SCIENCE FOR EVERYONE

I. K. KIKOIN

ENCOUNTERS WITH PHYSICISTS AND PHYSICS

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for Everyone

И.К. Кикоин

Рассказы о физике и физиках

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Encounters with Physicists and Physics

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Contents

Isaak Kikoin

Isaak Kikoin was one of those brilliant physicists who played a crucial role in the development of Soviet science. In the early 1920s, a new physics was being born in Moscow and Leningrad, and the two major Soviet cities began to attract gifted young people from all over the country, which was beginning to recover from a devastating civil war. The Physico-Technical Institute headed by Abram Ioffe was the centre of attraction in Leningrad. Its unusually concerned attitude to its youth and its scientific exactingness were the soil in which the Soviet school of physics sprang up.

Like many ot his own age, Kikoin came to the Institute from the depths of the country. He was born on 28 March 1908 into the family of a school teacher of mathematics in the tiny town of Zhigara. Isaak started his education in Pskov where he attended a high school and then a land-tenure technical school. In 1925, he went to Leningrad where he studied at the Polytechnical Institute till 1930. The professors there were closely associated with the Physico-Technical Institute and they used to select the most talented students and draw them in the research work at the Institute. The students took part in seminars and helped in the laboratories. Isaak found himself among those students. The scientific seminars were complemented by special seminars for students, during which Dmitry Rozhansky and Yakov Frenkel made their students learn the most up-to-date physical theories. The approach was highly successful, and the graduates developed their own scientific interests and were able to discern in the magnificent edifice of physics the domains where they could effectively apply their efforts.

Kikoin started his scientific activity at the Physico-Technical Institute by developing an idea that had emerged during one of Frenkel's seminars. At the time, the measurement of the electric conductivity of liquid metals in magnetic fields was very topical. Between 1931 and 1935, Kikoin completely cleared up this rather intricate subject, discovered why earlier experiments had failed, and explained how the experimental data did, in fact, fit the theory.

This first success influenced his interests for many years, and Kikoin became an authority on how magnetic fields and other external forces affect the electromagnetic properties of solids.

The work carried out by Kikoin (together with M. Noskov) in 1933-34 concerned the influence exerted by a magnetic field on photoelectric effects in semiconductors. The discovery of a new, photoelectromagnetic, effect made this work classical.*

In 1936, Kikoin moved to Sverdlovsk where a new physical centre, the Ural Physico-Technical Institute, was being created. In the Urals, he continued his research into the electric conductivity of metals in magnetic fields and performed some elegant experiments on superconductivity.

At the outbreak of the Second World War, Kikoin demonstrated his ability to apply achievements in physics to engineering. A new type of ammeter for measuring very high currents was his first practical project, which brought him the USSR State Prize.

At the dawn of nuclear power engineering, Kikoin was at the forefront in the research of one aspect of this field. He was aided in this task by his work in industry and the administrative experience he gained in the Urals. Kikoin was one of the founders of the Institute of Atomic Energy, and from 1943 he headed a large team of scientists there. During this period, Kikoin proved himself to be both a talented engineer and administrator. He courageously took upon himself enormous responsibility and acted as a scientific leader who fully understood the needs of industry in the period of the scientific and technological revolution. For this work Kikoin was twice made

* These effects are described in Kikoin and Lazarev's article "The Photoelectromagnetic Effect" in this collection.

a Hero of Socialist Labour and was awarded the Lenin Prize and USSR State Prizes.

In the mid-1950s, Kikoin's interests turned again to purely physical research. After a long interruption, he resumed his studies on the photoelectromagnetic effect. His investigations of this effect in single silicon and germanium crystals laid foundations for a study of the connection between the symmetry of a crystal and the photoelectromagnetic effect. If a mechanical stress is applied instead of a magnetic field, a new effect, called the photopiezoelectric effect, is observed. Basically, a potential difference arises in an illuminated semiconductor that is subjected to a mechanical stress.

Kikoin's ability to use whatever technological means available allowed him to measure the electrical characteristics of mercury vapour at high temperatures and pressures. This work has become a classic and it stimulated the development of plasma research.

In the last years of his life, Kikoin's interests centered on the effect exerted by ionizing particles on the electromagnetic properties of semiconductors. These studies led to the discovery of new effects, called the radiation electromagnetic and the radiation piezoelectric effect. The experimental setup he used was the same as in his experiments on the photoelectromagnetic and the photopiezoelectric effect, the only difference being that ionizing particles, such as alpha particles and protons, were used instead of light. However, the physical nature of these effects proved to be quite different and called for further study.

We have not mentioned many of Kikoin's other interests, but even this brief account shows the orientation of his efforts. Trained as a classical physicist, Kikoin gave physical clarity to his scientific research both in the formulation of a problem and in the simplicity of his experiments.

Kikoin's intensive research was not his only contribution to the development of Soviet science. From the very beginning of his scientific carrier, he strove to preserve the succession of the generations and to live in accordance with his teachers' behests. Kikoin put much time and effort into the teaching of physics, he gave lectures at the Leningrad Polytechnical Institute, at the Sverdlovsk Polytechnical Institute, at the Moscow Physical Engineering Institute, and at Moscow University. General physics was his favourite course, and he endowed it with all his physical intuition and experience. Kikoin devoted the last years of his life to the task of reconstructing the teaching of physics in schools and developing a system for discovering talented young people. As in his other activities, Kikoin embraced a broad range of problems. For many years he headed a committee on school olympiads. Together with Academician Kolmogorov, Kikoin set up the first physico-mathematical school in the Soviet Union. It was attended by gifted young boys and girls whose parents did not live in Moscow. He spent a great deal of time developing the school's curriculum. He wrote a textbook on physics for the eighth form. He did not just write curricula and textbooks, he actively promoted them as well. He gave lectures to school teachers and lessons to school pupils, and revised his textbooks again and again to achieve a clarity and brevity of presentation. Kikoin founded the first physico-mathematical journal for school pupils. Now the *Kvant*, which Kikoin edited for its first 15 years, is a widely acclaimed journal. Kikoin's contributions to school reforms have proved themselves in school teaching and thus can be put on the same level as his research and discovery of new physical effects.

Kikoin died on 28 December 1984. Not long before his death the school of the natural sciences at the Kurchatov Institute of Atomic Energy was awarded the Lenin Komsomol Prize. Addressing school pupils on the occasion, Kikoin said, "I would like to tell you what I thought when I received this award. I thought that I would be happy to give up all my decorations, titles, and rank as a Member of the USSR Academy of Sciences and the head of a large team of scientists to be your young age again, to become a boy of 15 or 17.

"You see, my life, however long it has been, has not been long enough to enjoy physics completely. I have always been short of time, I clearly see it now, though not a single day, not a single weekend, not a single holiday have I spent without physics. Often I even dream about physics. And withal I have never had enough time. You too will learn what happens when you have lived to the end of your life.

"So don't waste your time. You will never have enough all the same, but you will not regret it as much as if you do. You know, being a scientist is not a title nor is it a type of work. One becomes a scientist not by merely entering a laboratory and thinking about science. It is not as simple as that. A scientist is a permanent, agonizing, sometimes fascinating status. That was what I was thinking about when I received the award."

Let those parting words, a kind of testament to youth, be always with you, together with the memory of this distinguished scientist.

A.P. Alexandrov
V.A. Legasov

The Advance of Soviet Physics

(written to mark the 60th anniversary of the Great October Socialist Revolution)

From its early days the Soviet state paid great attention to the development of science.

On Lenin's initiative, a number of new scientific centres were set up in the USSR. The Leningrad Physico-Technical Institute, founded in 1918 by Abram Ioffe, was one of them. It was in this Institute that I started my research in physics.

Before the revolution, science in Russia was only pursued at the universities and was out of touch not only with practice but also with contemporary science. Ioffe said that when he began his research in physics, the predominant idea about what a scientific worker should do was to repeat experiments performed abroad, new ideas and independent work being considered unthinkable because the country allegedly lacked trained specialists.

Even in 1918, during the severity of the civil war, Ioffe understood that this socialist country should have a technology and industry based on a developed physical science. Modern physicists should know about technology, as they were to make physics serve the industries. In order to train such specialists, Ioffe set up the Physico-Mechanical Faculty at the Leningrad Polytechnical Institute. I entered this Faculty in 1925.

It was hard to study at the Faculty because students had to attend lectures on mathematics and physics at university level and at the same time read engineering. At the Institute I was plunged into an atmosphere of true science.

We knew that our dean was a distinguished scientist, whose name had been given to an effect he had discovered. He had found that when the surface of a rock salt crystal (NaCl) is wetted with water, the crystal's strength increases by a factor of several hundred. Ioffe's extremely simple experiments yielded very important results. I'll try to explain why.

In 1915, the famous German physicist Max Born proposed a rigorous theory of crystals. The theory explained various properties possessed by crystals, such as optical and electrical properties. Numerous experimental data at the time fitted the theory, with the exception of evaluations of crystal strength. It was known, for example, that a crystal of rock salt failed under tensile stresses of around 4.5×10^6 N/m^2. (Stress σ is defined as the elastic force $|\mathbf{F}_{elas}|$ per unit cross-sectional area S perpendicular to the force, $\sigma = |\mathbf{F}_{elas}|/S$. The value of σ at which a sample fails is called the ultimate strength of the material.) At the same time calculations gave a quite different value, of the order of 10^9 N/m^2. Nobody was able to explain this disparity in the framework of Born's theory.

Ioffe suggested that the model according to which a crystal fractures did not describe the real processes taking place in the crystal under deformation. The ultimate strength was calculated on the assumption that the crystal fails simultaneously over the entire cross-section of the sample. Ioffe, however, suggested that failure might be gradual, starting at a "weak" point and spreading in all directions over the cross-section of the sample. The gradual nature of the process would be due to microscopic cracks at which a sample would fracture at stresses lower than the theoretical ultimate strength. The crack would then gradually widen, eventually resulting in the failure of the sample.

To verify his idea, Ioffe performed an extremely simple experiment. A thin single crystal of rock salt was partially submerged in warm water. The water gradually dissolved the salt, making the submerged part of the sample thinner and smoother, i.e. eliminating the cracks. The sample was then stretched. It proved that its dry part fractured at stresses of 4.5×10^6 N/m^2, while the submerged part could withstand stresses as high as 1.6×10^9 N/m^2. This brilliantly verified Ioffe's hypothesis.

Many physicists still thought that Ioffe's model did not describe the way in which crystals broke down. However, repeatedly staged experiments verified it. The increase in a crystal's strength due to a smoothing of its surface became known as Ioffe's effect.

We closely followed the scientific success of our professors and we were proud that Alexander Friedmann, a world authority on mechanics, worked at our Faculty. We heard that he had significantly contributed to the general theory of relativity, having corrected the great Einstein.

In the first quarter of the 20th century, Einstein formulated the special theory of relativity and, in the wake of it, the general theory of relativity. The general theory yielded a mathematical model of the Universe, that is, a system of equations whose solution described the state of the Universe. Einstein found a steady-state solution, and so his model of the Universe was static and did not change over time. Friedmann correctly guessed that there was also a dynamic solution. This means that the state of the Universe is constantly changing in time, and the Universe is expanding.

Einstein was at first hostile to Friedmann's idea, but later he accepted it.* The

* On 18 September 1922, Einstein published his "Remark on Friedmann's paper 'About Space Curvature'" in which he said that he considered the results concerning a nonstationary universe suspicious. However, on 31 May 1923, Einstein wrote, "In a previous paper I criticized Friedmann's paper... . My criticisms, however, as I have become convinced, were based on an error in my calculations. I think that Friedmann's results are valid... ."

expanding Universe followed from general relativity. This practically completed the construction of the theory of relativity and means that Friedmann joins Einstein as an author of the general theory of relativity. We were very proud of this achievement.

Friedmann taught mechanics at our Institute. Our library had a typed course of lectures given by Friedmann at the Naval Academy entitled "Hydromechanics of a Compressible Fluid". We did not understand at the time what value it had, and it was only later that we learnt that in this course Friedmann had solved a problem on a fluid moving with very high velocities, when the fluid could not be considered perfect or its compressibility neglected. Friedmann's theory is widely accepted nowadays and is the basis for supersonic hydrodynamics, now called gas dynamics. Thus the foundations of gas dynamics were laid by our Professor Alexander Friedmann. Unfortunately, he lost his life in 1925 when still a relatively young man of 37.

Opposite our Institute, across the street called Doroga v Sosnovku (The Road to Sosnovka), stood the Leningrad Physico-Technical Institute (then called the Physico-Technical X-ray Institute). It was headed by Ioffe, and several mature physicists worked there attracted by Ioffe's reputation. These included Professor Dmitry Rozhansky, a well-known radio physicist, Ivan Obreimov (later to become an academician) and Nikolai Semenov (later an academician and Nobel Prize winner), both of whom had just graduated from university, Yakov Frenkel, who was one of the fathers of Soviet theoretical physics, and Alexander Chernyshev, an authority on electrical engineering. Most of the Institute's staff, however, were young graduates from the Physico-Mechanical Faculty. That is why opponents of the revolutionary changes in physics and the development of scientific research, that were being made at the Physico-Technical Institute, called the Institute a kindergarten. But by this time, however, the Leningrad Physico-Technical Institute had become one of the main centres for physics in the USSR.

The students who came to work at the Institute were chosen by those Faculty teachers who themselves were at the Institute and by final-year students who supervised the laboratory work of the younger students. Ioffe gave instructions that young people who showed an interest in and capability for experimental physics should be recruited for the Physico-Technical Institute. In 1927, when I was a second-year student, I was invited to work at the Institute. Nobody fussed over us and nobody minded that we had not completed our courses. Seminars held each Friday from 5 to 7 p.m. were devoted to the research being conducted at the Institute or published in foreign journals. We had to take part in the seminars and to understand what was going on. If not, we had to ask for explanation. At first, we did not dare ask because we understood nothing. However, we quickly began to understand things, probably because we became accustomed to the style of narration and also because we had to read a lot.

There were, of course, the regular seminars for students, one of them given by Professor Rozhansky and the other by Professor Frenkel. At these seminars we learnt about the latest advances in physics and we quickly found out what problems were being researched. In particular, in 1927, participants at Rozhansky's seminar discussed a recent paper by Davisson and Germer. They had shown for the first time experimentally that electrons are scattered from crystals in diffraction patterns in the same way as light is scattered by a diffraction grating. We knew that the diffraction of light is due to the wave nature of light, but the electron was considered to be a "normal" particle and subject to the laws of mechanics. At first, it seemed quite incomprehensible why electron scattering should take place as if they were part of a light beam. Students at Rozhansky's seminar discussed Davisson and Germer's experiment and its interpretation. This experiment was the first conclusive evidence for a suggestion the French physicist Louis de Broglie had made in 1924. He maintained that moving electrons display the properties of both particles (corpuscles) and waves, just as electromagnetic radiation, say, light, has the properties of both waves and particles. De Broglie also suggested that the relationships between corpuscular and wave properties for electrons and radiation should be the same. Davisson and Germer's experiment showed that indeed electrons scattered from the surface of a crystal behave like waves, and that the wavelength λ corresponding to a moving electron is h/mv, where h is Planck's constant, m the mass of the electron, and v its velocity. Now this is considered to be commonplace.

Frenkel's seminar also dealt with other problems that interested physicists. One of them concerned the structure of matter rather than separate atoms and electrons. We knew that atoms attract each other until their separation is approximately equal to the atom's size, but if they were brought closer, they began to repel each other. However, it was unclear why atoms are arranged in a solid as crystal lattices.

At the time the theory of solids had not been developed particularly well. The foundation of the modern theory of solids was laid by Einstein. In 1907, he constructed a quantum theory of heat capacity for solids. Einstein considered a solid to be an ensemble of atoms that vibrate about their equilibrium positions with the same frequency. Heating a body changes the amplitudes of these vibrations, thus changing the energy of the vibrating atoms. The change in the energy possessed by a body if its temperature is raised through one degree is called the heat capacity of the body. Einstein's formula for the heat capacity of a solid correctly described the heat capacity as a function of temperature, except at low temperatures, where the predicted value was out of line with the experimental findings.

Einstein's theory was perfected by Peter Debye in 1912. He suggested that the atoms in a solid do not vibrate independently, being connected instead, and thus form a single vibrating system. Calculations based on this suggestion gave results that were consistent with experimental heat capacities. They also fitted an empirical result, called Dulong and Petit's law, which stated that the heat capacity of one mole of any solid is the same and equals 25 J $mol^{-1}K^{-1}$.

There was, however, one "dark spot" in this theory of heat capacity, viz. the heat capacity of metals. It was known that a metal consists of ionized atoms arranged as a crystal lattice and free electrons. The electrons behave like a perfect gas (it is called electron gas). It would seem that the heat capacity of one mole of a metal should equal the heat capacity of the lattice (25 J $mol^{-1}K^{-1}$) and the heat capacity of the electron gas. The latter can readily be calculated as the heat capacity of a monatomic perfect gas, that is, the energy E of one mole of a gas is $(3/2)RT$ (R is the gas constant), and its heat capacity should be

$$C = \Delta E/\Delta T = (3/2)R\ \Delta T/\Delta T$$
$$= (3/2)R \simeq 12.5\ \mathrm{J\ mol^{-1}K^{-1}}.$$

Hence the heat capacity of one mole of the metal should be about 37.5 J $\mathrm{mol^{-1}K^{-1}}$. However, all the measurements gave a value of 25 J $\mathrm{mol^{-1}K^{-1}}$. This was so unexplainable that the paradox became known as the "heat capacity catastrophe".

It became possible to explain this anomaly only with the emergence of quantum mechanics. The quantum-mechanical theory of the electron gas in metals was developed by Arnold Sommerfeld in Germany and Professor Yakov Frenkel in the USSR. According to this theory, the properties of an electron gas differ from those of a monatomic gas. In particular, at ordinary temperatures, the energy of the free' electrons in a metal is practically independent of its temperature, while the kinetic energy of the gas atoms varies in proportion to the temperature. In other words, if the metal is heated, its internal energy only changes at the expense of the energy of vibrating atoms (more precisely, ions) in the crystal lattice; the energy of the electron gas does not change. Therefore, the heat capacity of a metal is the heat capacity of the atoms in the lattice and equals 25 J $\mathrm{mol^{-1}K^{-1}}$. Thus the "heat capacity catastrophe" paradox had been resolved.

At his seminars, Frenkel taught us Sommerfeld's theory and told us about his own research in the field.

There was yet another interesting problem in the physics of metals, and this was connected with the Hall effect. Imagine a rectangular metal plate carrying a current I (Fig. 1). Clearly, there can be no

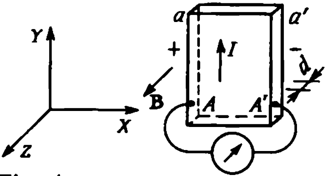

Fig. 1

potential difference across the plate between points A and A'. If, however, the plate is placed in a magnetic field, whose induction **B** is at right angles to the surface of the plate, a potential difference U does develop between points A and A'. This potential difference is called the Hall electromotive force. It can be measured by a galvanometer connected to points A and A'.

The emergence in a current-carrying conductor placed in a magnetic field of a potential difference in the direction perpendicular to the current direction is called the Hall effect. (This effect was theoretically predicted in the 1860s by Maxwell.) Why does the Hall electromotive force emerge?

A current is essentially the motion of electrons, and an electron moving in a magnetic field with a velocity **v** that is perpendicular to the magnetic induction **B** is acted upon by the Lorentz force $\mathbf{F}_L$, whose absolute value is $e\,|\mathbf{v}|\,|\mathbf{B}|$. The direction of the Lorentz force is determined by the left-hand rule. (If the thumb and the four fingers of the left hand are arranged at right angles to each other and the hand is oriented so that vector **B** impinges on the palm and the fingers point in the direction opposite to the velocity **v** of the electron, then the thumb will point in the direction of the Lorentz force.) Let the plate be placed as shown in Fig. 1. A current flows through the plate along the Y-axis (the velocity of the electrons is in the opposite direction!). Then the Lorentz force will push the electrons towards side a' of the plate and they will accumulate there. The accumulated electrons create an electrostatic field inside the plate proportional in strength to the number of the electrons. In this field electrons are acted upon by a force $|\mathbf{F}_{el}| = e\,|\mathbf{E}|$ directed against the Lorentz force, and hence decelerating them. Clearly, when this force becomes equal to the Lorentz force, which acts on the electrons "flowing" through the plate, the electrons will cease to be pushed to one side. By equating the two forces, we can find the strength $|\mathbf{E}|$ of the electrostatic field inside the plate:

$$e\,|\mathbf{E}| = e\,|\mathbf{B}|\,|\mathbf{v}|,$$

whence we obtain

$$|\mathbf{E}| = |\mathbf{B}|\,|\mathbf{v}|.$$

We can find the potential difference between points A and A' of the plate:

$$U = |\mathbf{E}|\,b = |\mathbf{B}|\,|\mathbf{v}|\,b,$$

where b is the width of the plate. The velocity of the electrons can readily be obtained given the current I, the electron concentration n in the sample (their number per unit volume), and the plate's cross-section S perpendicular to the direction of the current. The result is

$$I = ne\,|\mathbf{v}|\,S,$$

whence

$$|\mathbf{v}| = I/neS = I/nebd,$$

where d is the thickness of the plate.

Thus, the potential difference between points A and A' is

$$U = |\mathbf{B}|\,I/ned.$$

This potential difference was discovered and measured by the American physicist Edwin Hall.

The electron theory of metals readily explained the Hall effect, but one difficulty remained. The above explanation implies that the sign of the Hall electromotive force should be determined by the direction of the current flowing through the plate and by the direction of the magnetic field and should be the same for all metals. Experiments, however, indicated that a number of metals exhibited a Hall electromotive force with the opposite sign, as if positive charges rather than electrons were carrying the current. Nobody could explain the effect.

It was only in the 1930s that the British physicist Rudolf Peierls, Sommerfeld's student, explained the phenomenon using quantum-mechanical concepts about electron behaviour in metals. The reverse Hall electromotive force, like almost all quantum phenomena, cannot be visualized.

When Peierls' paper on the topic was published, Frenkel told me to report on it at the Friday seminar at the Institute. I did so although I poorly understood the problem. Only after Frenkel explained the situation did I and, I think, the others at the seminar grasp Peierls' paper.

The theory of metals offered another unsolved problem associated with the Hall effect. The effect at the time had only been observed in solid metals. The theory, however, predicted that liquid metals should exhibit the Hall effect, although it would be weaker than in solids.

When I started research at the Leningrad Physico-Technical Institute, I decided to work in this field, above all on the Hall effect. I took this decision after listening to Frenkel's lectures and seminars on current ideas in the physics of metals. I decided to check whether the Hall effect did in fact occur in liquid metals. Although the topic had been studied at the turn of the century by Hermann Nernst and Paul Drude, my survey of the literature led me to the conclusion that the early experiments had failed because of a wrong choice of liquid metal. For example, mercury had been chosen because it is in a liquid state at room temperature. The Hall effect had not been observed, but it became clear later that even solid mercury exhibits a hard-to-measure Hall effect. Bismuth had also been used in the experiments. It had seemed a good candidate because solid bismuth yields a Hall electromotive force several orders of magnitude higher than other metals (in ordinary metals the Hall effect is several microvolts, while in bismuth it is several millivolts). No Hall effect had, however, been observed. Now we know that the anomalously high Hall effect in solid bismuth is due to features of its crystalline structure, which disappear in the liquid state. Experimentalists had expected a strong effect and having discovered it a thousand times "too" weak, decided that there was no effect at all.

I took the simplest metal, an alkali metal, as my object. Alkali metals seemed to me a good choice because every other theoretical prediction concerning them was consistent with experiment. I chose an alloy of sodium and potassium, which, in proper ratios, is liquid at room temperature.

I thought that the early experiments had failed not only because of a poor choice of sample but also because the experiments were inaccurate. When a current is passed through a liquid metal in a magnetic field, the field displaces layers of the liquid metal. (Clearly, there is no such displacement in solid metals.) As a result, eddy currents emerge that "blur" the Hall effect in the liquid metal. It is, therefore, necessary to reduce, if not eliminate, the spurious currents. To do so, we took a thin layer of the liquid metal as a sample. Meticulous experiments yielded a Hall effect. A year and a half later Sommerfeld's paper was published, which described experiments confirming the modern theory of metals. Sommerfeld also referred to our experiment. To tell the truth, I was very proud that an authority such as Sommerfeld had taken note of my work.

Ferromagnetism was another burning problem in physics. It was known that only three metals in nature, iron, nickel, and cobalt, are ferromagnetic (now more are known). These metals can be magnetized in a very weak magnetic field, and their magnetization is several hundred thousand times greater than that of ordinary metals. For example, to attain in ordinary metals the magnetization of an iron sample in a 0.01-T field, it is necessary to place an ordinary metal into an external magnetic field of 1000 T. To account for this mysterious phenomenon, the French physicist Pierre Weiss developed the theory that the ferromagnetism of iron, nickel, and cobalt is due to the presence of small regions, called domains, where the magnetic fields of separate atoms point in the same direction, thus creating a large total magnetic field for the domain. The domain is very small, being of the order of a fraction of a micrometre in dimension, but it houses many hundred thousand aligned "elementary magnets". The domains are randomly distributed in the metal, and so in the absence of an external magnetic field, the ferromagnetic substance is not magnetized.

If the sample is placed in a magnetic field, the magnetic fields of the individual domains align themselves with the external field, and the sample as a whole becomes strongly magnetized. It is easier to align domains than to align the vast number of elementary magnets.

This was, roughly speaking, Weiss' theory of ferromagnetism. In order to explain the presence of domains, regions with aligned elementary magnets, Weiss suggested the existence of a magnetic field inside the metal, which orients the magnetic fields inside the domains. This field (Weiss called it the molecular magnetic field) was estimated by Weiss to be roughly 1000 T. But the origin of the field was unclear.

To detect this high hypothetical field, Professor Dorfman performed the following experiment. (At the time I was working in his laboratory at the Leningrad Physico-Technical Institute.) He placed a thin iron foil in a magnetic field so that the surface of the foil was parallel to the field's magnetic induction. As a result, the foil became strongly magnetized. A beam of fast electrons from a radioactive source was sent through a slit and then onto the foil perpendicular to its surface, and hence to the external magnetic field (Fig. 2). A photographic plate was placed behind the foil. The electrons that had passed through the foil blackened the plate. If the electrons had been acted upon by a very strong molecular field in the foil, the dark spot on the plate

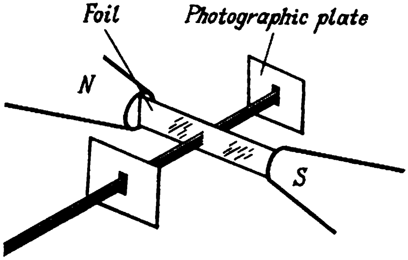

Fig. 2

would have been displaced. No such displacement was, however, observed in the experiment. This implied that whatever forces are responsible for orienting the elementary magnets in the domains, they are not magnetic in nature because they do not affect moving electrons.

Only in 1928 when the quantum-mechanical theory of ferromagnetism was constructed by Yakov Frenkel and practically at the same time by the German physicist Werner Heisenberg was it shown that there is no molecular field and the forces that orient elementary magnets inside domains are electrical in nature. They are called now exchange forces. A small paper dealing with the issue was published by Frenkel in the June issue of the German physics journal *Zeitschrift für Physik* in 1928, which was followed in July with a Heisenberg's in-depth paper. So they independently constructed the theory of ferromagnetism. Later Frenkel joked that his research in ferromagnetism had been prompted by experimentalists who had constantly "magnetized" him.

Many papers on magnetism in metals appeared in the wake of the theory of ferromagnetism. It was shown, for example, that the theory only implies the emergence of exchange forces in crystals, so no liquid ferromagnetics should exist in nature. It was also demonstrated that the exchange forces differ depending on direction inside the crystal, that is, the magnetic properties of ferromagnetic crystals are strongly anisotropic. This effect has been used to manufacture new magnetic substances on which electrical engineering is now based. Transformers, generators, and electric motors are made of ferromagnetics and the machines' performance is determined to a great extent by the properties of the substances. The theory of ferromagnetism was developed by the outstanding Soviet theoretician Lev Landau and his pupil Evgeny Lifshitz. So Frenkel, Heisenberg, Landau, and Lifshitz laid the foundations for the modern theory of ferromagnetism.

As I mentioned, special seminars for

students were held at our Physico-Mechanical Faculty. One seminar was intended for fourth- and fifth-year students. It was supervised by Academician Vladimir Fock and was called the "calculating" seminar. The seminar was somewhat unconventional. Fock would suggest an intricate problem whose solution he did not know and he would immediately begin to solve it at the blackboard together with us. So we could watch the creative work of an outstanding scientist.

We saw how Fock approached a problem. He would try one method, fail, try another method, and fail again. Finally, sooner or later, he would find a solution. Sometimes he would take one seminar, sometimes he would need the following one too. We saw not merely the solution but the process of finding it. It was quite a beneficial way of teaching. Once we had to solve a complicated asymmetric problem on electrostatics. We failed to solve it at one seminar and at the next seminar we obtained a very long differential equation. It occupied the whole blackboard. We followed the mathematical calculations very closely so as to be sure that there were no errors, but we could not perceive the physical meaning hidden behind the very long formula. Somebody asked Fock, "What is the physical meaning of this equation?" He looked at us sympathetically, "The physical meaning of this equation is that it has a solution."

Fock was mostly interested in theoretical physics but he did mind solving applied, purely practical, problems. For example, he was asked by geophysicists to help them study the distribution of the electric field inside the Earth. The topic had important consequences for geological prospecting. Fock solved the problem together with V. Frederix. In general, it was characteristic of the Leningrad Physico-Technical Institute that it combined theoretical and experimental physics research with the study of purely applied problems related to the needs of engineering, industry, and agriculture.

In 1930, when I graduated from the Institute as a physical engineer, I was sent, on the recommendation of Ioffe, to Germany. I stayed for three months during which I visited physics laboratories in Leipzig, Munich, and Hamburg. I was pleased to see that Soviet physicists, and, in particular, myself, were being trained no worse than the physicists I met abroad. True, they had well-equipped laboratories, while the Soviet Union had no instrument engineering sector so we often had to make our devices ourselves or to buy them abroad, which was a heavy burden on our national economy. However, when it came to knowledge, understanding, and experimental technique, we could compete with the best universities in Germany.

During my stay in Germany, I worked for a month in the laboratory in Munich which had once been headed by Röntgen. I noticed that undergraduates working at the laboratory were preparing for their finals by reading Frenkel's book *A Course of Electrodynamics* published in German. I asked, "Who will be your examiner?" "Sommerfeld," they replied. The Sommerfeld, the world-famous theoretician, the Sommerfeld about whom we, students, said, "There is no Bohr but Bohr, and Sommerfeld is his prophet." I know Sommerfeld had written a five-volume course of physics and asked the undergraduates why they were studying Frenkel's course. Because, they answered, Sommerfeld regarded Frenkel's course as the best in the world and so he would only examine students according to the course. When I said that I knew Frenkel personally, my prestige rose abruptly. I was very proud of our Soviet physicists who had risen to world-wide eminence.

In the late 1930s, Abram Ioffe and his coworkers turned to a new problem. They began studying semiconductors, which are substances with anomalous electrical properties, having conductivities intermediate between that of conductors and insulators.

At that time, semiconductors were not widely used. Foreseeing their great practical value, Ioffe devoted a great deal of time and effort to the hard task of investigating their properties. Experimentalists faced the difficulty that samples of semiconductors with seemingly identical chemical compositions exhibited different physical properties. The conductivities and the way they vary as a function of temperature of different samples of cuprous oxide (Cu_2O) were found to differ. Some samples acted like conductors, some like insulators, depending on the fabrication technique. Clearly, it was difficult to uncover a general pattern in these "capricious" substances. All that could account for the variation was that semiconductor properties strongly depend on the impurities present in them. For example, "pure" cuprous oxide is an insulator, but if the content of oxygen atoms is raised to 1/100 000th of a percent, the sample becomes a conductor.

This property of semiconductors predetermined the direction of further research. In the first place, the relationship between semiconductor properties and the amount of impurities had to be established, which, in turn, required technique for obtaining samples with specified compositions.

Boris Kurchatov (Igor Kurchatov's brother) took an active part in this research. He obtained samples of cuprous oxide with specified excess amount of oxygen and studied how their conductivity varied with oxygen content. The experiments showed that the conductivity grew sharply with oxygen content. This classical work laid the foundation for a new industry, fabricating semiconductors with specified properties by introducing a certain amount of an impurity (doping it). At present, semiconductors are widely used in practice.

After Ioffe had turned our attention to semiconductors, I decided to study the intrinsic photoelectric effect, that is, the emergence of free electrons under the action of light and, as a result, a rise in the sample's conductivity. I tried to establish how the mobility of the excess electrons compared with the mobility of dark electrons (free electrons in an unilluminated sample). A value of the mobility of electrons could be only obtained by measuring the Hall effect and the sample's conductivity. The effect would, therefore, have to be studied in semiconductors. Remember that if a current-carrying conductor is placed in a magnetic field, a potential difference, called the Hall electromotive force, is developed between points lying on a perpendicular to the direction of the field and the direction of the curent.

From the very beginning, a curious phenomenon interfered with our measurements of the Hall electromotive force. When a sample in a magnetic field was illuminated, a potential difference developed between points A and A' even if no current flowed through the sample (the experimental setup is shown in Fig. 3). To get rid of this spurious effect, we illuminated the plate of cuprous oxide by red light instead of white light (cuprous oxide is a red transparent crystal). Thus we were able to measure the "pure" Hall electromotive force, to estimate the contribution made by photoelectrons, and to calculate their mobility. It was found to be the same as for dark electrons. Now we know that photoelectrons created by light immediately collide with atoms, and their behaviour thereafter does not differ from that of dark electrons.

To explain the spurious effect, we took a 2-cm long plate of cuprous oxide, connect-

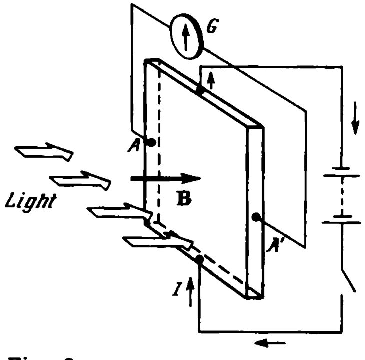

Fig. 3

ed a measuring device to it, placed it in a magnetic field parallel to the surface of the plate, and illuminated it by an intense source of light. The schematic of the experiment is shown in Fig. 4. The potential difference proved to be as high as 20 V even for a magnetic field of the order of 1 T.

I reported on our simple experiment, even demonstrated it, at a seminar at the Physico-Technical Institute. Everybody took it with a grain of salt. There were no doubts that the phenomenon existed, but there was no explanation of it. Qualitative and quantitative theories of the phenomenon (we called it the photomagnetic effect) were developed later. I will not dwell on it here, except to note that the photomagnet-

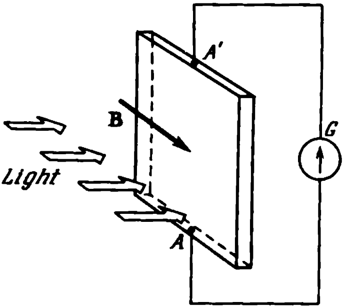

Fig. 4

ic effect in semiconductors is instrumental in studying a number of the properties that are of great importance in engineering.

These topics are only examples of the extensive research programme on electric and photoelectric phenomena in semiconductors which was carried out at the Leningrad Physico-Technical Institute under the supervision of Abram Ioffe.

The electrical properties of dielectrics was another field of interest at the Physico-Technical Institute. Igor Kurchatov was dealing with the problem. He headed a laboratory that was concentrating on the properties of Rochelle salt ($NaKC_4H_4O_6 \times 4H_2O$). Huge crystals of Rochelle salt are very beautiful, and it was spectacular to see Kurchatov growing them in large glass vessels. Rochelle salt is a dielectric with an anomalously high dielectric constant. (Remember that the dielectric constant is the ratio of the electric field inside a dielectric to the external field in which the dielectric is placed.) Ordinary dielectrics have small dielectric constants (3-5 for glass and 7-8 for mica), water's dielectric constant of 80 always being considered anomalously high. The dielectric constant of Rochelle salt may rise to several tens of thousands! Moreover, the dielectric constant behaves in an unusual way when the external electric field is changed, namely, in high fields the dielectric constant is small, but in weak fields it becomes enormous. Studies into the properties of Rochelle salt were thus of great importance because it could be used as the spacing material to create small capacitors with large capacitances. It should be noted, however, that Rochelle salt behaves anomalously in comparatively narrow temperature interval (from —30°C to +30°C).

Kurchatov's in-depth investigations showed that ferroelectrics (substances that behave like Rochelle salt) are in many ways analogous to ferromagnetics. Electric induction in ferroelectrics, for one thing, varies with the external electric field in the same manner as magnetic induction does in ferromagnetics in an external magnetic field. Ferroelectric crystals, like ferromagnetics, are very anisotropic with their electrical properties depending on the orientation of the external field with respect to the axes of the crystal. When a ferroelectric is heated to a "critical" temperature (roughly 30°C for Rochelle salt), its electrical properties change abruptly, the dielectric constant ceases to be anomalous, and it starts to behave like an ordinary dielectric. This is analogous to the transition from ferromagnetism to paramagnetism at the Curie point. The temperature marking the transition from ferroelectric phase to paraelectric phase is also called the Curie point, or Curie temperature. Kurchatov showed that the change from ferroelectric to paraelectric behaviour in ferroelectrics at the Curie point is accompanied by a heat release, which also occurs in ferromagnetics. This is termed the electrocaloric effect, and for ferromagnetics it is called the magnetocaloric effect. Kurchatov published his results in a book which became recognized as the foundation of ferroelectricity.

Somewhat later, Bentsion Wul (Ioffe's pupil) and his coworkers at the Lebedev Physical Institute of the USSR Academy of Sciences discovered that ferroelectric behaviour is inherent in a number of chemical compounds, one of them being barium titanate ($BaTiO_3$). This ferroelectric has become extensively used because its Curie temperature is about 80°C, much higher than that of Rochelle salt.

Another topic to attract Ioffe was electric breakdown in dielectrics and it was studied intensively at the Physico-Technical Institute. The object was to make dielectrics more reliable, that is, to raise their breakdown voltages. Among those who worked on the project was Nikolai Semenov.

There were several theories to explain breakdown at the time. According to one of them, a dielectric is heated under the action of an electric current, and current carriers collide, as a result, with the dielectric's atoms, imparting their energy to the atoms. As the dielectric heats up, the number of the current carriers and hence the current rises. This induces further heating and an avalanche-like increase in the number of the carriers. The dielectric's conductivity increases, and, finally, breakdown takes place.

Semenov studied a single act of creating new current carriers, the mechanism of collisions between the molecules and the atoms, and, in particular, chemical reactions that take place in the process. Semenov and his coworkers investigated the interaction between gaseous phosphorus and oxygen, which yields as a product a well-known solid compound, phosphorus pentoxide (P_2O_5). The formation of the compound is accompanied by an energy release, and the gas becomes fluorescent. Quite unexpectedly it was discovered that at low oxygen partial pressures (of the order of 1/100 000th of an atmosphere) no fluorescence is observed, that is, the gaseous phosphorus did not react with the oxygen at all! Moreover, the reaction started if the gas argon, which does not react chemically, was introduced into the vessel even when the partial pressure of the oxygen was kept constant. This astonishing fact contradicted existing hypotheses concerning the mechanism of chemical reactions. These hypotheses predicted that phosphorus should react with oxygen at any partial gas pressure. Semenov's research thus revealed the existence of a critical pressure for the reaction between phosphorus and oxygen.

These results were published in a German physics journal only to be criticized by the German chemist Max Bodenstein, a leading authority on chemical kinetics at the time. He considered Semenov's experiments inconclusive. The oxygen pressure in those experiments had been measured by a manometer, and to protect it against phosphorus vapour, a trap cooled by liquid air had been placed between the manometer and the reaction vessel. The phosphorus vapour had condensed in the trap, thus causing additional gaseous phosphorus to flow into the trap. Meanwhile the oxygen on its way to the vessel had also passed the trap by but in the opposite direction to the phosphorus vapour. Bodenstein argued that at low pressures the oxygen had been simply blown back by the phosphorus vapour and had not entered the vessel at all. The reaction, therefore, did not proceed because no oxygen was reaching the vessel.

Semenov decided to repeat his experiments and realized that Bodenstein was partially right in that the oxygen pressure had not been measured accurately enough. Excluding measurement errors did not, however, change the situation and gaseous phosphorus would only react with oxygen at some threshold pressure. Moreover, a new and quite unexplainable phenomenon was discovered. The critical pressure was found to depend on the vessel's dimensions. If the vessel was spherical, the critical pressure increased in proportion to the vessel's diameter. The larger the vessel, the higher the pressure at which the reaction is initiated. Semenov wrote later that after this he ceased to understand anything.

Semenov reported his findings at a seminar at the Physico-Technical Institute. Everybody knew about Bodenstein's criticism and they all found fault with the experiment. Semenov tried hard to convince those present that he had eliminated the errors in his experiments, but to no avail. The situation was made worse because Semenov himself could not explain his strange results.

Semenov was firmly convinced that his

results were valid and published a number of papers on them. Eventually he received a letter from Bodenstein agreeing with the results, acknowledging their significance, and suggesting that Semenov should publish his work in the journal Bodenstein edited. Later Semenov constructed a qualitative theory for the phenomena.

The discovery gained Semenov world-wide recognition and initiated a new scientific trend, namely, the study of branching chain chemical reactions. For this research Nikolai Semenov, jointly with the British chemist Cyril Hinshelwood, was awarded the 1956 Nobel Prize.

Nikolai Semenov founded a scientific school on chemical kinetics. Many outstanding scientists belong to the school, among them Academicians Yuly Khariton and Viktor Kondratev. Khariton's interests laid in explosive chemical reactions. Another of Semenov's pupil, Academician Yakov Zeldovich, was a leading theoretician in the field. He developed the theory of chain reactions and deflagration theory, which are very important in blasting.

In 1928, at one of the regular seminars Ioffe said, "I must inform you about the contents of a paper sent to me by Professor Chandrasekhara Raman from India." The paper was carried by the British journal *Nature*. It has a "Letters to the Editor" section, where scientists communicate their new findings. Since the *Nature* is a weekly, it can quickly publish brief information.

Raman's paper reported that the spectrum of light scattered in a liquid differed from that of the incident light. If the liquid were illuminated by light with a certain wavelength, say, yellow, the scattered light would contain both that wavelength and some new ones, that is, new colours, or new spectral lines.

After Ioffe had read the paper, Professor Rozhansky, who was sitting near me and who usually closely followed reports at seminars although only rarely taking the floor himself, became unusually agitated.

He stood up and said, "Something is wrong. I know that research like this was carried out in Moscow by Mandelshtam approximately two years ago. I am quite sure that Mandelshtam discovered this phenomenon for crystals and that for the last two years he has been investigating it." It was in this way that we, young physicists, heard for the first time about the large school of physicists headed by Leonid Mandelshtam.

It was clear from the paper that Raman had just observed the effect. Mandelshtam had not only discovered the phenomenon, but in association with Grigory Landsberg, had carried out an in-depth study, found basic patterns, constructed a complete theory for the effect, and sent off an extensive paper for publication. The journal received the paper two weeks after the *Nature* had received Raman's paper, which had been dictated by radio to shorten the time. Unfortunately, the emergence of additional spectral lines in scattered light is now called the Raman scattering, although some non-Soviet scientists did refer to the discovery as the Mandelshtam-Landsberg-Raman effect.

By the end of the 1920s, the Leningrad Physico-Technical Institute enjoyed worldwide eminence. Ioffe understood that in such a large country as the Soviet Union, science should not be concentrated in two cities, Leningrad and Moscow. He repeatedly and persistently discussed the issue with his coworkers and the authorities. In the long run, it was decided to set up a number of physico-technical institutes in the USSR's large industrial cities.

Ioffe decided to organize a physico-technical institute in Kharkov, then the capital of the Ukraine. Under his sponsorship a group of young physicists from the Leningrad Physico-Technical Institute went to Kharkov to staff the new institute. The institute was administered by Ivan Obreimov (Director) and Semenov's pupil Alexander Leipunsky (his deputy). Later both were elected to full membership of the USSR Academy of Sciences. Those who went to Kharkov included Ioffe's pupil K. Sinelnikov and Frenkel's pupil Ya. Gorovets. I was also invited and was inclined to go since many of my friends had moved to Kharkov, but our authorities were against it. Ioffe was abroad, and Semenov who was acting as his deputy objected strongly that the Institute had already been bled dry and that it shouldn't be deprived of all its young people. So I stayed in Leningrad.

The 15th Congress of the CPSU approved at that time the first five-year plan for developing the economy. A rapidly growing industry acutely needed qualified specialists, and even undergraduates were given permanent work in research institutions.

It was also at this time that the Ukrainian Physico-Technical Institute was set up in Kharkov.* Its first laboratory dealt with low temperatures, and a device for obtaining liquid helium was installed so it could conduct research at temperatures near 4 K. Not long before setting up the Ukrainian Physico-Technical Institute, Obreimov and Lev Shubnikov worked for a year in Holland at the first low-temperature laboratory in Leiden. They marked their stay in Leiden by performing a number of brilliant experiments and they ordered scientific equipment for the new laboratory in Kharkov. The Ukrainian Physico-Technical Institute, whose achievements have now gained it world-wide recognition, was the first swallow to leave the walls of the Leningrad Physico-Technical Institute.

Later Ioffe organized similar institutes in Tomsk and Dnepropetrovsk, since he

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* Now called the Kharkov Physico-Technical Institute.

believed that the Ukrainian Physico-Technical Institute alone had not sufficiently decentralized science. Groups of Leningrad physicists led by Piotr Tartakovsky and Georgy Kurdyumov (later an academician) went to Tomsk and Dnepropetrovsk.

Unfortunately, the efforts of the physicists from Leningrad were not supported by scientists in Tomsk, and the Institute practically disintegrated. By contrast, the Dnepropetrovsk Institute rapidly matured and won recognition. This happened, first, because Dnepropetrovsk was the centre of the Ukrainian metallurgy industry and, second, because Kurdyumov was a leading Soviet specialist in the field. His research at the Leningrad Physico-Technical Institute had centered on the radiographic analysis of the important martensite transformations in steel. Kurdyumov had elucidated the mechanism of martensite transformations which take place in the process of steel hardening. This classical work gained him world-wide recognition and had broadly been applied in practice.

In 1932, the Leningrad Physico-Technical Institute set up the Ural Physico-Technical Institute in Sverdlovsk, the largest industrial city in the Urals. This time I was included in the staff. We started work in Leningrad and only in 1936, when the Institute's building was constructed, did we move to Sverdlovsk. Now the Institute of Physics of Metals (it was called the Ural Physico-Technical Institute) is one of the largest physics establishments in the USSR. It is administered by the well-known theoretical physicist Academician Sergei Vonsovsky, who had graduated from university and started work at the Institute when it was set up.

In the late 1920s and early 1930s, physics in the Soviet Union was being pursued extensively, and the number of scientific associates grew rapidly. Between 1927 and 1930 the staff of the Leningrad Physico-Technical Institute tripled. Other institutes continued to branch out from it, among them the Institute of Chemical Physics headed by Semenov (later the Institute moved to Moscow), the Communication Institute led by Professor Rozhansky, and the High-Voltage Institute administered by Chernyshev. Ioffe maintained that advances in physics should be applied both in industry and in agriculture, so he organized and headed the Agrophysical Institute.

Thus, starting in 1928, Ioffe, in following the directives of the Soviet government and the Communist Party, initiated physics institutes in a number of Soviet industrial centres which have since significantly promoted the development of science and technology in the USSR. The Leningrad Physico-Technical Institute had, therefore, served as a breeding-ground for physics in the USSR.

In 1934, Piotr Kapitza, an outstanding

Soviet physicist, returned to the USSR after a prolonged mission to Britain. His stay in Britain had been marked by famous studies on the behaviour of substances in strong magnetic fields. The magnetic fields then ordinarily attainable in the laboratory were of the order of 1-2 T. To generate higher fields required large expensive electromagnets. It was possible, in principle, to produce such fields inside an iron-free solenoid, but this would involve very high currents and huge quantities of heat, which in turn would overheat the solenoid winding.

Kapitza reasoned that it was not necessary to use a strong constant field for a long time. Since the phenomena that take place inside a substance in a magnetic field are atomic in nature and take a very short time to occur, a millionth or even a thousand millionth of a second would be sufficient. It would, therefore, be enough to create a strong magnetic field for a very short time and to carry out the necessary measurements during this time. To implement the idea, Kapitza produced a magnetic field in a solenoid by sending a strong current through it from an a.c. generator for half a cycle (0.01 s).

The generator's armature was driven by an electric motor with the generator's terminals disconnected. When the armature attained a nominal rotational speed, the motor was switched off, but the armature continued to rotate by inertia. The voltage across the terminals (the electromotive force) changed sinusoidally. When the voltage was zero, a knife switch connected the generator's terminals on the winding of the solenoid. The circuit was broken again after half a cycle (0.01 s), when the voltage had once more dropped to zero, and so there was no electric arc. A high current flowed through the winding (and, hence, a strong magnetic field emerged) during the half-cycle, and the coil was not greatly heated over such a short period of time. But there arises another difficulty. When a current is sent through the solenoid, each turn is acted upon by a radial force that tends to pull the solenoid apart. At high currents the forces generated exceed the ultimate strength of the winding material and it will crush. (Kapitza said that when he staged his experiment in Britain for the first time, the coil broke down and its fragments flew apart. After this became known the laboratory assistants hastened to take out life assurance.) The strength of the magnetic fields is thus limited by the strength of the winding material, so Kapitza made the winding out of a very strong bronze with a diameter of about 25 mm and a length of about 100 mm. Current passes through the coil for one hundredth of a second, creating a magnetic field of roughly 30 T.

Kapitza studied a number of physical phenomena in those magnetic fields. He investigated how a magnetic field affects the resistivity of conductors. It was known that in weak fields the resistivity varied roughly as the square of magnetic induction. Kapitza found that in strong fields the resistivity deviated significantly from the expected quadratic relation, being instead in proportion to the magnetic induction.

Of great interest were studies on the behaviour of substances in high magnetic fields at low temperatures, and Kapitza tackled the hard task of obtaining temperatures close to absolute zero. Liquid helium has the lowest temperature of all liquids—with a boiling point at normal pressure of 4.2 K.

Liquid helium was first obtained by the Dutch physicist Heike Kamerlingh Onnes in 1908. The plant he designed at the Leiden laboratory could produce a small amount of liquid helium. Such plants were very expensive to build. Kapitza designed a much more productive and cheaper liquefaction plant.

The remarkable properties of liquid helium began to attract physicists' attention. As a matter of fact, liquid helium is the only substance that undergoes phase transformations in liquid state. At a temperature of 2.19 K its behaviour changes abruptly. At temperatures above 2.19 K liquid helium (called helium I) has the properties of a normal liquid and at $T \leqslant 2.19$ K liquid helium (helium II) exhibits remarkable properties such as extremely high thermal conductivity and vanishing viscosity.

Helium II was discovered by Kamerlingh Onnes and later its properties were studied by Willem Keesom at the Leiden laboratory. Keesom found that the thermal conductivity of helium II was several times greater than that of the most conductive metals.

Kapitza started his work on helium II in 1937. After surveying the available experimental evidence, he concluded that the extremely high thermal conductivity of helium II could not be attributed to the ordinary process of equalizing temperature inside a substance. He suggested that the intense heat transfer in helium II could be associated with convection. Theoretical findings confirmed that convection currents in helium II should flow with extraordinary ease, without friction, and so helium II might be considered a superfluid liquid, i.e. having no viscosity at all.

To verify this hypothesis, Kapitza staged an experiment in 1938 in which helium II was passed through a gap between two flat polished glass plates brought close together. The plates were polished so flat that the gap between them did not exceed half a micrometre. Helium II flowed through this narrow gap under the action of gravity with a velocity that could only have been attained in the absence of viscosity!

Thus the superfluidity of helium II had been experimentally observed.

There remained some difficulties connected with measuring the viscosity of helium II. The viscosity can be measured by two different techniques. One involves measuring the velocity of a liquid flowing from a capillary tube (or through a gap, as in Kapitza's experiment). At a specified pressure difference at the ends of the tube, the amount of outflowing liquid over a specified period of time varies in inverse proportion to the viscosity. The second method is to study the damping of torsional vibrations of a solid in a liquid. A thin disc suspended on a string is submerged in the liquid (with the disc's surface horizontal). The torsional vibrations of the disc about the axis passing through the string were observed. Naturally the vibrations are damped quicker in more viscous liquids. The two methods gave the same values of viscosity for every liquid, except helium II. The first technique yielded a vanishingly small viscosity, thus confirming the superfluidity of helium II, while the second yielded a small but measurable value.

All this was explained by the hydrodynamic theory of superfluidity formulated by Academician Lev Landau in 1941. He demonstrated that the conventional interpretation could not be applied to the behaviour of substances at such low temperatures. His quantum theory of helium II superfluidity brilliantly explained Kapitza's experiments and predicted some new effects, which were shortly afterwards discovered by experimentalists.

The superfluidity of liquid helium has not yet found wide application, but Landau's theory of superfluidity influenced the development of theoretical physics as a whole. It was instrumental in the construction of the theory of another remarkable low-temperature phenomenon, superconductivity. Although superconductivity theory was developed much later, I think it worth interrupting the chronological order of my narration to cover it.

Superconductivity was discovered by Kamerlingh Onnes in 1911 when he observed that mercury had a vanishingly small resistivity at a temperature of 4.25 K. Later many metals and alloys were shown to exhibit superconductivity. Clearly, conductors with practically zero resistivity would have many practical applications, and physicists vigorously tackled the issue. They failed, however, to construct a theory to explain the effect.

After the advent of quantum mechanics, the microscopic theory of solids was developed, which explained the properties of solids in terms of the behaviour of electrons and atoms. It gave a comprehensive qualitative interpretation of the properties of metals, insulators, and semiconductors under various conditions. Only superconductivity remained unexplained. It was only in 1957, some 46 years after the discovery of superconductivity, that the phenomenon was accounted for by a microscopic theory formulated by the Soviet scientist Academician Nikolai Bogolyubov and, independently, by the American physicists John Bardeen, Leon Cooper, and John Schrieffer (the Bardeen-Cooper-Schrieffer, or BCS, theory).

By that time superconductors had been thoroughly studied. Superconductivity was found to break down under the action of a magnetic field, thus making superconductors ordinary conductors. The magnetic induction of a field at which superconductivity vanishes is termed the critical magnetic field. Different metals have different critical magnetic fields which, in turn, vary inversely with temperature. The critical fields are zero at transition temperatures.

It was later discovered that a magnetic field does not penetrate into a superconductor and, if present inside the superconductor, is expelled from it during transition to superconducting state (when the temperature is lowered). These are the fundamental properties of superconductors.

These properties clearly demonstrate the limited possibility of generating high undecaying currents and producing strong magnetic fields. Indeed, a current flowing through a conductor creates its own magnetic field which increases with the current. As soon as the critical magnetic field is attained, the superconductor changes to normal state. It was shown experimentally that critical magnetic fields can be as high as 10^{-2}-10^{-1} T.

There existed several theories of superconductivity prior to the development of the microscopic theory in 1957. Starting from numerous experimental results, scientists established relationships between quantities that characterize the behaviour of superconductors.

In 1937, Landau, for example, analyzed the available experimental evidence to predict a new phenomenon pertaining to transition of a metal from superconducting to normal state in a magnetic field. According to Landau, the transition is a gradual process. Af first, the field partially penetrates into the superconductor at some value of the magnetic induction below the critical magnetic field, thus creating alternating layers of superconducting and normal states. When the critical magnetic field is attained, the superconducting state is completely destroyed.

Landau's predictions were conclusively confirmed in a series of experiments performed at the Kharkov Physico-Technical Institute by Lev Shubnikov and at the Institute of Physical Problems in Moscow by Alexander Shalnikov. I watched those brilliant experiments in Kharkov and Moscow, which graphically demonstrated the structure of the complicated intermediate state, the topography, so to say, of the alternating superconducting and normal layers inside a superconducting ball. This state of a superconductor is now called the Shubnikov phase.

In 1950-52, a group of Soviet physicists including Vitaly Ginzburg, Lev Landau, Alexei Abrikosov, and Lev Gorkov developed a theory that implied the existence of superconductors with extraordinary properties. Now this is known as the GLAG (Ginzburg-Landau-Abrikosov-Gorkov) theory of superconductivity. These superconductors were termed type II superconductors. They differ from other superconductors in that they have much higher critical magnetic fields.

Experiments staged shortly afterwards verified the theoretical findings. It was discovered that the metal niobium and some alloys are type II superconductors. The critical magnetic fields for these superconductors indeed proved to be very high, achieving 20-30 T for an alloy of niobium and tin. This property allows type II superconductors to be used to produce strong magnetic fields, which, in spite of the large expenditures on helium liquefaction, is much more economical than using ordinary electromagnets. There are now generators and electric motors with superconducting coils and rated powers of about 10 000 kW. Scientists are actively at work on long-distance power transmission via superconducting lines.

Thus the theory constructed by the Soviet physicists contributed significantly to the development of the new technology.

Up to the late 1920s, the physicists of the world were concentrating their efforts on the structure of the atom, its electron shell, and the physics of metals.

The atomic structure only attracted a few scientists, mainly physicists of Rutherford's school in Britain and that of Marie Curie in France. In the Soviet Union, only Lev Mysovsky at the Leningrad Radium Institute and Dmitry Skobeltsyn at the Leningrad Polytechnical Institute and the Leningrad Physico-Technical Institute were interested in nuclear physics.

At the time we were taught and subsequently we ourselves taught that the atomic nucleus consists of protons and electrons, that the number of protons is equal to the atomic mass of a chemical element, and that the number of electrons in the nucleus equals the difference between the atomic mass and the atomic number of the element.

In the 1930s, nuclear physics was rocked by an outburst of fundamental discoveries. In 1931, John Cockroft and Ernest Walton of Rutherford's laboratory disintegrated lithium nuclei by fast protons with energies of several hundred kiloelectronvolts. As a result, alpha particles with an energy of about 8 MeV each were emitted by the lithium nuclei. We discussed these experiments animatedly in our laboratories, in corridors, and even over our meals. This was the first time that the energy of created particles substantially exceeded the energy of bombarding particles. Subsequently the experiments were repeated in laboratories all over the world, and, in particular, by

Kharkov physicists led by Sinelnikov.

In 1932, the English physicist James Chadwick (Rutherford's student) established experimentally the existence of the neutron, a neutral particle whose mass is roughly equal to the mass of the proton. This made a big stir among scientists. The more so, as similar experiments had been performed not long before by German and French physicists who, like Chadwick, had observed penetrating radiation emitted by light chemical elements, such as beryllium, under bombardment by alpha particles. This radiation easily penetrated a thick layer of lead and knocked out protons from paraffin. Initially, physicists had thought that the penetrating radiation was essentially γ-rays and had not measured their energy. Chadwick, however, measured the energy and showed that γ-rays could not possess such energy. He conclusively demonstrated that neutral particles, neutrons, had passed through the lead. This is yet more evidence of how important quantitative experiments are in physics.

In the same year of 1932, a new elementary particle, the positron (a positively charged electron), was discovered in cosmic rays.

All these brief reports had been carried in the lighter scientific magazines, and we were looking forward to the in-depth articles that should appear in the physics journals.

To stimulate the development of Soviet

nuclear physics, Ioffe decided to call an All-Union Conference on Nuclear Physics and ask leading foreign scientists to participate. The conference was held at the USSR Academy of Sciences in Leningrad in late September, 1933. Outstanding scientists from all over the world took part in the conference. These included the American physicist Wolfgang Pauli, the French physicists Jean Perrin, Iréne and Frédéric Joliot-Curie.

The very first experiments on the disintegration of lithium nucleus made it clear to Ioffe that nuclear physics had entered a new era of development. Ioffe immediately began organizing investigations in this field at our Physico-Technical Institute. At first, a permanent seminar on nuclear physics was set up, in addition to the usual seminar on general physics I have mentioned. The seminar participants (as far as I remember, it was held on Wednesdays) discussed all the advances in nuclear physics at length. Although I did not want to become a nuclear scientist, since I was deeply involved in my studies on semiconductors and metals, I attended the seminar to follow new developments in physics. When a sensational topic was discussed, the hall was usually overcrowded. Shortly afterwards, two groups of nuclear physicists were organized, one led by Igor Kurchatov and the other by Abram Alikhanov. The groups tackled the task of constructing new experimental apparatus, such as sources of alpha particles, beta particles (electrons), γ-rays, and neutrons. These are the products of the radioactive disintegration of radium, which the Leningrad Radium Institute had at its disposal. Neutrons were emitted by ampoules of radon (a gaseous product of radium disintegration) and beryllium powder. The alpha particles emitted by the radon caused the powder to emit neutrons. At the same time, apparatus were designed for detecting various particles. These included counters, Wilson cloud chambers, and ionization chambers. All this was comparatively quickly designed, constructed, and soon being used in experiments.

Soon after the positron was detected in cosmic rays, attempts were made to obtain positrons in the laboratory. These attempts were not only crowned with success but also led to the discovery of artificial radioactivity. Iréne and Frédéric Joliot-Curie found that light chemical elements, like aluminium and magnesium, emit positrons when bombarded by alpha particles. Quite unexpectedly, positrons were observed in these experiments whose intensity decreased exponentially even when the aluminium foil was not being bombarded by alpha particles. So the Curies had both artificial radioactivity and a new type of radioactive decay, positron decay.

These experiments were as sensational as the discovery of the neutron. Artificial radioactivity could only be induced by high-energy alpha particles in light chemical elements. Heavy elements did not exhibit the effect. This is because the probability that a heavy nucleus can be penetrated by charged particles, say, alpha particles, is negligibly small. This prompted the Italian physicist Enrico Fermi to try and induce artificial radioactivity in heavy elements by bombarding them with neutrons. His efforts were crowned with success. Fermi published a paper in the *Nature* describing artificial radioactivity induced by neutron bombardment of some chemical elements.

By this time the Leningrad Physico-Technical Institute was approaching the end of its "incubation" period, so to say, for the preparation of apparatus for nuclear research in Kurchatov's and Alikhanov's laboratories. It did not take long time to determine that Kurchatov's interests were centered about neutron physics, to which he devoted the rest of his life, and Alikhanov's team tackled beta decay.

That our scientists were up to date in nuclear physics was clear when within weeks of the publication of Fermi's paper, Kurchatov and coworkers published "Fermi's Effect in Phosphorus". The paper described a new phenomenon. Phosphorus was found to exhibit a radioactivity with another half-life of 3 minutes, in addition to the value of 3 hours observed by Fermi.

In 1934, Kurchatov and his coworkers started a research project which had been brought about by the discovery of neutron moderation in hydrogenous substances, say, water. Large tanks of water containing various substances could be seen at the time in many of the laboratories and even in corridors at the Institute. The water moderated the neutrons which Kurchatov used to obtain for the first time radioactive ruthenium and new radioactive isotopes of palladium and rhenium.

The studies of artificial radioactivity induced by moderated neutrons in chemical elements had shown that the probability of a nuclear reaction is critically dependent on the energy of the bombarding neutrons. Kurchatov decided to study this phenomenon. This was a hard task since, in the first place, the exact values of the energy of bombarding neutrons, that is, their power spectrum, had to be ascertained. This is now a very complicated field of physics, called neutron spectroscopy. In 1935-36, physicists had only begun studying the problem, and Soviet scientists were among the first to set about the task.

In 1935, Kurchatov and his coworkers discovered nuclear isomerism. It was known that some substances have nuclei with the same charges but different masses. They are called isotopes. There are also substances whose nuclei have the same masses but different charges. They are called isobars.

Kurchatov's team investigated the neutron-induced artificial radioactivity of bromine and discovered that in the process bromine nuclei were formed that had the same masses and charges but different half-lives. These substances were called isomers.

The discovery of bromine isomerism came as a surprise and was received with distrust. Afterwards, however, the fact was accepted and became instrumental in studying atomic structure.

A field of the physics of the atomic nucleus parallel with neutron physics was the study of radioactive beta decay. Some features of the beta decay of natural radioactive elements were difficult to explain. It was known that the electrons ejected in beta decay have kinetic energies ranging from zero to a critical value characteristic of each nucleus. At the same time it is obvious that as a result of radioactive transformation a nucleus changes from some initial state to some final state. The energy released in the process is imparted to the electrons which are ejected from the nucleus. But why then do the ejected electrons differ in energy? For example, $^{210}_{83}Bi$ nuclei are transformed as a result of beta decay into $^{210}_{84}Po$ nuclei. The highest energy of the electrons ejected in the reaction is 1.05×10^6 eV. In other words, the energy of each $^{210}_{83}Bi$ nucleus decreases by 1.05×10^6 eV. However, the average energy per each ejected electron is 0.39×10^6 eV. Hence, some of the ejected electrons have less energy than is lost by the nucleus. Where does the rest of the energy go to?

This was a question of vital importance

in the early 1930s. Niels Bohr went as far as suggesting that energy conservation might be violated in elementary nuclear processes.

A way out of this difficult situation was proposed by Pauli. He maintained that when a nucleus decays, another particle is ejected (together with the electron) which carries away the "missing" energy. The particle has negligibly small mass and no charge, and so it was called the neutrino. However, all attempts to observe neutrinos experimentally failed. The neutrino remained "a mysterious particle without shape," we joked paraphrasing our writer Yury Tynyanov.

The first experiment to confirm the existence of the neutrino indirectly was performed by Leipunsky in Rutherford's laboratory, where he worked for some time. Leipunsky observed the "recoil" of an atom when an electron or a positron was ejected from its decaying nucleus. Clearly, if the beta decay of the nucleus involves the ejection of two particles (a neutrino and an electron or a positron), the recoil energy must be greater than that when only the electron or the positron is ejected.

Subsequently, Alikhanov suggested an ingenious experiment in which only neutrinos, if any, would be ejected from the decaying nuclei (the electrons emitted by the nuclei being "trapped" in the electron shells of the atoms). Hence, the existence of recoil would mean the existence of the neutrino.

The experiment was postponed by the outbreak of the Second World War. Alikhanov's idea was successfully implemented by the American physicist John Allen in 1942.

Advances in experimental nuclear physics in the USSR and elsewhere stimulated the work of Soviet theoretical physicists. Almost all the leading Soviet theoreticians worked on the atomic nucleus. Igor Tamm, Yakov Frenkel, and Lev Landau became widely known for their research in the field, and their reports at our nuclear seminar were avidly discussed.

In September 1936, the Second All-Union Conference on Nuclear Physics was held in Moscow. More than one hundred Soviet scientists took part, along with leading scientists from abroad, such as the American physicist Wolfgang Pauli, the French physicist Pierre Auger, and the British physicist Rudolf Peierls.

A report on the Cherenkov effect, which had been submitted by Ilya Frank, generated particular interest at the conference. The effect was discovered by Pavel Cherenkov when he was working under supervision of Sergei Vavilov. When an electron moves in a liquid at a speed greater than the speed of light in the liquid (but slower than the speed of light in a vacuum), the electron begins to emit light. The Cherenkov effect is now widely used in counters of charged particles. Cherenkov, Tamm, and Frank were awarded the Nobel Prize for the discovery of the effect and its theoretical explanation.

In closing the conference, Ioffe pointed out the importance of creating powerful experimental apparatus, above all accelerators of charged particles.

Soviet nuclear physics gradually began to acquire powerful experimental devices. In 1937, the first Soviet cyclotron was commissioned by Kurchatov's team and workers of the Radium Institute. The cyclotron could accelerate alpha particles to energies of about 1.2 MeV. A year later, a large electrostatic generator was put in operation in Kharkov. This widened the range of experimental studies, and Soviet physicists were ready to enter the "era of nuclear fission", which began in 1939.

An important discovery in 1939 dramatically influenced both nuclear physics and nuclear engineering. It was found that the neutrons bombarding a uranium target caused unusual nuclear transformations. Ordinarily, neutron bombardment of nuclei changes their charges by one or two. But when a neutron hits a uranium nucleus ($Z = 92$), nuclei emerge with charges much smaller than that of the uranium nucleus. This meant that the uranium nucleus splits into two nearly equal parts, called fragments. The total charge of fragments' nuclei is equal to the charge of the uranium nucleus. This nuclear transformation was termed the fission of uranium.

The fission of uranium was discovered in

Germany and immediately confirmed by experiments in the USSR, Britain, and the USA. Soon afterwards, two salient features of uranium fission were brought to light. First, the fragments of the uranium nuclei have an enormous kinetic energy of about 200 MeV, while the energy of neutrons which had induced the fission is only several electronvolts. A tremendous gain in energy! The simultaneous fission of all nuclei in a piece of uranium weighing several hundred grams would lead to a mighty explosion. In practice, however, neutrons for the most part pass through a small piece of uranium without causing fission.

The second feature was no less important. The fission of the uranium nucleus not only results in the formation of heavy fragments but also in the ejection of new free neutrons which, in turn, may also induce fission. Only two or three neutrons are generated per split nucleus, but if they encountered new uranium nuclei and fissioned them, then fission would avalanche: one neutron fissions a nucleus to eject two neutrons, which split two more nuclei, releasing four neutrons, which fission four nuclei, thus creating eight neutrons, and so on.

Having established that new neutrons are ejected by the fission of uranium nuclei, physicists calculated that even a small number of primary neutrons hitting a large piece of uranium would lead to an explosion. In the Soviet Union, Yakov Zeldovich and Yuly Khariton were the first to publish such calculations. They also showed that under certain conditions a gradual energy release during fission is feasible, and this energy can be used for peaceful purposes. Taking all this into account, an extensive programme for studying the fission of uranium nuclei was worked out in the USSR.

Soon afterwards (before the outbreak of the Second World War), Kurchatov's pupils Flerov and Petrzhak discovered a new phenomenon. Uranium nuclei can divide spontaneously, without needing neutron bombardment. This is very rare, but free neutrons are also ejected.

The war interfered with Kurchatov's plans. Many physicists were called up, many scientific institutions were moved far into the country, and Leningrad suffered a long blockade. Kurchatov and Anatoly Alexandrov tackled the important problem of protecting ships from magnetic mines. It was necessary to demagnetize ships so that they could not be "noticed" by German magnetic mines lying on the sea bottom or floating on the surface. They succeeded in solving the problem and saved the lives of many sailors and rescued many ships from the Black Sea Fleet and the Northern Fleet.

In 1941, scientific papers on uranium fission ceased to be published, although almost every issue of every physics journal had once carried papers on the topic. It was easy to understand that this research in the USA, Germany, and other countries was made secret because an extraordinarily powerful explosive was now feasible. In view of this, the Soviet government decided in 1942 to resume work on uranium fission.

The overall supervision of the problem (it was called the "uranium problem") was carried out by Kurchatov.

Kurchatov drew Abram Alikhanov, his pupil Grigory Flerov, and me into his research. Our group was called laboratory number two of the USSR Academy of Sciences, and we called it simply "two". We were given a small temporary building in the centre of Moscow. Later we moved to unfinished buildings, which had not originally been intended for us. In the long run, it became our "home", the Institute of Atomic Energy, and now it is known as the Kurchatov Institute of Atomic Energy.

At the time we had the following evidence concerning uranium fission. Natural uranium is a mixture of two isotopes with atomic masses of 238 and 235. The lighter ^{235}U makes up only a small fraction of natural uranium (one part in 140), and it is this uranium that is split by slow neutrons. ^{238}U nuclei, for their part, absorb slow neutrons and first transform into the 93rd element (neptunium-238) and then into the 94th element, which was subsequently called plutonium. Plutonium-239, like uranium-235, is easily fissioned by neutrons.

This suggested two ways for creating nuclear weaponry. One was to separate uranium-235 from uranium-238 or, at least, to raise its concentration, that is, enrich uranium in the lighter uranium-235. The second approach was to produce plutonium. Each approach presented numerous difficulties.

The country was at war, and we had every reason to believe that Germany was busy developing a nuclear weapon. We understood that we had to work hard and we stayed in our laboratories day and night.

To produce plutonium required nuclear reactors which, in turn, involved numerous complicated physical studies and engineering developments.

The second approach, isotope enrichment, was not easier. The only available techniques could be used to obtain micrograms of pure isotopes not kilograms. We had to find more effective methods of isotope separation which could be used in industry. Once developed, these methods for obtaining an exotic product had to be implemented at new plants. Ordinarily, it takes a new industry many years to be born, but we were given only two or three years. Nevertheless, we succeeded, and the problem was solved.

On 6 August 1945, the Americans dropped an atom bomb on the Japanese town of Hiroshima, on 9 August, the second American atom bomb was dropped on Nagasaki. Hundreds of thousands of people lost their lives. By that time Japan had been practically defeated, and the atom bombardment of its towns had not been dictated by military considerations. The US officials pursued other objectives, they thought that the monopoly on such a destructive weapon would help them dictate to the whole world, above all to the Soviet Union.

The atom bomb was developed in the USA under a veil of strict secrecy by many outstanding European physicists who had escaped fascism. Much effort and time were put in solving the problem, and Americans were convinced that the Soviet Union, which had suffered a devastating war, would not be able to produce such a weapon. The American experts D. Hogerton and E. Raimond in a paper published in 1948 predicted that the USSR would only be able to develop an atom bomb by 1954. Other American specialists cited even more pessimistic dates. But by 1949 the Soviet Union had tested its own nuclear weapon, thus burying forever the vain hopes of American imperialists.

In the early 1950s, a work began in earnest at our Institute on the peaceful uses of atomic energy. As a result, the first nuclear power plant, with a rated power of 5000 kW, was commissioned in 1954 in a small town of Obninsk near Moscow. At present, many nuclear power plants operate in the USSR, among them the Leningrad nuclear power station, one of the most powerful in the world. It generates 4 000 000 kW of power.

Scientists of our Institute helped design the first nuclear-powered ice-breaker, the "Lenin", which significantly prolonged the navigation period in polar regions. The ice-breakers "Arktika" and "Sibir" were put into operation later.

In the early 1950s, scientists began wondering whether the energy in fusion reactions could be utilized. In the 1930s, the German physicist Walter Bothe formulated the theory that the Sun is powered by fusion reactions. At the extremely high temperatures inside the Sun, light nuclei possess high kinetic energies and so can overcome Coulomb repulsive forces to fuse into heavier nuclei. The process is accompanied by the release of energy far in excess of the energy possessed by the fusing nuclei.

A fusion reaction was first used on Earth to produce explosions, i.e. the hydrogen, or fusion, bomb was developed. After that, of prime importance became the utilization of fusion energy for peaceful purposes. The natural uranium used in nuclear reactors exists in limited quantities, while the reserves of deuterium (heavy hydrogen ^2H), which can be used in fusion reactions, are enormous. Deuterium is a constituent of heavy water, of which there is one part in 6000 parts of all the water on Earth. The fusion of two deuterium nuclei is accompanied by an energy release of about 13 MeV, a value greatly exceeding the energy obtained by the fusion of nuclei. So this energy resource is practically inexhaustible.

To use this energy peacefully requires, in the first place, a means to control fusion reactions. This complicated problem can be solved. In 1952, the Institute of Atomic Energy began research in this field.

First, it was necessary to heat hydrogen to temperatures at which nuclei could fuse. The simplest method is to heat a gas by an electric discharge. At high values of the electric current, the gas is heated by Joule heating. The gas is ionized and turns into plasma. At very high temperatures, a hydrogen plasma is a mixture of electrons and nuclei which can enter into a fusion reaction. However, a high-temperature plasma is extremely unstable. At the enormous currents of the discharge, like charged layers of the plasma repel each other, collide with the walls of the gas-discharge tube, and are rapidly cooled.

The confinement of plasma is one of the most urgent problems to be solved in controlled fusion. Soviet physicists have made great contributions to this subject. Under the supervision of Academicians Lev Artsimovich and Mikhail Leontovich, a plant was designed at the Institute of Atomic Energy in which a specially chosen and oriented magnetic field confines a high-temperature plasma. This plant is called the Tokamak from the Russian "toroidal chamber in a magnetic field". At present, most plasma-confinement experiments all over the world are conducted on plants of this type, all of which are now called tokamaks.

The state-of-the-art in the field of controlled fusion allows engineers and designers to tackle the purely engineering aspects of developing a prototype of a future thermonuclear plant. We have every reason to believe that by the turn of the century a prototype will have been constructed and tested, and this will solve the problem of industrial use of fusion energy.

Clearly, it is impossible to give an exhaustive account of how Soviet physics developed. I have only dwelt on research in which I was involved and so I have not described many of the outstanding achievements of Soviet physicists. These include the birth of quantum electronics in work undertaken by the Nobel winners Academicians Nikolai Basov and Alexander Prokhorov, the discovery of electron paramagnetic resonance by Academician Evgeny Zavoisky, and the discovery of autophasing in accelerators of charged particles by Academician Vladimir Vexler. Nevertheless, I hope that my article has helped the reader to get an idea of how much Soviet physicists have contributed to the development of science and technology.

Abram Ioffe

(an essay to mark the centenary of his birth)

My intention when writing this article was not to present a scientific biography of the outstanding Soviet physicist Abram Ioffe, whose 100th anniversary is on 30 October 1980. Ioffe's biography is well known and is to be found in many books and papers. I only wanted to share with the reader my reminiscences of the founder of the Soviet school of physics, a person I was lucky to have as my teacher.

In 1922, when I was a school pupil in my final year, I came across a newspaper article entitled "The Physico-Mechanical Faculty". It had been written by Academician Abram Ioffe. I was 14 at that time, lived in Pskov, and had a vague idea about what the title academician meant. The surname was unfamiliar to me.

I read the article carefully. It was about a new faculty at the Petrograd Polytechnical Institute. Students there were trained both in physics and mathematics and in engineering. I was interested both in physics and engineering and decided to enter the Physico-Mechanical Faculty.

It was clear from the article that the person who wrote it had founded and headed the Faculty. Certainly, I wanted to know more about Ioffe and I began looking for books he had written. I was lucky and found a newly published book entitled *Lectures on Molecular Physics* in a bookshop. I studied the book. It was extremely interesting though not exactly easy to understand. Usually courses on physics began with the various methods for measuring physical quantities, but this book started with the structure of matter. It described in an entertaining manner Rutherford's experiments, which had revealed the planetary structure of atoms and the motion of electrons about an atom's nucleus. This was a novelty to school pupils and it was followed by a brief and unconventional account of the laws of mechanics. Only then did the author present the molecular theory of matter.

This was the way I met (without seeing) Academician Abram Ioffe. (It was not difficult to consult an encyclopaedia and learn that academician was the highest scientific title in Russia.)

I entered the Physico-Mechanical Faculty in 1925 when I was 17, no one under 17 being admitted to an institute.

At the Faculty Abram Ioffe had become somewhat legendary. It was believed, for instance, that the Academician himself checked all the entrance papers for someone entering the Faculty, decided whether to admit or not a particular person, delivered the lectures, invited other leading Soviet scientists to lecture at the Faculty, and, in addition, administered the Physico-Technical X-ray Institute (which was situated opposite our Polytechnical Institute).

Unfortunately, when we began the general physics course, Ioffe was abroad and during my first few months at the Institute, which seemed infinitely long to me, I did not see Ioffe, although I heard a great deal about him.

Undergraduates told us about his scientific work, such as the increase in material strength by removing tiny cracks from their surfaces and the creation of insulators which could withstand high electric voltages.

The important discovery of an elementary charge, the electron, had been attributed both to Robert Millikan and to Ioffe. We were very proud of this and were pleased to find references to Ioffe's papers in Millikan's book *The Electron*.

We also knew that many students at the Physico-Mechanical Faculty helped at the laboratories of the Physico-Technical X-ray Institute and we dreamt of becoming staff researchers of this famous Institute.

We were told that Academician Ioffe had given instructions to all our teachers, who nearly all worked at the Physico-Technical Institute, to look for talented students and recommend them for research work at the Institute.

Time went by and I still had not met Ioffe.

I saw him for the first time when the bicentenary of the Academy of Sciences was being celebrated in the late autumn of 1925. Ioffe was accompanying guests who had come to the celebration at the gates of the Physico-Technical Institute. He was a tall slender man with greying moustache and a large bald-spot. One of the guests, a man in a turban, probably an Indian, was attracting a great deal of attention; later I learnt that he was the well-known Indian physicist Raman.

In 1926, when I was in my second year at the Institute, I was recommended to work at the Physico-Technical X-ray Institute, at the laboratory of magnetic phenomena. The laboratory was headed by Yakov Dorfman. From this time on I saw Ioffe each Friday at the regular review meetings (as they were called) which he presided over. The Institute's staff delivered reports on their research and on the most interesting papers carried by the world's scientific journals. These review meetings were instrumental in training young scientific researchers, and the Institute's scientific staff for that matter. Nikolai Semenov said once that a major factor in his training in physics had been these review meetings at the Physico-Technical Institute rather than anything at the university. Indeed, however difficult and complicated the topics were, they could be brought up at the meetings, which always proceeded in an animated atmosphere. Ioffe usually closed a meeting with an explanation of the topic discussed, thus making it simple and easy-to-grasp. But at first we understood little of what was discussed at the meetings.

A broad range of topics were discussed because the Institute's interests embraced almost all branches of what was then modern physics. These included atomic collisions, acoustics, the physics of magnetic phenomena, optics, heat engineering, radio physics and radio engineering, and the physics of X-rays. The physics of dielectrics was Ioffe's main interest. We were always fascinated by Ioffe's deep understanding of those various topics in physics and his ability to present complicated things simply and clearly.

I recall one of Ioffe's first lectures to students about crystal strength, an urgent problem in crystal physics at the time. A rigorous physical theory had yielded values of crystal strength which were considerably higher than experimental values. Ioffe ascribed this discrepancy to the presence of microscopic cracks on the surface of a crystal. When a crystal is deformed, say, stretched, these cracks are subjected to enormous mechanical stresses that exceed by far external stresses applied to the crystal as a whole. This causes the crystal to fail where there are cracks even if the external stress is much lower than the theoretical value of ultimate stress.

Ioffe proposed that a crystal should be immersed in a liquid which dissolved it so that the surface layer with the defects was removed. As a result, the strength of the processed crystal with the smooth surface would approach the theoretical value.

The simplest way to check this was to use soluble crystals of common salt. If placed in water, crystals of rock salt should exhibit a much higher strength. Ioffe's experiments brilliantly corroborated this, and the phenomenon of crystals being stronger in solvents later became known as Ioffe's effect.

In his lecture Ioffe demonstrated that a body with tiny cracks on its surface was less strong. He took the ends of a strip of paper and tried to stretch it—the paper did not tear. But if he notched the strip, the paper would tear when stretched even if not much force was used.

In another experiment he had kept glass rods in a large vessel of water for several days. Similar glass rods lay on the table. Ioffe took one of the latter and bent it. As expected, the rod easily broke. Then he took a rod from the vessel and tried to bend it. He succeeded and even bent it into a ring. This phenomenon occurs because water dissolves, if only poorly, glass, and as a result of their extended stay in water, the cracks had been removed from the surface of the rods and the latter bent easily. Using these simple experiments in a very short lecture, Ioffe made the complicated problem of the theory of crystal strength understandable to students.

When I was in my second year at the Institute, I attended some of Ioffe's lectures to freshmen on general physics. Once again I saw that Ioffe could present complicated topics in physics in a simple, easy-to-understand, and, at the same time, rigorous way. Ioffe was not an orator, but his presentation of physical phenomena had an extraordinary clarity, and he accompanied it with elegant experiments. Later I learnt that courses on general physics were taught by leading scientists at most of the teaching centres in the world. It is clear why. These are the courses that give students a comprehensive picture of physics as a whole and this can only be done by outstanding scientists. Ioffe was one such scientist. He not only pursued his own scientific interests, he also looked after young researchers and, naturally, after the students of his Faculty.

I recall our first tour as freshmen about the Physico-Technical Institute. Ioffe was our guide. He showed us laboratories and we had the opportunity to see by ourselves how hard the staff researchers worked. Most of us saw for the first time a scientific laboratory and modern scientific equipment, such as vacuum pumps which could lower pressure to 10^{-6} mmHg (these were diffusion pumps constructed at the Institute's own workshop, which was also included in our tour), electrometers for measuring currents of the order of 10^{-6} A in dielectrics, ultraviolet mercury lamps, and X-ray apparatus. With bated breath we listened to

Ioffe as he explained the operation of those wonderful things.

True, we were somewhat disappointed by the "untidy" appearance of the devices. They didn't look elegant enough, we thought, but we didn't dare make any critical comments.

At the end of the tour, Ioffe took us to a laboratory where carefully assembled units stood on tables. Everything was in order. But there was nobody there. We were surprised and Ioffe hastened to explain in an apologetic tone, "Don't be taken aback by the cleanliness and order in these laboratories. Nobody is working here at the moment, all the staff are on leave." Those words made it clear to us that when working hard, researchers paid greater attention to the problem than to a tidy and elegant design of the apparatus. Note in passing that physicists of all ranks, including Academician Ioffe himself and students who had just begun to help at laboratories, took part in assembling apparatus. Every experimentalist at that time had to be a jack-of-all-trades—a mechanic, a glassblower, an electrician, and a carpenter. It goes without saying that after the tour we all thought that it would be a piece of good fortune if we were given a job at the Institute.

...I will remember for the rest of my life the year 1928, which is when the Sixth All-Union Congress of Physicists, organized by Ioffe, was held.

Usually, such congresses used to be only attended by mature scientists, who paid quite a sizeable, from our point of view, attendance fee. Naturally, students could not afford the fee and so could not attend. That congress was quite different!

First, the government gave the Congress a considerable grant. Second, some leading physicists from all over the world had been invited, and twenty participants came from Germany, France, Britain, the USA, Holland, Poland, and Czechoslovakia, among them such famous physicists as Peter Debye, Louis Brillouin, Paul Dirac, Gilbert Lewis, Robert Pohl, and Max Born. So it was an international congress to some extent. Third, the Congress was held in an unusual way: it opened in Moscow, but nearly all its proceedings took place aboard a chartered passenger-ship which sailed downstream the Volga from the town of Nizhni Novgorod (now Gorki). Certainly, as students we spoke about this wonderful Congress, but we did not dream of participating in it. Then what?

We were rocked to learn that Ioffe had requested the organizing committee to invite as participants the best students of the Physico-Mechanical Faculty of the Leningrad Polytechnical Institute and the Physico-Mathematical Faculties of Leningrad and Moscow Universities. I was one of those students.

The Congress was opened by Academician Ioffe in the assembly hall of Moscow University. About 160 reports had been submitted to the Congress, most of them concerning experimental research. The first general session was devoted to wave mechanics. Ioffe opened the session and surveyed the experiments that had proved and that would have proved the wave nature of matter.

I particularly recall a session devoted to an experiment performed by the American physicist Dayton Miller. He repeated well-known Michelson's experiment and obtained allegedly contrary results, thus contradicting special relativity. It should be noted that at the time there was no consensus among physicists concerning the validity of Einstein's theory of special relativity. I and all those who are over sixty now remember the hot debates on this topic. Both foreign and Soviet physicists opposed the theory. Naturally, they seized the opportunity to use Miller's results as "evidence" of the inconsistency of the theory. I clearly remember Ioffe's report in which he analyzed Miller's experimental setup in depth, severely criticized it, and proved the inconsistency of Miller's conclusions. In later years Ioffe was to defend Einstein's theory of relativity on many occasions.

Now back to the Congress of physicists. On the second or third day all the participants, about 150 people, went by special train to Nizhni Novgorod, where several sessions were held at the local University. Then the participants set off on their trip down the Volga aboard a ship. The Congress was not interrupted for a single day. In

Kazan and Saratov, sessions were held at the Universities. During the whole period we felt that our dear Ioffe was the heart and soul of the Congress. We saw that he was an authority recognized by both Soviet and foreign physicists.

During the trip, we stopped both for business and for pleasure at picturesque sites along the Volga. There we saw Ioffe in unusual situations. For example, he organized games, such as races, and himself took part in them. By the way, Ioffe was a good runner and often beat younger contestants.

After the official part of the Congress, the participants went to the Caucasus. On the first day of our trip, Ioffe, Pohl, Debye, and other famous scientists visited our "student" carriage. Ioffe suggested a game in which the participants sat in a circle and had to call out in turn the names of famous scientists. The first player called a name, the second repeated the first name and added another, and so on. If a player failed to remember one of the names, he or she was out. Thus, the number of participants kept diminishing until the player with the best memory was left. Some of the famous names were those of the players. It was funny because they were the first out since they forgot to call out their own names.

The year 1928 marked another significant event, the tenth anniversary of the Leningrad Physico-Technical Institute. It was celebrated at a grand meeting attended by almost every Soviet physicist. We were pleased to note that practically all the congratulations and speeches were addressed to Ioffe as a founder and director of the Physico-Technical Institute. A physicist from Kharkov, for one, warmly thanked Ioffe for creating a new physico-technical institute in Kharkov (then the capital of the Ukraine). A team of staff researchers from the Leningrad Physico-Technical Institute led by Ivan Obreimov and Alexander Leipunsky had been the nucleus for this institute. Thus Ioffe's idea of creating scientific centres in the large industrial regions of the USSR had begun to be implemented.

Ioffe had insisted on decentralizing science in the USSR. "It is wrong," he said, "to concentrate science in Moscow and Leningrad. Soviet physics should influence the development of the industries all over the country." After setting up the Ukrainian Physico-Technical Institute, physical institutes were founded in Dnepropetrovsk, Tomsk, and Sverdlovsk. Groups of experienced physicists from the Leningrad Physico-Technical Institute, Ioffe's pupils, were sent to staff these institutes.

An address, presented to Ioffe by staff at the Leningrad Physico-Technical Institute, said that it had been signed not only by Ioffe's "direct" students but by the students of his first students, who themselves had become good physicists by that time. Getting ahead of my story, I should say that Ioffe lived to see 15 of his pupils elected members of the USSR Academy of Sciences and about 30 became corresponding members of the Academy. There is hardly any other scientist in the world of whom the same can be said.

Ioffe was not only an outstanding scientist but also a splendid educator of young people. This is accounted for, in the first place, by Ioffe's ability to choose talented young people who quickly became well-known scientists. Besides, Ioffe had created in the Institute a creative atmosphere such that each researcher felt that he was participating in important and responsible work. Staff researchers worked with enthusiasm, sparing no effort, and it was not unusual to meet them at the Institute at any time, day or night.

We were so involved in our experiments that Ioffe often reprimanded us for paying too little attention to the scientific literature. He even asked his friend Yakov Frenkel, Chief of the Department of Theoretical Physics of the Institute, to set up a special seminar for experimentalists on the problems of current theoretical physics.

Let us return back to the celebration of the tenth anniversary of the Institute. Ioffe liked and appreciated a witty joke. After the ceremonial meeting we put on a friendly humorous revue. It was called "Ten Years That Thrilled Physics". We had written it for the anniversary, and nobody except the actors knew about the play. The play was in ten acts, each reflecting a year in the Institute's existence. We were very anxious as to how the audience, and in particular Ioffe, who sat in the first row, would react to it. The play was a great success, and everybody, including Ioffe, laughed all the time and cheered wildly.

The play was funny and witty. For instance, the two institutions which subsidized our Institute were presented as two czars on thrones marked "Czar Narkompros" and "Czar Sovnarkom". For greater effect, they wore Ioffe's doctoral gowns. Those who played the parts of the Institute's administration tried hard to please the czars and did conjuring tricks, like transforming water into blood and iron into a snake. For zeal they were rewarded by bags full of money. At the end of the play the actors found themselves aboard a rocket that was to be launched to outer space. They were to take part in a session of the Scientific Council there.

Inspired by the success of our play, we made it a tradition to put on a revue twice a year, on the May and October holidays. These performances, in which Ioffe often took part, were very popular.

I recall one occasion devoted to a rather significant event in the Soviet scientific community. In 1933, a decree was issued defining scientific ranks and titles. We did not consider it to be in the spirit of socialism, as it would pay according to scientific rank or title rather than for the work carried out.

The actors parodied a session of the Institute's Scientific Council presided by Ioffe which part was played by ... Ioffe himself. The audience applauded enthusiastically when Ioffe came on stage. Two dissertations were defended at the session. A number of entertaining experiments were demonstrated during the defence of the first, experimental, dissertation. Suffice it to say that alpha cheese was the subject of the investigation and ordinary forks were used as electrodes. The "sample" with "electrodes" stuck in it was placed between the poles of a real electromagnet, and tiny baby shoes were put on the poles (the pole pieces of electromagnets are sometimes called pole shoes). The results of the investigations were presented by an intricate curve passing through only two experimental points. The author of the dissertation explained that he had constructed the curve using the well-known physics theorem that only one curve can be passed through two given experimental points. He concluded by stating that alpha cheese possessed the property of hole conductivity. Indeed, a piece of porous cheese was displayed on the screen to "justify" this statement. It goes without saying that the performance was accompanied by laughter and cheers from the audience.

The second, theoretical, dissertation parodied a theorist who worked at our Institute and who was always boasting of his achievements. The author of the dissertation took the floor and unrolled a poster which said, "A list of scientists who quote me." It was followed by the names of Archimedes, Lucretius, Galileo, Einstein, Bohr, etc. Then the author of the dissertation showed another poster which said, "A list of people who can confirm that it was me who first said 'A'." It was signed by the Institute's watchman, superintendent, fireman, charwoman, and other employees.

After the "defence" and a brief session of the Scientific Council's members, Ioffe solemnly announced that the Council was conferring scientific ranks upon the authors of both dissertations, and he invited them to go to the table. They kneeled, and Ioffe put doctoral gowns on both men. All this was loved by the audience.

From the 1930s on, Ioffe began to concentrate on the physics of semiconductors. I think that Ioffe foresaw the great future awaiting semiconductors, which had been poorly studied at the time. Experimental data on semiconductors was scarce because semiconductors with identical chemical compositions exhibited broadly varying electrical properties, such as electric conductivity, and so experimentalists had lost hope of obtaining unambiguous data and gave up semiconductors as hopeless.

Ioffe was so interested in the topic that he persuaded most of the Institute's staff to take up the study of semiconductors. Clearly, this was not an administrative measure. Ioffe could always stimulate his colleagues' interest in new branches of physics.

The first experimental results demonstrated that the great scatter in data on the electrical properties of chemically identical semiconductors was caused by the negligible (from the chemical point of view) amounts of foreign substances present in the semiconductors. Hence, Ioffe concentrated research on how impurities influenced the electrical properties of semiconductors. Note that the term impurity implies millionths of a percent of a foreign substance in the main substance. Impurities cannot be detected by conventional chemical analysis.

Ioffe and his colleagues developed very sensitive physical techniques for controlling the amount of impurity in certain semiconductors, which made it possible for them to study how the electric conductivity varied with the amount of impurity. I think that the research Ioffe and his school conducted stimulated the rapid progress in semiconductor physics in many countries.

Ioffe became interested in yet another problem in this field, viz. the rectification of alternating current. It was found that a metal-semiconductor junction could act as a rectifier, namely, the electric resistance of the junction depends on the direction of current flowing through it. Such a rectifier in the form of a semiconductor with a metal deposited on its surface would be indispensable in engineering. Soon after the Cu_2O and Se semiconductors, which were the "popular" ones in the 1930s, had been investigated at the Leningrad Physico-Technical Institute, rectifiers based on them began to be used in industry.

Ioffe tried to find out what was taking place at the metal-semiconductor junction. Together with Frenkel he published a theory for the effect. Although the basic physical ideas proved to be valid, its quantitative predictions did not fit available experimental data.

Ioffe continued and even broadened his research in the field of semiconductors. In particular, he became interested in photoelectric phenomena in semiconductors. First, there is a change in the electric conductivity of a semiconductor affected by light. Second, there is the emergence of an electromotive force when a metal-semiconductor or semiconductor-semiconductor junction is illuminated. The latter is essentially a direct transformation of light energy into electric energy. Clearly, it would be very useful if industry could use free solar energy. Ioffe often talked about the rainbowed promise of semiconductors generating electric energy from solar energy. It seemed science fiction to us. The efficiency of the semiconductor photocells was around 1-2% at the time, but Ioffe tried to convince us that the efficiency could be raised to 10-15%, which is twice as efficient as a locomotive.

Only now can we appreciate Ioffe's extraordinary perspicacity. In the 1960s, semiconductor photocells, called photodiodes, began to be widely used in practice, with efficiency as high as 15%. Solar photodiodes are used as the power sources aboard spacecraft. Moreover, projects involving electric power plants operating on solar photodiodes are being developed. Thus we have witnessed how Ioffe's seemingly fantastic idea has come true.

Ioffe often suggested scientific ideas that seemed unreal to physicists but which later became feasible. I remember that at a session of the Institute's Scientific Council in the early 1930s Ioffe outlined the future development of the Institute. He said that the Institute's scientific interests should include nuclear physics and he maintained that the future would offer the feasibility of using the energy liberated during nuclear transformations. At the time such forecasts were taken with a grain of salt because many scientists remembered that Rutherford, the father of nuclear physics, had said that the atomic nucleus would be a grave for energy, rather than a source of energy.

In the late 1938, uranium fission was discovered and it became clear that Ioffe, and not Rutherford, had been right. Fortunately, Ioffe lived to see nuclear energy used for peaceful purposes and not just as a weapon of destruction. The first nuclear power plant was commissioned in the USSR in 1954, a year before Ioffe's 75th birthday. Ioffe never boasted of those prophetic forecasts which had come true.

Ioffe's pupils were involved in both nuclear weapons projects and the research into the use of nuclear energy for peaceful purposes. This might seem strange, at first sight, that by the early 1930s, i.e. the first

12-15 years of the Institute's existence, nobody except Skobeltsyn was interested in nuclear physics. However, when nuclear physics began to develop rapidly in the early 1930s (with the discovery of the neutron and the positron, and so on), Ioffe realized that the Institute's researchers should be more active in this field. I remember how Ioffe persistently and tactfully persuaded some of our leading physicists to change the subject of their investigations.

He succeeded, and soon two of the Institute's laboratories (those led by Kurchatov and Alikhanov) turned to the new topic. Ioffe initiated a special seminar on the physics of the atomic nucleus. The seminar dealt with the papers on the subject carried by physics journals all over the world and considered the development of the subjects at the Institute. This seminar was instrumental in acquainting our "nuclearists" with the ideas, terminology, and experimental techniques of this new branch of physics. It took no time for the laboratories to start work on full scale.

By the mid-1930s, our nuclear physicists had achieved the level of West laboratories. This was confirmed at the All-Union Conference on Nuclear Physics in Leningrad, which was in fact an international forum since many foreign scientists, such as the Joliot-Curies, Dirac, and Perrin, participated in it. Reports by staff of the Leningrad Physico-Technical Institute clearly demonstrated the high level of their scientific results.

In 1933, the Institute celebrated its 15th anniversary. In addition to the official ceremony, we prepared an entertaining revue. *It was opened with a sketch* of a grand session of the Institute's Scientific Council. Ioffe made a report, which he began thus, "Comrades, I would like to describe 15 days of activity at our Institute." When somebody corrected him, saying he meant "15 years," Ioffe repeated that his report was on the 15 days the Institute spent preparing for the celebration since the effort expended was of the same scale as the work conducted by the Institute during the previous 15 years. Naturally, the report was interrupted by the audience laughing and cheering. Then a number of staff were awarded prizes, each one being accompanied by a witty comment. The scientific secretary of the Council then read out some funny greetings allegedly sent by famous physicists and fictional characters.

Our entertaining programme was concluded by a play entitled "Nuclear Affairs" performed by Evgeny Demmeni's puppet-theatre. The staff of the Institute, and primarily Ioffe, were the main characters of the play. The puppets had been designed by a puppet-maker who had been to a session of the Institute's Scientific Council and sketched the main characters. It goes without saying that nobody but the organizers knew about the play.

When the audience was waiting for the performance to start, the lights suddenly went out. We explained there had been malfunction, but in reality the light was doused to give time to establish a screen for our puppet-show. It was done very quickly and when a projector illuminated a caricature of Ioffe, the audience gave it a great ovation. The reaction had been anticipated by the producer, and a big bell had been put on a rostrum. The puppet rang the bell and tried to soothe the audience, which naturally again induced laughter.

The show was a success, and all those present remembered it for a long time (especially, I think, the wives of the main characters who were given the puppets after the show).

In 1936, I moved to Sverdlovsk and this ended my day-to-day contact with Ioffe for some time.

In October 1940, Soviet physicists celebrated Ioffe's 60th birthday. I represented the physicists of the Urals at the jubilee. In our greeting we wrote, "You are the second person (after Sir Isaac Newton) to use food for scientific research." We meant famous Newton's apple and Ioffe's common salt.

At the outbreak of the Second World War, Ioffe and the Leningrad Physico-Technical Institute changed their scientific interests and turned to defence problems. Fortunately, the Institute had already worked on many defence projects, such as magnetic mine protection (under the guidance of Academician Alexandrov) and radar (under the guidance of Yuri Kobzarev).

When the war broke out, most of the Institute's staff, led by Ioffe, was evacuated to Kazan. Some scientists worked on the fleets, installing systems of magnetic mine protection aboard warships, some (headed by Pavel Kobeko) remained in Leningrad to work with the navy organizations to deliver cargo to the besieged city up the Ladoga.

In 1942, I met Ioffe in Sverdlovsk at a session of the USSR Academy of Sciences. Ioffe was full of strength and was very proud that his pupils had contributed so considerably to the military might of the Soviet army. It should be noted that early in 1943 Ioffe was persuading some of the staff of the Leningrad Physico-Technical Institute and some of its former staff researchers to turn to the uranium problem.

During the war, Ioffe, as Vice-President of the USSR Academy of Sciences, redirected the efforts of many physicists solving the urgent defence projects. I was able to find out more about Ioffe's activity in the Academy after I had been elected a corresponding member of the USSR Academy of Sciences and began to attend general meetings of the Academy and sessions of the Department of Physics and Mathematics.

I recall one of the sessions of the Department soon after the war. It was called to nominate a candidate for the presidency of the USSR Academy of Sciences. Up until

1945, the Academy had been headed by Academician Vladimir Komarov, but his poor health and old age was not allowing him to discharge his duties effectively. The Soviet government invited all members of the Presidium of the USSR Academy of Sciences to take part in a meeting to nominate a presidential candidate. The meeting nominated Sergei Vavilov.

All the departments of the Academy were convoked. At the session of the Department of Physics and Mathematics, Ioffe, as its Academician-Secretary, informed the Department who the government's nominee was and invited opinions. One of the oldest members of the Department, Alexei Krylov, was among those to take the floor. He said that once he knew the agenda, he had examined the Constitution of the Academy to find out what is required of the President of the Academy. It appeared that the words "President of the Academy of Sciences" were cited only once, namely, "The President of the Academy is elected at a general meeting of members of the Academy." Hence it was difficult to discuss a nomination without stricter specifications. As an example of rigorous wording, Krylov quoted the Judicial Laws of Peter the Great saying that

1. Theft is the felonious taking and removing of personal property in an underhand way.

2. Robbery is the taking of personal property by force.

"You see," said Krylov, "Peter's Laws are clearly and exactly formulated. But it is quite unclear what the words 'President of the Academy of Sciences' mean." Those participating at the session could not help laughing. However, Ioffe was quick to answer, "I acknowledge that the Constitution of the Academy is far from perfect, but the compiler of the Constitution could not have believed that the President would be involved either in theft or in robbery." The audience applauded, and it was decided to nominate Academician Vavilov as a candidate for the presidency. Soon afterwards he was duly elected President of the USSR Academy of Sciences at a general meeting of the Academy.

It should be said that Ioffe's life was not all roses. I witnessed some serious misfortunes. One arose over the problem of thin-layer insulation. Ioffe spent a great deal of time and efforts to solve the problem and failed. He lived down the failure with fortitude and admitted his mistakes.

In 1936, a general meeting of the USSR Academy of Sciences was held in Moscow to discuss the scientific activity of Ioffe's Leningrad Physico-Technical Institute. Ioffe made a report, which was followed by a discussion during which several physicists criticized the Institute and Ioffe himself.

I think Ioffe was pained to have to listen to biased criticism from fellow physicists, especially from pupils of his. Those who could have fairly assessed the Institute's activity were not permitted to take the floor (I was one of such).

Time has shown how unjustified that criticism was. Ioffe was, for one thing, reprimanded for developing the allegedly unfeasible subject-area of nuclear physics. He was also criticized for his work on semiconductor physics. Now it is clear how wrong his critics and how ridiculous their arguments were. The present generation should pay tribute to Ioffe, who initiated research in such promising branches of physics as the physics of the atomic nucleus and semiconductor physics.

It was not easy in 1950 for Ioffe to resign the directorship of the Leningrad Physico-Technical Institute, which he had founded and administered for more than 30 years. The more so, as the matter had been arranged by the authorities quite tactlessly. Not long before we had celebrated Ioffe's 70th birthday. The ceremony took place in the assembly hall of the USSR Academy of Sciences in Leningrad and it was deliberately modest in manner. Of the hundreds of greetings from all over the country and all over the world, only three were read out, namely, from the President of the USSR Academy of Sciences, from the Institute's staff, and from the district committee of the Communist Party. Only one report, that by Ioffe, was given at the meeting; it was on semiconductors.

Ioffe invited his closest pupils to a party at his flat in the evening. At the party

Ioffe said that, despite everything and even despite his old age, he was not looking back but looking forward to the future. He showed the honorary diplomas he had received from scientific establishments in the USSR and elsewhere. He had been elected an Honorary Member of the British Physics Society (1944), Paris University (Sorbonne, 1946), Bucharest University (1947), Graz University (Austria, 1949), and some others.

I particularly liked the citation making him an Honorary Member of the Chinese Society of Physicists (1949). It was a broad band of white silk with the text in Chinese characters (certainly, there was also a Russian translation).

That Ioffe was looking forward to the future was not just a witticism. Indeed, soon after resigning Ioffe enthusiastically set about organizing the Institute of Semiconductors of the USSR Academy of Sciences. The Presidium of the USSR Academy of Sciences and President Vavilov helped him greatly in this. Thus, Ioffe's scientific work was not interrupted for a single day.

In 1955, on the eve of Ioffe's 75th birthday, a group of his pupils, members of the Academy, sent a letter to the Soviet government asking that Ioffe be made a Hero of Socialist Labour. To justify our request, we listed Ioffe's most important scientific achievements and especially his role in training researchers, who had quickly and propitiously solved the uranium problem. We pointed out that fifteen of Ioffe's pupils had been elected members and around thirty corresponding members of the USSR Academy of Sciences.

I was appointed chairman of the organizing committee the Academy had set up to celebrate the jubilee. Naturally, I worried about the government's reaction to our letter. Only at the last moment, when we were on our way to Leningrad to celebrate the jubilee, was it broadcast that Ioffe had been made a Hero of Socialist Labour by a Decree of the Supreme Soviet of the USSR. I was overjoyed to hear the news.

The ceremony in the assembly hall of the USSR Academy of Sciences was held in an atmosphere of general enthusiasm. So many of us had come to congratulate Ioffe on the occasion that we could not give the floor to everyone, much as we wanted to.

In later years I only met Ioffe occasionally, though several times he was my guest in Moscow. Ioffe told us not only about his scientific ideas but also about some interesting events in his life. For example, he recalled the following funny event. Once, when he was staying in Holland, Ioffe visited the famous physicist Paul Ehrenfest; Niels Bohr and Wolfgang Pauli had also been invited. Ioffe, Ehrenfest, and Bohr sat on a sofa, and Pauli walked around the room to and fro saying something. Suddenly Bohr said, "Don't walk around. It annoys me." Pauli asked, "What particularly annoys you?" Bohr, who was notable for his ability to formulate his thoughts exactly, took time to answer, but Ehrenfest was quick to say, "It is annoying when you come back."

I recall another story Ioffe told. Once, when he was a young man working in Munich, Ioffe decided to spend a weekend in the Alps. One evening he took a train, and his companions in the compartment were two ladies. They got into a conversation, and when the ladies learnt that Ioffe was a physicist, they asked him what weather would be like the next day. Ioffe tried to explain that he was not a meteorologist and could not forecast the weather. This made no difference, and the ladies insisted that he should answer, because, they said, a physicist should know everything. It was June and it was very hot, and Ioffe joked that it would snow the next day. The ladies laughed and went on to another topic. How surprised Ioffe was next morning when he woke up in the hotel and saw through the window that ... it was snowing heavily.

I saw Ioffe for the last time in the summer of 1960 when my eldest daughter and I were in Leningrad. We were invited to spend a weekend at Ioffe's country house in Komarovo, and Ioffe sent his car to fetch us. Ioffe and his wife Anna showed us about their country house. They were very proud of the garden strawberries and vegetables they had grown themselves. Remembering that Ioffe was Director of the Agrophysical

Institute he had founded, I asked whether Ioffe had grown the strawberries and vegetables in accordance with agrophysical science. He laughed and answered that he had mainly used the methods of our grandfathers. Then he took us to a tower that had been built to admire the sea. Ioffe said that he liked sitting there.

We returned to our hotel late at night, but it was quite light because at the time the White Nights (midnight sun) were at their height in Leningrad.

Clearly, I did not inform Ioffe that physicists all over the country were preparing to celebrate his 80th birthday. Nor did I tell him I had sent off a paper dedicated to his jubilee to the journal *Uspekhi Fizicheskikh Nauk* for publication. On the morning of the 14th of October I was telephoned by the editor's office of the newspaper *Izvestiya* and asked to write an article about Ioffe to be published on the 30th of October, Ioffe's birthday. Two hours later I received the news from Leningrad that Ioffe had suddenly died in his laboratory.

He Had Lived a Happy Life

(written to mark the 80th anniversary of Kurchatov's birth)

We know of scientists whose work was ahead of their time. These include Mikhail Lomonosov, who constructed a molecular kinetic theory almost a hundred years too early, and Konstantin Tsiolkovsky, who described space engineering half a century before it came about. The contributions of these scientists to the development of science and technology were recognized too late because at the time science and technology could not assimilate their ideas. Happy is the scientist who keeps abreast with the times. Igor Kurchatov was one such scientist. He always dealt with topical problems in physics. In the mid-1920s, the electrical properties of dielectrics were quite topical, and it was at that time that Kurchatov undertook work on the electric strength of dielectric crystals, which ultimately resulted in his famous studies on ferroelectricity. Kurchatov was particularly lucky. He investigated ferroelectricity when the quantum theory of ferromagnetism (ferroelectricity is its electric analogue) was being constructed. Kurchatov's work thus embraced two topical problems of contemporary solid-state physics simultaneously, namely, the physics of dielectrics and the physics of magnetism.

The 1930s saw a rapid development in nuclear physics stimulated by a cascade of fundamental discoveries, such as the discovery of the neutron, the positron, and artificial radioactivity. At that time, Kurchatov changed his scientific interests dramatically and turned to this promising field of research.

At that time, the Leningrad Physico-Technical Institute, where Kurchatov was working, had only one small laboratory dealing with the physics of the atomic nucleus. It was headed by Dmitry Skobeltsyn, who was mainly interested in cosmic rays.

Kurchatov and his colleagues had to begin from the very beginning. Kurchatov surveyed the literature in the library for days on end. But the time taken by the literature search was not overly long, and Kurchatov's laboratory started nuclear experiments. Neutron-induced artificial radioactivity soon became the main object of Kurchatov's research. We used to see Kurchatov running along the corridor with an irradiated sample in his hands to study yet another short-lived nucleus.

The first cyclotron, with vertical 1-m long poles of the magnet, was being constructed at that time at the Radium Institute. The designers of the cyclotron were unable to adjust it, and only after Kurchatov lent a hand was it put into operation.

Kurchatov drew his brother Boris into the chemical identification of artificial nuclei, and soon methods were developed for the radiochemical analysis of very small quantities of a substance. The research in Kurchatov's laboratory was so intense that within a year and a half it was recognized at the world level.

Soon after starting research on nuclear physics, Kurchatov published a monograph entitled *Splitting the Atomic Nucleus* (1935).

Work on nuclear physics continued up to the outbreak of the Second World War. In 1937, I moved to Sverdlovsk and thus could not meet Kurchatov or follow his work. In late 1942, Kurchatov suddenly came to Sverdlovsk and visited me in my laboratory. He was interested in my scientific work, and I did not suspect that he had come to Sverdlovsk to explore the possibility of my participation in the new research. In early 1943, I was summoned to Moscow and there met Kurchatov, Alikhanov, and Kaftanov. I was told that the government was interested in the practical use of uranium fission. It goes without saying that after uranium fission had been discovered, its application became a burning topic among physicists. At the nuclear conference in Moscow in 1940 uranium fission was hotly discussed, and Kurchatov actively participated in the discussion. On his initiative, a report was sent to the government which underlined the importance of the problem and the necessity of organizing large-scale investigations in the field.

In early 1943, the Soviet government sanctioned research on the practical use of uranium fission, and so my work with Kurchatov began. Certainly, there were other important problems in physics awaiting their solution at the time. The protection of ships against magnetic mines was one such problem, and finding a way to provide it saved many thousands of sailors (this work was undertaken by Kurchatov and Alexandrov). However, the uranium problem was the most pressing. This was how the difficult task of creating nuclear weaponry was tackled. Initially, only a few scientists were involved in the research. Later Kurchatov recruited some outstanding theoreticians, such as Yakov Zeldovich and Ilya Pomeranchuk. "Spheres of influence" were divided. I was in charge of everything only indirectly associated with nuclear physics. As Kurchatov put it, "You are a specialist on bubbles" (he joked that everything unrelated to nuclear physics was bubble physics). Kurchatov and Alikhanov were responsible for nuclear physics.

The organizing period thus began, and we were to recruit workers and search for buildings and equipment. We made a temporary move to accommodations in Pyzhevsky Pereulok and in the Institute of Inorganic Chemistry in Kaluzhskaya Street. And again we saw Kurchatov running along the corridor with irradiated targets in his hands, like we had at the Leningrad Physico-Technical Institute. Kurchatov combined his scientific research with an enormous administrative burden. We used to stay late at our offices in Pyzhevsky Pereulok.

We were once told to estimate dates by which practical solutions would be available. Each of us was responsible for some part of the programme and we reported on it to the government. Each report indicated a deadline for obtaining practical results. As is known, we met our commitments.

Theoreticians and experimentalists exchanged their knowledge concerning the future nuclear engineering. All of us, and particularly Kurchatov, realized that we bore an enormous responsibility for obtaining results. We had every reason to believe that fascist Germany was working on the problem and we worried that Germany would be the first to solve it. In 1941, every mention of uranium fission ceased in scientific journals, and it was clear that every country, including Germany, had started work on the practical use of the phenomenon. Moreover, some estimates had been published of the effect a chain nuclear reaction would have if it could be induced.

We had no space to perform large-scale experiments, but theoretical and feasibility studies were carried out. After our report to the government we were given new facilities and our old buildings were repaired.

By the end of 1944, we had spacious and well-equipped laboratories.

Kurchatov was supervising the measurement of main nuclear constants of uranium. Those included the number of neutrons released in a single act of uranium nucleus fission and the neutron energy spectra.

Kurchatov "puzzled" (one of his favourite words) theoreticians demanding a theory of chain nuclear reactions, and the theoreticians, as we know, succeeded in developing one. Kurchatov supervised the construction of the first nuclear reactor and took a great interest in the host of problems pertaining to its design calculations and scientific and engineering developments. He realized, for one thing, that an enormous work had to be done to obtain plutonium. (Plutonium is a transuranic element with atomic number 94. Its isotope $^{239}_{94}Pu$ is used in nuclear reactors and nuclear weapons.) I remember how proud Kurchatov was when he demonstrated in the Kremlin a glass ampoule with the first micrograms of plutonium which had been obtained from our first experimental reactor.

Later Kuchatov, like other supervisors of the project, moved to the site where the first full-scale nuclear reactor was being constructed, and paid only flying visits to Moscow.

Finally, the day came when everything was ready to test the nuclear weapon. Kurchatov enjoyed the confidence of the Soviet government so greatly that he alone supervised the first nuclear explosion (usually it was done by a member of the government).

Kurchatov realized that the peaceful use of nuclear energy was the most pressing problem of the post-war period. So it is small wonder that Kurchatov supervised the construction of the first nuclear power plant. Kurchatov also realized that further development of nuclear physics would call for up-to-date equipment for research on elementary-particle physics. And although Kurchatov's scientific interests never included elementary-particle physics, he initiated and inspired the Joint Institute for Nuclear Research in Dubna, near Moscow.

There is no need to remind the reader how timely work on controlled fusion in the USSR was started. It was not known at that time that similar research was being conducted in other countries as well. By the beginning of 1952, Kurchatov was closely following the research, and later taking part in it himself. He quickly realized that the first forecasts were too optimistic and persistent, systematic work would be necessary in this field. He also understood that the veil of secrecy over the research efforts should be lifted. In 1956, Kurchatov delivered a lecture in the UK on the fundamental investigations being carried out in the USSR on controlled fusion.

I remember how meticulously Kurchatov prepared his report, he discussed it with his friends, and revised it again and again.

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This sensational report delivered in the UK astounded the world. It became known that similar work was being carried out in the USA and UK, and the era of international cooperation in the field began eventually involving scientists from many countries.

My Encounters with Debye

(written to mark Debye's centennial anniversary)

Peter Joseph William Debye (1884-1966) was an outstanding physical chemist and is widely known for his formulation of the theory of specific heat capacities for solids.

Constructing such a theory at the turn of the century presented certain difficulties, which were mainly associated with a curious phenomenon pertaining to *heat capacity*. Numerous measurements indicated that the product of the specific heat capacity of a solid and its molar mass is constant, practically independent of temperature, and equal to 25.2 J $mol^{-1}K^{-1}$. This is essentially Dulong and Petit's law.

It was then experimentally established that at low temperatures the heat capacities of solids decrease with diminishing temperature. The heat capacity vs. temperature curve tends to zero as the temperature falls off to absolute zero. Nobody could explain this phenomenon.

Many scientists tried to obtain mathematical formulas to describe the observed temperature dependence of heat capacity but failed to derive even approximate empirical ones. The first realistic theory of specific heat capacities for solids was constructed by Albert Einstein. He used Planck's idea that the energy of atoms changes in a discrete manner and in multiples of $h\nu$, where ν is the frequency of the atoms' vibrations. Einstein's rough theory erroneously assumed that all atoms vibrate with the same frequency.

Debye also used Planck's idea and in 1912 formulated his theory of specific heat capacities, in which he assumed that atoms could vibrate at different frequencies. This theory explained Dulong and Petit's law at comparatively high temperatures and the heat capacity vs. temperature dependence at low temperatures. In accordance with experimental evidence, the theory predicted that at low temperatures the specific heat capacity would be proportional to the cube of the thermodynamic temperature. This dependence is known as the Debye T^3 law.

Later it became clear which temperatures should be regarded as high and which as low. It turned out that each solid has a temperature, called the Debye temperature, which marks the transition from temperatures where the classical theory of specific heat capacities is applicable to temperatures where quantum theory should be introduced.

Debye's theory also implies that at low temperatures the *thermal conductivities* of solid dielectrics increase with decreasing temperature, which really does take place. For example, diamond has a Debye temperature of about 2000°C, so for it room temperatures are low, and, consequently, its thermal conductivity is very high and comparable with the thermal conductivity of the best conductors (say, copper).

Debye is known not only for this work on the theories of the specific heat capacities and the thermal conductivities of solids. His interests embraced various branches of science, such as magnetism and electrolytic dissociation. In 1936, Debye was awarded the Nobel Prize in chemistry.

I was lucky enough to meet Debye in 1928 at the All-Union Congress of Physicists, in which many outstanding scientists from abroad took part. I was a student at the time, and Debye was almost a legend to us as we often encountered references to his work in physics courses. To meet Debye was quite an event for me and for other young physicists.

Debye was 44 at the time. When he was invited to take the floor and deliver his report, we saw a sturdily built man who should have had a thunderous voice. Imagine how surprised we were when he began to speak in a very high, almost treble, voice.

We knew Debye as a theoretician and had heard little about his experimental research.

Debye was a witty and jolly man. When at the Congress theoreticians asked Debye questions, he answered that he was an experimentalist and had nothing to do with theory. And when experimentalists ventured questions, Debye laughed and explained that he was a theoretician. In reality, he was both.

It was funny to hear that Debye had once in jest wrestled with another strongly built man, the German physicist Robert Pohl, and won.

After the Congress, many of the scientists from abroad went home via the city of Batumi. Debye, for his part, went with us in a hard-seated carriage to Leningrad, maintaining that it was much more interesting to travel with students than with mature scientists. Debye told us numerous entertaining stories about physicists and himself. He even tried to teach us German (Debye was born in the Netherlands but worked in Germany) and we taught him Russian. He proved to be a better teacher than us because we understood him and he understood practically nothing in Russian.

I met Debye for the second time in 1930 when I graduated from institute and was sent on business to Germany. Debye headed the Chair of Physics at Leipzig University. He remembered and warmly welcomed me, showed his laboratory, and invited to his lectures and seminars. I saw for myself that indeed Debye was a brilliant and inventive experimentalist.

Physics and the Scientific and Technical Progress

Physics serves as a basis for almost all branches of modern engineering, the majority of the technical sciences having branched out from physics with only a few existing before physics had been born.* These include construction engineering (recall, for example, Egyptian pyramids), metallurgy (the bronze and iron ages), shipbuilding,** and printing (the first printing press with moveable type was invented in the 15th century). The situation changed dramatically with the appearance of such outstanding scientists as Galileo, Newton, and Lomonosov, and in the 19th century a real technological revolution took place, with physicists laying the foundations of modern electrical and heat engineering. It is justifiable to call the 19th century the age of electricity and steam.

The term electricity originates from the Greek *elektron*, which means amber. Ancient Greeks noticed that amber, if rubbed, say, by a piece of wool, would attract light insulators. At the end of the 16th century, this phenomenon was investigated by the

* We do not consider handicraft.
** See *Kon-Tiki* by Thor Heyerdahl.

English scientist William Gilbert (1544-1603), who, by the way, introduced the term electricity. These electrical phenomena, however, were poorly applied in practice at that time. The age of electricity began with investigations by the Italian physicist Alessandro Volta (1745-1827). It may seem funny, but Volta's investigations had been stimulated by a frog! The Italian physician Luigi Galvani (1737-1798) noted that if compass legs made of different metals are used to connect the ends of a freshly dissected leg of a frog, the muscles contract. Volta decided to uncover the reasons behind this phenomenon and discovered that if two dissimilar metals are connected and placed in a solution of an acid, alkali, or salt, a potential difference develops between the metals (electrodes). Volta constructed the first galvanic cell, called a voltaic pile. This was the first source of direct electric current and the prototype of modern electric batteries.

Physicists started experiments on the properties of electric current. At the beginning of the 19th century, the Danish physicist Hans Oersted (1777-1851) discovered that a magnetic needle turns at right angles to an electric current if it is placed parallel to a current-carrying conductor. In this way, a fundamental principle of electromagnetism was discovered. At approximately the same time, the French physicist André Ampère (1775-1836) showed that an electric current not only affects a magnetic needle but it also influences other current-carrying conductors placed near it. Thus the connection between electrical and magnetic phenomena had been established.

The forces induced by electric currents now drive the millions of electric motors humanity uses in various branches of engineering and in everyday life.

One of the first electric motors was constructed by Academician Boris Yakobi (1801-1874) in St. Petersburg.

The first electromagnetic telegraph, which subsequently became a main means of communication at distance, was designed by Pavel Shilling (1786-1837), Corresponding Member of the Russian Academy of Sciences.

In 1831, the English physicist Michael Faraday (1791-1867) discovered electromagnetic induction, the phenomenon which ultimately led to a revolution in main branches of physics and engineering. Electromagnetic induction is essentially the emergence of a closed electric field and of a respective electromotive force around a magnetic field that varies in time. The electromotive force (and the electric field) varies proportionally with the rate of the change in the magnetic field. Before Faraday's experiments, physicists had used the notions of electric and magnetic liquids. Faraday introduced the notion of a field both electrical and magnetic in nature. Electromagnetic induction was used to construct a generator of electric current. Any modern electric power plant is, in a sense, a large-scale implementation of Faraday's laboratory experiments.

The discovery of electromagnetic induction astounded the scientific world community and raised Faraday to world eminence. A story connected with the discovery says that the British Prime Minister read about it in newspapers. He became interested in the discovery and visited Faraday's laboratory. Faraday demonstrated his famous experiments using primitive devices he had designed. (Now these experiments are demonstrated at high schools.) The Prime Minister was not impressed and asked Faraday, "Can it be that these toys have made you famous?" It is maintained that Faraday's answer was, "Sir, I think that one day you will collect taxes from these toys!"

It is only a story, but in reality three decades afterwards the first commercial electric power plants were commissioned and their owners, without doubt, paid taxes. Electric motors are still the main source of electricity, without which modern society would be unthinkable. In the 1870s, James Maxwell (1831-1879), an outstanding British scientist, who can be called a Newton in electricity,* generalized the numerous results Ampère, Faraday, and other physicists obtained and derived mathematical equations (Maxwell equations)

* Maxwell called Ampère a Newton in electricity.

describing them. These equations explained all the phenomena in electromagnetism that had been observed earlier. Moreover, Maxwell suggested that the electromagnetic induction Faraday had discovered should coexist with another, reverse, phenomenon. Faraday had discovered that a change in a magnetic field leads to the emergence of an electric field, and Maxwell predicted that a change in an electric field would cause the emergence of a magnetic field around it, with the magnetic field's strength being proportional to the rate of the change of the electric field. This implies that a varying magnetic field would inevitably have an electric field emerging around it, and, vice versa, a varying electric field would always be accompanied by a varying magnetic field. The concept of an electromagnetic field had thus been formulated.

The Maxwell equations imply that at comparatively low magnetic fields (and even low rates of change) considerable electric fields emerge, which can readily be observed by the currents they induce in closed circuits. It is difficult to record the magnetic field a varying electric field induces since magnetic forces are weaker than electric forces. To get a tangible measurement, the electric fields must vary at an enormous rate. For example, to record a magnetic field by the most sensitive modern devices requires an electric field with a strength of 10^6 V/cm to vanish within approximately one billionth of a second. Such an experiment is impossible in laboratory conditions.

Maxwell's most important conclusion was that a time-dependent electromagnetic field should travel in space in the form of a wave much in the same way as an acoustic wave propagates from a vibrating string or other source of sound. The velocity of the electromagnetic wave propagation Maxwell calculated should be the velocity of light, viz. 300 000 000 m/s, that is, about million times higher than the velocity of sound in air. This led Maxwell to his brilliant idea that light is essentially propagating electromagnetic waves (the electromagnetic theory of light).

Initially most physicists considered the Maxwell equations to be purely mathematical, and his hypothesis that light was electromagnetic in nature unjustified. To verify it, Hermann Helmholtz (1821-1894), an outstanding German physicist, instructed his young colleague Heinrich Hertz (1857-1894) to check Maxwell's seemingly controversial findings experimentally.

In 1888, Hertz published the results of his experiments which brilliantly verified Maxwell's theory. He constructed an experimental setup (Hertzian oscillator) consisting of two capacitors whose plates were raised to a sufficiently high potential difference. The oscillator's voltage was periodically varied at a high frequency. Hertz detected electromagnetic waves emitted during the discharges, their wavelength being about hundred metres. This completely verified Maxwell's theory. For comparison, recall that the average wavelength of the visible region of the electromagnetic spectrum is approximately 10^{-6} m. Thus, that electromagnetic oscillations could be transmitted at distance had been proved. The Hertzian oscillator was essentially a prototype of the first radio transmitter. Paradoxically, Hertz said to newspaper men that his discovery only had scientific significance and would not be used in practice. However, Hertz proved to be a poor prophet. On 7 May 1895, Alexander Popov, Professor of physics, St. Petersburg University, demonstrated the first radio transmitter and receiver, thus proving the feasibility of wireless communication. Later he even communicated by radio with Kronshtadt Harbour and warships.

Popov's work was praised by the world scientific community, and in 1900 at the International Electric Engineering Congress in Paris he was awarded a Gold Medal and Honorary Diploma. Thus Maxwell's theory and Hertz and Popov's work formed the basis of radio engineering. Later the same principles were used by the Italian electrician and inventor Guglielmo Marconi (1874-1937). It is difficult to imagine modern society without radio communication. Clearly, modern radio stations and radio sets are a far cry from Popov's transmitter and receiver, but the physical principles of their operation are the same. At the turn of the century, the methods of radio communication were developed, for the main part, at physics laboratories, but soon an independent branch of engineering, viz. radio engineering, emerged and rapidly developed.

The year of 1895 saw another important discovery in physics. The German physicist Wilhelm Röntgen (1845-1923) discovered a new invisible radiation that affected a photographic plate. Röntgen called this mysterious radiation X-rays.

Röntgen's discovery created a sensation, particularly when X-ray photographs of bones of living persons were taken.

In 1913, it was shown that X-rays are essentially electromagnetic radiation with wavelengths of the order of 10^{-10} m. At present, X-rays are widely used in engineering and medicine.

In the wake of Röntgen's discovery, another discovery was made that led to revolutionary changes in engineering in the 20th century. In 1896, the French physicist Henri Becquerel (1852-1908), having heard about Röntgen's discovery, suggested that X-rays are emitted by fluorescent substances.* Becquerel had at his disposal many such substances, among which the most

* Fluorescence is the property of some substances to emit light after being illuminated. The phenomenon ceases as soon as the source of light is cut off.

fluorescent was a uranium salt. He conducted a series of experiments and discovered that the fluorescent uranium salt indeed affected a photographic plate wrapped in black paper. Once he accidentally left a uranium salt that had not been exposed to light near a photographic plate covered in black paper, and even in the absence of fluorescence, the uranium salt blackened the photographic plate. Becquerel explained this effect by the uranium salt emitting rays similar to X-rays. In this way the phenomenon of radioactivity (from the Latin *radius*, which means ray) had been discovered.

This phenomenon attracted the attention of the French physicists Marie and Pierre Curie. Their thorough investigations showed that uranium waste is much more radioactive than the uranium itself. They were the first to separate two unknown elements, radium and polonium, from radioactive waste.

Radium (it was radium chloride, as a matter of fact) proved to be millions of times more radioactive than uranium, with one gram of radium releasing about 580 J of energy per hour. This unceasing energy release by an element seemed to contradict the law of energy conservation.

That radium could emit, although slowly, considerable amounts of energy was of interest, above all, to physicists. What makes radioactive substances emit rays? What is the origin of these rays? Where do the radioactive substances get the energy they release in the form of the mysterious rays? All these questions were avidly discussed by physicists. Many of them racked their brains to explain the mystery of radium.

Marie and Pierre Curie continued their experimental research into the nature of radium radiation. In one experiment they placed a sample of radium in a magnetic field (between the poles of an electromagnet) and quite unexpectedly observed that the radium radiation attenuated considerably. The Curies suggested that this was due to some unknown particles being deflected in the magnetic field. They called them beta particles. Now we know that beta particles are electrons.

The British scientist Ernest Rutherford (1871-1937) discovered that radium also emits positively charged particles. These were called alpha particles. Finally, part of radium radiation that is not affected by a magnetic field at all was termed gamma rays.

Subsequent experiments, which we will not describe here (although they are very instructive), showed that the positive charge of an alpha particle is twice the charge of an electron, and an alpha particle's mass coincides with that of a helium atom. An atom, on the whole, is neutral, and it is clear that an alpha particle is essentially a helium atom with its two electrons stripped off. Gamma rays, for their part, proved to be electromagnetic waves with wavelengths much shorter than those of X-rays.

Rutherford decided to explore the atomic structure using alpha particles. He and his coworkers traced a change in the trajectories of alpha particles passing through thin foils. The foils should have been thin enough to let alpha particles pass through them without scattering them (although alpha particles have a velocity of about a million metres per second, they can be stopped by a plate several micrometres thick). Quite unexpectedly, Rutherford discovered that instead of a uniform widening of the beam of alpha particles after they passed through the foil some of them deviated from the initial trajectory by large angles. Sometimes the angles were almost 180°. This could not happen if the positive and negative charges constituting a neutral atom were arranged uniformly inside the atom.

These large deviations of alpha particles could only be explained if the alpha particle had approached a positive charge closely enough to be deviated from its initial trajectory. Estimates showed that for large repulsive forces to emerge in this case (according to Coulomb's law) these distances should be four orders of magnitude smaller than the size of the atom. Rutherford suggested an atomic structure in which the atom is like a tiny image of the Solar System with a positive charge as the Sun and electrons orbiting it as planets. In the Solar System the planets move under the action of Newtonian gravitational forces, while in the atom the electrons are held in orbit around the positive charge by Coulomb electrostatic forces.

"The Sun" was called the atomic nucleus, which has a positive electric charge equal to the sum of the charges of the electrons orbiting it, so the atom, on the whole, remains neutral. This is the planetary model of the atomic nucleus. The nucleus is less than 1/10 000th of the size of the atom (the Sun is also much smaller than the whole Solar System). So a new term, the atomic nucleus, made its appearance. The discovery of the nucleus prompted the development of a new branch of physics, called now nuclear physics.

Alpha particle scattering by various elements of the Periodic Table led to the important discovery that the positive charge of the nucleus is equal to the product of the atomic number of the element in the Periodic Table and the electron charge. This lent a physical meaning to Mendeleev's famous periodic law, namely, the atomic number in the Periodic Table equals the number of electrons revolving around the nucleus. It was also discovered that the nucleus contains positively charged particles, called protons. The proton's charge is equal to the charge of an electron, and its mass is approximately 1800 times greater.

Initially, only several laboratories tackled the problem of the atomic nucleus.

Those included Rutherford's laboratory in Cambridge, Marie Curie's laboratory in Paris, and Skobeltsyn's laboratory in Leningrad. By the early 1930s, the main properties of atoms had been thoroughly studied, and many scientists turned their attention to the atomic nucleus.

In 1932, one of the fundamental discoveries in the nuclear physics of the 20th century was made—the discovery of the neutron, an electrically neutral particle whose mass is roughly equal to the proton's mass. It thus became clear that the nucleus consists of protons and neutrons.

By that time, it was known that atoms with the same atomic numbers could have different masses. Such atoms are called isotopes of an element. Nuclei of different isotopes of an element contain equal numbers of protons but different numbers of neutrons.

In 1934, Irène and Frédérick Joliot-Curie made the very important discovery of artificial radioactivity. Basically, if light elements (say, beryllium) are bombarded by alpha particles, they become radioactive and emit neutrons.

But when heavy elements were bombarded, no such transformation took place. Enrico Fermi (1901-1954), an outstanding Italian physicist, suggested that since the nuclei of heavy elements carry a large charge, an alpha particle which also is positively charged, cannot approach them closely enough to induce radioactivity. Neutrons, for their part, have no charge and would not be affected by the Coulomb forces of the positive charge. Fermi performed a series of experiments bombarding various elements by neutrons and discovered that almost all elements exhibit neutron-induced artificial radioactivity. The majority of the elements in this case emit alpha and beta particles, gamma rays, and neutrons. When alpha or beta particles are emitted, new chemical elements form.

Soon afterwards, Fermi presented the results of his investigations in a long paper. He studied almost all the elements of the Periodic Table which exhibit neutron-induced artificial radioactivity and completely described the process for each element. Thus the artificial transmutation of chemical elements became possible.

However, Fermi failed to describe adequately the neutron-induced nuclear reaction involving the last element (at that time) of the Periodic Table, viz. uranium.

Naturally, the discovery of neutron-induced artificial radioactivity provoked interest in nuclear reactions among physicists at many laboratories, Hahn and Strassmann's laboratory in Berlin being one of them. Similar research was undertaken at Kurchatov's laboratory at the Leningrad Physico-Technical Institute.

Otto Hahn (1879-1968) and Fritz Strassmann (1902-1980) observed that when a uranium target was irradiated by neutrons, nuclei of elements (such as barium) were obtained whose mass was roughly half the mass of the uranium nucleus. The German physicist Lise Meitner (1878-1968), Hahn and Strassmann's former chief, who was living at that time in Sweden, helped clear up the complicated situation, and the Danish physicist Niels Bohr (1885-1962) constructed a detailed theory of the process, proceeding from an idea suggested in a short paper by the Soviet physicist Yakov Frenkel (1894-1952).

The main feature of the complicated processes that take place when uranium is irradiated by neutrons (we will not consider them in detail) is that the uranium nucleus splits (fissions) into two parts, called fragments. The isotopes of the chemical elements obtained as a result of the reaction can be identified by the mass and charge of the fragments. It soon became clear that only one uranium isotope, viz. ^{235}U (natural uranium contains only 0.7% of this isotope), could fission.

The energy of the fragments that form as a result of ^{235}U fission proved to be many times higher than the energy of the neutrons that induced the reaction. That the energy of the particles emitted by nuclei could exceed the energy of the bombarding particles had been known before, but in those processes only a tiny number of the bombarding particles (one millionth part) penetrated the nuclei to initiate nuclear reactions. Most of the particles flew by the nucleus and did not affect it. It is, therefore, clear that although the energy of the particles emitted by a radioactive substance is hundreds of times higher than the energy of the bombarding particles, the total energy spent in the process is ten thousands of times higher than the released energy. It was this that led Rutherford, the father of nuclear physics, to conclude that the atomic nucleus could not serve as an energy source.

Uranium was quite different. Experiments showed that neutron-induced uranium fission produces not only fragments but neutrons as well, with more than two neutrons being emitted, on the average, as a result of a single act of interaction between a nucleus and a neutron. This means that the neutron that penetrates into the uranium nucleus creates two extra neutrons which do not differ from the primary neutron and can cause further fission of uranium nuclei, generating in the process two more neutrons and thus increasing fourfold the number of split nuclei, and so on.

In other words, there occurs a spontaneous avalanche-like multiplication of neutrons (chain reaction). The only thing the reaction needs in order to start is for the neutrons formed by the uranium fission to be confined within the irradiated uranium sample so that they can cause further fission.

For this, a large volume and, consequently, a large mass, of uranium is needed. This mass is called the critical mass. In this case, neutron losses are negligible, and the huge kinetic energy of the uranium fragments is transferred to the uranium atoms. The uranium will thus be heated to a very high temperature. Rutherford's prediction proved to be unjustified, and uranium nuclei can serve as a source of energy.

If sufficient ^{235}U could be separated to make up the critical mass, huge amounts of energy would be obtained. Calculations made by the Soviet scientists Yakov Zeldovich (1914-1988) and Yuly Khariton (b. 1904) and other nonSoviet scientists showed that the neutron-induced fission of almost pure ^{235}U would proceed like an explosion. Moreover, no special neutron source would be needed since the Earth's atmosphere always contains a small number of neutrons of cosmic origin which would be sufficient to initiate an explosive reaction given the critical mass of uranium. It thus became possible to create a monstrous weapon, an atom bomb.

Many physicists all over the world started investigations of uranium fission. Almost every issue of all the physical journals carried a paper or short information concerning uranium fission. The separation of enough pure ^{235}U (of the order of tens of kilograms) seemed at that time a fantastic idea.

Soon it was discovered that a natural mixture of uranium isotopes also undergoes a chain nuclear reaction if the energy of the neutrons the ^{235}U nuclei emit during fission could be somehow lowered. Fortunately, that was quite easy to do. If the neutrons pass through a substance whose atoms are similar in mass to the neutrons, they transfer some of their energy rather quickly to the atoms, thus decreasing their velocities to those of the thermal motion of the atoms.

Substances consisting of light atoms are used to slow down (moderate) neutrons. The only requirement is that these substances do not absorb (or only slightly absorb) neutrons. Heavy water is one such substance. A molecule of heavy water contains two atoms of deuterium (an isotope of hydrogen with doubled mass) instead of two atoms of ordinary hydrogen. If rods made of natural uranium are placed in heavy water, the neutrons are moderated and a controlled self-sustained chain reaction of uranium fission takes place. This is the operational principle of one type of nuclear reactor, called the thermal reactor.

In a nuclear reactor, uranium rods (cylindrical in shape, as a rule) are embedded as a regular array in a moderator, graphite, or heavy water. By gradually increasing the number of rods, the critical mass is eventually attained. The number of neutrons from a fission process in the rods can be controlled, thus preventing the chain reaction from becoming explosive in nature. In an atom bomb, two subcritical masses of uranium are brought rapidly together to form a supercritical mass. An uncontrollable explosive chain reaction is thus set off. A nuclear reactor, on the contrary, can serve as long-term source of energy.

In nuclear reactors, another important phenomenon took place, viz. part of excess neutrons interacted with uranium nuclei and formed an isotope of a new element of the Periodic Table with atomic number 94 and nuclear mass 239. This element is not encountered in nature and only obtained when uranium is irradiated by neutrons. The element was called plutonium. Plutonium, like ^{235}U, undergoes neutron-induced fission, releasing excess neutrons in the process. It is better than ^{235}U in that its critical mass is severalfold less. Plutonium differs chemically from uranium and thus can be both separated from uranium and obtained chemically.

So, new energy sources, viz. uranium and plutonium obtained from uranium, made their appearance. To give an idea of how powerful the process is, suffice it to say that the energy given off by the complete fission of one kilogram of ^{235}U is equal to the energy released when 3000 tons of coal are burnt.

Unfortunately, nuclear energy was first applied for military purposes. In 1945, Americans dropped atom bombs on the Japanese towns of Hiroshima and Nagasaki. There was no need to do so since the war with Japan was coming to an end. The explosion of the first atom bomb in Hiroshima was equivalent to the explosion of 20 000 t of TNT.

The power of modern nuclear weapons is, in principle, unlimited, and so their use would be a catastrophe for humanity.

The USSR has always been against the use of nuclear weapons for military purposes, although as early as 1949 the USSR had at its disposal nuclear bombs. The USSR does its utmost to prevent a world nuclear catastrophe and to utilize nuclear energy only for peaceful purposes.

The USSR was the first to use nuclear energy for the welfare of mankind. In 1954, the first nuclear power station, which operated on uranium rather than on conventional fuel (petroleum or coal), was commissioned in Obninsk under the supervision of Academician Kurchatov. In subsequent years, nuclear power stations were constructed in the USSR and elsewhere. These include one of the most powerful in the world—the Leningrad nuclear power station with a rated power of 4×10^6 kW and the Voronezh nuclear power station with nearly the same power.

In conclusion, I should say that it would be wrong to think that the most important discoveries in physics that had led to the technological revolution in the middle of the 20th century followed each other triumphantly. Each of them involved great difficulties which had to be overcome by the efforts of many outstanding physicists.

Each technological revolution is preceded by a revolution in physics. In the 19th century, the creation of Maxwell's classical electrodynamics was such a revolution. The laws of electromagnetism paved the way to the wide application of electricity in engineering.

In the 20th century, revolutionary changes in physics resulted from the work of Albert Einstein and Niels Bohr. Einstein's theory of relativity dramatically changed the main concepts of the natural sciences, viz. space and time. Niels Bohr, for his part, laid the foundations of quantum mechanics. He showed that the motion of particles at the atomic level is not described by Newton's laws. These particles obey their own code of laws which is studied in quantum mechanics.

Relativity and quantum mechanics at first seemed to be abstract theories, and only a few physicists appreciated their significance. In the course of time, however, the theories won wide acceptance and were verified in numerous experiments. All this led, finally, to clear understanding of the laws of atomic and nuclear physics and to a new technological revolution, for which reason the 20th century may be called the nuclear age.

We have only considered some of the branches of physics which have led to revolutionary changes in modern engineering, above all power engineering. There are, however, other numerous examples which also show that the advances of physics in the 20th century are the basis for scientific and technical progress.

Physics in the USSR

(written to mark the 60th anniversary of the USSR)

Before the Great October Socialist Revolution only single physicists who mainly lived in Moscow and Leningrad contributed to the development of physics and astronomy in Russia. Those included Alexander Stoletov (1839-1896), Pavel Yablochkov (1847-1894), Alexander Popov (1859-1906), Piotr Lebedev (1866-1912), Nikolai Zhukovsky (1847-1921), Aristarkh Belopolsky (1854-1934), and Abram Ioffe (1880-1960).

The rapid development of science as a whole and physics in particular was initiated by Lenin in the first years of the USSR's existence. A number of scientific establishments were set up, among them the State Optical Institute headed by Rozhdestvensky and the Physico-Technical Institute administered by Ioffe in Leningrad, the Central Aerohydrodynamics Institute under the guidance of Zhukovsky in Moscow, and some others, also mainly in Moscow and Leningrad.

Soon after the Soviet Union had been formed, the CPSU and the Soviet government, following Lenin's instructions, took measures to promote the development of science in Soviet socialist republics.

It is within my recollection that in the late 1920s Academician Ioffe, Director of the Leningrad Physico-Technical Institute, sent a group of the Institute's young talented physicists to set up the Ukrainian Physico-Technical Institute in Kharkov (the then capital of the Ukraine). That was one of the first large physical institutes in the Ukraine. The Institute soon became known as the only one in the USSR having a low-temperature laboratory with a plant for obtaining liquid helium. It was the second cryogenic laboratory in the world after the Leiden laboratory. At present, the Kharkov Physico-Technical Institute is a world famous physical establishment. Soon afterwards, the Dnepropetrovsk Physico-Technical Institute was organized.

Another group of staff researchers of the Leningrad Physico-Technical Institute moved to Sverdlovsk to set up the Ural Physico-Technical Institute (now the Institute of the Physics of Metals). At practically the same time and in the same way the Tomsk Physico-Technical Institute was founded.

At present, physics, along with the other sciences, is rapidly developing in all the Soviet socialist republics. This was, to a great extent, prompted by the creation of republican academies of sciences. It is difficult to cover in a small article the advances in physics made by all the 15 Soviet socialist republics, and so I will only dwell on the achievements of those physical centres in the USSR where I have worked or with which I maintain scientific contact.

In 1938, I worked in the low-temperature laboratory of the Ukrainian Physico-Technical Institute. The laboratory was well known for its superconductivity experiments. Other laboratories of the Institute were involved in studies on the physics of the atomic nucleus. Emphasis was placed on interaction between matter and neutrons, a phenomenon that had been discovered not long before. The results proved very important when it came to the construction of the first nuclear reactors for nuclear power stations. At present, the Kharkov Physico-Technical Institute conducts important research into low-temperature physics, structural materials, and controlled nuclear fusion.

In Riga, the capital of the Latvian SSR, a well-equipped physical institute was set up. It has at its disposal a research nuclear reactor which is used as a neutron source.

Any nuclear reactor serves both as an energy source and a powerful neutron source. Research reactors are instrumental in studying a wide range of physical and chemical processes. These reactors are very expensive and can only be run by highly trained staff.

The physical and chemical properties of many substances are known to change significantly, under neutron bombardment. At the reactor in Riga, scientists study the changes in the structure of dielectric crystals, which lead to variation in their optical properties. This research is of importance for various technical problems. For instance, the effect was investigated of neutron irradiation on materials to be used in commercial nuclear reactors.

Under the action of neutrons, the molecules of different chemical compounds dissociate (decompose) at different rates. The search for compounds that do not undergo neutron-induced dissociation is the task at the research reactor of the Tashkent Institute of Nuclear Physics in the Uzbek SSR. Uzbek scientists together with associates from the Kurchatov Institute of Atomic Energy have found compounds that are stable under neutron irradiation and which could be used in engineering.

An important property of neutrons is that they can penetrate into the atomic nucleus and change its composition, either forming the nucleus of another chemical element or the nucleus of a radioactive isotope of the irradiated element. The formation of new chemical elements when uranium is irradiated by neutrons is a classical example of these nuclear transformations, and it is the process central to all nuclear engineering. Radioactive isotopes have wide applications in medicine, engineering, and agriculture. Uzbek scientists working at the Tashkent reactor produce radioactive isotopes of a number of elements.

Some very important fundamental and practical work is being carried out at the research reactor of the Institute of Nuclear Physics in Alma-Ata, the capital of the Kazakh SSR.

Neutrons have another important job to do. They are indispensable for chemical analysis of materials, especially when an element enters into a material under investigation in such tiny amounts that it is untraceable by conventional chemical analysis. The assay of rock samples for rare, and hence expensive, elements is an example where neutrons come in quite handy. We have already mentioned that a neutron can penetrate the nucleus of an element leading to the formation either of a new, usually radioactive, element or a radioactive isotope of the initial element. Note too that radioactive elements mainly emit either gamma quanta or fast electrons (beta particles), and modern devices can record a single gamma quantum or a single electron and measure their energies, which are typical for a nucleus of a given element. So if a rock sample is bombarded by neutrons, the number of emitted gamma quanta and beta particles is counted, and their energies are measured, then a chemical element can be identified and its concentration, however small, in the sample can be determined. This method of chemical analysis is known as neutron activation analysis. Such analysis can be carried out at any research reactor, but at the Institute of Nuclear Physics in Alma-Ata this method has been developed particularly well. The results obtained by the Institute's scientists are used in rare metal prospecting.

The Institute also has a cyclotron, which is as expensive as a research reactor.

A cyclotron accelerates charged particles, alpha particles in particular. The irradiation of some light metals, say, beryllium, by alpha particles produces neutron beams. True, fewer neutrons are produced this way than by a nuclear reactor, but a cyclotron has the advantage that the energy of the accelerated particles and, consequently, that of the knocked out neutrons, can be controlled.

Scientific institutions in the Soviet republics are equipped with sophisticated modern apparatus. One example is the cyclic electron accelerator in Erevan, the capital of the Armenian SSR. In this mighty apparatus, one of the most powerful in the world, electrons can be accelerated to kinetic energies of 6×10^9 eV (the energy an electron would acquire in an electric field of 6×10^6 V). The world-known Byurakan astrophysical observatory, also in the Armenian SSR, can serve as another example.

Recent years have witnessed rapid development of physics in the Byelorussian SSR. The Byelorussian Academy of Sciences administers a number of large physical institutes, which conduct some important studies on optics. The interests of the Institute of Physics lay in laser physics and technology. Byelorussian physicists carry out some important research on spectroscopy. A research nuclear reactor near Minsk, the capital of the republic, is instrumental in studying how the physical and chemical properties of materials used in industry can be improved by neutron irradiation.

I have been to Tbilisi, the capital of the Georgian SSR, on several occasions and visited some of its physics establishments. Semiconductor physics and radio electronics are the main interests of the Physics Faculty of Tbilisi University and some other institutes in the city. Interesting phenomena related to neutron effect on the physical properties of matter at low temperatures are being studied at the research nuclear reactor and the cryogenic plant of the Tbilisi Institute of Physics. These studies have clarified the physics behind the neutron-induced changes in material behaviour. The unique properties of superfluid helium II are also studied at the Institute. Liquid helium at a temperature of 2.17 K changes abruptly to a new state with vanishing viscosity (the fluid flows without friction) and exhibits a number of other remarkable properties, which are being studied by Georgian physicists.

Unfortunately, there is no space to dwell on the advances in physics in the largest Soviet republic, the Russian Soviet Federative Socialist Republic. Suffice it to say that many cities across this vast territory, from Kaliningrad to Vladivostok, have large local institutes with which I used to cooperate or cooperate now. A simple enumeration of these institutes would occupy too much space. The headquarters of Soviet science, the USSR Academy of Sciences, is in Moscow, the capital of the RSFSR.

It should be noted that Soviet physicists have played important roles in solving the urgent problems the country has faced. In particular, during the Second World War they significantly improved available military equipment and developed new weapons.

I was lucky enough to take part in the creation of nuclear engineering in the USSR and have witnessed how the underlying physical ideas were implemented in practice. Now the USSR is a leading country in this field, the first nuclear power station being constructed in the USSR and Soviet nuclear-powered ice-breakers being the best in the world.

Soviet physics marks the 60th anniversary of the foundation of the USSR with new advances in fundamental investigations and their application in various branches of national economy.

Science Is for Young

It is usually believed that scientific work, discoveries, formulations of laws is all done by mature scientists, i.e. by people of a venerable age who have accumulated knowledge and experience. In reality, the history of science demonstrates that the truth is somewhat different, and the most important discoveries are made by young people.

Although it is much easier for me to speak about physicists, I must mention the famous Lenin's book *The Development of Capitalism in Russia* which was published in March 1899, when Lenin was 28 years old. In writing the book, Lenin consulted or referred to about 600 books and papers. This fundamental work convincingly demonstrated that Russia after the reforms followed the capitalist way of development, in full accordance with Marx's teaching and contrary to the generally accepted viewpoint. The book considerably influenced the revolutionary movement in Russia. The subsequent course of events brilliantly corroborated the scientific ideas Lenin developed in the book. Note also that by that time Lenin had written more than 30 books and papers in which he had developed the programme and tactics of the party.

Many people know a picture where Galileo is portrayed as an old man with a long beard. Galileo Galilei (1564-1642) indeed lived a long life, but his first important discovery in physics was made in 1583, when he was about 20 years old. He watched the oscillations of a chandelier in a cathedral, compared the period of the oscillations with his own pulse rate, and in this way established that the period of the chandelier's oscillations is independent of the amplitude. Clocks were designed on the basis of this discovery. At 25, Galileo was made a professor and soon afterwards he experimentally established his famous laws concerning the fall of bodies under the action of gravity.

Classical mechanics, which for more than two hundred years served as a basis for physics, was created by Newton, who was born in the year of Galileo's death. Isaac Newton (1643-1727), like Galileo, made one of his famous discoveries, the law of universal gravitation, when 20 years old (though for various reasons he delayed publication until much later).

Every school pupil knows the name of the Russian physicist Emil Lenz (1804-1865), who in 1833 formulated his famous law concerning the direction of an induced electric field in a paper "About Determination of the Direction of Galvanic Currents Induced by Electrodynamic Induction".

He was 29 at the time. A year later he was elected to full membership of the St. Petersburg Academy of Sciences.

The Maxwell four famous equations are the theoretical foundation of modern electrical engineering, radio engineering, and optics, and James Maxwell (1831-1879) is justly called a Newton in electricity. Maxwell published his first scientific paper when aged 15. When he was 25, he was appointed a professor of Aberdeen University and at 29, a professor at King's College, London. It was then when he put out one of his most fundamental papers on the dynamic theory of electromagnetic field.

Dmitry Mendeleev (1834-1907), who is usually pictured as a grey-headed old man with a beard, published his first scientific paper when he was 21 and studied at the St. Petersburg Main Pedagogical Institute. When 29 years old, he was appointed a professor. He discovered his famous periodic law when he was 35.

Pavel Yablochkov (1847-1894) patented his arc lamp, the first electric source of light which became known all over the world as the "Russian light", in 1876 when he was 29.

Marie Curie (1867-1934) started her famous fundamental studies of radioactivity, on which all nuclear physics and engineering rests, when she was 30. Six years later, she, Pierre Curie, and Henri Becquerel were awarded one of the first Nobel Prizes in physics.

Piotr Lebedev (1866-1912) was 29 when he conducted the research in crystal optics that proved that light and electromagnetic waves in the millimetre range of the spectrum were the same thing (until then it had not been shown that "artificial" electromagnetic waves and "natural" light were similar). Further work led him to the discovery of light pressure.

Abram Ioffe (1880-1960) was the founder of the Soviet school of physicists. He trained as an engineer at the St. Petersburg Technological Institute. In 1902, he graduated but became more interested in physics and travelled to Röntgen's famous laboratory in Munich. There he was awarded a doctorate for a brilliant piece of research, when he was 25. Ioffe returned to Russia in 1906 and carried out a series of elegant experiments that won him world recognition. For example, he proved that cathode rays are essentially electric current and that the electric charge comes in discrete quantities (a discovery made jointly with Robert Millikan).

In 1905, the German physics journal *Annalen der Physik* published three papers by the same author, each of which was enough to earn fame. Albert Einstein (1879-1955) was 26 when "On the Electrodynamics of Moving Bodies" was published. It laid out Einstein's special theory of relativity, which led to a revolution in physics. The second paper was on the photoelectric effect, for which theory Einstein was awarded the Nobel Prize in physics. The third paper was entitled "On the Motion Required by the Molecular Kinetic Theory of Heat of Particles Suspended in Fluids at Rest". Ten years later, Einstein formulated the general theory of relativity.

The year 1913 saw another revolution in physics triggered by a paper written by the Danish scientist Niels Bohr (1885-1962). It laid the foundations for the quantum theory of atomic structure. Bohr was then only 28.

Alexander Friedmann (1888-1925) specialized in physics and mechanics. Although he was only 37 when he died, he made several important discoveries that were to influence the progress of science. Starting from the general theory of relativity, he proved that the Universe could expand, a postulate subsequently verified. He developed a new branch of mechanics, now called gas dynamics, and laid the foundations of modern dynamic meteorology.

Several of the physicists who rose to world eminence after the Great October Socialist Revolution, e.g. Igor Kurchatov and Lev Landau, did so on the basis of work they completed when young men.

Thus you can see that it is vital that anyone wanting to devote his life to science must do so as early as possible, whether at university or at school. In the USSR there are many opportunities for young people to start studying science. Young people may join scientific associations or societies, and there are several magazines for them that specialize in popularizing science, one being *Kvant*. It should, however, be emphasized that success in science requires hard work and effort.

Whilst I have paid tribute to the large part played by young people in science, I do not wish to diminish the role of mature scientists. They pass on their experience and knowledge to younger scientists, and by choosing good pupils learn from them. A young scientist is no good if his teacher learns nothing from him and gives his teacher nothing to be proud of.

The Photoelectromagnetic Effect*

This effect was discovered by one of the authors in 1934. Basically, when a semiconductor is placed in a magnetic field and illuminated, an electromotive force is induced.

When a rectangular plate made of a semiconductor is placed in a magnetic field with its long dimension oriented in the X-axis and illuminated along the Y-axis (Fig. 1),

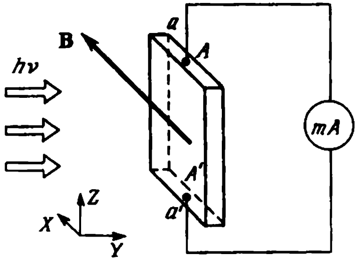

Fig. 1

a potential difference develops between sides a and a' in the Z-direction. It is called the photoelectromagnetic electromotive force. If the two sides are connected into a circuit, a current will flow.

* Co-authored with S.D. Lazarev.

In the first experiments on this effect, Cu_2O plates were used. At the time cuprous oxide was the most fashionable compound when studying semiconductors. The 1930s were the start of what might be called the semiconductor age, and it heralded a revolution in radio electronics. At that time, experiments using Cu_2O were conducted at the temperature of liquid nitrogen (77 K). In a low magnetic field of 1 T a sample was illuminated with a weak light source, a torch, and a potential difference of 15-20 V was generated between points A and A' (about 2 cm apart).

The experiments also demonstrated that the sign of the emf, and hence the direction of the electric field within the sample, depends on the direction of the external magnetic field. If the opposite surface of the sample is illuminated, the emf also changes sign, for the same magnetic field. If the sample is illuminated without a magnetic field, no emf arises.

A magnetic field only influences moving charges, and so to understand this effect, we must see why moving charges arise in a semiconductor in the absence of an emf source.

Light incident on the surface of the semiconductor plate is absorbed if the semiconductor is opaque. In most cases the light is absorbed by the electrons of the semiconductor atoms, and when the energy $h\nu$ of light quanta (photons) is large, the electrons are torn from their atoms, becoming free and moving within the illuminated body. Metals have a great many free electrons even when not illuminated, but there are very few such electrons in semiconductors. When the light is absorbed, their number increases. Since semiconductors are opaque, the photons are absorbed in a thin surface layer (of the order of a light wavelength thick). Consequently, free electrons are only generated in the surface layer, and the bulk of the sample remains unchanged. Thus the concentration of free electrons near the surface is greater than that in the bulk, and hence diffusion takes place with the particles moving from where they are concentrated to where there are smaller concentrations. This movement of electrons from the illuminated surface into the bulk is an electric current (we call it a diffusion electric current). The current emerges without any external current source, or rather the light is the current source. It is this diffusion current source that is affected by the magnetic field.

A Lorentz force $\mathbf{F}_L$ acts on a moving charge in a magnetic field at right angles to both the velocity **v** of the charge and the magnetic induction **B** of the field. Given the directions of the magnetic induction and the incident light as in Fig. 1, electrons are pushed by the Lorentz force to side a' and accumulate there. As a result, the side becomes negatively charged, and a potential difference develops between sides a and a'. If the sides are connected together, a current will flow through the conductor.

It would seem that this completely explains the photoelectromagnetic effect. However, the argument does not explain why the electric current flows so long as there is light. In order to maintain a potential difference between a and a', a constant electron flux to a', and hence a constant electron diffusion current, should be needed. However, the electron diffusion current should cease after some time because some electrons will diffuse into the bulk of the sample, reach the dark surface, and accumulate there. The negative charge thus formed should decelerate the diffusing electrons, and the diffusion (and hence the current in the external circuit) should cease. Calculations show that the diffusion current should cease in 10^{-6}-10^{-5} s. The actual time depends on the external conditions (the intensity of incident light and magnetic induction), as well as on the properties of the sample (its size, composition, etc.).

Therefore, in order for a current to continue in the circuit (for there to be a constant potential difference between sides a and a'), the negative charge that accumulates on the dark side must somehow be neutralized by a positive charge of the same magnitude. Imagine that when the sample is illuminated, positive particles are created at the same time and in the same quantity as the electrons. The absolute value of the particles' charge should then be equal to the absolute charge of the electrons. The positive particles would then diffuse into the bulk of the sample, and the joint diffusion of the positive particles and electrons would last a long time, since when the particles reach the other side of the sample, they would not charge it. The total diffusion current would then be zero, but the unlike charges would move independently.

It was proved that this indeed takes place. The positive charges induced by the light are holes. This idea came from quantum mechanics, and the photoelectromagnetic effect was one of the first to require the idea for it to be explained. The concept of holes is widely used in the modern theory of conductivity.

When the surface of a semiconductor plate is illuminated, free electrons and holes (or rather electron-hole pairs) are created and they diffuse in the same direction. When a magnetic field is present, the Lorentz force pushes them in opposite direction, and so electrons accumulate on one side and holes on the other. Clearly, if the opposite side of the sample is illuminated, or the direction of the magnetic field is changed, the emf of the photoelectromagnetic effect will be changed in sign. The sign of the emf can be determined by the left-hand rule, namely, if the left hand is oriented so that the vector of the magnetic induction impinges on the palm and the four fingers of the hand point in the direction of the incident light, then the thumb (held at right angles to the fingers and the palm) will point in the direction of the electric field in the sample.

This is the qualitative theory of the photoelectromagnetic effect. It took many experiments to be established, and the effect at first came as a surprise to scientists. The theoretical model yielded the following approximate formula for the current I of the photoelectromagnetic effect in a closed circuit (the resistance of the external circuit being negligible in comparison to that of the semiconductor):

$$I = KeN \mid \mathbf{B} \mid,$$

where e is the electron charge, N is the number of light quanta that are absorbed per square metre of the sample's surface per second (clearly, N is proportional to the intensity of light incident on the sample), $\mid \mathbf{B} \mid$ is the value of the magnetic induction, and K is a proportionality constant which depends on the material. The fact that the current is proportional both to the intensity of incident light and to the magnetic induction was established in the first relevant experiments.

Under ordinary experimental conditions, a low magnetic field of about 1 T and natural daylight (which corresponds to $N \simeq 10^{21}$ quanta/($m^2 \cdot s$)) produce a photomagnetic current of about 10^{-3} A in a sample made of a single crystal germanium (with a width of 0.01 m in the direction of the magnetic field).

Given the external parameters N and $|\mathbf{B}|$, the photomagnetic current yields the semiconductor parameters that determine the coefficient K. The photoelectromagnetic effect is widely used for determining simply and reliably important semiconductor parameters such as carrier (electron and hole) lifetime τ, surface recombination velocity S, diffusion length L, and current carrier mobility μ. We will explain the meaning of these quantities in a moment.

A light quantum can "tear" a valence electron away from the atom, thus making it a conduction electron. However, this excess current carrier cannot exist for an infinitely long time. Soon after being created it will again become bound, say, to an ionized atom (this process is called recombination). The average time τ during which a current carrier exists in a free state is called its lifetime. The lifetime varies from 10^{-10} to hundredths of a second depending on the type of a semiconductor. Electrons, or holes, recombine both in the bulk of a semiconductor and on its surface. The quantity S that characterizes the rate of current carrier disappearance on the surface is called the surface recombination velocity. The carrier diffusion length L is the average distance travelled by an electron or a hole during its lifetime τ. The carrier mobility μ is the average velocity of carriers per unit electric field.

These parameters govern the quality of semiconductors used in electronics.

In conclusion, we would like to describe an elegant experiment which illustrates the mechanism of the photoelectromagnetic effect. A small cylinder is cut out of a semiconductor (germanium). A small hole is drilled in the cylinder, and a solid bearing is inserted. The sample is put on a needle (like the magnetic needle of a compass). If the cylinder is placed between

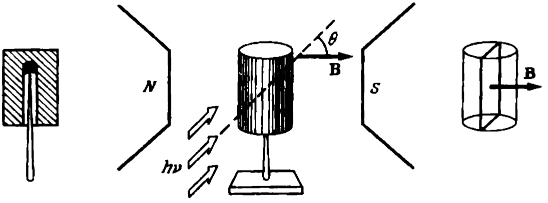

Fig. 2

the poles of a magnet (Fig. 2) and illuminated (the angle between the direction of the incident light and the magnetic induction, θ, is about 45°), it starts rotating! The experiment graphically demonstrates the direct conversion of light energy into mechanical energy. This phenomenon can be called the photomagnetomechanical effect. Let us explain how the effect comes about.

A light ray incident on the side surface of the cylinder illuminates a narrow vertical strip along the entire length of the cylinder. Light-induced free electrons and holes diffuse from the illuminated region into the bulk of the cylinder. The electrons and holes are affected by the Lorentz force and the emf emerges. All the processes involving the diffusion and recombination of light-induced carriers take place in a surface layer of the sample, with thickness of the order of the diffusion length. The remainder of the sample is passive and acts as a conductor closing the circuit for the emf induced by the photoelectromagnetic effect. The cylinder can be regarded as an infinite number of closed frame-shaped circuits (the narrow illuminated strip of the sample being one side of a frame). Each frame is acted upon by the magnetic field, the maximum moment of the acting force being proportional to the area of the frame and the current in it. Since the cylinder is symmetrical, all the frames can be replaced by an equivalent frame whose plane is determined by the direction of the incident light. If the angle θ between the frame's plane and the magnetic induction differs from 90°, the frame will rotate in the magnetic field (just like a current-carrying frame does in an ordinary electric motor). In the above experiment $\theta \simeq 45°$, and the torque acting on the equivalent frame makes the whole sample rotate. As the cylinder rotates, new regions of surface become illuminated, and so the cylinder keeps rotating. If you have understood how the photoelectromagnetic effect emerges, you can now state whether the direction in which the cylinder rotates will change if the direction of the field is reversed.

Exercises

1. What is the sign of the emf of the photoelectromagnetic effect in *n*- and *p*-type semiconductors?

2. Graph the emf of the photoelectromagnetic effect against light intensity. Note that when a semiconductor is illuminated, its conductivity σ consists of two components, viz. the dark conductivity σ_d, which is independent of light intensity, and a component aN (a is a constant), which is proportional to light intensity N: $\sigma = \sigma_d + aN$.

3. Suppose light is absorbed deep inside a sample. Light-induced carriers perish more quickly near the surface than in the bulk of the sample. Determine the sign of the emf of the photoelectromagnetic effect.

What Is a Wave?*

> When throwing stones into water, watch the ripples; otherwise throwing the stones would be empty time wasting.
> Kozma Prutkov, *Fruits of Meditation*

The concept of a wave seems obvious and we intuitively connect it with a motion. If we throw a stone into water, we will see a wave running over the water surface. If, however, a twig floats on the surface, we note that it moves up and down rather than in the direction of the wave propagation. So what is it that is displaced when a wave propagates? Let us consider some examples.

It is said that the Empress Elizabeth, the daughter of Peter the Great, wanted that a salute of salvoes to be fired from the Petropavlovsk fortress in St. Petersburg, the new capital of Russia, at the climax of her coronation. By tradition, the coronation of Russian czars took place in the Cathedral of Dormition in Moscow. Nowadays it would be sufficient to send a radio signal from Moscow to Leningrad for a gun to be fired in time. But at that time another method had to be used to notify the officer in command of the exact moment the patriarch placed a crown on the Empress' head.

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* Co-authored with L.G. Aslamazov.

So, a line of soldiers was stationed along the road from the cathedral in Moscow to the fortress in St. Petersburg (about 650 km) each within sight of each other (a distance of about 100 m). At the moment of the coronation the first soldier waved a small flag, the next repeated his motion, and so on. The reaction time of a man is tenths of a second, and, consequently, this piece of information reached the artillery man in the Petropavlovsk fortress in 10-20 min.

What is it that travelled from Moscow to St. Petersburg? The soldiers did not move and the only thing they did was to wave their small flags. In scientific parlance, it could be said that having raised and lowered his flag, a soldier changed temporarily his state. It is this change in state that moved along the soldier line.

Travelling of a change in state in space or in a medium is called a wave.

In 1905, workers in St. Petersburg went on strike and then, as the press wrote, the wave of strikes spread all over Russia to its remotest regions. In this case, the state that spreads was a cessation of work by workers to enforce compliance with their political and economical demands.

Another example concerns the spread of rumours. A rumour set afloat by one person can quickly spread all over a city. The time it takes a rumour to spread is much shorter than that it would take a person to call on or ring up all the people in the city. The carriers of the rumour do not move, and it is the state of being informed that propagates. It could be said that a wave of rumour spreads in the city.

Finally, let us consider a physical example. Suppose a billiard ball hits a line of similar balls (Fig. 1*a*). The moving ball

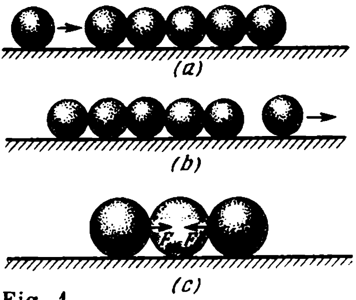

Fig. 1

stops as a result of the collision, and the last ball in the line bounces off (Fig. 1*b*). This is due to a deformation wave that propagates along the line of the balls. The first ball is deformed when the projectile ball hits it and transfers this deformation to the next ball, and so on. All the intermediate balls are acted upon on both sides by equal and opposite forces (Fig. 1*c*) and so they remain motionless. The last ball is acted upon by the elastic force only from one side and, hence, it bounces off.

The deformation waves that propagate in elastic media are called acoustic waves. So, an acoustic wave runs through the line of the balls as a result of the collision.

Such waves can propagate in any elastic body. If, for example, a fixed rod is struck by a hammer at one end (Fig. 2*a*), a defor-

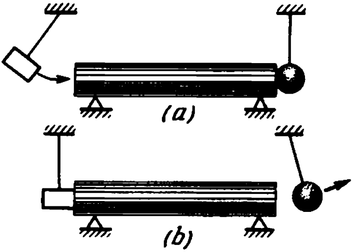

Fig. 2

mation (acoustic) wave will run through the rod, and a ball suspended near the other end of the rod and touching it will bounce off (Fig. 2*b*). In a similar way, an acoustic wave can be excited in a liquid or a gas (naturally, in this case it is better to use a piston instead of a hammer).

Let us explore how acoustic waves propagate in elastic bodies, and, in particular, what governs the velocity of wave propagation. At first, we consider a simplified problem for the model of an elastic

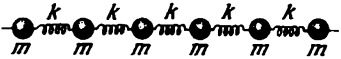

Fig. 3

body. Suppose that we have a chain of small balls of mass m each connected by springs with spring constant k (Fig. 3).

The balls are small compared with a distance between them, and the spring mass it negligibly small in comparison with the ball mass. Essentially, it is the same chain of billiard balls in which we "separate" inertia (mass) and rigidity (spring constant).

This closely resembles the real situation in a solid. In a crystal lattice, the atoms are arranged so that in equilibrium the vector sum of all the forces acting on each atom is zero.* When the atoms deviate from their equilibrium position, attractive and repulsive forces emerge which act as elastic forces in the above example.

Let us impart momentum to a ball, say, the left-hand one (by hitting it), the momentum being directed along the chain. This will result, as was the case with the billiard balls, in an elastic deformation wave running through the chain and ultimately reaching the right-hand end of the chain. Since the last ball is connected to the chain by a spring, it will not bounce off completely, and the extended spring will make it return. Moving by inertia, the ball will compress the spring, and the deformation wave will again run from the right to the left. It is usually said in this case that the wave is reflected from the end o the chain and propagates in the opposite

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* At large distances, atoms are attracted and at small distances, repelled (quantum mechanics forbids atoms to penetrate each other). Only at an equilibrium distance (about the atomic size) are interaction forces zero.

direction. For the same reasons, the wave is reflected from the left-hand end, and so on. These reflected waves complicate the situation and to get rid of them, we consider an infinite (without ends) chain. This can be achieved by looping a chain of many balls (Fig. 4). A wave of elastic

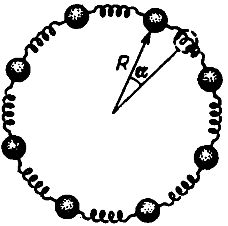

Fig. 4

deformation runs along an "infinite" chain without reflections until it is damped.

Let us move a ball from its equilibrium position (say, clockwise) and let it go. Under the action of the springs, the ball will periodically change its position in space. Such a motion is called an oscillation (vibration).

Oscillations are very important in nature and engineering. The pendulum in a clock oscillates, current and voltage oscillate in electrical appliances, and so on. The alternations of day and night and of the seasons are also oscillatory processes caused by the Earth's rotation and motion in orbit around the Sun. All rotating mechanisms cause oscillations in their foundations, and this must be taken into account when designing them.

Harmonic motion is the simplest type of oscillation. The distance of a body from its equilibrium position in this case is given by

$$\alpha = \alpha_{max} \sin (2\pi t/T) = \alpha_{max} \sin 2\pi \nu t$$
$$= \alpha_{max} \sin \omega t,$$

where for a closed chain α is the angular deviation of a ball from its equilibrium position. It can easily be seen that a harmonic motion is characterized by two quantities (parameters): the maximum deviation (amplitude) α_{max} and the period of oscillations T (the interval after which an oscillation repeats itself exactly). The frequency ν is the number of oscillations per unit time, the cyclic frequency $\omega = 2\pi\nu$ is introduced to simplify the mathematical description of an oscillatory motion, and the quantity $\varphi = \omega t$ that determines the position of the ball at a specified moment of time t is called the phase of the oscillation.

Let us consider another example. Let a ball go through one complete oscillation over a time $T = 4$ s. At the initial moment it was in its equilibrium position, and the maximum displacement was $\alpha_{max} =$ 0.1 rad. Then, if the ball oscillates harmonically, its displacement versus time dependence is given by

$$\alpha = 0.1 \sin (\pi t/2).$$

At $t_1 = 1$ s, the phase of the oscillations is $\varphi_1 = \pi/2$, at $t_2 = 2$ s, it is $\varphi_2 = \pi$, at $t_3 = 3$ s, it is $\varphi_3 = 3\pi/2$, and so on.

The frequency of oscillations, and hence the period and cyclic frequency, is governed by the properties of a system. For instance, the cyclic frequency of a ball of mass m connected to a spring with spring constant k_0 is (see the Appendix to the article)

$$\omega_0 = \sqrt{k_0/m}. \quad (1)$$

The state of oscillatory motion can propagate in space. In our example, for instance, all the balls repeat the oscillations of the first after a certain delay. The second ball will be maximally displaced later than the first one, and so on. When the first ball returns to its equilibrium position, the second in the chain is displaced and will return to its equilibrium position later.

The time delay of oscillations is mathematically described by phase shift. The angular displacement of a ball with number n is given by the formula

$$\alpha_n = \alpha_{max} \sin(\omega(t - \Delta t_n))$$
$$= \alpha_{max} \sin(\omega t - \Delta\varphi_n).$$

The quantity $\Delta\varphi_n = \omega\Delta t_n$ is called the phase shift, with Δt_n being the delay time of oscillations of the nth ball. In this case each ball in the chain executes harmonic motion. All the balls have the same amplitude α_{max} and cyclic frequency ω but different phase shifts $\Delta\varphi_n$. The farther the nth ball from the first one, the more the delay and, consequently, the greater its phase shift.

Figure 5 shows the graphs of oscillatory motions that are shifted in phase by $\Delta\varphi_1 =$

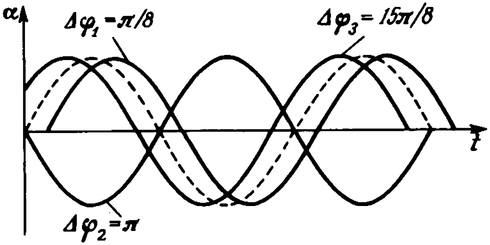

Fig. 5

$\pi/8$, $\Delta\varphi_2 = \pi$, and $\Delta\varphi_3 = 15\pi/8$ with respect to the motion depicted by the dashed line. In the first case, the phase shift is small, and the balls oscillate almost in unison. In the second case, the balls completely lack coordination: when the first ball is maximally displaced, the second ball is also maximally displaced but in the opposite direction. In this case it is said that the balls are in antiphase. Finally, in the third case, the phase shift is close to 2π, and the balls, as can be seen, are oscillating almost in unison. It can easily be understood since 2π is the period of the sine function, and oscillations that are shifted in phase by a multiple of 2π simply coincide.

Since the phase shift of the balls in a chain increases with distance, it is clear that at some distance it becomes equal to 2π, and the ball at this point oscillates in unison with the first ball. This distance is called the wavelength λ.

How many wavelengths can the chain accommodate? Since the beginning and the end of the chain are the same (the ring!), clearly, only an integer number of wavelengths (if they coincide, they oscillate similarly). If the length of the chain is L ($L = Na$, where a is the separation between the balls in equilibrium and N is the number of the balls), the longest

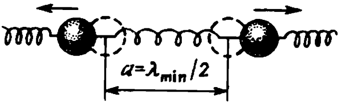

Fig. 6

wavelength that can pass along the chain is $\lambda_1 = L$. The next, shorter, one is $\lambda_2 = L/2$, then $\lambda_3 = L/3$, and so on. What is the shortest wavelength that can propagate in the chain?

The smaller the wavelength, the more two neighbouring balls are shifted in phase. They completely lack coordination when their phase shift is π. In this case the balls oscillate in antiphase (Fig. 6), and the corresponding wavelength is $\lambda_{min} = 2a$.

Let us calculate the frequency of the oscillations that correspond to the minimum wavelength (this will make it possible to estimate the velocity at which the wave propagates in the chain). If we assume that the middle ball oscillates according to the equation

$$\alpha_n = \alpha_{max} \sin \omega t,$$

then the middle ball but one oscillates as

$$\alpha_{n-1} = \alpha_{max} \sin (\omega t + \pi),$$

and the ball to the right of the middle one as

$$\alpha_{n+1} = \alpha_{max} \sin (\omega t - \pi).$$

Knowing how the ends of the springs move, it is easy to find their deformation versus time dependence and calculate, by Hooke's law $F = kx$, the elastic forces that act on the middle ball. The resultant force is

$$F = kx_{max} [\sin (\omega t - \pi) - \sin \omega t + \sin (\omega t + \pi) - \sin \omega t] = -4kx_{max} \sin \omega t,$$

where $x_{max} = R\alpha_{max}$ is the maximum linear displacement of a ball (R is the radius of the closed chain). It is clear that the middle ball oscillates as if it were connected to one spring with a spring constant a factor of four greater. Substituting $k_0 = 4k$ into formula (1), we find that when a wave with the minimum wavelength $\lambda_{min} = 2a$ propagates along the chain, the frequency of the oscillations is $\omega = 2\sqrt{k/m}$. This is the maximum frequency of oscillations of the balls in a closed chain. Any real solid is characterized by a maximum frequency with which its atoms can oscillate.

Let us derive the velocity of wave propagation. If the frequency of oscillations is ω, then their period is $T = 2\pi/\omega$. If the wave propagation is v, then a wave will move a distance $l = vT = 2\pi v/\omega$ over time T. This path is equal to the wavelength, since oscillations shifted in time by T will occur in phase and thus

$$\lambda = vT = 2\pi v/\omega,$$

and

$$v = \frac{\lambda\omega}{2\pi} = \frac{2}{\pi} a \sqrt{\frac{k}{m}},$$

Let us derive the velocity of propagation and the frequency of oscillations for larger wavelengths. They can be calculated in a similar way, although it is more complicated. It turns out that the frequency decreases with increasing wavelength, and the velocity of propagation increases with increasing wavelength, if only insignificantly. For very large wavelengths ($\lambda \gg a$), the velocity of wave propagation becomes constant and is

$$v_0 = a\sqrt{k/m}.$$

So the expression we have obtained for the velocity of wave propagation in a chain of connected balls is good enough for use in other wavelengths as well.

Let us return to solids. What governs the velocity of acoustic waves in them? By analogy with a chain of balls, it can be concluded that the velocity is determined by the elastic properties of a material, the mass of the atoms that constitute it, and the separation between them. The density ρ of a material increases as the separation between the atoms diminishes and their mass increases. The spring constant k in our model can be considered proportional to Young's modulus E. The exact formula for the velocity of sound in a solid is

$$v = \sqrt{E/\rho}.$$

For instance, the velocity of sound in steel calculated by this formula is about 5000 m/s.

So we have examined the propagation of sound in elastic bodies, that is, the propagation of the oscillations of the atoms constituting these bodies.

Other physical quantities can also oscillate in space. If the strength of an electric field and the induction of a magnetic field change periodically, it is said that an electromagnetic wave propagates in space. There are, for example, temperature waves (the propagation of temperature oscillations) and magnetization waves (the propagation of the induction of a magnetic field). Figuratively speaking, the whole edifice of modern physics is permeated, with waves of various sorts.

Appendix

Let spring wire be wound around a rod AB lying along a diameter of a ring (Fig. 7). A ball is attached to one end of the spring, while the other is

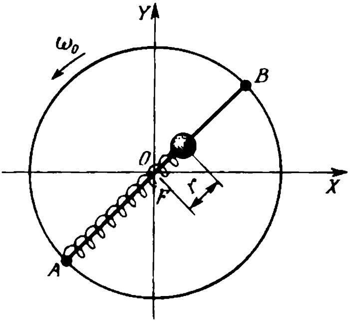

Fig. 7

fixed at end A. The ball can freely move along the rod, being at the centre O of the ring at equilibrium. If we rotate the ring in the horizontal plane with an angular velocity ω_0, the ball will move away from the centre. If it moves by r, the spring will exert on the ball a force equal, by Hooke's law, to $F = k_0 r$ and directed towards the centre of the ring. According to Newton's second law, this force will be responsible for the centripetal acceleration $a_c = \omega_0^2 r$:

$$m\omega_0^2 r = k_0 r.$$

Consequently, in order for the ball to be stationary when the ring is rotated, it is necessary that the rotational speed be $\omega_0 = \sqrt{k_0/m}$.

The projection of the ball on a fixed axis in this case undergoes a harmonic motion with a cyclic frequency equal to the angular velocity of rotation. For example, if $x = r \sin \omega_0 t$, then the frequency of the harmonic motion of the ball with mass m along spring with spring constant k_0 is given by

$$\omega_0 = \sqrt{k_0/m}.$$

Exercises

1. You can "feel" a wave made by a group of people. Stand in a circle, join hands, and let one person bend his knees and straighten again, then his neighbour must repeat this a moment later, the next person in the chain will do the same, and so on. As a result, a wave will propagate along the circle. What governs the velocity of the propagation of this wave?

2. The length of a transmission line is $l = 3000$ km and the voltage frequency is $\nu = 50$ Hz. What is the shift in the voltage oscillation in terms of the period at the beginning and the end of the line? Find also the phase shift.

3. Estimate the time τ of the collision between two steel balls with diameters $d = 0.01$ m. The density of steel is $\rho = 7.8 \times 10^3$ kg/m^3 and Young's modulus is $E = 2 \times 10^{11}$ N/m^2.

4. To produce strong magnetic fields, Piotr Kapitza took the rotor of a generator turning in the magnetic field of the stator and stopped it abruptly, thus inducing a large electromotive force. The rotor circuit was connected to a low-resistance coil. A strong current pulse emerged in the circuit, thus creating a magnetic field (of about 30 T), which was the highest ever obtained at the time. Why has the coil that houses a sample under investigation to be placed a long way from the generator? What is the minimum distance l between the generator

and the coil if the experiment lasts $\Delta t = 0.01$ s and the floor in the laboratory is made from concrete?

5. The CO_2 molecule can be modelled as three spheres connected by springs and arranged, in the equilibrium position, along a straight line. This

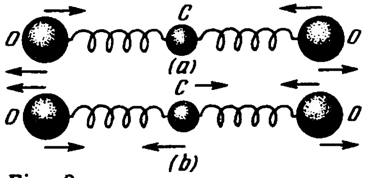

Fig. 8

molecule can oscillate in different ways as shown in Fig. 8. What is the relation between the oscillations?

How Physical Quantities Are Introduced

Physics differs from the other natural sciences in that objective laws of nature are expressed mathematically. To do this, physicists introduce quantities that characterize a phenomenon or process. The mathematical relationships between the physical quantities are established experimentally and take the form of equations or formulas. The latter are called physical laws of nature.

How are physical quantities introduced? Each physical quantity should have a method for measuring it. Let us illustrate this referring to some examples. We start with the quantities used in mechanics.

1. Speed

The notion of speed was known from time immemorial. It can easily be imagined how. Perhaps, somebody, who had a device for measuring time (say, a sundial) watched how a caravan was moving in a desert. He could determine the path traversed by the caravan over some time interval. He might have done this by counting the number of paces the camels walked. In this case, the pace of a camel is the measure of length. Having compared the numbers that expressed the time interval and the path traversed, the person established a

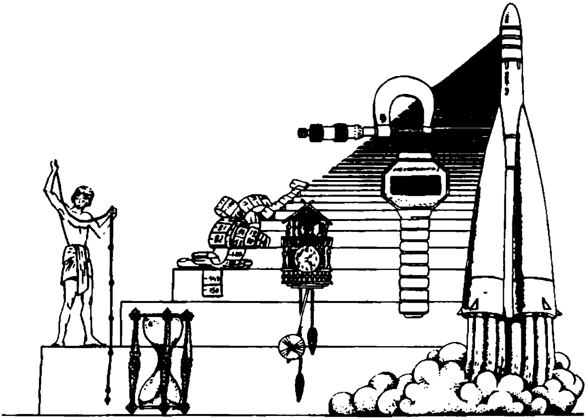

Fig. 1

curious relation between them. The ratio of paths traversed by the caravan over any time intervals would have been equal to the ratio of these intervals. In modern parlance, it means the following: if we denote the path traversed by the caravan over the time interval t_1 by s_1 and the path traversed by the caravan over the time interval t_2 by s_2, then $s_1/s_2 = t_1/t_2$. A very curious fact! The observer might have told about this fact an acquaintance or maybe somebody thought the relationship had no particular meaning since both ratios, on the left-hand and right-hand sides, are abstract numbers and there is nothing astonishing in the fact that $2 = 2$ or $3 = 3$. He might have suggested to write this relationship in the form

$$s_1/t_1 = s_2/t_2$$

and call these ratios the speed of the caravan. This quantity was quite handy since it could be used to predict how far from the initial point the caravan would be at

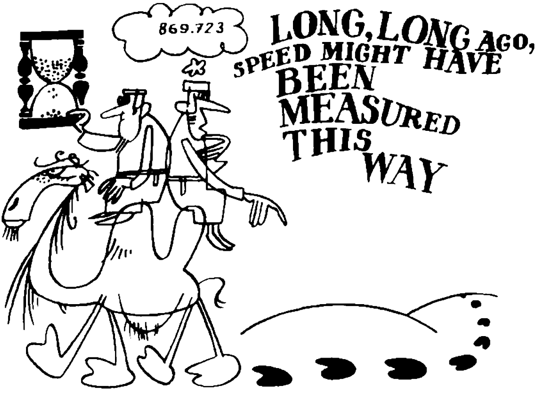

Fig. 2

any time. If we write $s/t = v$, then we find $s = vt$. In this way a quantity was introduced which we now call speed. The equation $s = vt$ cannot be considered to be a law of nature. This equation follows from the *definition* of speed. We could call the ratio $s^2/t^2 = u$ speed too and determine the quantity s from the equation $s = t\sqrt{u}$. But we agreed, *just agreed*, to call the ratio s/t speed.

2. Acceleration

There are motions for which the ratio of paths traversed in two time intervals is equal to the ratio of the squares of these

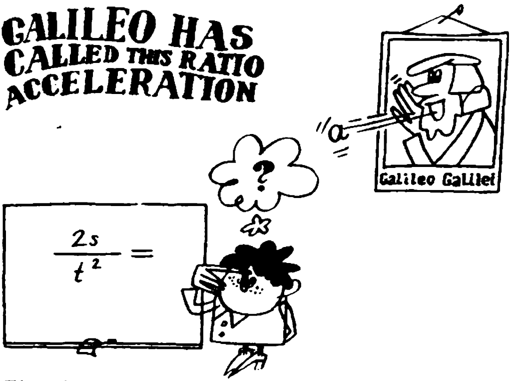

Fig. 3

time intervals. In modern language, this is given by the following equality:

$$s_1/s_2 = t_1^2/t_2^2, \quad (1)$$

where s_1 and s_2 are the distances a moving object traverses in the two time intervals t_1 and t_2, respectively. Objects freely falling in a vacuum and objects sliding down an inclined plane without friction are examples of such motion.

These motions were explored by the Italian physicist Galileo. He wrote equation (1) in the form $2s_1/t_1^2 = 2s_2/t_2^2$* and called the ratio $2s/t^2$ the *acceleration* of a body (a particle). The notion of acceleration is clearly connected with the fact that the speed of a moving body can change in time. If the speed is proportional to time, that is, $v = v_0 + at$, then $a = (v - v_0)/t$, where $(v - v_0)$ is the change in the speed over the time t.

In this way, a new physical quantity, acceleration, had been introduced. The well-known formula $s = at^2/2$ (it is assumed that the initial speed is zero) also does not express any law of nature, and is simply a corollary of the accepted definition of acceleration.

Later these notions were refined, namely, to describe correctly various types of motion, it should be taken into account that the displacement s, speed v, and acceleration a are vector quantities (speed with a specified direction is called velocity).

3. Mass

Numerous experiments indicate that a body unaffected by other bodies (very far away from them) cannot move with acceleration

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* The coefficient 2 is introduced for purely mathematical reasons.

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if the motion is considered relative to some reference frames called inertial reference frames. The body is at rest or moving uniformly in a straight line with respect to an inertial reference frame. If a body accelerates, another body, or bodies, is responsible for the acceleration. In this case, the bodies are said to interact.

Consider the simplest case of an interaction between two bodies. Experiments have shown that the bodies acquire opposite accelerations. Although the absolute values of the accelerations may differ, the ratio of the absolute values of the accelerations of the bodies remains constant and is independent of the conditions in which the interaction takes place. Thus, the interaction does not depend on the mutual arrangement of the bodies in space, or on time, or on the velocities of the bodies, or on the surroundings. This ratio is governed only by the properties of the interacting bodies.

Physics only studies those properties of bodies that can be expressed by numbers, and in order to study these properties, physical quantities are introduced to characterize them. Take the acceleration, the larger it is, the larger the change in the velocity over a specified time interval. By contrast, if the acceleration of the body is small, its velocity changes little over the same time interval. The velocity cannot change instantaneously, and any change in the velocity of a body occurs over some time interval.

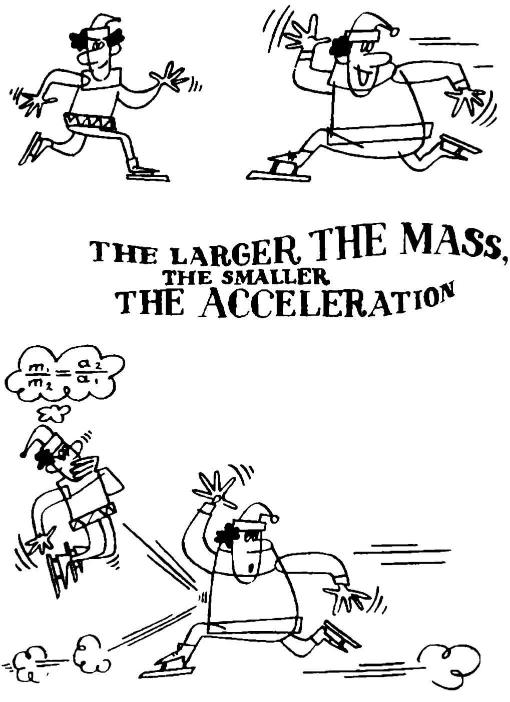

Fig. 4

The accelerations of two bodies are due to their interaction. Clearly, the time interval over which the velocities of two interacting bodies change is the same, it is the duration of their interaction. The body with the smaller acceleration should be ascribed a larger *inertia*, since its motion more resembles motion by inertia. If its acceleration were zero, the body would move only by inertia (with a constant in magnitude and direction velocity), thus rejecting the fact that the bodies interact. The body with the smaller acceleration possesses more inertia. Hence, inertia is a property of a body and should be characterized by some quantity. This quantity is mass.

The property of bodies which governs the ratio of their accelerations after they have interacted is called a *mass*. The mass of a body is usually denoted by m. So, we have introduced a new quantity, mass, but we have not indicated how it can be measured.

Let us ascribe one body a mass m_1 and the other a mass m_2, and denote the accelerations of the bodies after the interaction by a_1 and a_2, respectively. We know from experiments that the ratio of the absolute values of the accelerations is constant. Let us assume that the ratio a_2/a_1 equals the ratio m_1/m_2

$$m_1/m_2 = a_2/a_1. \quad (2)$$

This means that the body with the larger mass acquires a smaller acceleration. We can measure the accelerations and determine the ratio of the masses from formula (2). But only the *ratio*! How can the mass of each of the bodies be determined? Recall what is done when we measure a physical quantity, say, the length of a body. For the purpose, a standard is chosen whose length is taken to be unity (in the SI, it is the metre). Then the number that expresses the length of a body is found as the ratio of this length to one metre. Proceeding in the same way in our case, let us choose a standard mass, that is, a body whose mass is unity (in the SI, it is the kilogram). Let us denote the mass of the standard by m_s. What remains to do is simply to make the body interact with the standard and to measure the accelerations of the two bodies.

If we denote the acceleration of the standard by a_s and the acceleration of the body whose mass is to be measured by a, then, in accordance with formula (2), $m/m_s = a_s/a$. Hence,

$$m = a_s m_s/a, \quad (3)$$

that is, *the mass of the body is equal to the mass of the standard multiplied into the ratio of the standard's acceleration to the acceleration of the body.*

We could, clearly, equate the ratio of the masses of two bodies to the square of the ratio of their reciprocal accelerations, to the square root of the ratio, or to some other function of the ratio, but it proved best to use the definition of mass corresponding to the relationship (2). To explain why, we start by noting how the mass of a body can be measured using a standard. Then we can measure, by formula (3), the masses of several bodies and demonstrate experimentally that the mass of several bodies taken together equals the sum of the masses of the constituent bodies. If we defined the mass of a body so that the ratio of the masses is equal to the square of the ratio of their reciprocal accelerations, then the mass of several bodies taken together would not be equal to the sum of the masses of the bodies. In this case mass would not be additive. So the use of formula (2) as the definition of mass is justified.

4. Force

As has already been said, a body acquires acceleration as a result of interaction with other bodies. The physical quantity that serves as the measure of this influence is *force*. Hence we usually say that a force acts on a body rather than that a body acquires an acceleration under the influence of other bodies. How can the force be expressed in numbers? Sir Isaac Newton resolved this when he formulated one of the most important laws of mechanics, his famous second law.

Newton's second law is given by the equation

$$\mathbf{F} = m\mathbf{a}, \tag{4}$$

where $\mathbf{F}$ is the force, $\mathbf{a}$ the acceleration of a body, and m the mass of the body. Equation (4) does not imply that the force $\mathbf{F}$ acting on a body is dependent on the body's mass or acceleration. Force is not governed by the properties of a body or its motion, it is determined entirely by the nature of interaction of the body with other bodies.

Fortunately, nature only has a limited number of types of interaction and in me-

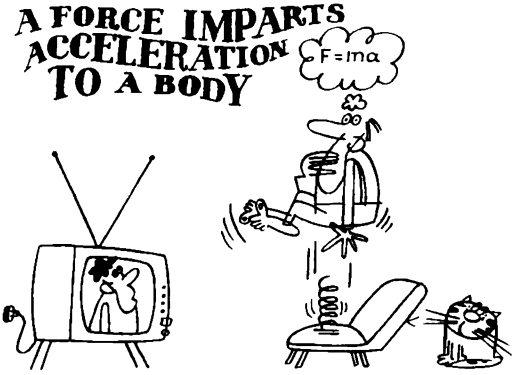

Fig. 5

chanics we only deal with two, namely, gravitational and electrostatic forces.*

The gravitational force is given by the formula

$$F = G\frac{m_1 m_2}{r^2}$$

(Newton's law of universal gravitation). On Earth, the gravitational force is the

* Magnetic forces also emerge when electric charges move, but usually they are much weaker han electrostatic forces.

force of gravity acting on all bodies and directed towards the Earth's centre.

The electrostatic force is

$$F = k \frac{q_1 q_2}{r^2}$$

(Coulomb's law). In mechanics, the electrostatic forces that characterize interactions between charged particles manifest themselves as elastic forces and friction. An elastic force emerges when a body is deformed, that is, when the arrangement of its parts changes (say, when a spring is stretched or compressed). Friction arises when two bodies in contact move relative to each other.

Thus, mechanics usually studies three types of force, namely, gravitational force, elastic force, and friction.

If any of these forces is applied to a body of mass m and causes an acceleration $\mathbf{a}$, the magnitude of the force will be $m\mathbf{a}$. In other words, if an acceleration $\mathbf{a}$ should be imparted to a body of mass m, a force $\mathbf{F}$ equal to $m\mathbf{a}$ should be applied to the body (the direction of the force $\mathbf{F}$ should coincide with the direction of the acceleration $\mathbf{a}$). The force $\mathbf{F}$ could be gravity, an elastic force, friction, or all three acting together. This is the essence of Newton's second law.

Let us see what was the basis for Newton's second law. Let us imagine that two particles A and B interact and are accelerated as a result. Experiments show that these accelerations are opposite in direction.

Clearly, the two interacting particles have equal status in that they can change places. In other words, none of the interacting particles has any advantage over the other. Hence, there should be some physical quantity that is the same for both particles. This quantity can readily be found. The relationship (2) implies that

$$m_A/m_B = a_B/a_A,$$

where m_A and m_B are the masses of the interacting particles and a_A and a_B are the absolute values of their accelerations. Consequently,

$$m_A a_A = m_B a_B. \tag{5}$$

Thus, we have found a quantity that is the same for both interacting bodies. This quantity characterizes the influence the particles exert on each other and is responsible for their accelerations. The existence of such a quantity was the basis for Newton's second law.

Since acceleration is a vector quantity, we can rewrite (5) in the form

$$m_A \mathbf{a}_A = -m_B \mathbf{a}_B.$$

Introducing the notation $m_A \mathbf{a}_A = \mathbf{F}_A$ and $m_B \mathbf{a}_B = \mathbf{F}_B$, we obtain

$$\mathbf{F}_A = -\mathbf{F}_B.$$

The vector quantities $\mathbf{F}_A$ and $\mathbf{F}_B$ Newton called *forces*. Evidently, *the force with* *which a particle A acts on a particle B is equal in magnitude and opposite in direction to the force with which the particle B acts on the particle A*. This is essentially Newton's third law. Sometimes this law is called the law of action and reaction.

All we have said about the physical quantity called force implies that if a force acts on a body (a particle), the net result is the acceleration the body acquires under the action of the force.

5. Momentum

We now know that when two bodies interact, they acquire accelerations that are proportional to their masses. Let us find the quantity that is the same for both interacting bodies and does not depend on the mass of the bodies.

We shall find this quantity if we rewrite Newton's second law in a somewhat different form. Recall that the acceleration of a body can be written as $\mathbf{a} = (\mathbf{v} - \mathbf{v}_0)/t$. Then

$$\mathbf{F} = m\frac{\mathbf{v}-\mathbf{v}_0}{t},$$

whence

$$\mathbf{F}t = m\mathbf{v} - m\mathbf{v}_0.$$

The quantity $m\mathbf{v}$ is called the *momentum* of a body, and the quantity $\mathbf{F}t$ the *impulse* of a force.

Now we can say that when two bodies interact, what is changed are the momenta of the bodies. However, Newton's third law implies that the impulses of the forces

Fig. 6

with which the bodies act on each other are equal and opposite, and hence the changes in the momenta of the bodies must be equal and opposite. So, *the geometric sum of the momenta of interacting bodies remains unaltered* (conservation of momentum). It can be shown that this law holds for any number of interacting bodies. This law is one of the most important in nature.

6. Work and Energy

An impulse is the product of force F and the time t for which it acts. By analogy, we can introduce a quantity that is equal to the product of a force acting on a body and the distance moved by the body. This quantity is called *work*. When the directions of the force F and displacement s coincide, the work is Fs. In general, when the direction of a force and the direction of the distance moved by a body are at an angle α to each other, the work is

$$A = Fs \cos \alpha.$$

In contrast to the momentum of a body, which is a vector, work is a scalar. It can be proved that the work done by the forces acting on a body can always be written as

$$A = \frac{mv^2}{2} - \frac{mv_0^2}{2}. \qquad (6)$$

The quantity $mv^2/2$ is called the *kinetic energy* of a moving body. Equation (6) is essentially a theorem on kinetic energy: *a change in the kinetic energy of a body is equal to the work done by the forces acting*

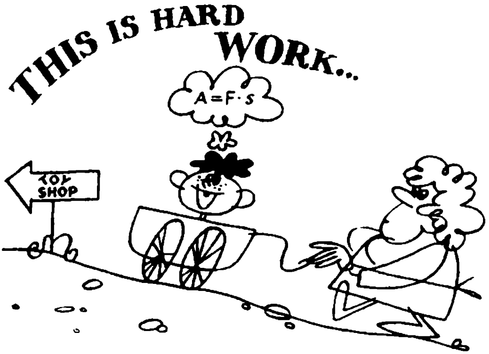

Fig. 7

on the body. Recall that an interaction between bodies is characterized by force and *potential energy.* For potential energy, the following theorem holds true: *a change in the potential energy of interacting bodies, taken with the opposite sign, is equal to the work done by the forces of interaction.*

Thus, we have introduced three important physical quantities, namely, the work done by a force, the kinetic energy of a body, and the potential energy of interacting bodies. It can easily be demonstrated that for a system of bodies interacting via gravitational and elastic forces total energy is conserved, that is, *the sum of the po-*

tential and kinetic energies of the interacting bodies remains unaltered. Conservation of energy and conservation of momentum are the most general laws in nature.

We have illustrated how physical quantities are introduced, limiting ourselves to examples and quantities from mechanics.

Properly chosen physical quantities have made it possible to discover and formulate the important laws of classical mechanics (Newtonian mechanics). These laws are extensively used in engineering. In other branches of physics, quantities are introduced in a similar way.

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