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Professor Solomon Isaakovich Pekar

To 100-th anniversary of his birthday

Professor Solomon Isaakovich Pekar belongs to the pleiad of outstanding physicists-theorists whose works have been made considerable contribution to the fundamentals of the modern theory of solids. Being of a great profundity and lucidity, Pekar's works prove to be the principal in a number of scientific directions. His name is tightly bound with several the most important discoveries in physics of solids, including theory of rectifiers and autolocalized states of electrons that were named by him as "polarons", the Pekar's waves, prediction of the zero-phonon line in spectra of crystals and many others. These achievements are considered as classical results in physics, and up to date they serve as a source of new physical ideas.

When estimating the significance of polaron theory creation, it is necessary to emphasize two different aspects of its influence on development of modern physics.

The first should be considered as the contribution to a general basis of the theory. Indeed, the theory of polarons was formulated by S.I. Pekar as a continual theory, which made it to be an ideal model for the field theory. His first work devoted to polarons was published by Pekar in 1946, *i.e.*, several years before appearance of works by J. Schwinger and R. Feynman, who provided a powerful pulse for development of quantum electrodynamics. This Pekar's work was rather timely, and the significance of the theory describing polaron as the simplest model in the field theory was apprehended by all theorists. Then, Solomon Isaakovich focused his efforts on the case of strong coupling that can be described in the adiabatic approximation. In that time, the adequate formalism for description of this case was absent in theoretical physics, and it was S.I. Pekar who created it. Pekar's equation for the polaron ground state and the formula by Landau–Pekar for the effective mass of polaron comprises the central place in this theory. This formalism developed by S.I. Pekar became the first example of currently popular semiclassical solutions for equations in the non-linear field theory. The studied by him adiabatic limit corresponds to the non-perturbative theory that was impossible within the framework of diagram technique. M.M. Bogolyubov was the first who appreciated highly the role of polaron in the field theory and compared it with a diamond that should be transformed into the brilliant by using "mathematical grinding". M.M. Bogolyubov in cooperation with S.V. Tyablikov (1952) has created the original approach to the adiabatic theory of a particle interacting with a quantized field. The developed by them formalism serves as the adequate basis for obtaining the highest approximations in the polaron theory, in particular, for creation of the theory describing the polaron mobility.

In succeeding years, H. Fröhlich has reformulated the polaron theory within the frameworks of the standard formalism inherent to the field theory and has developed the theory of weak coupling. T.D. Chi, F.E. Low and D. Pines have offered the first version of polaron theory with intermediate coupling, as well as R. Feynman has created his variational method in the polaron theory, which later has acquired wide popularity. Owing to all these works, the theory of polarons became one of the main channels, via which the powerful methods of the field theory began to penetrate into the theory of solid state, enriching its mathematical instruments.

The second aspect of the significance of the developed ideas is the effect of polaron theory on physics of solids. Before Pekar's works, interaction with lattice was considered only as a source of scattering (in particular, it was believed there that, between scattering acts, electron moves as a free particle). The crucial step was made in Pekar's works (1947–1948), where he considered the translation motion accessible for autolocalized electron as a carrier of the current. In the work by L.D. Landau and S.I. Pekar (1948), the effective mass of the polaron was calculated. The significance of this work is difficult to overestimate.

In 1951, S.I. Pekar together with M.F. Deygen developed the theory of electron autolocalization in non-polar crystals and showed that this autolocalization process occurs only in the case when the coupling constant exceeds some threshold value. As this takes place, the radius of these autolocalized states is always of the order of lattice parameter. When performing this work, the method of deformation potential was introduced practically simultaneously with J. Bardeen and W.B. Shockley.

The works on the polaron theory were followed by Pekar's investigations (1949–1953) devoted to the theory of impurity centers interacting with lattice. As a result of these works, there developed was the general theory of absorption and luminescence spectra of impurity centers. The derived by Pekar characteristic curve describes the spectral shape of these centers interacting with dispersionless optical phonons, and in the world literature it is known as "Pekarian". When studying interaction with phonons possessing an arbitrary dispersion of vibration frequencies (1953, together with M.O. Kryvoglaz), he predicted, in particular, the existence of the extremely narrow zero-phonon line in spectra of impurity centers. The analogous lines in X-ray spectra of intranuclear transitions were experimentally found and explained by R. Mössbauer in 1958 and soon acquired its great significance. The role of the zero-phonon lines in optical spectra was appreciated in recent decades after development of the methods for selective spectroscopy with high resolution.

The next great cycle of Pekar's works is related with discovery of additional waves in crystals. This cycle was opened by the article "Theory of electromagnetic waves in crystals, where excitons arise" published in 1957. To explain the significance of this work, let us begin from a remark of historical character. It seems improbable but it is the fact that, for the first 25 years of its existence, the theory of electron excitons was built exclusively as the quantum-mechanical one, where electrodynamical effects were not taken into account. And this situation took place despite the fact that in the dynamics of ion lattices (where polarization phonons can be certainly considered as "vibration excitons") electrodynamical effects were traditionally taken into account and in various forms studied in the works by M. Born, M. Göppert-Mayer, K.B. Tolpygo and K. Huang. Light-mechanical vibrations – polaritons arising after account of electrodynamical effects were introduced to handbooks.

Simple use of the electrodynamical approach to electron excitons was a pure technical task – it was not related with principal problems. However, S.I. Pekar noticed an important quantitative difference between electron and vibration excitons, which results in interesting physical phenomenon – appearance of new branches in the spectrum of electromagnetic waves that were called by him as "additional waves". These waves occur near exciton resonances, in the dispersion formula denominator of which frequency terms are practically reduced in full. Therefore, it becomes dominating the term related with the exciton kinetic energy that contains its momentum. As a result, the order of dispersion equation for electronic polariton (*i.e.*, a hybrid "photon–exciton") raises, and there observed a new root responsible for these additional waves. The difference between electron and vibration excitons lies in the fact that electronic excitons possess typical values of effective masses two orders lower than those of the vibration ones (and, consequently, the kinetical energies at the same momentum are two orders higher). It is due to this small mass value that the wavelength for respective additional waves falls into the macroscopic range, and therefore this phenomenon can be totally described within the framework of macroscopic electrodynamics.

At the same time, great attention in this period was paid by S.I. Pekar to development of a set of new directions in investigations based on original ideas formulated by him.

In 1965, Solomon Isaakovich published the work where he offered the idea to enhance or generate utrasound in non-piezoelectric crystals. This idea was based on electrostriction interaction of deformation with external electric field. This effect is especially pronounced in the crystals with a high value of dielectric permittivity and can exceed similar effects related with other mechanisms of electron-phonon interaction. It is noteworthy that in up-to-date nanostructures where extremely high electric fields are realized Pekar's electron-phonon mechanism is responsible for relaxation of electron energy at low temperatures.

In 1966–1969, S.I. Pekar and V.M. Mal'nev performed the cycle of works devoted to properties of gases with a high concentration of electron-excited atoms (molecules). It was shown by them that in these systems an essential role can be played by dipole-dipole interaction, which is considerably stronger than the Wan-der-Waals one. It was ascertained that, in gases with a high concentration of excited particles, departure from "ideal gas" occurs even at low pressures, and there is a phase transition into the nonuniform state of the gas with two phases of different densities of the excited particles, *i.e.*, condensation and other effects. These works initiated the origin of investigations aimed at substance photo-phases and transitions between them.

In 1969, S.I. Pekar offered the principally new type of the gas lasers, operation of which is based on using the photo-stimulated chemical reactions. Pekar's idea relies on the possibility to stimulate elementary acts of chemical reactions, when electron photo-transformation occurs under collisions of initial molecules (which is related with creation of reaction products). Photons of a corresponding frequency cause stimulated photo-transitions and induce chemical reaction that, in their turn, causes the appearance of new photons, *etc*.

The significance of Pekar's activity is explained not only by his scientific results. He was an extraordinary pedagogue and for many years paid great attention to education of young scientists.

This essay would be incomplete, if being finished without mentioning the splendid personal, really human qualities inherent to S.I. Pekar. He always had intrinsic striking integrity, independence of thoughts, deep adherence to his principles, absence of vanity, purity of his soul. These qualities created specific scientific and ethical atmosphere around him, especially in the department of theoretical physics. He always avoided small administrative conflicts, but he was irreconcilable in the principle matters: when estimating the level and quality of considered scientific works, when choosing the scientific subject areas and deciding the fate of young scientists. These Pekar's qualities opened a way to science for many young theorists, defining their scientific style and ethical criteria. When discussing the scientific problems, he was particularly exacting and correct, aspired to disclose weak features of discussed works, and, at the same time, to provide the maximum possible help to overcome the arising difficulties. Especially exacting he was concerning his own works and thoroughly thought all details. These remarkable human qualities of Solomon Isaakovich were opened in full for those who was happy to know him personally.

The main dates of S.I. Pekar's life

1917, 16 March – born in Kyiv.
1933 – entered the physical department of Kyiv university.
1938 – completed his studies at Kyiv university.
1938 – joined to the Institute of Physics, Academy of Sciences of UkrSSR.
1941, May – was conferred with the doctor's degree (Phys&Math).
1944 – revived the chair for theoretical physics at Kyiv university.
1944 – created and headed the theoretical department at the Institute of Physics, Academy of Sciences of UkrSSR.
1946–1948 – created the theory of polarons.
1957 – formulated crystal-optics of excitons.
1960 – began to work at the newly-created Institute of Semiconductors, Academy of Sciences of UkrSSR.
1961 – was elected as academician of Academy of Sciences of UkrSSR.
1981 – awarded with the State Prize of UkrSSR.
1985, 8 July – died in Kyiv.

Selected bibliography

1. Pekar, S.I. Journ. of Physics USSR, **10**, 341 (1946).
2. Pekar, S.I. (1951) Research in Electron Theory of Crystals (Moscow), English Edition: US AEC Transl. AEC-tr-555 (1963).
3. Pekar, S.I. On the computation of polarons by direct variational methods. West Concord, Mass., Morris D. Friedman (1955).
4. Pekar, S.I. Zh. Eksp. Teor. Fiz. **33**, 1022 (1957) [Sov. Phys. JETP **6**, 785 (1958)].
5. L.D. Landau and S.I. Pekar, Effective mass of polaron, Zh. Eksp. Teor. Fiz. **18**, 419–423 (1948) [in Russian], English translation: Ukr. J. Phys., Special Issue, **53**, 71–74 (2008).
6. Pekar, S.I. (1982) Crystal Optics and Additional Light Waves (Naukova Dumka, Kiev) [in Russian]; English Edition: (1983) (Benjamin/Cummings, Mento Park, CA).

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