of this kind is based on the determination of the spectral characteristics of plasma. Under the direction of A. N. Zaĭdel', a number of refined methods of spectroscopic analysis was developed: the determination of ion energies from the Doppler line broadening (the application of this method for the case of hot plasma presented considerable but successfully-surmounted difficulties), research into collective plasma displacements, etc. Recently work on the use of lasers in plasma analysis has been commenced (holographic methods, analysis based on the scattering of laser light).

The totality of experimental methods of plasma analysis developed at the Physicotechnical Institute makes it possible to measure a large number of parameters over a broad range of their variation. There moreover exist regions in which the various methods overlap, thus making possible their mutual verification.

We note that, along with the research on plasma diagnostics, the Physicotechnical Institute has currently commenced research (under the direction of V. E. Golant) on the physics of high-temperature plasma. We shall not describe it in detail and instead we just list the principal orientations of this research. The studies of the interaction between high-frequency waves and plasma are intended to develop methods of creating plasma with separately controlled electron and ion energies. In this field the most interesting result was the discovery of a broad band of the absorption of high-frequency energy by plasma. Another method of obtaining high-temperature plasma investigated at the Physicotechnical Institute consists in its adiabatic compression with an increasing magnetic field. The use of this method in a toroidal trap made it possible to effectively separate the plasma column from the walls of the container, which resulted in a marked increase in the lifetime of a hot plasma.

The credit for a new approach to the creation of magnetic traps for plasma retention belongs to V. G. Skornyakov. He proposed using a toroidal magnetic trap with a complex field topology and demonstrated the stability of that topology.

The astrophysical research with whose description we will end this article also had a prehistory of its own at the Physicotechnical Institute. In the late 1920s the Institute's theoreticians carried out a number of studies of the application of quantum mechanics to stellar structure (L. D. Landau, Ya. I. Frenkel'); the radiative equilibrium of the stars and the applicability of the second law of thermodynamics to the entire Universe were investigated by M. P. Bronshteĭn.

The past decade was characterized by a quantum jump in the development of astrophysics. The role of physicists in the conduct of corresponding research has also been affected by the growth of the arsenal of observational means (from the narrow regions of visible electromagnetic radiation to practically the entire gamut of wavelengths enclosed in between radio waves and γ rays) and by the transition from means of "passive diagnostics" to active diagnostics—to the radar ranging of planets and experiments on their surface as well as in circumterrestrial space. At the same time, the physicists themselves also are attracted by the fundamental nature of the physical and gnoseological problems of modern astrophysics with its grandiose space and time scales and the range of densities and temperatures characterizing its objects.

All this influenced the aforementioned decision of B. P. Konstantinov to introduce the astrophysical research orientation at the Physicotechnical Institute. In 1961 a number of co-workers from other laboratories of the Institute, experienced in the comprehensive whole of the experimental methods currently being employed in astrophysical research (and particularly in nuclear radioelectronics), were mobilized for research into astrophysics. In 1963, on the decision of the Presidium of the USSR Academy of Sciences, the Physicotechnical Institute organized the Division of Astrophysical Research, headed by B. P. Konstantinov, which includes a number of laboratories and groups directed by M. M. Bredov, A. M. Romanov, A. M. Stefanovskiĭ, N. S. Ivanova, and others.

The fundamental problem proposed by Konstantinov and selected as the first research orientation was the problem of the charge symmetry of the Universe. Since the discovery of the positron, an unresolved question has been whether this symmetry, which to this day is observed in the "table of elementary particles," is preserved in the Universe on the macroscopic scale with respect to matter and antimatter.

On examining the various cosmological and cosmogonic aspects of the solution of this alternative in favor of symmetry of the Universe, Konstantinov pointed out, in particular, the fundamental possibility of the exchange of macrobodies between systems consisting of matter and antimatter if they do exist. One of the phenomena that might ensue from such an exchange could possibly prove to be the unique phenomena associated with the behavior of a definite type of comets in the solar system. The assumption of the possible antimatter nature of these comets in principle admits experimental verification based on the observation of the entry of the products of disintegration of the comets—micrometeor showers—into the Earth's atmosphere.

Experiments performed in this direction in the Astrophysics Division of the Physicotechnical Institute[50] (B. P. Konstantinov, M. M. Bredov and associates) led to the discovery of effects which may be regarded as facts supporting such a hypothesis.

Roughly at the time when astrophysical research was commenced at the Physicotechnical Institute, reports on the existence of a dust cloud around Earth, established with the aid of satellite measurements, appeared in the literature. These data, obtained in the USSR and United States with the aid of similar apparatus (piezoelectric pickups installed in artificial satellites and recording the incidence of microparticles on their surface) were proved to be dubious from both theoretical and "instrumental" standpoints on the basis of an analysis of this apparatus. Studies performed by B. P. Konstantinov, M. M. Bredov and E. P. Mazets[51] with the aid of the Kosmos-135 and Kosmos-163 satellites equipped with apparatus specially developed for this purpose at the Physicotechnical Institute established practically unambiguously the absence of a dust cloud.

Of interest is the work on the modeling of comet phenomena in laboratory conditions, which is being developed at the Astrophysics Division (E. V. Kaĭmakov and V. I. Sharkov).[52] Their aim was to verify the Vsekhsvyatskiĭ-Whipple hypothesis that the cores of the comets represent a conglomeration of ice with inclusions of various refractory components. In this connection, they investigated the sublimation of ice in conditions of deep vacuum and low temperatures and showed that over a broad range of the values of received power (values such that the power of solar radiation over the distance of 1 a.u. remains within that range) the stationary temperature of ice varies little, remaining within the limits of from -100°C to -60°C. The consumption of ice due to sublimation at low temperatures, measured in the study[52], is in good agreement with theoretical formulas and can provide information on the temperature of the ice nuclei of comets and their lifetimes. The study of the sublimation of ice containing inclusions of dust particles (over a broad range of weight ratios between dust and ice) showed that as the sublimation of ice increases these dust particles form a distinctive matrix which becomes disintegrated when the power received by the surface is sharply increased and that this disintegration is accompanied by an explosion-like ejection of matter. It can thus be stated that this study modeled the dynamics of the formation of the dust tails of comets.

For a number of years research into theoretical astrophysics also has been under way at the Physicotechnical Institute. As far back as in the 1950s L. É. Gurevich and A. I. Lebedinskiĭ (Leningrad State University) had investigated the theory of formation of the planetary system, further developing the well-known works of O. Yu. Shmidt; a theory of the bursts of novae and supernovae under the influence of the nuclear explosions occurring in their peripheral layers was worked out and a hypothesis of supernova bursts due to nuclear explosions in their interiors was proposed.

The organization of the Astrophysics Division was followed by the establishment of the Special Sector of Theoretical Astrophysics under the Theoretical Division of the Physicotechnical Institute (A. Z. Dolginov), which has carried out interesting studies of the theory of the multiple scattering and passage of γ particles through a medium with randomly distributed scattering sources and worked out a theory of the scattering and passage of charged particles during their motion in a magnetic field with randomly varying orientations. Aspects of the formation of the atmosphere of the comets are being investigated (A. Z. Dolginov and associates).

As is known, practically all of the information on the physical conditions existing in outer space (temperature, partial densities of various elements, etc.) is obtained by analyzing the data on the passage of radiation through that space in which this radiation undergoes resonance absorption and scattering. D. A. Varshalovich has theoretically investigated the interaction between a rarefied gas and oriented radiation fluxes. It was shown that the anisotropy of these fluxes, associated with the location of the stars "nearest" to the examined region of the gas, accounts for a definite orientation of the spins of its particles; owing to this orientation effect the transparency of outer space can change markedly. Studies of the interaction between the hydrogen atoms of the interstellar medium and the $\lambda = 21$ cm radiation showed that the population of the sublevels of hyperfine structure of the ground state markedly depends on the curvature of spectrum in the resonance range, i.e. on whether the traveling clouds of interstellar hydrogen interact with the red or the violet wing of the spectral line L_α. In the latter case we would be dealing with an inverse population of levels, accompanied by coherent stimulated emission. Thus the possibility of the existence of the maser effect on hydrogen under outer-space conditions was demonstrated for the first time. These results have most recently made possible a reinterpretation of the previously seemingly incomprehensible data of radioastronomic observations.[53]

It can be confidently stated that, despite the relatively brief period of time elapsed since research into plasma physics and astrophysics began to be intensively pursued at the Physicotechnical Institute, the results achieved so far have confirmed the correctness of including these problems in the Institute's program, have elicited a stimulating response, and have received recognition.

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