Abram Fedorovich Ioffe (Biographical sketch)

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1. Abram Fedorovich Ioffe lived almost 80 years; these years spanned enormous social and scientific revolutions that radically changed the appearance and order of his homeland and transformed physics, which was his life's work. At the beginning of 1896, while still a youth, he learned from sensational newspaper articles and enthusiastic publications in popular scientific journals about Roentgen's discovery of invisible rays (did he ever think that several years later he would be working as an assistant to the renowned Roentgen in his Munich Institute?). And, a year later, he read about the unusual phenomenon of radioactivity. Already as a student at the Technological Institute in St. Petersburg and as a trainee (later—assistant) at the University of Munich, by reading the latest physical journals, he became acquainted with the work of Planck and Einstein on the quantum theory of radiation and the theory of relativity.

Together with his friends at the Technological Institute, A. F. Ioffe took part in the student disturbances, which reflected the sharp dissatisfaction of the leading youth with the reactionary internal and external politics of the Tsarist government, and as a mature scientist he enthusiastically greeted the revolution and forever cast his lot in with the Soviet regime. A. F. Ioffe's scientific and scientific organizational work won him widespread fame in our country; he was given many awards for his service to science in his country and to the Soviet government and he was nominated to many academies in the world. The Academy of Sciences of the USSR established a prize in his name and in 1974–1977 the Academy published three volumes of his work.

Abram Fedorovich could be proud of the fact that he directly participated in organizing the most outstanding physical institutes in the Soviet Union, that there arose a school of science led by him, and that the most distinguished Soviet physicists, his own students and closest colleagues, through their research placed our country at the forefront of many areas of science and technology. It is under his initiative and within the walls of his favorite offspring—the Physicotechnical Institute, which now bears the name of A. F. Ioffe—that such fields as the physics of semiconductors, nuclear physics and the physics of polymers, i.e., precisely those areas of knowledge that determine progress in the vitally important areas of science, technology, and industry, were first formulated and began to develop rapidly.

Abram Fedorovich occupied key positions in Soviet physics for over forty years. This explains the natural and enthusiastic interest in his work shown by his scientific colleagues and by scientific historians, journalists, and writers. A well-earned place is given to A. F. Ioffe in many publications reviewing the accomplishments of Soviet physicists and published in the last ten years in connection with the fiftieth and sixtieth anniversaries of the October revolution and the formation of the USSR and the two hundred fiftieth anniversary of the Academy of Sciences. The widely celebrated in the Soviet scientific establishment anniversaries of Abram Fedorovich Ioffe (1940 and 1950), and anniversaries of the institutes established by him or with his close participation, have led to the exceptionally copious literature concerning him. We should add that A. F. Ioffe himself often appeared in print with short sketches and extensive autobiographical articles, and in the last years of his life he often made use of the scientific memoir. His last—in a long series!—book entitled *Encounters with Physicists* was sent to press on September 8, 1960, approximately one month before his death. He was able to proofread the book, but did not live to see his recollections published.

We recall that also after October 1960 much scientific—biographical and popular material about the scientist was published in our country (including a book about him, a collection of his reminiscences, a separate pamphlet and numerous articles and essays). Under the circumstances, it would seem that it would be much easier to write one more biographical sketch of Abram Fedorovich. On the other hand, it is natural to want to avoid recounting once again those parts of his biography that have already been well-covered in the literature and to present less well-known material, published only in part comparatively many years ago.

In this article, we will briefly summarize the biography of A. F. Ioffe in chronological order, and we will emphasize the early period in his scientific research as well as his work on the physics of solids (mechanical properties of crystals) and the physics of semiconductors from the 1920's through the 1950's.

The varied scientific-organizational work of Abram Fedorovich played a special role in the development of Soviet physics and will be described in Secs. 19–21.

2. Abram Fedorovich Ioffe was born on October 29 (17), 1880 in Romny—a small town in the province of Poltava—and was the eldest son of Fedor Vasil'evich and Rashel' Abramovna Ioffe. His father was a merchant of the second guild and later worked in a private business; his mother managed the hospitable Ioffe house and raised the children: Abram Fedorovich, the eldest, had three sisters and brothers. Several letters from R. A. Ioffe to her son, relating to the student years of Abram Fedorovich—affectionate testimony to the love of a mother forever worrying about her first son—have survived.

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Abram Fedorovich began to attend the Romny modern school—a two-story stone building (there was no boy's grammar school in town) in 1888. S. P. Timoshenko, sitting next to Ioffe, was among the 32 students in his class. It is a rare occurence when two eminent scientists come from among the students of the same class in a provincial school.[1)] Timoshenko recalls that Ioffe—the boy—"was a good student and usually did not participate in the noisy games of his classmates."[1] The fragmentary stories of Abram Fedorovich do not closely correspond to this picture. Timoshenko recalls that in the 6th (last) grade Ioffe fell ill and, due to the illness, fell behind an entire year. The reason for this was that in the spring of 1895 the young scholar, as a result of a bet, swam four times across the Sukhoĭ Romen stream, which was cold at that time of the year—an action that contradicts the characteristics described by Timoshenko! Abram Fedorovich described to Ya. I. Frenkel' in the early years following the war that after more than one month's illness the doctor that carefully examined him voiced the suspicion that the young man had contracted tuberculosis in his lungs. When asked how he reacted to this news, Abram Fedorovich answered, smiling: "I went down to the stream and had a swim!"

With the exception of the physicist Mileev and the mathematician Izhitskiĭ, Abram Fedorovich regarded his teachers with more than skepticism. "All teaching in our time was formal: it was necessary to know, not to understand. And yet the school did not do the harm, that could be expected, it could not prevent the students from learning how to think" (Ref. 2, p. 23). One of the motivations for a deeper, informal mastering of knowledge was, together with natural inquisitiveness, the desire to spite the bureaucrat-teachers by reading precisely those books that they did not recommend and so on.

And, indeed, this desire was so strong that many of the students in the Romny modern school graduated successfully and entered the post-secondary institutions in the capital. In St. Petersburg there was even formed a society of Romny students, which Abram Fedorovich headed for a while as a student at the Technological Institute.

A. F. Ioffe recollected that even during the school years two problems, among others, had attracted his attention for a long time: the nature of the luminiferous ether and the mechanism for perceiving smells. Gases, liquids, and solids appeared as objects in which sound waves were excited and propagated, but this capability of material media was not used at all for discovering the richness and variety of their properties. For this reason, young Ioffe had a difficult time accepting the fact that space was filled with some substance that existed only in order to transmit light waves without manifesting itself in any other way. The role ascribed to the ether was reduced to, in Ioffe's words, "to languish in inaction" until an electromagnetic signal would arrive at a given point and then be transmitted further. The physics instructor at the Romny modern school could not give a satisfactory answer to the qeustions that worried Ioffe. We have no direct evidence as to how Abram Fedorovich accepted and how rapidly he assimilated the ideas of the theory of relativity, which eliminated the concept of the ether, but we can assume that his own thoughts about this substance and about the propagation of light laid the ground work for rapid assimilation of the basic assertions of Einstein's revolutionary theory.

The other question that excited Ioffe's youthful imagination was related to the nature of smells. Ioffe supposed that the ability to perceive a wide spectrum of smells was related to the interaction of the centers of the sense of smell with infrared radiation which, in his opinion, originated from molecules of aromatic substances. This point of view was supported by the experiments of Tyndall, about which Abram Fedorovich read in a book of popular lectures by the English physicist on the nature of heat and cold and which ran into several editions in Russia in the years before the revolution.[2)] In this book, Tyndall wrote about the fact that the presence in air of substances emitted by various grasses with aromatic smells characteristic of them is related to absorption of infrared radiation. From here, it is natural to assume that the nerves associated with the sense of smell are sensitive to this region of the spectrum of electromagnetic radiation, just as the retina of the eye is sensitive to the visible part of the spectrum. Ioffe, remembering that plates of rock salt are transparent to infrared radiation (a fact which was used repeatedly by Tyndall in his experimental demonstrations), performed the following simple experiment. He placed different aromatic substances in a tin can used for cocoa. He cut an opening in the top of the can, covering the opening with a thin plate of rock salt. However, the plate constituted an insurmountable obstacle to the aromatic agent and Ioffe had to discard the explanation!

It is worth noting here, however, that Abram Fedorovich's ideas are to some extent related to those developed by G. Dyson about twenty years ago. According to the vibrational theory of smells proposed by this scientist, the sense of smell arises as a result of the absorption of the molecular vibrations of aromatic substances and, in addition, these vibrations arise as a result of collisions between molecules of such substances and air molecules (in the nasal cavity). R. H. Wright, an eminent specialist on the physics of smells, begins his book on the subject with the following spirit-

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[1)] Stepan Prokof'evich Timoshenko was an outstanding scientist and specialist in the area of theoretical mechanics, theory of elasticity, and the theory of oscillations. His books are widely used throughout the world and have been repeatedly published and republished in the USSR. Since the 1910's, S. P. Timoshenko has lived abroad and is a foreign member of the Academy of Sciences of the USSR. He visited the Soviet Union twice since the war and met with A. F. Ioffe.

[2)] Another book, which A. F. Ioffe studied carefully in connection with these problems, was a handbook on obtaining a aromatic compounds from plants and their subsequent use for the production of cosmetic products, written by the English perfumer George William Piece. This handbook, published in London, was later translated into French.

ed phrase: "I will try to tell something of the fascination and the importance of the so-far unsolved mystery of smell, because it is a problem that has held my interest for a long time and because I think it is one of the most neglected fields of scientific enquiry."[3] As we can see, the interest of the young A. F. Ioffe in this field was not naive, however naive his ideas.

At the Technological Institute, Ioffe's interest in the questions of biophysics led to the fact that he enthusiastically began conducting studies on the effect of ultraviolet light on typhus bacteria. Another problem that attracted Abram Fedorovich's attention reduced to the study of the effect of small doses of certain poisons, for example strychnine, on yeast bacteria (Ioffe started the latter work as a result of a course he took in microbiology, which was in the program of students of the Technological Institute and had a direct bearing on brewing technology). The work begun by Abram Fedorovich was interrupted by a student strike and it was impossible to renew the work once the strike was over: the bacteria cultures that he grew perished. However, his taste in biophysical studies and interest in them remained forever. His thoughts on the nature of smells, judging from the later recollections of Ioffe, according to his correspondence with Ehrenfest, became a symbol of purely scientific studies, free of the organizational work freely accepted by Abram Fedorovich, but nevertheless a heavy burden. Even in his own immediate work at the Physicotechnical Institute, A. F. Ioffe remained faithful to his longstanding interests: here, at the beginning of the 1930's, biophysical research was conducted by G. M. Frank (later an Academician and director of the Institute of Biophysics of the Academy of Sciences of the USSR). It would not be an exaggeration to say that Ioffe's organizational work, leading approximately at the same time to the appearance of agrophysics as an independent area of science, originated not only in urgent economic problems but also in his longstanding striving to use physics with its aresenal of ideas and methods to understand the processes that occur in the organic world and for progress in biology.

3. A. F. Ioffe graduated from the Technological Institute with the title of engineer-technologist. However, engineering work in itself did not attract him, although at the time that he undertook practical work as a student during the summers of 1899 and 1900, he worked at it very intensively: on the construction of the railroad bridge on the Poltava–Rostov line (i.e., not far from his birthplace) and the construction of shops in the Izhorskiĭ factory in St. Petersburg. Direct acquaintance with the prevalent order in factories in those days and the attitude toward workers, which the young man strived in vain to improve as much as possible, made a strong impression on A. F. Ioffe. When, in 1901, the question of summer work on the construction of bridges came up, this time on the Siberian railroad, the young Ioffe agreed to direct this work on the condition that the administration would not interfere in his relationships with the workers and in the organizational work as a whole. This offer was turned down. Recalling his mental state at the time that he graduated from the Technological Institute (June 1902), Ioffe wrote: "The clash with the realities of working class politics in Russian factories and the obvious hopelessness of overcoming them as an engineer working in a factory finalized my decision not to pursue engineering work. It was impossible to study science in a university.... The only thing that remained was to study experimental work and particularly in the field in which such work was best developed, i.e., in physics.... In the opinion of physicists in St. Petersburg, the best experimental physicist was Roentgen, a professor at the University in Munich. So, I went to him. I had the means to live modestly for half a year" (Ref. 2, p. 234).

Ioffe went to Roentgen having enlisted the support of St. Petersburg professors N. A. Gezekhus and N. G. Egorov and their distinctive letters of recommendation: reprints of their articles with dedicatory inscriptions to the famous German physicist. As far as economic support was concerned, Abram Fedorovich obtained support from his (maternal) aunt, Sof'ya Abramovna Sheftel'. S. A. Sheftel', an unusually intelligent and kind woman, played a very big role in A. F. Ioffe's life and he stressed this time and again. It is worth noting that in 1920, she published in France a book concerning the position of women, culture, and education in the USA. The famous French writer Pierre Mille greatly praised the book in his preface to it.[3)]

Ioffe worked with Roentgen for four years, first as a student engaged in practical work, while supporting himself, and then as an assistant. In 1906, Roentgen proposed to Abram Fedorovich that he remain in Munich to work on his team. Ioffe declined this flattering proposition and returned to Russia in August, 1906. However, he kept up his friendly relationship with Roentgen and he continued to work every year for several weeks during the summer in the Physics Institute at the University of Munich.

4. In St. Petersburg, A. F. Ioffe began to work in the Polytechnical Institute, which was run by the more progressive (in comparison with the Ministry of Education) Ministry of Finances. At that time, a strong faculty gathered at the Institute; A. F. Ioffe developed both personal and professional relationships with some of them. During the early years, Ioffe was a laboratory assistant and later, after defending his master's dissertation (1913), he became an extraordinary professor, and in 1915 (after defending his doctor's dissertation concerning research on the mechanical and electrical properties of quartz, he became an ordinary professor on the general physics faculty, which was headed by professor Vladimir Vladimirovich Skobel'tsyn.

The scientific results obtained by Ioffe during this period of his life are described in Secs. 6–9. We note three important events in Abram Fedorovich's life that occurred in the years preceding the Revolution.

[3)] A copy of the book inscribed as a gift to Abram Fedorivich has remained in his library. S. A. Sheftel' had the degree of a Doctor of Social Studies from Brussels University and was a professor at the University in Northampton (USA).

The first relates to his personal life: in 1908, he married Vera Andreevna Kravtsova, who later worked in the library of the Physicotechnical Institute (their daughter, Valentina Abramovna Ioffe, now a Doctor of Physicomathematical Sciences, for many years directed the Institute's Laboratory of Silicate Chemistry of the Academy of Sciences of the USSR, where she is now a senior scientist. The second important event, also largely personal in nature, was his making the acquaintance in 1907 of P. S. Ehrenfest, a Viennese physicist and student of Boltzmann. Having married Tat'yana Alekseevna Afanas'eva, a Russian mathematician, Ehrenfest arrived together with her in 1907 in St. Petersburg, where he met A. F. Ioffe almost immediately, and once having met him, he made friends with him for life. It is said that Ehrenfest was Ioffe's closest friend. Both physicists, having the same age, strongly and beneficially affected each other. The published correspondence between them[4] and the article written by Abram Fedorovich in memory of his friend, who died prematurely (in 1933), clearly reveal their relationship (Refs. 2, p. 219; 5, p. 86).

Ioffe became one of the most active participants of the Ehrenfest seminar, which regularly convened in St. Petersburg in 1907–1912 and which played a large role in the development of physics during the ten years preceding the Revolution.

Finally, the third event was the organization in the spring of 1916, this time under the direction of A. F. Ioffe, of a seminar on the new physics at the Polytechnical Institute. The participants of the seminar were young physicists at the Polytechnical Institute and the University, who quickly became Ioffe's closest companions in organizing the Physicotechnical Institute and in developing Soviet physics as a whole. The most active members of the seminar were, aside from Abram Fedorovich, Ya. G. Dorfman, P. L. Kapitsa, P. I. Lukirskiĭ, N. N. Semenov, and Ya. I. Frenkel', names which are widely known in our country and abroad. These people, as well as N. I. Dobronravov, M. V. Milovidova-Kirpicheva, K. F. Nesturkh, and Ya. R. Shmidt-Chernysheva, became the first staff members of the Physicotechnical Division of the State X-ray and Radiological Institute.

5. The long collaboration and personal contacts with W. Roentgen had an extremely strong influence on Abram Fedorovich's work, performed during the first two decades of this century. It was in Roentgen's laboratory, in those several tens of standard student laboratory experiments that he performed, and then in the first independent investigations, that A. F. Ioffe assimilated the basic principles of fruitful experimental work: the choice and statement of an interesting and important problem, care and attention toward details (in particular, toward the precision of the measurements performed) in its solution. The basic direction of A. F. Ioffe's work became the study of the mechanical, electrical, and photoelectric properties of solids.

At the same time, as justly noted, "it is difficult to imagine a sharper contrast than the contrast between the purely phenomenological attitude of Roentgen and the attitude of his new young colleague—A. F. Ioffe, for whom facts were of interest only in connection with theory that allowed understanding them, i. e., reduction to a single harmonious scheme, even one that did not correspond to old schemes and principles" (Ref. 6, p. 5).

Scrupulous accuracy and thoroughness, a certain unhurried attitude in performing the work, Roentgen's characteristic of never hurrying to publish his work, all led to the fact that some of the research carried out by A. F. Ioffe in Munich, in part together with W. Roentgen, was never published.

An example of such work, which never saw the light of day, that Ioffe later recalled more than once relates to a precision method that he proposed for measuring a quantity of heat continuously liberated by a sample of radium (in Roentgen's laboratory there was a little more than 60 mg of radium, an enormous quantity by the standards of the time). The "generation" of heat by radium was established by Pierre Curie and interested Roentgen. The German scientist, on the one hand, had difficulty in accepting the existence of such an unusual, in terms of the science known to him, phenomenon, but, on the other hand, he considered Pierre Curie one of the best experimentalists. The work of A. F. Ioffe, to whom Roentgen assigned the problem of repeating the research on this effect, verified Curie's results. However, Ioffe's work contained a certain technical touch in the spirit of the classical experimental methods of the end of the last and the beginning of the present centuries. A granule of radium was placed in a test tube with oil; an electrically heated coil was placed in an identical test tube. The equality of the intensity of both heat sources was established with the help of a thermocouple—a precise differential method. It seems that if this work had been published it could have established A. F. Ioffe among the pioneers who studied the phenomenon of radioactivity.

Consideration of the reason for the continuous generation of energy (unwittingly associated by physicists of those days with the notion of perpetual motion) at first led Pierre Curie to the idea that radium replenishes the energy that it loses by absorption from some external source. A. F. Ioffe proposed that such a source could be small oscillations in the earth's magnetic field, which could cause such an effect if radium were a "superferromagnet," i. e., a substance with an unusually high magnetic susceptibility. A simple check of the magnetic properties of radium rejected this exotic proposal. However, in doing this work, A. F. Ioffe discovered the effect of focusing of β-rays by a magnetic field: an important experimental discovery that had far reaching consequences in the following years. But this work also was never published.

If Wilhelm Roentgen was the direct teacher of A. F. Ioffe, then Pierre Curie must be considered as an indirect teacher. Abram Fedorovich wrote more than once of the influence that the French scientist's research had on his own work and scientific interests. For all its significance, the example just given is still more incidental than not. Much more important was

Pierre Curie's influence on A. F. Ioffe's work concerning the mechanical and electrical properties of crystals. The classical research of P. Curie (conducted together with his brother, Jacques Curie), leading to the discovery of piezoelectricity, was mostly carried out using quartz crystals. While carrying out this work, the new effect of piezoelectricity was used by Curie as an instrument for precision measurements. When Roentgen suggested to Ioffe the detailed study of the reasons for the electrification of quartz, Ioffe, naturally, immediately encountered Curie's work. This is how Abram Fedorovich recalled the incident in 1956: "It was suggested to me that I should determine which is the cause of the elastic aftereffect—strain or the voltage giving rise to the strain. It seemed that it should be possible to separate these effects with the help of a (piezoelectric) quartz crystal. The voltage determined by the suspended load, remains unchanged; if the strain continues to increase, then it will create an additional charge on the electrodes. In the course of this research, the elastic aftereffect accompanying the bending of a Curie plate was observed. I ascribed it to piezoelectric charge, which in this case fills the entire volume of the crystal. In order to eliminate in this case the appearance of charges on bending, it was necessary to cut out the plate in a different crystallographic direction.

I wrote to Pierre Curie about this and asked him to put in a shop order for such a plate, if he considered my ideas to be correct. I quickly received an answer supporting my ideas, followed by the plate itself, with the help of which I established the absence of a true elastic aftereffect in quartz." (Ref. 2, p. 214).

The excerpts presented above present in an extremely condensed form the results of the difficult studies begun by A. F. Ioffe in Munich and continued by him and his students over a long period of time in the 1910's in St. Petersburg. It should be noted that many outstanding physicists of the last century, including Boltzmann, Helmholtz, and Maxwell, studied the experimental and theoretical problems of the elastic aftereffect.[4)] Maxwell ascribed the elastic aftereffect to inhomogeneity of the tested materials and rearrangement of their structures caused by the load. This suggested the idea of using a perfect single crystal, for which quartz was chosen in Munich, to check the existing hypotheses.

At first, it appeared that an aftereffect was observed even in quartz. However, A. F. Ioffe showed that this effect was caused by specific piezoelectric properties of quartz and is determined by the charges that appear on the quartz surface as a result of the load. In order to eliminate their influence, i.e., to discharge the quartz capacitor, A. F. Ioffe exposed the crystal being studied to penetrating radiation: radium rays, x-rays, and ultraviolet light.

Thus, with his work on the aftereffect phenomenon, Ioffe not only clarified the question that remained unanswered, but he also cleared the path for two of the most important directions for future research: the study of the mechanical properties of real solids and their electrical properties, above all the study of the effect of radiation on electrical conductivity. It is well known that both these directions played and continue to play an exceptionally prominent role in science and technology.

6. Abram Fedorovich liked to recall the fact that Roentgen at first refused to believe in the sharp increase in the electrical conductivity of pre-irradiated samples as a result of the action of radiation. The old and eminent scholar wavered in his conviction after Ioffe, working in one of the rooms in Roentgen's laboratory, showed him how sharply the magnitude of the current passing through the system changes under the action of variable illumination (for example, shading of sunlight by clouds) and how sharply it increased if the sample were illuminated by light from an ordinary match. Commenting on this work, Ya. I. Frenkel' wrote in 1948 that to A. F. Ioffe "belongs the honor of discovering the internal photoeffect in crystals exposed to x-ray radiation, as well as the entire complex of phenomena related to this effect, in particular, the phenomenon of coloration of crystals, the absorption spectra for light in these crystals, the transition of *F*-centers into *U*-centers and vice versa.

These phenomena were rediscovered and studied in detail twelve years later by R. Pohl and his school in Goettingen; the related publications began to appear only in 1919–1920, while the publication of A. F. Ioffe's pioneering work was delayed until 1922. "This entirely unjustifiable delay of many years in the publication of the wonderful work of A. F. Ioffe concerning the electrical and photoelectrical properties of dielectric crystals is"—Ya. I. Frenkel' summarized—"in my opinion, a serious retarding force in the history of the development of Russian physics." (Ref. 6, p. 8).

Together with his own research on the internal photoeffect, A. F. Ioffe, in the course of the subsequent development of these studies, as well as being stimulated by the classical work of Planck and Einstein that was being conducted under his own eyes, at first became interested and then immediately set about studying the properties of the classical (external) photoeffect and of radiation. Here, it should be recalled that the work of the German physicists mentioned above was not immediately widely accepted in scientific circles. This makes A. F. Ioffe's active interest in this work particularly revealing. In one of his first articles, he carefully analyzed and criticized the research of E. Landenburg "Initial velocity and quantity of photoelectrons."[7] The related published work of Ioffe appeared simultaneously in German,[8] as well as in the pages of the Zh. Russ. Fiz-Khim. 06. (Ch. Fiz.) [Journal of the Russian Physico-Chemical Society (Physics Section)].[9,5)] This article, the first written in Russian

[4)] The phenomenon of elastic aftereffect consists of an increment in elastic strains that appears with a constant load acting on a sample. The gradual return of the sample to its initial state after the load is removed is called reverse elastic aftereffect.

[5)] A. F. Ioffe's first published work appeared in 1906. This was his dissertation, published in German, for the doctoral degree at the University of Munich. Part of this work was published in Annalen der Physik in the same year.[10]

by A. F. Ioffe, is notable also for the fact that Einstein's name was mentioned in it, perhaps, for the first time in our physics literature; this article was, in general, the first one to bring attention in Russia to Einstein's work on the theory of radiant energy and the photoeffect. Ioffe's article begins with a concise review of these theories, following which the author examines the experimental data on the photoeffect obtained by Ladenburg in the same year of 1907. Having analyzed these data in the spirit of the basic assumptions of Einstein's theory of the photoeffect, A. F. Ioffe showed that they completely support this theory, although, as Ioffe writes, Ladenburg "has the opposite point of view; he considers the separation of electrons to be a result of a resonance with the oscillations of the light and in order to explain the results obtained he resorts to arbitrary and unlikely hypotheses. The author makes no mention of the correspondence of his observations with Einstein's predictions."[9]

7. It was already noted that Ioffe's years of study with Roentgen and his active scientific work (at first in Munich and then in St. Petersburg) coincided with the revolution in physics: the discovery of radioactivity and the appearance of the quantum theory of radiation. These same years also saw the final experimental proof of the discrete nature (graininess as it was called then) of electricity. The work carried out along these lines connected mainly with the names of English physicists: J. J. Thompson, G. Wilson, I. Townsend, and others, it would seem, was finally brought to a conclusion by the famous work of the Americal physicist R. Millikan, begun in the spring of 1909 (and continued in the following years). However, it is well known that soon after the publication of the basic results of his studies the work of the Austrian physicist F. Ehrenhaft, a student of L. Boltzmann, was published in which doubt was expressed in Millikan's data and the existence of subelectrons with fractional electronic charge was proved, (the value of the fractional charge in some cases constituted 1/200 of the unit charge measured by Millikan). A. F. Ioffe participated in the extended argument between Millikan and Ehrenhaft. On March 8, 1911, Ioffe presented a paper in St. Petersburg at the meeting of the Russian Physico-Chemical Society in which he analyzed Ehrenhaft's experiments and proposed an hypothesis which, in his opinion, explained the results of the Austrian physicist and simultaneously preserved all of Millikan's conclusions. Ioffe proposed that the ultramicroscopic, i.e., very tiny, particles (drops) moving in the capacitor are affected by charged and even smaller (submicroscopic) particles which are invisible to the ultramicroscope through which the Austrian researcher carried out his observations.

Somewhat later A. F. Ioffe decided to reproduce—with some constructive changes and improvements—the now well-known experiments of Millikan and Ehrenhaft. He was not alone in this intention: thus, in the fall of 1912, a series of similar control experiments were being prepared by the Goettingen physicist R. Pohl (Ref. 4, p. 92). The problem of the discrete nature of the electron and the measurement of its charge had not been removed from the agenda of the day, so that Abram Fedorovich's efforts can by no means be considered as being too late.

Unfortunately, we do not have the information that would allow making a clear judgment of Ioffe's motives in carrying out such precise experimental research, made all the more difficult by the fact that in Russia at that time laboratories were extremely poorly equipped. It is worth noting that the leadership of the physico-mathematical department of the St. Petersburg University tried to instill in every conceivable way the then traditional departmental rule of choosing the subject for the research of young physicists based on the idea of reproducing the best scientific work carried out abroad. Khvol'son, in conversation with Ioffe, called this tradition "wonderful."[5] It may be that as a result of the necessity of defending his *Master's dissertation* (1913), Ioffe suggested carrying out the series of studies for measuring the charge of the electron, not so much to follow the tradition mentioned above, but rather due to his desire to improve on Millikan's technique, as well as to check experimentally his own ideas concerning the statistical properties of radiation.

Establishing at the outset of his dissertation the intention of his work, A. F. Ioffe especially emphasized that the Maxwell-Lorentz electro-dynamics has been brilliantly verified by the effects connected with macroscopic bodies and the phenomena that occur in them (electrical conductivity, magnetic field generated by electrical currents, optics, and so on), while the "attempts to discover the same properties for free electricity led to negative results." (Ref. 11, p. 27). Ioffe saw his problem in terms of generalizing the "idea of the elementary electrical charge and the magnetic field of moving electricity to free electricity, arising in the photoelectric effect and in cathode rays." (Ref. 22, p. 27).

At the same time in Millikan's experiments, to which Ioffe referred as classical already in 1913, the problem was not to measure the "free electricity" (i.e., the charge of the electron itself), but rather to measure the electricity connected with atoms, i.e., ions. Indeed, Millikan observed in his experimental setup the change in the charge of drops (small particles) arising from ions in the surrounding atmosphere, which is subjected to the action of an ionizer, that stick to the drops. During the course of his work, working with elementary photoelectronic emission events, Ioffe hoped to clarify the extent to which conclusions concerning the charge of ions can be transferred to the charge of electrons. At the same time, he wanted to show that this event is "elementary and not only from the point of view of radiant energy." (Ref. 11, p. 28).

Of great significance was A. F. Ioffe's improvement in technique, whereby the position of the zinc particles that he was observing was fixed (by altering the intensity of the field in the capacitor) making it stationary, while Millikan measured the speed of the particles before and after the charges on them changed (attachment of ions) and then used Stokes' formula for calculating the charge. As is well known, the latter procedure, in spite of the improvements in accuracy introduced in it by Millikan and Cunningham, remained approximate.

We recall that the conditions for balancing a particle with mass M and charge e has the following simple form in the field of a capacitor:

$$e\frac{V}{d}=Mg.$$

Here, V is the potential difference, d is the distance between the capacitor plates, and g is the acceleration due to gravity. The change in e as a result of the emission of photoelectrons under the action of ultraviolet light was compensated by a corresponding change in V, so that the following series of equalities was satisfied:

$$e_1V_1=e_2V_2=e_3V_3=\ldots,$$

from whence arose the extremely simple—null, as it was called by A. F. Ioffe—method for determining the change in the charge, which always turned out to be a multiple of the elementary charge determined by Millikan. We note that the precision attained by Ioffe in his apparatus permitted detection of the loss of a single electron by the particle. The absolute magnitude of the charge was measured by determining the speed at which the particles, the density of which was firmly established, fell and verified Millikan's results. The method for obtaining the small particles used in the experiment corresponded to that proposed by Ehrenhaft.

8. It would not be incorrect to assert that A. F. Ioffe considered the study of the nature of the photoeffect as the main part of his Master's work. It was not without reason that his closest friend, P. S. Ehrenfest, referred in his letters to this period in Abram Fedorovish's work as the "photoMillikan" period (Ref. 4, p. 128). A. F. Ioffe indicated in his doctoral dissertation that soon after the discovery of the photoeffect, in particular, in the work of the St. Petersburg physicist I. I. Borgman and the Moscow physicist A. G. Stoletov, the delay between the instant that the samples were irradiated with light and the instant that the photocurrent appeared was carefully studied. Since, as Ioffe's own experiments on the measurement of the electronic charge clearly showed, the photocurrent is made up of individual electrons, it is evident that if the source of light in the experiments becomes very weak, the time intervals between the emission of photoelectrons from the irradiated sample (rest periods) must noticeably increase. Having this idea in mind and as a result of carefully performed experiments, A. F. Ioffe uniquely proved that the photoeffect is, in essence, a statistical phenomenon. The statistical nature of the effect is concealed in the case of macroscopic values of the photocurrent. In the case of elementary electronic emission events, observed with constant values of the intensity and other characteristics of the illuminating radiation, as well as the mass of the particles and the medium in which they are located,[6)] it is manifested especially clearly and the magnitude of the delay varied from immeasurably small time intervals to many minutes.

It is the statistical nature of the radiation in particular that follows from Einstein's theory of radiation, based on the concept of light quanta (the atomistic theory of light, as A. F. Ioffe called it).[7)] It is worth recalling that the quantum or discrete nature of radiation was already established by Planck in 1900. However, later, in 1911–1912, the German scientist attempted, even though only partially, to eliminate this discrete description by developing a theory according to which the electron continuously (and not as a result of an elementary, sudden event) accumulates energy from a source of radiation of frequency ν, emitting it only at the instant when the accumulated energy equals the amount $h\nu$. Planck's ideas were used to explain the delay mentioned above.

Soon after A. F. Ioffe's work on the elementary photoeffect was published in Germany in 1912,[12] Sommerfeld sent him his calculations concerning the statistics of the emission of photoelectrons, which supported well the experimental data. Recalling this letter, Ioffe adds: "And from Millikan, I received a very long letter, in which, together with greetings and congratulations, he expressed his dismay at not having been the first to use the technique of balancing a particle in an electric field." (Ref. 5, p. 109).[8)]

Abram Fedorovich kept P. S. Ehrenfest informed about all his work. The correspondence between the two physicists attests to the attention with which Ehrenfest followed this research. His letter to A. F. Ioffe on January 6, 1913 is indicative in this respect. Apparently, having obtained the text of Ioffe's dissertation, Ehrenfest wrote to him from Leiden: "Your photo Millikan work is excellent. I request that you immediately send me a short preliminary report for the Amsterdam Academy. Lorentz is already very interested in the totality of your previous work. . . . It is very probable that this work is being discussed now in Berlin (Pohl!). You should immediately establish your priority. And I request that you do so in the Amsterdam Academy, and not in Munich. I must receive your manuscript by January 23rd, the 24th at the latest, so that Lorentz can present it to the Academy on January 25th. For this, you must mail your manuscript by January 16th or 17th. In the manuscript you should only report that as a result of the photoelectric effect you were able to remove electrons one after another

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[6)]In Millikan's early experiments, an important source of errors was the loss of weight due to evaporation of oil drops with which he was experimenting. The zinc particles with which A. F. Ioffe worked not only had maximum photosensitivity to ultra-violet light, but they were also characterized by a constant mass.

[7)]*It is interesting to note that the well-known experiments of* S. I. Vavilov on quantum fluctuations of light are undoubtedly related to A. F. Ioffe's work discussed above as well as to his important experiment (together with N. I. Dobronravov) on fluctuations in x-ray radiation, carried out in 1925.

[8)]Unfortunately, part of the letters that A. F. Ioffe received before the war was lost during the siege of Leningrad. Abram Fedorovich took the letters from Ehrenfest and Roentgen with him when he evacuated to Kazan.

from unoxidized spherules, that the limiting value of the potential approximately equals such a value that you could maintain the spherules at rest and that the main points of your technique are:

1) discrimination of elementary events of photoelectric processes, as a result of which the disputed questions can now be studied more precisely and in greater depth;

2) the possibility of measuring extremely small forces—and that's all." (Ref. 4, pp. 111–112).

It would seem that these exhortations led to the German publication of Ioffe's results as mentioned above, eliciting the interest of Sommerfeld and Millikan and establishing Ioffe's priority for the work to which Millikan later directly referred. As far as the account to be sent to the Amsterdam Academy is concerned, apparently, A. F. Ioffe never wrote it on time.

9. Before describing the second part of A. F. Ioffe's Master's dissertation, we note that he used the technique developed in the first part of the dissertation, with some modifications, a decade later in his work with N. I. Dobronravov.[13] At that time (1923–1924), Compton's experiments on the scattering of x-rays, later named after him, were being actively discussed. The experiments demonstrated the validity of Einstein's conception of photons (sharply directed emission) and, thereby, rejected Planck's second hypothesis (1911) concerning the quantum oscillators that emit energy discontinuously as quanta but absorb energy continuously. However, doubts were expressed in the correctness of Compton's experiments. In the work carried out by Ioffe and Dobronravov,[13] a miniature (8 mm diameter) x-ray tube was placed inside a capacitor. The metallic point, serving as a cathode, was irradiated by ultraviolet light from an arc, which knocked out an electron from the point approximately 1000 times per second. Accelerated in the field of the x-ray tube, this electron caused a burst of x-rays at the anode, which in their turn acted on a bismuth particle suspended in the field of the capacitor. The bismuth particle periodically lost its equilibrium at times corresponding to the emission of a photoelectron from it. Measurement of its energy together with the fixed frequency of the process in the experiments (the loss of equilibrium occurred approximately once every two hours) uniquely confirmed the validity of the corpuscular representation of light quanta.

It is interesting to note that almost six decades after the experiments of Millikan, Ehrenhaft, and Ioffe became a part of the history of physics, they were again turned to in attempts to prove experimentally the existence of quarks with fractional charge. These attempts, however, did not lead to the results sought after (see, for example, Ref. 14).

Let us return to Ioffe's Master's dissertation. This dissertation included another independent part: an investigation of the magnetic field of cathode rays. In the introduction to this part, A. F. Ioffe masterfully and thoroughly expounds on the past history of these studies, which at the time extended over three decades. In the 1880's, the nature of cathode rays was actively discussed. H. Hertz rejected, on the basis of his experiments, their corpuscular nature, assuming that in this case a pure wave process, with which the existence of the deflecting magnetic field is connected, takes place. The subsequent work of Perrin, Thompson, and others refuted Hertz's first assertion and cathode rays began to be examined as a flux of electrons. Under such conditions, the idea concerning the existence of a magnetic field around them, similar to the magnetic field of a convection current, did not evoke any particular doubts. At the same time, the attempts made to detect this field with direct experiments were unsuccessful for many years. Having analyzed the reasons for this, A. F. Ioffe in his work constructed an apparatus in which it was possible to measure directly the deflection of magnets placed above a discharge tube due to the effect of the cathode rays created in it. By rotating, the magnet caused a mirror suspended on a thread to turn, thereby causing a deflection of a light beam incident on the mirror. Calibrating the device with the help of an ordinary current-carrying conductor replacing the discharge tube, Ioffe uniquely, and by direct experiment, established the existence of a magnetic field created by cathode rays, the value of which turned out to correspond well (within the limits of the accuracy of the method, which comprised several percent) with his computed values.

On May 9, 1913, L. S. Termen, Ioffe's future collaborator and at the time a very young man, attended, among others, the defense of Ioffe's Master's thesis in the physics auditorium at St. Petersburg University. In his recollections of Abram Fedorovich, he shared his impressions of this event, which he remembered so clearly: "A tall young man approached the blackboard and with a soft voice and an easy smile began to explain the essence of the photoelectric effect, the emitted electrons, and the experimental setup for actually observing these phenomena." (Ref. 15, p. 109). L. S. Termen was especially impressed by the fact that Abram Fedorovich talked about these subjects, which in those days were associated in people's minds with complex mathematical formulas and symbols, as if they were observable, common and immediately understandable objects. L. S. Termen wrote: "He demonstrated with his hands how they collided or were absorbed, move about in space, and change their trajectory. All the while, his gestures were very characteristic, just as soft as his voice and the construction of his sentences."

10. We will conclude our review of A. F. Ioffe's pre-revolutionary work by examining his research (together with M. V. Kirpicheva) on the electrical conductivity of crystals, performed in 1916.[16] By that time, it had already been demonstrated by Warburg that in ionic crystals with their close-packed lattice, there is a motion of ions and that the passage of current is accompanied by electrolysis. However, there was no clear determination of which particular ions take part in the process of electrical conductivity. It was only established that in certain samples, so-called natural, i.e., unpurified ionic crystals, the electrical conducti-

vity varies over two orders of magnitude. Ioffe's work stated and solved the problem of which particular ions—foreign (impurity) ions or ions that belong naturally to the crystal—take part at all stages of this process. Using the method of electrolytic purification, i. e., repeated passage of a constant current through the crystal, the researchers obtained pure crystal samples (ammonium and potassium alum, copper sulfate). If the modern terminology of semiconductor physics is used, then Ioffe and Kirpicheva separated out the impurity and intrinsic (ionic) conductivity. It is these particular perfect crystals that turned out to be the objects permitting a determination of the true mobility of ions, since in electrolytic solutions (or in gases) ions are surrounded by a quite dense atmosphere of dipole molecules. Using such perfect crystals (just as before, as in the case of quartz), it was demonstrated that the magnitude of the current as a function of the applied voltage follows Ohm's law (corrected for the electromotive force due to polarization).

What then is the reason for the appearance of intrinsic ionic conductivity? A. F. Ioffe correctly views it as originating in the phenomenon of thermal dissociation of the lattice (as well as dissociation under the action of external radiation): the ions contributing to the conductivity are those ions in the lattice that "due to the random nature of thermal motion or as a result of a weak position in the crystal lattice, are instantaneously completely removed from equilibrium." (Ref. 16, p. 129). At the same time, it was shown experimentally that the electrical conductivity depends exponentially on the (inverse) temperature. As far as the behavior of the dissociated ions is concerned, it is no longer determined, according to Ioffe, by the intrinsic electric field in the crystal, but is controlled by the external field (inasmuch as it is applied to the crystal). Thus, in this work, generically related to Abram Fedorovich's earlier research, carried out by him in Munich, there are clear indications of the picture of a real crystal (not necessarily ionic) developed later with his so-called internal evaporation of atoms from lattice points into the interstitial space and their subsequent motion in this space—disordered or directed, depending on external conditions.

A. F. Ioffe returned to the general problem of electrical conductivity of crystals once again in a review presentation made at the fourth Solvay Congress in Brussels in April 1924.[17] In this report, he summarized all the results of research on this problem spanning twenty years. Ioffe's report stimulated active discussions, in which the leading physicists of the world took part, including experimentalists (Madame M. Curie, Rutherford, Richardson, von Hevesy), as well as theoreticians (Debye, Langevin, Schrödinger); the report further strengthened Abram Fedorovich's scientific authority.

11. Experimental and theoretical discoveries in physics, made abroad during the nineteenth and twentieth centuries, convincingly showed that this science was destined to play an extraordinary role in the development of technology. There arose the problem of its spreading beyond the seclusion of the university, where the catch word "science for science sake" was traditionally professed and researchers took pride in their isolation from technology and industry. At the same time, it became ever clearer that physics with its new ideas, methods and instrumentation can help progress in closely related fields of knowledge and, in particular, in medicine. In mentioning the latter, we have in mind first of all the discovery of x-rays and radioactivity, the therapeutic and diagnostic capabilities of which were rapidly recognized by scientists.

In Russia, the person who understood this better than others was Professor M. I. Nemenov, who worked in the Women's Medical Institute and in 1913 founded the All-Russia Society of Radiologists. At about the same time, he began to organize the institute in which research on x-rays would be concentrated. However, his initiative ran up against the inaction and indifference characteristic of bureaucrats in czarist Russia. It appeared that the First World War, which had just broken out, completely buried this idea.

The October Revolution radically changed the entire way of life in Russia and, in particular, opened up completely new possibilities for the development of science in the country. This was due to the farsightedness of the head of the Soviet government, Vladimir Il'ich Lenin, and his closest colleagues, particularly Anatoliĭ Vasil'evich Lunacharskiĭ, who headed the People's Commissariat of Education. Thus, it is not surprising that the government did its utmost to support the initiative of the progressive thinking intelligentsia in Russia, directed toward the development of science and technology. In St. Petersburg, M. I. Nemenov, A. F. Ioffe, and D. S. Rozhdestvenskiĭ came forward with such an initiative. M. I. Nemenov turned, during that most difficult year of 1918 for the young Republic, to A. V. Lunacharskii for support for the idea of organizing a new institute and, recalling many years later his meeting with him, was surprised how rapidly he understood the situation and promised to support in every way he could this initiative and to put it into practice. Nemenov considered it useful and necessary to perform, together with the study of the therapeutic action of x-rays and the rays from radium, purely physical research (from his point of view—applied), for the purpose of providing a bridge between the properties of the radiation and its biological effect. Together with this, he intended to organize the production of x-ray apparatus in the country.

At that time, there were two suitable men for managing the realization of these plans in Russia: P. P. Lazarev, a well known physicist, student and successor of P. N. Lebedev (M. I. Nemenov attracted his attention to biophysics—P. P. Lazarev was, essentially, the first Russian physicist who also had a medical education) and Abram Fedorovich Ioffe, who at that time was the greatest specialist on x-rays in the country. P. P. Lazarev's candidacy almost immediately fell away—he was busy with the organization of a new institute in Moscow (the Institute of Physics and Biophysics). A. F. Ioffe responded to M. I. Nemenov's suggestion and took upon himself the development of the plans of the physicotechnical division of the future institute. It was proposed to include at the same time a medico-biological (M. I. Nemenov) and a radiological (L. S. Kolovrat-Chervinskiĭ) division in the organization of the institute.

The present Physicotechnical Institute of the Academy of Sciences of the USSR, named after Abram Fedorovich Ioffe, dates from September 23, 1918. On this day, as the minutes of the meeting of the Small Regional Commission on Education indicate, its meeting was convened at 16 h. 45 min. Among the nine questions on the agenda for the day (solved within half an hour: the meeting adjourned at 17:15) the commission heard also "the report of Comrade Lunacharskii on the State X-Ray and Radiological Institute" and decided: "to assign to Professor Ioffe the development of a plan for the physico-technical and radiological divisions of the State X-Ray and Radiological Institute." [18]

12. Beginning in 1918 and until 1950, when A. F. Ioffe was the director of the Physicotechnical Institute and headed a laboratory in it (the laboratory had different names at different times, depending on the changing subject field), and then in the 1950's, when he at first managed a separate laboratory within the division of physico-mathematical sciences, which was transformed soon after into the Institute of Semiconductors, Ioffe intensively worked in many physical and physicotechnical research areas. We will give a brief overview below of the results that he obtained in the areas of the physics of crystals and the physics of semiconductors.

In the article mentioned above "My Life and My Work," [2] A. F. Ioffe stated four basic problems on which he and his team of students and colleagues worked with the greatest determination and to the solution of which the maximum possible effort was applied. At the top of this list of problems, Ioffe placed the mechanical properties of solids.[9)] Abram Fedorovich remembered how in his years with Roentgen, having worked out the problem that in a perfect (or a nearly perfect) crystal there is no elastic aftereffect and having satisfied himself with this important result, he went on to other research. At the same time, from the point of view of practical applications, it was necessary to carry out research on real engineering materials. Such research, not mentioning its applied significance, is also very interesting from a purely scientific point of view, since the problem at hand encompasses an entire spectrum of effects, inasmuch as the diversity of the properties of real crystals is determined by the deviation from the model of a perfect lattice.

Ioffe turned to the problem of real crystals immediately after the revolution in the Institute that he created. He formulated the idea of the necessity of observing the deformation of the crystal lattice under the action of a load, with the help of x-rays. For this purpose, a special apparatus was constructed for recording Laue diffraction patterns of a crystal; the picture thereby obtained could be recorded not only on a photographic film, but also on a special screen,[10)] fluorescing under the action of x-rays. The change in the position of interference spots, which arise as a result of the reflection of x-rays from the corresponding surfaces, allowed following visually the kinetics of the process of deformation. In doing this work, A. F. Ioffe discovered the so-called phenomenon of "asterism," which consists of the fact that when a particular value of the load is attained (the elastic limit) the spots begin to shift and change their shapes: the spots are stretched into bands and they break up. In appearance, the spots began to look like a primitive image of flowers or stars from which the name of the effect derives. The reason for this change consists in the restructuring of the crystal under the load, and the formation of a polycrystalline structure in it. At the same time, the polycrystals into which the sample is divided rotate relative to each other during the process of deformation, while maintaining the integrity of the loaded crystal.

If the first experiments carried out with crystals of rock salt during the years 1910–1920 (together with M. V. Kirpicheva)[19] provided only a qualitative picture of the phenomenon, then the subsequent research (in which M. A. Levitskaya participated)[20] already was of a quantitative nature, and led to the possibility of estimating the magnitude of the elastic limit and its temperature dependence and to compare the experimental and theoretical values of the strength.[11)] Rock salt was chosen as a sample for study not only because the strength parameters were calculated for the lattice of this particular substance by M. Boron, but also because this crystal was carefully researched in many previous experiments and a great deal of experimental material had been accumulated concerning this substance.

An important result, obtained in the process of these studies by Ioffe, was the experimental fact that the difference between plasticity and brittleness is relative. Ioffe described this as follows: "There are no brittle and soft materials: everything depends on the ratio at given temperatures between the yield stress and the strength." (Ref. 2, p. 249).

At the same time, Ioffe introduced the important idea of the critical fracture temperature. This quantity is found from the intersection of the curves showing the temperature dependence of the yield stress and the fracture strength. The latter is almost constant over a wide range of temperatures, while the former, as we have seen, decreases with increasing temperature. Below the critical temperature, the fracture strength

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[9)] The other problems were: the electrical properties of solid dielectrics; electronic and light quanta; development of new technology (A. F. Ioffe had in mind mainly the energetics and physics of semiconductors).

[10)] Prepared for this purpose by L. S. Termen.

[11)] Essentially, A. F. Ioffe proposed that the elastic limit of a crystal be defined as that value of the stress at which stretching and the general evaluation of Laue spots begin. As the temperature increases, the elastic limit, defined in this manner, decreases and vanishes on melting.

manifests itself, the sample fails, according to Ioffe, without deformation: above this temperature, there is time for viscous flow to begin in the sample, and the strength of the sample increases.[12)] Similar behavior in crystals, first observed for rock salt, but also appearing in many metals, has been named "Ioffe's scheme" and for many years was the starting point for performing static and dynamic tests of materials.

In 1924, P. S. Ehrenfest, who was in Leningrad during August and September of that year, joined A. F. Ioffe's research on the strength and plasticity of crystals. Together with Ehrenfest, Ioffe continued to study the phenomenon of asterism. In experiments with zinc crystals, it was shown that for a given load the displacements have a discontinuous or quantum character, and in addition, the time intervals between two successive displacements remains strictly constant, while their number per unit time increases with increasing load, and, at a high enough load they follow one another so often that the formation of displacements appears as an almost continuous process. Each displacement is accompanied with its own acoustic emission—a ticking, which is reminiscent of the sound of a running clock. This effect, which should be called the Ioffe-Ehrenfest effect, was later studied in detail by M. V. Klassen at the Physicotechnical Institute and was explained theoretically by N. N. Davidenkov (in the 1930's), while in the 1950's–1960's the effect was explained in terms of the dislocation theory in M. V. Klassen's laboratory at the Institute of Crystallography of the Academy of Sciences of the USSR.

Another important result of A. F. Ioffe's research was the conclusion that such formation of displacements is accompanied by a strengthening: the tensile strength for rock salt increases by a factor of ten—twelve, from hundreds of gram(force)/mm^2 to several kilogram(force)/mm^2.

The study of the fracture strength of crystals and the discovery of a sharp difference in its theoretical and technical values constituted a new and important stage in the work of Ioffe and his school on the strength of solids. The disagreement had a catastrophic character—400 gram(force)/mm^2 instead of approximately 200 kg(force)/mm^2!—and, from another point of view, it was so convincingly demonstrated in Ioffe's experiments (as well as by other researchers) that it cast doubt on the validity of Born's theoretical calculations.

A. F. Ioffe, in expanding the research of the English physicist Griffiths, showed that the reason for such a disagreement is related to the presence of macroscopic cracks, the weak spots from which the process of brittle failure begins, on the surface of the tested samples. Ioffe first pointed this out in 1924 (Ref. 20); the complete research was published a year later.[21] Freeing the surface of the tested samples of the cracks on it (by dissolving them), Ioffe and M. A. Levitskaya showed that this is accompanied with a sharp increase in strength, the magnitude of which approaches the theoretical value. Born's reaction to the results obtained in Leningrad is interesting. Born wrote to Ioffe on April 5, 1924 from Goettingen: "The disagreement between the observed strength and the calculated strength on the basis of electrostatic considerations greatly disturbed me; this was the darkest spot in the theory of lattices."[13)] Born gave the highest praise to Ioffe's experiments and considered Ioffe's explanation of the effect completely correct.

Some physicists at first expressed their objections to Ioffe's work (such objections were made by the German scientists Müller and Smekal), but most researchers accepted his explanation of the strengthening effect and confirmed his results, so that it may be asserted that this work quickly received general acceptance, and the strengthening phenomenon itself, due to the removal of cracks normally present on the surface (and defects, arising during the deformation process itself[14)]), was named the Ioffe effect. The description of this vivid phenomenon has entered the textbooks (not only university textbooks, but school books as well!) and now serves as a subject for lecture demonstrations. On the other hand, the development of methods for curing surfaces was further physically and technically advanced and led to the creation of ultrastrong glass (the work of F. F. Vitman and his colleagues at the Physicotechnical Institute, see Ref. 22). The significance of the indicated work of Ioffe consists of the fact that this work first drew the attention of researchers to the influence on the strength properties not only of defects, but also of the physical state of the surface as a whole. Intensive research is now being carried out in this direction.

A. F. Ioffe generalized his work on the problems of the physics of solids in the well known book *The Physics of Crystals*, based on lecture materials presented in 1927 during a long assignment in the USA. The book was published in America and in our country almost simultaneously (1928 and 1929)[23] and received a very satisfactory response.[24,25]

At the beginning of the 1930's, A. F. Ioffe returned to these studies, but now he worked on them more intermittently. Together with S. N. Zhurkov and A. F. Val'ter, he investigated the problem of the tensile strength of thin filaments and foils, and concluded a series of investigations of this problem in 1934 with a report at the International Conference on Physics in London (the related articles were published in the transactions of the conference a year later).[26,27] In the discussion concerning these presentations, the research of A. F. Ioffe and his school earned high praise of his colleagues.

The problems of the physics of strength continued and continue to remain at the center of attention of a large group of students and colleagues of Ioffe, both in the Physicotechnical Institute and in other institutes in our country. In the 1930's A. P. Aleksandrov, S. N. Zhur-

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[12)] A. V. Stepanov showed that brittle fracture is nevertheless preceded by plastic deformation (twinning, creep, and so on), however small.

[13)] Leningrad division of the Archives of the Academy of Sciences of the USSR, collection 910, entry 94.

[14)] This clarification of Ioffe's effect is due to A. V. Stepanov.

kov, and A. V. Stepanov made great contributions to the further development of this work. The research on strength continued during the war when it was applied to problems of defense technology, as well as after the war up to the present day: research on the problems of the strength of materials is traditional for the A. F. Ioffe Physicotechnical Institute. Further work along these lines is being carried out on a new level by S. N. Zhurkov, V. R. Regel', V. A. Stepanov and their colleagues. This work involves, together with crystals, composite materials as well, with the application of the most modern methods for performing this research. The wide research on the static and dynamic strength characteristics of diverse materials has led to the construction of a kinetic theory of strength that is generically related to the pioneering research of Abram Fedorovich, begun sixty years ago.

13. J. Bardeen, one of the most eminent specialists on the physics of solids, stated in a review presented at the International Conference on the Physics of Semiconductors in the summer of 1960 in Prague (this was the last conference in which A. F. Ioffe participated in referring to the history of the development of this field of science, that its "foundations were built by Wilson and Mott in England, Schottky and Wagner in Germany, and by Ioffe and Frenkel' in the Soviet Union."[28]

A. F. Ioffe made, if it can be said, a double contribution to the physics of semiconductors. He was one of the first who saw the possibilities stored by nature in these unique materials. It is at the Physicotechnical Institute and at his initiative that at the beginning of the 1930's the systematic study of their diverse properties and technical applications began. Abram Fedorovich attracted many colleagues at the Physicotechnical Institute to the study of semiconductors, as well as physicists from other cities in the country (A. N. Arsen'eva, B. M. Gokhberg, Yu. A. Dunaev, V. P. Zhuze, B. T. Kolomiets, B. V. Kurchatov, I. V. Kurchatov, Yu. P. Maslakovets, D. N. Nasledov, L. M. Nemenov, V. M. Tuchkevich, P. V. Sharaveskiĭ, and others). A. F. Ioffe himself was involved in studying semiconductors from the moment these studies were initiated at the Physicotechnical Institute to the end of his life, i.e., for three decades, completing a series of important studies, which had a great effect on the development of this entire field as a whole.

To the two indicated aspects of Abram Fedorovich's semiconductor activity, a third not insignificant aspect can be added: he was a passionate propagandist for semiconductors. This incessant work began with the well-known article "Semiconductors—a new material for electrical technology," published in the popular journal "Socialist Reconstruction and Science,"[29] and continued in numerous journals and newspaper articles, with appearances at conferences and meetings, including a speech by A. F. Ioffe at the Plenary Session of the Central Committee of Communist Party of the USSR in June of 1960.[30] We should also add Ioffe's books on the physics of semiconductors. The first of these—*Electronic Semiconductors*[31]—was published in 1933 among the research monographs at the Physicotechnical Institute, dedicated to the fifteenth anniversary of the Institute (two years later the French edition was published). From 1954 to 1958, Ioffe wrote one book per year on the subject of semiconductors. These books were very quickly translated into foreign languages and published in new editions. Abram Federovich's work in organizing All-Union semiconductor conferences, of which already before the war there were five, was also of great significance.

14. Chronologically, Ioffe's first scientific work on the physics of semiconductors,[32] performed by him together with Ya. I. Frenkel', was presented at the first of these conferences, occurring in the fall of 1931 in Leningrad. This conference was concerned with the theoretical analysis of junction phenomena at a metal–semiconductor boundary. The rectifying property of such a junction(discovered experimentally a fairly long time ago) was explained in this work within the framework of the theory of tunneling, due to which the electron passes through the gap (barrier layer) between the metal and the semiconductor. This theory could not satisfactorily explain the effect of rectification in copper oxide rectifiers. However, it was revived a quarter of a century later in application to the description of the behavior of Esaki tunnel diodes and, more generally, tunneling effects in semiconductors.

The problems of rectification and photoelectric properties of junctions were studied experimentally in great detail in a series of studies by A. F. Ioffe completed together with A. V. Ioffe. Based on this work, the Soviet theoreticians B. I. Davydov, D. I. Blokhintsev, S. I. Pekar, and A. I. Gubanov laid the foundations for the diffusion theory of rectification at a metal–semiconductor junction and a junction between two semiconductors with different types of conductivity, and in addition, the conclusions of the theory were later experimentally verified in work performed by A. F. and A. V. Ioffe.

An important result of the work on the photoelectric effect in semiconductors was the proof of the proportionality of photoconductivity to the number of absorbed photons and the recognition of the connection between the position of the maximum of the internal photoeffect on the spectral curve and the thickness of the sample, as well as the determination of the connection between the temperature coefficient of electrical conductivity and the width of the forbidden band (for copper oxide crystals). The negative photoeffect (i.e., a decrease in the magnitude of the current with increasing illumination) was also studied in great detail.

A. F. Ioffe's work on the photoelectric effect in semiconductors allowed him to state the well-founded and bold hypothesis that it is semiconductors that are in particular capable of profitable conversion of the energy in radiation into electrical energy. In the years before the war, the first steps were taken in A. F. Ioffe's laboratory by B. T. Kolomiets and Yu. P. Maslakovets using photocells made of thallium sulfide, the efficiency of which constituted 1.1%. This was the principal results that pointed the way to research along these lines, leading up to the present silicon solar energy converters with an efficiency of the order of 15%.[15)]

15. During the war, the work on the physics of semiconductors was put into second place: the semiconductor physicists were concerned with solving defense problems (creating high-strength armor, antimine defense for ships, and other problems). In the early post-war years, the main direction of work at the Physicotechnical Institute was applied nuclear physics. The work on the physics of semiconductors was renewed, but only gradually increased in intensity. It received a great stimulus after the discovery of the transistor effect by American physicists. Recognizing the enormous possibilities opened up for radiotechnology (and electrical technology) with the discovery of the transistor, a small group of researchers headed by V. M. Tuchkevich began to study successfully the new problems in the physics of semiconductors. This group served as a nucleus for several influential semiconductor laboratories in the present A. F. Ioffe Physicotechnical Institute.

As far as Abram Fedorovich is concerned, from the end of the 1940's, he concentrated his interests on the study of new semiconductor materials and, mainly, on developing a new physical basis for thermoelectrical phenomena and other applications. Here, A. F. Ioffe was motivated by the need for energy: this problem, under conditions of limited supplies of traditional fuels, had already concerned him for a long time.[16)] Once again in the years before the war, promising results were obtained along these lines in his laboratory. Yu. P. Maslakovets and his coworkers developed thermoelements made of lead sulfide, providing a current of tens of amperes. Already at the time of the war, thermoelectric generators (TEG) were developed under his direction for providing power to guerilla radio stations. After the war, similar types of TEG were mass produced by our inductry and were used for powering radio receivers in rural areas. Later, their significance sharply decreased due to the continuous electrification as well as due to the development of transistorized radio receivers powered by miniature batteries. However, the simultaneous development of technology in other areas created the need for autonomous sources of power for distant and hard to reach objects, such as, for example, automatic weather stations in the mountains, beacons, buoys, space satellites, relay stations, and cathodic protection for gas and oil pipelines. At the present time, TEG, powered by radioactive as well as organic fuel, are used in many industrially developed countries for solving the problems mentioned above. The efficiency provided by multistage TEG can attain 20%.

In a pamphlet entitled "Energetic basis for thermoelectric batteries made of semiconductors,"[34] A. F. Ioffe in 1950 constructed a theory which was used to formulate requirements for semiconducting materials used in thermopiles and providing maximum efficiency. These requirements basically involved reducing the thermal conductivity of the semiconductor as much as possible, increasing the mobility of the current carriers in it, and providing the optimum concentration of current carriers. They also determined the alloying characteristics and the choice of materials for the thermoelements. This work opened up the way for widespread practical application of thermo-elements in small scale energetics and first proved the theoretical promise of semiconducting thermoelement refrigerators. Immediately afterwards (1951), in the Physicotechnical Institute under the direction of A. F. Ioffe and Maslakovets, L. S. Stil'bans developed the first semiconductor refrigerator in the world, which served as a starting point for the development of a new field of technology—thermoelectric cooling. In subsequent years, a series of thermoelectric refrigerators was developed at the Institute of Semiconductors (L. S. Stil'bans, A. N. Voronin, and E. A. Kolenko). At the present time, thermo-electric refrigerators and thermostats are widely used all over the world for solving many problems in radio electronics, instrumentation, medicine, space biology, and others. Multistage refrigerators cool from room temperature down to 150 °K and even lower temperatures.

The work described above, having a clear cut significance for applications, is directly related to the important theoretical and experimental research of A. F. Ioffe and A. V. Ioffe on thermal conductivity of semiconductors (in particular, in the course of this work a new and effective nonstationary method was developed for measuring thermal conductivity, providing high precision with good, fast operation).

All the work on thermoelectrical properties of semiconductors, begun during the years before the war and still increasing in pace, performed by Abram Fedorovich in the last ten years of his life, led to the creation in our country of a new field of energetics—thermoelectric conversion of thermal energy and semiconductor cooling technology together with a whole series of instruments developed for the first time in the world.

With the appearance of the above mentioned American work on the transistor effect at the end of the 1940's and with the invention of the transistors, the attention of researchers all over the world was at first concentrated on semiconducting materials belonging to the fourth group of the periodic chart, above all germanium and silicon. Among the credits of A. F. Ioffe in the field of semiconductor physics, we must include his work on researching new materials with promise for technological applications—on researching solid solutions, amorphous and liquid semiconductors, and studying their properties over a wide range of temperatures, including also the temperature range near the melting point. In addition, the band structure of semiconductors, as demonstrated in the experiments performed by A. F. Ioffe's student and colleague over many years, A. R. Regel', does not change significantly as the tem-

[15)] The heterojunction transformers recently developed at the Physicotechnical Institute by Zh. I. Alferov and his colleagues have the highest known efficiency equal to 25%.

[16)] We mention, as an example, A. F. Ioffe's speech delivered at the All-Union Conference on the formulation of the general plan for electricification in 1931.[33]

perature moves through the melting point: the electrical conductivity properties, so characteristic of semiconductors, are conserved and so on. This work demonstrated the decisive role of short-range order, on which depend the electrical properties and energetic (band) characteristics of semiconductors, which do not undergo basic changes with the transition from the solid to the liquid state—in accordance with Ioffe's point of view concerning the fact that the properties of semiconductors depend directly on the nature of the chemical bond.[36] The research of B. T. Kolomiets and N. A. Goryunova on glass-like semiconductors (chalcogenide glasses) and the theoretical work on amorphous semiconductors by A. I. Gubanov are all directly related to A. F. Ioffe's ideas on the band structure of semiconductors—all this work was carried out at the A. F. Ioffe Physicotechnical Institute.

16. In the article to which we have already referred more than once,[2] Abram Fedorovich, in the paragraph concerning the presentation of the results of his scientific research, writes: "I not only carried on my own work, but I also directed the scientific work of the rapidly growing institute. For the first 7–8 years, I in fact participated in setting up and developing almost all the work of the institute, and groups that moved forward independently began to appear only gradually at the institute. . . . On the other hand, I also did not carry on my own work alone, but together with a team of 10–15 people. For this reason, even if I wanted in all honesty to identify my personal contribution in the scientific work, this would be impossible and would serve no purpose." (Ref. 2, p. 244).

Ioffe's name is not listed among the authors of many of the articles originating at the Physicotechnical Institute during the 1920's–1940's, but his contribution to these articles is immediately evident from the text—a conscientious historian can identify the "personal participation" of Abram Fedorovich. It is significant that we are here dealing not only with the periodic consultations or remarks that he made either while reviewing the text of an article or in discussing it at a seminar (which, generally speaking, is also not insignificant!). Very often, the idea itself or the method used for translating it into an experiment belong to Ioffe. Abram Fedorovich's position in these cases, his extraordinary generosity, conformed with his moral principles and were part of the "art of leading young colleagues" of which he wrote enthusiastically in an article dedicated to his teacher N. N. Semenov.[37] Abram Fedorovich mastered this art to perfection, which is what made him the head of the most influential school of Soviet physicists. N. N. Semenov concisely expressed the above mentioned moral principles of Abram Fedorovich in several commandments, two of which we will recall here: "If you want a student to develop some new idea of yours or a new direction, do so inconspicuously, striving to the utmost to have him arrive at this idea, embracing it as his own, having come into his head as a result of conversations with you." The other commandment is as follows: "Do not get carried away with excessive supervision of students, give them the chance to show their initiative as much as possible and let them handle their difficulties themselves. Only in this manner will you cultivate a real scientist, rather than a laboratory assistant." (Ref. 37, p. 10).

Many examples can be given of Ioffe's behind the scenes participation in the work of his coworkers; we will limit ourselves to only one example, albeit, a very significant one. One of the first fundamental results obtained at the Physicotechnical Institute in researching semiconductors, belonged to V. P. Zhuze and B. V. Kurchatov. In their work,[38] it was shown for the first time that the conductivity of semiconductors is proportional to the quantity of impurities contained in them (the experiments were performed with copper oxides; the impurity studied was excess oxygen, which could change the magntide of the electrical conductivity by seven orders of magnitude). At the same time, the effects of impurity and intrinsic conductivity were differentiated. The significance of this work becomes all the greater, if one recalls that at that time there were no effective methods for purifying crystals, and in order to see anything on a dirty background, particular skill and inventiveness were required. At the beginning of the 1930's, many physicists in general doubted that a semiconductor could have intrinsic conductivity, i.e., all the conductivity in their opinion was due to impurities, while an ideal semiconductor is an insulator.

The authors of Ref. 38 wrote: "Following the idea of Academician A. F. Ioffe, this problem can be solved by changing the temperature behavior of the electrical conductivity of the semiconductor with different impurity content, and in addition, it may be expected that the curves obtained for the temperature dependence at high temperatures will coalesce into a single curve, corresponding to the intrinsic electrical conductivity of copper oxide, since the concentration of electrons originating from the impurities under such conditions will be small in comparison with the concentration of electrons contributed by the dissociation of the copper oxide itself." (Ref. 38, p. 310). In concluding the work, the authors express their gratitude to Abram Fedorovich "for suggesting the topic and for valuable suggestions in the course of the work." (Ref. 38, p. 317).

17. The Physicotechnical Institute of the Academy of Sciences of the USSR, named after A. F. Ioffe, was undoubtedly Abram Fedorovich's favorite offspring. A. F. Ioffe put all of his energy, talent, and his heart and soul into its organization and development, and into training his coworkers, who later occupied key positions in modern physics. It is difficult to overestimate the significance of this institute in the history of Soviet physics. It truly forged the cadres of physics in this country: more than fifty of the present members of the Academy of Sciences of the USSR and academies in the Republics, more than twenty corresponding members of the Academy of Sciences of the USSR, and several hundreds of Doctors of Science came from this institute. All of them are alumni of Ioffe's school, and many of them themselves lead entire research directions and have created their own individual schools of science as indicated by the published literature.[39]

Abram Fedorovich's anniversaries—his sixtieth, seventieth, seventy-fifth—invariably attracted to Leningrad the alumni of his wonderful school. Due to their work, not all were able to attend, in which case letters were sent to Leningrad which expressed gratitude to Abram Fedorovich and evaluated his role in establishing Soviet science. Here is one such letter, addressed to Ioffe by his students P. L. Kapitsa, L. D. Landau, P. G. Strelkov, and A. I. Shal'nikov, and signed by them and several other coworkers of the Institute of Physical Problems of the Academy of Sciences on October 28, 1955:

"Dear Abram Fedorovich!

We do not have a physicist who would have more grateful and devoted students. This is why our celebration today is a celebration of all of Soviet physics.

On this day your old students and coworkers remember with deep gratitude your attention to and care of them and they remember your institute—their institute, in which they learned to love and do science with the kind of warm feeling with which one remembers the old family home.

Please accept, dear Abram Fedorovich, our deep gratitude, our devotion, and our wishes for much happiness for you and much success for your new institute."[17)]

18. A. F. Ioffe's research examined above made a great contribution to the physics of the first half of this century; due to this work, A. F. Ioffe occupies a solid place in the history of physics. However, his influence on the development of physics in this country does not end there. Ioffe was one of the first, if not the first, physicist whose scientific organizational work in its breadth and significance for this country allows placing him among statesmen. Along with his name, we must include the names of D. S. Rozhdestvenskiĭ and P. P. Lazarev, who belong to the same generation of physicists as Ioffe. Abram Fedorovich is rightfully considered as one of the founders of Soviet physics. He gave an exceptional amount of time and effort to establishing it, planning its development, creating centers of physical science in the Russian Soviet Federal Socialist Republic and in the allied Republics, and to the preparation of cadres.

In carrying out this work, A. F. Ioffe counted on the support of the Soviet government: a series of documents have been preserved, which document his repeated contacts with S. M. Kirov, A. V. Lunacharskiĭ, V. V. Kuĭbyshev, and G. K. Ordzhonikidze. A. F. Ioffe in his discussions with coworkers often expressed his regret that he never had an opportunity to meet V. I. Lenin. He was, naturally, interested to what extent the head of the Soviet government was familiar with the initiative of physicists in organizing new institutes and whether or not he was aware of Ioffe's work and of the work performed at the Physicotechnical Institute. The volume of the Literary Heritage published in 1971 entitled *Lenin and Lunacharskiĭ* provides direct evidence of this interest.

In March 1921, the People's Commissar of Education, Lunacharskiĭ, received from V. I. Lenin a letter that contained a request to report the Commisar's opinion concerning many of the representatives of the St. Petersburg intelligentsia who cooperated with the Soviet government, in particular, concerning V. A. Steklov, A. F. Ioffe, V. M. Bekhterev, several engineers, architects, and so on. In answering this question on the day after it was received, A. V. Lunacharskiĭ wrote: "Academician A. F. Ioffe was recently elected. The election of a person with such radical political beliefs and a Jew to the Academy of Sciences could not even be discussed in the old days and in addition, Ioffe is a wonderful physicist, especially in the area of x-rays and the theory of atomic structure. Recently he published an excellent textbook on molecular physics. Together with the eminent physician-organizer Nemenov, he directs our radiology and x-ray institute (the State X-Ray and Radiological Institute—V.F.), which was created totally by the Revolution and already has a reputation in Europe." (Ref. 40, p. 257).

Further proof of his interest is the story of Professor L. S. Termen. In March 1922, in the Kremlin, L. S. Termen demonstrated to V. I. Lenin some of his inventions. Recalling this, L. S. Termen writes: "I told Vladimir Il'ich about my work under the direction of A. F. Ioffe. He said he already knows many good things about Ioffe and my devices clearly show what miracles electricity can perform." (Ref. 15, p. 119; see also Ref. 41.)[18)]

19. Chronologically, the first result of A. F. Ioffe's scientific organizational work was the creation of the Physicotechnical Institute; we already spoke of this above. There is no doubt that Ioffe recognized the importance of this step, but, it would seem that he was still unaware of how significant this event would turn out to be, two to three decades hence. Indeed, acknowledging the achievement of P. P. Lazarev, who organized in Moscow the Institute of Physics and Biophysics even somewhat earlier than the Physicotechnical Institute, and not forgetting the enormous service of D. S. Rozhedestvenskiĭ—the first director of the State Optics Institute, which was created simultaneously with the Physicotechnical Institute and which played such a large role in establishing optics and optical industry in this country, we cannot deny that the Physicotechnical Institute occupied the leading position in Soviet physics. Under the direction of A. F. Ioffe, it served as a unique and defectless nucleus of the crystal which represents today's enormous body of Soviet physicists. And we can judge the smallness of this nucleus, for example,

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[17)] The letter is preserved by the Leningrad Division of the Archives of the Academy of Sciences of the USSR.

[18)] In examining the numerous books published for the 50th and 60th anniverseries of the Great October Socialist revolution, for the 100th anniversary of V. I. Lenin's birthday, the half-century anniversary of the USSR, and the 250th anniversary of the Academy of Sciences of the USSR, we are once again assured of how great a role A. F. Ioffe played in building up new science and technology and new culture; his name appears often in documents that organizationally bind together the efforts of Soviet scientists, directed toward developing scientific research in this country.

from the payroll preserved in the archives of the Physicotechnical Institute (for December 1925—in comparison with 1918, the Institute almost doubled in size by this time!). The list included forty-seven people, of which 38 were scientists. We will present this impressive list, the majority of names on which need no commentary: A. F. Ioffe—director; A. A. Chernyshev—manager, V. R. Bursian—scientific secretary. Research directors: N. N. Semenov, N. Ya. Selyakov, I. V. Obreimov, Ya. I. Frenkel', L. S. Termen, P. I. Lukirskiĭ, Ya. R. Shmidt-Chernysheva. Physicists: D. V. Skobel'tsyn, M. A. Levitskaya, P. S. Tartakovskiĭ, A. V. Moskvin, V. N. Kondrat'ev, Yu. B. Khariton, G. A. Grinberg, L. V. Shubnikov, D. A. Rozhanskiĭ, F. A. Miller, A. K. Val'ter. Senior assistants: A. I. Krasnikov, A. V. Strutinskiĭ, P. G. Strelkov, M. M. Sitnikov. Junior assistants: V. S. Gorskiĭ, B. M. Gokhberg, É. Kaminskiĭ, A. I. Chal'nikov, Yu. P. Maslakovets, B. K. Shembel', P. N. Shukin. Administrator—V. N. Glazanov.

We add here V. N. Dyn'kov, who from 1918 headed the mechanical shop at the Physicotechnical Institute (late, Doctor of Technical Sciences, who after the war headed the design office of the Physicotechnical Institute), N. G. Mikhaĭlov, who from 1921 headed the glass-blowing shop at the Institute and who trained a galaxy of wonderful Soviet glassblowers, and A. M. Stepanov, supervisor of the Physicotechnical Institute building, without whom the prewar picture of the Physicotechnical Institute would be incomplete.

By 1930, the scientific personnel at the Institute already constituted 105 persons; by this time the following scientists worked in it: A. I. Alikhanov, A. I. Alikhan'yan, N. N. Andreev, V. V. Arkharov, L. A. Artsimovich, N. N. Davidenkov, S. N. Zhurkov, I. K. Kikoin, P. P. Kobeko, Yu. B. Kobzarev, B. P. Konstantinov, G. V. Kurdyumov, I. V. Kurchatov, L. D. Landau, A. V. Stepanov, V. A. Fok, and many others. About eighty members of the Physicotechnical Institute, either during the years of work at the Institute or later, having left it, became active members and corresponding members of the Academy of Sciences of the USSR or of the Academies of Sciences of the Republics of the Union.

The Physicotechnical Institute, directed by A. F. Ioffe, was not only an excellent school for physicists; extremely influential science administrators matured at the Institute also. It is sufficient to say that the leading physical institutes in the country are directed over a period of many years by the students and closest colleagues of Ioffe. Such institutes include: in Leningrad, the Physicotechnical Institute itself (B. P. Konstantinov, V. M. Tuchkevich) and the Institute of High-Molecular Compounds (M. M. Koton); in Moscow, the Institute of Chemical Physics (N. N. Semenev), the Institute of Physical Problems (P. L. Kapitsa), Institute of Atomic Energy (I. V. Kurchatov, A. P. Aleksandrov), Scientific Research Institute of Nuclear Physics at the Moscow State University (V. N. Vernov), Institute of the Physics of Solids (G. V. Kurdyumov), P. N. Lebedev Physical Institute (D. V. Skobel'tsyn), Institute of Experimental and Theoretical Physics (A. I. Alikhanov), Institute of Biophysics (G. M. Frank); in Khar'kov, Ukranian Physicotechnical Institute (I. V. Obreimov, A. I. Leĭpunskiĭ, K. D. Sinel'nikov); in Kiev, Institute of Physics (A. F. Prikhot'ko) and The Institute of Semiconductors (V. E. Lashkarev); in Baku, Institute of Physics (G. B. Abdullaev); in Vil'nius, Institute of the Physics of Semiconductors (Yu. K. Pozhela).

20. Throughout his life, A. F. Ioffe was always closely connected with the system of higher education. His most important contribution to the development of post-secondary education in this country was, undoubtedly, the organization in the fall of 1919 of the physicomechanical department at the St. Petersburg Polytechnical Institute. Using this department as a model, toward the end of the 1920's–1940's, an entire series of engineering-physics departments was created in different institutions of higher education in the country, including also the Moscow Physicotechnical Institute, in the organization of which Ioffe's students took such an active part in the early postwar years. The now obvious necessity of putting together an education program that would ensure smooth coordination of the courses in physico-mathematical and technical (special) sciences was not understood by everyone at the beginning stage in the creation or reorganization of the new departments. Much effort was required for the new system of teaching, developed by A. F. Ioffe and his colleagues and coworkers (M. V. Kirpichev, A. N. Kyrlov, F. É. Levinson-Lessing, A. A. Fridman, P. L. Kapitsa, N. N. Semenov, Ya. I. Frenkel' and others), to become accepted. An indication of the difficulties that had to be overcome is revealed by an excerpt from a salutatory address directed to Abram Fedorovich in the fall of 1940 by the administration and community organizations at the physico-mechanical department: "More than once you saved the department during its infancy and youth—until its special significance for the needs of our socialist industry became obvious to all and the department became strong enough to move forward successfully. Although we regret that other responsibilities prevented you from daily participation in the work of the department in recent years, we know that the department can always count on your assistance. Your relationship to the department remains intact not only in terms of using the best graduates of the department but also in preparing them, inasmuch as this preparation is carried out by your students or coworkers in the spirit of the ideas and principles that you expounded."

However, A. F. Ioffe's contribution to educating cadres of physicists is not limited to the creation of the physico-mechanical department and his leadership of that department over many years. As long ago as the 1910's, he lectured not only at the Polytechnical Institute but also at the St. Petersburg University, the College of Mines, and at the well known Lesgaft courses. A. F. Ioffe's work in education is closely connected with his teaching. He contributed to the well-known volumes of collected articles of his time *New Ideas in*

Physics, published starting in 1911.[19] This series was temporarily interrupted during the First World War and resumed after the Revolution, when the volumes were edited by Abram Fedorovich, who determined their subject matter and selected the group of authors, mostly consisting of his students from the Physicotechnical Institute.

A. F. Ioffe wrote for the last (fourth) volume of the famous physics course by O. D. Khvol'son the chapters on the thermodynamics of radiant energy and the photo electric effect. In the early year following the Revolution, his *Lectures on Molecular Physics,* published by Sobashnikov in 1919 (they were republished twice during 1923), were very popular.[20] From 1919, Ioffe became the editor of a series of books published by Sobashnikov entitled *Handbook of Physics,* edited by the Russian Association of Physicists, which at that time was headed by Abram Fedorovich.

In the mid-1920's, A. F. Ioffe began to work on *A Course in Physics,* which unfortunately, was never completed. He wrote the first volume of this course—*Basic Concepts in Mechanics. Properties of Thermal Energy, Electricity and Magnetism* (first edition was published in 1927, the second edition in 1933, and the third edition, radically revised, in 1940). In addition, together with N. N. Semenov, he wrote the first part of the fourth volume—*Molecular Physics* (published in two editions in 1932 and 1935). In the mid-1930's, under the direction of A. F. Ioffe, there was a fruitful discussion in Moscow at the session of the physics group of the Academy of Sciences of the USSR in the principles for constructing a physics course for technical institutions of higher education; the publication of the excellent course of general physics by G. S. Landsberg can be considered as one of the results of the stormy discussion of those years.

Two books written by A. F. Ioffe's students and coworkers at the Physicotechnical Institute played a large role in preparing experimental physicists: *Techniques for Physical Experiments* (V. S. Gorskiĭ, V. N. Kondrat'ev, K. D. Sinel'nikov, P. S. Tartakovskiĭ, É. P. Khalfin, A. I. Shal'nikov) and *Tables of Physical Constants* (N. I. Dobronravov, Ya. G. Dorfman, A. N. Zagulin, N. I. Idel'son, P. P. Kobeko, V. N. Kondrat'ev, M. I. Korsunskiĭ, I. V. Kurchatov, B. Ya. Pines, N. Ya. Selyakov, N. N. Semenov, K. D. Sinel'nikov, P. S. Tartakovskiĭ, S. É. Frish, É. P. Khalfin); Ioffe initiated the publication of these books and edited them.

Among the many monographs and educational aids, published under the editorship of A. F. Ioffe, we would like to mention the unusually popular in the 1920's to 1940's *Problems in Physics,* compiled by Ioffe's students in the Department of Physics and Mathematics and at the Physicotechnical Institute—A. F. Val'ter, V. N. Kondrat'ev, and Yu. B. Khariton, of which more than ten editions were published in 1925–1938.[21]

21. In the 1920's, A. F. Ioffe, as President of the Russian Association of Physicists, organized a series of international and All-Union conferences in different cities in the country, which played a large role in the development of physics and its new directions.

In a short autobiography in 1951, Abram Fedorovich considered it important to point out that in December of 1918 he convened a conference of physicists (in Moscow) and in January of 1919 the first conference in Petrograd. The purpose of these conferences "was to place Russian physics in the service of the Socialist construction of the Republic."[43] The conferences of Russian physicists convened later—up to 1930—once every two years, and, beginning in 1924 (the fourth conference in Leningrad), Ioffe, making use of his authority and position, attracted leading scientists from abroad to participate in them: among them were M. Born, L. Brillouin, C. Darwin, P. Debye, P. Dirac, A. Sommerfeld, O. Richardson, W. Pauli, J. Franck, F. Franck, P. Ehrenfest).

Among All-Union conferences, devoted to various branches of physics, that were convened by A. F. Ioffe and his closest coworkers (N. N. Semenov, I. V. Kurchatov, and others), we must mention the conferences on nuclear physics. The first of these conferences occurred in 1933 in Leningrad, and its participants included the husband and wife team Joliot-Curie, F. Perrin, P. Dirac, F. Rasetti;[22] before the war, there were five conferences. During the decade before the war, there were six conferences on the physics of semiconductors, several conferences on the special problems of physical chemistry, the physics of solids, and compounds of high molecular weight.

22. We have considered in some detail three areas of A. F. Ioffe's organization work. For lack of space, we will limit ourselves to a simple mention of the enormous work that Abram Fedorovich carried on at the Academy of Sciences of the USSR: he served as vice president of the Academy twice: during 1926–1929 and again during 1942–1945; he took many other high-level responsibilities at the Academy—he was the academic secretary for the division for physico-mathematical sciences (1942–1945), member of the Presidium of the Academy (1945–1952), and representative of the committee on semiconductors to the Presidium (1952–1960), he headed numerous committees, created by the Academy at different times.

A. F. Ioffe's scientific connections with foreign scientists played a big role in strengthening the international influence of Soviet physics. We recall that over the course of more than thirty years, from 1902 up to the mid-1930's, he (with interruptions as a result of the

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[19] Thus, in the 4th volume, published in 1912 and dedicated to the memory of P. N. Lebedev, A. F. Ioffe published a long review of the photoeffect (not cited in the bibliography of his work).[42]

[20] A. V. Lunacharskiĭ referred to this particular book in the letter to V. I. Lenin mentioned above.

[21] We already mentioned the series of books on the physics of semiconductors that were written by A. F. Ioffe in the years following the war.

[22] The proceedings of this conference were published under the editorship of M. P. Bronshteĭn. V. M. Dukel'skiĭ, D. D. Ivanenko, and Yu. B. Khariton.[44]

First World War and the Civil War) travelled abroad almost every year, establishing close scientific, and often friendly, relationships with eminent physicists; in the second half of the 1950's, these trips were resumed, and Ioffe made contact with the new post-war generation of scientists.

Abram Fedorovich proudly carried the banner of Soviet physics. He was its true ambassador. He appeared at numerous conferences abroad, taking part in the work of international organizations: in 1930–1948, he was a member of the Solvay committee, while in 1957, he was chosen as vice-president of the International Union of Pure and Applied Physics and chairman of the International Commission on Semiconductors of this Union. At conferences, congresses, and seminars, Ioffe described the successes of Soviet physics as a whole and of the physicists belonging to his school in particular, justifiably ascribing great significance to propagandizing these achievements.

It is difficult to name an eminent physicist who was a contemporary of Ioffe and who was not acquainted with Abram Fedorovich and the work that was performed by him as well as by his students and coworkers. This allowed Ioffe to establish during the early post-revolutionary years close connections between the Physicotechnical Institute and the laboratories of Rutherford in England, Marie Curie in France, Kamerling-Onnes in Holland, J. Franck in Germany, and the western centers of theoretical physics (N. Bohr, M. Born, A. Sommerfeld, P. Langevin, M. Planck, and A. Einstein). Ioffe sent the more capable of his coworkers and especially the younger scientific workers to the above-mentioned centers of physics, and in addition, he more than once paid for these trips from honoraria that he received for his consultation and lecture work in the West (the rest of this money went to buying equipment for the Physicotechnical Institute and scientific literature for the Institute's library).

It is also difficult to imagine a foreign physicist, who, having been in Leningrad in the 1920's–1950's, did not visit the Physicotechnical Institute (and later, the Institute of Semiconductors) in order to see A. F. Ioffe, to discuss with him the problems that worried him, to become acquainted with the work of the researchers at the Physicotechnical Institute or at the Institute of Semiconductors at the Academy of Sciences, and often to work in their laboratories. A visit to Abram Fedorovich became traditional for foreign physicists visiting the USSR. A great deal of proof attests to this fact, in the form of letters, preserved at the A. F. Ioffe foundation at the Leningrad Division of the Archives of the Academy of Sciences of the USSR.

23. A. F. Ioffe, as any other person, had to make important decisions that would determine the course of his life and scientific work for many years in the future. One of these decisions was the trip to Munich (1902) and the subsequent years of work with Roentgen, and then the rejection of the flattering, but completely unacceptable to Ioffe, offer to remain in Germany (1906).

The critical years turned out to be the years of the Revolution and the Civil War, when A. F. Ioffe created the Physicotechnical Institute and the Physico mechanical department at the Polytechnical Institute. At the end of the 1920's, the Physicotechnical Institute grew into an influential research center and a great deal of outstanding work was done there. There arose the question of the future development of the Institute. Abram Fedorovich boldly proceeded toward creating new, independent scientific establishments, providing them with space, with valuable equipment, and, most important, with his most capable students and coworkers whom he had trained or, more accurately, fostered. For some time Ioffe headed the "complex of physicotechnical institutes"—the Physicotechnical Institute itself, the Institute of Chemical Physics (N. N. Semenov), the Electrophysical Institute (A. A. Chernyshev) and others, and then, in the mid-1930's, he gave them full independence.[23)]

A. F. Ioffe was concerned with the choice of new promising directions of research and about new personnel: the "maternal" Physicotechnical Institute since the beginning of the 1930's went through, in essence, a second rebirth. The new directions, as mentioned above, became: the physics of semiconductors, nuclear physics, and the physics of polymers. The amazing intuition, always characterizing Abram Fedorovich, once again enabled him to make an optimum choice: everyone now knows the role that these fields of physics play in modern science and technology, as well as Ioffe's well-known contribution to these developments.

The end of the 1920's saw a change in Abram Fedorovich's personal life. In 1928, he married for the second time; Anna Vasil'evna Echeistova (Ioffe) became his wife. A. V. Ioffe, working at the Physicotechnical Institute (after graduating from the Physics Department at the Leningrad University), became her husband's closest collaborator in his experimental research on the physics of semiconductors and to the end of his days she was his true companion and helper.

[23)] In all, 16 institutes were created based on the Physicotechnical Institute from 1927 to 1977. We will list them here. Institutes formed on the basis of the A. F. Ioffe Physicotechnical Institute of the Academy of Sciences of the USSR are as follows: 1. Institute of Heat Technology, Leningrad, 1927; 2. Ukrainian Physicotechnical Institute, Khar'kov, 1929; 3. Siberian Physicotechnical Institute, Tomsk, 1929; 4. Leningrad Institute of Physical Chemistry, 1931; 5. Leningrad Electrophysical Institute, 1931; 6. Institute of Telemechanics, 1931; 7. Central Asian Institute of Solar Engineering, Samarkand, 1931 ; 8. Institute of Musical Acoustics, Leningrad, 1931; 9. Ural Physicotechnical Institute, 1933; 10. Dnepropetrovsk Physicotechnical Institute, 1933; 11. Physicoagronomy Institute VASKhNIL, Leningrad, 1934; 12. Laboratory No. 2 (later the I. V. Kurchatov Institute of Atomic Energy), Moscow, 1943; 13. Laboratory No. 3 (later the A. I. Alikhaonov Institute of Theoretical and Experimental Physics), Moscow, 1945; 14. Institute of Semiconductors of the Academy of Sciences of the USSR, Leningrad, 1954; 15. Leningrad B. P. Konstantinov Institute of Nuclear Physics, Academy of Sciences of the USSR, Gatchina, 1972; 16. Leningrad Scitific Research Computation Center of the Academy of Sciences of the USSR, 1977.

Organization of science, directing large teams of scientists, personal research—all this required maximum attention, and necessitated overcoming numerous difficulties. Of course, this difficult path included failures, which are unavoidable for a man who works so intensively; fortunately, these periods were comparatively short-lived. Such failures include the unfulfilled hopes that Ioffe placed on thin-layered insulation and the creation of miniature electrical storage batteries, hopes shared by his coworkers and many scientists abroad. The time during the debates following a report dedicated to the almost twenty-year existence of the Physicotechnical Institute, at a session of the Academy of Sciences of the USSR (March 1936), when he was subjected to much too sharp and at times unwarranted criticism from many of his immediate students, was difficult for A. F. Ioffe. It was especially difficult for Abram Fedorovich in 1950 when he had to leave his post as director of the Physicotechnical Institute, where he was a director for more than thirty years. During the last one-and-a-half years of work at the Physicotechnical Institute, he headed the division that combined a number of semiconductor laboratories at this Institute.

We must observe with regret that the new leadership of the Physicotechnical Institute did not show the proper tactfulness under the circumstances that occurred: this made it necessary for Abram Fedorovich to leave the Physicotechnical Institute. Before doing so, he asked the Academy of Sciences whether it would be possible to organize an independent semiconductor laboratory. This request received complete support from the leadership of the Academy. In March 1952, such a laboratory was created within its physico-mathematical division. Abram Fedorovich became the head of the laboratory. Its staff included many of his coworkers (including A. I. Ansel'm, V. P. Zhuze, A. V. Ioffe, Yu. P. Maslakovets, A. R. Regel', L. S. Stil'bans, and others, at the outset thirty-six people at the laboratory). The tempo and scale of the work grew continuously. In the fall of 1954, it doubled in size, mainly, due to the young people arriving from the institutes of higher learning. Research was conducted on the electrical and thermal properties of semiconductors, thermoelectricity (the latter had a clear technical prupose). Proof of the success of this work was the decision of the Presidium of the Academy of Sciences, made in November 1954, to organize on the basis of the semiconductor laboratory an institute of semiconductors at the Academy, thereby becoming the last in a long series of institutes organized by A. F. Ioffe.

The remaining years of Abram Fedorovich's life saw the joyous creative work at this young institute, which the old scientist directed with the youthful and sharp mind of the researcher and organizer. The number of publications by A. F. Ioffe in scientific journals, reflecting the scientific activity of the scientist, increased sharply in 1954. His capacity for work could only give rise to amazement and admiration.

Abram Fedorovich's work during the last years of his life included a series of purely physical studies on semiconductors and their technical applications (see Sec. 15).

Under his leadership, research on thermoelectricity was developed widely. It was not for nothing that one of Ioffe's books on this subject[45] was referred to abroad as the "bible on thermoelectricity." Devoting, as before, a great deal of time to the problem of energetics, A. F. Ioffe persistently emphasized the role of semiconducting materials in solving the problems of solar energy conversion. All of this work was supported not only in our country, but among foreign colleagues as well. Thus, F. Joliot-Curie and M. Born, to whom Ioffe sent copies of his last publications on this subject, gave a very flattering appraisal of Ioffe's research on thermoelectricity.

The Academy of Sciences of the USSR, the workers at the Institute of Semiconductors, the physicists in Leningrad, Abram Fedorovich's students working in Moscow and other cities in the Soviet Union were preparing to celebrate at the end of October 1960 the eightieth anniversary of the outstanding Soviet scientist. Abram Fedorovich died suddenly on October 14th of that year—two weeks before his anniversary.

Already by the end of the 1940's, A. F. Ioffe was the most senior scientist among the physicists and mathematicians of the Soviet Union according to the time of election to the active membership in the Academy of Sciences. He was an honorary or foreign member of many academies in the world and renowned universities conferred honorary doctoral degrees on him. His achievements have won high praise from the Communist Party, of which A. F. Ioffe was a member from 1940, and from the Soviet government. He was awarded three orders of Lenin; in 1955 he was named Hero of Socialist Labor; in 1942 his research on the physics of semiconductors was awarded the State Prize of the USSR First Class, and in 1961 (posthumously), the Lenin Prize.

Abram Fedorovich left behind a great scientific legacy, that has become part of the gold reserves of the science of the twentieth century, and he has left behind a broadly based scientific school and devoted students. His name is inseparably connected with the history of science and culture of our Socialist State, of which he was a true son all his life.

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