

PERSONALIA

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Leonid Veniaminovich Keldysh (on his 80th birthday)

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Leonid Veniaminovich Keldysh

Leonid Veniaminovich Keldysh, a full member of the Russian Academy of Sciences (RAS), an outstanding expert in physics, the author of classic theories, celebrates his 80th birthday on 7 April 2011.

After his graduation from Moscow State University in 1954, Keldysh joined the Lebedev Physics Institute (FIAN) postgraduate program under the supervision of V L Ginzburg. Ever since that moment, Keldysh's life in research has been inseparable from the Division of Theoretical Physics of FIAN (now the Tamm Division of Theoretical Physics, FIAN).

Keldysh's career in physics began when semiconductor electronics was coming into being, in the 1950s. Relatively low concentrations (in comparison with metals) of charge carriers — 'free' electrons and 'holes' — and the miniature size of semiconductor devices produce conditions in which even weak external signals create strong internal fields and cause essential deviations of the electron energy distribution from the equilibrium distribution. The challenges for theorists brought about by the physics of semiconductors have to a large extent dictated the main directions of Keldysh's research. These are the quantum theory of condensed matter, particularly the strongly nonequilibrium state and nonlinear response to strong external fields (electric, electromagnetic, pressure, etc.), covering accompanying transformations of the electronic spectrum and metal–insulator transitions. From the outset of his career, Keldysh worked closely with groups of experimentalists, primarily from the FIAN Department of Semiconductor Physics.

One of Keldysh's most important first results was the introduction of the concept of inelastic quantum tunneling of electrons, i.e., the tunneling accompanied by the emission or absorption of phonons (quanta of vibrations of the crystal lattice). He showed that depending on the details of the electronic spectrum of a specific semiconductor, the contribution of this process can be many orders of magnitude greater than the contribution of the 'direct' (phononless) tunneling. A year later, the tunneling effect in semiconductors was discovered experimentally and formed the basis of a new type of device. And it became immediately clear that the phonon-assisted tunneling is dominant in many semiconductors, including the most important ones, silicon and germanium. This work also launched so-called inelastic tunneling spectroscopy, i.e., investigation of phonons, magnons, and other quasiparticles in crystals based on the role they play in the tunneling current.

After this, Keldysh applied similar ideas to the process of light absorption by semiconductors in the presence of an external electric field. He was able to show that this significantly changes the absorption spectrum, and absorption becomes possible for the photons for which the crystal is transparent in the absence of the electric field. This shift of the absorption edge in the electric field was also soon discovered experimentally and found wide application both in various optoelectronic devices and in the optical spectroscopy of solids. This phenomenon is currently known as the Franz–Keldysh effect.

After the creation of lasers capable of generating immensely strong electromagnetic fields in the optical frequency range, Keldysh studied the action of these fields on electrons in both solids and atoms. In contrast to the simplest approach applicable only to the case of a weak radiation field and based on taking the impact of light on the atom into account as a weak perturbation, Keldysh's theory was based on a totally different approach: an accurate description of the interaction of an electron with a strong radiation field. He found that two familiar phenomena — the tunneling effect and the photoelectric effect — are essentially two limit cases of a single more general process, and they transform smoothly into each other in response to changes in the parameters of the imposed field, its strength or frequency. The tunneling effect is the limit case of strong fields and relatively low frequencies, and the photoelectric effect is the limit case of weak fields and high frequencies. Even though

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the results of this work seemed baffling, they were fully confirmed by subsequent experiments and have become the basis of our current understanding of the effect of high-power laser radiation on atoms, molecules, and solids. The proposed approach was substantially developed both in Russia and in other countries. One of the fields that actually grew out of these results was the generation of ultrashort, attosecond pulses. Owing to the very strong nonlinearity of tunneling ionization, tunneling transitions occur mainly in a short time interval when the wave field reaches a maximum. Therefore, the process can be very fast in strong fields, of the order of the atomic time, which allows exploring intra-atomic processes in the attosecond range. The 1964 paper [''Ionization in the field of a strong electromagnetic wave,'' *JETP* **47** 1945 (1964)] has a very high citation index, and researchers continue to return to it: nearly 800 new citations have appeared over the past three years.

Many research problems that attracted Keldysh included processes involving interacting electrons in strong external fields. A difficulty encountered in such problems was to find a method of the description of nonequilibrium states and their kinetics. Therefore, when he was writing his PhD thesis (unusually late: 10 years after the start of his postgraduate studies), Keldysh started developing a new theoretical technique for describing the impact of strong fields on the quantum systems of many interacting particles. He was able to construct such a technique based on so-called nonequilibrium Green's functions in 1964. The impact of the work itself was such that Keldysh was immediately awarded the higher degree of DSc. The diagram technique developed by Keldysh is now widely used in various branches of theoretical physics: low-temperature physics and the physics of quantum fluids, including superconductivity, the physics of metals, semiconductors and nanostructures, laser physics, quantum field theory, and quantum cosmology. In fact, this formalism allows extending the celebrated Feynman diagram technique to the entire quantum kinetics. This paper, also published in *JETP* in 1964 (vol. 47, p. 1515) is, together with the paper on the ionization of atoms, one of Keldysh's best-known papers. These two papers published in *JETP* in 1964 are among the ten most cited papers by Russian physicists.

The electron spectrum in the quantum systems of many interacting particles essentially depends on the distribution of electrons over states, and therefore deviations of the system from equilibrium under external actions can lead to a substantial modification of the spectrum, and sometimes even to its qualitative rearrangement accompanied by a change in the physical properties of the object. In the mid-1960s, Keldysh published a series of papers on the collective properties of nonequilibrium electron–hole systems and phase transitions in them. He proposed a model (jointly with Yu V Kopaev) in which electrons and holes form bound electrically neutral pairs; this is accompanied by the spectrum restructuring into that of a semiconductor type. Various modifications of this model, sometimes called the excitonic dielectric model, are widely used to explain various metal–semiconductor transitions. In 1967, Keldysh formulated a hypothesis that the ground state of a nonequilibrium electron–hole system in highly excited semiconductors must not be the exciton system but is instead a collective bound state of the liquid metal type, which became known as the electron–hole liquid (EHL). The EHL is a very specific two-component (electrons and holes) degenerate Fermi liquid with the concentration and work function (binding energy) well defined for particles of each type, and also with surface tension. The phenomenon was soon observed experimentally and studied in detail in germanium and silicon. It turned out that it exists in the form of mobile stable metal drops that move freely inside a semiconductor crystal at speeds up to the speed of sound.

We need to specially mention the brilliant idea formulated by Keldysh in the mid-1960s regarding the possibility of modulation of the electronic properties of semiconductors by ultrasound. This was essentially the idea of creating superlattices — that the laws of motion of electrons in semiconductor crystals can be modified and controlled using spatially periodic modulations of the crystal properties. The present-day technology allows modulating the composition of structures in a wide range, and modern solid state physics is unimaginable without superlattices.

Keldysh continues to be actively interested in the interaction between excitons and strong electromagnetic fields in modern semiconductor structures; this opens new opportunities to control the properties of polaritons (bound states of excitons and photons). He has studied the optical response of dielectric and semiconductor quantum wells and the processes of interaction between high-power electromagnetic pulses and excitons in nanostructures.

Keldysh's work played a crucial role in the development of solid state physics, serving as the starting point for a number of scientific fields. His research achievements were officially lauded on numerous occasions: he received the Lenin Prize and the Prize of the European Physical Society, and was elected full member of the RAS and a member of the National Academy of Sciences of the USA. Keldysh's work continues to receive recognition. In the last decade, he became the first physicist to win the nongovernmental Triumph Prize (2001) and was awarded the Prize of the Russian President for Achievement in Education (2003) and the Vavilov Gold Medal (2005). Very recently, Keldysh won the RUSNANOPRIZE-2009 International Award in Nanotechnologies in the category of Nanoelectronics for ''Pioneering studies of semiconductor superlattices and tunneling effects in semiconductors, widely used in the technology of nanoelectronic devices, especially in molecular-beam epitaxy.''

Teaching has always occupied an important place in Keldysh's life. Ever since 1965, when he became a professor at Moscow State University, he has been closely associated with the Faculty of Physics there. He was the chairperson of quantum radiophysics there for more than two decades, from 1978 to 2001, and continued to deliver the lecture course ''Interaction of radiation with matter.'' Those who have been privileged to work with Keldysh are familiar with the high standards he applies to his own work. As happened often, he would obtain an interesting original result but would not publish it, passing it on to one of his students for further development; consequently, many of his results were 'circulating' and were essentially incorporated into the work of his students. His role as a constant participant in Ginzburg's famous seminar was also very important; his profound critical remarks helped many authors of future publications. Therefore, his role in building his science school is, in fact, considerably wider than what would be suggested by the formal list of his publications. Many of his students have become well-known theoreticians and have received PhD and DSc degrees, and several of them have been elected to RAS membership. They are working actively in the fields whose foundations were built by Keldysh or were outlined by him for his students.

As a citizen who feels personal responsibility for the survival and advancement of science in Russia, Keldysh has had to carry a heavy administrative burden, which has distracted him from his scientific activities and for which he has had no great desire; nevertheless, he has managed to accomplish a very great deal in this unfamiliar field of activities. At the end of the 1980s and the beginning of the 1990s, Keldysh headed FIAN's Theoretical Physics Division and in 1989 was elected FIAN director; he was successful in not allowing the institute to close, despite very hard times. In 1991–1996, Keldysh held the position of academician secretary of the RAS Division of Physics and Astronomy and did everything in his power to help preserve the scientific potential of the country.

We toast Leonid Veniaminovich Keldysh from the bottom of our hearts on this occasion, and wish him excellent health and new creative achievements.

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A V Gurevich, Yu V Kopaev, O N Krokhin,
E G Maksimov, G A Mesyats, V I Ritus,
V A Rubakov, O V Rudenko, M V Sadovskii