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FIFTY YEARS OF SOVIET PHYSICS

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É. V. SHPOL'SKIĬ

CONTENTS

I. PHYSICS IN RUSSIA BEFORE THE REVOLUTION AND START OF ORGANIZATION OF SOVIET PHYSICS

THE great October socialist revolution heralded a new epoch in the development of physics in Russia. This is clearly seen from a comparison of the level of development of physics in Tsarist Russia with the advances made in this science in the USSR in our time. However, regardless of this detailed comparison, one single event is the brightest proof of the outstanding accomplishments of Soviet science. This event is the launching of the first and second artificial earth satellites during the fortieth anniversary of the historic date of October, 1917 This event made a shattering impression on the entire world, as is best demonstrated by the fact that the word "sputnik" was adopted by all languages without modification, and the data of the launching of the first satellite is frequently regarded abroad as the start of a new era in the organization of science and scientific education. Of course, the growth of physics in the USSR, in all its branches, including the mastery, within the shortest time, of nuclear energy and all its possible applications, is perhaps not so concentrated but equally convincing proof of the remarkable accomplishments of Soviet science in the field of physics. It is therefore interesting and instructive to compare, against the background of the development of world science, the scale and the general character of pre-revolutionary physics in Russia with the physics of the Soviet Union in our days.

Approximately seventy years ago physics experienced the beginning of a deep revolution, which continued in the subsequent decade and determined the trend and the character of development of this science for many years, and perhaps centuries. Let us recall the main fact and the most important decisive feature of this revolution. X-rays were discovered in 1895, and radioactivity in 1896. Although the existence of the electron was foreseen already in the middle Seventies and Eighties of the 19th century, the conclusive proof of its reality, the determination of its charge and mass, in 1898 was an event probably no less stunning in that time than the discovery of x-rays and radioactivity. The investigation of Brownian motion at the beginning of the 20th century has made the concept of atoms and molecules of matter just as "perceptively" real as the macroscopic objects surrounding us. Finally, the discovery of interference between x-rays in 1912 confirmed in most lucid fashion, from a new point of view, the reality of atoms and uncovered a way of investigating the structure of crystals. At the same time, research on the structure of the atom was initiated—first in the form of J. J. Thomson's model, developed after Rutherford discovered the atomic nucleus in 1912.

The development of the physics of the 19th century, both experimental and theoretical, was summarized at the end of that century and during the early years of the 20th in those most important physical theories which determine now the entire character of physics and will continue to determine it for many years in the future. These were quantum theory, relativity theory, and physical statistics.

Let us examine now the situation in Russia during this most remarkable epoch in the history of physics. We note first that in sciences related to physics—chemistry and mathematics—the discoveries made in Russia in the 19ty century and at the beginning of the 20th were far reaching in their significance and revolutionary influence. It is sufficient to recall, in chemistry, the discovery of the periodic system of elements by Mendeleev and the remarkable work by the organic chemists Zinin, Butlerov, Markovnikov, Zelinskiĭ, and many others, who won a predominant place for Russia in organic chemistry, both in the field of systhesis (Zinin, Zelinskiĭ, and others) and in the field of structural theory (Butlerov). Outstanding prominence was won by Russia in mathematics during the same time by such scientists as Ostrogradskii, Chebyshev, Lyapunov, and Steklov. In astronomy, V. Ya. Struve, Bredikhin, and Belopol'skiĭ won world renown for the Pulkovo observatory. Finally, in the field of crystallography, which from the modern point of view is the basis of solid state physics, a firm position was assumed in this science by the work of E. S. Fedorov, who constructed the universally accepted classification of crystal systems.

The fate of physics in Russia was different. Of course, one can name many outstanding Russian scientists, to whom physics owed important research (Stoletov, Lebedev, Umov, Golitsyn, and others). However, whereas mathematics in Russia was backed at the end of the 19th century by 150 years of continuous fruitful development, starting with the brilliant genius of Leonhard Euler, and including in the first half of the 19th Century the name of the mathematical genius, N. I. Lobachevskiĭ, physics in Russia was a much "younger" science and could not match any names of significance equivalent to the foregoing names. An analysis of the causes of this unfavorable position of physics is beyond the scope of the present review. However, one cannot fail to note the fact that the only pure research laboratory, divorced from teaching functions, existing in Russia since the 18th century to the start of the revolution was the small physical laboratory of the Academy of Sciences in Petersburg (called until 1912 the "Physics cupboard" which obviously was in accord with the scope of its activity*). However, it is precisely this small laboratory where work was done by V. V. Petrov, who discovered the electric arc several years before Davey; it is there where E. H. Lenz, who should rightfully be listed among the founders of modern electromagnetism together with Oersted, Ampere, and others, performed all of his work. Another worker in this laboratory was B. S. Yakobi, a brilliant representative of the still embryonic field of technical physics. S. I. Vavilov† characterized this outstanding but unfortunately half-forgotten scientist as follows: "Yakobi was one of the most remarkable representatives of that new phase of the history of physics, when its results were immediately transformed into active phases of engineering, when electromagnetism was transformed into electrical engineering." Among the scientists working in that laboratory at the end of the 19th century and the beginning of the 20th, mention should be made of O. D. Khvol'son, and especially B. B. Golitsyn, who performed there a number of precise optical investigations, and who devoted himself at the end of his life exclusively to seismology, where he did pioneering work.

We can see even from this cursory review that this modest "physics cupboard" in which the academicians of the 18th and 19th Century "performed their experiments usually alone or only with an assistant" (S. I. Vavilov), made a significant contribution to science. This was undoubtedly due to the fact that the problems of this cupboard-laboratory involved only scientific research for which suitable material means were provided.

To be sure, besides this laboratory, there was in Peterburg the Main Board of Measures and Weights, the director of which was, at the end of his lifetime, D. I. Mendeleev. But although on high scientific level, this was a purely metrological institution.

In the main, physics in Russia was a university subject. This means that the universities, or the higher schools in general, had to provide not only instruction but also scientific research in the field of physics. But physics is an experimental science, and in order to organize properly the teaching and especially the research, it requires large and specially outfitted laboratory buildings, an appropriate technical base, instruments which are frequently expensive, and, finally, of equal importance to the scientists--enough free time from teaching. None of these conditions were satisfied in the Russian universities up to the very start of the 20th century, and—what is most important—the administration did not understand the importance of developing physics as a science in the universities.

The highly unfavorable state of physics in pre-revolutionary Russia is emphasized with remarkable brightness in an article by one of the outstanding physicists of that time, Professor N. A. Umov of the Moscow University. In an article "The Physics Institute of the Moscow University" Umov wrote* in 1898: "The political importance of a nation can be firmly established if its cultural level corresponds to its political development. In our days weapons or courage are not the only factors that ensure a nation's success in its struggle for its development and existence." Noting that the most important characteristic of the cultural level of a country is "its contribution to the field of knowledge," Umov writes further: "If we look at our country we recognize that, unfortunately, for the most part we have so far borrowed and received, but contributed very little to the cultural life of humanity. And if we examine what has been done by us for the development of knowledge, it becomes clear that our efforts were directed towards study, and we were satisfied if we studied well... A museum, or an instrument crib—these are the terms characterizing our earlier views—study; an institute—this is the new view—study and create, produce."

In the late 90's and the early 1900's, the condition of physics in the universities improved. Physical institutes were constructed and equipped at the Moscow, Peterburg, and Odessa universities—special buildings provided with auditoria suitable for teaching experimental physics, teaching laboratories for the general and specialized experimental courses, and scientific laboratories. An inestimable historical role was played in Moscow at the end of the 19th century and at the start of the 20th by the activity of P. N. Lebedev, whose heroic efforts created the first Russian school of physicists (P. P. Lazarev, V. K. Arkad'ev, A. B. Mlodzeevskii, N. A. Kaptsov, A. K. Timiryazev, N. K. Shchodro, T. P. Kravets, A. R. Kolli, and others). As early as in 1900, Lebedev himself presented in his classical papers an undisputed quantitative proof of the existence of the pressure of light on solids, in full agreement with Maxwell's predictions, and yet such an outstanding physicist of the 19th century as William Thomson (Lord Kelvin)

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*This history of this establishment, which is in fact the embryo, so to speak, of the modern giant Physics Institute of the USSR Academy of Sciences, (FIAN), is splendidly described in a book by S. I. Vavilov "Physics Cupboard–Physics Laboratory Physics Institute of the USSR Academy of Sciences over 220 Years", M. 1945.

†Op. cit. p. 40 ff.

*N. A. Umov, Collected Works, v. 3, M., 1916, p. 142.

did not believe in the reality of this phenomenon. Several years later, in 1908, Lebedev reported at the Convention of Russian Naturalists and Physicians his new work, of unsurpassed difficulty, concerning the pressure of light on gases. At approximately the same time Lebedev's childhood friend, A. A. Éĭkhenval'd, an outstanding physicist and a brilliant professor, completed his important investigations of the magnetic field produced by displacement and convection currents. Many lectures were delivered by Lebedev on vital and timely topics of physics at various scientific societies, and especially at the weekly physics colloquium (seminar, in modern terminology) organized by him at the University, which was attended not only by physicists but also by representatives of related specialties. All this led to a greater vitality in Moscow's scientific life. But in spite of all, the conditions under which Lebedev performed this most important activity were extremely unfavorable. There was no financing of the scientific work, and the laboratory had no technical base. A lone mechanic (Alekseĭ Ivanovich Akulov) helped Lebedev in his difficult work and could not service the staff members (who were then called “trainees”). Lebedev found a way out of the situation by requiring that every student who desired to experiment in his laboratory complete a preliminary “training course” in the private machine shop of P. I. Gromov (Lebedev jokingly referred to it as “Gromov's university”) and “obtain credit” by constructing some small instrument. During the course of the work the “trainees” had to do all their own work, including all mechanical work when required. It goes without saying that there were no “fellowships” for scientific workers: the “trainees” who were already graduated from the university did their scientific work in their spare time, earning their living by teaching in secondary schools, or, in exceptional cases, by teaching in other higher institutions of learning.

However, Lebedev was deprived even of these modest means in 1911, when he, together with all the progressive professors and instructors of the university regarded it his civic duty to quit the university in protest against the repressions of the elected university administration on the part of the reactionary minister of education.[*] Leaving the university, Lebedev was deprived of everything—his position, laboratory, and even dwelling. Society came to his aid. The A. L. Shanyavskiĭ Municipal University organized for Lebedev a laboratory, which was located in the ground floor of a residential house (no. 20) in Mertvyi pereulok (now Ostrovskiĭ na Kropotkinskoĭ), where Lebedev himself also resided. This event, of tragic consequences for Russian science and culture, aroused a widespread social commotion: outstanding scientists—Lebedev himself, K. A. Timiryazev, N. A. Umov, and others--published articles proving the need for organizing, in addition to universities, research institutes without teaching functions, called “national laboratories” by Lebedev. Here is what Lebedev wrote on this subject in an article published in the newspaper “Russkie vedomosti” (Russian Record)[*]: “If Russian society wants to lend a helping hand to its scientists, if it recognizes its moral obligation to all humanity to provide science with means enabling it to live and develop, if it wishes to protect it in the future against unexpected upheavals--society can do this by taking part in the construction of a number of separate specially equipped laboratories devoted exclusively to scientific research and completely independent of institutions whose purpose is teaching... Large scientific physics laboratories, intended exclusively for scientific research, have been long in existence in the West—in England, Germany, and America. Persistently solving scientific problems, they also enrich technology in entirely unpredicted ways, as shown by experience... Unfortunately, we still have no such national physics laboratory, but the need for it and the required scientific forces are already on hand.”

The government remained deaf to these appeals. Nonetheless, the resultant social movement was not in vain. The scientists succeeded in convincing representative of the large Russian buorgeoisie of the need for developing physics in Russia, and through private donations they organized the “Moscow Society for a Scientific Institute”[†], whose task was to collaborate with the organization of “national research institutes,” primarily a physics institute for P. N. Lebedev and a biology institute for N. K. Kol'tsov. Unfortunately, Lebedev did not live to see the realization of his dream: the departure from the university aggravated the heart disease from which he suffered for a long time, and in March, 1912, a year after leaving the university, Lebedev died at the age of 46 in full bloom of his creative powers.

His activities were continued in Moscow by his student and closest collaborator, P. T. Lazarev. In 1915, after the council of the Society for a Scientific Institute approved the project for the building of the physics institute, the construction began, and in 1917, in the completed building on Third Miusskaya Street, the physics institute was opened under the direction of P. P. Lazarev, chosen to be the director of the institute.[‡] I am purposely noting this fact, since this was the first research physics institute, large for its time, to begin extensive activities immediately after the revolution. After several renamings, which did not reflect the program of its activity, this institute was named the “Institute of Physics and Biophysics.”

Its director, P. P. Lazarev, elected an academician in 1917, was undoubtedly Lebedev's favorite student. This is evidenced by Lebedev's letters, some of which were published in P. P. Lazarev's book, “Outlines of the History of Russian Science,” and the fact that he alone was made by Lebedev his direct assistant and deputy.

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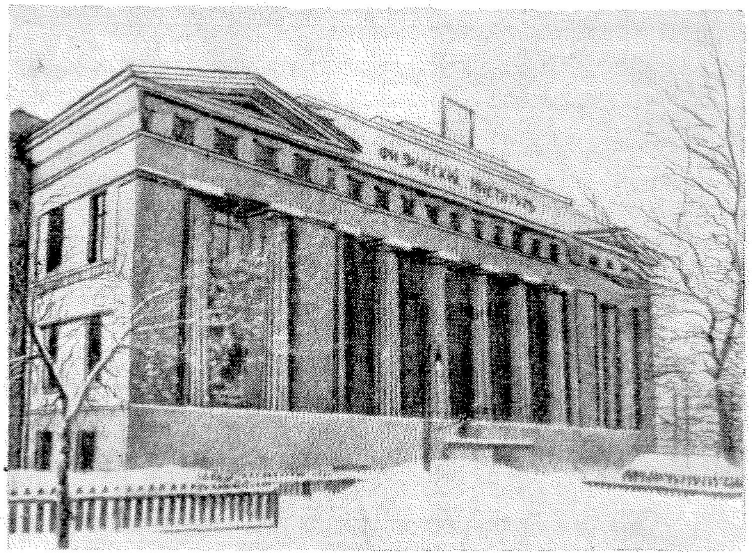
[*] The minister of education L. A. Kasso, himself a former professor of the Moscow university (a jurist), in response to a protest by the administration against violations of the autonomy of the university, ordered the dismissal “with transfer to the Ministry of Education” of the rector, his assistant, and his deputy, all outstanding scientists, well known for their scientific and social activity.

[*] P. N. Lebedev, Collected Works, M., 1913, p. 352x,

[†] Information concerning this society can be found in the brochure of Professor V. M. Khvostov “The Significance and Tasks of a Scientific Institute”, Moscow, 1913.

[‡] P. P. Lazarev, The Physics Institute of the Moscow Scientific Institute (in the book by Academician P. P. Lazarev “Outlines of the History of Russian Science,” edited by Academician S. I. Vavilov and Professor M. P. Volarovich, Moscow, 1950).



The institute of physics and biophysics (Moscow, Third Miusskaya St., 3).

A physician and physiologist by education, he was attracted to physics under the influence of Lebedev's colloquia, and rapidly retrained himself to become a full fledged physicist, acquiring during this process appreciable skill in mathematics and in theory of classical physics. This allowed him to turn to high-level research on applications of physics to biology, and to become one of the founders of biophysics. Being undoubtedly a romantic scientist in terms of the classification of W. Ostwald (W. Ostwald, Great Men), he had a great variety of interests; in particular, he played an outstanding role, which is insufficiently appreciated at the present time, in the investigations of the Kursk magnetic anomaly. Having the temperament of a romantic scientist, he eagerly inspired young people to work in the tradition of Lebedev's laboratory, starting from their student days. After leaving the university together with Lebedev, he surrounded himself, first in the already mentioned laboratory of the Shanyavskiĭ Municipal University, with a large group of young scientists, most of whom joined the newly opened physics institute. This group included P. N. Belikov, S. I. Vavilov, B. V. Il'in, G. S. Landsberg, T. K. Molodyĭ, A. S. Predvoditelev, S. N. Rzhevkin, N. T. Fedorov, V. V. Shuleĭkin, and É. V. Shpol'skiĭ. They were later joined by A. S. Akhmatov, the physiologist I. L. Kan, V. L. Levshin, P. A. Rebinder, and others. The names of these staff members of the first Soviet physics research institute—at that time young scientists, but subsequently occupying leading positions in scientific institutes and in the faculties of higher institutions of learning—are so well known, that they need no special elaboration. A group of older physicists was centered around the Moscow Physical Society (A. A. Éĭkhenval'd, V. K. Arkad'ev, A. I. Bachinskiĭ, S. A. Boguslavskiĭ, Yu. V. Vul'f, A. B. Mlodzeevskiĭ, and others).

Some of these scientists deserve special mention. We already referred to Éĭkhenval'd above. V. K. Arakd'ev one of the most talented students of Lebedev, distinguished for numerous original ideas. To be sure, he attempted unsuccessfully to interpret classically the "magnetic spectra" of iron, which were discovered by him, but, as shown subsequently by Ya. G. Dorfman, they were none other than manifestations of ferromagnetic resonance. The lack of a theoretical base for explaining the phenomenon discovered by him (1907–1913), the reality of which was confirmed by a number of foreign physicists (R. Gans et al.), and the primitive nature of the experimental techniques of that time (compared with the techniques presently used for the investigation of magnetic resonance) did not enable him to find a correct explanation for his discovery. In subsequent years he did much for the development of the phenomenological theory of ferromagnetism. A. I. Bachinskiĭ had a thorough knowledge of phenomenological thermodynamics; he is credited with a well known simple empirical formula connecting the viscosity of liquids with the specific volume, or more accurately, with the volume free of molecules; a theoretical derivation of this formula was presented by Ya. I. Frenkel'.* Yu. V. Vul'f was a crystallographer. And although the crystallography was in his time a branch of mineralogy rather than physics, Vul'f's main work was purely physical. Particularly important among his researches was the investigation of the surface energy of crystals. After the discovery of x-ray diffraction in crystals, Vul'f presented a correct geometrical explanation of the Laue x-ray patterns as the consequence of interference reflection of x-rays from suitably placed grid-like planes of the crystal. He was also one of the pioneers of x-ray structure analysis in Russia and in the USSR. S. A. Boguslavskiĭ, who unfortunately arrived in Moscow late (he worked for a long time abroad, particularly with M. Born), was a highly cultured theoretician, with full mastery of all the advanced ideas and methods of the theoretical physics of his day (the Bohr-Sommerfeld quantization, the correspondence principle, etc.). He developed the quantum theory of pyroelectricity and did important work on the motion of electrons in electromagnetic fields. Unfor-

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*See Ya. I. Frenkel', Kinetic Theory of Liquids, Moscow, 1945, p. 192

tunately, serious illness (active tuberculosis) did not enable him to create his own school in Moscow and led to his early death.

In our days, noting the outstanding progress of Soviet physics in the last fifty years, we must not forget the names of these predecessors whose labor and whose activity as scientists and university professors prepared a firm foundation for the grandiose edifice of Soviet physics of which we are proud.

The development of physics in Leningrad was different. In the early 90's, during the blooming of the activity of Lebedev and his school in Moscow, they did not feel the pulse of modern science in Petersburg. This is what the outstanding physicist, academician A. F. Ioffe, wrote on this subject[*]: "When I started to work in Petersburg (this was in 1906), the traditions of the 19th century were still strong there, and even the mid-century ideas of the school of F. F. Petrushevskiĭ. The teaching of physics at the university followed the line of the so-called measuring physics—methods of measurement as the foundations for precise knowledge. In all the higher institutions of St. Petersburg, the first course was devoted to a description of measuring instruments; the laws of heat, electricity, magnetism, optics, and acoustics were taught only in the second course. Theoretical physics, or more accurately, mathematical physics, was reduced in the universities to a phenomenological formulation of the laws and to a solution of partial differential equations in the field of thermodynamics and electrostatics. The professors and the instructors in the higher schools had profound erudition, but paid little attention to creative activity. The scientific work of those remaining at the university frequently amounted to only a repetition of already published work."[*]

However, it was just then when a group of young physicists appeared in Leningrad, destined to play an important role in the organization of Soviet physics. D. S. Rozhdestvenskiĭ carried out at that time at the Petersburg university, quite independently, his classical work on the anomalous dispersion in sodium vapor. A. F. Ioffe presented as a master's dissertation a brilliant paper on the "elementary photoeffect," where he proved, by a direct experiment using metal filings suspended in a Milliken capacitor, the electronic nature of the photoeffect from metals and the statistical independence of the elementary acts of the photoeffect. By the same token, in parallel with Milliken's work, he presented experimental proof of the existence of electrons and of optical quanta.

Belonging to the same pleiad of young physicists was D. A. Rozhanskiĭ, "whose dissertation (investigation of the spark) has attracted universal attention for the freshness of his physical ideas"[†].

Finally, a great influence was exerted by the then outstanding representative of theoretical physics, P. S. Ehrenfest, who worked at that time in Petersburg.[‡] Ehrenfest had by that time acquired great reknown, especially after the "Encyclopedia of Mathematical Sciences" published his monograph, written jointly with his wife T. A. Afanas'eva-Ehrenfest, on the principles of statistical mechanics. Having a sharp critical sense and extensive and varied interests in the most vital problems of theoretical physics at that time, he attracted to himself the young people by his unusually lively temperament. In 1912 he occupied the chair of theoretical physics at Leyden, which became free after the death of G. A. Lorentz. However, in spite of this he retained close connection with the Soviet physicists, and not only with his old friend A. F. Ioffe, but with the young physicists, students, and budding theoreticians. During his stay in Petersburg he organized at the university a seminar on the new physics literature, where papers on the most "burning" problems of physics—relativity and quanta—were hotly discussed. The rapid growth of theoretical physics in Petrograd, on the eve of the first world war (1907—1914) and during the first years of the revolution, are due to a considerable extent to his influence. Talented and highly erudite young theoreticians appeared—Yu. A. Krutkov, V. R. Bursian, G. G. Veĭkhard (who died young of typhoid). Later they were joined by A. A. Fridman, V. K. Frederiks, Ya. I. Frenkel', and V. A. Fock. These were persons whose age in those days was 25—30. Concentrated around them was a group of talented youth, thirsty for knowledge, aged approximately 20, and a sort of "chain reaction" occurred, which led to the appearance of so bright a representative of the next generation as L. D. Landau—one of the outstanding leaders of modern theoretical physics.

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[*] A. F. Ioffe, Soviet Physicists and Prerevolutionary Physics in Russia, UFN 33, 454 (1947).

[*] See article by G. Uhlenbeck and A. F. Ioffe, Usp. Fiz. Nauk 62, 367 (1957).

[†] A. F. Ioffe, ibid., p. 465.

[‡] A. F. Ioffe, ibid.

Group of Moscow physicists—students of P. N. Lebedev (middle row) and P. P. Lazarev (1913). Standing: P. N. Belikov, É. V. Shpol'skiĭ, F. K. Kurepin, V. V. Srebnitskiĭ, N. P. Neklepaev, K. A. Leont'ev, S. I. Vavilov, A. G. Kalashnikov, N. V. Baklin, A. S. Berkman, N. K. Shchodro, S. Ya. Turlygin, S. N. Rzhevkin, B. F. Rozanov. Sitting: V. S. Titov, G. B. Port, V. K. Arkad'ev, A. K. Timiryazev, L. I. Lisitsyn, P. P. Lazarev, M. A. Chuprova, A. B. Mlodzeevskiĭ, N. E. Uspenskiĭ. Sitting in front: N. B. Bausov ("tutor"), Fevralev, N. Ya. Selyakov, ?, T. K. Molodyĭ, P. P. Pavlov, P. V. Shmakov, A. I. Akulov (P. N. Lebedev's mechanic).

At the very start of the revolution there were in Petrograd two groups of physicists. One was connected with the seminar of A. F. Ioffe and included at that time young scientists whose names are presently known to the entire world. These were P. L. Kapitza, N. N. Semenov, Ya. I. Frenkel', and P. I. Lukirskiĭ. The second group consisted of enthusiasts of scientific and applied optics headed by D. S. Rozhdestvenskiĭ and his companions in arms struggling for the organization of an optical-mechanical industry in Russia (A. I. Tudorovskiĭ, A. L. Gershun Sr., and others). Among the youths belonging to this group at that time were I. V. Obreimov, I. V. Grebenshchikov, and the students A. N. Terenin, S. É. Frish, V. K. Prokof'ev, and others. These groups, together with the Moscow group of P. P. Lazarev, which was referred to earlier, made up the centers about which there were created and grown the large Soviet scientific physics and research institutes constructed during the first years of the revolution.

From the first days of the revolution, the Soviet government undertook large-scale organization of scientific research. The intense development of scientific research institutes was the logical outcome of the undeviating principle of the Soviet government, whereby scientific research was made the basis of the industrial development of the country, of its agriculture, of health preservation, and of culture. Science was recognized to be an essential element of state development. The dream of the outstanding Russian scientists at the end of the 19th century and the start of the 20th was realized by the Communist party and the Soviet state.

As to physics, the planned development of scientific institutes began as early as in 1918. During those severe years, at the height of the war with counterrevolution and intervention, with many economic difficulties which the revolution inherited from the first world war, there were organized the largest institutes, which soon lead science in the USSR to a new higher level. The pioneers in this historically important matter were the outstanding Soviet scientists P. P. Lazarev, A. F. Ioffe, and D. S. Rozhdestvenskiĭ. The first of them, P. P. Lazarev, as already mentioned, created in Moscow the Institute of Physics and Biophysics on the basis of the physics institute of the Moscow Scientific Institute, organized just before the revolution, and including in its program a large group of problems in physics, biophysics, and geophysics. A. F. Ioffe and D. S. Rozhdestvenskiĭ organized in Leningrad the physico-technical and optical institutes. Their first co-workers of these institutes were young scientists, then gathering around their leaders. Subsequently, many of them created their own scientific schools, which by now extend over two generations of scientists.

In December, 1918 the first congress of the Russian physicists* was convened in Petrograd and played the role of an organizing congress for Soviet physics, since the "Russian Association of Physicists" was based on it. Petrograd went through a hard time during those days: it was empty, cold, and hungry. But the enthusiasm of a relatively small group of scientists of different ages, vividly discussing the scientific problems of those days, was so large that it caused the participants to forget quickly these external difficulties.

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*One must not confuse this congress, which, owing to the circumstances of that time, could be attended only by physicists from Leningrad and Moscow, with the first congress of the Russian (which at that time was equivalent to "All-union") Association of Physicists, which was held in Moscow in 1920.

First congress of Soviet physicists (Petrograd, 1918). Front row: ?, P. N. Nikiforov (geophysicist), Yu. V. Vul'f, P. P. Lazarev, A. N. Krylov, O. D. Khvol'son, S. Ya. Tereshin, ? , In the third tow on the left side: A. S. Predvoditelev, A. I. Bachinskiĭ, P. V. Shmakov, K. N. Shaposhnikov.

The mood of those gathered can be characterized by the splendid words of D. S. Rozhdestvenskiĭ, expressed one year later on 15 December 1919, at the conclusion of his lecture "Spectral Analysis and Atomic Structure" at the first annual gathering of the already organized Optical Institute[*]: "We live in the whirl of a social revolution. The structure of human life is rapidly being recast to provide the future with sought and desired happiness--with inevitable severity and with unavoidable, destruction of the old... And if it turns out that the vigorous tendencies of social revolution are unavoidable, then science, the source of the material benefits of the near future must be conserved in this revolution."

"We, however, in spite of the words of the poet, will not 'carry away the lit candles into catacombs, deserts, caves,' in 'fear of change,' but will make them brighter and raise them on a mountain, so that they produce light for everyone."

In the late 20's and in the 30's, the organization of new physical research institutes was greatly expanded. The greatest activity in this important matter, as in the organization of Soviet physics in general, was that of A. F. Ioffe, a brilliant physicist, gifted with an unusually subtle physical intuition, who was at the same time an outstanding social worker in the field of organization of science, strongly devoted to the matter of advancing Soviet physics At his initiative, institutes were organized in a number of important commercial centers and on the periphery of the country. Wishing to collaborate most closely with these newly organized institutes, he adopted such an effective measure as assigning to them important and talented members of the physico-technical institute led by him, thus endangering for a time the normal development of his own institute. Finally, mention must be made of Ioffe's initiative in the training of cadres of physicists, namely the organization of an entirely new type of department at the Leningrad polytechnic institute, namely the physico-technical department.

New large institutes were also organized in the center of the country, in Moscow and in Leningrad. One of them was the P. N. Lebedev Physics Institute of the USSR Academy of Sciences. It was initially based on the same physical laboratory of the Academy of Sciences which was mentioned earlier, but, starting with 1934, when the academy moved to Moscow, it turned into a powerful scientific center, owing to the energy and initiative of its director S. I. Vavilov.[*]

We note further the Institute of Physics Problems of the USSR Academy of Sciences, organized by P. L.

[**] D. S. Rozhdestvenskiĭ, Spectral Analysis and Atomic Structure, Trudy (Transactions) of the State Optical Institute, Vol. 1, No. 6, Petrograd, 1920, p. 87.

[*] For the history of this institute see the article by S. I. Vavilov, "Physics Cupboard–Physics Laboratory–Physics Institute of the USSR Academy of Sciences over 220 years," USP. Fiz. Nauk 28 (1), 1 (1946); see also the article by D. B. Skobel'tsyn and I. M. Frank, ibid. 63 (3), 503 ff (1957).

A. F. Ioffee

Kapitza and famous for its remarkable work in the field of low-temperature physics, theoretical physics, and other branches. The Ukraine has a number of large institutes, including the physico-technical institute in Kharkov and the physics institute of the Ukrainian Academy of sciences in Kiev. The Siberian Physico-technical Institute was organized in Tomsk, and the Institute of metal physics in Sverdlovsk. Scientific centers devoted to physics were organized in Belorussia, Georgia, Armenia, Kazakhstan, and other republics. Recently, many institutes were organized in the Siberian Division of the USSR Academy of Sciences. It is not the purpose of this article to review the activities of all the institutes and the research laboratories organized after the revolution, which carried out intensive work on a high modern scientific and technical level. An important role in the development and strengthening of the physics institutes of the USSR Academy of Sciences, its branches, expeditions, and bases was played by the activity of the president of the USSR Academy of Sciences, S. I. Vavilov (1945–1951).

Special note should be taken of the growth of nuclear physics and physics of elementary particles in the Soviet Union during the postwar years, in connection with the exceptional significance of work in these fields. As is well known, work in nuclear physics imposes particularly heavy demands both on the creative activity of the scientist and on the scientific and technical level of the institutes and laboratories; this in turn imposes unprecedented high requirements with respect to the general level of technology in the country. The organization of work in this field was undertaken in the Soviet Union on a large scale. A number of laboratories, with the latest type of equipment, were organized. Among them were also large institutes, namely the Institute of Atomic Energy in Moscow and the Joint Institute for Nuclear Research in Dubna.

D. S. Rozhdestvenskiĭ

In subsequent years, owing to the rapid growth of the role of semiconductors in physics and engineering, a special Institute of Semiconductors was organized at the USSR Academy of Sciences by A. F. Ioffe, and now bears his name.

Besides the organization of institutes specially engaged in research, the old university centers were also

S. I. Vavilov

greatly expanded. The largest of them was the Physics Institute of Moscow University, which played a most important role in the development of physics in the USSR, principally owing to the work of L. I. Mandel'shtam and his school in the field of physical optics and oscillation theory. In 1953 this institute has acquired very richly equipped scientific laboratories in a new building in Leninskie Gory. Much work was also performed at the Physics Institute of the Leningrad university, in the Odessa, Kiev, and Tomsk universities, and in many other places.

II. REVIEW OF WORK OF SOVIET PHYSICISTS

We shall attempt in what follows to review the most important work performed by the Soviet physicists during the last fifty years. During this half-century, physics itself has indeed undergone tremendous changes. In this victorious movement, which established mastery of man over nature on a scale of unprecedented grandeur and which led to deeper penetration into nature's laws, Soviet physicists march in the forefront in all fields of their immeasureably wide science. In an article of limited size, as the present one, we cannot even think of completely describing all the work performed by the Soviet physicists, nor even provide a list of physicists to whom our science owes its growth. I had to confine myself willy-nilly in the choice of the discussed problems, and particularly to disregard borderline regions such as astrophysics, which has become much closer to physics than before as a result of latest research. Nor did I touch upon biophysics, which has entered upon an entirely new and highly promising period of development, chemical physics which was created during the same fifty-year period, or geophysics. All these, although connected with physics, are major branches independent of science, and each would require a large article for itself. The possible imbalance in the emphasis on different branches of physics is unavoidable in an article written by a single author. The repetitions found in some places are purposely intended to spare readers with a limited group of interests the need of reading the entire article.

With all these stipulations, I would be unable to perform this most difficult task of presenting a competent, modern, and at the same time sufficiently extensive picture of the remarkable accomplishments of Soviet physics, were it not for the friendly cooperation of a number of the editorial staff of this journal, as well as other colleagues to whom I turned for advice.

General Problems of Theoretical Physics

Theoretical physics as an independent "profession" arose as a result of the unusual development of physics in the 20th century.* In the 19th century, most prominent physicists were theoreticians and experimenters. Examples among the scientists of the 19th century and the beginning of the 20th are Lord Rayleigh or J. J. Thomson. The deep theoretical papers of L. Boltzmann are universally known, but it is possible that not all know that he performed subtle experiments on the dielectric constants of gases. Many physicists in Russia were simultaneous theoreticians and experimenters—A. G. Stoletov, N. A. Umov, N. N. Shiller—and their activity was confined either exclusively or principally to the 19th century. Gradually, however, both mathematical and experimental methods have become so much more complicated that the physicists had to make the unique decision of "choice of a profession," whether to become a theoretician or an experimenter.


A. A. Fridman

Since the theoretical physist may be engaged in any physical problem, the concept "theoretical physics," strictly speaking, encompasses all of physics. In our review we include in the special classification "theoretical physics" those investigations that pertain to the most common problems and theories of modern physics: relativity theory, quantum mechanics, and statistics. At the same time, references to the work by the theoreticians will be given in practically all subsequent headings. It goes almost without saying that in a review such as ours, which encompasses all of physics, the deepest and most difficult works of theoretical physics can be described only cursorily and superficially—practically only by name.

Prior to the revolution, theoretical physics in the sense in which it is now understood was weakly represented in Russia. And this took place in spite of the fact that relativity theory, both special and general, Planck's quantum theory, the Bohr atom with its problems of quantization of different systems, and finally, classical statistics, already existed at the time of the revolution. Under the new conditions for scientific work created by the Soviet government the freshly organized scientific research institutes and the old universities already had in attendance at that time young theoreticians such as I. E. Tamm, Ya. I. Frenkel', Yu. A. Krutkov, V. A.

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*Incidently, M. Planck, whose activity as a scientist started in the 70's of the 19th century, was already a pure theoretician. He regarded F. Neumann (1798-1895) as the "father" of theoretical physics in Germany (see M. Planck, Vortrage und Erinnerungen, Stuttgart, 1949).

Ya. I. Frenkel'

Fock, A. A. Fridman, and a few others, who formed the nucleus for subsequent intense quantitative and qualitative development of theoretical physics in the USSR.

At the present time our country has large schools headed by theoretical physicists. We note the large groups of students of I. E. Tamm (S. A. Al'tshuler, S. Z. Belen'kiĭ, D. I. Blokhintsev, S. V. Vonsovskiĭ, A. D. Galanin, V. L. Ginzburg, A. S. Davydov, M. A. Markov, S. I. Pekar, A. D. Sakharov, E. L. Feĭnberg, S. P. Shubin, V. S. Fursov and others) and L. D. Landau (A. A. Abrikosov, A. I. Akhiezer, V. B. Berestetskiĭ, L. P. Gor'kov, I. E. Dzyaloshinskiĭ, V. G. Levich, E. M. Lifshitz, I. M. Lifshitz, A. B. Migdal, L. P. Pitaevskiĭ, I. Ya. Pomeranchuk, I. M. Khalatnikov, Y. A. Smorodinskiĭ and others). Most of these theoreticians, who are in fact the third generation of Soviet physicists, already have their own students (we mention M. Ya. Azbel', V. V. Zheleznyakov, É. A. Kaner, L. V. Keldysh, D. A. Kirzhnits, M. I. Kaganov, L. B. Okun', V. P. Silin, S. I. Syrovatskiĭ, V. Ya. Faĭnberg, E. S. Fradkin and others). In the 40's a school was founded by N. N. Bogolyubov (A. A. Logunov, S. V. Tyablikov, M. K. Polivanov, V. L. Bonch-Bruevich and others).

Among the works on the most general problems of theoretical physics, mention must first be made of the well known paper by A. A. Fridman on general theory of relativity. In this paper, A. A. Fridman showed, for the first time, that Einstein's gravitation equations of general relativity theory admit of nonstationary solutions. Yet Einstein introduced in 1917 the so-called cosmological term into his gravitation equation, with a "cosmological constant" λ, precisely for the purpose of ensuring stationarity of the universe, that is, constancy of its radius. Fridman's conclusion was that, in spite of this seemingly obvious requirement, Einstein's gravitation theory leads to the possibility of a change in the "radius of the universe" in course of time, particularly, to an expanding universe. This conclusion was first refuted by Einstein, but he later admitted that the conclusion is correct, and his objection was based on an error in the calculations. Seven years after the publication of Fridman's paper, the American astronomer Hubble made a striking discovery that remote galaxies travel away from us with tremendous velocities, which increase in proportion to the distance to these galaxies. This conclusion was made on the basis of the strong red shift of the lines in the spectra of the galaxies, which was naturally interpreted as a Doppler shift; an attempt to interpret this shift as a consequence of "aging of photons" on the long path from the galaxy to the earth is untenable.* Later contributions to the development of general relativity theory and to its applications to cosmology were made by Ya. B. Zel'dovich, E. M. Lifshitz, I. D. Novikov, A. Z. Petrov, I. M. Khalatnikov, and a few others. A very important work on the theory of gravitation was made by V. A. Fock, devoted to an approximate solution of the n-body problem in Einstein's gravitation theory.

Modern quantum mechanics was developed in the 20's in papers, which appeared in rapid sequence, by L. de Broglie, E. Schrödinger, W. Heisenberg, N. Bohr, and P. A. M. Dirac. From the instant of formulation of the principal ideas of the equations of quantum mechanics, the Soviet theoretical physicists took most active part in the development of approximate methods of solving Schrödinger's equation and in the application of the methods of quantum mechanics to solutions of a great variety of particular problems. In this section, as already mentioned, we shall dwell only on the result of investigations of most general character.

These include the studies by V. A. Fock, devoted to an approximate method of solving Schrödinger's equation for many bodies. As is well known, Schrödinger's equations can solve in principle any problem of quantum physics. For a many-body system, however, the problem soon becomes so complicated that an exact solution is impossible. But there is no need for an absolutely exact solution for such problems, since the measurement accuracy is always limited. Therefore the greatest importance attaches to good approximate methods. One such reliable method in quantum mechanics is the so called Hartree-Fock method proposed by Hartree and then radically improved by V. A. Fock. This method is based on the model of the so called "self-consistent field," in which, for example, to solve the problem of the many-electron atom, each electron is assumed to move in the field of the nucleus and in the average field produced by the remaining electrons. The radical improvement introduced by V. A. Fock leads to equations for the wave functions of the individual electrons; these equations contain, besides the terms that enter in the earlier equations, also terms corresponding to the interaction between the electrons, namely the exchange interaction. Solution of these equations makes it possible to calculate, in the case of the atom, the energy

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*See the article by Ya. B. Zel'dovich "A. A. Fridman's Theory of the Expanding Universe, Usp. Fiz. Nauk 80, 357 (1963) [Sov. Phys.—Usp. 6, 475 (1964)].

levels and the intensities of the spectral lines. For example, this method was used by V. A. Fock and M. A. Petrashen' to solve the problem of the sodium atom, and to obtain the principal term and the ionization potential of sodium, with accuracy to 2%. One must not forget that all these calculations were made in the 30's, when modern computers were still non-existent.

Among the trail-blazing papers in which general problems of quantum physics were solved is the paper by L. I. Mandel'shtam and M. A. Leontovich concerning the behavior of a quantum particle in the presence of a potential barrier in space. This paper contained the principles of the theory of "tunnel transitions"—a unique phenomenon which, as is well known, plays a most important role in numerous processes on the atomic or nuclear scale, that is, processes constituting the fundamental phenomena in atomic physics and electronics.

In subsequent years, the efforts of the theoreticians were aimed at the development of relativistic quantum mechanics and quantum electrodynamics or, more accurately, the quantum theory of fields in general (bearing in mind not only electromagnetic but also meson fields). In these most important problems, which are connected with the application of the most refined mathematical methods, the Soviet theoretical physicists felt themselves "at home" and introduced major contributions. Without claiming to present even a sketchy idea of the results, we mention I. E. Tamm's theory of nuclear forces and the approximate method developed by him for the solution of the equations of quantum mesodynamics, a method different from the usually employed perturbation theory (the so called Tamm-Dancroff method; a similar method was used earlier by V. A. Fock to solve certain problems of quantum electrodynamics).

Of great importance in the field of general thermodynamics and statistics were the investigations of L. D. Landau on the thermodynamic theory of second-order phase transitions, which include certain transitions in alloys, transformations of ferromagnets into paramagnets, and in general transformations connected with "Curie points." Important work on the principles of statistical mechanics was published by N. N. Bogolyubov and M. A. Leontovich. N. N. Bogolyubov published well known papers on the theory of kinetic equations and the theory of wave fields (a rigorous proof of the dispersion relations, etc.).

One of the most sensational discoveries of the last decade was the establishment of the striking fact that the concept of "left" and "right" exist in the properties of space. The experimentally observed seeming contradictions in the behavior of K mesons was explained by Lee and Yang (USA) as being due to violation, in K meson decay, of one of the most important laws of conservation of quantum mechanics, namely the law of "parity" conservation. The gist of the parity conservation principle, simply speaking, is the requirement that the laws of nature must remain invariant against mirror reflection. The initial hypothesis advanced to explain the violation of the principle of parity conservation in so called "weak interactions" in the special case—in K-meson decay—was soon confirmed quite convincingly by the experiments of Wu and a group of workers at the National Bureau of Standards in the USA with β decay of oriented Co^{60} nuclei.

In connection with this problem, L. D. Landau advanced an unusually interesting principle, by virtue of which the left-right symmetry is connected with electric charge. This means that if a particle with positive charge possesses a spatial asymmetry of a definite type, say right-hand helical, then a particle having a negative charge should have an opposite asymmetry, that is, left-hand helical. Since the mirror reflection of a right-hand screw is a left-hand screw, the violation of symmetry in the mirror reflection is compensated by the reversal of the sign of the charge. Thus, the asymmetries existing in nature—the asymmetry of the electric charge and the spatial left-right asymmetry—combine into some new higher type of symmetry, which is manifest in a principle which Landau called the "combined parity principle," or in the principle of so called CP invariance (C—charge, P—parity). We are possibly on the eve of new important discoveries in this interesting region, where very deep fundamental laws of nature become manifest. It should be noted in this connection that certain doubts were also expressed recently concerning CP invariance.

Connected with parity nonconservation, is the so called two-component neutrino theory, proposed by L. D. Landau. According to this theory, two spin states correspond to each momentum and not the four that must be assumed in order to satisfy the parity-conservation principle. These states are such that the spin of the neutrino is parallel to the momentum, and the spin of the antineutrino is antiparallel. One can visualize this by assuming that the spin and the parity of the neutrino correspond to rotation and translational displacement of a right-hand screw, and the spin of an antineutrino to rotation and translation of a left-hand screw. This theory has many important consequences and introduces considerable simplifications in the previously existing notions of the theory of elementary particles.

Physics of Elementary Particles

This fundamental new field of research has been attracting special attention recently. Its development is closely linked with the possibility of "probing" matter by high-energy and ultra-high-energy particles, by which we mean particles with energies measured in billions ($1 \text{ GeV} = 10^9$ eV and tens and hundreds of billions of electron volts, and in recent years efforts have been undertaken in the US and in the USSR to obtain, in a controlled manner, particles with energies of 1000 GeV, that is, 10^{12} eV. In view of the connection between elementary particle and high-energy-particle research, this field is frequently called high-energy physics.

The reason for the lively interest in high-energy physics and for the tremendous expenditures on research in this field, undertaken by the major countries, including of course the USSR, lies in the possibility that it affords for an extremely deep insight into the world surrounding us, and a discovery of the fundamental laws of nature and possibly also of the structure of space and time. Without going into details, we can justify these expectations by a simple reference to a quantum law—the direct consequence of the wave properties of all types of matter—stating that the smaller the dimensions of the region of investigated space or time interval, the shorter the wave length used for this purpose must be, and consequently the higher the energy. This law is universally valid; it encompasses all problems of resolution, starting with the resolution of optical and electronic microscopes and ending with that of accelerators rated many GeV; the latter are also microscopes of a sort, which make it possible to delve into the finest detail on the structure of the microcosm. However, the most important property of high-energy particles is the fact that, besides penetrating into the structure of "elementary" particles, they themselves serve as generators of new particles with very unique properties.

During the first steps of the development of high-energy physics it was impossible to organize experiments that could be controlled in detail. There was only one source of high-energy particles, cosmic rays. These, as is well known, are streams of charged particles, mostly protons, that reach the earth from outer space. The number of cosmic-ray particles incident on one square centimeter per second is relatively very small, but because of their high energy it was possible to observe with the aid of cosmic rays many important phenomena pertaining to elementary-particle physics. It suffices to recall that the most important new elementary particles, namely positrons, μ mesons, and π mesons, were discovered just in cosmic rays. At the present time, in view of progress in accelerator technology, which has made it possible to perform experiments in this field under controlled conditions, many phenomena which could earlier be observed only in cosmic rays became accessible to laboratory experimentation. In spite of this, a study of cosmic rays has retained its significance for the investigation of phenomena at ultra high energies. In connection with the wide range of the results obtained in this field, the study of cosmic rays has become an independent and rather broad field of science. Notice must be taken, however, of the important discoveries which were made by Soviet physicists during the first stages of the study of this most interesting phenomenon, which for a long time was the only way of investigating the unique laws of nature that take place at high energies.

We mention first that during the earliest stages of the research on this field, in the 20's, following Millikan's very well known study of cosmic rays by burying charged electroscopes in deep mountain lakes, many observations of similar character were made by L. V. Mysovskiĭ. The most important investigations, which were the first to uncover the nature of this apparently puzzling radiation, were made in the late 20's by D. V. Skobel'tsyn. In 1927, while studying the recoil electrons resulting from the Compton effect on gamma rays with the aid of a cloud chamber placed in a magnetic field, Skobel'tsyn observed in his photographs a number of particles which were not deflected by the magnetic field at his disposal. Assuming that these particles are electrons, Skobel'tsyn estimated their energy from the curvature of the track to be not less than 15 MeV; he ascribed them to the results of the interaction between cosmic rays and matter.

In his next study, in 1929, Skobel'tsyn observed that frequently one photograph showed tracks of two or three such high-energy particles. A statistical analysis of the frequency of such a simultaneous appearance of several particles has shown that, with a high degree of probability, one can state that this coincidence is not accidental and that these particles are related with one another. This revealed a remarkable phenomenon, called particle showers. Subsequently, using a cloud chamber in a magnetic field, triggered by counters connected for coincidence, (a set-up which permits a cloud chamber to operate precisely when high-energy particles pass through it), Blacke and Occhialini photographed a large number of showers of many particles, and subsequently Anderson discovered positrons in the showers. All these facts justify the claim that the aforementioned research by Skobel'tsyn laid the foundation for the understanding of the nature of cosmic rays—a phenomenon which differs greatly from ordinary phenomena, and essentially pioneered the research in the field of high-energy physics.

For the reason indicated above, I am unable to trace further the history of research on cosmic rays and the part played in it by Soviet physicists in a number of expeditions. Much material on these questions can be found in the book of N. A. Dobrotin.*

A particularly intense development of elementary-particle physics began when accelerator techniques improved and made it possible to obtain streams of charged particles with energies measured in billions of electron volts, and with intensity greatly exceeding the very weak intensity of cosmic radiation. This has made it possible to reproduce under laboratory conditions, phenomena were observed in cosmic rays as very rare events, and to accumulate by the same token tremendous amounts of information. To be sure, in cosmic rays one encounters a small fraction of particles with energies up to 10^{20} eV, i.e., at least six orders of magnitude larger than the energy realized in the modern most powerful accelerators. But since progress in any branch of physics depends not only on the perfection of the experimental techniques but also on the status of the theory, which makes it possible to interpret the results of the observations, the data that can be obtained with existing accelerators and will be obtainable with the accelerators now under design or construction, creates a vast field for the work of experimenters and theoreticians.

A decisive advance in the construction of modern powerful cyclic accelerators was attained as a result of the work of V. I. Veksler, who proposed and proved the so called phase-focusing principle (1944)†. The gist of the matter, in short, is as follows. As is well known, the particle energy attainable with a cyclotron is limited by the relativistic dependence of the mass on the velocity; when the particle velocity becomes comparable with velocity of light, the period of revolution of the particle T becomes different from the period of the accelerating electric field T_0, as a result of which the resonance between the field and the cyclic revolution of the particle is disturbed and the particle begins to decelerate upon entering the gap between the dees. However, Veksler called attention to the fact that this deceleration and the associated change in energy will continue until T again

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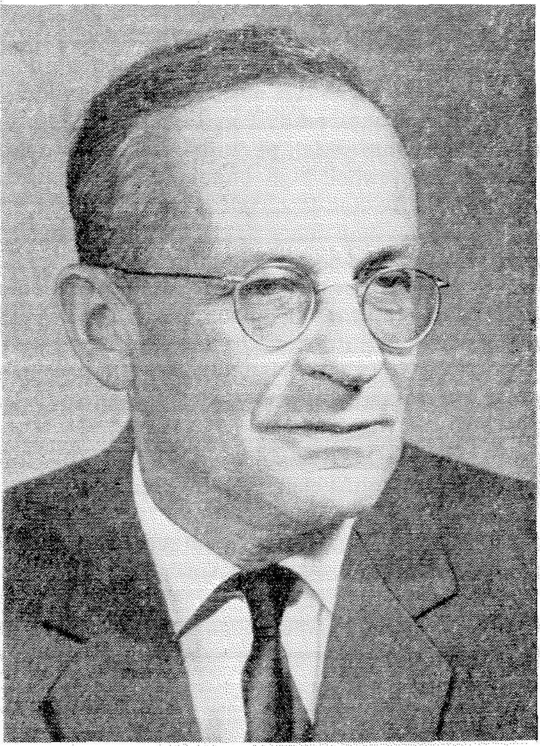
*N. A. Dobrotin, Kosmicheskie luchi (Cosmic rays), Gostekhizdat, 1954.

†The same principle was used by McMillan in the USA, somewhat later than Veksler and independently of him, in a project for improving cyclic accelerators.



V. I. Veksler

becomes equal to T_0. If therefore one varies T_0 adiabatically, then T will oscillate about T_0, change together with it, and the energy will oscillate about a growing value corresponding to T_0; it is possible therefore in principle to increase the particle energy in the accelerators without limit without greatly increasing the potential difference between the dees. This is the extremely clever principle of phase focusing, which has immediately started a new era in the construction and consequently also the application of accelerators. The FM and proton synchrotrons created on this basis have made it possible to progress from particle energies amounting to several dozen MeV to energies of several dozen GeV. In general, the attainable energies has come to be limited only by the technical possibilities and by economic considerations (by way of an example of the role of the latter, we can cite the following figures: the 6.2-GeV bevatron of Lawrence laboratory at Berkeley, California cost $30,000,000 to build, and its annual operating cost is $22,000,000.[*]

Great accomplishments were the launching of powerful accelerators for protons—the proton synchrotron of the Joint Institute for Nuclear Research (Dubna), rated 10 GeV, and the first strong-focusing proton synchrotron in our country, rated 7 GeV, of the Institute of Theoretical and Experimental Physics in Moscow. These installations were the result of joint work by a large staff of Soviet physicists headed by V. I. Veksler, A. I. Alikhanov, V. V. Vladimirskiĭ, D. V. Efremov, E. T. Komar, the staff of the Radio-technical Laboratory of the USSR Academy of Sciences headed by A. L. Mints, and was aided by a number of other scientific and technical establishments, among which we must mention the P. N. Lebedev Physics Institute of the USSR Academy of Sciences (A. A. Kolomenskiĭ, V. A. Petukhov, M. S. Rabinovich).

Besides these powerful accelerators and a number of proton accelerators rated less than 1 GeV, there are in operation in the USSR electron accelerators for 2 GeV (A. I. Alikhanyan, Erevan) and 6 GeV (K. D. Sinel'nikov, Khar'kov). Finally, the largest accelerator in the world, for a proton energy of 70 GeV, is now under construction at the High-energy Physics Institute in Serpukhov.

Although phase focusing in cyclic accelerators makes it possible in principle to increase the energy of the particles without limit, two principal difficulties hinder further development of this technique. The first lies in the dimensions and cost of these structures. The second is that, by virtue of the laws of relativistic dynamics, only a fraction of the energy of the particles accelerated in these devices can be used for its direct purpose; when the energy of the incoming particle exceeds the rest energy of the investigated particle, the greater part of the energy is consumed in the motion of the common center of mass of the two particles, and only an insignificant part remains in the center of mass system. Yet it is precisely the latter energy which is the cause of the phenomena whose study requires the construction of the accelerator. In order to avert such an ineffective utilization of expensive energy, it was proposed to direct particles with equal momenta head-on towards each other. In this case both coordinate systems—the laboratory system and the cns—coincide, and even in the nonrelativistic case the collision energy of two identical particles turns out to be four times larger, and whereas the energy gain is even greater in the relativistic case. This is the basic principle of a perfectly new trend in the development of charged-particle accelerators—colliding beam accelerators. The practical realization of this principle encounters the following difficulty: in a colliding-beam installation, the target is the second beam, and its density is lower by many orders of magnitude than the density of the condensed medium which serves as a target in experiments with ordinary accelerators. However, this difficulty can be greatly reduced by causing the beams to pass through each other many times in so called storage rings.

Work on the construction of electron accelerators with colliding particle beams is carried out at the Novosibirsk Institute of Nuclear Physics under the leadership of G. I. Budker, where accelerators with both colliding electron beams and colliding electron-positron beams were started. Work is under way toward the construction of accelerators with colliding proton-proton beams.[*]

After the invention of the betatron, Soviet physicists have demonstrated that the "ceiling" for the acceleration of electrons by this instrument is due to the fact that in final analysis the accelerated electrons should, by virtue of the laws of classical electrodynamics, start to lose energy as a result of radiation of electromagnetic waves (D. D. Ivanenko, I. Ya. Pomeranchuk, and

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[*] According to the report on the state of physics in the USA: Physics, Survey and Outlook, National Academy of Sciences—National Research Council, Washington, 1960, p. 53, Table 2.

[*] G. I. Budker, Usp. Fiz. Nauk 80, 553 (1966). [Sov. Phys.-Usp. 6, 542 (1967)].

A. A. Sokolov, and later—L. A. Artsimovich and I. Ya. Pomeranchuk). Such radio and visible radiation (coherent and incoherent), which for understandable reasons is called "synchrotron radiation" was in fact discovered and investigated by Pollock in the USA and by A. M. Prokhorov at the Physics Institute of the Academy of Sciences. We note, incidently that the fact that radiation is produced when electrons move in a magnetic field along curvilinear trajectories recently found an unexpected application in astrophysics. Namely, according to a hypothesis advanced by V. L. Ginzburg and I. S. Shklovskiĭ and confirmed by subsequent polarization measurements, the continuous spectrum emitted by nebulas—envelopes of supernovas—is attributed to precisely similar motion of cosmic electrons in interstellar magnetic fields. According to the hypothesis developed by V. L. Ginzburg and I. S. Shklovskiĭ, the "synchrotron" radiation of charged particles makes it possible to observe regions where cosmic rays are generated.

In parallel with the growth of the energy of the "probing" particles, tremendous progress and modernization took place in the physical-experimentation techniques used in all branches of high-energy physics. One of the main instruments which make it possible to investigate in detail the particle interactions (especially multiparticle interactions) is a bubble chamber filled with liquid hydrogen or with a heavy liquid. The dimensions of such chambers now reach two meters (Dubna, institute of Theoretical and Experimental Physics (ITÉF) in Moscow). To measure the hundreds of thousands of photographs obtained with the chambers, automatized devices were developed, in which the data are processed with the aid of high speed computers. Widely used in accelerator experiments are spark chambers, which make it possible to determine with high accuracy the coordinates of the particle trajectories. The capabilities of physical experiments were greatly extended by track instruments of a new type—spark chambers with large gaps (Chikovani, Alikhanyan, Dolgoshein). The use of spark chambers operating "in line" with computers (Dubna) has made it possible to create spectrometers with high resolution and with a high particle-registration speed.

The main particle detectors in accelerator experiments are now high-speed scintillation and Cerenkov counters; the latter are based on the radiation discovered by S. I. Vavilov and P. A. Cerenkov, which accompanies particles that move with a velocity exceeding the velocity of light in the medium (see p. 000 of present article). The counters based on this phenomenon have in some cases great advantages over other types. For the investigation of rare processes of decay and interaction of particles, complex experimental setups were developed, containing a large number of such detectors and registering particles with accuracy better than 10^{-9} sec (Dubna, ITÉF).

All these new and exceedingly powerful means of research have extended to a tremendous degree the ability to penetrate into the nature of matter. When the probes 3--5 MeV particles, it was possible to penetrate inside the atoms up to distances of the order of 10^{-12} cm, and this led to the discovery of the atomic nucleus. But when the probes are 700-MeV electrons, it is possible to study the entire structure of the very nucleons that make up the nucleus, heretofore considered to be "true" elementary particles, the "building blocks of the world structure." This has made it possible to increase the penetration by two more orders of magnitude—to distances 2×10^{-14} cm. Finally, protons with energies of several or several dozen GeV have unexpectedly revealed an entirely new world—more than 200 new particles. Some of them are long-lived, with lifetimes 10^{-6}--10^{-10} sec, or more accurately "long-lived" in nuclear time, the unit of which is 10^{-22} sec, and therefore a particle that "lives" 10^{-10} sec in accordance with our time, "lives" 10^{12} units of nuclear time, that is, it can even be called "stable." Besides these long-lived particles, many short-lived particles were recently discovered—resonances with lifetime shorter than 10^{-20} sec.

The main task of elementary-particle physics is the investigation of interactions between these particles. There are four main types of interaction: strong, weak, electromagnetic, and gravitational.

Strong interaction is characterized by a very small radius ($\sim 10^{-13}$ cm), and was first observed in the study of atomic nuclei. On coming closer than 10^{-13} centimeters, strongly interacting particles, the so called hadrons, attract or repel each other with such an intensity that the energy of their interaction can become comparable with their mass. An experimental investigation of strong interaction is proceeding in several different directions.

Extensive and valuable material at energies up to 1 GeV was accumulated with the aid of the Dubna synchrocyclotron. This accelerator, whose maximum energy is 680 MeV, was used to investigate the interactions of protons, neutrons, and pions with protons and nuclei. The properties of nucleon-nucleon and pion-nucleon scattering were established during the course of these investigations in a wide range of energies (B. M. Pontecorvo, V. P. Dzhelepov, M. G. Meshcheryakov, and others).

Strong interactions at energies on the order of several GeV are dealt with in research on K mesons, hyperons, and most resonances. The Dubna synchrotron helped discover the $\bar{\Sigma}^-$ hyperon, observe the $\Lambda\eta$ resonance, and determine the properties of several other resonances (V. I. Veksler, I. V. Chuvilo, A. V. Lyubimov). The meson resonance with mass 1600 MeV was discovered with the Moscow ITÉF synchrotron (Smolyankin).

Strong interactions at exceedingly high energies can explain the so called asymptotic properties of strong interactions. In this connection, great interest attaches to measurement of the scattering cross sections of high-energy particles through different angles. In the synchrotron experiments in Dubna it was shown, in particular, that the real part of the amplitude of the zero-angle nucleon-nucleon scattering is comparable with the imaginary part (Strunov, Sviridov). Experiments with artificial satellites of the "proton" series yielded preliminary data on the cross section for the interaction between protons and carbon nuclei (N. L. Grigorov).

No theory of strong interaction has yet been developed. Perturbation-theory methods cannot be used here, owing to the large interaction energy. The main efforts of the theoreticians were aimed at developing an approach that makes use of the important circumstance that causality (the absence of superluminal signals in nature) leads to analyticity of the amplitudes describing the particle-interaction processes. Analyticity of the amplitudes makes it possible to establish for them the so called dispersion relations, the proof of which was obtained by N. N. Bogolyubov. On the basis of the properties of analyticity and the so called crossing symmetry, I. Ya. Pomeranchuk formulated a theorem whereby the cross sections for the proton-proton and anti-proton-proton interactions are equal at extremely high energies. This theorem was confirmed by experiments on strong interactions at energies up to 30 GeV. A theory of strong interactions at extremely high energies, based on the property of analyticity of the amplitude as the function of the angular momentum, was developed by I. Ya. Pomeranchuk and V. N. Gribov.

A number of important properties of amplitudes at threshold points (at small relative energies and near the particle creation thresholds) was investigated by A. B. Migdal, V. N. Gribov, A. I. Baz' and others. Equations for the determination of the position fo the singularity of the amplitudes were obtained by L. D. Landau.

In recent years many efforts have been made to obtain strong-interaction symmetry properties capable of generalizing the concept of isotopic invariance (charge independence) of strong interactions. High-symmetry schemes, especially the so called SU_3-symmetry, have made it possible to make a number of predictions that agree with experiment. And in particular, it was possible to systematize the known hadrons.* However, there are still many unclear points in this field.

Experimental investigations of weak interaction progressed both at low and high energies.

The investigation of beta decay of neutrons in atomic nuclei yielded many important results, which include precise measurements of the lifetime of the neutron (P. E. Spivak), measurement of electron polarization (P. E. Spivak, A. I. Alikhanov), and establishment of an upper limit for the double beta decay of the Ca^{48} nucleus (S. Yu. Luk'yanov).

Recent research at low energies has made it possible to observe a new type of weak interaction—the so called odd nuclear forces (Yu. G. Abov, V. M. Lobashov). These forces, which are weaker by six orders of magnitude than the ordinary nuclear interaction, do not conserve spatial parity; this causes, in particular, the gamma quanta in the electromagnetic transitions in nuclei to turn out to be circularly polarized.

Soviet experimenters have also obtained a number of important results at high energies. The probability of the pion beta decay was measured (Yu. D. Prokoshkin) and the result confirmed the theory of the conserved vector current. Measurements were made of muon polarization in $K_{\mu 3}$ decay (A. O. Vaĭsenberg) and in $\pi_{\mu 2}$ decay (A. I. Alikhanov). Muon capture by nuclei, particularly in He^3, was investigated in Dubna (B. M. Pontecorvo). Exact measurements of the electron symmetry and polarized-muon decay were made by I. I. Gurevich.

Decays of neutral K mesons were measured with the Dubna synchrotron. In particular, the $K_2^0 \rightarrow 3\pi_0$ decays were measured there directly.

I. Ya. Pomeranchuk

Notice should also be taken of the work by M. A. Markov and B. M. Pontecorvo, who proposed neutrino experiments and made estimates showing the feasibility of such experiments. The experiments were subsequently performed at the Brookhaven Laboratory and in the CERN European International Laboratory.

Soviet physicists made also a very important contribution to the development of weak-interaction theory. An important role is played in modern theory of universal weak interaction by the hypothesis of conservation of weak vector current and the similarity between this current and the ordinary electromagnetic current. This hypothesis was first considered by S. S. Gershteĭn and Ya. B. Zel'dovich. An inseparable part of modern weak-interaction theory is the theory of the two-component neutrino, proposed by L. D. Landau.

Unlike electrodynamics, the weak-interaction theory is phenomenological. It describes well the phenomena at relatively low energies, but meets with serious difficulties on going to higher energies ($\gtrsim$ 100 GeV in the c.m.s. of the interacting particles). This circumstance was observed as early as in 1934 by I. E. Tamm in an attempt to construct a theory of β forces. The point is that the weak interaction between particles grows rapidly when the particles come closer together; a theoretical analysis shows that it can become very strong at small distances. Interesting results were obtained in this direction by B. L. Ioffe and M. A. Markov.

Fundamentally important results were obtained during the last decade in investigations of nonconservation of spatial parity and combined parity (see page 688).

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*See, for example, the article of Gell-Mann, Rosenfeld and Chew, "Strong interactions".

The violation of CP invariance, discovered in 1964, apparently means that the elementary particles, like living beings, are disymmetrical. Further investigation of this question can lead to very important consequences.

Electromagnetic interaction has been the most thoroughly studied. All the remaining branches of physics (optics, acoustics, solid-state physics, etc.) deal essentially only with electromagnetic interactions. When one speaks of electromagnetic interaction between elementary particles, one has in mind the study of this interaction either at high energies or at low energies, but with such precision as to be able to observe the structure of the elementary particles (their dimensions and the charge and current distributions in them).

Until recently, the interaction between photons and nucleons was investigated experimentally only at FIAN (Moscow) using 270- and 650-MeV electron synchrotrons (P. A. Cerenkov, A. M. Baldin, etc.). Interesting results were obtained here on the scattering of photons by nucleons and on the photoproduction of pions from hydrogen and deuterium. An extensive study program was organized at Dubna on μ atoms, that is, on the electromagnetic interaction between μ mesons and electrons or nuclei. The electromagnetic decays of mesons (π^0, ω^0, ρ^0) were experimentally investigated (Dubna, ITÉF).

Work is now in progress with the Khar'kov accelerator (2 GeV) and with the Novosibirsk colliding-beam accelerator.

The theoretical work done by Soviet physicists in the field of electromagnetic interactions encompasses a wide range, starting with investigations of the degree to which the ordinary Lagrangian formulation of quantum electrodynamics is valid (L. D. Landau, I. Ya. Pomeranchuk) and ending with calculations for numerous concrete processes. As early as in 1930, I. E. Tamm derived a formula for the cross section of the Compton scattering of a photon by an electron (the Klein-Nishina-Tamm formula). A number of effects were calculated by I. Ya. Pomeranchuk (annihilation of ortho and para positronium, level shifts in the μ-mesic atoms, and scattering of light by light).

A semiphenomenological analysis of the interaction between photons and nucleons at energies on the order of several hundred MeV was made by A. M. Baldin.

Further investigation of the electromagnetic interaction is of interest from several points of view, two most important of which are the use of electromagnetic interactions for the investigation of the structure of hadrons, and the search for effects that might demonstrate that quantum electrodynamics is valid also for leptons at not arbitrarily short distances. Neither effect could be observed so far.

With these brief remarks we are forced to conclude our incomplete review of work on elementary particles in the USSR.

Physics of the Atomic Nucleus

The rapid growth of this important branch of physics began soon after Rutherford accomplished the first nuclear reaction almost 50 years ago. The necessary condition for the occurrence of a nuclear reaction is the penetration of an incident fast particle into the target nucleus, and to this end the "bullets" bombarding the target must have sufficient energy, provided of course that they, like the nuclei, carry a positive charge.

During that time, fifty years ago, the only source of such fast particles were radioactive compounds, which emit α particles with energies of several MeV. Such sources were very weak both in the number of particles and in their energy. Consequently, an important role was played in the development of nuclear physics by the creation of particle accelerators, which made it possible to obtain in controlled fashion unmeasureably large powerful streams of fast particles. All this led to the well known progress in the knowledge of the structure of the atomic nucleus and the use of atomic energy. The subsequent development of accelerators led ultimately to the fact that high-energy physics or, what is the same, the elementary-particle physics discussed in the preceding section became a field separate from nuclear physics proper.

During the time when Rutherford effected the first nuclear reaction (1918), then referred to as "transmutation of elements," atomic physics in Russia was at a low level: there was not a single physicist working in the field of natural radioactivity, which led to all the progress in nuclear physics, starting with the very discovery of the atomic nucleus.

Only after revolution did a number of institutes begin to work in nuclear physics. Great initiative was exhibited in this field in Leningrad by A. F. Ioffe, who always persistently emphasized the importance of the study of the atomic nucleus. A number of important researches were performed at the physico-technical institute created by him, but most importantly, he attracted young and talented scientists (I. V. Kurchatov, the Alikhanov brothers, A. I. Leĭpunskiĭ, and others), around whom still younger students were grouped. A large activity was carried out at the Radium Institute by L. V. Mysovskiĭ, who proceeded to construct the first Soviet cyclotron before the war. In Moscow, at the Lebedev Physics Institute, work on nuclear physics was undertaken at S. I. Vavilov's initiative (V. I. Veksler, L. V. Groshev, I. M. Frank, N. A. Dobrotin, and others). Finally, the construction of a large electrostatic generator was undertaken at the Ukrainian Physico-technical Institute in Khar'kov (A. F. Val'ter, K. D. Sinel'nikov, A. I. Leĭpunskiĭ, and others).

All this has brought about conditions whereby experience and staff were available when the acute need arose, and in the postwar years, when the problem of the atomic nucleus came to the forefront as one of the most important state problems, very great progress was made in this most difficult field, bringing the Soviet Union to a leading position in world science.

Even if we disregard the well known development of threatening atomic weapons within an unexpectedly short time, an incomplete list of the advances in the application of nuclear physics made mostly in the last 20–25 years would include the first atomic electric station in the world, the atomic ice breaker "Lenin," and various applications of artificially radioactive isotopes in all fields of science and technology. However, successful experimental and theoretical work in the field of atomic nuclear physics has been going on during the entire fifty years. When speaking of the accomplishments of recent years, we must not forget the pioneer work which by now has become commonly known in all textbooks, and those who realized this work under difficult conditions, with lack of experience and apparatus.

I V. Kurchatov

The late 30's and the early 40's were characterized by intense development of work on the study of nuclear fission of heavy elements. Soviet physicists obtained during that time many important results, which played a major role in the solution of the problem of obtaining and utilizing atomic energy. As is well known, the nuclear chain reaction is based on the fission of heavy nuclei under the influence of neutrons. A qualitative explanation of this phenomenon from the point of view of the electrocapillary model was first presented in 1939 by Ya. I. Frenkel' (this representation was developed simultaneously and independently by N. Bohr and J. Wheeler). In 1940, K. A. Pertrzhak and G. N. Flerov have shown that the process of uranium fission also occurs spontaneously, although with very low probability. Subsequently Ya. B. Zel'dovich and Yu. B. Khariton have shown (1933–1940) that when a natural mixture of uranium isotopes is enriched slightly with the light isotope U^{235}, a chain reaction can be effected using ordinary water as the moderator.

Subsequently, Soviet scientists (I. V. Kurchatov, A. I. Alikhanov, V. S. Fursov, A. P. Aleksandrov, A. I. Leĭpunskiĭ, D. I. Blokhintsev, N. A. Dollezhal', and others) constructed many experimental nuclear reactors for research purposes and performed numerous researches on the most important problems of nuclear physics. These investigations laid the foundation for the development of applied nuclear physics. The most important accomplishment was the creation of nuclear weapons, and in the field of peaceful application—the already mentioned development of nuclear power engineering, and the operating experience of the first atomic electric station, which was constructed in the USSR, has made it possible to undertake a large program of development of a nuclear power industry. The large number of artificial radioactive isotopes obtained with the aid of nuclear reactors has led to an extensive development of the method of "tracer atoms" in metallurgy, biology, medicine, and agriculture.

The guiding spirit of this entire tremendous work was I. V. Kurchatov, who exhibited earlier a great talent for research in his experimental studies of the physics of dielectrics and in nuclear physics. In this new field, however, he came to the forefront not only as an outstanding scientist, but also as an organizer of tremendous energy and wide scope. He has become a hard working public servant performing an important and responsible mission for the country.*

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*The inspiring history of this activity by Kurchatov is well described in a recently published booklet by I. N. Golovin, "Kurchatov," Moscow, 1967.

Let us note now a number of important physical researches in nuclear physics performed in the prewar time.

The notion that atomic nuclei do not contain electrons but consist of positively charged protons and uncharged neutrons, was formulated in 1932 by D. D. Ivanenko. The presently universally accepted concept that nuclear forces result from exchange of particles was simultaneously developed by I. E. Tamm and D. D. Ivanenko (1934). Although the initial assumption that this exchange is effected by electrons and neutrinos leads, as shown by Tamm's calculations, to the assumed existence of forces that are many orders of magnitude smaller than the real forces that hold the atomic nucleus together, the main ideas of this theory still remain dominant. In fact, as shown subsequently by Yukawa, the nuclear forces turn out to be of the required order of magnitude if the exchange is effected by the particles heavier than electrons, namely pions, which were predicted by him and soon discovered.

I. V. Kurchatov, B. V. Kurchatov, L. I. Rusinov, and L. V. Mysovskiĭ have discovered (1935) the remarkable phenomenon of nuclear isomerism of radioactive nuclei. Using bromine isotopes as an example, they have shown that there exist radioactive nuclei which are isotopes and isobars, that is, which have exactly the same composition, but have essentially different half-lives. Thus, for example, the bromine isotope Br^{80} has two half lives (18 minutes and 4.4 hours). This phenomenon turned out to be widespread. It was called nuclear isomerism in view of a certain analogy with a phenomenon known in organic chemistry, where molecules are called isomers if they have the same composition but a different structure. The cause of nuclear isomerism, however, lies not in the different structure of the isomeric nuclei, but in the existence, for γ radiation, of metastable nuclear levels, the transition from which to the normal state is more or less strongly "forbidden": owing to the small probability of the transition, the nuclei which reach such a metastable excited level will become de-excited and emit γ rays during a long time interval.

Many important investigations of β decay (β spectra, internal conversion) were made by A. I. Alikhanov, A. I. Alikhanyan and their co-workers with the aid of magnetic β spectrographs. An important stage in the experimental proof of the existence of neutrinos were the experiments of A. I. Leĭpunskiĭ, who showed that the momentum conservation law is violated in the "electron plus recoil nucleus" system. L. V. Groshev and I. M. Frank were among the first to investigate in great detail the process of electron-positron pair production by γ quanta and to demonstrate the validity of the theory developed by Dirac for this process.

In the postwar years, the development of atomic power engineering was stimulated by the great expansion of research on nuclear physics. Not only were the old centers of nuclear research expanded, such as the Leningrad Physico-technical Institute (LFTI), the Radium Institute, FIAN, and the Khar'kov Physico-technical Institute (KhFTI), but many new research centers were organized. These include some establishments which are now widely known, such as the I. V. Kurchatov Institute of Atomic Energy, the Institute of Theoretical and Experimental Physics (A. I. Alikhanov), the Physics and Power Engineering Institute at Obninsk (D. I. Blokhintsev and A. I. Leĭpunskiĭ), and the Nuclear Physics Research Institute of the Moscow State University (D. V. Skobel'tsyn and S. N. Vernov).

Starting with the second half of the 50's, a large number of nuclear centers came into being in the capitals of the union republics—Kiev, Tashkent, Tbilisi, Minsk, Riga, and Alma Ata. One should add to this list also the Joint Institutes for Nuclear Research, organized in Dubna in 1956, and in whose laboratories scientists from most socialist countries work together.

A result of the intense development of the research in the USSR and abroad is, first of all, the rapid progress in the methodology of nuclear experimentation, which has become more and more refined in our days. The Geiger counters were replaced by scintillation counters, and in the 60's by semiconductor detectors for particles and γ quanta, combining higher efficiency, high speed, and good spectrometric properties. Separated isotopes of elements, multichannel and multidimensional pulse analyzers, and nanosecond electronic circuitry have come into universal use. Electronic computers are used directly in the experiments. Electrostatic generators, cyclotrons, and research reactors have become indispensible equipment in nuclear laboratories. Let us note one of the most remarkable installations of this type. The first accelerators using the phase-focusing principle of V. I. Veksler are the 30- and 270-MeV electron synchrotrons which are still in operation at FIAN. They are intensely used for the study of photonuclear reactions (L. E. Lazareva, P. A. Cerenkov, A. N. Gorbunov). An electronic accelerator delivering a much larger current--the microtron, also invented by V. I. Veksler--was installed recently for the same purpose, at the Institute of Physics Problems. This machine "came into being" as a result of developments by S. P. Kapitza. A cyclotron with pole diameter 300 cm, specially adapted for the acceleration of heavy ions (oxygen, neon, argon, etc), has been in operation since 1960 in the Laboratory of Nuclear Reactions in Dubna. It produces ion beams with power larger by one order of magnitude than that produced by the foregin accelerators; this turned out to be decisive for work towards the synthesis of the elements 102 and 104, performed by G. N. Flerov and his co-workers. As is well known, the element 104 has been named Kurchatovium. In another Dubna laboratory—the Neutron Physics Laboratory--there is in operation a post fast-neutron reactor (IBR) developed at the Physics and Power Engineering Institute (D. I. Blokhintsev, I. I. Bondarenko, Yu. Ya. Stavisskiĭ, and others). This original reactor, with an average power of 6 kW, affords the same or better facilities for experiments in which it is necessary to determine or measure the energy of slow neutrons than an ordinary stationary reactor with power of tens of megawatts. The success of the IBR reactor has stimulated the development, in a number of countries, of pulsed reactors having a rating larger by several orders of magnitude. Among the research reactors having the largest neutron flux (on the order of 10^{15} neutrons/cm^{2}sec) is the SM-2 reactor of the Reactor Institute in Melekess, developed under the leadership of S. M. Feĭnberg.

The factual information on atomic nuclei has grown tremendously during the postwar decades. Hundreds of various nuclear reactions were investigated in detail.

The ground states and many lower excited states of all the stable nuclei and some thousand radioactive nuclei were investigated. Although there is still no unified and self-contained theory of nuclear forces and nuclear structure, impressive progress in the description and explanation of nuclear forces was attained with the aid of several quite common nuclear models, which were developed in detail. These include the statistical and the optical models of nuclear reactions, the shell model of nuclear structure, the unified model, which takes into account the collective motion of the nuclear (rotations and surface oscillations) connected with their nonsphericity and deformability, and a few others. Soviet scientists have taken active part both in the accumulation of the experimental data on nuclei and in the development of the theoretical concepts. Within the framework of the present article, we can only name several trends of the work; in order not to confine ourselves to a dry listing, we shall briefly mention also some of the most interesting investigations performed in recent years.

The study of the characteristics of the energy levels of atomic nuclei is the subject of the so-called nuclear spectroscopy, and one usually deals with the lower excited levels, which can be easily investigated and described theoretically. In the Soviet Union, investigations in this direction are quite extensive and are discussed annually at traditional conferences on nuclear spectroscopy, initially organized by B. S. Dzhelepov. Besides α, β, and γ spectroscopy of artificial radioactive isotopes (B. S. Dzhelepov, S. A. Baranov, and others), great significance is attached to information obtained in the study of nuclear reactions and of new type of radioactive decay. As regard nuclear reactions, mention should be made here of the world famous work of L. V. Groshev and co-workers on the spectra of γ rays produced when neutrons are captured by nuclei, investigations of Coulomb excitation of nuclei (the theory of this process was developed by K. A. Ter-Martirosyan, and the experiments were made by I. Kh. Lemberg and others at LFTI), investigations of stripping of deuterons, etc. Two new nuclear decay processes were discovered at the Laboratory of Nuclear Reactions in Dubna. These are the emission of protons following β decay (delayed protons, V. A. Karnaukhov) and spontaneous fission of heavy nuclei, occurring at a rate which is faster by twenty orders of magnitude than the rate of ordinary spontaneous fission (S. M. Polikanov). In the latter case, the fission apparently proceeds from the isomeric state of the nuclei, which differs from the ground state in having a larger deformability.

In the field of theory, very important work was done by N. N. Bogolyubov on the application of the theory of superfluidity to atomic nuclei; in this manner it became possible to describe quantitatively many peculiarities of the nuclear excitation spectrum (S. T. Belyaev, V. G. Solov'ev). Great interest was aroused by the work of A. S. Davydov on the theory of nuclei that have no axial symmetry, and the work of A. B. Migdal, who applied to nuclei the theory of the quantum Fermi liquid, first constructed by L. D. Landau. Much attention has been paid to the study of the properties of systems with few nuclei, especially theoretical studies (Y. A. Smorodinskiĭ, K. A. Ter-Martirosyan, Faddeev, et al). Analysis of the stability of the lightest nuclei, carried by A. I. Baz', V. I. Gol'danskiĭ and Ya. B. Zel'dovich, stimulated the search for such "strange" nuclei as the recently discovered helium-8. The excited levels of the lightest nucleus capable of being excited—helium-4—was first investigated experimentally by N. A. Vlasov and I. Ya. Barit. In most recent times, experiments performed in Dubna with polarized neutrons and a polarized deuteron target resolved the long-standing uncertainty in the neutron-deuteron-scattering amplitudes.

In the field of the study of nuclear reactions, perhaps most was done with neutrons, this being due to the demands of nuclear technology. Prior to the first Geneva conference on the peaceful use of atomic energy (1955), publication of papers in this field was restricted in all countries, and Soviet physicists had to develop their neutron research independently. The Geneva conference demonstrated the high level of this work in the study of neutron cross sections and neutron resonances of fissioning and non-fissioning nuclei (V. V. Vladimirskiĭ, S. Ya. Nikitin, V. I. Mostovoĭ, M. I. Pevzner, M. V. Pasechnik, and others). The work by I. M. Frank and coworkers, who developed the emulsion method of studying neutron transport in media, was continued by many workers. There was also developed at FIAN an original method of investigating the cross sections of neutron reactions, based on measurement of the neutron deceleration time; this method is in use to this very day. In subsequent years, neutron measurements continued to develop (polarization effects—I. I. Levintov, nanosecond procedures as applied to fast neutrons—N. A. Vlasov, V. Sidorov, et al., time of flight spectrometry in the resonance region with high resolution—the apparatus with linear electron accelerator of IAÉ (Atomic Energy Institute), the post reactor with microtron injector in Dubna, etc.). The theoretical interpretation of the obtained data on the properties of highly excited states of nuclei and the characteristics of nuclear reactions were based on the statistical model of the nucleus. foundations for which were made by L. D. Landau even before the war, and on the optical model of the nuclues. Contributions to further development of this theory were made by M. V. Strutinskiĭ, P. É. Nemirovskiĭ, and others. Important experimental investigations of nuclear fission were made by N. A. Perfilov, G. E. Belovitskiĭ, Yu. A. Zamyatin, L. A. Mikaélyan, and others. Investigations of nuclear reactions induced by fast charged particles (P. A. Klyucharev, O. F. Nemets, Ogloblin, and others) and fast neutrons have clearly demonstrated long ago the inadequacy of the compound-nucleus model and the need for taking into account the direct mechanism of nuclear reactions. A new trend in the theory of direct nuclear reactions was developed recently by I. S. Shapiro.

In conclusion, notice should be taken of the ever increasing utilization of the methods of nuclear physics in related fields of science and technology. Examples are neutron-activation analysis, neutron and gamma well logging in geological prospecting, neutron diffraction structure analysis of crystals, especially crystals of magnetic materials (see the recent monograph by Yu. A. Izyumov and R. P. Ozerov), numerous applications of the Mössbauer effect in solid-state physics and chemistry (experiments—V. I. Gol'danskii, V. S. Shpinel', et al., theory—Yu. M. Kagan, M. A. Krivoglaz, et al). More complicated technically is the method of inelastic scattering of slow neutrons, which makes it possible to investigate the frequency spectra and the dispersion relations for phonons and magnons, as well as the dynamics of atoms in liquids and in molecules. A number of results were obtained in this direction already at the Institute of Atomic Energy and in Dubna, with the pulsed reactor turning out to be very promising equipment for research of this type. An entirely new promising trend in the study of crystals was initiated recently by A. F. Tulinov (Moscow State University), who discovered the so called shadow effect—the influence of the ordered arrangement of the atoms in crystals on the angular distribution of fast charged particles scattered or emitted by the nuclei of the crystal.

Plasma Physics

The most vigorous development of plasma physics in the USSR began in the postwar years, but the foundation for this research was liad much earlier by the theoretical work of A. A. Vlasov (1938), who proposed a kinetic equation with a self-consistent field for the description of collective processes in a plasma, and by the work of L. D. Landau (1937), who obtained the collision term for the charged particles. Vlasov's equation with the collision term in Landau's form is now universally used and serves as the basis for the understanding of the processes in a fully ionized plasma. A major role in the development of plasma theory was also played by a 1947 paper by L. D. Landau, in which he solved with mathematical rigor the problem of plasma oscillations and showed that waves in a plasma experience a specific damping connected with their interaction with resonant particles.

Experimental research in the prewar period was stimulated for the most part by practical needs—the development of fluorescent lights and gas-discharge tubes (gasotrons, thyratrons, etc.) and involved the study of elementary processes in a gas discharge and the macroscopic characteristics of the discharge. Among the Soviet physicists who worked and are still working in this field we note N. A. Kaptsov (ignition of a gas discharge, corona), G. V. Spivak (role of metastable atoms in a gas discharge, the theory of probes, accommodation coefficients), N. D. Morgulis (cathode sputtering), and V. L. Granovskiĭ (gas-discharge plasma). Among the investigations connected with the development of economical gas-glow lamps, note should be taken of the work of V. A. Fabrikant (study of a discharge in metal vapor), B. N. Klyarfel'd, and A. M. Shemaev.

The rapid development of atomic physics in the postwar years very soon influenced other branches of physics, particularly plasma physics. Investigations aimed at electromagnetic separation of isotopes (L. A. Artsimovich, P. M. Morozov, V. S. Zolotarev) coped for the first time with the unusually complicated processes occurring in a plasma situated in a strong magnetic field. A full-scale study of these processes began with investigations of controlled thermonuclear reactions.

In 1950, A. B. Sakharov and I. E. Tamm advanced the idea of magnetic thermal insulation of a plasma in order to obtain controlled thermonuclear reactions. Soon, under the leadership of L. A. Artsimovich and M. A. Leontovich, experimental and theoretical studies began for the purpose of attaining controlled thermonuclear fusion. In the first experiments on strong-current discharges (L. A. Artsimovich, A. M. Andrianov, O. M. Bazilevskaya, V. S. Komel'kov, S. Yu. Luk'yanov, N. V. Fillippov, et al.) it was possible to attain very high temperatures and confirm by the same token the principle of magnetic thermal insulation. Neutrons and hard x-rays were observed. Soon, however, plasma instability was encountered in these experiments and the investigators of controlled thermonuclear reactions turned to a thorough study of the physical properties of plasma. To this end, they used toroidal discharges with strong longitudinal fields (N. A. Yavlinskiĭ), traps with magnetic mirrors (G. I. Budker, I. N. Golovin, I. S. Ioffe), systems with high-frequency fields (S. M. Osovets), etc. All these investigations prepare a scientific foundation for the solution of the problem of controlled fusion of light nuclei.

The work of Soviet physicists on controlled nuclear reactions is among the greatest accomplishments of Soviet science. Soviet scientists have made a substantial, and in some cases the basic contribution to the development of theory of instability and collective processes in plasma (V. D. Shafranov, B. B. Kadomtsev, V. P. Silin, A. A. Vedenov, E. P. Velikhov, etc.) the theory of electromagnetic waves in plasma (V. L. Ginzburg, K. N. Stepanov, et al.), the theory of nonlinear waves in a plasma (R. Z. Sagdeev, V. I. Karpman). Experiments on plasma stabilization in magnetic traps (M. S. Ioffe), on turbulent plasma heating (E. K. Zavoĭskiĭ), and on the interaction of beams with plasma (Ya. B. Faĭnberg) have gained deserved recognition in the world's scientific literature. Work on plasma physics is being carried out in a large number of other institutions: Leningrad Physico-technical Institute (LFTI) (V. P. Konstantinov, V. E. Golant, N. V. Fedorenko), FIAN (M. S. Rabinovich), the Institute of Nuclear Physics of the Siberian Division of the Academy of Sciences (G. I. Budker, R. Z. Sagdeev).

By now plasma physics has grown into a rather large division of modern physics. It has become clear that the physical properties of a plasma become manifest in a large number of phenomena in outer space, on the sun, and in the ionosphere of the earth. New applied problems are the use of plasma in magnetohydrodynamic converters of thermal energy into electricity and in jet engines.

Optics. Physics of Atoms and Molecules

The great importance of this branch of physics is due, in particular, to the fact that it is directly connected with the optical industry, which is exceedingly important both from the defense and from the cultural points of view.

In an interesting article written on the fifteenth anniversary of the State Optical Institute (GOI), D. S. Rozhdestvenskiĭ described the cultural significance of the optical industry by means of the following glowing words: "The wide abundance of optics is an attribute of a high culture. The microscope, the photographic camera, the telescope, or the binoculars always distinguished a cultural family. The optical industry is the most significant industry also because it is the most subtle and the most difficult, and because it leads us most rapidly, via the microscope and the telescope, to culture, to true scientific materialism, and to the abolishment of superstitions."*

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*D. S. Rozhdestvenskiĭ, The Fate of Optics in the SSSR, in: "Fifteen Years of the State Optical Institute," edited by S. I. Vavilov, 1934, p. 25.

What was the level of the optical industry in Russia before the revolution? We have on this subject authoritative evidence of D. S. Rozhdestvenskiĭ in the same article: it can be briefly described by the following words: "With respect to 1917, it is more appropriate to note what did not exist at that time." Rozhdestvenskiĭ lists further the then existing small machine shops with a total of less than 100 workers (including the machine shops producing optical devices for military purposes). "There was not a single person capable of designing an optical system, and no one in Russia engaged in optical technology. The plants therefore understood little of the subject and could only copy slavishly foreign models. There was no production of eyeglasses, geodetic instruments, photographic cameras and lenses, motion picture equipment, microscopes, or scientific instruments."*

But already in 1933, according to data given in the same article, the picture radically changed. There were already seven plants of the optical-mechanical industry with 11,000 workers, producing a great assortment of optical devices for military, scientific, and civilian use. Whereas in 1917 there was not a single designer, in 1933 the GOI already had a design bureau with several dozen workers, for which "there are no more secrets or difficulties in the complicated matter of calculating optical systems, including photographic and microscopic objectives of maximum aperture." Another 34 years have elapsed since that time, and now our optical industry provides fully all the necessary equipment for the Soviet army, for the navy, and for aviation. It produces a variety of perfectly modern photographic cameras with splendid lenses, even the most complicated ones, made of Soviet optic glass, as well as various scientific instruments: microscopes, astronomic telescopes, spectral apparatus, etc.

A tremendous role in this vigorous development of the optical industry was played by the S. I. Vavilov State Optical Institute with its founder D. S. Rozhdestvenskiĭ and his successor S. I. Vavilov in charge.

The most important raw material for the optical manufacture is optical glass. Before the revolution, during the first world war, Russia was in an exceedingly difficult situation, since the stockpiles required to equip the military with optical glass, previously imported from Germany, was negligible and was consumed in several months. "The unique and difficult manufacture of optical glass was at that time essentially a monopoly of only three firms in the entire world, and was kept highly secret. It was impossible to find in Russia a single person who had some knowledge of this subject, nor was there a printed line in any language devoted to this forbidden topic."† Attempts to fuse optical glass, made in 1916, using recipes from the British firm Chance Bros., yielded a negligible amount of glass of poor quality. One of the first tasks undertaken upon organization of the GOI by a group of enthusiasts of Soviet optics headed by D. S. Rozhdestvenskiĭ was to develop their own methods of fusing optical glass—methods based on a solid foundation of broad scientific physical and chemical research on this unique process, and not in the form "some intricate trick, kept as a rigorously guarded secret,"* as was the glass recipe of the foreign firms. Credit for the development and perfection of these methods belongs to a large group of scientists, especially I. V. Grebenshchikov, N. N. Kachalov, A. A. Lebedev, and A. I. Stozharov. Control over the process was greatly facilitated by a clever method, developed by I. V. Obreimov, of rapidly determining the refractive index of big glass pieces of irregular random form. Owing to all this work, the Soviet Union could dispense as early as in 1925 with importation of optical glass.

An important role in the development of applied optics was played by the creation of the Soviet school of optical designers (A. I. Tudorovskiĭ, G. G. Slyusarev, E. G. Yakhontov, and others). Original methods were developed for the calculations, and auxiliary tables were compiled, facilitating the choice of the grade of glass and the calculation method. The construction of reflecting objectives (E. M. Brumberg and S. A. Gershgorin) has made it possible to develop an original type of ultraviolet microscope (E. M. Brumberg). A completely unique construction of astronomic telescopes—of the mirror and meniscus type—was developed by D. D. Maksutov (1941). Many original designs of photographic lenses were also developed (M. M. Rusinov, D. S. Volosov et al). Clever methods for controlling optical systems were proposed by V. P. Linnik; he and A. A. Lebedev deserve credit for a number of original designs of optical instruments. Special notice should be taken of the creation and commercial development of all types of spectral apparatus, fully equipping the numerous plant laboratories, scientific-research institutes, and institutions of learning with the necessary instruments. Finally, an important accomplishment of recent times is the production at GOI, under the leadership of F. M. Gerasimov, of Soviet diffraction gratings of high quality.

An important branch of applied optics is illumination engineering and the directly related photometry. In the field of theoretical foundations of illumination engineering, great significance attaches to the theory of the light field, developed by Soviet scientists, especially V. A. Fock, A. A. Gershun, M. M. Gurevich, and N. V. Boldyrev. In this theory, the problem of illumination engineering, that is, the problem of providing efficient illumination, is solved with the general physical theory of fields as a model, by introducing the "density of optical energy," the "light vector," and by subsequent mathematical development of the theory with the aid of vector analysis. The significance of this work was clearly formulated by the editor Parry Moon of the English translation of the book "Theory of the Optical Field" by A. A. Gershun (published in the USA), who emphasized that the theory developed in this book, by one of its pioneers, is the first important step in photometry since the time of P. Bouguer (that is, the middle of the 18th Century). In the field of physical optics, the work of Soviet physicists are numerous and varied. We already mentioned the classical work of D. S. Rozhdestvenskiĭ on anomalous dispersion in sodium vapor, per-

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*Ibid., pages 19-20

†Ibid., p. 170

*I. V. Grebenshchikov and N. N. Kachalov, in: "Fifteen Years of the State Optical Institute," pp. 160 and 161.

formed even before the revolution. In these investigations, Rozhdestvenskiĭ developed the clever "method of hooks," which made it possible to investigate conveniently and rapidly the dispersion in metal vapor and to determine from these measurements the exact values of the transition probabilities and the intensities of the spectral lines. Owing to further improvement of the procedure, namely the construction of a fluorite interferometer, designed by D. S. Rozhdestvenskiĭ, his students V. K. Prokof'ev, and A. N. Filippov were able to extend the study of anomalous dispersion to the ultraviolet region and obtain many valuable results.

In the field of atomic spectroscopy, the work of D. S. Rozhdestvenskiĭ, published back in the 20's, was of outstanding significance. Using the lithium atom and other alkali metals as an example, he demonstrated in his paper the close similarity between the higher levels of these monovalent atoms with the terms of hydrogenlike atoms. On this basis he clearly formulated the so called model of the radiating electron. Further, by comparing the spectrum of ionized magnesium with the spectrum of helium, he established the so called "spectroscopic displacement law," according to which the spectrum of a singly-ionized atom with atomic number Z is similar to the spectrum of a neutral atom with atomic number Z − 1.*

Two circumstances must be noted in connection with these investigations of D. S. Rozhdestvenskiĭ. First, although Rozhdestvenskiĭ's work was based entirely on Bohr's theory of the atom, the model of the optical electron and the spectroscopic displacement law still retain their heuristic significance and serve as a guide for experimental spectroscopicists to this day. Second, in the historical aspect, these investigations were of particular significance for Soviet physics. They were made during a period of blockade, when the Soviet scientists were completely isolated from foreign science. Although it became known after the lifting of the blockade that the same results were obtained by Sommerfeld, Schrödinger, and other western scientists, the fact that the young Soviet science, completely isolated from the developments of the foreign scientific schools, was able to formulate and solve the most important problems of this time was a source of joy and confidence in our own forces.

The most important organizational result of these investigations was the creation, with Rozhdestvenskiĭ as the center, of a brilliant school of Soviet spectroscopicists (A. N. Terenin, S. É. Frish, E. F. Gross, A. N. Filippov, V. K. Prokof'ev, M. A. Veĭngerov and others). Let us note the results of the work of this school, which by now are part and parcel of modern spectroscopy.

The end result of a spectroscopic investigation of the atom is to establish the system of its terms, i.e., its energy level scheme. This level scheme can be verified by direct experiment, by exciting the atom to a definite upper state and establishing the subsequent downward transitions. The very excitation can be produced either by electron impact or by optical means, by letting the atoms absorb quanta of strictly defined frequency. In the 20's, the electron impact method was highly popular and was used with great success in the classical investigations of J. Franck and H. Hertz. An advantage of this method is the possibility of continuously changing the energies of the electrons bombarding the atom. However, in spite of all the significance of the first investigations in this direction, subsequent work gave results which were quite crude quantitatively and did not always admit of a clear interpretation qualitatively. A much more precise method is that of optical excitation. It was widely used by A. N. Terenin in a number of his investigations devoted to resonance radiation and fluorescence of metal vapor. Owing to different improvements introduced by A. N. Terenin in the experimental techniques, he succeeded in investigating in detail the level scheme and to trace the transitions between different levels of a large number of atoms—mercury, cadmium, thallium, bismuth, lead, zinc, and also to study the so called stepwise excitation, in which an already-excited atom absorbs one more quantum of energy and goes to a higher level. In our days all these concepts have become part and parcel of the makeup of the physicists, so that it is even difficult to imagine the important role played in their day by these investigations, which made it possible to perceive with extreme clarity the stream of new ideas that swept into spectroscopy upon development of the quantum theory of the atom.

An important result of the noted cycle of investigations was the discovery, by A. N. Terenin and L. N. Dobretsov, of the hyperfine structure of the mercury lines (the hyperfine structure was discovered independently of the Soviet investigators by Schuler in Germany). The main significance of this seemingly special result lies in the fact that by investigating the hyperfine structure it was possible to establish such properties of the atomic nucleus as its spin and magnetic moment. Until recently this optical method was the only way of determining these important nuclear constants. Extensive investigations of the hyperfine structure of atomic lines were made by S. É. Frish.

From optical excitation of the atoms it is natural to go over to the study of the optical excitation of the molecules. Of great significance in this field are the investigations of A. N. Terenin and his co-workers, who clarified, by spectroscopic study of excited molecules, the mechanism of the elementary photochemical act. Attention should be called here to the fact that although the study of the photochemical processes has a long history, until the development of modern spectroscopy and its improved experimental methods and lucid theoretical premises, the main problem of the mechanism of the elementary photochemical act could not even be formulated clearly in physical fashion. Yet we are dealing in this case with a very concrete physical problem of the mechanism of conversion of the energy of the electron excitation of the molecule, completely or partly, into vibrational energy of nuclei but subsequent decay. The tremendous sensitivity of the spectroscopic procedure, which incomparably exceeds the usual chemical methods of analysis, not only makes it possible to perceive in the most subtle manner the very fact of the de-

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*D. S. Rozhdestvenskiĭ, Spectral Analysis and Structure of Atoms. Delivered at Annual Meeting of the State Optical Institute in Petrograd, 15 December 1919. Proceedings of the State Optical Institute, V. 1, No. 6, Petrograd, State Publishing House, 1920.

cay, but also makes it possible to establish the state in which the decay products are released. In fact, when one of the decay products is released in an excited state, the fragments of the molecules become visible by the light emitted by them, the spectral composition of which indicates their energy state. As expressed by A. N. Terenin, the spectroscopic procedure makes it possible not only to perceive the decay products in statu nascendi, but, what is more important, in statu luminiscendi, in particular, at concentrations which are inaccessible to any other analysis methods. In these investigations they used a highly perfected technique: a powerful 10-kilowatt discharge hydrogen tube produced very intense radiation, up to the extreme ultraviolet where the photon energy amounts to 150—200 kcal, and other subtle methods besides the spectroscopic method were also used for the identification of the decay products.

Numerous investigations of the electronic spectra of molecules and of optical dissociation and predissociation were reported by V. N. Kondrat'ev. He also discovered the interesting and important phenomenon of induced predissociation.

The phenomena of molecular fluorescence in solutions at room temperature, and also the glow of crystal phosphors, is of great interest from the theoretical and practical point of view. Soviet physicists also made a very important contribution in this field. S. I. Vavilov, V. L. Levshin, and their co-workers made a comprehensive and thorough study of fluorescence in solutions. Above all, S. I. Vavilov investigated the fluorescence yield of solutions of dyes. It turned out that the energy yield of the fluorescence is in many cases close to 100%, and the quantum yield and the duration of the excited state do not depend on the exciting wavelength. This law, which plays an important role in the clarification of the mechanism of fluorescence of complicated molecules, is called Vavilov's law.

The remarkable phenomenon of fluorescence polarization, discovered by F. Weiger in 1920, was subjected to an exhaustive investigation in a number of fundamental studies of S. I. Vavilov and V. L. Levshin. Interest in this phenomenon lies in the fact that it is undisputedly connected with the structure of the radiating molecules, and in its unusual sensitivity to any kind of disturbing influences on the radiating molecule. Because of this, any degree of polarization of fluorescence can serve as a very subtle attribute of molecular interactions.

Of particular importance and interest is the strong dependence of the degree of polarization of the exciting wavelength, discovered by S. I. Vavilov; for certain wavelengths the fluorescence polarization even reverses sign, that is, it becomes negative. Owing to the existence of this dependence, it becomes possible to establish a new characteristic of molecular properties, namely polarization spectra, knowledge of which makes it possible to draw conclusions concerning the structure of the fluorescent molecules. The possibilities uncovered by knowledge of the fluorescence polarization spectra were demonstrated by S. I. Vavilov's student P. P. Feofilov, who investigated the polarization spectra of a large number of complex organic molecules and who showed that the dependence of the degree of polarization of the exciting wavelength, discovered by S. I. Vavilov, is a manifestation of the difference between the spatial orientation of the oscillators which simulate different bands in the absorption spectra of molecules.

S. I. Vavilov and his co-workers (I. M. Frank, B. Ya. Sveshnikov) investigated in detail also the phenomena of fluorescence quenching and developed a complete phenomenological theory of these phenomena.

V. L. Levshin established, by means of extensive experimental data, the law of "mirror symmetry" of the fluorescence and absorption spectra, which holds for spectra plotted in the frequency scale. A number of theoretical questions pertaining to luminescence of complex molecules were investigated by B. I. Stepanov.

In investigations of fluorescence of vapors, B. S. Neporent observed the phenomenon of luminescence buildup when extraneous gases are added to vapors of aromatic compounds, and also the "extinction" of absorption under the action of light gases. These phenomena led to the development of what seems to be the most subtle of the existing methods of detailed investigations of energy transfer in collisions, and of the collision mechanism itself. Neporent also investigated the conversion of vibrational energy in complex molecules. In these investigations, he developed new concepts concerning the structure of levels and the origin of continuous spectra of such molecules. These investigations are being continued by N. A. Borisevich at the Physics Institute of the Belorussian Academy of Sciences in Minsk.

Among the most recently founded centers for research on luminescence and spectroscopy are the Physics Institute of the Belorussian Academy of Sciences in Minsk (A. N. Sevchenko, B. I. Stepanov, M. A. El'yashevich, and their co-workers) and the Tartu University in Estonia (F. D. Klement, M. A. Moskvin), and the Luminescence Laboratory of the Estonian Academy of Sciences (K. K. Rebane, Ch. B. Lushchik, and others).

Besides ordinary fluorescence, characterized by a glow duration on the order of 10^{-8} sec, organic substances, especially dyes in "rigid" media (for example, in solid solutions in boric acid or rock candy), and also many organic compounds in frozen solutions in organic solvents produce a prolonged glow with a lifetime that is measured in seconds. This phosphorescence of organic compounds was also investigated by Soviet scientists (S. I. Vavilov, B. Ya. Sveshnikov). In particular, P. P. Dikun has demonstrated that vapors of aromatic hydrocarbons reveal a weak prolonged glow having the same spectrum as in the rigid media, thus indicating that the glow has a purely molecular character. After the Polish physicist A. Jablonski gave a correct phenomenological explanation of this prolonged glow, as being the result of the existence of a metastable level located between the normal and first-excited levels, A. N. Terenin, and simultaneously and independently Gilbert Newton Lewis, advanced the hypothesis that the metastable level is a triplet level. To the contrary, the normal state of aromatic hydrocarbons and of fluorescent dyes is singlet, since the number of optical electrons in these molecules is even, and the spins of each pair of electrons cancel each other mutually. When the molecules are excited, as a result of a complicated chain of processes, the spins of one pair of electrons are arranged in parallel and a triplet state is produced, and the transition from this state to the normal singlet state is strictly forbidden. However, owing to spin-orbit interaction, the forbiddenness is partially lifted and a long-lived excited state is produced, the lifetime of which reaches 15 seconds in individual cases (for example in triphenylene), as against the $10^{-7}-10^{-8}$ seconds characteristic of allowed singlet-singlet transitions. A direct consequence of the transition to the triplet state is the occurrence of a magnetic moment in the molecule, as was indeed demonstrated in a number of investigations by foreign workers—first by difficult direct experiment (G. N. Lewis, M. Kasha and M. Calvin, J. Evans), and subsequently, after a number of unsuccessful attempts, by the method of electron paramagnetic resonance (C. Hutchison and Mangum, Van der Waals). It has become clear most recently that such "triplet" or in other words "biradical" molecules, which remain for a long time in an excited state, can apparently play in important role in some most important biological processes.

Also worthy of mention are a number of experimental determinations of the duration of the excited state (the glow duration) in luminescence. L. A. Tumerman, and subsequently in an improved form A. M. Bonch-Bruevich, constructed fluorometers—apparatus with which it is possible to determine, in the latest version, glow duration down to 10^{-11} sec. A very valuable instrument for the investigation of the kinetics of high-speed processes (luminescence, photoconductivity, etc.) is the so called "taumeter," constructed by N. A. Tolstoĭ and P. P. Feofilov. Initially developed for times $10^{-1}-10^{-5}$ sec, the method was extended by N. A. Tolstoĭ to shorter times (down to 2×10^{-8} sec, ultrataumeter).

The luminescence of crystal phosphors was also subjected to many investigations by Soviet physicists (V. V. Antonov-Romanovskiĭ, B. L. Levshin, and others). We note the extensive and highly precise investigations of the law of damping of zinc-sulfide phosphors, performed by Soviet physicists. The results of these investigations, which are of fundamental significance for assessment of the phosphorescence mechanism, have soon become standard reliable material for those engaged in the theory and experiment of this field.* P. P. Feofilov first started a systematic investigation of the spectral-luminescence characteristics of single crystals with rare-earth activators, and observed a hitherto unknown luminescence of a number of ions (trivalent neodymium and holmium, ytterbium, uranium, etc.). This led to the discovery of new interesting and important phenomena.

Modern theory of luminescence of crystal phosphors is based on the band theory of crystals. This theory, on which modern concepts concerning electric and optical properties of solids are based, turns out to be highly fruitful for the understanding of the mechanism of crystal-phosphor glow. At the present time it is an essential working pattern for theoretician and experimenters engaged in the investigation and in technical applications of crystal phosphors. The value of this theory for the interpretation of luminescence phenomena in solids was demonstrated in a number of papers by D. I. Blokhintsev, S. I. Pekar, et al.

We note also investigations closely related to those just considered, namely on the photochemistry of crystals. T. P. Kravets and M. V. Savost'yanov, followed later by M. V. Savost'yanov alone, were able to show that the formation of the latent image in silver-bromide crystals is closely related to the phenomenon of coloring of crystals under the influence of ultraviolet and x-rays. This result, which was independently discovered also by Hilsch and by R. V. Pohl in Gottingen, served as the start of numerous important investigations on the theory of the production of the photographic image.

Among the most recent investigations we note the cooperative phenomena observed by P. P. Feofilov in activated crystals, namely cumulation of excitation energy and cooperative sensitization of luminescence. These investigations uncovered new ways for the study of sensitization of various photophysical and photochemical processes (spectral sensitization of photographic emulsions, photosynthesis in plants, etc.).

Experimental and theoretical investigations in the field of luminescence of crystal phosphors, the development of technology of preparation of crystal phosphors, and the investigation of glow conditions in gas discharges, have all made it possible for industry to develop economic "daylight" lamps, the use of which is continuously increasing.

Progress in atomic spectroscopy has created a solid foundation for the development of qualitative and quantitative atomic spectral analysis. The methods of atomic spectral analysis, which is incomparably faster than ordinary chemical analysis, have found very extensive use in metallurgy and in the machine building industry, in the analysis of ores and minerals, and in a number of other fields. At the present time, none of these industries can get along without a spectral-analysis laboratory, and the number of analyses performed annually in geological investigations adds up to millions. Credit for the development and introduction of various methods of spectral analysis, for the collaboration in the design and in the design and in construction of all types of modern spectral apparatus and auxiliary equipment for spectral analysis, belong both to the Moscow school of physicists (G. S. Landsberg, S. L. Mandel'shtam, N. N. Sobolev, A. K. Rusanov et al.) and to the Leningrad school (A. N. Filippov, V. K. Prokof'ev, S. E. Frish, et al.).

Recently, besides methods of atomic spectral analysis, methods of molecular spectral analysis are gaining in significance and in popularity (infrared and ultraviolet absorption spectra, random scattering spectra, luminescence spectral analysis). These methods find new and extensive use in medicine, biology, the pharmaceutical industry, the oil industry, and others. Credit for the development and introduction of the corresponding methods belongs to V. M. Chulanovskiĭ.

Much progress was made in the field of the spectroscopy of crystals—both organic and inorganic (semiconductors)—and also in the spectroscopy of individual complex organic compounds. Pioneer work in the field of spectroscopy of molecular crystals under deep cooling (nitrogen, hydrogen, and helium temperatures, i.e., 77°, 20° and 4.2°K) was done by I. V. Obreimov and A. F. Prikhot'ko. A decisive role in the interpretation of the complicated phenomena observed both in molecular crystals of aromatic compounds and semiconduct-

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*See, for example, N. Mott and R. W. Gurney, Electronic Processes in Ionic Crystals, ch. VI, Oxford, 1940.

ing crystals (Cu_2O, CdS), was played by the notion of special quasiparticles, excitons, advanced by Ya. I. Frenkel'. This concept turned out to be exceedingly flexible and fruitful, and its role in the interpretation of different optical phenomena in crystals is continuously increasing.

The exciton concept was advanced by Frenkel' in the study of the mechanism of conversion of light into heat in monatomic solid crystalline insulators. In this case, an essential difficulty arises, consisting in the fact that elastic or harmonic oscillators in the solid are incapable of accepting a quantum of energy accumulated in the electron shell of the excited atom, since this quantum is at least 100 times larger than the highest-energy quantum of the thermal oscillators of the crystals. A way out of this difficulty, according to Frenkel's concept, is provided by the fact that the excitation cannot remain localized on individualized molecules: translational symmetry of the crystal causes the regular stationary state of the crystal to form wave packets, which start to propagate in the crystal in the form of an excitation wave. This excitation wave corresponds to motion of a neutral quasiparticle, which Frenkel' called exciton. The exciton travels over the crystal until it encounters some defect or extraneous particle, to which it gives up its energy, which becomes transformed into heat.

The exciton mechanism of absorption was used by A. S. Davydov for the interpretation of the spectra of molecular crystals of aromatic hydrocarbons (benzene, naphthalene, anthracene). In this case the interaction forces acting inside the molecule exceed by many times the weak Van-der-Waals forces which couple the molecules in the crystal. Applying to this case the model of the Frenkel' exciton, A. S. Davydov has shown that in the case when in each unit cell of the crystal there are two molecules in different (that is, translationally nonequivalent) positions, a doublet should occur in the absorption spectrum of the pure crystal, with components polarized in the direction of the axes of the unit cell of the crystal. This splitting is now firmly established in the world's literature as the "Davydov splitting."

Extensive experimental and theoretical investigations performed at low temperatures in polarized light by A. F. Prikhot'ko and her co-workers (V. L. Broude, M. S. Brodin, M. T. Shpak and others) have in general confirmed Davydov's theory. These investigations have become well known in the entire world and initiated an important trend in the spectroscopy of the crystal state.

For an interpretation of the spectra of semiconductor crystals (likewise at low temperatures), such as cuprous oxide (Cu_2O) or cadmium sulfide (CdS), a somewhat different exciton model, proposed by Wannier and Mott, turned out to be exceedingly fruitful. According to this concept, the exciton can be regarded as a neutral pair, consisting of an electron situated at some "exciton level" in the forbidden energy band, and a "hole," equivalent to a positive charge equal in magnitude to the electron charge, in the valence band; both centers can be located at large distances from each other (according to data by E. F. Gross, this distance reaches 2500 Å at high excitation levels). Such a neutral pair, coupled by Coulomb forces, constitutes a quasi-hydrogenlike atom, or more accurately, positronium, which moves through the crystal. Corresponding to it are hydrogenlike stationary levels located in the forbidden band. Transitions between these levels should yield a hydrogenlike spectrum, that is, a spectrum with frequencies obeying a formula similar to the Balmer formula, and approaching on the long-wave side the intrinsic absorption spectrum of the crystal molecules. Such a unique spectrum was discovered and investigated with an unusual degree of detail in the absence of a field, and also in strong electric and magnetic fields by E. F. Gross and his co-workers (B. P. Zakharchenya, B. V. Novikov, et al.). This discovery made a great impression; it was initially disputed, but later fully recognized, and at the same time adding to the glory of the Frenkel' exciton idea.

The phenomena just considered, which can be explained on the basis of exciton theory, pertain, as already emphasized, to crystal spectroscopy, that is, to atoms, ions, or molecules located in the crystal lattice and having the symmetry properties of the crystal, but not of the units making up the crystal. Much progress in the study and various applications of the spectroscopy of individual complex organic compounds was due to a discovery, by É. V. Shpol'skiĭ and his co-workers (A. A. Il'ina, L. A. Klimova, T. N. Bolotnikova et al.), of the so called quasi-line spectra. The gist of the phenomenon lies in the fact that, owing to the isolation of the molecules in suitably chosen microcrystalline matrices, deep cooling (at nitrogen, hydrogen, or helium temperatures) causes the broad bands of the absorption and luminescence spectra to split into hundreds of narrow lines of width 10–15 cm^{-1} in the less favorable cases, and to values less than 1 cm^{-1} in the most favorable cases. The frequencies of the natural oscillations of the molecules in the ground state, determined by a vibration analysis of the luminescence spectra of this type, turned out to agree with high accuracy with the frequency determined from the random-scattering spectra, in those cases when the latter were unknown. This fact, and also the weak polarization of the spectra in a single-crystal matrix (M. T. Shpak), indicate unequivocally that these spectra indeed belong to individual molecules frozen in the matrices in the form of an "oriented gas." The reason why the lines are not smeared by the continuous spectrum of the phonons is explained, in accordance with the theory of K. K. Rebane and E. D. Trifonov, by the fact that the lines occur in "phononless" transitions, and the spectra themselves are the optical analog of the Mössbauer effect. Owing to the simplicity of the manipulations needed to obtain the spectra and to the accuracy of the results, the method of quasi-line spectra has found extensive use in a number of laboratories in the USSR and abroad. It was used to investigate by now approximately 200 organic molecules of various types and of different degrees of complexity—from simple aromatic hydrocarbons to such large and complicated molecules as porphine—the structural base of chlorophyll and hemoglobin—and its derivatives—porphyrins (A. N. Sevchenko, K. N. Solov'ev, S. F. Shkirman, T. F. Kachura—Institute of Physics of the Belorussian Academy of Sciences). The individuality, additivity, and high sensitivity of the spectra have made it possible to develop on their bases effective methods of qualitative and quantitative analysis, which have found application in the analysis of cancerogenic substances (P. P. Dikun, L. M.

Shabad, A. Ya. Khesina—Academy of Medical Sciences USSR) and identification of the aromatics of oils and bitumens, organic compounds of minerals in the earth's crust and in meteorites (A. A. Il'ina, T. A. Teplitskaya, R. I. Personov, et al.).

Molecular scattering of light is a field to which Soviet physicists have made very important contributions. We recall first of all that the very existence of molecular scattering was subject to doubt for a long time. It required work by such outstanding scientists as Lord Rayleigh, M. Smoluchowski and A. Einstein to determine the conditions under which molecular scattering of light is possible. Great clarity into the discussion of this phenomenon was introduced by the precise work of L. I. Mandel'shtam, performed prior to the revolution. In 1920, the French physicist Cabannes first succeeded in reproducing the blue color of sky in the laboratory, that is, in reproducing and investigating in detail the true molecular scattering in gases. After that time, in 1927, G. S. Landsberg proved beyond a doubt the existence of molecular scattering in solids—in crystalline quartz. Continuing the investigation of this phenomenon, G. S. Landsberg and L. I. Mandel'shtam discovered in 1928 that the spectrum of molecular scattering of light contains, besides the unshifted excited spectral lines, also lines which are shifted in the red and the violet directions. The discovery of this phenomenon, which is usually called in the USSR combination scattering of light, is one of the most important and the most fruitful discoveries in the physics of the 20th century. It served as a stimulus for a tremendous number of investigations (counted in the thousands) performed in all countries. The method of experimentally determining the natural frequencies of molecule oscillations, based on the random scattering, has uncovered tremendous possibilities for physics, physical chemistry, and also for inorganic and organic chemistry.

As is well known, combination scattering was also discovered almost simultaneously with Landsberg and Mandel'shtam and independently of them by Raman and Krishnan in India, who published their first communication ahead of the Soviet scientists. In view of this, it is traditional in the formal literature to call the phenomenon itself the Raman effect. However, this is clearly a technical circumstance—the date of publication—which does not detract in any way from the merit of the Soviet physicists, who not only discovered this new phenomenon, but developed a rigorous theory for it (L. I. Mandel'shtam, M. A. Leontovich, G. S. Landsberg, I. E. Tamm).

The fact that molecular scattering of light can be connected with a change in the wavelength was not unexpected to Soviet scientists. Regarding molecular scattering as an interference reflection of light by Debye elastic thermal waves, L. I. Mandel'shtam and L. Brillouin demonstrated back in 1918, independently of each other, that in such a scattering, in a medium with refractive index n, the excited wave λ_0 should experience a splitting into two waves, which are shifted relative to λ_0 by an amount

$$\Delta\lambda = \pm\, 2\lambda_0 n \frac{v}{c} \sin\frac{\theta}{2},$$

where v is the speed of sound in the medium and θ is the scattering angle. In view of the presence of the factor v/c, the shift $\Delta\lambda$ is smaller by one order of magnitude than the shift in random scattering. However, even this more subtle effect was observed experimentally by E. F. Gross.

L. I. Mandel'shtam

Great interest attaches also to the work of E. F. Gross, M. F. Vuks, I. L. Fabelinskiĭ and their coworkers, devoted to the investigation of the so called "wings" of Rayleigh scattering. These investigations have made it possible to study time-varying fluctuations of anisotropy, connected with rotary diffusion and vibrations of the molecules. Recently, Fabelinskiĭ and his coworkers discovered a new nonlinear optical phenomenon, called stimulated scattering of the Rayleigh-line wing (see page 000).

M. A. El'yashevich and B. I. Stepanov developed the theory of oscillation of molecules and methods for calculating the frequencies and the forms of the oscillations. M. V. Vol'kenshteĭn developed a theory of intensities in vibrational spectra (infrared and random spectra), explaining the empirically established regularities in vibrational spectra. These investigations of M. V. Vol'kenshteĭn, M. A. El'yashevich, and B. I. Stepanov are summarized in their two-volume monograph "Vibrations of Molecules."

One of the most important discoveries in the field of optics was made in 1934 by P. A. Cerenkov and S. I. Vavilov. Even in the early observations of the properties of radioactive substances, the Curie husband-and-wife team observed that solutions of certain mineral salts emit weak radiation under the influence of radioactive substances. This glow is usually considered to be fluorescence.

Cerenkov has demonstrated in 1934, however, that gamma rays produce weak glow not only in solutions (such as solutions of uranyl salts, the fluorescence of which was under investigation by Cerenkov), but also in pure liquids, such as distilled water, xyrol, toluene, glycerine, and different alcohols. This glow patently in its properties differed from fluorescence: it was not quenched under the influence of the strongest fluorescence "quenchers" (KI solution etc.), its polarization was greatly different from the fluorescence polarization. S. I. Vavilov, who directed Cerenkov's work, correctly saw in this glow a new effect, which he related not to the gamma rays themselves, but to the free electrons released by the gamma rays in the medium.

A complete theory of the Vavilov-Cerenkov radiation (it is more frequently called in the literature "Cerenkov radiation") was developed by I. M. Frank and I. E. Tamm (and later by I. E. Tamm in a more rigorous form), and was confirmed experimentally in all details by P. A. Cerenkov. Frank and Tamm explained the origin of this radiation from the point of view of classical electromagnetic theory as being a wave accompanying an electron that moves uniformly with a velocity exceeding the phase velocity of light in the given medium, that is, a velocity larger than c/n (n—refractive index of the medium). The simple condition for coherence of elementary Huygens waves that occur when an electron moves in a medium with a velocity $\beta = v/c$, is

$$\cos\theta = \frac{1}{\beta n},$$

where θ is the angle between the normal to the front of the wave and the direction of motion. It follows from this that an electron moving with velocity $v > c/n$ should be accompanied by a V-like wave, an illustrative analog of which may be a shock wave in air accompanying the flight of a bullet having a velocity larger than the velocity of sound in air, or the bow wave accompanying the motion of a ship when its velocity exceeds the velocity of the waves of the surface of the water.

V. L. Ginzburg presented a quantum treatment of the Vavilov-Cerenkov effect, applying to the emission of the photon by the moving particle the laws of energy and momentum conservation. Ginzburg showed further that the Cerenkov radiation should be observed when a charged particle moves near the surface of a dielectric and parallel to it. Ginzburg demonstrated at the same time that it is possible to produce in this manner a source of microwave electromagnetic radiation of wave lengths that are difficult to obtain in any other way.

Recently, counters for fast particles were constructed on the basis of the Cerenkov effect and found very extensive use in nuclear research. Such a counter consists simply of a pure liquid (for example, water) or a Plexiglas cylinder and a photomultiplier which registers the radiation flash.

Cerenkov radiation and all the effects associated with it is observed when a charge moves in a medium with superluminal velocity. V. L. Ginzburg and I. M. Frank have indicated, however, that there should exist a so called "transition radiation," consisting in the fact that when a uniformly moving charge crosses the boundary between two media, it should emit electromagnetic wave no matter what its velocity. This effect was calculated by Ginzburg and Frank and was recently observed experimentally.

G. S. Landsberg

We note, finally, two fundamentally important experiments, which clearly demonstrate the quantum nature of light. The first experiment, performed by A. F. Ioffe and H. I. Dobronravov, observed fluctuations of the "falling" of photons of very weak x-radiation into an ultramicroscopic charged bismuth particle suspended in a Millikan capacitor.

The second experiment, performed by S. I. Vavilov and co-workers (E. M. Brumberg, Z. M. Sverdlov), revealed statistical fluctuations of the number of photons of visible light falling into the eye under extremely low intensities (an eye adapted to darkness was chosen as the detector in view of its exceeding sensitivity).

We shall conclude our review of work on physical optics by listing the investigations devoted to the extreme regions of the spectrum. The optical nature of x-rays was established by the discovery of interference of x-rays in crystals. However, classical interference and diffraction experiments with x-rays are difficult to perform, in view of their short wavelength. In spite of this difficulty, V. P. Linnik succeeded in duplicating Lloyd's interference experiment with x-rays; this experiment is a modification of Fresnel's experiment with two mirrors, and yields the wavelength of the x-rays directly from the distance between the interference fringes.

The spectral region lying on the other side of the visible region, namely the section between the long infrared and the short electromagnetic waves, was discovered as a result of investigation by A. A. Glagoleva-Arkad'eva and M. A. Levitskaya (in the 20's), which were performed quite independently of each other. Owing to a clever method of exciting the rays in this region, it was possible to observe them, with the aid of a so called "mass radiator," with full clarity and thus fill the last gap in the unified scale of electromagnetic waves long before the development of modern methods.

Quantum Electronics

Since 1951, A. M. Prokhorov has been carrying out in the USSR investigations of radiospectroscopy, that is, investigations of the behavior of molecules in electromagnetic fields of the radio-frequency band. Soon after, N. G. Basov and A. M. Prokhorov advanced the idea of producing a molecular generator of electromagnetic oscillations at ultrahigh frequencies, based on stimulated emission of molecules, that is, on the radiation produced by excited atoms or molecules under the influence of a radiation field; the existence of such radiation, alongside the spontaneous radiation, was predicted by Einstein back in 1918. However, the realization of the idea of a molecular generator required three years of persistent work. In 1954 a molecular generator was constructed in the USA by C. Townes and his co-workers, and a few months later in the USSR by N. G. Basov and A. M. Prokhorov.

The creation of the molecular generator heralded the creation of a new branch of physics—quantum electronics--situated at the junction between radiophysics and optics. This field is vigorously developing also at the present time, and the leading role in this development is played by Soviet physicists; this was recognized by awarding the Nobel prize to N. G. Basov and A. M. Prokhorov jointly with C. Townes.

The operating principle of the molecular generator consists in first producing a beam of molecules which are at a high energy level, followed by induced "de-excitation" of the molecules in the field of electromagnetic oscillations of a resonator. The beam of excited molecules thus causes negative absorption (stimulated emission) of electromagnetic energy in the resonator, and this in turn causes self-excited oscillations.

We note that negative absorption in the optical region, independent of any work on quantum electronics, was experimentally realized by V. A. Fabrikant and F. A. Butaeva, who distinctly observed, by means of a clever experimental procedure, negative absorption at the mercury lines 5461, 4358, and 4047 Å.*

A molecular generator emits waves having the same frequency as the molecule vibrations. Since the external conditions have very little influence on the parameters of the molecule, such a generator has very high frequency stability, and has therefore come into use as a frequency standard. An important role in the study of the physics of molecular generators and in the development of different generator schemes were played by A. I. Oraevskiĭ, M. E. Zhabotinskiĭ, and G. M. Strakhovskiĭ.

During the first stage of development of quantum electronics, the molecule beams which are at the upper energy level were produced in a sorting device based on the Stark effect. The molecules emitted on entering the resonator and were then taken out of the resonator.

In 1956, N. G. Basov and A. M. Prokhorov proposed a new method for obtaining repopulation of the upper levels, namely the three-level method, which made it possible to use the same molecules for the production of negative absorption. Using this method, Bloembergen (USA) proposed a microwave amplifier based on transitions in ions of paramagnetic crystals. The transition frequency is easily varied by varying the magnetic field intensity. Paramagnetic quantum amplifiers have the unusually low intrinsic noise. This property caused the use in supersensitive receiving radio apparatus such as in radio telescopes.

In the late 60's it has become possible to realize a quantum generator for the optical range--a laser. N. G. Basov, B. M. Vul, Yu. M. Popov and O. N. Krokhin proposed methods for producing repopulation of the higher energy states in semiconductors and of constructing on their basis semiconductor quantum generators. C. Townes and A. Schawlow (USA) analyzed the problem of developing lasers as a whole. Following these investigations, lasers of different types were realized in 1960—1961, using transitions of impurity centers in crystals, in glass (called saline-state lasers), gas lasers and semiconductor lasers.

The development of semiconductor lasers in the USSR was particularly successful. Several methods of exciting the semiconductors were proposed, and some of them were realized for the first time at the P. N. Lebedev Physics Institute of the USSR Academy of Sciences by O. V. Bogdankevich, A. Z. Grasyuk, et al. Much progress in the development and the study of neodym-glass lasers was made by A. M. Bonch-Bruevich, M. P. Vanyukov, and P. P. Feofilov. A new powerful laser operating in the infrared was developed by A. M. Prokhorov and T. M. Murina.

A significant most recent accomplishment is the development of lasers with optical pumping, using dye solutions. Such lasers have sufficiently high power and can be developed in many regions of the optical spectrum. A number of important theoretical and experimental investigations in this field were made in the USSR by B. I. Stepanov and his co-workers.

The creation of lasers led to a new vigorous development of optics. It is no secret that for some time prior to the appearance of lasers the prevalent opinion among the scientists was that optics, as a branch of physics, has already played its role and is significant only as an applied discipline. This point of view was fully rejected when, owing to the possibility of using the highly intense emission from lasers, an unexpectedly new field was uncovered for the investigation of optical phenomena. This includes the optics of high-intensity radiation, or nonlinear optics. More than 40 years ago S. I. Vavilov and V. L. Levshin observed that the absorption coefficient of uranium glass is decreased by 1.5%, with an average error ± 0.3%, in experiments with light of an intensity that was high for that time. The phenomenon was interpreted as being the result of violation of the linearity of the equations of optics when radiation interacts in matter. Later, in 1944, S. I. Vavilov emphasized that the real optics of matter with which we are dealing, is in general "undisputedly nonlinear."*

In the case of uranyl, the relative ease of observing nonlinearity is due to the long duration of the excited state ($\tau \sim 10^{-4}$ sec) and the associated possibility of ac-

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*See, for example, V. A. Fabrikant and F. A. Butaeva in the G. S. Landsberg Memorial Volume, Moscow, 1959.

*See also S. I. Vavilov, The Microstructure of Light, Moscow, 1950.

cumulating active centers at the excited level. But in the scattering of light, for example, nonlinear deformation of the polarizability of the atoms and molecules is possible only if the electric field intensity of the light wave is of the same order as the intensity of the atomic electric field ($\sim 10^8$ V/cm). Such fields are produced only by light from monochromatic lasers. The first nonlinear effect realized with the aid of lasers was frequency doubling. The initially observed effect was very small, but soon capabilities were developed for an appreciable increase of the conversion efficiency, and effective light-frequency doublers were produced on this basis. Such multipliers make it possible to obtain full emission in a spectral region for which no lasers exist, including the ultraviolet. Such radiation can be used in physics and in engineering. In this connection, notice must be taken of the work by S. A. Akhmanov and R. V. Khokhlov, who also write the first monograph on nonlinear optics.*

The effects of scattering--Raman, Mandel'shtam-Brillouin, and "Gross"--at high incident-radiation intensity acquires new features—the scattering becomes stimulated, in contrast with the spontaneous scattering which takes place at low levels of the incident radiation. We note in this connection the investigations of I. L. Fabelinskiĭ. In particular, it is to him that we owe the so called stimulated scattering of the Rayleigh line wing. The phenomenon consists in the fact that exciting light of high intensity produces an appreciable force which orients the inisotropic molecules of the medium, thus causing a time-varying anisotropy which modulates the light.

In 1962, S. A. Akhmanov and R. V. Khokhlov proposed a so-called parametric light generator, which essentially converts the emission of a laser (solid-state or gas) operating at a fixed wavelength into emission with continuously variable output frequency. Such generators were recently constructed in the USSR and in the USA. The use of these generators greatly broadens the sphere of utilization of the lasers.

Indeed, the parametric generators constructed by now cover continuously a range consisting of 50% of the central wavelength, and the line width of the generated oscillations is a fraction of an Angstrom, while the power reaches hundreds of kilowatts.

The use of such generators is capable of revolutionizing experimental spectroscopy, increasing greatly the accuracy and sensitivity of spectral analysis (in particular, absorption spectroscopy). The capabilities of nonlinear optics itself are greatly expanded; parametric generators make it possible to realize resonant interaction between high-intensity coherent radiation and any molecular system.

A very interesting nonlinear effect in optics is the self-focusing of powerful light beams, first proposed by G. A. Askar'yan. This effect is based on the dependence of the refractive index of a medium on the emission intensity.

Thus, the regions occupied by the radiation turn out to be optically denser, and this leads, as a result of nonlinear refraction, to self-focusing of the beams. The self-focusing phenomenon plays an important role in nonlinear optics, changing, in particular, the thresholds of stimulated scattering, etc.

An important cycle of investigations of multiphoton processes was carried out by L. V. Keldysh, who developed a consistent theory of this phenomenon, and by M. G. Delone and G. V. Voronov, who performed an interesting experiment on multiphoton ionization of gases.

Great interest attaches to the work by P. P. Feofilov, devoted to a disclosure of a new mechanism of resonant multiphoton absorption. Until recently, the visible glow induced in crystals with rare-earth ion by infrared radiation was interpreted as a result of successive absorption of two or three photons and emission of one photon with double or triple the frequency. Investigations have shown that such a mechanism is incorrect. P. P. Feofilov proposed a new mechanism, wherein the activator centers absorb single of infrared quanta and subsequently interact with one another, thus redistributing their energy and causing cumulation of energy of several centers into one center, finally followed by its de-excitation and emission of a quantum at double or triple the frequency.

The development of lasers is one of the major accomplishments of physics during the last decade. The specific properties of the radiation of such generators—high coherence, directivity, large power, etc—served as a basis of many new branches of physics and engineering, primarily nonlinear optics, communication engineering, etc.

Radiophysics and Theory of Oscillations

The history of the development of radiophysics in the USSR recalls in many respect the history of the development of optics. Both were disciplines of great importance for the defense and the culture of the country; in spite of their importance, these disciplines were at their low level of development in prerevolutionary Russia.

To be sure, at the beginning of the 20th century radio engineering has not yet emerged as a separate technical science, and even the terms "radiophysics" and "radio engineering" did not exist. A branch of physics called "electromagnetic oscillations and waves," with practical applications in the form of "wireless telegraphy," was still very young. Nonetheless, the lag in this field on the part of pre-revolutionary Russia--a country where A. S. Popov invented "wireless communication"—was evident. Before the first world war there were in Russia neither special laboratories or departments in higher institutions of learning in which work could be done in radiophysics, and there was no domestic industry for "wireless telegraphy." It is precisely this latter circumstance, connected with the dependence of the industry on foreign capital, which hindered the development of radiophysics in Russia.

Some livlier activity in the field of radiophysics occurred already during the time of the first world war (1914—1918), owing to the activity of M. V. Shuleĭkin, N. D. Papaleksi, and their co-workers. However, just as in the field of optics, the intense development of radiophysics and radio engineering began after the October revolution. An important role during the first stage of this development was played by the "Nizhegorod Radio Laboratory" organized at the personal order by

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[*] S. A. Akhmanov and R. V. Khokhlov, Problems of Nonlinear optics, Moscow, 1964 [Gordon and Breach, in prep.]

V. I. Lenin in Nizhniĭ Novgorod (now Gor'kiĭ) under the scientific leadership of M. A. Bonch-Bruevich. We should also mention with gratitude the activity of V. K. Lebedinskiĭ, who was among the founders of the Nizhegorod Laboratory and played an important role not so much by his creative work as by his organizational, pedagogical, and publishing activities. At approximately the same time, a number of radiophysics and radio engineering centers were founded in other cities, principally in the restored higher institutions of learning. These were the departments headed by M. V. Shuleĭkin at the Moscow Higher Technical School (now the Bauman Moscow Higher Technical School), the department headed by L. I. Mandel'shtam and N. D. Papaleksi in Odessa, and the Radio Laboratory organized by A. A. Chernyshev at the Leningrad polytechnic institute.

So much progress was made in the field of oscillation theory, the significance of which to physics and engineering goes far beyond the limits of radio engineering alone, that the results in this field can be rightly regarded as among the most brilliant accomplishments of Soviet physics during the last fifty years. An outstanding role in these accomplishments were played by the investigations of L. I. Mandel'shtam, N. D. Papaleksi, and their large school. We note also that these accomplishments were the fruit of close collaboration between physicists, mathematicians, and engineers.

As is well known, the classical theory of oscillations was heretofore the theory of linear oscillations, that is, oscillations obeying a very simple widely-known linear differential equation. In spite of the great degree of completeness of this theory, we owe to the school of Mandel'shtam and Papaleksi an appreciable uplift in the scientific level in this field, too. This uplift appeared in such problems, for instance, as the extension and the deepening of what is seemingly such a well known concept as resonance. That the concept of resonance must be made more general is seen from the elementary mechanical example of the pendulum, which can be made to oscillate either in the usual manner, under the influence of a periodic external force, that is, by periodically "pushing" it at a period equal to the natural period of the pendulum, or else by periodically varying the length of the pendulum. The latter method, which is realized also in the buildup of the oscillations of a swing, where the height of the center of gravity of the swing above the earth is varied periodically, is an illustrative example of the so-called parametrical resonance, since resonance is accomplished here by periodically varying the parameters such as the length and the moment of inertia of the swing.

Another example of parametric resonance is the excitation of oscillations in an electric network by periodically changing the capacitance or the inductance of the system (without an external voltage). This case is particularly interesting because a deeper analysis of this case, performed by L. I. Mandel'shtam and N. D. Papaleksi, led them to the discovery of a new method of generating alternating currents, realized in the so called parametric machines constructed by them.

N. D. Papaleksi

Interest in parametrically excited oscillating systems recently has increased strongly in connection with the appearance of low-noise parametric amplifiers and high-speed elements for computing machinery—parametrons. We note the important role played in the study of parametric amplifiers by the group of N. N. Malov (V. S. Étkin, E. M. Gershenzon, and others). They were the first to demonstrate the possibility of electronic tuning of parametric amplifiers, they studied the problems of increasing their sensitivity and broadening the bandwidth, and investigated multifrequency parametric systems having one or several variable parameters.

Several new applications of parametric devices were proposed in the USSR: two-circuit generators with frequency band stabilization (S. A. Akhmanov, G. M. Utkin), frequency dividers of larger multiplicity (A. E. Kaplan) etc.

Fifty years ago, classical theory of linear oscillations satisfied practically all the demands of physics and engineering. However, with appearance of such an important physical and technical device as the vacuum tube, whose operation as an undamped oscillator or as a detector is based entirely on its nonlinearity, has brought to the forefront the problem of developing the theory of nonlinear oscillations.

Credit for the initial development of the theory of nonlinear oscillations belongs to Van der Pol, who created a scientific center devoted to these problems in Holland. However, in the 40's, owing to the investigations of the school of L. I. Mandel'shtam and N. D. Papaleksi (A. A. Andronov, A. A. Vitt, S. É. Khaĭkin, G. S. Gorelik, S. M. Rytov, S. P. Strelkov et al.), and also of N. M. Krylov, N. N. Bogolyubov, and Yu. B. Kobzarev, the center of work in the field of nonlinear oscillations shifted from Holland to the USSR.

The effective methods developed as a result of these investigations have found numerous applications, first principally in the field of radiophysics, and then in a number of other fields far removed from radiophysics. Thus, for example, already after the second world war, the theory of nonlinear oscillations was extended by A. A. Andronov and his school (M. A. Aĭzerman, Yu. M. Neĭmark, M. A. Zheleztsov et al.) to include problems in automatic control, particularly control of machinery; this theory yielded new results in the theory of the clock and the theory of operation of the autopilot. The same methods were successfully applied to the theory of the action of charged-particle accelerators and to the astrophysical problem of the Cepheid stars, which change their brilliance periodically (S. A. Zhevakin). A more detailed description of this entire field, which is just as important as it is interesting, is beyond the scope of the present general review of the development of Soviet physics. Those interested can find a number of brilliant articles and lectures in the collected works of L. I. Mandel'shtam and N. D. Papaleksi. An extensive monograph on the theory of nonlinear oscillations, translated into foreign languages and since acclaimed as a classic, was written by A. A. Andronov, A. A. Vitt, and S. É. Khaĭkin.

The development of radio engineering and radiophysics followed the path of shortening the wavelength of the employed radiation. Already in the first postwar years the radiation wavelength began to be measured in decimeters and centimeters, and became comparable with the linear dimensions of the receiving and transmitting apparatus. The nonlinear processes on which the action of this apparatus is based ceased to be vibrational and acquired a wave character. This paved the way for the development of nonlinear wave theory, in the formulation of which Soviet radiophysicists took a very active part.

Unlike oscillation theory, which is based on ordinary differential equations, wave theory is based on partial differential equations, for which there is practically no nonlinear theory. It was therefore necessary to develop a mathematical formalism for the analysis of nonlinear wave processes, and also to derive on its basis some qualitative laws governing such processes. Important results in this new field were obtained by A. V. Gaponov, R. V. Khokhlov, and their co-workers. These investigations served as the basis for such new trends as the study of electromagnetic shock waves, nonlinear optics, further development of nonlinear acoustics, etc.

Another branch of radiophysics in which Soviet physicists attained great successes is the theory of propagation of electromagnetic waves, which is most important for all types of radio transmission. As is well known, the propagation of wadio waves, which makes possible radio communication over small and large distances, is governed from the point of view of physics by two phenomena—diffraction and refraction—the relative role of which depends essentially on the distance or, more accurately, on the ratio of the distance to the wavelength. At the same time, a distinguishing feature of the propagation of waves in the radio band is, unlike optics, the closeness of the radiation (in the wavelength scale) to the separation boundary, for example, the boundary between the earth and the air. As a result of this, the mathematical problem of the propagation of radio waves is so complicated, that its solution required efforts on the part of such outstanding representatives of mathematical physics as A. Sommerfeld in Germany and V. A. Fock in the USSR. V. A. Fock's work was published in final form in 1933. Many other problems, for example, the problem of the so called shore refraction, was solved in the papers of M. A. Leontovich, G. A. Grinberg, and E. L. Feĭnberg.


A. A. Andronov

Subsequently E. L. Feĭnberg developed a general theory of propagation of radio waves over an inhomogeneous and rough surface.

Diffraction theory has greatly advanced recently, in connection with progress in antenna and waveguide techniques, and also in connection with lasers. New methods for the analysis of diffraction problems were developed, in particular the parabolic-equation method (M. A. Leontovich and V. A. Fock) and the factorization method (L. A. Vaĭnshteĭn), and new systems were developed and found application in engineering. Thus, A. M. Prokhorov proposed open resonators for lasers, B. Z. Katsenelenbaum and V. M. Talanov proposed open waveguides for the transmission of energy in the millimeter and submillimeter bands, etc.

In the investigation of the propagation of radio waves, interest was usually attached exclusively to the amplitude of the electromagnetic waves. L. I. Mandel'shtam and N. D. Papaleksi discovered a new region for research, focusing their attention on the propagation of the phase of the oscillations. As a result of a deep analysis of the singularities of interference between radio waves, compared with interference in optics, they have shown how to measure the propagation velocity with the aid of radio-wave interference, or the distance if the propagation velocity is known. This method was used by them and their co-workers in practice for the measurement of distance as well as for the measurement of propagation velocity. Mandel'shtam and Papaleksi constructed a spectral instrument for the measurement of distances, a radio range finder, with the aid of which distances on the order of 100 kilometers can be measured within 4–5 minutes with accuracy to several hundredths of one per cent. This instrument, as well as others based on radio interference, found use in marine navigation and in geodetic surveying. The speed of propagation of electromagnetic waves was measured in a number of expeditions, and in measurements in the Black Sea the results obtained were accurate to 2–3 tenths of one per cent. These measurements have shown that the speed of propagation of electromagnetic waves over the sea is equal to the speed of light.

The foregoing investigations far from cover all the research performed in the USSR on radio wave propagation. Work on the laws of propagational waves in the meter band was performed by B. A. Vvedenskiĭ and his co-workers. The theory of diffraction propagation of radio waves was developed by V. A. Fock. Many other valuable experimental and theoretical investigations by M. A. Bonch-Bruevich, A. N. Shchukin, and others on the propagation of radio waves are beyond the scope of the present review. L. I. Mandel'shtam and N. D. Papaleksi called attention, as early as during the second world war, to interesting possibilities of using radio in astronomy (radar sounding of the moon). Subsequently, at the initiative of N. D. Papaleksi, theoretical calculations were made on the coefficients of reflection of radio wave from the solar corona and it has become clear that the sun should produce intense radio emission (V. L. Ginzburg). The theory was confirmed during the solar eclipse in the summer of 1947, by an expedition in Brazil headed by S. É. Khaĭkin. This was the start of the development of radio astronomy in the USSR. By now it has already yielded many important results, both theoretical (V. L. Ginzburg, I. S. Shklovskiĭ, G. G. Getmantsev, I. M. Gordon, V. V. Zheleznyakov, N. S. Kardashev, S. I. Syrovatskiĭ) and experimental (V. V. Vitkevich, V. S. Troitskiĭ, Yu. N. Pariĭskiĭ, A. E. Salamonovich, V. A. Razin, A. D. Kuz'min). We point, for example, to the investigation made by V. V. Vitkevich made by the solar "supercorona"--electronic inhomogeneities that extend over tremendous distances from the sun (on the order of 15 solar radii and more). A group headed by V. A. Kotel'nikov received radar signals reflected from a number of planets; we note also V. S. Troitskiĭ's investigations of the properties of the external cover of the moon, performed by purely radiophysical methods. We confine ourselves to this brief mention of radioastronomical research, since they now pertain to a greater degree to astrophysics.

Even during the first stages of the development of the theory of nonlinear oscillations in the USSR, L. I. Mandel'shtam and A. A. Andronov called attention not only to the dynamic description of oscillating systems, but also to the statistical description which takes into account the presence of random (fluctuating) processes. Further investigations of the role of fluctuations in a vacuum-generator have made it possible not only to estimate theoretically its essential nonmonochromaticity, but also to measure this "natural" spectral linewidth of the generator, in spite of its extreme smallness (in relative measure—on the order of 10^{-13}). This was done by I. L. Bernshteĭn, and was made possible as a result of a very clever radiophysical method proposed by him for the measurement of very small phase differences (down to hundredths of a second of angle). G. S. Gorelik proposed and subsequently realized a number of exclusively interesting applications of this phase-measurement method; these applications are significant in themselves. This includes the repetition of Sagnac's experiment in the radio band, the use of a modulation method in optical interferometry, the measurements of very small mechanical oscillations of amplitude comparable with the wavelength of light (on the order of hundredths of an Angstrom), the measurement of angular diameters of stars, etc.

Further progress was made also in theoretical work on statistical phenomena in self-oscillating systems and in other nonlinear devices.

Low Temperatures

The investigations in this field were carried out in three large centers: at the Institute of Physics Problems in Moscow, headed by P. L. Kapitza, and in the Cryogenic Laboratory of the Physico-technical Institute of the Ukrainian Academy of Sciences in Khar'kov, and most recently in the newly created Physico-technical Institute of Low Temperatures in Khar'kov (V. I. Verkin).

Kapitza's work was above all a major step forward towards the creation of new machinery for the liquefication of gases on a commercial scale. It should be recalled that in general there are two methods of cooling and liquefying gases. In the first, the cooling is due to the performance of internal work (the Joule-Thompson effect). This method is used in the Linde machines, which are extensively employed and described in all textbooks. In the second method the gas is cooled by adiabatic expansion, and this cooling is the result of external work performed by the gas. This cooling was observed as long ago as 1819 by Clement and Desormes in adiabatic expansion of gas, wherein the pressure in the vessel was lowered when part of the gas was allowed to escape through a valve. It can be shown that in such an expansion, the gas remaining in the vessel imparts a definite kinetic energy to the outgoing gas and is adiabatically cooled. This phenomenon is known to anyone who has performed the physics experiment on the determination of the ratio of the specific heat by the method of Clement and Desormes. It was used at times in laboratory experiments on cooling and liquefaction of gases: by Olszewski in 1895 to liquefy hydrogen, by Simon in 1933 to liquefy helium, and was developed and realized on a commercial scale (for the liquefication of air) in France by J. Claude. However, the construction of commercial machinery for continuous liquefication of helium on the basis of this principle encountered great difficulties. which were first overcome by Kapitza in the helium liquefier constructed by him in 1934.

Subsequently, helium liquefiers based on adiabatic cooling found extensive use both in our country and abroad. The Institute of Physics Problems has now in operation a large liquefier producing 100 liters of liquid helium per hour.

The same principle of cooling at the expense of the external work performed by the gas in adiabatic expansion was used by P. L. Kapitza in a new type of machine for commercially producing liquid air. In this machine, the gas performed external work and rotated a high-efficiency turbine (turbodetender). This experimental turbine had a diameter of only 8 centimeters, weighed only 250 grams, but operated at 40,000 rpm. On the basis of this turbine, Kapitza developed and constructed an experimental setup for the production of liquid air. In this machine, the air was first compressed to only 4--5 atmospheres, whereas in commercial equipment, where the cooling is by the Joule-Thompson effect, the initial compression is 200 atmospheres, and in the Claude machines to approximately 40 atmospheres. Thus, by successfully constructing a machine on the basis of the turbodetender, a new principle was introduced into the technique of obtaining low temperatures--the principle of the low-pressure machinery. The efficiencies of these machines, especially when used for air reduction, were found in practical and commercial applications in the USSR and abroad to be exceedingly high. Soviet engineers did much work towards introducing and further improving this method.

In the present time, the production of large amounts of oxygen, which has important applications in metallurgy and other fields of engineering in the USSR and abroad, follows precisely the path indicated by P. L. Kapitza, of using machines with turbodetenders.

The most interesting physical phenomena observed at the lowest temperatures are, as is well known, the superconductivity of metals and the superfluidity of helium II. The latter phenomenon was discovered and described in great detail, both theoretically and experimentally, by Soviet physicists. At the temperature 2.19° K (the so called λ point) helium, which remains liquid down to the lowest obtainable temperatures, goes over into a state called helium II, in which it has a number of striking properties. One of the most remarkable properties of helium II is its unusually high heat transfer in narrow capillaries, discovered by Keesom and his daughter (Holland). On the other hand, Kapitza's experiments have shown that even the most detailed determinations of viscosity during the flow of helium II through narrow gaps can yield only an upper limit for the viscosity: the true value of the viscosity is so low, that it cannot be determined. It is easy to see, however, that negligible viscosity is in contradiction with thermal superconductivity. Indeed, the transfer of heat via thermal conductivity presupposes the transfer of momentum and energy from atom to atom, that is, it presupposes interaction between the atoms. But under this condition, the viscosity cannot be vanishingly small. This apparent paradox was resolved by Kapitza in a number of experiments that were very subtle and yet remarkably lucid, and demonstrated fully that the high heat transfer in helium II is due not to its thermal conductivity, but to the transport of heat by convection: helium II is a liquid which is thermally not superconducting, but superfluid. Thus, Kapitza's experiments have discovered and made it possible to investigate in detail a new phenomenon, superfluidity.

The process of heat transfer in helium II was investigated both in gaps and in capillaries as well as in free helium II. To study the heat transfer in free helium II by optical means, P. G. Strelkov constructed an optical dewar with plane-parallel optically polished flanges, which made it possible to employ Toepler's well known optical method. The superfluidity of helium II was explained by L. D. Landau after preliminary investigations by F. London and E. Tisza. Generally speaking, superfluidity is a quantum property of helium II. In fact, at a temperature 2--3° K the de Broglie wavelength becomes comparable with the interatomic distances in the liquid, as a result of which quantum phenomena should be observed in the properties of helium II. These quantum phenomena become manifest already in the fact that helium II remains liquid down to the temperature of absolute zero, whereas, according to classical physics all bodies should be in the solid crystalline state at absolute zero. It is interesting to note that helium is the only quantum liquid existing in nature; all the other liquids solidify long before quantum properties begin to appear in them.

By regarding helium II as a quantum liquid, Landau was able to determine theoretically the energy spectrum of this liquid, that is, the aggregate of its energy levels. Since we are dealing here with a system of strongly interacting particles, we have in mind here the levels of the entire liquid as a whole, and not of its individual atoms. Although such a problem cannot be completely solved, a number of statements, sufficient to explain the properties of helium II, can be made on the basis of general theoretical considerations. Landau uses in this case a concept, which is valid in quantum mechanics, of weakly excited states as aggregates of "elementary excitations," which correspond, in turn, to "quasiparticles." We recall that, for example, the thermal excitation of a crystal can be regarded either as Debye thermal waves propagating in the crystal, or as an aggregate of quasiparticles—acoustic quanta, phonons—which are in correspondence to these waves just as photons correspond to electromagnetic waves. Landau considers in his theory two main types of energy spectra of microscopic systems, in one of which the corresponding quasiparticles obey Bose-Einstein statistics (Bose particles), and in the other Fermi statistics (Fermi particles). It turns out here that liquid helium should have a spectrum of the Bose-particle type, whereas the spectrum of the Fermi particles does not lead in general to superfluidity. Using such very general concepts concerning the properties of a quantum liquid, Landau not only explained the properties of helium II, but predicted successfully a number of new phenomena.

Of great significance for further development of the theory of helium II was work by N. N. Bogolyubov (1947), who solved in a brilliant manner the problem of the energy spectrum of a non-ideal Bose gas, that is, a Bose gas with weak interaction between the particles. In such a formulation of the problem a simple, albeit schematic, model can be used to describe the energy spectrum of a macroscopic body having the properties stipulated by the Landau quantum-liquid theory. It turns out indeed that the energy spectrum of a non-ideal Bose gas is similar to the spectrum of helium II in the Landau theory.

It followed further from the theory of superfluidity that two types of motion can exist in helium II, one corresponding to motion of an ordinary viscous liquid and the other to motion of an ideal liquid having no viscosity.

In other words, helium II can be regarded in a certain sense as a mixture of two liquids: ordinary and superfluid. It follows hence that when a solid body moves in helium II, it drags with it only the "ordinary" part of the helium II, whereas the superfluid part remains stationary. This paradoxical conclusion of the theory was confirmed by experiments of É. L. Andronikashvili, who investigated torsional oscillations of a stack of metallic discs immersed in helium II.

One of the most interesting consequences of Landau's theory is the need for the existence in helium II, besides ordinary or first sound, of also the so called "second sound," which consists of thermal waves propagating with a velocity greatly different from the velocity of first sound. Second sound was predicted by Landau, and its emission from sources of different types was calculated by E. M. Lifshitz. Second sound was observed experimentally and investigated in detail by V. P. Peshkov. The interaction between elementary excitations in helium was investigated by Landau and Khalatnikov. This enabled Khalatnikov to calculate the kinetic coefficients of helium—the viscosity, the thermal conductivity, etc.

In addition to the superfluid quantum liquid—liquid He^4, another helium isotope, liquid He^3, is under extensive study. These investigations were carried out in the USSR by V. G. Lazarev and B. N. Esel'son in Khar'kov and by V. P. Peshkov at the Institute of Physics Problems in Moscow. It turns out that liquid He^3 is not superfluid, at any rate at temperatures higher than 5×10^{-3}°K. As already stated, this is connected with the fact that the elementary excitations in He^3 have Fermi-type statistics. The theory of such a Fermi liquid was developed in 1956 by L. D. Landau. Landau demonstrated, in particular, that at very low temperatures there can propagate in such a liquid oscillations of a peculiar kind—zero sound, the velocity of which, unlike ordinary sound, is not determined by the compressibility of the liquid. Zero sound in He^3 was recently observed by Abel, Anderson, and Wheatley in the USA.

The superconductivity phenomenon was also investigated successfully. Notice should be taken here of the theoretical papers of L. D. Landau and V. L. Ginzburg, N. N. Bogolyubov, A. A. Abrikosov and L. P. Gor'kov. Experimental studies of superconductivity were made by L. B. Shubnikov, A. I. Shal'nikov, and N. E. Alekseevskiĭ. Landau's investigations were devoted to the nature of the transition state between superconductivity and the nonsuperconducting state. According to his theory, the intermediate state is a mixture of superconducting and normal layers which alternate with one another. This layered structure was fully confirmed by experiments of A. I. Shal'nikov and Yu. V. Sharvin.

The macroscopic theory of superconductivity developed by V. L. Ginzburg and L. D. Landau has gained wide popularity. This theory describes the behavior of superconductors near the point of phase transition to the normal state. An advantage of this theory is that it makes it possible to investigate superconductors in strong magnetic fields. In particular, on the basis of the Ginzburg-Landau equations, A. A. Abrikosov developed a theory of superconductors of the second kind, which include the majority of superconducting alloys. These superconductors differ from ordinary ones in that a sufficiently strong magnetic field can penetrate in them without loss of their superconducting properties. Abrikosov's theory attributes this phenomenon to the fact that the magnetic field is not distributed in these superconductors continuously through the entire volume, but concentrated in individual filaments.

A great event in physics occurred in 1957, when a macroscopic quantum theory was developed for superconductivity after a number of unsuccessful attempts spanning the 45 years elapsed since the discovery of this phenomenon.

The experimental investigations performed in the 50's have shown that the critical temperature of transition to the superconducting state depends on the mass of the isotopes that form the metal. H. Froehlich called attention to the fact that this is a direct indication of the role played by the metal lattice in the onset of superconductivity. The next step was made by the British theoretician L. Cooper, who showed that the interaction between the electrons, which have energies close to the Fermi surface, and the lattice vibrations (phonons) is such that it can produce attraction between the electrons. As a consequence of this attraction, the electrons combine into pairs with oppositely directed spins (Cooper pairs). These pairs are formations with integer spin, obeying therefore Bose and not Fermi statistics. This is of decisive significance, since the mechanism of the interaction between the conduction electrons and the lattice defects or the impurities, which dissipates the energy of the electrons to a value below the Fermi level, stopping in final analysis the flow of the current, is not effective in the case of Cooper pairs, which do not obey the Pauli principle. On the other hand, the energy necessary to break the pair is finite, albeit small, which in turn leads to the occurrence of an energy gap between the normal and the superconducting states.

Thus there exist below the critical temperature, besides the normal electrons, also pairs forming the superconducting current—a model similar to the two-fluid picture of superfluidity. The mathematical theory was developed on the basis of this physical picture by Bardeen, Cooper, and Schrieffer in the USA; the same results were obtained later by N. N. Bogolyubov by a brilliant mathematical method.

Of great importance for the calculation of different concrete effects was a new formulation proposed for this theory by L. P. Gor'kov. This enabled Gor'kov to present a microscopic derivation of the Ginzburg-Landau equation, and to develop with A. A. Abrikosov the theory of the properties of superconducting alloys, with account taken of the finite length of the mean free path of the electron in the metal.

Superconducting alloys recently have found a concrete technical application for the construction of superconducting magnets, which make it possible to obtain strong magnetic fields with very low loss of energy (at the present time, up to 100 kOe). A large number of theoretical and experimental investigations were devoted to the study of the low-temperature properties of nonsuperconducting metals in strong magnetic fields. Experimental investigations on the de Haas—van Alphen were made by Shoenberg and by B. G. Lazarev and his co-workers at the Institute of Physics Problems. The resistance of metals in an electric field (galvanomagnetic properties) was investigated by P. L. Kapitza, E. S. Borovik, and B. G. Lazarev. A new impetus to such research was given by the theoretical papers of I. M. Lifshitz and his students. The point is that in most of the preceding investigations the electrons in the metal were regarded as free, but actually they constitute quasiparticles with complicated energy spectra. In I. M. Lifshitz's papers, the properties of metals are investigated in general form, without simplifying assumptions concerning the form of the spectrum. It turned out that the entire dynamics of the conduction electrons, and with it also the various electronic properties of metals--galvanomagnetic, high-frequency, resonant (and also numerous oscillatory effects of the de Haas--van Alphen effect, Shubnikov--de Haas effect, and others) can serve as splendid indicators of the energy spectrum of the conduction electrons, particularly such important characteristics as the shape of the Fermi surface, about which physicists had practically no information before. The corresponding experiments were carried out by N. E. Alekseevskiĭ and Yu. F. Gaĭdukov at the Institute of Physics Problems and by B. I. Verkin and E. S. Borovik in Khar'kov.

Further information on the electronic properties of metals were obtained by studying metals in high-frequency fields. Mention should be made here first of all of the phenomenon of cyclotron resonance in metals, discussed in the Semiconductor Physics and Magnetism sections. Other resonance phenomena were revealed by the experiments of M. S. Khaĭkin and V. F. Gantmakher at the Institute of Physics Problems. Anomalies of thermodynamic and kinetic properties of metals at high pressures arise near the point where the topology of the Fermi surface changes. This phenomenon, predicted by I. M. Lifshitz, was first observed experimentally by V. G. Lazarev and his co-workers.

Special mention should be made that the basis of progress in the experimental investigation of metals is a possibility of obtaining very pure metals, in which the electron mean free path reaches several millimeters.

Physics of Dielectrics

Major results in this field were due to the school of A. F. Ioffe. Even in his early investigations, performed jointly with W. K. Roentgen, Ioffe has shown that although the electric conductivity of dielectric crystals is essentially ionic in nature, the photoconductivity of x-irradiated or naturally colored rock salt is due to the electrons. As a result, the confusing picture observed when current flows through a dielectric is due primarily to volume charges that accumulate in different places.

Thus, for example, the decrease of the current with increasing time, observed in most dielectric, is due to an inverse voltage produced by the space charge accumulating near the electrodes. The presence of a negligible amount of extraneous impurities leads to accumulation of ions near these impurities; these ions produce a space charge. Fruitful investigations, both from the scientific and practical points of view, were made on the dielectric properties of amporphous bodies by P. P. Kobeko, A. P. Aleksandrov, S. N. Zhurkov, and others.

Closely related with research on dielectrics and semiconductors is the study of so called ferroelectrics. A typical representative is Rochelle salt, which has an anomalously large dielectric constant and exhibits hysteresis, properties characteristic of ferromagnetic substances; this is why Rochelle salt and similar substances are called ferroelectrics. A thorough experimental and theoretical investigation of the properties of Rochelle salt was first performed in 1930--1932 by I. V. Kurchatov, B. V. Kurchatov, and P. P. Kobeko.

In 1945, B. M. Vul and I. M. Gol'dman discovered a new ferroelectric, barium titanate, which is superior in many properties to Rochelle salt and to similar crystals. This discovery served as an impetus to numerous investigations of ferroelectrics of a new type, and it turned out that barium titanate is only one of many ferroelectrics of this type. Ferroelectric materials are finding recently more and more new applications in different fields of engineering.

The modern phenomenological theory of the transition of a material into the ferroelectric state was developed by V. L. Ginzburg. He was also the first to predict the now widely held point of view, according to which, from the microscopic point of view, the ferroelectric transition is the result of the fact that at a certain temperature the modulus of elasticity vanishes for one of the normal oscillations of the crystal lattice.

Great attention has been paid to the problem of electric strength. V. A. Fock constructed in his papers the most complete and finished theory of thermal breakdown of dielectrics; this breakdown was investigated experimentally by N. N. Semenov, L. D. Inge, A. F. Val'ter, and others. It described well the process of disintegration of dielectrics in strong electric fields under sufficiently long loadings and relatively high temperatures. On the other hand, at low temperatures and for short pulses, the breakdown picture, as shown by numerous investigations, is greatly altered and has a purely electrical nature. In this connection, A. F. Ioffe introduced the concept of cascade ionization as the cause of dielectric breakdown; this concept has played a fundamental role in the subsequent development of physics of dielectrics and semiconductors. Among the later investigations, which have fully confirmed this point of view, the most important ones were those of A. F. Val'ter and L. D. Inge, who first demonstrated, in particular, the pure electronic nature of electric breakdown. Further development of the physics of dielectrics is connected with the investigation of polarization and dielectric losses. Fundamental investigations in this region were carried out by G. I. Skanavi and his co-workers. In particular, G. I. Skanavi explained the existence of a high dielectric constant in the titanates of certain metals and their solid solutions. These investigations serve as the basis for the development of our domestic capacitor industry.

The influence of the structure of high polymers on their dielectric properties was investigated by P. P. Kobeko and co-workers.

In the postwar years, the general development of solid state physics has led to a more detailed study of the electron structure and electronic spectra of dielectric crystals. S. I. Pekar and his co-workers developed the idea, advanced earlier by L. D. Landau, that mobile electrons in ionic crystals exist in the so called polaron state, that is, they polarize the crystal lattice surrounding them, the electron are then bound with the "polarization cloud'' surrounding it, and the two move together, so that the effective mass of such a formation increases greatly, its mobility decreases, etc. Similar concepts of a strong coupling between the motion of electrons and the motion of the crystal lattice were used by M. A. Krivoglaz, S. I. Pekar, and many other authors to describe the nature of the so called color centers of ionic crystals and the characteristic features of their optical spectra.

Physics of Semiconductors.

Research in semiconductors has moved recently to the forefront as a most important scientific and scientific-technical problem. From the point of view of their characteristic properties, semiconductors constitute the largest class of bodies encountered in nature. Numerous technical devices are based on semiconducting properties--rectifiers, photocells, thermistors, semiconductor triodes (transistors), and many others.

Research on semiconductor physics began in the Soviet Union in the 30's at the initiative of A. F. Ioffe, who insistently emphasized the possibility of using semiconductors as energy converters: photocells, thermocouples, etc. Even before the war, the Soviet physicists obtained many results of basic significance for further advancement of semiconductor physics.

The physical properties of semiconductors are determined essentially by the structure of their electronic spectra. Accordingly, the electric conductivity of semiconductors can vary greatly in nature and origin, depending on whether the electrons in the conduction band are excited by thermal motion from the valence band (intrinsic conductivity), are excited by light (photoconductivity), or are introduced by some impurities (impurity conductivity). The impurity can either give up its electron to the conduction band (donor), or else capture an electron from the valence band, producing a hole there (acceptor). It is the presence of different types of conductivity, and the possibility of controlling them, on which all the technical applications of semiconductors are based.

The existence of intrinsic and impurity conductivity and the possibility of their separation were first demonstrated by V. A. Zhuze and B. V. Kurchatov in 1932.

According to modern notions, the electron levels in the crystals form broad ''bands'' of closely lying levels, separated by large gaps. These levels belong no longer to individual atoms or molecules, but to the entire crystal as a whole, that is, the electron can move through the crystal. Using Ya. I. Frenkel's picturesque expression, the electrons of the centers forming the crystal ''collectivize.'' Since, in accordance with the Pauli principle, there can be no more than two electrons at any one level, all the levels of the lower or valence band are already filled, whereas the upper band remains free. Transition of an electron from the lower band to the conduction band requires the consumption of a large energy, greatly in excess of the average thermal-motion energy, this explains the poor conductivity of insulators and semiconductors at sufficiently low temperatures (no current can flow in a completely filled band, since the electrons can not be accelerated, that is, can not take energy from the field, all the neighboring levels being occupied by other electrons).

However, an electron that gets over somehow from the lower valence band to the conduction band can move freely through the crystal, and an empty place, a ''hole'' equivalent to a positive charge, appears in the valence band. B. I. Davydov proved theoretically in 1938, and V. E. Lashkarev experimentally in 1941, that the rectification of current at the contact between two semiconductors is due to the presence of different types of conductivity--electron and hole--on the two sides of the contact. This is the operating principle of the electron-hole junction (p-n junction), which is the central element of all of semiconductor electronics. I. E. Tamm showed that special ''surface'' electron levels should appear on the surface of a semiconductor, and should play an important role in the interpretation of various complicated phenomena in real semiconductors. During the same years, I. K. Kikoin and M. M. Noskov discovered an effect wherein an electromotive force is produced when a semiconductor is illuminated in a transverse magnetic field; this effect now bears their name and is widely used for the investigation of electronic processes in semiconductors. An important role was played subsequently by the work of B. I. Davydov, who demonstrated that in semiconductors, as well as in plasma, even relatively weak electric fields cause a noticeable deviation from equilibrium: the temperature of the electrons and of the holes becomes higher than the temperature of the crystal lattice, as a result of which the current flow becomes essentially nonlinear.

A study of the flow of electric current through a semiconductor is of great interest. The catastrophic increase of the number of current carriers when a definite electric field intensity is reached (breakdown) is caused by shock ionization--a process which is well known from the investigations of electric discharges in gases. In semiconductors this process also plays an important role, but it is complicated here by many phenomena that are characteristic of semiconductors. This question was investigated by B. I. Davydov and I. M. Shmushkevich, by L. V. Keldysh, by V. A. Chuenkov, and others.

Besides shock ionization, an increase in the number of electrons in the conduction band of the semiconductor is caused also by another important phenomenon, namely direct transition through the forbidden band, tunnel transition, or tunneling for short. L. V. Kel'dysh called attention to the role of lattice vibrations, in other words, emission and absorption of phonons, during the tunneling process. He predicted that, as a result of interaction with the phonons, tunneling in semiconductors can take place at fields that are much weaker than in the case of ordinary tunneling between regions of equal energy. It is important to note that a noticeable increase in conductivity as a result of the participation of the phonons in the tunneling process should occur at definite potential values that are directly connected with the phonon energy. This uncovers a new way for a sensitive determination of the natural lattice vibrations.

A study of the absorption of light by crystals led Ya. I. Frenkel' to the development of a hypothesis that special excitation states exist and move through the crystals, but are not connected with transport of electric charge.

Frenkel' called attention to the fact that if an atom or a molecule becomes excited in any one cell of an ideal crystal, then this excitation can be transferred resonantly from cell to cell. Consequently, an excitation wave will propagate through the crystal, and will cause migration of energy without transport of charge. This excitation wave can be likened to a quasiparticle, which Frenkel' called "exciton." This idea turned out to be exceedingly fruitful. It made it possible to explain certain peculiarities of the internal photoeffect in cuprous oxide, which were experimentally discovered by A. V. and A. F. Ioffe but which could not be explained; it paved the way to the understanding of the mechanism of light absorption, and served as a basis of a theory of light absorption by molecular crystals, developed by A. S. Davydov (see page 702). Subsequently, Wannier and Mott made the exciton concept somewhat more concrete by considering a system of an electron and a positive "hole" which are bound by Coulomb forces, as a quasihydrogenlike atom, or, more accurately, a quasipositron, since the effective masses of the electron and the hole are of the same order of magnitude, and E. F. Gross and his co-workers discovered and investigated in detail, in certain semiconductors at low temperatures, the "hydrogenlike spectrum," which is an aggregate of narrow lines converging in the limit and satisfying a formula of the Balmer type. They proved that this spectrum belongs to the exciton, a quasiparticle capable of moving through the crystal.

V. M. Agranovich, V. L. Ginzburg, S. I. Pekar, and many others have shown that the presence of excitons can greatly change the optical properties of crystals. The refractive index of the medium becomes in this case a function not only of the frequency but of the wave vector of the light; this leads to the appearance of new types of electromagnetic waves in the crystal and to a number of other fundamental effects.

When the photon energy reaches the width of the forbidden gap separating the valence band from the conduction band, strong absorption of light by the semiconductor sets in. At a lower photon energy, a semiconductor free of impurities and of other absorption centers is practically transparent. Therefore the absorption of light in a sufficiently pure semiconductor is characterized by a sharp edge on the long-wave side. L. V. Kel'dysh has shown that, owing to the ability of the electron to acquire energy from the field, the edge of the absorption band becomes smeared in an electric field, and shifts towards longer wavelengths. This prediction was confirmed experimentally, and the phenomenon itself, namely the shift of the absorption edge in a strong electric field, is called in the literature the Kel'dysh-Franz effect, since it was also predicted theoretically, independently of Kel'dysh, by the German physicist Franz.

A particularly vigorous development of semiconductor physics began in the late 40's after the discovery of the transistor and the appearance of new semiconductors--germanium, silicon, indium antimonide, gallium arsenide, etc., which are greatly superior to the traditional semiconductors such as cuprous oxide, selenium, etc. An important role in the creation of the semiconductor electronic industry in the USSR were played by the works of V. S. Vavilov, B. M. Vul, S. G. Kalashnikov, V. E. Lashkarev, D. N. Nasledov, N. A. Panin, A. V. Rzhanov, V. M. Tuchkevich, and their co-workers.

A tremendous role was played in those years by the ideas of A. F. Ioffe concerning the possibility of transforming certain types of energy into others with the aid of semiconductors. In 1950 Ioffe developed a theory of thermoelectric conversion in semiconductors, and prepared a program for further research in this field. To a considerable degree as a result of the work done at the Semiconductor Institute at the USSR Academy of Sciences, which he founded, the efficiencies of thermoelectric converters exceed by one order of magnitude the values prevailing in the thirties. During the same time, the efficiencies of semiconductor photocells (solar batteries) increased by dozens of times.

The demands of the technology, and also the possibility of working with very pure single crystals, have created conditions for a wide front of purely physical research on semiconductors, so that at the present time the properties and the electronic structure of semiconductors have been studied and understood to a considerably greater degree than the properties of any other class of solid. An important role was played here by the exceeding sensitivity of semiconductors to a great variety of external influences, making it possible to determine quite readily in experiment different peculiarities of their electronic spectra. A central role in these researches was played by the phenomenon of cyclotron resonance, based on the quantization of the energy levels of the electron in a magnetic field, predicted by L. D. Landau back in the thirties ("Landau levels"). Highly productive for the investigation of semiconductors is also an effect proposed and theoretically investigated by G. L. Bir and G. E. Pikus, namely the action of uniaxial deformation: such a deformation, by lowering the symmetry of the crystal, splits its energy levels, and this leads to many clearly pronounced qualitative changes in the electronic properties.

In recent years greatest interest in semiconductor physics was attracted by research on the emission of light from semiconductors when electrons recombine with holes, and in particular on stimulated coherent emission (semiconductor lasers). The first suggestions that semiconductors be used for this purpose were made by N. G. Basov, B. M. Vul, and their co-workers, who also indicated the most promising methods of exciting stimulated emission in semiconductors and the many advantages which can be possessed by semiconductor lasers over others. An important role in the realization of these ideas was played by the work of D. N. Nasledov, A. A. Rogachev, S. M. Ryvkin, and B. V. Tsarenkov, who were the first to investigate experimentally recombination radiation of gallium arsenide, on the basis of which the first semiconductor lasers were soon developed.

The flow of strong currents through semiconductors turned out to be frequently accompanied by the development of different instabilities, that is, by the buildup of oscillations of electron-hole plasma, electron plasma, the crystal lattice, etc., similar to the instabilities occurring in an ordinary plasma. A study of this group of phenomena has recently attracted persistent attention, since they can be used for generation and amplification of electromagnetic oscillations in a wide range of frequencies, from the lowest to the very highest. A major role in the development of a theory of these phenomena and in the prediction of a number of new types of waves in a solid-state plasma was played by the work of O. V. Konstantinov and V. I. Perel'. One of the first experimental observations of instabilities of current in a semiconductor was made by Yu. L. Ivanov and S. M. Ryvkin (1958). Later S. G. Kalashnikov and I. A. Kurova observed a new class of low-frequency instabilities characteristic of semiconductors. Recently interest has been increasing in the investigation of new classes of semiconductors, particularly liquid ones. A leading position in this field is occupied by the work of A. P. Regel' and his co-workers.

Mechanical Properties of Solids

Important results pertaining to the study of mechanical properties of solids were obtained by A. F. Ioffe and his large school.

From the point of view of modern physics, a solid is a crystal. But the real solids with which we deal in technology and in everyday life differ strongly from ideal crystals in their mechanical properties. An ideal crystalline body should immediately return to its initial state after the strain is removed, but in fact any elastic deformation produces in a solid only a slowly disappearing trace—an elastic aftereffect. How is this contradiction to be explained? First of all, the solids in which aftereffect, fatigue, and other phenomena are observed are in fact far from homogeneous crystals. A. F. Ioffe has shown in one of his earlier papers that no true aftereffect is observed in a quartz crystal. Thus, all the phenomena that occur beyond the elastic limit are the results of the physical inhomogeneity of the solid.

When the strain is sufficiently large, the solid begins to flow like a viscous liquid. The mechanism of such plastic deformation was also elucidated by A. F. Ioffe, who first used x-ray analysis for this purpose, observing on a fluorescent screen the Laue pattern produced upon stretching of rock salt. It turned out that when the tension stress exceeds a certain limit (yield point) the spots of the x-ray pattern suddenly double, then multiply, and finally, stretch out into entire tails. This shows that the mechanism of the plastic deformation consists in the fact that the initially undivided crystal breaks up into individual small crystallites, which shift and rotate relative to one another. These investigations by A. F. Ioffe served as a stimulus for the development of an entire new field (x-ray diffraction analysis of plastic deformation), which was the subject of hundreds of investigations in all countries. We cannot describe here the numerous further investigations of A. F. Ioffe's students and co-workers in this direction. We shall note only two facts. First, I. V. Obreimov has demonstrated, by means of a subtle optical method, that displacements occur along definite crystallographic planes long before the appearance of distortions in the x-ray pattern. Second, A. F. Ioffe observed and M. V. Klassen-Neklyudova investigated in detail an entirely new effect, namely the intermittency of the deformation process. While the load is applied continuously, the strain is produced in jumps, which repeat in strikingly equal time intervals and are accompanied by a slight sound, recalling the ticking of a watch. This phenomenon was investigated by a large number of Soviet scientists (N. N. Davidenkov, A. V. Stepanov) and also abroad. Its theory was presented by N. N. Davidenkov and M. V. Klassen-Neklyudova.

The mechanical properties of solids have been the subject of many investigations performed also in other laboratories. We note here the numerous studies by V. D. Kuznetsov and his co-workers. They developed convenient methods for the measurement of hardness and other mechanical constants of solids, investigated the influence of different factors on the elastic limit, the surface energy of solids, etc. The results of all these investigations are summarized by V. D. Kuznetsov in the monograph "Solid State Physics."

The application of x-ray diffraction analysis to the study of mechanical properties of solids has been the subject of so many investigations by Soviet physicists, that we are unable either to describe them or list their authors. We shall note only a few works of pioneering character. We owe to S. T. Konobeevskiĭ and N. E. Uspenskiĭ the first published substantial work on the use of x-ray diffraction analysis in the study of the internal mechanism of metal working processes (rolling). N. Ya. Selyakov and G. V. Kurdyumov were the first to show that hardened steel has a crystal lattice different from the iron lattice. The use of x-ray structure methods has assumed very great importance in metal physics and metallurgy. Particularly varied and extensive researches in this field are due to G. V. Kurdyumov and his numerous co-workers. These investigations, which were important from the scientific and practical points of view, were devoted to the structure of alloys, to the nature of quenching and tempering, and to other problems of direct interest and great significance for metallurgy.

X-ray structure analysis was used to determine the structure of many silicates and to develop general considerations concerning the role of close packing in the structure of inorganic compounds (N. V. Belov); new data were obtained with respect to the structure of organic crystals (A. I. Kitaĭgorodskiĭ); systematic work on the use of x-ray structure analysis in theoretical chemistry was performed by G. S. Zhdanov.

We must not fail to note also the great organizational work done in this field. X-ray diffraction analysis is presently an indispensable adjunct of any plant laboratory. The x-ray laboratory of a plant, specially a metallurgical one, performs a very important function. Owing to the development of research on x-ray diffraction analysis in our country, the plant x-ray laboratories were staffed with trained workers, and much work was done to organize these laboratories and to publicize their importance to manufacture.

Electron diffraction analysis, with the aid of which the structures of many inorganic and organic compounds are determined, was strongly developed as an independent method of structure analysis (V. E. Lashkarev, Z. G. Pinsker, N. A. Shishakov, B. K. Vaĭnshtein, et al.). A thorough review of Soviet work in this field was presented by Z. G. Pinsker in the monograph "Electron Diffraction" (Moscow, 1949).

Very great attention was paid in the USSR and abroad to the work of A. F. Ioffe on the strength of solids. The crystal lattice theory developed by Born has made it possible to calculate the stresses necessary to rupture crystals. These calculated values of the stress turn out to be many times larger than the actually observed ones. Thus, rock salt should theoretically withstand stresses up to 200 kg/mm^2, whereas in fact it is ruptured by a load of only 400 g/mm^2. A. F. Ioffe has shown that this discrepancy is due to the properties of the crystal surface. By loading a rock-salt crystal in warm water, he was able to strengthen it by a factor 10–12. A. F. Ioffe attributed this strengthening to the dissolution of the surface layer and to the consequent elimination of surface cracks, which greatly lower the ultimate strength. These investigations made a strong impression in the entire world and gave rise to lively discussions, as a result of which both the experimental results and the theoretical premises advanced by A. F. Ioffe were confirmed.

Further progress in the understanding of the nature of strength and plasticity of solids is connected with the development of dislocation theory. A pioneering role was played in this problem by Ya. I. Frenkel’. Among the further work done in this direction, mention should be made both of studies of dislocation structure of deformed and strengthened materials, and work on the study of the influence of dislocations on the physical properties of crystals.

We note further the work of P. A. Rebinder, who has shown the tremendous role played in the plastic properties of a sample by the surface forces: introduction of a negligible amount of surface-active substances on a surface lowers the yield point by many times.

Work by P. P. Kobeko, A. P. Aleksandrov, E. V. Kuvshinskiĭ and others, based on extensive experimental material, led to extensive generalization and to a new understanding of elastic-relaxational properties of high molecular compounds such as rubber.

Among the investigations closer to crystallography, we note the work of A. V. Shubnikov, who pointed out the important role of the antisymmetry concept in the description of the crystal properties. He obtained important results in the field of theory and experimental realization of crystal growth. Research by the Institute of Crystallography of the USSR Academy of Sciences, formerly headed by A. V. Shubnikov, supplied the domestic industry with crystals of corundum, which are needed for the manufacture of watches, with piezoelectric crystals, semiconducting crystals, and others. The thermal properties of solids were investigated in the precise researches of P. G. Strelkov.

Magnetism

In the field of magnetism we note first three fundamentally important investigations pertaining to the magnetism of elementary particles. In 1920, one year before the publication of the well known paper by Gerlach and Stern (1921), P. L. Kapitza and N. N. Semenov outlined a method of determining the magnetic moment of an atom by measuring the deflection of an atomic beam in a homogeneous magnetic field, and presented a complete design of the installation. This is precisely the method used by Gerlach and Stern, independently of the Soviet scientists, to prove experimentally the existence of space quantization.*

L. V. Shubnikov

The second fundamentally important result pertains to the diamagnetism of free electrons. It is well known that from the classical point of view a gas of free electrons in a bounded volume, for example the “gas” of conduction electrons inside of a piece of metal of finite size, should not have diamagnetic susceptibility. Bohr explained this illustratively as being due to the fact that the diamagnetic moment of the orbits of the electrons in the magnetic field are fully cancelled by the opposite moment of the broken trajectory of the electrons reflected from the boundaries of the sample. Yet it is known that metals in general do possess diamagnetism and some of them, such as antimony and bismuth, have an appreciable diamagnetic moment. This difficulty is of great fundamental importance, and Bohr regarded it as one of the important manifestations of the inapplicability of classical physics to the explanation of magnetic phenomena.

Landau has shown, however, that the situation is different in quantum theory: projections of the bent electron trajectories in a magnetic field on a plane perpendicular to the magnetic field are closed circles, that is, they are periodic and hence quantized. When the magnetic field is turned on, the distribution of the electrons with respect to the levels changes and a diamagnetic moment is produced. This proves, by the same token, that the diamagnetism of free electrons is strictly a quantum phenomenon. This unique phenomenon is called to this day Landau diamagnetism.

The third important investigation was performed and published in 1937 by B. G. Lazarev and L. V. Shubnikov (Khar’kov). Owing to the presence of a spin magnetic moment of the electron, this spin paramagnetism of the electron is a weak phenomenon. But nuclear paramag-

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*In view of the fact that this paper by Kapitza and Semenov is not well known, owing to accidental historical circumstances, we present here the exact reference and the name of the paper. The paper was published in English in 1922, but dates back from December, 1920: On the Possibility of Experimental Determination of the Magnetic Moment of an Atom, Journal of the Russian Physical and Chemical Society, Physics Div. 50, Nos. 4–6 (1922).

netism is even weaker, since it is determined by the magnetic moments of the proton and neutron proper, which are smaller by about one thousand times in order of magnitude than the magnetic moment of the electron. Therefore, when Lazarev and Shubnikov succeeded in observing and measuring by a direct experimental method (with the aid of a magnetic balance) the nuclear susceptibility of solid hydrogen cooled to 2°K, this result could be acclaimed as one of the great accomplishments of experimental technique.

Related to the diamagnetic properties of the electron gas is the work of Ya. G. Dorfman, who predicted that resonance absorption of electromagnetic waves in semiconductors and in metals should be observed. The cause of this resonance is essentially identical with the cause of the Landau diamagnetism. However, since this phenomenon consists of resonance absorption of an alternating electromagnetic field when the frequency of the electric vector of the field coincides with the frequency of revolution of the electric charge around the magnetic field, this phenomenon is perfectly analogous to the acceleration of a particle in a cyclotron. It was therefore called cyclotron resonance. The quantum theory of cyclotron resonance was developed by Dingle in England, and the phenomenon itself was observed in semiconductors in the USA. Since it depends on the effective mass of the electron, this phenomenon serves to determine the effective mass, and thus its study uncovers important possibilities for solid state physics.

In metals, the phenomenon is made complicated by the presence of the skin effect, which prevents the magnetic field from penetrating into the metal. However, a rigorous theory of cyclotron resonance in metals, developed by M. Ya. Azbel' and E. A. Kaner, has made it possible to find the conditions under which this phenomenon can be observed in metals, too. It has been widely employed since that time.

One of the brightest achievements in physics during the last twenty years was the discovery in 1945, by E. K. Zavoĭskiĭ, of the so called "paramagnetic resonance" (it is more frequently called now electron spin resonance to distinguish it from nuclear magnetic resonance).

This phenomenon consists in the fact that the magnetic moments of atoms or molecules with "unpaired" electron spins and oriented in accordance with the rules for spatial quantization by a strong constant magnetic field, becomes reoriented perpendicular to the constant field by a weak alternating magnetic field of an electromagnetic wave. If the frequency of the electromagnetic field of the wave and the reorientation frequency are at resonance, the reorientation of the moments of the atoms or molecules in a solid paramagnet causes a strongly pronounced selective absorption of the electromagnetic wave.

From the historical point of view, it is important to note that back in 1923 Ya. G. Dorfman* pointed out the inevitability of selective absorption of electromagnetic waves "flipping" when the paramagnetic moments oriented by a perpendicular constant magnetic field are "flipped" by the alternating field of the wave.

The discovery of paramagnetic resonance has attracted unusually great attention. The high sensitivity of the resonance picture to interactions between the spins of the electrons and the nuclei, as revealed by the hyperfine structure, and also the high sensitivity to the interactions between the molecule and the surrounding lattice, uncover wide prospects for the use of the phenomenon as a method for investigating molecular structure and molecular interaction. The development of splendid instruments, relatively simple in use, for paramagnetic resonance has made this method very popular among chemists, by physicists, and in general representatives of related fields of knowledge. The number of investigations performed with the aid of the electron-spin resonance method certainly amounts to several thousand. In the USSR, intense development of the paramagnetic resonance method and its application is carried out in the Kazan' branch of the Academy of Sciences under the leadership of B. M. Kozyrev and S. A. Al'tshuler.

Similar electron-resonance phenomena should be observed not only in paramagnets, but also in ferromagnets. Ferromagnetic resonance was experimentally discovered likewise by E. K. Zavoĭskiĭ (and independently by Griffiths in the USA). However, the theory of ferromagnetic resonance was developed back in 1935 by L. D. Landau and E. M. Lifshitz, and the very idea of ferromagnetic resonance was advanced and founded in 1923 by Ya. G. Dorfman, who pointed out in the previously cited paper the significance of selective absorption of electromagnetic waves in iron wires, discovered by V. K. Arkad'ev back in 1913 and then investigated in the 20's, called by Arkad'ev "magnetic spectra."

The most important problem in the science of magnetism is the explanation of the strong magnetization of iron and other ferromagnets. Early in the 20-th century it became quite clear that the cause of this magnetization should be a special molecular field, but the physical nature of this field could not be satisfactorily explained within the framework of classical physics: on the one hand, from experiments with gyromagnetic phenomena (the Einstein—de Haas and the Barnett experiment) indicated that the carriers of the elementary magnetic moment ("elementary magnets") in a ferromagnet are the electron spins, and on the other hand, the magnetic interactions between the electrons were too weak to explain the nature of the molecular field. This riddle was qualitatively solved by a brilliant idea of Ya. I. Frenkel', who indicated that the electrons should experience interactions much stronger than purely magnetic ones as a result of the quantum-mechanical exchange effect, the order of magnitude of which is the same as that of the electrostatic interaction. The energetically favored state in this case is one in which the spins of the electrons in the sites of the crystal lattice are parallel. As is well known, the same idea is the basis of the quantum theory of ferromagnetism developed later by Heisenberg.

It was subsequently established that the magnetic moment of a ferromagnet is not constant in the entire sample. In the absence of an electric field, the ferromagnet breaks up into individual regions—domains. Inside the domain, the moment is constant, and the domains themselves are so arranged, that their fields cancel one another. The idea of the existence of domains

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*J. Dorfmann, Z. Physik 17, 98 (1923)

was first advanced by F. Bloch, and the complete theory was developed by L. D. Landau and E. M. Lifshitz.

Many important investigations on the theory of ferromagnetism were made by S. V. Vonsovskiĭ, N. S. Akulov, N. N. Bogolyubov, S. V. Tyablikov, E. M. Kondorskiĭ and their co-workers. The most important problem in the investigation of ferromagnetism is the problem of the technical magnetization curve. The first steps in this direction were made back in the 20's by N. S. Akulov, who formulated the general law of magnetic anisotropy. Further developments were made by S. V. Vonsovskiĭ, Ya. S. Shur, and others. Magnetic methods of quality control of metals (magnetic flaw detection) found wide application in industry. The main work in this direction is due to V. K. Arkad'ev and R. I. Yanus.

An important class of magnetic bodies are antiferromagnets. In its structure, an antiferromagnet constitutes two (or several) ferromagnetic crystal lattices, "sublattices," which are shifted relative to each other in such a way that their magnetic moments cancel each other. Antiferromagnetism was independently predicted by L. D. Landau and by Neel (France). Experimental investigation of this phenomenon began in the USSR by L. V. Shubnikov, O. N. Trapeznikova, and S. S. Shalyt. Further development of the theory of antiferromagnetism was made by I. E. Dzyaloshinskiĭ, who generalized the theory of second-order phase transitions of L. D. Landau and E. M. Lifshitz to include this case. In particular, he was able to explain the phenomenon of weak ferromagnetism, consisting of incomplete compensation of the magnetic moments of the sublattices. This phenomenon and other properties of antiferromagnets were investigated in detail by A. S. Borovik-Romanov. He also discovered the phenomenon of piezomagnetism—the occurrence of a magnetic moment upon deformation of a crystal.

The technique of obtaining strong magnetic fields has recently attracted attention. Back in 1924, P. L. Kapitza, in his widely known investigation performed in Rutherford's laboratory, obtained magnetic fields of unprecedented intensity, 500,000 G in pulses lasting several thousandths of a second. What was particularly significant was that, in spite of the shaking of the building by the powerful pulse, a clever organization of the experiment has made it possible for Kapitza to study many properties of matter in such strong fields. Finally, most recently A. D. Sakharov and his co-workers obtained, by compressing the magnetic flux in explosions, superstrong magnetic fields amounting to millions of Gausses, and in individual experiments tens of millions Gausses (up to 25 million). The first explosion experiment aimed at obtaining superstrong magnetic fields in explosions was realized in the USSR as early as in spring of 1952.* At the present time, superstrong magnetic fields are also being investigated in the USA and in other countries, and there was even an international conference devoted to this subject, held in Rome in September, 1965. It is clear that these experiments offer entirely new prospects for the investigation of the properties of matter under exclusive hitherto unattained conditions. However, the solution of the difficult problem of organizing measurements under similar conditions a apparently still lies in the future.

Acoustics

The greatest variety of branches of acoustics—from the general theory of acoustics of a moving medium to problems of architectural acoustics and practical methods of precision measurement of acoustical quantities—is dealt with in the papers of N. N. Andreev. He created a large school of Soviet acousticians, who solved theoretical problems in the propagation of sound in inhomogeneous, layered, and turbid media with boundaries (L. M. Brekhovskikh, L. A. Chernov), problems of nonlinear acoustics (B. P. Konstantinov, K. A. Naugol'nykh, Z. A. Gol'dberg, L. L. Polyakova, P. N. Kubanskiĭ), problems in the acoustics of moving media (D. I. Blokhintsev), and problems of so called sound optics, pertaining to the refraction and focussing of sound waves (L. D. Rozenberg). Extensive investigations were made in 1930—1940 in the field of musical acoustics by a group of workers of the research institute for the musical industry (A. V. Rimskiĭ-Korsakov, A. A. Kharkevich, B. P. Konstantinov, N. A. D'yakonov, A. I. Belov, I. G. Rusakov, P. A. Matveev and others). These investigations concerned the physics of musical instruments, their materials, construction, and acoustic properties. A number of investigations in architectural acoustics were performed in the 30's in connection with the design of the Palace of the Soviets. A great accomplishment was the successful acoustic design and the design of the sound system of the Kremlin Palace of Congresses (V. V. Furduyev). S. N. Rzhevkin and G. D. Malyuzhinets made a number of theoretical and experimental investigations of special resonant absorbers, which made it possible to solve successfully the problem of sound absorption in very large halls. In the field of ultrasound, notice should be taken of the work by P. A. Bazhulin and the work of I. G. Mikhaĭlov on the propagation of sound waves in liquids, and also the work of S. Ya. Sokolov, who created an original method of ultrasonic flaw detection.

Recently Soviet acousticians made a major contribution to the development of a new trend—quantum acoustics, (L. D. Rozenberg, L. G. Merkulov). Important investigations were made on the acoustic of the ocean (L. M. Brekhovskikh, I. B. Andreeva). Great interest attaches to Soviet research on speech and speech communication (V. N. Fedorovich, L. A. Chistovich).

III. ORGANIZATION PROBLEMS. SCIENTIFIC LITERATURE

The cadres of physicists have grown to a tremendous degree. Prior to the revolution the number of physicists engaged in scientific work in Russia did not exceed 100, now we have thousands of physicists, among which several hundred with doctor's degrees. Instead of few very modestly equipped laboratories at university departments we now have the very large scientific research institutes and many hundreds of branch technical institutes, in each of which research is carried out to one degree or another.

Congress and conferences play a major role in the country's scientific life. Prior to revolutions, there were more or less periodic gatherings of "Congresses

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*A. D. Sakharov, Magnetic Implosive Generators, Usp. Fiz. Nauk 88, 725 (1966). [Sov. Phys.- Usp. 9, 294 (1966)] of Russian Natural Scientists and Physicians,'' where one section was devoted to physics. In 1908, in one such congress, Lebedev triumphantly reported his work on the pressure of light on gases. After the revolution, starting with the first 1918 congress mentioned at the beginning of the article, regular congresses of physicists with several sections began to be convened in the 20's and in the early 30's. The number of the participants at these congresses continuously increased, and foreign physicists attended practically all of them (M. Born, J. Darvin, P. Debeye, R. Pol etc.), delivering papers and taking part in the discussions. Finally, after the war, the volume of the work and accordingly the number of participants and of papers have increased so much, that the gathering of general congresses of physicists became disadvantageous. The congresses gave way to topical conferences: on semiconductors, spectroscopy, luminescence, low temperatures, different nuclear problems etc. The number of participants in these conferences has also been growing continuously, and in certain conferences it is necessary to organize two and sometimes more sections. In recent years, participation of foreign physicists in the work of these conferences has become a common phenomenon.

The Russian scientific literature in physics was exceedingly poor prior to the revolution. There were several excellent textbooks, such as ''Introduction to Acoustics and Optics'' by Stoletov, ''Electricity'' by Éĭkhenval'd, the university lectures on physics by Umov, and also a number of lithographed lectures by the professors, and these make it possible for the students of the lower course to study physics. For a deeper study of this science, particularly for the study of theoretical physics, it was necessary to report to monographs and the major books in foreign languages. The only exception was the five-volume ''Course of Physics'' by O. D. Khvol'son, which played an important role in the raising of the level of culture in the field of physics in Russia and which was translated into German and French, but which, incidently, was more of an encyclopedia, with the shortcomings characteristic of publications of this type.

From the very start of the revolution, the publication of scientific, didactic, and popular-science literature was reorganized on an entirely different and incomparably larger scale. As a result, in fifty years, the physics literature has grown so much, that one can point to serious monographs and handbooks in Russian on almost all topics not only for specialized university courses but even for candidate's examinations as well as for a deeper study of various problems. The textbook and popular-science literature is also developing in the languages of the nations of the USSR. A large number of Soviet manuals and monographs have been translated into foreign languages.

A review of the Soviet physics literature could be the topic of a separate article. We confine ourselves here only to several examples. The unique multivolume course of theoretical physics of L. D. Landau and E. M. Lifshitz occupies a special place in the world's literature. There is no course of theoretical physics of higher level in any language, capable of combining such a complete coverage of all of physics and complete originality: the entire course has been written from a unified point of view and is entirely in contrast with ordinary electric courses on this scale. Several volumes of the ''Theoretical Physics'' of Landau and Lifshitz have been translated into English.

Numerous manuals on almost all branches of theoretical physics and monographs on special problems, written by Ya. I. Frenkel', are also distinguished for their originality, although some of them were debatable. They all were published in German and English translations. A manual of quantum mechanics and an original monograph on general theory of relativity were published by V. A. Fock. An important role in the raising of the level of teaching of theoretical physics was played by the texts ''Principles of the Theory of Electricity'' by I. E. Tamm, ''Statistical Physics'' and ''Introduction to Thermodynamics'' by M. A. Leontovich, ''Principles of Quantum Mechanics'' by D. I. Blokhintsev, ''Introduction to Statistical Physics'' by V. G. Levich, they are easy to read and are at the same time sufficiently profound manuals dealing with these difficult branches of theoretical physics. May I be allowed to mention also my own two-volume ''Atomic Physics,'' which has gained wide popularity in the Soviet Union and far beyond its borders (it has been translated into several foreign languages).

The important problem of publishing fully modern texts on general physics was also successfully solved by Soviet authors. From among the many textbooks published during the last fifty years, we mention the widely popular three-volume university course by S. É. Frish and A. V. Timoreva, which was translated into foreign languages and which is the result of many years' teaching by the authors at the Leningrad university. Experience in teaching physics at the Moscow university was utilized in the many-volume ''General Course of Physics,'' each part of which is of independent interest and significance. The published volumes, ''Mechanics'' by S. É. Khaĭkin, and also ''Mechanics'' by S. P. Strelkov, ''Optics'' by G. S. Landsberg, and ''Electricity'' by S. G. Kalashnikov are distinguished for great freshness, originality, and thoroughly thought out didactic program.

Many valuable monographs of great scientific interest were published during the elapsed time. We already mentioned the monograph of A. A. Andronov, A. A. Vitt and S. É. Khaĭkin on nonlinear oscillations. We shall now mention ''Crystal Physics'' and ''Semiconductor Physics'' by A. F. Ioffe, ''Modern Theory of Magnetism'' by S. V. Vonsovskiĭ, the two-volume monograph ''Vibrations of Molecules'' by M. A. El'yashevich, M. V. Vol'kenshtein and B. I. Stepanov, ''Cosmic Rays'' by D. V. Skobel'tsyn, which presented a complete picture of the status of the problem at the time of publication of the book (1936), and a new monograph on the same topic by M. A. Dobrotin. We confine ourselves to these examples, although the list could of course be expanded.

The Soviet literature was also enriched by translations of the most important foreign manuals and monographs. ''The Theory of Electricity'' by Abraham and Becker, ''Optics'' by Drude and ''Physical Optics'' by Wood, ''Methods of Mathematical Physics'' by Courant and Hilbert, ''Mathematical Physics'' by Mieses and Frank, and many other books, well translated, are now easily available to the Soviet student and scientific worker. A large number of fundamental scientific monographs of foreign authors were published during the last twenty years by the Foreign Literature Publishing House (now called "Mir"), the activity of which deserves great gratitude. We note also a series of monographs on spectroscopy by Condon and Shortley, Herzberg, fundamental monographs on nuclear physics, monographs on semiconductors, ultrasound, piezoelectricity, and many other timely problems of physics.

Finally, of great importance in the raising of the level of culture in the field of physics was played by the publication of the classics of science, published with great love by the State Publishing House for the Technical and Theoretical Literature (now the Main Editorial Branch for Physical and Mathematical Literature of the "Nauka" Publishing House) and by the Academy of Sciences. During the last fifty years, they published splendid translations and beautiful editions of the works of Archimedes, Galileo, Newton, Huygens, Lagrange, Hilbert, Leonardo da Vinci, Faraday, Helmholz, Mayer, Lomonosov, Lebedev, Stoletov, Einstein, and many other classics of our science. Particular credit in this important matter of publicizing the history of physics is due to the deceased president of the Academy of Sciences S. I. Vavilov, who knew extremely well and loved the history of science and who enriched literature with translations and commentaries on all the optical works of Newton and also works on the optical studies of Galileo and Lomonosov.

Finally, very valuable additions are the collected works of outstanding Soviet scientists (Mandel'shtam, Papaleksi, Vavilov, Lazarev, Frenkel') published by the Academy of Sciences.

Periodic journals, intended for the publication of original papers and reviews, have also grown considerably. Prior to the revolution, there was only one journal where original physics papers were published, the "Journal of the Russian Physical-Chemical Society, Physics Section." Its small volume was sufficient for the publication of 30--40 papers annually, and this practically covered at that time the original scientific production in physics. A second part of this journal, also published separately under the title, "Problems of Physics," was devoted to review articles and was of very modest size.

After the revolution, the following periodicals were intended for the publication of original papers: "Journal of Experimental and Theoretical Physics," "Journal of Technical Physics," "Bulletin Izvestiya of the Academy of Sciences, Physics Series," their purpose was principally to publish papers of scientific conferences. Brief communications on the most important investigations were published in the "Proceedings (Doklady) of the Academy of Sciences." Within the last few years, the production of the Soviet institutes and laboratories has grown so much, that the foregoing publications were quite inadequate for timely publication of the papers. In view of this, an entirely new series of new specialized journals were launched. These are "Optics and Spectroscopy," "Crystallography," "Electronics," "Atomic Energy," "Physics of Metals," "Procedures and Techniques of Physical Experiments," "Acoustic Journal," etc. It must be noted, however, that even this greatly increased number of journals cannot cope with the flow of papers received by the editors, and their publication is delayed by a long time.

The channels for scientific information concerning the present day status of timely problems of physics have also grown tremendously. The review journal, "Uspekhi Fizicheskikh Nauk" was launched in 1918 and has been published ever since. This journal is quite well known in the USSR and abroad. Its reviews of research by Soviet physicists published in this journal are broadly cited in the world scientific literature. It is completely translated into English and is published by the American Institute of Physics under the name "Soviet Physics--Uspekhi." Many of its articles are translated also into other languages. In 1953, the Academy of Sciences has organized a large Institute for Scientific and Technical Information—VINITI), which publishes abstract journals on different branches of knowledge, including, of course, physics. The physics abstract journal greatly exceeds in the completeness in coverage of the world literature on physics the similar foreign abstract journals.

We can now summarize and return to the statement made at the beginning of the article. The foregoing far-from-complete sketch of the development of physics in the USSR in fifty years speaks for itself: "The contributions to the field of knowledge" (repeating the initially cited words of N. A. Umov) by Soviet physicists have more than paid their debt of our country to the history of science. In fact, the work of our physicists encompasses all fields of this science, and there is no branch in which the investigations do not make essentially new contributions. Important discoveries in the field of physics, made in our country, have blazed new trails in science, created new disciplines, which were developed to a considerable degree by Soviet scientists, and also, of course, by scientists of foreign countries.

Translated by J. G. Adashko