ACADEMICIAN SOLOMON ISAAKOVYCH PEKAR
(to the 90th Anniversary of his Birthday)

Academician of the Academy of Sciences of the Ukrainian SSR S.I. Pekar belongs to that galaxy of outstanding theorists in physics, whose works comprise the basis of the modern solid state theory. S.I. Pekar's papers, being amazing by their profundity and clarity of presentation, are fundamental for quite a number of physical branches. His name is associated with several most important discoveries in solid state physics, the theory of rectifiers, and the theory of electron autolocalized states named as "polarons" by himself. The Pekar waves, the "Pekarian", the prediction of a zero-phonon line became the classic conceptions in physics and remain today as a source of new ideas and progress.

Solomon Isaakovych Pekar was born on March 16, 1917 in Kyiv (Ukraine). His father was a lawyer, his mother was a teacher. In 1933, he entered the Faculty of Physics at the Kyiv University. In those years, there was no specialization in the domain of theoretical physics at the University, but such known theorists as G. Bek and N. Rozen lectured there. The students, who attempted to specialize in theoretical physics, studied at the Faculty of Electrophysics headed by N.D. Morgulis and practiced at the Theoretical Department of the Leningrad Physicotechnical Institute of the AS of the USSR. This department was headed by Ya.I. Frenkel, and it was there that Solomon Isaakovych made his first scientific contacts with theorists.

S.I. Pekar's aspiration to the independent scientific activity has revealed itself as early as in his student's years. In that period, he carried our a research work concerning the determination of the electron distribution function in the gas discharge plasma, provided that inelastic losses were taken into account. In 1938, the results of the work were reported at the session of the Physics Branch of the AS of the USSR and stimulated hot discussions, where the young student defeated his opponents.

After graduating from the University in 1938, S.I. Pekar began to work at the Institute of Physics of the AS of the UkrSSR. First, he started to develop the theory of the rectification at the contact between a metal and a semiconductor. Simultaneously, he continued studying as a postgraduate student under the supervision of I.E. Tamm. The choice of the topic of researches was determined to a great extent by the direction of the experimental activity at that institute. The theory of rectification at that time has been a focus of the attention of many outstanding physicists. In his works carried out in 1939–1941, S.I. Pekar succeeded in developing the most general theory of the rectification in a monopolar system. The progress in the field of heavy currents through a contact was considerable: an exact solution of the problem was obtained and a non-ordinary effect – a transition in the gate layer from the depletion mode to the enrichment one as the reverse bias voltage across the contact grows – was predicted. Almost at once, this effect was confirmed experimentally. S.I. Pekar's work was highly estimated. After it had been discussed at the seminar of L.D. Landau, the latter said: "The self-generation of theoretical physics occurred in Kiev". At the defence of his Ph.D. thesis in May 1941, the 24-year-old Pekar – by the suggestion of V.E. Lashkarev, I.E. Tamm, and Ya.I. Frenkel – was conferred a degree of Doctor in Physics and Mathematics.

The scientific relations of S.I. Pekar, which were established at that time between him and such outstanding theorists as Ya.I. Frenkel, I.E. Tamm, and L.D. Landau, as well as – some later on – M.M. Bogolyubov, strengthened in the years to come. Solomon Isaakovych always wished to discuss the scientific problems he was interested in and the new results with them. The especially close scientific relations were established with L.D. Landau; at Landau's seminars, he craved to approbate his own basic works. Their mutual rapprochement was favored in many respects by S.I. Pekar's work at the theory of polarons.

In the war years, dwelling in Ufa (Russia), where a plenty of the employees of the Institute of Physics of the AS of the UkrSSR worked at that time, S.I. Pekar concentrated his efforts to the development of semiconductor-based devices that were necessary for the front. During that period, the new sides of his talent became revealed; he showed himself as a skilled engineer and designer. The technological problems, which he had resolved, allowed the manufacture of semiconductor-based rectifiers to be intensified significantly.

In 1944, after having returned to Kyiv, S.I. Pekar became keen on the problem concerning the strong interaction between an electron and the crystal lattice. At that time, there existed only a work of L.D. Landau (1933) in this domain, where an idea about an opportunity of the electron capture by the lattice was put forward. Solomon Isaakovych proposed an amazingly exquisite scenario of the strong coupling between an electron and the crystal lattice – in particular, the electron interacts with the macroscopic field of the polarized lattice of an ionic crystal – and, in the framework of this model, developed a complete theory for quasiparticles of a new type, which were called polarons by him. The polaron is an electron, which becomes "dressed" by the field of the polarized lattice and moves across the lattice being accompanied by this polarization "cloud". The mass of such a quasiparticle considerably exceeds that of a "bare" electron, so that its thermal motion is slow. Therefore, S.I. Pekar called such particles "autolocalized". He has demonstrated that their band states are unstable; hence, the formation of polarons does not require overcoming the potential barrier, and they are the majority charge carriers. The idea of a polaron became that "pearl", around which S.I. Pekar and his disciples had grown the theory, which is valid for a number of phenomena related to the electron–lattice interaction; in particular, these include various types of autolocalization, the influence of the lattice on the electron states of impurity centers, and so on. Appreciating those works, Ya.I. Frenkel wrote in 1948: "... the fundamentality of the interpretation and the accuracy of the results obtained are amazing. These works will go down in the history of physics as classical ones. Beyond doubt, they are the most remarkable among the works that have been published by Soviet physicists-theorists for last years".

While estimating the significance of the polaron theory, one should distinguish between two different aspects of its influence on the development of modern physics. The first of them concerns the general issues of theory. The theory of polarons has been formulated by S.I. Pekar as the theory of a continuum, which made it a perfect model for the field theory. S.I. Pekar published his first work devoted to the polaron theory in 1946, i.e. some years before the appearance of the works of Ju. Schwinger and R. Feynman, which gave a powerful impetus to the development of quantum electrodynamics. This Pekar's work appeared in quite a good time, and the significance of the polaron theory as an elementary model of the field theory has shortly been recognized by all theorists. As to Solomon Isaakovych himself, he had focused all his efforts on the case of strong coupling which is described in the adiabatic approximation. In the theoretical physics, the adequate mathematical tool for the description of such a situation was absent at that time, and S.I. Pekar created it. The Pekar equation for the ground state of a polaron and the Landau—Pekar formula for the polaron's effective mass occupy the leading position in this theory. The method developed by S.I. Pekar became the first example of the classical – popular now! – solution of the equations of the nonlinear field theory, and the adiabatic limit studied by him corresponded to the nonperturbative theory, not formulated in the diagram technique. M.M. Bogolyubov was the first who apprehended the role of a polaron in the field theory, having called it a rough diamond, which must be transformed into a brilliant by mathematical polishing; in 1952, he together with S.V. Tyablikov developed an original approach to the adiabatic theory of a particle coupled with a quantized field. The formalism developed by them comprises an adequate basis for producing the higher approximations in the polaron theory, in particular, for constructing the theory of polaron mobility.

In the subsequent years, N. Fröhlich reformulated the theory of polarons in the framework of the standard formalism of field theory and developed the theory of weak coupling. T.D. Lee, F.E. Low, and D. Pines proposed the first variant of the intermediate-coupling theory of a polaron, and R. Feynman suggested a modified variational method, which became widely recognized in due course, for the polaron theory. Owing to all these works, the polaron theory became one of the basic channels, through which the powerful methods of field theory started to penetrate into the theory of solids, thus having enriched the mathematical tool of the latter.

The second aspect consists in the influence of the polaron theory on solid state physics. Before S.I. Pekar's works, the interaction between an electron and the crystal lattice was considered as either the reason of the electron scattering (and the electron was regarded as moving freely between scattering events) or the factor that results in capturing the electron by the lattice, owing to which the particle becomes completely localized. The decisive step was made in S.I. Pekar's works in 1947–1948, where a possibility for the autolocalized electron – a charge carrier – to move forwardly has been considered. In the mutual paper of L.D. Landau and S.I. Pekar which was published in 1948, the effective mass of a polaron was calculated. Hardly could one overestimate the significance of this work.

The success of the strong-coupling polaron theory stimulated a larger and larger scale of researches all over the world. We dwell only on some works fulfilled by S.I. Pekar and his collaborators in the following years. Together with I.M. Dykman, Solomon Isaakovych created the theory of the autolocalization of Wannier—Mott excitons in the framework of the adiabatic coupling model. In 1951, he (together with M.F. Deigen) developed the theory of the autolocalization of electrons in non-polar crystals, where the autolocalization was demonstrated to occur only if the coupling constant exceeds some threshold value, with the radius of autolocalized states being always of the order of the lattice constant. In this work executed practically simultaneously with those of J. Bardeen and W. Shockley, the method of deformation potential has been formulated.

A significant place in further researches was occupied by the theory of polarons with regard for their intermediate interaction with phonons. The progress in this direction was governed both by the internal logic of the theory development and by experiment. Therefore, actual became the creation by S.I. Pekar (together with V.M. Buimystrov and M.O. Krivoglaz) of the effective methods for the intermediate-coupling theory of a polaron in 1957.

Closely related to S.I. Pekar's works on the polaron theory are his works carried out in 1949–1953 and dealing with the theory of impurity centers that interact with the lattice. These works brought about the general theory of the shape of absorption and luminescence spectra for such centers. The characteristic curve plotted by Pekar, which describes the shape of the spectra of impurity centers that interact with dispersionless optical phonons, was named "Pekarian" in the world literature. In 1953, while studying the interaction between impurity centers and phonons with an arbitrary dispersion of the frequencies of oscillations, S.I. Pekar (together with M.O. Krivoglaz) succeeded in predicting, in particular, the existence of an extremely narrow zero-phonon line in the impurity spectra. The analogous line in the x-ray spectra of intranuclear transitions was experimentally discovered and theoretically explained by R. Mössbauer in 1958 and at once became of great importance. The role of zero-phonon lines in optical spectra was elucidated within last decades, after the methods of high-resolution selective spectroscopy had been developed, which has allowed a large inhomogeneous expansion to be excluded from the spectra.

The modern theory of the solid state is unimaginable without the polaron theory as its constitutive part; and S.I. Pekar's works fulfilled in 1946–1948 form, as it was before, its core and continue to amaze us by their aesthetic perfection.

The second large cycle of S.I. Pekar's works is connected with the discovery of additional waves in crystals. This cycle was started by the article "Theory of electromagnetic waves in crystals in which excitons appear" published in 1957. In order to explain the significance of this work, we shall make a remark that has a historical character. It is incredible, but, within the first 25 years of its existence, the theory of electronic excitons had being built as exclusively a quantum-mechanical one, where no electrodynamic effects were taken into account. And all that was despite the fact that the electrodynamic effects were traditionally made allowance for in the dynamics of ionic lattices, where polarization phonons can be regarded to the full extent as "oscillatory excitons"; those effects were studied in that or another form in the works of M. Born and M. Goeppert-Mayer, K.B. Tolpygo, and K. Huang. The description of light-mechanical vibrations – polaritons that arise if the electrodynamic effects are taken into account – was included into textbooks. A simple extrapolation of the electrodynamic approach onto electronic excitons was a merely technical problem, because it did not invoke some basic difficulties. Nevertheless, S.I. Pekar has noticed an important quantitative difference between the electronic and oscillatory excitons, which has led to an interesting physical phenomenon – the emergence of new branches in the spectrum of electromagnetic waves; these waves were named "additional" by S.I. Pekar. The Pekar additional waves arise near exciton resonances. In the denominator of the dispersion formula for them, the frequency-dependent terms almost completely compensate one another; therefore, the role of the term, which is associated with the kinetic energy of the exciton and contains its momentum, increases correspondingly. As a result, the order of the dispersion equation for the electronic polariton – a hybrid "photon–exciton" – increases, and a new root appears; it is this root that is responsible for the emergence of additional waves. A difference between the electronic and oscillatory excitons manifests itself in that the typical values of effective masses for the former are two orders of magnitudes smaller than those for the latter; so that the relevant kinetic energies are two orders of magnitude higher, provided the same momenta. It is because of this smallness of the mass, that the wavelengths of the corresponding additional waves fall within the macroscopic band, and the phenomenon can be completely described in the framework of macroscopic electrodynamics.

Therefore, the work published in 1957 contained, in essence, the theory of crystal optics for excitons, where the retardation effects were made allowance for, and predicted an absolutely new physical phenomenon – additional waves. In so doing, the spectral range, where those waves should be searched for, was neatly indicated. The result obtained was striking, if for no other reason than the idea of linear crystal optics as the accomplished discipline supported by numerous experiments for a century. The unexpectedness of the result obtained was figuratively expressed by A.I. Anselm, who said that it was as good as "to find a cep in the Nevski Prospect".

The theory developed gave rise to a number of consequences which admitted a direct experimental verification. Besides the very fact of the existence of additional waves, these consequences included a possibility for the dielectric permittivity to possess a strong dispersion in the range, where the absorption was practically absent; the light transmission through a crystal in the frequency range which was traditionally considered as the range of total reflection (an analog of the "residual ray" band in the crystal optics of lattices); and so on. There also emerged a number of theoretical issues concerning the inclusion of the additional wave theory into macroscopic crystal optics. Those issues caused a vivid discussion, which, in its turn, drew attention of many known physicists to the problems arisen. The problem concerning the character of modifications, which had to be introduced into the phenomenological theory for the latter to describe the appearance of additional waves, was resolved unequivocally. The origin of their occurrence, which consists in the dependence of the exciton energy on its quasi-momentum, is treated in terms of the phenomenological theory as the spatial dispersion of yjr dielectric permittivity, i.e. as its dependence on the photon wave vector. But, in contrast to the weak spatial dispersion, which exists in a wide frequency range and predetermines the natural optical activity in crystals with noncentral-symmetical structure (i.e. it gives rise to corrections in the law of propagation for ordinary waves), the spatial dispersion is so strong near exciton resonances that it is a source of the appearance of new waves. It is also important that, for the spatial dispersion to be introduced into the tensor of dielectric permittivity, it is insufficient to know the symmetry of the crystal class only, but the symmetry of a specific exciton transition has to be taken into consideration as well. Therefore, the phenomenological description in this case must inevitably consider the data that are inseparably associated with the microscopic theory. Much more difficult turned out the problem of additional boundary conditions. Such conditions inevitably arise in connection with the fact that making allowance for the spatial dispersion increases the order of the system of Maxwell equations. S.I. Pekar proposed an adequate solution for this problem.

In 1986, the pioneering work of S.I. Pekar published in 1957 and dealing with additional waves in crystals, was officially recognized as a discovery. The active researches of S.I. Pekar in the field of crystal optics, which concerned the excitonic absorption, were carried on in the 1960s and 1970s and generalized in the monography *Crystal Optics and Additional Light Waves* (Naukova Dumka, Kyiv, 1982) [English version: *Crystal Optics and Additional Light Waves* (Benjamin/Cummings, Menlo Park, Calif., 1983)].

On the other hand, S.I. Pekar paid a large attention during that period to the development of the new directions of scientific researches which were based upon his original ideas.

In 1965, Solomon Isaakovych published a paper, where he put forward an idea of the amplification or generation of ultrasound in a non-piezoelectric crystal. The idea was based on the electrostrictive interaction between a deformation and an external electric field. The effect turned out especially large for crystals with a high dielectric permittivity; it can exceed similar effects produced by other mechanisms of electron-phonon interaction. It is interesting, that in modern nanostructures, where very high electric fields are realized, the Pekar mechanism of the electron–phonon interaction is responsible for the electron energy relaxation at low temperatures.

In 1966–1969, S.I. Pekar executed a cycle of works concerning the study of the properties of gases with a high concentration of electronically excited atoms (molecules). It was shown that a substantial role in such systems belongs to the dipole-dipole interaction which is much stronger than the Van der Waals one. It was established that deviations from the ideal behavior in gases with a high concentration of excited particles begin to manifest themselves even at low pressures; phase transitions into states which are characterized by gas stratification into two phases with different concentrations of excited particles can occur; condensation and other effects become possible. These works have started the researches of the photophases of a substance and the transitions between them.

In 1969, S.I. Pekar proposed an essentially new type of gas lasers, which are based on the application of photo-stimulated chemical reactions. Pekar's idea was based on a capability to stimulate the elementary events of chemical reactions, at which the electronic reconstruction of initial molecules caused by their collisions with one another and the formation of reaction products are accompanied by a phototransition. Photons with a corresponding frequency stimulate photo-induced transitions and give rise to such reactions which, in their turn, produce new photons.

S.I. Pekar was endowed with a bright and original talent which revealed itself in both the choice of subjects for his principal works and the approach he applied to solve the problems. The relations between his works and the works of his contemporaries published at that time were almost imperceptible at first; his works appeared isolated, and it was not clear how they appeared. But after several years had passed, the picture changed. Their close relations to the actual state of science became obvious. The influence of Pekar's works on other researchers became well pronounced; and it seemed already unclear why the necessity of carrying out such a work was not obvious at once.

Solomon Isaakovych had a rare structure of his thinking which allowed him to estimate the works of others and to do his own works, not confronting them with the works that were published recently, but proceeding from "the first principles". Every time, he logically passed through the whole succession of reasons, from "the principles" to a specific work. This allowed him, by avoiding the widespread mistakes or incorrect ideas, to find the most consecutive way of thought.

The activity of S.I. Pekar is well-known not only due to his scientific results. He was an excellent teacher and devoted much his attention to the training of young scientists. This aspect of his activity resulted in the creation of the first school of physicists-theorists in Kyiv. In 1944, S.I. Pekar revived the Chair of Theoretical Physics at the Kyiv University. In 1948, a specialization, in which physicists-theorists could be trained, was introduced for the first time at the Chair. The courses of theoretical physics and quantum mechanics, which Solomon Isaakovych lectured, had a huge influence on several generations of students of the Faculty of Physics at the Kyiv University and attracted them to the fundamentals of modern science. His lectures were distinguished by the extreme clarity and profundity and often became remarkable events for the audience.

Simultaneously, S.I. Pekar created and headed the Department of Theoretical Physics at the Institute of Physics of the AS of the UkrSSR and, from 1960, at the Institute of Semiconductor Physics of the AS of the UkrSSR. He played the role of a focus, around which a group of collaborators and post-graduate students rallied. The disciples of Solomon Isaakovych and the disciples of his disciples comprised the basis for the groups of theorists in Kyiv, Kishinev, and Donetsk. Many theorists, who work nowadays at leading scientific institutions, not only in the former Soviet Union but oveer the world, consider themselves as belonging to "S.I. Pekar's school".

According to the initiative and under the direction of S.I. Pekar, the All-Union conferences on the theory of semiconductors had been organized regularly for thirty years. Those conferences had a great influence on the development of researches in this field, as well as on the training of young theorists.

The scientific merits of S.I. Pekar were recognized by his election as Academician to the AS of the UkrSSR in 1961, by awarding the State Prize of the UkrSSR in

1981. He was decorated with two Orders of Labor Red Banner and an Order "The Sign on Honor".

The life of Solomon Isaakovych regular and quiet, as was seemed from the outside, was not easy. Even in the first post-war years, when his excellent scientific achievements created some type of an aura around him, he had quite often to spend forces for a struggle against the scientific conservatism, by defending – for his department and himself – the right to be engaged in the activity, which obtained the general recognition in due course. But Solomon Isaakovych never lost his optimism, inherent sprightfulness, and presence of mind. All that was directed toward working; and he attempted to habituate his colleagues to the same concentrated purposeful work. At the same time, he did it always mildly, without any pressing, but by the personal example. He had been working in such a way almost up to the end, to his death on July 8, 1985.

This essay would remain incomplete if we do not mention the remarkable personal, specifically human features of Solomon Isaakovych. The impressing integrity, independence of thoughts, profound adherence to principles, lack of vanity, and spiritual cleanliness were always inherent to him. Those qualities created a specific scientific and ethical atmosphere both around him and at the Department of Theoretical Physics, in particular. He always avoided insignificant administrative conflicts but was irreconcilable in fundamental issues, while estimating the level and the quality of scientific works, choosing the subjects for scientific researches, deciding the destinies of young scientists. Just these features of S.I. Pekar opened a way to science for many young theorists and determined their scientific style and ethical criteria. While discussing the scientific problems, he was exacting and fair; he aimed at revealing weak points of the works under discussion and, at the same time, attempted to render the maximal assistance for overcoming the difficulties arisen. Especially exacting was Solomon Isaakovych with respect to his own works, where all details had been thought through carefully. Although not being a "communicative" person, who easily and quickly made acquaintance with unfamiliar people, he was, at the same time, very benevolent and democratic intrinsically. Those wonderful human qualities of Solomon Isaakovych revealed themselves to the full extent before those, who had happiness to be near him.

Disciples of Academician S.I. Pekar