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Works by D. I. Blokhintsev and the Development of Quantum Physics

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Abstract—In connection with the 100th anniversary since the birth of D. I. Blokhintsev (January 11, 1908–January 27, 1979), a brief survey is given of the development of quantum physics in the period in which he formulated his views on physics and science as a whole. Studies by Blokhintsev in the fields of solid state and statistical physics and related problems are considered in the context of modern development of these fields of physics. His studies devoted to interpreting quantum physics and general problems in the development of science are touched upon briefly.

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1. INTRODUCTION

The name of Corresponding Member of the Academy of Sciences of the USSR D. I. Blokhintsev (January 11, 1908– January 27, 1979) is widely known in Russia and abroad. His books are being republished; information on his biography and his scientific heritage can be found in multiple papers and collections of papers [1–6]. However, for many scientists, his name is related mainly to his works in the field of atomic and nuclear physics, applied acoustics, participation in the creation of the first nuclear power station in Obninsk, reactor construction, and multiple studies in high energy and elementary particle physics. It is not so well known that at first he wrote some quite interesting and important works in the field of quantum solid state physics and statistical physics. The objective of this paper is to recall these papers and correlate them with certain modern directions in condensed matter and quantum physics. To do all this, the scope of this summary had to be considerably extended to include the analysis of a number of works by other researchers and describe the general situation in quantum physics in the 1930s–1950s.

It is known [7–14] that over a hundred years have passed since the quantum hypothesis was formulated by M. Planck in 1900. According to Jammer [10], by 1928, quantum theory had acquired a certain maturity. The first manual in wave mechanics was the publication of papers written by Schrödinger in the form of a book in late 1926. Jammer said that the development of quantum mechanics after 1927 and its applications to molecular, solid state, condensed matter, statistical, and nuclear physics demonstrated an infinite generality of its methods and results—that in reality, no other physical theory gave a key to explaning and calculating such a wide array of dissimilar phenomena and reached such good agreement with experiment as quantum mechanics has done [10].

In Moscow, M.A. Leontovich and L I. Mandelstam in 1928 published a fundamental work "On the Theory of the Schrödinger Equation" [15, 16]. In 1932, Ya.I. Frenkel [17, 18] and V.A. Fock [19] published textbooks on quantum mechanics. K.V. Nikol'skii wrote a solid monograph [20] devoted to detailed formulation of the achievements in quantum mechanics and its applications to atomic and molecular physics (the book contains 45 pages of spectroscopic tables). At the end of the first chapter, Nikol'skii noted: "The main literature for studying quantum mechanics consisted of papers by different authors published in 1926–1932 in the main German, British, and American journals" [20]. The book by W. Heisenberg *Physical Principles of Quantum Theory* [21] was published in Russian in 1932. Dirac's book [22] was also published in Russian in 1932 (see the review of the English edition by M.P. Bronstein [23]). In 1933, a textbook on quantum mechanics written by A. Marx [24] was translated into Russian (references to this work can be found in Blokhintsev's works). Three Nobel Lectures by Heisenberg, Schrödinger, and Dirac were published in 1934 [25]. In 1935, R.W. Gurney published his book [26]. Thus, mastery of the latest achievements in the field of quantum physics was very fast, and promptness of translation made them available to a wide circle of students and young researchers. Blokhintsev entered the Physics Faculty of Moscow State University (MSU) in 1926. "In 1925, Mandelstam was invited to the university as the director of the chair of theoretical physics and optics at the initiative of S.I. Vavilov. Academician Mandelstam created a large scientific school at MSU" [27]. Thus, Blokhintsev's student years brought him great and fruitful experience in communicating, at lectures and in laboratories, with brilliant and interesting representatives of physical sciences of the time. Later, Blokhintsev recollected those years as follows: "In Moscow, the Physics Faculty of Moscow State Univer-

sity and the newly created Physics Institute were the center (of mastering quantum mechanics)….I met many people who did not think of their career, for example, Vladimir Konstantinovich Arkad'ev and his wife Aleksanra Andreevna Glagoleva-Arkad'eva. We began working for them as a students. We had the impression that those people worked in science like children, sincerely and with enthusiasm" [28]. Blokhintsev considered Mandelstam, Vavilov, N.N. Luzin, D.F. Egorov, and I.E. Tamm his teachers. Tamm had the greatest influence on Blokhintsev and became his scientific advisor in postgraduate studies. S.M. Rytov in his memoirs mentioned Tamm's students: S.P. Shubin, Blokhintsev, and S.A. Altshuler [29].

Blokhintsev was certainly influenced strongly by Mandelstam [30] and learned a lot from him [31], in particular, his breadth of views on physics as an indivisible science, lecturing skills, understanding the importance of a scientific school, organization of science, etc. As was noted in [27], "Lectures and seminars given by Mandelstam at the university in 1925–1944 were of special importance. They were devoted to a wide field of the most topical problems in physics in which the lecturer delivered an extremely deep analysis of the modern state of the art without concealing existing difficulties, and he outlined original solutions to very complex problems. These lectures attracted a wide audience of physicists of various ages and ranks from all parts of Moscow." Mandelstam delivered his famous lectures on the principles of quantum mechanics (the theory of indirect measurements) in spring of 1939 [32]. He intended to read a series of lectures on the connection of the mathematical tools of quantum mechanics and its statistical interpretation, causality, etc., as a continuation of these lectures; the basis of this series of lectures was supposed to be the work written by Neumann [33] (see [34] for more details on lectures delivered by Mandelstam). Later, this program was realized by Blokhintsev. Among others, M.A. Markov, I.M. Frank, S.I. Vernov, S.V. Vonsovskii, E.L. Feinberg also belonged to the Mandelstam–Vavilov–Tamm school. Markov described the following interesting episode. Once, quite unexpectedly, Leontovich suggested that I become a postgraduate student under Vavilov. I remember him saying something to the following: 'I don't know how you are with theory. Blokhintsev here has proved himself a theoretician. I see that you're good with your hands and could become an experimentalist.' That was how I became a Vavilov's postgraduate student." [35]. The esteemed Markov was not very accurate in his prediction: he became a theoretician [36] and worked mainly on the most fundamental problems, while Blokhintsev, without leaving theory, switched easily to applied and engineering problems when required by the needs of the nation [1–4]. It was not by chance that Frank called his memoirs about Blokhintsev *Scientist and Engineer* [37]. Frank recollected that in the 1920s, "Blokhintsev, Markov, Sh.I. Drabkina, myself, and some other students studied at the same group at MSU. His student life behind him, Dmitrii Ivanovich was sent to Leningrad to intern at the Svetlana plant. He received a complex experimental task to perform spectral analysis on the filament of a bulb; there was only one bulb, which would be destroyed in the course of analysis. He completed this task brilliantly" [37]. This same tendency continued into the future. Feinberg noted that when World War II began, "Blokhintsev switched to solving the problem of reducing the noise of airplane engines; this required serious advances in acoustics [38].

2. BEGINNING OF SCIENTIFIC ACTIVITY: 1932–1933

In the above-mentioned book by Gurney [26], also referred to in Blokhintsev's works, quantum mechanics is characterized as a new language of physics and chemistry. "The program of quantum mechanics includes no more and no less than the reconsideration of atomic and molecular physics in their entirety on the basis of new laws of behavior of particles following from quantum mechanics" [26]. Blokhintsev joined the realization of this program with enthusiasm. As he later recollected, "During that period (1927–1929), new quantum mechanics originated and great capabilities in the application of this new physical concept and new methods of calculation of various atomic phenomena were found" [31].

The work "A Model Representation of the Electronic Cloud of Hydrogen-like Atoms" [39] occupies first place in the complete list of Blokhintsev's publications. The objective of the author was a survey of the studies performed by White [40, 41]. Already in this work, his talents of clear vivid presentation of the subject, peculiar style, concreteness, the ability to point out most significant things and, most important, emphasis on the *physical meaning* were fully manifested. We

give a brief citation: "According to wave mechanics, the electron motion is represented by the wave function ψ, whose physical meaning is as follows: the product

$$P = \psi\psi^* dV, \quad (1)$$

where ψ* is the function adjoint to ψ and dV is the volume element, gives the probability of finding the electron in the spatial region determined by the volume element dV. If the electron is represented as a droplet of fog and in each spatial region a large number of these droplets proportional to ψψ* is placed, we obtain a cloud whose density at each point is the probability P. The shape of this cloud yields a clear image—literally—of the electron distribution in the space around the atomic nucleus; the obtained models of the electron cloud correspond to reality, which is the entirety of the brilliant successes in understanding the properties of matter obtained in the last few years of wave mechanics [39].

This paper is interesting even today, and its style predates what was later called "quantum mechanics in pictures" [42]. Already this first publication on quantum mechanics contains the seed of his textbook *Principles of Quantum Mechanics* [43].

At that time, solid state physics [18, 44], in particular, the theory of metals [45–59], attracted great attention. The new quantum mechanics allowed one to describe many thermal and electronic properties of metals, including their surface properties and contact phenomena [18] more deeply and more fully. In 1931, Tamm and Shubin published the work on photoelectric effect [60] (see [18, 61, 62] and Section 95 of [43] concerning the photoelectric effect). It is not surprising that in 1932, the work "Temperature Dependence of the Photoeffect on Pure Metals" was published by Blokhintsev [63], following the course of investigations performed by Tamm and Shubin.

The next paper was "The Work Function of Electrons from metals" (jointly with Tamm) [64, 65]. This paper was received by the editorial board of *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki* (Journal of Experimental and Theoretical Physics) on November 29, 1932. As the authors wrote: "It was known that the work function of electrons from a metal can be explained either by the presence of the potential jump at the metal boundary or the action of an electrical image. In classical physics, none of these ideas could result in a quantitative theory. What follows represents an attempt to apply methods of quantum mechanics to determine the work function." Further, the authors used simplifying assumptions on the basis of the physical meaning of the studied problem. The approximate Thomas–Fermi method was used "since the goal was to understand the general relations." (See monograph [66] on the Thomas–Fermi approximation; in this monograph, the study by Tamm and Blokhintsev is also cited.) "It was found using this method that the work function is equal to the average kinetic energy of electrons (for $T = 0$ K) calculated using the Sommerfeld theory,

$$\chi = e\varphi_0 = \frac{\overline{mv^2}}{2} = \frac{3}{5}E_0. \quad (2)$$

By expressing E_0 in terms of the number Z of free electrons per atom, the atomic volume V of the metal, and the universal constants, we obtain

$$\chi(\text{eV}) = 15.6\left(\frac{Z}{V}\right)^{2/3}. \quad (3)$$

The values of χ calculated using this formula were compared graphically and numerically with experimental data" [64, 65]. Then, the authors studied the application of the general expression for the energy of the atomic system established by Fock [67, 68] for the case of two electrons on each quantum orbit, as it actually is in metals at low temperatures. Thus, to solve this problem, methods of electrodynamics, quantum mechanics, statistical physics, and solid state physics, in particular, the physics of metals, were applied. It is interesting that the reference to the Sommerfeld theory was given without indication of particular works. At that time, two surveys, written by Sommerfeld and Frank [52] and Sommerfeld and Bethe [53], were known to all physicists (see also [51, 54]).

The authors then graphically represented the work function χ depending on $(1/V)^{1/3}$ for uni- and bivalent metals, and the compared it with experimental data and data obtained using the Fowler method [63, 69]. They concluded that "Taking into account the roughness of the model of the metal used and the approximate Fermi method, better agreement with experiment (than that obtained by the authors) could hardly be expected. At any rate, it seems definite that the electron work function is in essence determined by the forces of the electrical image, rather than the potential jump at the metal boundary"; that is, these forces occurred due to the fact that when electrons were knocked out of the metal, other electrons tended to be located near the surface in such a way that the field formed inside the metal should be compensated. In the monograph written by Mott and Jones [59], this study by Tamm and Blokhintsev was cited together with other basic works on the problem. Further development and specification of the theory of the work function and thermion emission was continued in works by Sommerfeld (1934), Frohlich (1935), Bardin (1935), Bardin and Wigner (1935), etc. (on cold emission of electrons from metals, see Section 98 of [43]). In particular, Blokhintsev and Drabkina [70] considered Richardson's theory [71] (see [72] for details). Modern approaches to the description of the self-consistent electron theory of the metal surface, including the work function, can be found in [73].

F. Bloch [46–49, 58, 59, 72] made a fundamental contribution to electron solid state theory. His dissertation *Uber die Quantenmechanik der Electronen in Kri-*

stallgittern [46, 49] was an important step in the construction of the consistent quantum theory of solids [74–76]. In a large work by Blokhintsev in 1933 "Theory of Electron Motion in a Crystal Lattice" [77], the Bloch theory of motion of strongly coupled electrons was generalized for the case of degeneration of initial atomic states and for the electron motion in a bounded crystal. It was shown that unlike other approaches, the Bloch method reflected the physical reality more precisely; the representation for wave functions in a bounded crystal formulated in that work gave hope for possible investigation of surface phenomena taking into account the atomistic structure of the surface.

Clearly, the desire for a more precise reflection of physical reality was the important guiding idea of the young researcher starting from his first works. This was attended by skillful mastering of various mathematical tools that, however, never became an end in itself. The following words by Blokhintsev's older contemporary Ya.I. Frenkel apply to the Blokhintsev's scientific style: "In those cases when the physical meaning of the problem is unclear, mathematics should not be required to provide the thread to its explanation; it is far more useful to work out the essence of the problem, the factors of importance or, on the contrary, of no importance, for correct understanding of the physical phenomenon of interest, in other words, the qualitative analysis of the physical problem, rather than attempts to solve it quantitatively without data on the essence of the phenomena under study" [18].

Further, the approach proposed by Bloch was developed in works by Nordheim [78–83], Houston [75, 84], Slater [85–90], and many others [74, 89–96]. General formulas for calculating the energy $E(\vec{k})$ of the Bloch wave with a reduced wave vector $\vec{k}$ were obtained in [97] on the basis of applying the dynamical lattice theory [98] to electron waves in a crystal. However, it is in the Blokhintsev's work "that a representation of the electron wave functions was given in the form of Fourier series using a method similar to the known Born method in crystal lattice theory" [77]. Blokhintsev did this 14 years earlier than Korringa [97].

3. QUANTUM PHYSICS AND SOLID STATE THEORY: WORKS PERFORMED IN 1933–1934

The next work was the paper "Theory of Anomalous Magnetic and Thermoelectric Effects in Metals" [99] coauthored with Nordheim. In this work, the consistent theory of thermoelectric and galvanomagnetic effects in metals was constructed, and unlike earlier works, the case of two metals was considered. The authors based their study on the work by Peierls [72], who considered the behavior of monovalent metals in a magnetic field H and studied the Thomson and Hall effects. Peierls derived the equation for the electron distribution function f in a metal in the approximation of the relaxation time τ,

$$\frac{\chi}{\tau} + e(\vec{v}\vec{F}) + \frac{eH}{c}\Omega_\chi = 0, \quad f - f_0 = \frac{\partial f_0}{\partial E}\chi,$$
$$\hbar\Omega = v_y\frac{\partial}{\partial k_x} - v_x\frac{\partial}{\partial k_y}, \tag{4}$$
$$f_0 = [\exp(E - E_0)/kT + 1]^{-1}.$$

Here, E is the law of electron dispersion in the lattice, $\vec{v}$ is the velocity, and k_x, k_y, k_z are the components of the quasimomentum vector $\vec{k} = \vec{p}K/\hbar$ ($\vec{p}$ is the momentum). The quantity K determines the cyclic boundary conditions [83] $\psi(x + K) = \psi(x)$; $K = aG$, where a is the lattice constant and G is the reciprocal lattice vector.

Blokhintsev and Nordheim considered more general equations that made it possible to obtain a more general expression for χ.

They introduced the quantity M assuming that

$$\mathrm{grad}(f - f_0) = \frac{2\pi\hbar}{K}\left(\frac{\partial\chi}{\partial E}v\right)v + (M^{-1}\chi). \tag{5}$$

Here, the symmetric tensor M^{-1} with the following components was introduced:

$$(M_{xy})^{-1} = \frac{K^2}{h^2}\frac{\partial^2 E}{\partial k_x \partial k_y}. \tag{6}$$

Blokhintsev and Nordheim called this the tensor of reciprocal effective masses [59].

In [99], the general solution to an equation of type (4) was obtained for an arbitrary form of the dispersion function $E(k)$ under the assumption that the relaxation time τ is constant on the Fermi surface and the magnetic field H is small. The solution has the form

$$\chi = -e\tau\left((\vec{v}\vec{F}) - \frac{eH\tau}{c}\Omega(\vec{v}\vec{F}) + \left(\frac{eH\tau}{c}\right)^2\Omega^2(\vec{v}\vec{F}) + \ldots\right). \tag{7}$$

Further development of the quantum theory of thermomagnetic and galvanomagnetic phenomena in metals and semiconductors is given in [59, 83, 100–107].

Thus, in [99], the notion of the tensor of reciprocal "effective" masses was introduced. It should be mentioned for accuracy that the authors used for m^* the expression "scheinbarer Masse," i.e., the "imaginary" or "apparent" mass. The same term was used when the survey by Nordheim [83] was translated into Russian in 1934: "We see that for the case of low terms (electrons in the periodical lattice), there is quite a considerable deviation from the properties of free electrons, for which we have

$$E(k) = \frac{h^2|k|^2}{2mK^2}. \quad (8)$$

The dependence of $E(k)$ on $\vec{k}$ no longer possesses spherical symmetry. We only obtain this symmetry in the case if $|\vec{k}|$ is close to 0 or if

$$k_{x,y,z} \sim \pm\frac{G}{2}. \quad (9)$$

If $|\vec{k}| \ll G/2$, we can consider that the electron in this state behaves in the same way as the free electron with the apparent mass

$$m^* = \frac{h^2}{8\pi^2 a^2 \beta}. \quad (10)$$

In other words, the electron in the periodic field moves as if it has the mass m^* in the absence of field" [83]. Here, we use the following expansion:

$$E(k) = \alpha - 6\beta + \beta\frac{4\pi^2}{G^2}(k_x^2 + k_y^2 + k_z^2). \quad (11)$$

In the book by Mott and Jones [59] (1936), the commonly accepted term effective mass was used (note that sometimes, in the English-language literature, the term apparent mass can still be found). Thus, due to the works by Sommerfeld (1928), Bloch (1928), Nordheim (1928) and Brillouin (1929–1931), the concept of the scalar effective mass in the crystalline solid was formulated. Note that in surveys [52, 72], the notion of effective mass was not used. The detailed theory of electron motion in a periodic field and the concept of effective mass were developed by Blokhintsev in Section 55 of book [43].

It should be noted that in the work by Bronstein in 1932 [108, 109] (Blokhintsev and Nordheim refer to this work), it was shown that in the general case, the "equivalent" mass of the electron in the lattice was not a scalar, but could be a symmetric second rank tensor. The achievement made by Blokhintsev and Nordheim was that they showed that the concept of effective mass was much more general and meaningful than had been assumed before and for the first time demonstrated the tensor character of the effective mass by considering the behavior of the electron in external fields.

Let us explain the above-said using modern notation [110]. The eigenfunctions of electrons in the field of the periodic lattice $\psi_n(\vec{k}, \vec{r})$ have the form (n is the band number)

$$\psi_n(\vec{k}, \vec{r} + \vec{R}_l) = e^{i\vec{k}\vec{R}_l}\psi_n(\vec{k}, \vec{r}),$$
$$\psi_n(\vec{k}, \vec{r}) = e^{i\vec{k}\vec{R}_l}u_n(\vec{k}, \vec{r}), \quad (12)$$

and are called the Bloch functions. Electrons in the crystal described by them are called Bloch electrons, accordingly. The form of Bloch functions points to the physical meaning of the vector $\vec{k}$, namely, that the electron in the crystal can be represented in the form of a flat wave modulated with the period of the lattice. The investigation of the general properties of the function $E_n(k)$ near the specific points of the $\vec{k}_0$ region results in the relation [110]

$$E_n(\vec{k}) = E_n(\vec{k}_0) + \frac{\hbar}{m}\vec{s}\cdot\vec{p}_{nn} + \frac{\hbar^2\vec{s}^2}{2m} + \frac{\hbar^2}{m^2}\sum_{j\neq n}\frac{(\vec{s}\cdot\vec{p}_{nj})(\vec{s}\cdot\vec{p}_{jn})}{E_n(\vec{k}_0) - E_j(\vec{k}_0)} + \ldots. \quad (13)$$

The quantities $\vec{p}_{nj}$ and $\vec{s}$ are determined below (see [110]).

This relation shows that the electron described by the Schrödinger equation with the periodic potential should be considered as the particle subject to the influence of the interaction with the potential, or the *quasiparticle*. This quasiparticle includes into its properties the interaction with the static lattice.

Let us consider the case in which the point $\vec{k}_0$ corresponds to the extremum. For the second derivative of the energy with respect to $\vec{k}$, it follows that

$$\frac{m}{\hbar^2}\frac{\partial^2 E_n}{\partial s_\alpha \partial s_\beta} = \frac{m}{\hbar^2}\frac{\partial^2 E_n}{\partial k_\alpha \partial k_\beta} = \delta_{\alpha\beta} + \frac{1}{m}\sum_{j\neq n}\frac{(p^\alpha_{nj}p^\beta_{jn} + p^\beta_{nj}p^\alpha_{jn})}{E_n(\vec{k}_0) - E_j(\vec{k}_0)}. \quad (14)$$

Here, s_α and s_β are the rectangular coordinates of the vector $\vec{s}$ in some fixed coordinate system, and p^α_{nj} are the corresponding components of the matrix element of the momentum operator. Using the relation

$$\left(\frac{m}{m^*}\right)_{\alpha\beta} = \frac{m}{\hbar^2}\frac{\partial^2 E_n}{\partial k_\alpha \partial k_\beta}, \quad (15)$$

the tensor of reciprocal effective mass is introduced. Then relation (14) is written as

$$\left(\frac{m}{m^*}\right)_{\alpha\beta} = \delta_{\alpha\beta} + \frac{1}{m}\sum_{j\neq m}\frac{(p^\alpha_{nj}p^\beta_{jn} + p^\beta_{nj}p^\alpha_{jn})}{E_n(\vec{k}_0) - E_j(\vec{k}_0)}. \quad (16)$$

This equality is often called the sum rule for effective masses; sometimes, it is also called the *f*-summ rule [110]. The diagonal elements in (16) have a simpler form,

$$\left(\frac{m}{m^*}\right)_{\alpha\alpha} = 1 + \frac{2}{m}\sum_{j\neq n}\frac{\left|(p_{nj}^{\alpha}\right|^2}{E_n(\vec{k}_0) - E_j(\vec{k}_0)}. \quad (17)$$

It is seen from the above that the interaction of this energy level with lower levels or states of the ion core for which $E_j < E_n$, results in the decrease in the effective mass, while the interaction with higher states ($E_j > E_n$) increases the effective mass.

The notion of the effective mass is sufficiently well defined near the minimum or the maximum of the zone. In this case, the effective mass near the minimum m^*,

$$E = E_0 + \frac{k_x^2\hbar^2}{2m^*}, \quad (18)$$

differs from the effective mass m^{**} near the upper limit of the zone

$$E = E_1 + \frac{(k_x - \pi/a)^2\hbar^2}{2m^{**}}. \quad (19)$$

In both cases, the masses m^* and m^{**} can differ strongly from the true electron mass. Thus, if the energy zone is very narrow and the curvature of the energy surface near the bottom of the zone is small, the effective mass m^* is large, sometimes considerably larger than the true mass. At the same time, near the upper limit of the zone, if the curvature is large, the mass m^{**} is very small. The tensor character of the effective mass due to which the electron or the hole can be accelerated in a different way depending on the direction of the force, is important for crystals with nonsymmetric structure or in the case when the minimum or the maximum is not at the center of the Brillouin zone. In some cases, the quantities m_x^*, m_y^*, m_z^* should be considered negative; in this case, near the saddle point, some m^* will be positive, and some negative. It was noted earlier [89, 108] that this mechanism is very similar to the Dirac theory of the positron. At present, a number of systems have been studied, for example, a two-dimensional graphite layer [111], in which the electron motion is described in terms of relativistic quantum physics; in this case, the electron behaves as a relativistic particle with zero mass.

The effective mass is measured using different methods: the de Haas–van Alfven effect, cyclotron resonance, Hall effect, optical methods, electric conductivity and heat capacity [89, 110, 107], etc. These data result in strongly differing effective mass values. Depending on the measurement method, the following terms are introduced: optical effective mass, thermal effective mass, cyclotron effective mass, etc. [110, 107]. The concept of effective mass became widely spread, especially in semiconductor physics and the physics of semiconductor devices [112–114], the polaron theory [115–119], semiconductor superlattices [120, 121], microelectronics and physics of nanostructures [122–125]. It turned out that the notion of effective mass is extremely useful in the conductivity theory and other fields of solid state physics, nuclear physics, etc. In semiconductor physics, the effective mass method proposed by S.I. Pekar in 1948 for calculation of discrete levels in the forbidden zone is widely used [116, 117]. It is known that impurity atoms similar to other structural defects of the lattice can create such levels. In this case, the potential energy of the electron is added to the term which represents the nonperiodic function describing electron interaction with the imperfections of the lattice. The effective mass method proposed by Pekar allows one to reduce the Schrödinger equation with the periodic and nonperiodic potential to a simpler form containing explicitly only the nonperiodic part of the potential. In this case, the role of the periodic potential is the variation of the operator of kinetic energy: the free electron mass is replaced by effective masses describing the behavior of the charge carrier in the corresponding ideal crystal. The modern "zone engineering" provides the possibility of creating substances with the desired value of effective mass and various devices on their basis.

The theory of systems of many interacting particles considers the general concept of quasiparticles [126–128] which represent the spectrum of elementary excitations of the system if electron–electron, electron–phonon, and other interactions are taken into account. The quasiparticle represents the renormalized ("covered in clouds of virtual particles") "seed" (or "bare") particle with the effective mass of the form

$$m^* = m(1 + \lambda_{e-e} + \lambda_{e-\mathrm{ph}}). \quad (20)$$

In this case, the renormalized (effective) mass can differ from the initial mass quite considerably, such as for systems with heavy fermions [129].

In some problems of collision theory [130], the concept of effective mass allows one to write the generalized Schrödinger equation in which the real mass m is replaced by the effective mass m^*, which depends on particle position (the same situation is realized in some semiconductor heterostructures). In nuclear physics [130], the application of the nonlocal optical potential $V(\vec{r}, \vec{r}')$ results under certain conditions in the wave equation for the local potential $V(\vec{r})$ with the effective mass of the form [130]

$$M^*(r) = M\left(1 - \frac{M\alpha^2}{\hbar^2}V(r)\right)^{-1}. \quad (21)$$

In [131–133], the problem of interaction of a small subsystem (in the limit, one particle) with a large system (a thermostat) was studied (see also [134]). Upon the derivation of the generalized evolution equations using methods of nonequilibrium statistical mechanics [135], it turned out that the canceling of the thermostat variables results, similar to [130], in the generalized Schrödinger equation, in which the real mass m is

replaced by the tensor of reciprocal effective masses $(m^*)^{-1}_{ij}$ and the mass depends on the particle position,

$$i\hbar\frac{\partial\psi(\vec{r})}{\partial t} = \left(-\frac{\hbar^2}{2}\sum_{i,j=1}^{3}\left(\frac{1}{m^*(\vec{r})}\right)_{ij}\nabla_i\nabla_j + v(\vec{r}) + U(\vec{r}) + \frac{ie\hbar}{mc}\vec{A}(\vec{r})\vec{\nabla} + iT(\vec{r})\right)\psi(\vec{r}). \quad (22)$$

In relativistic quantum field theory, the problem of calculating the renormalized mass of the seed particle taking into account its interaction with the quantized field, and generally, the origin of mass [136] is an important problem in modern science.

In 1933, Blokhintsev published "Theory of the Stark Effect in a Time-Dependent Field" [137]. Stark studied the variation of the atomic energy levels and, therefore, the variation of their spectra [138] under the action of a constant electric field. The first and second order Stark effects (see Section 72 in [43]) (these effects have a linear and a quadratic dependence on the strength of the applied field, respectively) and the atomic and the molecular Stark effects are distinguished. The Stark effect results not only in the line splitting, but also causes small line broadening and shifts the limits of series toward smaller frequency. Modern experimental methods of investigation of the Stark effects in atoms are described in survey [139].

The strong electric field can tear electrons off gas atoms (see Section 101 in [43]). If the field is switched on, a barrier is created through which electrons penetrate the external space. The quantum mechanical tunneling makes it possible to construct the theory of ionization of atoms in strong electric fields and couple it with the observed shift and damping of spectral lines. Considering the Stark effect in a strong variable field, Blokhintsev showed that the atomic levels move and the picture of light scattering depends nonlinearly on the intensity of the incident light (see section 93 in [43]). This work was one of the first in this field of physics, which was later called nonlinear optics [140].

In 1934, Blokhintsev published two works [141, 142]. In the first work "Theory of Phosphorescence" [141], an interesting phenomenon of a very long luminescence of the so called Lenard phosphors, i.e., crystalline substances produced upon addition of small amounts of admixtures that bring about phosphorescence in heteropolar crystals [62], was studied. It is known that phosphorescence is a kind of luminescence which differs from fluorescence by the duration of the afterglow [62]. In "Theory of Phosphorescence," according to the author, "An attempt was made to explain this phenomenon on the basis of quantum mechanical ideas of the electron motion in the crystal lattice." It was said concerning work [141] in the study "Essay on the History of Semiconductor Physics" [143], "In 1934, on the basis of experimental data obtained by V. L. Levshin et al., Blokhintsev made a first attempt to discover the elementary law of damping of luminescence of crystallophosphors in theory from the structure of their energy spectrum."

He assumed that the afterglow duration can be related with the capability of formation of "quasilocalized" electronic states in a real crystal as a result of the "local lattice deformation" due to the introduction of impurities and estimated the time of reciprocal recombination of these states, which exceeds the usual duration of the electron lifetime in the excited state by a factor of 10^{15}. Thus, the theory of local states made it possible to qualitatively interpret the afterglow duration in phosphors. This point of view was included in textbooks on optics [62]. This and subsequent works by Blokhintsev [144–149], in which the detailed theory of the kinetics of phosphorescence in heteropolar crystals and the theory of dyed crystals were constructed, contributed considerably to deeper understanding of this problem and showed once more that the quantum mechanical approach is indeed the "new language of physics and chemistry," providing effective description of phenomena considered "mysterious" in classical physics. The calculation of the fluorescence lifetime of complex molecules is still a topical problem. The discussion of the correlation between the radiative lifetime with the spectra of fluorescence and absorption of aromatic molecules is discussed in [150].

The same approach was used by Blokhintsev in the work "Quantum Mechanical Theory of Adsorption" [142], cowritten with Sh. Shekhter. This work is a very useful and clear survey of the problem as a whole. The paper "Lifetime of Particles in Adsorbed State" [151] is devoted to the calculation of the lifetime of particles in the adsorbed state. It is known that adsorption is one of the types of interaction of gas molecules with the surface of a solid [142, 152–157]. The results obtained by Blokhintsev and Shekhter were included in the survey [152] devoted to the quantum theories of adsorption. The following problems of the theory of adsorption are underlined [152]: (1) to explain the mechanism of elementary processes on the surface; (2) to establish the dependence of adsorption properties of the surface on different observable parameters (temperature, composition and concentration of impurities, etc.). In this case, quantum mechanics should yield the "microscopic picture of phenomena." Blokhintsev and Shekhter took the wave functions of the harmonic oscillator as the functions of the discrete spectrum upon calculation of the lifetime of adsorbed molecules on the surface. It was assumed that the process of energy exchange between the crystal and the adsorbent molecules is due to thermal lattice vibrations. Taking into account a set of additional simplifications, adsorption coefficients were calculated. In spite of the coarse model, the authors obtained the correct qualitative behavior of the average lifetime of the molecule on the surface, which demonstrated once more the effectiveness of the quantum mechanical approach. In subse-

quent years, experimental and theoretical investigations of adsorption phenomena developed rapidly.

For example, an interesting phenomenon of the metallization of adsorbed hydrogen on the surface of silicon carbide was discovered not long ago [158]. It was found that when hydrogen is adsorbed by silicon carbide, quasi-one-dimensional strips (with a width of two atoms) with the conductivity of a metal are formed on the surface. These one-dimensional structures are very similar to nanowires and partly have similar properties. The quantum mechanical theory of this phenomenon has not been formulated yet. Further discussion and development of quantum mechanical theory of adsorption and chemosorption can be found in [156].

In 1934, Blokhintsev defended his Candidate of Sciences thesis *Some Problems of the Theory of Solids, Especially Metals* at the Physics Institute of MSU. As a result of the high level of the work, he received a degree of Doctor of Sciences in 1935. Frank, recollecting how Blokhintsev delivered his thesis at the MSU Scientific Council in 1934, said that the presentation was brilliant. It was obvious that Dmitrii Ivanovich was undoubtedly a mature scientist who was making a weighty contribution to science [37]. At the time, Blokhintsev was 26 years old.

3.1. Lotar Wolfgang Nordheim

Here, we would like to mention Blokhintsev's coauthor Lotar Wolfgang Nordheim (1899–1985). Nordheim belonged to the Hettingen school of theoretical physics. He was a PhD student with M. Born, and after defending his PhD thesis in 1923, his assistant and colleague till 1933. All his works are marked by bright talent and deep insight into a problem. In [10], the following fact is given: "In autumn of 1926, Hilbert began systematic studies of the mathematical principles of quantum mechanics. Lotar Wolfgang Nordheim, Born's former apprentice, and the 23-year-old John von Neumann helped him in these studies. Hilbert also gave lectures on the mathematical principles of quantum theory, which were published in shorter form [159] in the spring of 1927."

Nordheim worked successfully in the application of quantum mechanics to statistical physics and solid state physics. He gave a successful description of the electron work function in metals, thermoelectron emission, electron kinetics in metals and alloys [81] (see the analysis of this work in [58]; here, the effective approximation of "rigid" ions for alloys was introduced), the influence of quantum corrections on collisions and the gas distribution function [108, 160], and the rectifying action of the semiconductor–metal contact [161]. In 1934, Heitler and Nordheim predicted the existence of higher order Compton processes [162, 163].

In 1928, interning with Fowler (1889–1944) at Cambridge, Nordheim explained the phenomenon of cold electron emission from metals on the basis of electron cyclotron tunneling. This theory was called the Fowler–Nordheim theory [55, 79, 80, 108, 164–166]. In his lecture at Oxford in May, 1929 [55], Fowler noted that the success in the development of this problem was mainly due to the efforts of Nordheim; it was the result of his work on the topic during a year at Oxford and little could be added to his brilliant review paper [80]. The Fowler–Nordheim tunneling was observed in nonconducting thin films, for example, SiO_2 films. In 1932, Nordheim applied the idea of quantum mechanical tunneling to consideration of the rectifying action of the semiconductor–metal contact [161] (see Section 97 of [43] on quantum mechanical tunneling).

The Fowler–Nordheim model is still widely used and cited (see, e.g., [166–170]). In [169], for calculation of electronic high-vacuum devices (relativistic diodes [171]), electron emission was described by quantum mechanical Fowler–Nordheim equations [55, 79, 80, 108, 164–166]. In [170], a new method for the manufacture of graphite nanotubes was proposed. During analysis of devices with graphite nanotube emitters (integrated with a metallic anode), secondary emission was analyzed within the Fowler–Nordheim model, which made it possible to considerably improve the fabrication process.

Thanks to a grant from the Rockfeller Foundation, Nordheim visited Moscow in 1933 as an invited professor to MSU. His studies were quite close to those performed by the Tamm's group. It was during that visit that he performed his joint work with Blokhintsev.

After Hitler came to power, Nordheim emigrated to the United States with the help of the Rescue Committee for Displaced German Scientists [172]. He obtained the position of invited professor to Pardue University (1935–1937). There, he studied the resistance of monovalent metals [173].

However, his basic interests shifted to the field of cosmic ray physics. He cooperated with his wife Gertrude Poschl, who also actively worked in the field of the theory of the structure of multiatomic molecules and their spectra. In 1937, he became a professor of physics at Duke University, and his interests shifted toward nuclear physics. Results of his works on nuclear physics were summarized in [174] and included in monograph [175].

Nordheim participated in the atomic project from the very beginning. He worked at Oak Ridge Laboratory as head of the department, and in 1945–1947, he was the Director of the Department of Physics of this laboratory. He studied diffusion and neutron retardation and multiplication; he proposed the method for calculating the efficiency of a rod for nuclear reactor control, etc. In 1947, Nordheim returned to Duke, remaining a consultant of the Oak Ridge and Los Alamos laboratories. He worked on cosmic ray theory and the shell structure of the nucleus. In 1956, Nordheim accepted an invitation to head the department of theoretical physics at the John Hopkins Laboratory of General Atomics

in San Diego, California; there he continued his investigations in the field of reactor and neutron physics.

The similarity of his scientific carrier and interests to those of Blokhintsev is quite remarkable. Probably, both felt the requirements and tasks put forward at a particular time and directed their efforts toward their solution.

4. QUANTUM PHYSICS AND SOLID STATE THEORY: 1935–1937

In 1935–1936, Blokhintsev continued his work on the theory of light absorption in heteropolar crystals [144], the theory of phosphorescence [145], and the theory of dyed crystals [146]. Let us discuss in more detail the work "Theory of Dyed Crystals" [146]. Pekar wrote in his monograph [115] that "in 1933, L.D. Landau [176] put forward the important idea of the autolocalization of an electron in an ideal crystal as a result of lattice deformation by the field of the electron. These local states were assumed to be motionless, and Landau attempted to identify them with *F* centers in dyed alkali halide crystals. In 1936, Ya.I. Frenkel [177] noticed that the conduction electron should deform the closest atoms of the crystal and this local deformation should move along the crystal, following the electron. In 1936, Blokhintsev [146] attempted to find out in which crystals the autolocalization of electrons pointed out by Landau should be expected on the basis of the approximation of tightly bound electrons. At that time, a correct method for considering autolocal states had not been found, and the attempt to prove their existence and investigate their properties failed. However, the above papers had a definite influence on the studies performed by Blokhintsev in this field."

The studies performed by Pekar (1917–1985) on polaron theory [115] and semiconductor theory [116] are widely known. He constructed the theory describing the behavior of the "redundant" electron in ionic crystals. It was found earlier that in ionic crystals, the interaction of the additional electron with the lattice vibrations plays an important role; in this case, the interaction is due to the polarization of the lattice by the field of the electron. Pekar's achievement was that his choice of the type of interaction was correct (unlike the standard zone model in which the interaction of the electron with the lattice vibrations was usually considered weak) and the substantiation of the existence of autolocal electronic states was clear. The main idea [115] is that the electron polarizes the ambient crystal lattice; this polarization in turn influences the electron, and this action is equivalent to the action of some effective potential well.

The depth of this well in some crystals can be sufficiently large for discrete energy levels to exist in it. Local polarization caused by the electron is related to the displacement of ions from their average equilibrium positions. Since ion displacements lag behind instantaneous electronic states, the polarization also lags behind and forms the potential well for the electron. Due to the inertial character of ions, they are influenced by the average electron field, which can be calculated as the static field of the charge distributed with the density $e|\psi|^2$, where ψ is the electron wave function in the polarization well. The states of the crystal with the polarization well in which the electron is localized were called polarons by Pekar [178]. The contribution made by Blokhintsev to this direction of research is mentioned in [143].

In 1950, Frohlich and colleagues [179, 74] applied a simple model of interaction of a particle with a quantized field to describe the polaron. This was one of the first applications of quantum field theory to problems of condensed matter physics. This direction was developed in studies by N.N. Bogolyubov [119, 180, 181], S.V. Tyablikov [182–189], and others [190]. Frohlich developed and formulated the quantum mechanical model of the electron in the field of the crystal lattice [191], which is used for the description of a polaron with a large radius (Frohlich polaron). Mott put forward similar ideas in [192, 193].

Later, experimental and theoretical investigations of polaron states and their mobility in various materials became rather large-scale (see surveys [116, 194–199] and books [115, 200]).

The pioneering approach applied by Blokhintsev in [146] consisted in an attempt to describe the problem of autolocal electronic states on the basis of the approximation of tightly bound electrons. This approximation was formulated by Bloch [46, 110] and later became widespread (in an improved form) in condensed matter physics, especially for the description of localized states of different nature and unordered systems [110, 201]. The tight binding method is one of the most well known and widely used semiquantitative methods for calculation of wave functions and energies. It is also known under another, more appropriate, name as the method of linear combination of atomic orbitals. The tight binding method is based on the fact that functions of the type of Bloch functions can be constructed in the form of the linear combination of atomic wave functions. In [146], Blokhintsev said, "In that study, the starting point was the Heisenberg approximation, in which the state of the crystal was known to be derived from the states of isolated atoms."

Indeed, it can be shown [110, 201] that the Bloch sums $\psi_{\vec{k}}(\vec{r})$ constructed with the atomic wave functions

$$\psi_{\vec{k}}(\vec{r}) = \sum_n e^{i\vec{k}\vec{R}_n}\phi(\vec{r} - \vec{R}_n) \qquad (23)$$

possess the same periodicity as exact electronic states in a crystal with a wave vector $\vec{k}$. The Hamiltonian of the problem includes the sum of potentials centered at

separate nodes of the lattice. The Schrödinger equation is written in the form

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V_{\text{at}} + V'\right)\psi = (H_0 + V')\psi = E\psi. \quad (24)$$

Here, V_{at} is the electron potential in the isolated atom and V' is the additional potential energy of the electron in the field of the lattice. In this case,

$$H_0\phi = E_a\phi,$$

where E_a is the self energy corresponding to the atomic orbital ϕ. If one assumes the applicability of perturbation theory, the solutions to the Schrödinger equation can be represented in the form of the linear combination of atomic wave functions (23). The coefficients in this expansion are determined from the condition of Bloch periodicity. As a result, we have

$$\begin{aligned}\psi_{\vec{k}}(\vec{r} + \vec{R}_a) &= \sum_n \exp(i\vec{k}\vec{R}_n)\phi(\vec{r} + \vec{R}_a - \vec{R}_n) \\ &= \exp(i\vec{k}\vec{R}_a)\sum_n \exp[i\vec{k}(\vec{R}_n - \vec{R}_a)]\phi(\vec{r} - (\vec{R}_n - \vec{R}_a)),\end{aligned} \quad (25)$$

which yields the relation

$$\psi_{\vec{k}}(\vec{r} + \vec{R}_a) = \exp(i\vec{k}\vec{R}_a)\psi_{\vec{k}}(\vec{r}). \quad (26)$$

Let us consider the equality

$$\int \psi^*_{\vec{k}} H_0 \psi_{\vec{k}} d\tau + \int \psi^*_{\vec{k}} V' \psi_{\vec{k}} d\tau = E\int \psi^*_{\vec{k}}\psi_{\vec{k}} d\tau. \quad (27)$$

Let us substitute Eq. (23) into this relation. It is convenient to introduce the following parameters:

$$\begin{aligned}t_\alpha &= -N\int \phi^*(\vec{r} - \vec{R}_n)V'\phi(\vec{r} - \vec{R}_n)d\tau, \\ t_\beta &= -N\int \phi^*(\vec{r} - \vec{R}_m)V'\phi(\vec{r} - \vec{R}_n)d\tau,\end{aligned} \quad (28)$$

where n and m are the neighboring nodes of the lattice. The parameters t_α and t_β are positive quantities. As a result, we find that

$$E = E_a - t_\alpha - t_\beta\sum_m \exp(i\vec{k}(\vec{R}_n - \vec{R}_m)). \quad (29)$$

For a simple cubic lattice, we have

$$\begin{aligned}E(k) &= E_a - t_\alpha \\ &- 2t_\beta(\cos(k_x a) + \cos(k_y a) + \cos(k_z a)).\end{aligned} \quad (30)$$

It is seen that the electron energy is bound within the region $\pm 6t_\beta$. In this case, each electronic state in the isolated atom corresponds to the zone energy in the crystal. For small values of $\vec{k}$ in the simple cubic lattice, we obtain

$$E(k) = E_a - t_\alpha - 6t_\beta + t_\beta k^2 a^2. \quad (31)$$

The following expression for effective mass is implied by this equation (compare with (10)):

$$m^* = \frac{\hbar^2}{2t_\beta a^2}. \quad (32)$$

It is obvious that the zone width is determined by the degree of overlapping of atomic orbitals in neighboring atoms; the narrower the zone, the larger the effective mass near the zone bottom. Thus, the approximation of tightly bound electrons is not only practically useful, it also allows one to consider the character of Bloch states in a new fashion, adding the picture of almost free electrons. It can be said that in the tight binding method, a solid is considered as a set of weakly interacting neutral atoms or, in other words, as a gigantic molecule [202] of approximately 10^{23} atoms.

The investigation of localized states in the framework of the tight binding method [146] led Blokhintsev to the need to describe the interaction of the electron with the lattice vibrations corresponding to the spirit of this method. He said that the localization of the electron in some mth node of the lattice can occur only in the deformed crystal; the electron would move from one node to another only if some energy was spent on eliminating the deformation holding the electron at the mth node. However, the description of the electron–phonon interaction in the approximation of tightly bound electrons began much later.

The construction of the theory of electron–phonon interaction in the approximation of tightly bound electrons was initiated by Frohlich [203] in 1966 and then continued in a number of works [204–208]. Frohlich [203] proposed describing the interaction of tightly bound electrons with the lattice vibrations similar to the approximation of "rigid ions," when electron wave functions "rigidly" follow moving ions. This approximation was called the modified tight binding approximation (MTBA).

The integral of the jump between two lattice nodes is

$$\begin{aligned}t_{ij} &= \int d^3 r w^*(\vec{r} - \vec{R}_j) \\ &\times\left[\frac{\hbar^2 p^2}{2m} + \sum_l V_{sf}(\vec{r} - \vec{R}_l)\right]w(\vec{r} - \vec{R}_i).\end{aligned} \quad (33)$$

Here, V_{sf} is the self-consistent lattice potential taking into account the corresponding shielding, and $w(\vec{r} - \vec{R}_i)$ are the Wannier functions. Let us consider small deviations of the ion $(\vec{R}_i^0 + \vec{u}_i)$ from the equilibrium $\vec{R}_i$. It is assumed that the electron wave functions weakly vary upon ion displacement and, therefore, the

following orthogonality relations are still valid for the deformed lattice:

$$\int d^3 r w^*(\vec{r} - \vec{R}_j^0 - \vec{u}_j) w(\vec{r} - \vec{R}_i^0 - \vec{u}_i) \approx \delta_{ij}. \quad (34)$$

For small displacements $\vec{u}_i$, we obtain

$$t(\vec{R}_j^0 + \vec{u}_j - \vec{R}_i^0 - \vec{u}_i)$$
$$\approx t(\vec{R}_j^0 - \vec{R}_i^0) + \left.\frac{\partial t(\vec{R})}{\partial \vec{R}}\right|_{\vec{R} = \vec{R}_j^0 - \vec{R}_i^0} (\vec{u}_j - \vec{u}_i) + \ldots. \quad (35)$$

In [205], it was use of the following relation was proposed due to the exponential drop in the radial part of the electron wave functions in the Slater or Wannier form:

$$\frac{\partial t(\vec{R})}{\partial \vec{R}} \simeq -q_0 \frac{\vec{R}}{|\vec{R}|} t(\vec{R}). \quad (36)$$

Here, q_0 is the Slater coefficient characterizing the decrease in the radial part of the electron wave functions. Using the representation of the secondary quantization, the Hamiltonian of the electron–phonon interaction in the approximation of tightly bound electrons is written in the form [207, 208]

$$H_{ei} = \sum_{kk_1} \sum_{qG} \sum_{\nu\sigma} g^{\nu}_{kk_1} a^{\dagger}_{k_1\sigma} a_{k\sigma} (b^{\dagger}_{q\nu} + b_{-q\nu}) \times \delta(\vec{k}_1 - \vec{k} + \vec{q} + \vec{G}), \quad (37)$$

where

$$g^{\nu}_{kk_1} = \left(\frac{1}{(\mathcal{N} M \omega_{\nu}(k))}\right)^{1/2} I^{\nu}_{kk_1}, \quad (38)$$

$$I^{\nu}_{kk_1} = 2iq_0 \sum_{\alpha} t(\vec{a}_{\alpha}) \frac{\vec{a}_{\alpha} \vec{e}_{\nu}(\vec{k}_1)}{|\vec{a}_{\alpha}|} [\sin(\vec{a}_{\alpha}\vec{k}) - \sin(\vec{a}_{\alpha}\vec{k}_1)]. \quad (39)$$

The operators $b^{\dagger}_{q\nu}$ and $b_{q\nu}$ describe the phonon production and annihilation, and $\omega_{\nu}(k)$ the phonon acoustic frequencies.

Later, it was shown [209] that the Hamiltonian of the electron–phonon interaction in the approximation of tightly bound electrons upon consideration of various properties of solid bodies yields results equivalent to those following from the Frohlich Hamiltonian [191] in the case of the harmonic approximation for the lattice vibrations and the spatial isotropy. For anharmonic and strongly anisotropic systems, results may differ. The application of the Hamiltonian of electron–phonon interaction in the approximation of tightly bound electrons for investigating the normal and superconducting properties of metals and their disordered alloys showed [204–208, 210–212] that this approach has a number of advantages for a particular class of substances. Details can be found in [204–208, 210–213].

5. QUANTUM PHYSICS AND SOLID STATE THEORY: 1938–1939

In 1938, Bloikhintsev and B.I. Davydov published the work "Theory of Solid Rectifiers" [214], which was devoted to a problem that was attracting increasing attention at that time due to its applied value [44, 143, 215]. I.V. Kurchatov also studied this problem at that time [216]. A large number of works were devoted to the investigation of the metal–semiconductor contact, since it is the investigation of contact phenomena that made it possible to raise to a qualitatively new level the explanation of the phenomenon of rectification and the photovoltaic effect in semiconductors. Properties specific to semiconductors [117] were found upon investigation of phenomena at the contact. The task was to find out the nature of the barrier layer, the mechanism of rectification, and the photovoltaic effect in it. For explanation of the nature of the barrier layer, Nordheim [161] and Frenkel and Ioffe [217] proposed a qualitative theory based on the notion on quantum mechanical tunneling through the barrier of the layer. However, these theories had some disadvantages, which finally resulted in the development of the alternative diffusion theory of rectification. According to this theory, due to the existence of the contact field, a layer depleted of carriers is formed at the semiconductor–metal interface. If external field is applied, depending on its direction with respect to the contact field, this depleted layer is either increased or decreased as a result of the diffusion of current carriers under the action of the field forces. The variation in the resistance of the depleted layer due to the applied external field results in rectification of current in this layer. This theory was developed in the Soviet Union in the period between 1938 and 1941 by Davydov, Blokhintsev, and Pekar. Simultaneously, similar ideas were developed abroad by Mott and V. Schottky [143]. The authors of [44] wrote that "the theory of rectification for cuprous rectifiers was constructed by Davydov (and soon developed in investigations performed by Blokhintsev and Pekar before 1941)." Note that in the work by Blokhintsev and Davydov [214], the passage of the current through the interface between two semiconductors of one type with different specific resistances was studied [117].

In 1938, Blokhintsev and B.I. Spasskii turned to a more general problem of semiconductor theory. The work "Generalization of the Wilson Semiconductor Theory" [218] is devoted to the analysis of possible "consequences of the idea of the possibility of chemical reactions inside the crystalline semiconductor." In the Wilson theory, the electron distribution over quantum levels corresponding to equilibrium at some temperature determines the electric and many optical properties of the semiconductor at this temperature. Unlike the Wilson theory, it was assumed in [218] that the num-

Table 1. Types of crystal solids

Name	Substance
Ionic crystals	Alkali halide
Covalent crystals	Diamond, silicon, etc.
Metallic	Various metals and alloys
Molecular crystals	Ar, He, O_2, H_2, CH_4
Substances with hydrogen bonds	Ice, KH_2PO_4, fluorides
Quantum crystals	Solid He, Ar, etc.
High-temperature superconductors	$HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$, etc.
Fullerenes, nanomaterials	C_{60}, C_3O_4, etc.
Photon crystals, left media	Yablonovite

bers of electron levels were considered as functions of temperature. As a result of chemical reactions inside the crystalline semiconductor, the dependence of many properties, in particular, electric conductivity, on the concentration of impurities is considerably complicated. In essence, in [218], the theory of alloyed semiconductors [117, 219] was considered; the need for this theory was already being felt.

In another survey work, "Modern Ideas of the Nature of Dielectrics and Conductors" [220], Blokhintsev gave a clear and distinct description of the achievements in the quantum theory of solids. He wrote, "Over the course of a decade, quantum theory contributed to the development of quite new ideas on atomic structure and the motion of electrons and other microparticles. Basic laws established by quantum (wave) mechanics were already a conquered field and contributed to a new understanding of conductivity of semiconductors and dielectrics." Blokhintsev, in essence, considered the problem of classification of solids, i.e., the problem of how many types of solids existed [221, 222] and what principles underlay a particular classification. At the time, this question was quite topical. However, in subsequent years, discussions on this question have continued [223–228], and this problem becomes even more topical now, as the number of new materials with specific properties, which do not always fall within the usual classification, are increasing [120, 122, 124, 229–236].

Wilson's classification of solids [91–93, 95, 89] introduced three classes of substances: dielectrics, semiconductors, and metals; i.e., it was based on the ability of a particular substance to conduct electric current. This partition goes back to the initial single-electron Bloch picture and the approximation of weakly bound electrons. The list of studied substances increased rapidly with the increasing needs of technique and technology and the accumulation of data on their physicochemical properties [221, 222]. That is why F. Zeitz [237] reconsidered and added Wilson's classification. He took into account not only the ability of conducting electric current but also the type of bonding [225] that forms the solid. It is interesting that his known book *Modern Theory of Solids* begins with the chapter "Empirical Classification of Solids," in which five types of solids are introduced, which is as follows [237]:

(a) metals,

(b) ionic crystals;

(c) valence crystals;

(d) semiconductors;

(e) molecular crystals.

Kittel [238] extended Zeitz's classification and added one more class of substances: crystals with hydrogen binding. F. Anderson specified more precisely the classification developed by Zeitz and Kittel and criticized it. Anderson thought that "in reality, the difference between semiconductors and metals or valence crystals with respect to the type of bonding and between semiconductors and other types of dielectrics with respect to conductivity are quite artificial; semiconductors do not represent a separate class of crystals in a real sense" [223]. The generally accepted classification by Ashcroft and Mermin [239] was developed in the spirit of Anderson's remark. It is also based on two characteristics: the type of bonding and the conductivity, although the authors emphasize its conditional character and incompleteness (see also [240]). For example, quantum crystals [241, 242] do not completely satisfy this classification. The existence of the so-called Wigner crystal, i.e., the crystalline phase of a degenerate electron gas [243, 244] in semiconductor heterostructures, was proved. The existence of such objects as quasicrystals [245] is a challenge to all existing classifications.

At present, the creation of new materials proceeds at a rapid pace [232]. It is possible that in the near future, the common classification of crystalline solids will be considerably widened. It is possible that it will include as a separate line high-temperature superconductors [246–248], nanomaterials [122, 233–236], photonic crystals [249], etc. The proposed classification may look like the one given in Table 1.

Concerning dielectrics, although they had been studied for a long time [250], a consistent theory of the dielectric state was proposed by W. Kohn [224] only in 1964. The question how the dielectric differednfrom the metallic state required more specification, as demonstrated by Resta in [227]. In relation to the investigation of oxides of transition metals, high-temperature superconductors, and complex oxides with the perovskite structure [251–254], it turned out that the metal–insulator transition is due to the competition between the zone width and the Coulomb interelectron interaction (Hubbard model [251–254]). In this regard, it was proposed to consider the so called "Mott–Hubbard insulator" as a special state [255]. Thus, the comparison of the nature of metallic and dielectric states of the substance considered by Blokhintsev has remained a topical direction of research.

5.1 Lamb Shift

In 1938, Blokhintsev was preparing his work "The Shift of Spectral Lines Caused by the Inverse Action of a Radiation Field" for publication. He presented it at a seminar of the Physical Institute of the Academy of Sciences of the USSR, where he was employed; he also submitted it to *Zhurnal Experimental'noi i Teoreticheskoi Fiziki* [Journal of Experimental and Theoretical Physics] (ZhTEF). The work was rejected by the editorial board and published only in 1958 in Dubna in a collection of Blokhintsev's scientific works and papers. This work was mentioned in the survey report delivered by Ya.A. Smorodinskii [256]. In [6], the following was written: "Already in early works by Dmitrii Ivanovich, deep understanding of the essence of quantum mechanics, fresh and bold ideas, an original way of thinking that foreshadowed the further development of physics were evident. Typical in this respect was his work on the calculation of the 'shift of spectral lines caused by inverse action of a radiation field,' which in essence contained the theory of the Lamb shift, which was the beginning of quantum electrodynamics. It was reported at the seminar at the Physics Institute of the Academy of Sciences of the USSR and submitted to ZhTEF in 1938. The formula for the Lamb shift obtained by Blokhintsev became famous; it differs from the Bethe formula only by the numerical factor added in 1948 as a result of ultraviolet cutting. Unfortunately, this important discovery was not published at that time in ZhTEF. There were no other outlets for publication.

The genesis of the work "The Shift of Spectral Lines Caused by the Inverse Action of a Radiation Field" was best related by Blokhintsev himself [31]. "I delivered the work that, in essence, contained the theory of the Lamb shift discovered ten years later, at a seminar at the Physics Institute. However, my work was not published, since the editorial board of ZhETF returned the manuscript because the calculations were considered unusual. I kept the manuscript, which was stamped by the journal certifying the date of its receipt (February 25, 1938). I found no support from my colleagues at the Physics Institute. There were no other outlets. Thus, this important work was not published in due time. The main idea of the work followed from my deep belief that a physical vacuum existed in reality; however, I refrained from painting the affair in this light, a cry for the Boeotians."

The Lamb shift is indeed related to quite remarkable and interesting effects of quantum physics [256–261]. Lamb and his colleagues performed very precise, thorough, and elegant experimental studies [261] on the determination of the structure of levels with $n = 2$ for hydrogen, deuterium, and singly ionized helium. Since the energy difference for these levels is very small, the probability of spontaneous transitions turns out to be negligible. However, if the atom is placed in a rotating (or oscillating) magnetic field with the corresponding frequency, induced transition can be observed. This frequency can be exactly measured; it is equal to the difference in energies of the two levels divided by $\hbar$. The measurement of the rotation frequency in Lamb's experiments yielded a value of the energy difference of two levels with the same principal quantum number in Rydberg units; it is interesting that this does not require any preliminary data on the Planck constant $\hbar$. The Lamb shift is mainly determined by the variation in the "scale" in wave functions of the atom, which are used upon calculation of the mathematical expectation of corresponding expressions. The total shift ΔE, which is independent of the virtual photon frequency, is [260]

$$\Delta E = \frac{\alpha}{3\pi}\left(\frac{\hbar}{mc}\right)^2\left[\ln\frac{mc^2}{K_0} - \ln 2 - \frac{3}{8} + \frac{5}{6} - \frac{1}{5}\right]\langle e\Delta\varphi(\vec{r})\rangle_{00} - \frac{\alpha}{2\pi}i\left(\frac{e\hbar}{2mc}\right)\langle\beta\alpha\mathscr{E}(\vec{r})\rangle_{00}. \quad (40)$$

The exact calculation of expression (40) for the radiation correction of the energy of a hydrogen-like atom is given in [260]. For fine splitting $F\Gamma$, Bethe calculated the energy difference of $2P_{1/2}$ and $2P_{3/2}$ states of hydrogen-like atoms. The theoretical expression has the form [260]

$$F = \frac{cR_D}{16}\alpha^2\left[1 + \frac{5}{8}\alpha^2 + \left(1 - \frac{m}{M_D}\right)\frac{\alpha}{\pi} - \frac{0.656}{\pi^2}\alpha^2\right], \quad (41)$$

where R_D is the reduced Rydberg constant for deuterium, M_D is the deuterium mass, and α is the fine structure constant.

Blokhintsev wrote about his calculations in [31]: "As a result of them, the following expression is obtained for the frequency shift:

$$\delta\omega_0 = k\left(\frac{e^2}{\hbar c}\right)^3\frac{Z^4}{n^3}R\log\left(\frac{\mu c^2}{\Delta E_{\text{av}}}\right), \quad (42)$$

where k is the numerical coefficient, ΔE_{av} is the average energy, n is the principal number of the level, and R is

the Rydberg constant. Due to the inaccuracy in cutting, the coefficient k and the values of ΔE_{av} differ somewhat from exact values obtained using the method of electron mass renormalization (note that (42) can be rewritten in the form $\delta\omega_0 \cong |\psi_s(0)|^2$, as is usually done now; here, $\psi_s(0)$ is the value of the wave function at the point $r = 0$). The ratio $\delta\omega_0/\omega = 2.8 \times 10^{-8}$ calculated using this formula for the He ion is in good agreement with respect to its absolute value and sign with the value measured by Paschen (10^{-6}–10^{-7}). At the time, there were no more precise measurements. This circumstance was of course unfavorable for further improvement of an unpublished work. Only after World War II, in 1948, did the importance of this work for theoretical physics become clear."

The Lamb shift in levels in hydrogen, i.e., the energy by which the $2S_{1/2}$ state is higher than the $2P_{1/2}$ state, is obtained by combining different terms contributing to the theoretical expression for the Lamb shift. This procedure is described in detail in [260]. Experimental investigations of the Lamb shift continue.

It was reported not long ago [262] that two-loop corrections to the Lamb shift were first measured in strongly ionized atoms of heavy elements using the ion trap technique.

The history of theoretical calculation of the Lamb shift value is quite interesting. It is known from first-hand accounts and has been well described in papers [263, 264] and books [265, 266]. According to Weisskopf [265], "Since 1936, there have been vague data that the position of observed hydrogen levels does not exactly match the predictions following from the Dirac equation, the so-called Pasternak effect. Certain considerations existed on possible ways of calculating this effect using quantum electrodynamics in the presence of deviations. After the war, I decided to investigate this problem together with a very capable PhD student, B. French. We wanted to calculate this effect, which was more well known as the Lamb shift, by isolating the infinite self-energy of the electron. These were complicated calculations, since the renormalization technique had not been developed yet. It was necessary to calculate the energy difference of the free and bound electrons when both energies were infinite. We had to be very accurate, since the calculation of the difference of diverging quantities often results in errors. We overcame difficulties slowly, since there were no good experimental results at that time. Then Lamb and Rutherford set up a good experiment, and finally, we obtained a result that agreed well with experimental data. I informed Julian Schwinger and Dick Feynman; they repeated the calculations; however, their results were different from ours, and Schwinger and Feynman obtained the same number. We postponed publication to find the error, spending half a year on it. Meanwhile, Lamb and Kroll published calculation result of the same effect, which more or less agreed with our result. Then Feynman called me from Ithaca, 'You were right; I was wrong!' Thus, if we had had courage to publish our results, our paper would have been the first one to explain the experiment performed by Lamb and Rutherford. What's the moral of this story? You have to believe in what you do."

6. STATISTICAL PHYSICS: 1939

In 1939, Blokhintsev published his work "Hydrodynamics of an Elecron gas" [267]. In this work, the hydrodynamic description of the system of many particles (electrons), i.e., description in terms of a "reduced" set of variables characterizing the system, the current $I(x)$ and the particle density $\rho(x)$, is considered. Blokhintsev was basing this on an analysis performed by Pauli in his "Handbuch der Physik" (Part 1, Section 5) [268]. Blokhintsev maintained that since a multiparticle problem could not be solved exactly, an approximate solution should be sought. It is known [269] that an efficient way for calculating the energy eigenfunctions and eigenvalues is the self-consistent field method. This method was first developed by Hartree without taking into account electron exchange and then by Fock [67, 68] with this exchange taken into account. There exist a large number of works on this method [269] both with and without the exchange account. Blokhintsev wrote in [267] that from the very beginning he used the Hartree–Fock approximation, which assigns an individual function $\psi_k(x)$ to each electron n. In this approximation, the system of electrons is described by the density matrix

$$\rho(x, x') = m\sum_k \psi_k(x)\psi_k^*(x'), \tag{43}$$

where m is the electron mass. The summation is performed over all occupied states. This matrix satisfies the equation

$$i\hbar\frac{\partial}{\partial t}\rho = H\rho - \rho H''. \tag{44}$$

This equation is none other than the Liouville equation for the density matrix. Considering the dynamic equations (equations of motion) for the current, Blokhintsev derived the "hydrodynamic" equation for a system of many particles (electrons) that contained gas density gradients in the stress tensor. To obtain closed expressions, he used approximations characteristic of statistical Fermi–Thomas theory. It is known [66, 269] that the statistical model of the atom describes the electrons of the atom statistically as an electron gas at a temperature of absolute zero. The model yields good approximation only for atoms with a large number of electrons, although it had been used for up to ten electrons. For the statistical approach, the details of the electronic structure had not been described; therefore, the application of a hydrodynamic description was quite relevant. Following the spirit of the statistical model of the atom, the total energy of the atom is

obtained from the energy of the electron gas in separate elementary volumes dv by integrating over the whole volume of the atom. Working in this way and using the continuity equation, Blokhintsev derived an expression for the gas energy that (in the statistical case) coincided with the expression obtained earlier by Weizsacker [270] using a different method. The Thomas–Fermi–Weizsacker model was developed and discussed in [271]. Further development of the statistical model of matter in the framework of the Thomas–Fermi model is given in [272–276].

It is appropriate to note here that the work "Hydrodynamics of an Electron Gas" [267] contains one more aspect that does not seem striking at first sight but is nonetheless of great interest. In essence, it was shown in this work that a system in the low-energy limit can be characterized by a small set of "collective" (or hydrodynamic) variables and equations of motion corresponding to these variables. Going beyond the framework of the low-energy region would require the consideration of plasmon excitations, effects of electron shell restructuring [277], etc. The existence of two scales, low-energy and high-energy, in the description of physical phenomena is used in physics, explicitly or implicitly. Recently, this topic enjoyed interesting and deep development, which is why we will consider it in more detail.

6.1. Quantum Protectorate

It would be appropriate here to discuss an interesting concept formulated relatively recently, namely, the concept of the "quantum protectorate." In a work with a remarkable title, "The Theory of Everything" [278], authors R. Laughlin and D. Pines discussed the most fundamental principles of the description of matter in a wide sense. Since we will use this mysterious term "matter" more than once, let us give the definition according to the modern dictionary of scientific usage [279]: "Matter is that which occupies space at any given time and is observable or detectable, i.e., any object or any material, or any organism comprised of matter. Matter has structure; various types of matter have different structures; however, matter as a whole is assumed to be consisting of discrete particles (atoms). The value of matter can be measured by its mass or its volume, or the amount of substance."

We will return to this topic later. Now let us consider the work by Laughlin and Pines [278]. The authors put forward the question what the "theory of everything" was; "a theory applicable to description of all things and phenomena that describes the common world of human beings, air, water, stone, fire, people, etc." The answer given by the authors was that "this theory was nonrelativistic quantum mechanics," or, more precisely, the equation of nonrelativistic quantum mechanics, which they wrote in the form

$$H\psi = -\frac{\hbar}{i}\frac{\partial\psi}{\partial t}. \quad (45)$$

That was the only formula in their work; they also gave detailed definition of the Hamiltonian of a system consisting of many interacting particles. The authors agreed, however, that "such objects in the Universe as the planet Jupiter, nuclear fission, the Sun, or the occurrence of isotopes of elements in space are not described by this equation, since such important things as gravity and nuclear interactions are not taken into account. However, with the exclusion of light, which could easily be included in the consideration, and possibly gravity, these omitted elements are insignificant to phenomena on a human scale. Equation (45) is the precisely the Theory of Everything necessary for our everyday world.

Note that the construction of the universal picture of the Universe based completely on the data of natural sciences is a long-standing dream in many circles. In this regard, it is appropriate to mention the interpretation of the notion Universe in one of the authoritative dictionaries of scientific terms "The Universe is the totality of astronomical objects, events, relations, and energies that admit objective description" [280]. The end of the nineteenth century was probably a time of strong expectations for timely constructing a unified physical picture of the world. Since olden times, since its very existence, the study of nature has had, as an ideal, the ultimate higher task of unifying the variety of physical phenomena into a unique system, and if possible, in a single formula [281].

Possible, to continue this line, Feynman wrote in his famous course on physics that "often people, in unjustified fear of physics, say that it is impossible to write the equation of life. But maybe we can. Very possible we already have a sufficiently good approximation with quantum mechanics equation (45). We have just seen how phenomena in their complexity could be remarkably and easily obtained from simple equations describing these phenomena. Not knowing the capabilities of simple equations, people often conclude that to explain the entire complexity of the world, something divine, rather than just equations, is required." This passage by Feynman is partly in line with remarks made by Einstein more than once concerning attempts at implementing a program to unify the description of the physical reality by fields without singularities and satisfying partial differential equations.

The end of the nineteenth century coincided with a change in the physical paradigm from the mechanical picture of the world with two concepts (the law of motion and the expression for force) to a much deeper concept of the field. Einstein considered this a revolution. In essence, he predicted and initiated works in the field of constructing the unified field theory (the predecessor of the theory of everything). He wrote in 1922 that "it should be expected that the progress of science will overturn its principles, and it will be as deep as the

revolution related to field theory. However, we are far from a logically clear foundation" [282].

At present, the problem of unification of the weak, electromagnetic, gravitational, and strong interactions has been posed [283]. Many researchers work in this direction; however, one can speak of the success in the theory of electroweak interaction so far. Einstein, unlike Feynman, never spoke of the "equation of life." He preferred to be more cautious, saying that the objective of science was, on the one hand, possibly more complete cognition of the connection between a set of perceptions, and on the other hand, reaching this objective by applying the minimum primary notions and relations (with as much logical unity in the picture of the world as possible, i.e., with minimum logical elements) [284].

He wrote in another work that a researcher should instead obtain clearly formulated general principles of nature reflecting particular general features of a large set of experimentally established facts [285].

Speaking of construction of the unified physical picture of the world, M. Planck stressed that at all times, two methods stood opposed to each other in solving this problem; often, these methods competed, and even more often, mutually corrected and augmented each other, especially when they were combined in the hands of one researcher. One of these methods, the more resolute one, boldly unites the results of separate studies and focuses on one particular notion or law to subordinate all of nature in all its manifestations to this notion. The second method is more cautious, modest, and reliable; however, it does not lead to the goal as rapidly as the first one; this method received recognition much later. It rejects final results from the very beginning and introduces only those features into the general picture which seem reliably established on the basis of direct experiments and leaves their generalization to further investigation [286].

We leave to the reader to decide which direction was selected by Laughlin and Pines in their considerations on the theory of everything. The following is important to us: "In spite of the above list, it became obvious that the Theory of Everything is not, even remotely, the theory of all things. We knew that Eq. (45) is correct because it allows one to find sufficiently accurate solutions for a small number of particles (isolated atoms and small molecules). However, this equation cannot be solved exactly if the number of particles exceed approximately ten. No existing computers or a computer that would at some time exist would be capable of overcoming this barrier, since this is a catastrophe of dimension. If the amount of computer memory necessary for representing the quantum wave function of one particle is N, the amount of memory for representing the wave function of k particles is equal to N^k. It is possible to perform approximate calculations for systems of large dimensions; these calculations allow one to discover why atoms have their dimensions, why chemical bonds have their length and strength, why solids have their elasticity, and why some materials are transparent and others reflect or absorb light. It is also possible to predict atomic conformations of small molecules, rates of simple chemical reactions, structural phase transitions, ferromagnetism, and sometimes even the temperature of a superconducting transition by applying a certain amount of experimental data for this purpose. However, these approximate schemes are not calculations from first principles; they are, rather, a kind of skill in explaining an experiment. Therefore, in essence, they are inclined to be a less reliable tool in cases when reliability and authenticity are most needed; i.e., when experimental data are poor and insufficient, the physical behavior has no analogues and key problems have not been clearly formulated. Therefore, the triumph of reductionism practiced by the ancient Greeks is a Pyrrhic victory. We have succeeded in reducing all common physical behavior to the simple correct Theory of Everything, only to find that this theory is incapable of discovering anything about a whole aggregate of very important things and phenomena of great significance" [278].

Laughlin and Pines showed that there exist true facts (e.g., the value of e^2/hc) which cannot be obtained from the Theory of Everything because an approximate theory cannot predict a exact result, and therefore, there exist certain higher principles of a nature deeper than a particular microscopic scheme.

Then, the authors formulated their main thesis that occurring physical phenomena regulated by higher physical principles have a certain property characteristic to these particular phenomena. This property is their insensitivity to microscopic description. Thus, here, in essence, a very important question on what is cognizable (conceivable) in the deepest sense of this stratum is formulated. For example, the low-energy spectrum of excitation of a common crystalline dielectric consists of the transverse and the longitudinal acoustic waves only, irrespective of details. Therefore, in the opinion of Laughlin and Pines, it is not necessary to "prove" the existence of sound in a solid; this is a consequence of the existence of other elastic moduli on the large-length scale, which in turn follows from the spontaneous violation of the translational and rotational symmetry characterizing the crystalline state. This implies the inverse proposition that little can be learned concerning the atomic structure of crystalline solids by investigating their acoustic properties. Therefore, the authors come to the conclusion that the crystalline state is the simplest known example of a "quantum protectorate," a stable state of matter whose low-energy properties are determined by nothing else than higher physical principles.

The existence of two scales, low-energy and the high-energy, in the description of magnetic phenomena was stressed in [287, 288] upon comparative investigation of localized and zone quantum models of magnetism. It was shown that the low-energy spectrum of

magnetic excitations in magnetically ordered solids represents the hydrodynamic pole ($\vec{k}$, $\omega \longrightarrow 0$) of the generalized spin susceptibility and is present in the Heisenberg, Hubbard, and combined *s–d* models. In the Stoner model, the hydrodynamic pole is absent; this model does not contain spin waves. Stoner single-particle excitations (an analogue of plasmon excitations in an electron gas) are absent in the spectrum of the Heisenberg model. The Hubbard model [251, 254] of narrow energy zones contains both types of excitations: collective spin waves (low-energy spectrum) and Stoner single-particle excitations (high-energy spectrum). This is the great advantage and high flexibility of the Hubbard model as compared to the Heisenberg model. However, the Heisenberg model is a very good approximation of real behavior in the region of applicability of the hydrodynamic description, i.e., for large wavelengths and small energies. The concept of quantum protectorate was applied to the theory of magnetism in [289]. We succeeded in formulating the criterion of applicability of quantum models of magnetism to particular substances on the basis of analyzing their low-energy and high-energy spectra.

Note that, earlier, in-depth analysis of the applicability of the hydrodynamic description on the basis of calculating the poles of the generalized susceptibilities of multiparticle systems was performed in [290].

7. STATISTICAL PHYSICS: 1940–1947

In 1940, Blokhintsev's attention was attracted to the problem of statistical description of quantum systems. Interest to these problems stemmed from lectures and works on quantum mechanics by Mandelstam and Nikol'skii. Nikol'skii's book *Quantum Processes* [291] is mentioned many times in his papers.

In the work "Correlation of a Quantum Ensemble with a Classical Gibbs Ensemble" [292], the limiting transition from quantum equations of motion for the density matrix to the equations of motion for the classical distribution function was studied. The problem of the limiting transition from quantum to classical mechanics was considered by Mandelstam as well. In 1936, Ya.P. Terletskii, a student at that time, performed the study "Limiting Transition from Quantum Mechanics to Classical Mechanics" [293, 294] under the Mandelstam's supervision. However, there was the problem of agreement of quantum mechanical and classical descriptions, which had existed from the beginning of quantum mechanics. Already in 1924–1925, Jaffe [295, 296] showed that if the phase distribution density is expressed as a function of the energy integral and the integral expressing the conservation of motion of the center of mass, the energy will not be distributed uniformly over degrees of freedom. In these works, Jaffe managed to show that in some cases for oscillators, the energy turns out to be proportional to the oscillation frequency; i.e., to some extent, he reproduced the transition from classical to quantum description. In [292], Blokhintsev studied the possibility of correspondence between the classical distribution function $f(q, p)$ and the quantum density matrix ρ from the general point of view. For this purpose, the "mixed" (q, p) representation for the density matrix ρ was used. Then, the following function was introduced:

$$R(q, p) = \langle q|\rho|p\rangle e^{-\frac{ipq}{h}}\sqrt{2\pi h}, \qquad (46)$$

which was assumed to be an analogue of the classical distribution function $f(q, p)$ at $h \longrightarrow 0$. This function is a complete analogue of the classical density in the phase space $f(q, p)$ for the Gibbs ensemble. The function $R(a, p)$, similar to the function $\langle q|\rho|q'\rangle$, allows one to find the average values of any quantity $L(q, p)$. However, investigation of the possibility of expanding the function $R(q, p)$ in powers of h for $h \longrightarrow 0$ showed that this is possible only in the case when the symmetry or antisymmetry of wave functions is not taken into account. According to Blokhintsev, it was shown in [292] that there does not exist any distribution function depending on (q, p) which could describe the quantum ensemble [43] (see Section 46 in [43] concerning the density matrix).

In the next work on the topic [297], the problem of the conditions of approximation of quantum statistics by classical statistics was considered. It was shown that there is no limiting transition ($h \longrightarrow 0$) from a quantum ensemble consisting of similar particles to a classical ensemble. The classical description is obtained if the state of the system is characterized by the position in the phase cell $\Omega \gg h$. Thus, in [292, 297], a new direction of physics was initiated: quantum mechanics in the phase space [298].

Earlier, in 1932, Wigner [299] proposed an approach for calculating statistical averages of measurable observable quantities. For this purpose the "weighting" function $w(Q)$ related to the density matrix was introduced; it was as though statistical data were "shifted" from the density matrix to the weighting function. The complex argument of the weighting function Q represented the point in the phase space (q, p) of the system under study. The main objective of [299] was the use of the probability distribution function in the phase space *instead* of the wave function. The Wigner function was widely applied in statistical physics, in particular, in plasma physics [300], investigation of coherent properties of light [301], etc. In essence, Wigner [299] proposed a special method of averaging over a quantum mechanical ensemble consisting of integration over c numerical variables in the phase space. It was established that a wide variety of quasi-probability distribution functions in the phase space could serve this purpose [302]; the Wigner function is a special case of such distributions. The term "quasi-probability" should be pointed out; the Wigner function plays the role of the probability distribution function in the phase space (for a detailed analysis see [301, 303]).

In this work, general recipes for finding correspondence between distribution functions in the phase space and rules of finding quantum mechanical analogues (operators) [302, 304, 305] to classical quantities were established. There exist a large number of quasi-probability distribution functions in the phase space that serve the same purpose as the Wigner function [298, 306, 307]. In particular, Moyal [308] in 1949 formulated the general approach to quantum mechanics as the statistical theory, or, more precisely, as the form of "indeterministic statistical dynamics". In this approach, the distribution function for complete systems of dynamical variables characterizing the system is expressed in terms of wave vectors of quantum theory. These phase distribution functions play the main role in the statistical theory. It was shown that the used procedure is equivalent to the choice of a particular type of the theory of functions of noncommuting operators and therefore can be considered as an interpretation of quantum kinematics [308]. Then, on the basis of the equations of motion of quantum dynamics, relations determining the evolution of these phase distributions were derived. It turned out that they have a form characteristic to dynamical stochastic processes. It was shown that these evolution equations in the phase space can be used instead of the Schrödinger equation.

The correlation between the probability density in the unified coordinate–momentum representation of quantum mechanics and the uncertainty principle was studied by V.V. Kuryshkin [309]. Further discussion of these problems can be found in surveys [306, 307] and books [298, 310]. Note that an interesting, although debatable, approach to the construction of classical models of quantum mechanical systems was proposed by B.T. Geilikman [311] in 1979. He investigated a general classical model reproducing quantum mechanical regularities that was described by an equation that can, in a certain sense, be considered an analogue of the Schrödinger equation.

The title of the next work written by Blokhintsev [312] (jointly with Ya.B. Dashevskii in 1941) is "Partition of a System into Quantum and Classical Parts." According to the authors, "Among physical problems that should be solved using quantum mechanical methods, there are such problems in which the system of interacting particles under study has a property that one of its parts during the processes occurring in the system moves as though it obeys classical laws of motion, i.e., moving along a trajectory."

In this work, they studied the possibility of partitioning an interacting system into quantum and classical parts. They demonstrated the type of perturbation when the classical part acts on the quantum part. Examples from collision theory [130] and the equations for modulated motion were also considered. Blokhintsev wrote in [31] that this work had been performed jointly with Ya.B. Dashevskii (who tragically perished, killed by fascists in the Darnitzkii concentration camp) and had followed from my long-term interest in the problem of interaction of the classical and quantum systems. Later, this led me to n important step in understanding the mechanism of quantum mechanical measurements.

The essence of this work is as follows: let x be the variables of the quantum part and X be the variables of the classical part of the system. Then, the Schrödinger equation is written as

$$i\hbar\frac{\partial\Psi}{\partial t} = [H_0(x) + \mathcal{H}_0(X) + W(x, X)]\Psi, \qquad (47)$$

where $H_0(x)$ and $H_0(X)$ are the Hamiltonians of the free parts, and $W(x, X)$ is their interaction. It was shown that the separable solution to Eq. (47)

$$\Psi(x, X, t) = \psi(x, t)\Phi(X, t), \qquad (48)$$

where $\psi(x, t)$ and $\Phi(X, t)$ satisfy the equations

$$i\hbar\frac{\partial\psi(x, t)}{\partial t} = H_0(x)\psi(x, t) + v(x, t)\psi(x, t), \qquad (49)$$

$$i\hbar\frac{\partial\Phi(X, t)}{\partial t} = \mathcal{H}_0(X)\Phi(X, t), \qquad (50)$$

$$v(x, t) = \int\Phi^*(X, t)W(x, X)\Phi(X, t)dX, \qquad (51)$$

can be obtained if

$$W(x, X) - \int W(x, X)|\Phi(X, t)|^2 dX \cong 0". \qquad (52)$$

This field attracted great interest in subsequent years, especially in many problems of physical chemistry. A large number of works are devoted to this topic; some of them are considered in detail in surveys [313, 314].

In 1946, after switching to defense problems, Blokhintsev returned to quantum physics. The work performed in 1946 is titled "Calculation of the Natural Width of Spectral Lines Using a Stationary Method" [315]. This small work demonstrated high flexibility in handling tools of quantum mechanics when the result was reached in a simple and elegant way. Blokhintsev wrote, "Usually the problem of emission and absorption of light ia considered using the method of quantum transitions. However, this problem, similar to the dispersion problem, can be solved in an extremely simple way using the method of stationary states" [315]. Then, the author wrote out the system of equations for *state amplitudes* of two types: (a) when the emitter is in the state m and light photons are absent, and (b) when the emitter is in the state n and one light photon has been emitted. Taking into account the energy conservation law, the solution for the amplitude was obtained, and on its basis, the approximate expression for the level position of the whole system (emitter and radiation). "This expression resulted in exactly the same shift and smearing of levels as those obtained by Dirac upon calculation of resonance scattering."

Then, the spectral distribution within the line width was found. The author noted that upon transformation

of the amplitude to the coordinate representation, "we obtain a divergent wave with an amplitude that slowly increases with increasing distance from the radiation source in the same way as took place for a classical decaying oscillator" [315].

Later, the problem of the natural width of spectral lines was used many times for testing various new schemes of calculation and theories of quantum physics [316, 317]. It was noted in [318] that the variety of interpretations of the problem of natural width of spectral lines is so large that it is sometimes confusing and prevents one from seeing to what extent different approaches describe (or don't describe) the same effect. It is known that excited levels of an isolated atomic system with the probability of emitting light due to interaction with the electromagnetic field proper have finite lifetimes. This results in the levels becoming quasidiscrete and acquiring finite small width, which is called the natural width of spectral lines. In [131–133], using the method of nonequilibrium statistical operator, the Schrödinger-type equation with damping for a dynamical system weakly interacting with the thermostat was obtained (see Eq. (20)). In this case, the concept of "quantum noise," allowing one to construct the nonequilibrium statistical operator with noise "sources" and obtain the system of coupled equations for average amplitudes and densities, was used. In essence, the obtained system of equations is similar in a certain sense to the system of equations obtained by Blokhintsev for amplitudes and simulates the behavior of a "damped oscillator" [315]. The interaction of the small system with the medium (thermostat) $\varphi_{\alpha\beta}$ plays the role of friction. The equation for the average amplitudes is written in the form

$$i\hbar\frac{d\langle a_\alpha\rangle}{dt} = E_\alpha\langle a_\alpha\rangle + \sum_\beta K_{\alpha\beta}\langle a_\beta\rangle, \qquad (53)$$

where

$$K_{\alpha\beta} = \frac{1}{i\hbar}\sum_\gamma \int_{-\infty}^{0} dt_1 e^{\varepsilon t_1}\langle \varphi_{\alpha\gamma}\tilde{\varphi}_{\gamma\beta}(t_1)\rangle_q. \qquad (54)$$

Here, $\langle\ldots\rangle_q$ denotes the statistical averaging with quasiequilibrium statistical operator ρ_q (see [131–133]). The expression for the natural width of spectral lines [319] follows from this equation:

$$\Gamma_b = \frac{4}{3}\frac{e^2\omega_0}{m^2c^3\hbar}\left|\langle a|\vec{p}|b\rangle\right|^2 = \frac{4}{3}\frac{\omega_0^3}{c^3\hbar}\left|\vec{d}_{ab}\right|^2, \qquad (55)$$

where $\vec{d}_{ab}$ is the matrix element of the dipole momentum. This expression coincides with the well-known expression for the natural width of spectral lines obtained earlier [316, 317].

Later, in the work "Principle of Detailed equilibrium and Quantum Mechanics" [320], Blokhintsev considered the fundamental problem of physics, the reciprocity principle. "As is known in classical mechanics that when forces are invariant with respect to the change of sign of all velocities, the reciprocity principle holds. According to this principle, if the sign of all velocities is changed to the opposite, or, equivalently, if the sign of time is changed to the opposite, the motion occurs in the reverse order. It is the same situation in quantum mechanics. The validity condition of the principle of detailed equilibrium was established; according to this principle, the probabilities of the direct and the reverse transitions are equal to each other. We give an example of a system for which the principle of detailed equilibrium has not been satisfied." Thus, in [320], the problem of validity of the principle of detailed equilibrium for quantum systems was considered. This principle is required for proving the Boltzmann *H* theorem, which expresses the irreversibility of the relaxation process. It was shown that in the case of the central law of interaction between particles, the principle of detailed equilibrium is unconditionally satisfied. However, for interactions depending on angular coordinates, special consideration is required, since the principle of detailed equilibrium in these cases is not always satisfied. In particular, this is attributed to systems with spin interactions. Blokhintsev wrote [31], "In classical mechanics, the principle of detailed equilibrium is satisfied in cases when forces are invariant with respect to the change of sign of velocities of all particles. In other cases, this principle is violated. Precisely the same situation takes place in quantum mechanics." Various aspects of the principle of detailed equilibrium were considered in [132, 133, 135, 321].

7.1. The Atom under an Electron Microscope

In 1947, Blokhintsev published the work "The Atom under an Electron Microscope" [322], which is worth special discussion (see also Section 16 of [43]). Blokhintsev wrote that "this work, devoted to a very special problem, is worth mentioning due to a somewhat unusual formulation of the problem. The origin is thus. I paid attention to the fact that under the action of a scattered electron, the atom receives recoil and can be knocked out of its position on the surface of the 'object plate.' If it were not knocked out at first scattering, it could be knocked out at subsequent scatterings. It should be noted that this experiment is unusual from the point of view of the common formulation of measurements in a quantum ensemble. Indeed, in this case, we consider the repetition of measurements with the same sample of the atom, rather than a set of atoms, as is usually done. After each measurement the state of the atom, generally speaking, changes, and it becomes a sample of another quantum ensemble. Thus, the series of scatterings necessary for obtaining an image of the atom consists of a series of scatterings related to objects from different quantum ensembles. This seems to be a unique case of such a situation."

Further in this paper, Blokhintsev noted, "In connection with a distinct tendency of increasing the resolution power of the electron microscope, both by transition to shorter wavelengths and by improvement of the optical system, the problem of the capability of observing a separate atom becomes of practical interest" [322]. Here, it is appropriate to mention what Schrödinger said in 1955: "We cannot see, hear, or feel individual atoms" [323]. Of course, Schrödinger did not mean observation with human senses. It is interesting to note that already in 1922, P.A. Florenskii wrote, "Man is a creature who makes tools, or, more precisely, extends tools….A tool is a continuation of our senses; all tools for observation, all weights, measures, scales, micrometers, microscopes, thermometers, etc., are *artificial extensions* of senses" [324].

Since physicists, chemists, metallurgists, and biologists needed improved microscopes, this problem always stirred interest. In [30], remarkable works performed by Mandelstam on the theory of the microscope are noted; Mandelstam displayed his inherent the strength and depth of thought and his keen understanding of the physical nature in analyzing this problem. Blokhintsev's work [322] continued the development of the theory of the microscope at the new quantum stage. The interest in this problem not only stemmed from the applied value. According to Blokhintsev, "The development of the theory of the microscope is of interest from the theoretical point of view, since when observing a single atom using an electron microscope, the image will emerge as a result of repetition of single scattering acts on the same object, while in quantum mechanics, results are usually formulated with respect to a set of objects in the same initial state. Due to the action on the atom, each new scattering act, generally speaking, will force the atom to be in a new initial state. Therefore, it is important to analyze the influence of electron scattering on the state of the observed atom" [322]. Blokhintsev analyzed this problem and showed that "it is possible to obtain several thousand scattered electrons before the atom will be knocked out of its place." (See Section 16 of [43] for details.) In [31], Blokhintsev concluded that "calculations showed [322] that it is possible to obtain many thousand scatterings on a heavy atom like Cu, Hg, etc., without completely knocking the atom out of its position." In that work, he used the following expression: "a man being photographed can be knocked out of his chair." At that time, such a portrait could not be obtained. A photo of a single atom was obtained only later by American researchers.

Further development in physics proved that Mandelstam and Blokhintsev's interest in problems of the theory of the microscope was justified. This direction was developed in subsequent years [303, 325–329] and is being extensively developed now [330]. Using this technique, it is possible to observe single iron atoms adsorbed on a platinum surface [331], observe local details of the quantum Hall state [332], and trace individual molecular bonds of atoms on a metal surface [333]. Moreover, with the combination of electron and x-ray microscopy, it was possible to "observe" the real "shape" of certain electronic d orbitals in CuO_2 planes in superconducting cuprates [334]. Not long ago, it was demonstrated that it is possible to localize, identify, and measure the electronic environment of an individual atom in the bulk of a solid, rather than on its surface [335]. A detailed survey of different types of modern microscopy equipment is given in [336]; this direction of research is developing rapidly.

8. STATISTICAL INTERPRETATION OF QUANTUM THEORY AND THE ENSEMBLE METHOD

Blokhintsev recollected [31] that "in the 1930s–1940s, the interest of many physicists–theoreticians at the Lebedev Physics Institute and MSU was concentrated on the principles of quantum mechanics, which seemed full of paradoxes to many people."

At present, quantum mechanics is quite an advanced branch of science with a very wide field of application: from interpreting the ideas of psychoanalysis [337] and the phenomenon of consciousness [338–340] to such phenomena as teleportation [341, 342]. It seems that all propositions of quantum theory have been perfected; its physical [343–345] and logical [346–350] principles have been formulated and investigated both from the mathematical [351, 352] and conceptual [353] points of view. It was justly noted in [354]: "The majority of modern physicists unanimously agree that quantum theory is mathematically grounded, and its formalism is sufficiently transparent; however, many are convinced that its interpretation is complex and paradoxical. The most difficult problems occur in relation to understanding the correlation between the formalism of quantum mechanics and the way physicists think of 'physical reality.'" Indeed, in interpreting quantum mechanics, physicists speak of "reality hidden beneath a blanket" [355], of "shadows of the mind" [338], etc. (see the interesting discussion in [356–358]). Discussions on interpreting quantum mechanics [361–364] that began in the first years of quantum mechanics [8, 10, 359, 360] continue now [365–373]. One active participant discussion testifies to the heatedness of the: "Many in physicists have been blindly repeating the points of view of Bohr and Heisenberg concerning the principles of quantum mechanics for years without a clear understanding of their meaning. We note with satisfaction that the predominance of the Copenhagen orthodoxy has been weakened, and physicists are beginning to consider with open minds alternative points of view on fundamental problems" [370] (see also an interesting presentation of this problem in [374]).

Blokhintsev's name is closely related to the problem of interpreting quantum mechanics. A large number of his papers [375, 376] and books [43, 377, 378] were devoted to this problem. His views of the problem changed and evolved with deepening and perfection of

arguments. The last edition of his textbook [43] differs radically from the first and second editions [379]. It is interesting to trace this evolution and try to understand the sources and the meaning of discussions on the principles of quantum theory at that time.

M.A. Markov recalled, "During the formation of quantum mechanics, many things in this theory seemed unclear from the point of view of old common ideas….A new theory—quantum theory—provided many causes for reflection and discussions" [35]. It was noted in [30] that Mandelstam paid much attention to these problems. "He was more and more interested in theoretical investigations concerning certain key problems of wave mechanics, especially problems of great cognitive–theoretical importance. His interest in such problems related to axiomatics and logical substantiation of the basic methods of physics was always lively; during the last years of his activity, this direction probably become decisive" [30]. Since Mandelstam reflected a lot on the principles of quantum theory and often discussed them at his lectures and seminars [30], this certainly influenced the young researcher Blokhintsev.

Most physicists in the Soviet Union and a number of most distinguished Western scientists (Bohr, Einstein, Heisenberg, M. Born, de Broglie, etc.) were involved in discussions concerning the principles of quantum theory. In the Soviet Union, ideological context was sometimes introduced into these discussions (see, e.g., [380–383]). Blokhintsev recounted [31] that "the meddling of certain philosophers in these discussions contributed to the entanglement of clearly formulated physical problems and unnecessary heatedness of discussion."

Meanwhile, there were enough causes for discussions, even without an ideological context. The most topical problems of interpreting quantum mechanics were the problem of measurement and the role of the observer, and the probabilistic interpretation of the ψ function. Feynman noted [384]: "There exist several problems related to interpretation that could be worked on further; one of these is proving that the probabilistic interpretation of the ψ function is the only consistent interpretation of this quantity; it would be interesting to prove that it is impossible to propose any other consistent interpretation of this quantity." As a result of long-term research and reflections, Blokhintsev developed his own approach to interpreting quantum mechanics, which included ideas put forward by Neumann [33], Mandelstam [32], and Nikol'skii [291]. He wrote in a summary work [377], "The presentation of quantum mechanics undertaken in these lectures is essentially based on the ideas of von Neumann, which in their time attracted the attention of the Moscow school of theoreticians; in 1930s this school was headed by Academician Mandelstam; Nikol'skii contributed considerably to the understanding of quantum mechanics." Blokhintsev thought that "this approach to the principles of quantum mechanics had an advantage, as compared to traditional interpretations on the basis of the wave function, since it allowed one to include the theory of quantum measurements as a chapter of quantum mechanics" [377].

Blokhintsev noted [31]:

> Although Bohr was the recognized ideologist of quantum mechanics, his concept had always caused a feeling of dissatisfaction; and I had never shared the expectations of some physicists that quantum mechanics needed "hidden parameters" whose discovery would reduce it to a special type of statistical mechanics. However, most of those who were not satisfied with Bohr's ideas or, as it was then formulated, the ideas of the Copenhagen school, opposed these ideas of "hidden parameters." My dissatisfaction with the Copenhagen concept had other reasons. Two items in this concept seemed unsatisfactory to me: (1) An insufficiently clear definition of the statistical ensemble to which objects of measurement and measuring devices were attributed. As a result, the wave function ψ was readily assigned to one sample of the microsystem μ taken as is, ignoring the circumstance that the wave function, which is a measurable quantity, cannot be obtained from measurements on one sample of the microsystem. (2) According to Bohr's concept, an observer occupied with measurements in the quantum field plays a special role, as compared to his role in classical physics. This implies a purely informational view of the wave function, as if it were the observer's notebook. This view resulted in natural difficulties in application of quantum mechanics to phenomena that had occurred (or is occurring) without the participation of any observers. I listened with great interest and respect to the opinion of the esteemed Bohr; however, von Neumann's position, stated in his famous book *Mathematical Concepts of Quantum Mechanics*, was closer to my scientific ideology. The statistical approach to understanding quantum mechanics found substantial response in Mandelstam's lectures and studies performed by Nokol'skii and myself. I became interested in investigating the nature of a quantum ensemble, its connection with a classical Gibbs ensemble.

Discussions continued. The variety of opinions concerning the interpretation of quantum mechanics increased with time. Blokhintsev wrote [31]: "Those discussions are reflected in my works; the polemical character of my papers devoted to critical analysis of the ideas of the Copenhagen school and those of Fock gradually brought me to a consistent materialistic concept of quantum ensembles and mathematical measurement theory. Only in the 1960s, after discussions with the Hungarian physicist L. Janosi, did I manage to formulate a reasonable theory of quantum measurements free from inconsistencies in interpreting the role of the observer. In this new concept, the measuring device and its interaction with the microobject were transformed from the subject of philosophical discussions to the subject of theoretical physics; it was demonstrated how

to calculate the interaction….The other side of this concept was that the objective character of randomness and nonremovability of this randomness from quantum mechanics were admitted. Randomness characteristic of microphenomena manifests itself in the macroscopic world as well. Microphenomena influence macrophenomena via unstable states of matter."

As noted in [385],

> Some scientists think that quantum mechanics directly studies properties of statistical ensembles and is inapplicable to describing the behavior of individual microobjects. "Investigating phenomena considerably dependent on the quantum of action $\hbar$, we are dealing with statistical problems; the application of quantum theory to the analysis of an individual measuring process in the atomic region does not provide complete characteristics of the latter due to the statistical character of any quantum problem" [291]. A large group of scientists in our country shared a very similar point of view, first formulated by Nikol'skii. This concept was developed, in particular, in Blokhintsev's famous textbook.

The first mention of quantum ensembles appeared in works written by Blokhintsev [292, 297] in 1940. In 1948, he returned to this problem in the work "Correlation of Mathematical Tools of Quantum Mechanics with That of Classical Mechanics" written together with Ch.M. Briskina [386]. In this work, the idea of classical statistical mechanics in the configuration space was considered, unlike the common idea with the phase space. The correlation with coordinate representation in quantum mechanics was shown. In classical mechanics, dynamic variables are represented by real functions of coordinates, momenta, and time. Quantum mechanics always deals with statistical ensembles, while classical mechanics usually uses the dynamic description of motion for exactly defined initial conditions [386]. It is interesting that in [387], the authors put forward practically the same question: what was the origin of those phenomenological, deterministic laws that approximately control the quasiclassical region of our everyday experience in a universe controlled at the fundamental level by quantum mechanical laws characterized by uncertainty and probability distribution; what characteristic features and limits of applicability of these classical laws could be traced to underlying quantum mechanical concepts. (An interesting discussion of how quantum mechanics helps to unite and better understand complex regularities of classical mechanics and classical statistical mechanics is given in [388].)

In Blokhintsev's approach, the statistical operator describing the state of the microsystem in a quantum ensemble of the general type plays the primary role. The wave function describes a special type of quantum ensemble, the coherent ensemble [377] (see also [389]). Blokhintsev's approach to the interpretation of quantum mechanics became widely known. In the book *Philosophy of Quantum Mechanics* [390], a lot of attention was paid to Blokhintsev's ideas. De Witt and Graham [391] in their survey of different approaches to interpreting quantum mechanics wrote about Blokhintsev's books [43, 378] (published in 1964 and 1968, respectively): "These editions show what happened when political opinions intrude in scientific discussions; however, both of these books are very well written and informative; in reality, the retreat from orthodoxy occurs only in particular points and wording; in general, the presentation of quantum mechanics is very clear and distinct; the second book is a fascinating presentation of quantum mechanics and contains a brilliant consideration of measurement theory" [391].

Blokhintsev's approach to interpreting quantum mechanics is a constituent part of the scope of ideas of different researchers. One of the authoritative historians of quantum mechanics, Hooker, [392] noted that "Einstein and his colleagues, Podolskii, Blokhintsev, Bopp, de Broglie, Popper, Schrödinger, Lande, and Ballentine (who later joined the group), formed a small group of physicists and philosophers who dared to interpret quantum mechanics as a kind of statistical mechanics; many of these scientists hoped to finally restore the classical concept of reality." A detailed survey of the interpretation of quantum mechanics on the basis of quantum ensembles can be found in [393].

The interpretation of quantum mechanics on the basis of quantum ensembles is one of many in existence. They are given in Table 2 for convenience. The list of various interpretations of quantum mechanics is far from being complete. We do not mention various "exotic" interpretations.

Thus, the interpretation of quantum mechanics on the basis of quantum ensembles occupies a separate (noticeable) place among other possible approaches to interpretation of quantum mechanics. The fact that it is widespread is emphasized, for example, by the first phrase of the paper entitled "Meaning of the Wave Function" [419]: "Up until now, the wave function has been interpreted as the probability amplitude, whose physical meaning is obtained by averaging over an ensemble consisting of a large number of identical systems at the given time. We give an alternative interpretation of the wave function for a single system by measurement, which continues for a long time. This is protective measurement; therefore, it lends a different ontological meaning to the wave function." Here, we can trace the analogy with statistical mechanics [351, 425], for which the problem of the equality of ensemble-averaged quantities to time-averaged quantities has not been solved to conclusion [133].

A more detailed discussion of modern approaches to interpreting quantum mechanics can be found in [339, 365, 368–372, 414, 426–433].

Table 2. Various interpretations of quantum mechanics

Name	Authors	Year
Electrodynamical [394]	Schrödinger	1926
Probabilistic [361, 362]	Born	1926
Copenhagen [391, 392, 365, 360]	Bohr, Heisenberg	1927–1930
Statistical [391, 392]	Einstein, Schrödinger	1935–1953
Quantum ensembles	Nikol'skii [291]	1936~1947
Quantum ensembles	Blokhintsev [375–378]	1940–1977
Statistical	de Broglie, Popper [395]	1950–1980
Statistical	Bopp, Ballentine [396, 397]	1970
Generalized probabilistic	Fukuda, Maki [398, 399]	1988
Quantum ensembles	Youm, Whittakker [393]	1992
Fock [363] (theory of predictions)	Fock	1936–1965
Integrals along trajectories [384]	Feynman	1949
Many-world [400, 401, 354, 366]	Everett	1957
Bohm [402–404]	Bohm, Goldstein [405–407]	1951–2002
Dialogue [408, 409]	Mittelstaedt	1983
Operationalistic [410]	Lamb	1969
Spontaneous localization [411]	Ghirardi et al.	1980–1996
Transactional [412]	Cramer	1986
Interactive [413, 414]	Healey	1989
Modal [415]	Kochen	1985
Modal [416]	van Fraassen	1981–1991
Modal [356, 417, 418]	Vermaas, Dicks	1990–1996
Protective measurement [419]	Aharonov, Anandan, Vaidman	1993
Information [420]	Kadomtsev	1994
Consistent [421–423]	Griffith	1996–2003
Immaterial [424]	Onyszkiewicz	1996–1999

8.1. Probability and Quantum Mechanics

It is known that the main specific feature of quantum mechanics that distinguishes it from classical physics is the fact that canonical variables are related to each other by Heisenberg uncertainty relations [10]. Uncertainty relations result in canonical variables being considered as operators in the Hilbert space. From the mathematical point of view [352], this means that quantum mechanics is the implementation of the representation of commutation relations by operators in the Hilbert space. Quantum physics uses two basic ideas, namely, the "state" and the "observable." The interpretation of quantum mechanics on the basis of quantum ensembles allows one to assign a physical meaning to the notion "observable."

There exist various attitudes to the statistical description of real systems on the basis of ensembles [385]. For example, Hinchin [425] avoided the use of the notion "ensemble" because of its (in his opinion) "onerousness," and the foreign origin of this term. Interpretation of quantum mechanics on the basis of quantum ensembles was considered in detail by Ya.A. Smorodinskii [434]. The conclusion he made is quite remarkable: "Discussion showed that if the theory of quantum ensembles is used, these ensembles should be assigned unusual properties that could not be consistent with common probability theory; these properties are not manifested for one particle and can be found only in correlated effects; similar to non-Euclidean geometry necessary for the description of the velocity space in special relativity, quantum mechanics has generated the non-Kolmogorov probability theory; this is probably the deep meaning of analysis of the properties of a quantum ensemble" [434].

Indeed, the problem of probability in physics [435], especially in quantum theory [351, 425], is quite com-

plicated. The following question was formulated: whether the probability is a "normal" physical quantity [436]. It is known that Mandelstam was greatly interested in the problem of probabilistic description in physics [30, 437]. He was closely acquainted with Mises, whose book (translated into Russian) he cited (see [438]). The problem of probability in quantum physics was analyzed from the general point of view in the survey "Origin of Probabilistic Interpretation of the Wave Function" [439]: "Born had more than once pointed out that the idea of the probabilistic interpretation of the wave function belonged, in essence, to Einstein."

It was shown by Cohen [440] that the concept of probability used in quantum mechanics differs considerably from standard probability theory. According to Cohen [440], "In spite of the fact that quantum mechanics is probabilistic theory, it radically differs from standard probability theory, as regards the calculation and manipulation of probabilities and expected values."

Detailed analysis of probabilistic postulates of quantum mechanics was performed in [441–443]. The following paradoxical conclusion follows from this analysis: quantum mechanics applies probability theory for its substantiation; however, probability theory itself is so multifaceted and diverse [436, 438, 444] that its substantiation, or at least exact definition of its interpretation (empirical approach, axiomatic approach, Bayes approach, etc.) is necessary. Therefore, it is not surprising that some researchers reformulate the problem and use the notion of information [420] instead of the notion of probability, or rules of interactive logics [413] for simulation of the probabilistic nature of quantum mechanics in order to overcome this difficulty. n this case, in the information approach developed by B.B. Kadomtsev [420], it was necessary to introduce the special notion "perception" for the description of classical measurements in terms of information processes and to use the notions "intention" and "decision making" introduced earlier. Nonetheless, due to the fact that the information approach [420] is based on common physical sense and intuition, it should be considered quite useful and stimulating. Recent investigations seem to prove the opinion that "the universe is indeed random on the fundamental level" [445]. An approach that uses the concepts of the information theory and the concept of quantum ensembles turns out to be quite useful in analyzing optical measurements, which result in entanglement of states of two atomic ensembles separate from each other [446] (see also the survey on entangled quantum states of atomic systems [447]).

Note that a number of researchers adhere to the opinion formulated in [385]: "If the problem on the reasons for the statistical character of classical theories is basically clear, the reasons for the statistical character of quantum mechanics are still under discussion; it is not excluded that the formulation of the question on the reasons for the statistical character of quantum laws is vacuous, since they are the most fundamental laws of nature."

One of the most involved researchers of the correlation of probability theory and physics was E.T. Jaynes (1922–1998) [448]. His fundamental investigations of the problem concerning the nature of probability [449–451] and the role of probability in physics are a unique phenomenon. The influence of his ideas (which are by far not shared by all scientists) on many researchers in various fields of science is quite large; its scientific heritage requires investigation and comprehension [451].

8.2. K.V. Nikol'skii

Here, it is appropriate to briefly mention the scientific heritage and ideas of K.V. Nikol'skii because of their influence on Bloknintsev. In the biography of Fock [452], Konstantin Bladimirovich Nikol'skii is mentioned among the first group of Fock's apprentices. This was in early the 1930s. At that time, Fock continued his successful activity in the field of quantum mechanics [452], which is proved by his monograph [19]. Nikol'skii worked on atomic physics problems [453, 454] (references to both these works can be found in [163]).

In 1934, Nikol'skii published his book *Quantum Mechanics of a Molecule* [20] and a review [455] of Marx's book [24]. After 1935, Nikol'skii moved to Moscow, where he most likely worked at the Physics Institute at MSU. G.E. Gorelik in his work "Prehistory of the Lebedev Physics Institute" wrote about the project of G.A. Gamov formulated in 1931. Gamov suggested creating a new institute of theoretical physics for developing problems of theoretical physics and allied branches (astro- and geophysics) (on the basis of dialectical materialism) [456]; he wanted to engage a number of younger theoreticians (Nikol'skii, Chumbadze, Zolotukhin, Shubin, etc.) who could work in one of institute's directions [456, 457]. Thus, as early as 1931, Nikol'skii's reputation was rather large. That project was not realized according to Gamov's plans [456, 457].

In 1936, Nikol'skii published his translation of a large paper written by Mott [458]. In the same year, he published his work "Principles of Quantum Mechanics: I" [459], in which he strictly formulated the basic difference between a classical and a quantum process [459]. The objective of the author was to develop (irrespective of physics) the most rational statistical method for this purpose and then, using it, formulate quantitative quantum laws [459]. This paper was included in a more detailed version into Nikol'skii's chief monograph *Quantum Processes* [291]; in this monograph, the interpretation of quantum mechanics on the basis of quantum ensembles was formulated.

"Principles of Quantum Mechanics: I" [459] was criticized severely by Fock in [460], where he said that

the paper induced the impression that quantum mechanics was a kind of statistics. Nikol'skii replied to Fock in the same volume of the journal *Uspekhi Fizicheskikh Nauk* [Advances in Physics] [461] in an even sharper form; unfortunately, apprentices of the Copenhagen concept were accused of "idealism" and "machismo." In 1938, Fock [462] answered this by stressing that the criticism was related exclusively to the Nikol'skii's proposed method for deriving the mathematical tools of quantum mechanics. Concerning the question of the concept of quantum mechanics, he thought it worthy of discussion; Fock devoted a separate paper published in the journal *Pod Znamenem Marksizma* [Under the Banner of Marxism] to this discussion. In this paper, his basic thesis was that quantum mechanics was a materialistic theory for the simple reason that it was the true theory of matter. The history of this dispute was analyzed in [383] (see also [463]). In "Philosophy of Quantum Mechanics" [390], specific attention was paid to Nikol'skii's ideas regarding this dispute.

Later, Fock [464, 465] developed and deepened his criticism of the interpretation of quantum mechanics on the basis of quantum ensembles. Blokhintsev's reply to this [466] was clear and constructive; however, they never found agreement.

The fact that Nikol'skii left Leningrad for Moscow and the sharp form of the dispute in 1937 were surprising. We take the liberty of assuming (unauthentically) why the relations between Fock and Nikol'skii were so negative. Fock's closest apprentice, M.G. Veselov, speaking of his scientific heritage, noted: "In 1935, Fock obtained an elegant solution to the complex problem of the symmetry group of the Coulomb field [467]. It seemed that this solution to a quite particular problem was very important, in terms of its results; Fock became interested in this problem after reading the book written by his apprentice Nikol'skii, *Quantum Mechanics of a Molecule*, in which the term "random" degeneration was applied to Coulomb degeneration of energy levels in a hydrogen atom. Vladimir Aleksandrovich posed the task of finding a group of transformations corresponding to this symmetry; it turned out that such a group could be found in the momentum space: i.e., it had a dynamic character" [468]. In Fock's biography [452], the following was said: "The work on hidden symmetry of the hydrogen atom performed by Fock in 1935 was of fundamental importance; this study was reported on March 23, 1935 at a session of the Academy of Sciences; next day, in the newspaper *Izvestiya* in the article devoted to the session, it was especially noted that the report delivered by Corresponding Member of the Academy of Sciences Fock "The Hydrogen Atom and Non-Euclidean Geometry" at a session of a group of physicists, mathematicians, and astronomers was met with warm approval by all participants; professors Tamm and Frenkel, who participated in debates qualified the work as extremely beautiful and elegant" [467]. There are no references to Nikol'skii in the article.

In *Quantum Mechanics of a Molecule*, in the section "The Hydrogen Atom" (see [20, p. 64], the following is said: "It can be seen that for the hydrogen atom there are two sources of degeneration. One source is the splitting of the angular dependence, which yields $(2l + 1)$-fold degeneration. The other source is the special character of the potential energy $U(r)$, Coulomb interaction. It is easily seen that the first degeneration is conserved for any quantum system whose potential energy possesses central symmetry. The second type of degeneration is called *random degeneration*, since it vanishes at deviations from the Coulomb law; for most atoms, their potential energy, being centrally symmetric in the first approximation, is not Coulomb" [20]. Then, Nikol'skii studied the problem of the symmetry of rotations and came close to solving the problem in terms of group theory. However, he did not take the step that Fock did [467], i.e., the construction of the corresponding symmetry group in the momentum space. A paradoxical situation occurred: an apprentice formulated and posed an important problem on a qualitative level, and a teacher solved this problem on a mathematical level. Possibly, that was Fock's style. It was noted in his biography [452] that "many of his apprentices noted that if he began to think of an exact formulation of a particular topic (of the work of his apprentice), he automatically pointed out a constructive method for solving it, and sometimes, solved the problem himself; Vladimir Aleksandrovich did not like to write joint works (there are very few such works in his list of publications)." It is possible that this episode resulted in worsening relations between Nikol'skii and Fock; the dispute in 1937 parted them even farther. A modern presentation of the problem of the symmetry group of the Coulomb field as applied to the hydrogen atom is given in [469, 470].

Later, Nikol'skii's interests shifted more and more toward the development of a rational statistical method that could serve as a tool for quantum mechanics. In 1940, Nikol'skii published his monograph *Quantum Processes* [291], which, together with Neumann's book [33], influenced Blokhintsev greatly. In the same year, Nikol'skii published two interesting reviews of books: *Electrons, Protons, Photons, Neutrons, and Cosmic Rays* by R. Millikan [471] and *The Mathematical Theory of Nonuniform Gases* by C. Chapman and T. Cowling [472]. At the time, he was working on a translation of a very difficult book by Gibbs, *Elementary Principles in Statistical Mechanics Developed with Especial Reference to the Rational Foundations of Thermodynamics* [473]. This book was published only in 1946; 5000 copies were printed, which seems a lot in our day and age. The preface to the book, written by Nikol'skii, was dated November 30, 1940. Both the publication of the book and Nikol'skii's work as a translator were highly appreciated in *Uspekhi Fizicheskikh Nauk* [474]. In 1947, Pauli's book *General Principles of Quantum Mechanics* was published. It was indicated on the front page that the book had been translated from the German

under Nikol'skii's editorial supervision; this book has neither preface nor editor's notes. After 1947, the name of Nikol'skii is not encountered, and his destiny is unknown to us.

9. PHYSICS AND PHILOSOPHY

In 1947, the journal *Voprosy Filosofii* began publication. In the second volume of this journal, the paper "The Nature of Physical Knowledge" was published by Markov [364], written at the insistence of Vavilov [35], who also was compelled to participate in so-called "philosophical" discussions [38, 475, 476]. Markov wrote: "It is not by accident that physicists have begun philosophizing; they have to philosophize, since it is especially characteristic of modern physics that it cannot be represented without touching upon deep problems of epistemology; these problems are closely related with the specific content of the new theory" [364]. Thus, the complexity of the reality being investigated forced one to interlace the language of physics with threads of philosophical discourse and use a "mixed" physical and philosophical language. The above-said is even truer for the modern situation in which physics uses such complex objects as vacuums, Planck quantities, superstrings, dark matter and dark energy, etc. We mention the following passage from [477] on the physics of vacuum: "The problem of the matter or "solid" on which the world stands has excited mankind since ancient times; ancient thinkers would have been greatly surprised if they learned that, according to the ideas of twentieth-century physicists, a vacuum is such a basis of the world; a vacuum in elementary particle physics is determined as a state without particles; nonexistence as the absence of particles and a field is impossible. Looking into a vacuum, we see separate glowing sparks—fluctuations of the vacuum, or the zero field of the vacuum, rather than darkness; the presence of the zero field results in the fact that both vacuum energy and energy density in space turn out to be infinite; thus, in elementary particle physics, a paradoxical situation occurs when the basis of one of the most rational fields of knowledge, theoretical physics, contains an absolutely irrational idea." If this concept is continued using philosophical language, it could be said that a vacuum is a "superexistence" rather than "nonexistence." The attitude of actively working physicists toward the "philosophy of physics" is ambiguous.

According to A.B. Migdal [478], "The following should be understood under the term "philosophy of physics," or "the philosophy of quantum physics": the increasing specialization of science during the last decades has resulted in the situation that "natural philosophy" as a whole has become too wide a field for constructive investigation of cognition methods; these problems should be solved by physicists, biologists, psychologists—experts constructively working in their fields."

The question of how accurately physics describes the real world is still discussed intensely [357, 358]. Blokhintsev's thoughts and considerations on the question are in part topical at present. The complete list of his publications contains 78 works (from a total 300) on general and philosophical problems of science. The first publication on this topic "The Struggle Surrounding the Conservation Law and Energy Transformation in Modern Physics" was published in 1934 in *Pod Znamenem Marksizma* [479]. In 1936, the paper "Matter, Mass, and Energy" was published in the journal *Antireligioznik* [480]. Bloknihntsev, similar to most leading physicists (Vavilov, Tamm, Fock, Langeven, Einstein, etc.), published his papers in *Pod Znamenem Marksizma*. There was no other tribune for discussions. There existed a "conditional language" in which it was allowed to discuss philosophical problems of natural science, the language of dialectical materialism [481]. This language was used by all who wrote papers on problems of quantum physics during those years [38, 475, 476, 482].

From the modern point of view, a certain "obsession" with the idea of "matter" and "materialism" [481, 483] during that period would not be clear if the historical context were not taken into account. Indeed, let us pose the question why the quite particular philosophical doctrine of materialism that occurred in Ancient Greece had such a strong hold on the minds of people [484–487] at the end of the nineteenth century and the first half of the twentieth century. It is well known [488] that, "if the basic problems of the philosophy of Ancient Greece were analyzed, the main problem characteristic of the whole dialectic of philosophical cognition can be formulated: the inadequacy of logical thinking and contradictory empirical reality." In other words, the system of philosophy of ancient Greece, which was the basis of dialectical materialism, was from the start incapable of expressing very complex notions of modern physics. Therefore, the intellect of Niels Bohr was required to approach the philosophical interpretation of quantum mechanics from quite a different viewpoint.

Blokhintsev wrote the following onhis philosophical [31]: "My philosophical concept was formed under the influence of Lenin's ideas, which were brilliantly presented in *Materialism and Empirical Criticism.* I had to defend more than once the ideas of the founders of dialectical materialism both from its opponents and his primitive advocates and dogmatists among Russian philosophers; it would be inappropriate to describe the struggle, which became dramatic at times; my principal works in this field are devoted to the methodological problems of quantum mechanics."

It was justly noted by Gorelik in "Vladimir Aleksandrovich Fock: Philosophical Lesson of the History of Physics" [489] that the philosophical puzzle left by Fock (and Blokhintsev) to historians still exists. Gorelik asked why these distinguished scientists had used the conditional language of dialectical materialism. Not

being experts in the history of science, we cannot answer this question.

10. LAST THOUGHTS

In 1984, the collection of works *Epistemology and Modern Physics* [490] was published. This book contains what is probably Blokhintsevs's last published work, "Considerations of Problems of Cognition and Creation and Regularities of Development Processes." This work continues the topic of the earlier paper "Prerequisites of Scientific–Technical Progress" [491], but is much more extended and rich in content and touches upon the most fundamental problems of science and existence. In essence, it can be considered the "last message to the future" of a great scientist and humanist. The content of this book has something in common with the book by G. Caglioti [492]. The style of this publication differs strongly from all of Blokhintsev's previous so-called "philosophical" publications. In this work, citations and references to great Marxists are absent; there is only a cursory note concerning materialism ("we, materialists…"). In this work, the character of Blokhintsev that was known and appreciated by those who worked and communicated with him is clearly manifested. His inherent approach to science, art, and life is expressed with extreme clarity in the particular manner of "painting with large strokes and bright colors." According to Blokhintsev, "The ability of a human being to perceive his surrounding reality is related to the feeling of surprise and admiration in front of the inconceivable beauty and harmony of the world." We cannot cite the entire content of this interesting paper here, but we present several of Blokhintsev's ideas on basic science. "Following the principle of beauty of a logical construction, a beauty which cannot be defined, the human mind becomes capable of predicting possible regularities of the outer world in the Universe, the micro- and macroworld; society should be patient and deliberate in evaluating new ideas, which become clear to a wide circle of people only gradually; basic science should be protected from the too straightforward and intolerant influence of a paradigm (a particular level of thinking of society). Basic science should not be hastened or urged on. This plant, open to injury, requires a careful and loving attitude; the only thing that organizers of basic science should care about is engaging people for whom obtaining truth and knowledge is their life's passion, passion free of commercialism and money-grubbing; it should be added that only very self-confident people can judge the importance or unimportance of a particular scientific quest; predictions are seldom justified, since in this case, one has to comment on future discoveries, which are called discoveries for the reason that they uncover something unknown before. Basic research does not provide people with instant fare; therefore, if they cease, for the time being, probably nothing bad would happen to mankind would not. I believe, however, that mankind cannot limit itself to short-term problems. This is the essence of mankind; anyhow, basic science doesn't cost society much at all. Armaments are far more expensive" [490].

These thoughts of Blokhintsev expressed what was considered by many physicists. P.N. Lebedev (1866–1912) wrote at the beginning of the twentieth century: "Any progress in applied science and technique is wholly due to the success in the field of basic sciences, in the field of pure knowledge" [493]. Nothing can be added to these words.

11. AFTERWORD

We conclude this paper with the idea by Born formulated in his lecture "Experiment and Theory in Physics" delivered in 1943. "Those who want to master the art of scientific prediction should, instead of relying on abstract deduction, try to comprehend the secret language of Nature, which is represented by experimental data." Blokhintsev in his lectures and talks more than once expressed similar thoughts in different words.

In this work I have tried not only to write about Blokhintsev's studies, but build them into appropriate lines of the development of quantum physics and connect them, directly or indirectly, to the modern development of these fields of science. I have tried to show that Blokhintsev's book *Principles of Quantum Mechanics*, which is justly considered one of the best textbooks in quantum physics, was compiled by a witness to and a participant in the formation and development of quantum mechanics. It organically includes most of his original works in an integrated description of the subject. This, together with the definite literary talent of the author and his gift for presenting the subject clearly and lucidly, is the foundation on which *Principles of Quantum Mechanics* stands, and it describes the world using the language of a quantum.

In this work, not all the topics and problems that I wanted to discuss are here. For example, due to the lack of space, we omit the history of the dispute between Blokhintsev and N.P. Kasterin [494, 495]. This episode was described in detail in [496]. Permit me to refer any reader who wants to reflect on Blokhintsev's works to a collection of selected works in two volumes that will be published in 2008.

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REFERENCES

1. B. M. Barbashov, Usp. Fiz. Nauk **94**, 185–186 (1968) [Phys.–Usp. **1**, 139 (1968)].
2. N. N. Bogolyubov, B. B. Kadomtsev, A. A. Logunov, and M. A. Markov, Usp. Fiz. Nauk **124**, 193–194 (1978) [Phys.–Usp. **21**, 91 (1978)].
3. S. N. Vernov, N. A. Dollezhal, and I. M. Frank, At. Energ. **43**, 491–492 (1977).
4. B. M. Barbashov, G. V. Efimov, A. V. Efremov, et al., Usp. Fiz. Nauk **130**, 185–186 (1980) [Phys.–Usp. **23**, 100 (1980)].
5. In *Proc. of Science Seminar of 75 year of D. I. Blokhintsev, Dubna, 23 Jan., 1983* (OIYaI, Dubna, 1986), p. 211.
6. In *Proc. of Science Seminar of 85 year of D. I. Blokhintsev, Dubna, 27 Jan., 1993, 25 Jan., 1994* (OIYaI, Dubna, 1995), p. 272.
7. F. Hund, *The History of Quantum Theory* (Naukova Dumka, Kiev, 1980; Bibliographisches Institut AG, Zurich, 1975).
8. V. Geizenberg, *Physics and Philosophy. The Part and the Whole* (Nauka, Moscow, 1989; München, 1969).
9. V. Geizenberg, *At the Origin of Quantum Theory* (Moscow, Taideks, 2004) [in Russian].
10. M. Jammer, *Conceptual Development of Quantum Mechanics* (McGraw-Hill, New York, 1966; Nauka, Moscow, 1985).
11. *50 years of Quantum Mechanics*, Ed. by L.S. Polak (Nauka, Moscow, 1979) [in Russian].
12. A. B. Kozhevnikov and T. B. Romanovskaya, "Quantum Theory (1900–1927)," in *Physics of XX Century, and its Connection with Other Sections of Natural Sciences,* Ed. by G. M. Idlis (Yanus-K, Moscow, 1997), pp. 56–85 [in Russian].
13. V. I. Kogan, Usp. Fiz. Nauk **170**, 1351 (2000) [Phys.–Usp. **43**, 1253 (2000)].
14. *100 Years of the Planck's Quantum*, Ed. by J. Duck and E. C. G. Sudarshan (World Sci., Singapore, 2000).
15. M. A. Leontovich and L. I. Mandelstam, Z. Phys. **47**, 131 (1928).
16. B. B. Kadomtsev, V. I. Kogan, B. M. Smirnov, and V. D. Shafranov, Usp. Fiz. Nauk **124**, 547 (1978) [Phys.–Usp. **21**, 272 (1978)].
17. J. I. Frenkel, *Wave Mechanics. Elementary Theory* (Clarendon Press, Oxford, 1932); J. I. Frenkel *Wave Mechanics* (GTTI, Leningrad, Moscow, 1933) [in Russian].
18. J. I. Frenkel, *In the Beginning of New Physics* (Nauka, Leningrad, 1970) [in Russian].
19. V. A. Fock, *The Base of Quantum Mechanics* (GTTI, Leningrad, Moscow, 1932) [in Russian].
20. K. V. Nikolskii, *Quantum Mechanics of Molecule* (GTTI, Leningrad, Moscow, 1934) [in Russian].
21. W. Heisenberg, *Physical Principles of Quantum Theory* (GTTI, Leningrad, Moscow, 1932; Leipzig, 1930).
22. P. A. M. Dirac, *The Principles of Quantum Mechanics* (Oxford, 1930).
23. M. P. Bronshtein, Usp. Fiz. Nauk **11**, 355 (1931).
24. A. Marx, *Physical Principles of Quantum Mechanics,* Ed. by J. I. Frenkel (GTTI, Leningrad, Moscow, 1933; Leipzig, 1930).
25. V. Heisenberg, E. Schrödinger, and P. Dirac, *Modern Quantum Mechanics. Three Nobel Reports* (GTTI, Leningrad, Moscow, 1934) [in Russian].
26. R. W. Gurney, *Elementary Quantum Mechanics* (ONTI, Moscow, 1935; Cambridge Univ., Cambridge, 1934).
27. B. N. Spasskii, L. V. Levshin, and V. A. Krasilnikov, Usp. Fiz. Nauk **130**, 149 (1980).
28. D. I. Blokhintsev, in *Proc. of Science Seminar Devoted to 75 year from Birthday of D. I. Blokhintsev, Dubna, 23 Jan., 1983* (OIYaI, Dubna, 1986), pp. 18–20.
29. S. M. Rytoe, *Memories about I. E. Tamm* (Nauka, Moscow, 1986) [in Russian].
30. *Akademician L. I. Mandelshtam. To 100 years from Birthday* (Nauka, Moscow, 1979) [in Russian].
31. D. I. Blokhintsev, *My Way in the Science* (Abstrast of the Works) (OIYaI, Dubna, 2007) [in Russian].
32. L. I. Mandelshtam, *Lectures on Optics, Relativity Theory and Quantum Mechanics* (Nauka, Moscow, 1972) [in Russian].
33. I. Neumann, *Mathematical Bases of Quantum Mechanics* (Nauka, Moscow, 1964; Springer, Berlin, 1932).
34. A. A. Pechenkin, Voprosy Istorii Estestvoznaniya Tekhn. **2**, 54 (1997).
35. M. A. Markov, *Sergei Ivanovich Vavilov. Essays and Memories* (Nauka, Moscow, 1981), p. 230 [in Russian].
36. M. A. Markov, *Thinking about Physicists, Physics, World* (Nauka, Moscow, 1993) [in Russian].
37. I. M. Frank, in *Proc. of Science Seminar Devoted to 75 year from Birthday of D. I. Blokhintsev, Dubna, 23 Jan., 1983* (OIYaI, Dubna, 1986), pp. 21–24.
38. E. L. Feinberg, *Epoch and the Person. Physicists. Essays and Memories* (Nauka, Moscow, 1999) [in Russian].
39. D. I. Blokhintsev, Usp. Fiz. Nauk **12**, 160–171 (1932).
40. H. E. White, Phys. Rev. **37**, 1416 (1931).
41. H. E. White, Phys. Rev. **38**, 513 (1931).
42. S. Brandt and H. D. Dahmen, *The Picture Book of Quantum Mechanics* 2nd ed. (Springer, Berlin, 1995).
43. D. I. Blokhintsev, *Elementary of Quantum Mechanics* 5-th ed. (Nauka, Moscow, 1976) [in Russian].
44. M. I. Kaganov and V. Ya. Frenkel, *History Landmarks of Physics of Solids* (Znanie, Moscow, 1981) [in Russian].
45. Ya. I. Frenkel, Usp. Fiz. Nauk **8**, 155 (1928).
46. F. Bloch, Z. Physik **52**, 555 (1928).
47. F. Bloch, Z. Physik **53**, 216 (1929).
48. F. Bloch, Z. Physik **59**, 208 (1930).
49. F. Bloch, Phys. Today **29** (12), 23 (1976).
50. R. Peierls, Ann. Physik (Leipzig) **3**, 1055 (1929).
51. A. Sommerfeld, Usp. Fiz. Nauk **8**, 765 (1928).

52. A. Sommerfeld and N. H. Frank, Rev. Mod. Phys. **3**, 1 (1931).
53. G. Bete and A. Zommerfeld, *Electronic Theory of Metals* (ONTI, Leningrad, Moscow, 1938; Springer, Berlin, 1933), Vol. 24/2, p. 333.
54. A. Sommerfeld, *Puti poznaniya v fizike,* Ed. by Ya. A. Smorodinskii (Nauka, Moscow, 1973) [in Russian].
55. R. Fauler, Usp. Fiz. Nauk **10**, 136 (1930).
56. R. Fauler, Usp. Fiz. Nauk **11**, 103 (1931).
57. I. E. Tamm, Usp. Fiz. Nauk **11**, 801 (1931).
58. L. Brillouin, *Quantum Statistics* (ONTI, Kharkov, 1934; Die Quantenstatistik, Berlin, 1931).
59. N. F. Mott and H. Jones, *The Theory of the Properties of Metals and Alloys* (Clarendon, Oxford, 1936).
60. I. E. Tamm and S. P. Shubin, Z. Physik **68**, 97 (1931).
61. P. I. Lukirskii, Usp. Fiz. Nauk **9**, 277 (1929).
62. R. S. Landsberg, *Optics,* 5-th ed. (Nauka, Moscow, 1976) [in Russian].
63. D. I. Blochinzev, Physikal. Zeit. Sowjetunion **1**, 781–797 (1932).
64. I. E. Tamm and D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **3**, 77–100 (1933).
65. I. E. Tamm and D. I. Blokhintsev, in *I. E. Tamm. Sobranie nauchnykh trudov,* Ed. by V. L. Ginzburg (Nauka, Moscow, 1981), Vol. 1, p. 227 [in Russian].
66. P. Gombas, *Statistical Theory of Atom and Its Using* (Inostrannaya Liter., Moscow, 1951; Wien, 1949).
67. V. A. Fock, Z. Physik **61**, 126 (1930).
68. V. A. Fock, Usp. Fiz. Nauk **16**, 943 (1936).
69. R. H. Fowler, Proc. Roy. Soc. A **122**, 36 (1929).
70. D. I. Blochinzev and S. I. Drabkina, Physikal. Zeit. Sowjetunion **7**, 484–500 (1935).
71. O. W. Richardson, *The Emission of Electrons from Hot Bodies* (Longmans, London, 1921).
72. R. Peierls, *Elektronic Theory of Metals* (Inostrannaya Liter., Moscow, 1947); Ergeb. der Exakt. Naturwissensch. **2**, 264 (1932).
73. M. B. Partenskii, Usp. Fiz. Nauk **128**, 69 (1979).
74. H. Frohlich, Rep. Prog. Phys. **24**, 1 (1961).
75. H. E. Rorschach, Am. J. Phys. **38**, 897 (1970).
76. J. S. Harris, Intern. J. Mod. Phys **4**, 1149 (1990).
77. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **3**, 475–498 (1933).
78. L. W. Nordheim, Z. Physik **27**, 65 (1924) (1990).
79. L. W. Nordheim, Z. Physik **46**, 833 (1928).
80. L. W. Nordheim, Phys. Z. **30**, 177 (1929).
81. L. W. Nordheim, Ann. Physik (Leipzig) **9**, 607 (1931).
82. L. W. Nordheim, Metallwirtschaft. **9**, 135 (1932).
83. L. W. Nordheim, Usp. Fiz. Nauk **15**, 570, 675, 799, 939 (1935); L. W. Nordheim, *Static and Kinetic Theory of Metallic States*, Müller-Pouillets Manual of Physics (Braunschweig, 1934), Vol. 4, Part 4.
84. W. V. Houston, Phys. Rev. **34**, 279 (1929).
85. J. C. Slater, Rev. Mod. Phys. **6**, 209 (1934).
86. J. C. Slater, Phys. Rev. **45**, 794 (1934).
87. J. C. Slater, Phys. Rev. **76**, 1592 (1949).
88. J. C. Slater, Phys. Today **3** (1), 6 (1949).
89. J. C. Slater, *Insulators, Semiconductors and Metals* (Mir, Moscow, 1969; McGraw-Hill, New York, 1967).
90. J. C. Slater, *Solid-State and Molecular Theory: A Scientific Biography* (Wiley, New York, 1975).
91. A. H. Wilson, *The Electrical Properties of Semiconductors and Insulators* (Cambridge Univ., Cambridge, 1934).
92. A. H. Wilson, *Semiconductors and Metals* (Cambridge Univ., Cambridge, 1939).
93. A. H. Wilson, *Semiconducting Materials* (Cambridge Univ., Cambridge, 1951).
94. R. Peierls, *Quantum Theory of Solids* (Inostrannaya Liter., Moscow, 1956; Clarendon, Oxford, 1955).
95. A. Wilson, *Theory of Metals* (GTTI, Moscow, Leningrad, 1941; Cambridge Univ., Cambridge, 1965).
96. W. Kohn, Rev. Mod. Phys. **71**, 59 (1999).
97. J. Korringa, J. Physica **13**, 392 (1947).
98. M. Born, Rep. Prog. Phys. **9**, 294 (1942).
99. D. I. Blochinzev and L. W. Nordheim, Z. Phys. **84**, 168–194 (1933).
100. F. J. Blatt, "Theory of Mobility of Electrons in Solids," in *Solid State Physics*, Ed. by F. Seitz and D. Turnbull (Fizmatlit, Moscow, 1963; Academic, New York, 1957), Vol. 4, p. 1.
101. J. P. Jan, "Galvanomagnetic and Thermomagnetic Effects in Metals," in *Solid State Physics*, Ed. by F. Seitz and D. Turnbull (Academic, New York, 1958), Vol. 5, p. 1.
102. H. W. Lewis, "Wave Packets and Transport of Electrons in Metals," in *Solid State Physics,* Ed. by F. Seitz and D. Turnbull (Academic, New York, 1959), Vol. 7, p. 1.
103. J. M. Ziman, *Electrons and Phonons. The Theory of Transport Phenomena in Solids* (Inostrannaya Liter., Moscow, 1962; Oxford Univ., Oxford, 1960).
104. S. Raims, *The Wave Mechanics of Electrons in Metals* (North-Holland, Amsterdam, 1961).
105. T. L. Olsen, *Electron Transport in Metals* (Pergamon, Oxford, 1962).
106. P. S. Zyryanov and G. I. Guseva, Usp. Fiz. Nauk **95**, 565 (1968) [Phys.–Usp. (1968)].
107. F. J. Blatt, *Physics of Electronic Conduction in Solids* (Mir, Moscow, 1971; McGraw-Hill, New York, 1968).
108. R. H. Fowler, *Statistical Mechanics,* 2nd ed. (Cambridge Univ., Cambridge, 1980).
109. M. P. Bronstein, Physikal. Zeit. Sowjetunion **2**, 28 (1932).
110. J. Callaway, *Energy Band Theory* (Mir, Moscow, 1969; Academic, New York, 1964).
111. C. L. Kane, Nature **438**, 168 (2005).
112. W. Shockley, *Electrons and Holes in Semiconductors* (Van Nostrand, Princeton, 1950; Inostrannaya Liter., Moscow, 1953).
113. B. K. Ridley, *Quantum Processes in Semiconductors* (Clarendon, Oxford, 1982; Mir, Moscow, 1986).
114. Yu. Piter and M. Cardona, *Fundamentals of Semiconductors* (Fizmatlit, Moscow, 2002; Springer, Berlin, 2002).
115. S. I. Pekar, *Investigations on Electronic Theory of Crystals* (GTTI, Moscow, Leningrad, 1951) [in Russian].
116. S. I. Pekar, Usp. Fiz. Nauk **60**, 191 (1956).

117. V. L. Bonch-Bruevich and S. G. Kalashnikov, *Semiconductors Physics* (Nauka, Moscow, 1977) [in Russian].
118. R. P. Feynman, Phys. Rev. **97**, 660 (1955).
119. N. N. Bogolyubov and N. N. Bogolyubov, Jr., *Aspects of Polaron Theory* (Fizmatlit., Moscow, 2004) [in Russian].
120. M. A. Herman, *Semiconductor Surerlattices* (Academie, Berlin, 1986; Mir, Moscow, 1989).
121. G. Bastard, *Wave Mechanics Applied to Heterostructures* (Les Editions de Physique, Paris, 1988).
122. A. I. Gusev, *Nanomatherials, Nanostructures, Nanotechnologies* (Fizmatlit., Moscow, 2005) [in Russian].
123. S. Datta, *Quantum Transport: Atom To Transistor* (Cambridge Univ., Cambridge, 2005).
124. P. Harrison, *Quantum Wells, Wires and Dots: Theoretical and Computational Physics of Semiconductor Nanostructures* (Wiley, New York, 2005).
125. I. Filikhin, T. Deyneka, and B. Vlahovic, *Nanotech 2007* (NSTI Press, Cambridge, MA, 2007), Vol. 1.
126. P. Nozieres, *Interacting Fermi Systems* (Benjamin, New York, 1963).
127. D. Pines, *Elementary Excitations in Solids* (Benjamin, New York, 1963; Mir, Moscow, 1965).
128. J. W. Negele and H. Orland, *Quantum Many Particle Systems* (Addison-Wesley, New York, 1988).
129. Y. Kuramoto and Y. Kitaoka, *Dynamics of Heavy Electrons* (Clarendon, Oxford, 2000).
130. N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Clarendon, Oxford, 1965; Mir, Moscow, 1969).
131. K. Valyasek, D. N. Zubarev, and A. L. Kuzemskii, Teor. Mat. Fiz. **5**, 280–292 (1970).
132. A. L. Kuzemsky, Intern. J. Mod. Phys. B **19**, 1029–1059 (2005); cond-mat/0502194.
133. A. L. Kuzemsky, Intern. J. Mod. Phys. B **21**, 2821–2942 (2007); cond-mat/0707. 0753.
134. E. Joos and N. D. Zeh, Z. Physik B **59**, 223 (1985).
135. D. N. Zubarev, *Non-Stable Statistical Thermodynamics* (Nauka, Moscow, 1971) [in Russian].
136. F. Wilczek, Mod. Phys. Lett. A **21**, 701 (2006).
137. D. I. Blochinzev, Physikal. Zeit. Sowjetunion **4**, 501–515 (1933).
138. G. Herzberg, *Atomic Spectra and Atomic Structure* (Inostrannaya Liter., Moscow, 1948; Wiley, New York, 1944).
139. A. M. Bonch-Bruevich and V. A. Khodovoi, Usp. Fiz. Nauk **93**, 71 (1967) [Phys.–Usp. (1967)].
140. N. Bloembergen, *Nonlinear Optics* (Mir, Moscow, 1966; Benjamin, New York, 1965).
141. D. I. Blokhintsev, Dokl. Akad. Nauk SSSR **2**, 78–81 (1934).
142. D. I. Blokhintsev and Sh. Shekhter, Usp. Khim. **3**, 586–609 (1934).
143. V. M. Konovalov and V. A. Dubchak, Essays on the History of Semiconductor Physics, in *History of Physical-Matematical Sciences* (Nauka, Moscow, 1960), Vol. 34, p. 73 [in Russian].
144. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **5**, 470–477 (1935).
145. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **6**, 1060–1061 (1936).
146. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **6**, 1053–1059 (1936).
147. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **7**, 1242–1251 (1937).
148. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **9**, 459–466 (1939).
149. D. I. Blokhintsev, Izv. AN SSSR, Ser. Fiz. **9**, 391–402 (1945).
150. J. B. Birks and I. H. Munro, Usp. Fiz. Nauk **105**, 251 (1971); Progress in Reaction Kinetics **4**, 239 (1967).
151. D. I. Blokhintsev and Sh. Shekhter, Zh. Eksp. Teor. Fiz. **5**, 771–778 (1935).
152. V. L. Bonch-Bruevich, Usp. Fiz. Nauk **60**, 369 (1950).
153. V. F. Kiselev and O. V. Krylov, *Adsorbtion Processes on the Surface of Semiconductors and Insulators* (Moscow) [in Russian].
154. O. V. Krylov and V. F. Kiselev, *Adsorbtion and Catalis on Transition Metals and Oxides* (Khimiya, Moscow, 1981) [in Russian].
155. F. I. Dalidchik, *Spectroscopy of the Surface* (Znanie, Moscow, 1982) [in Russian].
156. O. M. Braun and V. K. Medvedev, Usp. Fiz. Nauk **157**, 631 (1989) [Phys.–Usp. (1989)].
157. M. Prutton, *Introduction to Surface Physics* (Clarendon, Oxford, 1994; RDKh, Moscow, 2000).
158. M. Wilson, Phys. Today **56**, 18 (2003).
159. D. Hilbert, J. von Neumann, and L. Nordgeim, Matematische Annalen **98**, 1 (1927).
160. L. W. Nordgeim and R. Kikuchi, Z. Physik **60**, 652 (1930).
161. L. W. Nordgeim, Z. Physik **75**, 434 (1932).
162. W. Heitler and L. W. Nordgeim, J. Phys. (Paris) **5**, 449 (1934).
163. N. F. Mott and I. Sneddon, *Wave Mechanics and Its Applications* (Clarendon, Oxford, 1948; Nauka, Moscow, 1966).
164. R. H. Fowler and L. W. Nordgeim, Proc. Roy. Soc. A **119**, 173 (1928).
165. L. W. Nordgeim, Proc. Roy. Soc. A **121**, 626 (1928).
166. R. H. Fowler, Phys. Rev. **38**, 45 (1931).
167. N. H. Frank and L. A. Young, Phys. Rev. **38**, 80 (1931).
168. E. Guth and C. J. Mullin, Phys. Rev. **61**, 339 (1942).
169. M. G. Lin and D. S. Chuu, Appl. Phys. Lett **80**, 4262 (2002).
170. Y. M. Wong, W. P. Kang, J. L. Davidson, and J. H. Huang, in *Proc. of the Joint ICNDST-ADC 2006 Int. Conf.*; Diamond Related Mater. **15**, 1859 (2006).
171. S. A. Goldstein and R. Lee, J. Phys. Rev. Lett **35**, 1079 (1975).
172. J. Medawar and D. Pyke, *Hitler's Gift: The Story of the Scientists Expelled by the Nazi Regime* (Arcade, New York, 2000).
173. E. L. Peterson and L. W. Nordgeim, Phys. Rev. **51**, 355 (1937).
174. L. W. Nordgeim, Rev. Mod. Phys. **23**, 322 (1951).
175. J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (Wiley, New York, 1952).

176. L. D. Landau, Sow. Phys. **3**, 664 (1933).
177. Ya. I. Frenkel, Sow. Phy. **9**, 158 (1936).
178. S. I. Pekar, Zh. Eksp. Teor. Fiz. **16**, 341 (1946).
179. I. Frohlich, H. Pelzer, and S. Zienau, Phil. Mag. **41**, 221 (1950).
180. N. N. Bogolyubov, UMZh **2**, 3 (1950).
181. N. N. Bogolyubov, Fortschr. Physik **4**, 1 (1961).
182. S. V. Tyablikov, Zh. Eksp. Teor. Fiz. **18**, 1023 (1948).
183. S. V. Tyablikov, Dokl. Akad. Nauk USSR **6**, 3 (1950).
184. S. V. Tyablikov, Dokl. Akad. Nauk SSSR **81**, 31 (1951).
185. S. V. Tyablikov, Zh. Eksp. Teor. Fiz. **21**, 17 (1951).
186. S. V. Tyablikov, Zh. Eksp. Teor. Fiz. **21**, 377 (1951).
187. S. V. Tyablikov, Zh. Eksp. Teor. Fiz. **23**, 381 (1952).
188. S. V. Tyablikov, Fiz. Tverd. Tela **3**, 3445 (1961).
189. S. V. Tyablikov, Fortschr. Physik **4**, 231 (1961).
190. V. A. Moskalenko, P. Entel, and D. F. Digor, Phys. Rev. B **59**, 619 (1999).
191. H. Fröhlich, Adv. Phys. **3**, 325 (1954).
192. N. F. Mott and R. W. Gurney, Proc. Phys. Soc. **49**, 32 (1937).
193. I. G. Austin and N. F. Mott, Adv. Phys. **18**, 41 (1969).
194. J. J. Markham, Rev. Mod. Phys. **31**, 956 (1959).
195. *Polarons in Ionic Crystals and Polar Semiconductors*, Ed. by J. T. Devreese (North-Holland, Amsterdam, 1972).
196. *Polarons,* Collected Volume, Ed. by Yu. A. Firsov (Nauka, Moscow, 1975) [in Russian].
197. T. K. Mitra, A. Chatterjee, and S. Mukhopadhyay, Phys. Rep. **153**, 91 (1987).
198. B. Gerlach and E. Lowen, Rev. Mod. Phys. **63**, 63 (1991).
199. *Polarons and Applications*, Ed. by V. D. Lakhno (Wiley, New York, 1994).
200. P. S. Zyryanov and M. I. Klinger, *Quantum Theory of Phenomenons of Electronic Transfer in Crystallic Semiconductors* (Nauka, Moscow, 1976) [in Russian].
201. S. M. Goringe, D. R. Bowler, and E. Hernandez, Rep. Prog. Phys. **60**, 1447 (1997).
202. R. F. W. Bader, *Atoms in Molecules. A Quantum Theory* (Mir, Moscow, 2001; Clarendon, Oxford, 1990).
203. H. Frohlich, *Perspectives in Modern Physics*, Ed. by R. E. Marshak (Wiley, New York, 1966), p. 539.
204. T. K. Mitra, J. Physics C: Solid St. Phys **2**, 52 (1969).
205. S. Barisic, J. Labbe, and J. Friedel, Phys. Rev. Lett. **25**, 919 (1970).
206. J. Friedel, J. Physics F: Metal Phys **3**, 785 (1973).
207. A. L. Kuzemsky, A. Holas, and N. M. Plakida, Physica B **122**, 168–182 (1983).
208. A. L. Kuzemsky and A. P. Zhernov, Intern. J. Mod. Phys. B **4**, 1395–1407 (1990).
209. J. Ashkenazi, M. Dacorogna, and M. Peter, Solid State Commun. **29**, 181 (1979).
210. V. Christoph and A. L. Kuzemsky, Phys. Stat. Sol. B **111**, K1–K6 (1982).
211. V. Christoph and A. L. Kuzemsky, Phys. Stat. Sol. B **120**, K219–K224 (1983).
212. K. I. Wysokinski and A. L. Kuzemsky, Phys. Stat. Sol. B **113**, 409–420 (1982).
213. K. I. Wysokinski and A. L. Kuzemsky, J. Low Temperature Physics **52**, 81–98 (1983).
214. D. I. Blokhiptsev and B. I. Davydov, Dokl. Akad. Nauk SSSR **21**, 22–25 (1938).
215. L. O. Grandahl, Usp. Fiz. Nauk **14**, 253 (1934); Rev. Mod. Phys. **5**, 141 (1933).
216. I. V. Kurchatov, Usp. Fiz. Nauk **12**, 365 (1932).
217. Ya. I. Frenkel and A. F. Ioffe, Sow. Phys. **1**, 60 (1932).
218. D. I. Blokhintsev and B. I. Spasskii, Zh. Eksp. Teor. Fiz. **8**, 945–947 (1938).
219. R. Smith, *Semiconductors* (Mir, Moscow, 1982; Cambridge Univ., Cambridge, 1978).
220. D. I. Blokhintsev, "Modern Views onto the Nature of Insulators and Semiconductors," in *Electric Insulation*, Collected Volume (Glavelectroprom, Moscow, 1938), pp. 144–154 [in Russian].
221. N. V. Sidgwick, *The Chemical Elements and Their Compounds* (Clarendon, Oxford, 1950).
222. G. B. Bokii, *Crystalic Chemistry* (Nauka, Moscow, 1971) [in Russian].
223. P. W. Anderson, *Concepts in Solids* (Benjamin, New York, 1964).
224. W. J. Kohn, Phys. Rev. **133**, A171 (1964).
225. D. G. Pettifor, *Bonding and Structure of Molecules and Solids* (Clarendon, Oxford, 1995).
226. P. P. Edwards, R. L. Johnston, F. Hensel, et al., "A Perspective on the Metal-Nonmetal Transition," in *Solid State Physics*, Ed. by H. Ehrenreich and F. Spaepen (Academic, New York, 1999), Vol. 52, p. 229.
227. R. Resta, J. Physics: Condens. Matter. **14**, R625 (2002).
228. G. V. Bokii, Kristallografiya **47**, 497 (2002).
229. W. A. Harrison, *Elementary Electronic Structure* (World Sci., Singapore, 1999).
230. J. I. Gerstein and F. W. Smith, *The Physics and Chemistry of Materials* (Wiley, New York, 2001).
231. U. Mizutani, *Introduction To the Electron Theory of Metals* (Cambridge Univ., Cambridge, 2001).
232. R. W. Cahn, *The Coming of Materials Science* (Pergamon, New York, 2001).
233. P. J. F. Harris, *Carbon Nanotubes and Related Structures* (Tekhnosfera, Moscow, 2003; Cambridge Univ., Cambridge, 1999).
234. C. P. Pool and F. J. Owens, *Introduction to Nanotechnology* (Tekhnosfera, Moscow, 2004; Wiley, New York, 2003).
235. A. V. Eletskii, Usp. Fiz. Nauk **177**, 233 (2007).
236. Yu. E. Lozovik and A. M. Popov, Usp. Fiz. Nauk **177**, 786 (2007).
237. F. Zeitz, *The Modern Theory of Solids* (GTTI, Moscow, Leningrad, 1949; McGraw-Hill, New York, 1940).
238. C. Kittel, *Introduction to Solid State Physics* (Nauka, Moscow, 1978; Wiley, New York, 1976).
239. N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Mir, Moscow, 1979; Holt, Rinehart, Winston, New York, 1976).
240. A. G. Jackson, *Handbook of Crystallography. For Electron Microscopists and Others* (Springer, Berlin, 1991).
241. A. F. Andreev, Usp. Fiz. Nauk **164**, 1278 (1994).

242. L. Bonacina, P. Larregaray, F. van Mourik, and M. Chergui, Phys. Rev. Lett. **95**, 015301 (2005).
243. A. Khurana, Phys. Today **43** (12), 17 (1990).
244. V. M. Pudalov, Usp. Fiz. Nauk **164**, 997 (1994).
245. *Quasicrystals: Proc. of the Anniversary Adriatico Research Conf. Quasicrystals, ICTP, Trieste, July 4-7, 1989*, Ed. by M. V. Jaric and S. Lundqvist (World Sci., Singapore, 1990).
246. F. J. Owens and C. P. Poole, Jr., *The New Superconductors* (Plenum, New York, 1996).
247. A. L. Kuzemsky and I. G. Kuzemskaya, Physica C **383**, 140–158 (2002).
248. A. L. Kuzemsky and I. G. Kuzemskaya, "The Structural, Superconducting and Transport Properties of the Mercurocuprates and Other Layered Systems," in *Studies in High-Tc Superconductors*, Ed. by A. Narlikar (Nova Science Publ., New York, 2003), Vol. 44, pp. 1–80.
249. V. I. Beloteloe and A. K. Zvezdin, *Photonic Crystals and Other Metamatherials* (Kvantum, Moscow, 2006) [in Russian].
250. H. Frohlich, *Theory of Dielectrics* (Clarendon, Oxford, 1958; Inostrannaya Liter., Moscow, 1960).
251. A. L. Kuzemskii, Teor. Mat. Fiz. **36**, 208–223 (1978).
252. A. L. Kuzemsky, Nuovo Cimento A **109**, 829–854 (1994).
253. A. L. Kuzemsky, "Correlation Effects in High Temperature Superconductors and Heavy Fermion Compounds," in *Superconductivity and Strongly Correlated Electron Systems*, Ed. by N. Noce, A. Romano, and G. Scarpetta (World Sci., Singapore, 1994), pp. 346–376.
254. A. L. Kuzemsky, Rivista del Nuovo Cimento **25**, 1–91 (2002).
255. N. F. Mott, *Metal-Insulator Transitions* (Taulor and Fransis, London, 1974; Nauka, Moscow, 1979).
256. Ya. A. Smorodinskii, Usp. Fiz. Nauk **39**, 325 (1949).
257. W. E. Lamb and R. C. Retherford, Usp. Fiz. Nauk **45**, 553 (1951); Phys. Rev. **79**, 549 (1950).
258. W. E. Lamb, Rep. Prog. Phys. **14**, 19 (1951).
259. W. E. Lamb, Phys. Rev. **85**, 259 (1952).
260. H. Bethe and E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (Fizmatlit, Moscow, 1960; Springer, Berlin, 1957).
261. G. L. Trigg, *Landmark Experiments in Twentieth Century Physics* (Mir, Moscow, 1978; Crane, Russak and Co., New York, 1975).
262. P. Beiersdorfer, H. Chen, D. B. Thom, and E. Trabert, Phys. Rev. Lett. **95**, 233003 (2005).
263. V. Weisskopf, Usp. Fiz. Nauk **41**, 165 (1950); Rev. Mod. Phys. **21**, 305 (1949).
264. V. Weisskopf, Usp. Fiz. Nauk **138**, 455 (1982).
265. V. Weisskopf, *Physics in the Twentieth Century* (Atomizdat, Moscow, 1977; MIT, New York, 1972).
266. J. Mehra and K. A. Milton, *Climbing the Mountain. The Scientific Biography of Julian Schwinger* (Oxford Univ., Oxford, New York, 2000).
267. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **9**, 1166–1168 (1939).
268. W. Pauli, *General Principles of Wave Mechanics*, Ed. by K. V. Nikolskii (GTTI, Moscow, Leningrad, 1947) [in Russian]; *Handbook of Physics*, Vol. XXIV (Springer, Berlin, 1933).
269. P. Gombas, *The Problem of Many Particles in Quantum Mechanics* (Inostrannaya Liter., Moscow, 1953; Basel, 1950).
270. C. F. von Weizsacker, Z. Physik **96**, 431 (1935).
271. K. Yonei and Y. Tomishima, J. Phys. Soc. Jpn. **20**, 1051 (1965).
272. D. A. Kirzhnits, Yu. E. Lozovik, and G. V. Shpatakovskaya, Usp. Fiz. Nauk **117**, 3 (1975) [Phys.–Usp. **18**, 649 (1975)].
273. E. H. Lieb, Rev. Mod. Phys. **48**, 553 (1976).
274. E. H. Lieb and B. Simon, Adv. in Math. **23**, 22 (1977).
275. E. H. Lieb, Rev. Mod. Phys. **53**, 603 (1981).
276. *Theory of the Inhomogeneous Electron Gas*, Ed. by S. Lundqvist and N. H. March (Plenum, New York, 1983; Mir, Moscow, 1987).
277. M. Ya. Amusja and V. K. Ivanov, Usp. Fiz. Nauk **152**, 185 (1987).
278. R. D. Laughlin and D. Pines, Proc. Natl. Acad. Sci. USA **97**, 28 (2000).
279. A. Godman and E. M. F. Payne, *Longman Dictionary of Scientific Usage* (Longman Group, London, 1979).
280. *McGrow-Hill Dictionary of Scientific and Technical Terms*, 5th ed., Ed. by S. P. Parker (McGrow-Hill, New York, 1994).
281. M. Plank, *The Unity of Physical View of the World* (Nauka, Moscow, 1966), p. 23 [in Russian].
282. A. Einshtein, "On Modern Crisis of Theoretical Physics," in *Work Collection in 4 vols* (Nauka, Moscow, 1967), Vol. 4, p. 57 [in Russian].
283. S. Weinberg, *Dreams of a Final Theory* (Random House, New York, 1992).
284. A. Einshtein, "Physics and the Reality," in *Work Collection in 4 vols* (Nauka, Moscow, 1967), Vol. 4, p. 203 [in Russian].
285. A. Einshtein, "Introduction," in *Work Collection in 4 vols* (Nauka, Moscow, 1967), Vol. 4, p. 14 [in Russian].
286. M. Plank, *The Unity of Physical View of the World* (Nauka, Moscow, 1966), pp. 23–24 [in Russian].
287. A. L. Kuzemskii, Fiz. Elem. Chastits At. Yadra **12**, 366-423 (1981) [Sov. J. Part. Nucl. **12**, 146 (1981)].
288. A. L. Kuzemsky, "Fundamental Principles of the Physics of Magnetism and the Problem of Itinerant and Localized Electronic States," JINR Commun. E17-2000-32 (Dubna, 2000).
289. A. L. Kuzemsky, Intern. J. Mod. Phys. B **16**, 803–823 (2002); cond-mat/0208222.
290. L. P. Kadanoff and P. C. Martin, Ann. Phys. (New York) **24**, 419 (1963).
291. K. V. Nikolskii, *Quantum Processes* (GTTI, Moscow, 1940) [in Russian].
292. D. I. Blokhintzev, J. Phys. USSR **2**, 71–74 (1940).
293. Ya. P. Terletskii, Zh. Eksp. Teor. Fiz. **7**, 1290 (1937).
294. A. A. Beilinson et al., Usp. Fiz. Nauk **164**, 235 (1994) [Phys.-Usp. **37**, 233 (1994)].
295. G. Jaffe, Ann. Physik (Leipzig) **74**, 528 (1924).
296. G. Jaffe, Ann. Physik (Leipzig) **76**, 680 (1925).

297. D. I. Blokhintsev and P. Nemirovskii, Zh. Eksp. Teor. Fiz. **10**, 1263–1266 (1940).
298. C. Zachos, D. Fairlie, and T. Curtright, *Quantum Mechanics in Phase Space* (World Sci., Singapore, 2005).
299. E. Wigner, Phys. Rev. **40**, 749 (1932).
300. Yu. L. Klimoptovich, *Statistical Theory of Nonstable Processes in Plasma* (Mosc. Gos. Univ., Moscow, 1964) [in Russian].
301. K. E. Cahill and R. J. Glauber, Phys. Rev. **177**, 1882 (1969).
302. L. Cohen, J. Math. Phys. **7**, 781 (1966).
303. D. Leibfried, T. Pfau, and C. Monroe, Phys. Today **56** (4), 22 (2003).
304. W. Schleich, D. F. Walls, and J. A. Wheeler, Phys. Rev. A **38**, 1177 (1988).
305. Go. Torres-Vega and J. H. Frederick, Phys. Rev. Lett. **67**, 2601 (1991).
306. M. Hillery, R. F. O'Connell, M. O. Scully, and E. P. Wigner, Phys. Rep. **106**, 121 (1984).
307. N. L. Balazs and B. K. Jennings, Phys. Rep. **104**, 347 (1984).
308. J. E. Moyal, "Quantum Mechanics as Statistical Theory," in *Causing Questions in Quantum Mechanics* (Inostrannaya Liter., Moscow, 1955), p. 208 [in Russian]; Proc. Camb. Phil. Soc. **45**, 99 (1949).
309. V. V. Kuryshkin, "Uncertainty Principle and the Problem of Joint Coordinate-Momentum Probability Density in Quantum Mechanics," in *The Uncertainty Principle and Foundations of Quantum Mechanics*, Ed. by W. C. Price and S. S. Chissick (Wiley, New York, 1977), p. 61.
310. J. E. Bayfield, *Quantum Evolution* (Wiley, New York, 1999).
311. B. T. Geilikman, "Classical Models of Quantum Mechanical Systems," in *Investigations in Low Temperature Physics* (Atomizdat, Moscow, 1979), p. 204 [in Russian].
312. D. I. Blokhintsev and Ya. B. Dashevskii, Zh. Eksp. Teor. Fiz. **11**, 222–225 (1941).
313. R. Kapral, "Progress in the Theory of Mixed Quantum-Classical Dynamics," Ann. Rev. Phys. Chem. **57**, 129–157 (2006).
314. R. Kapral and G. Ciccotti, "Transport Coefficients of Quantum-Classical Systems," Lect. Notes Phys. **703**, 519–551 (2006).
315. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **16**, 965–967 (1946).
316. W. Heitler, *The Quantum Theory of Radiation*, 3rd ed. (Clarendon, Oxford, 1954; Inostrannaya Liter., Moscow, 1956).
317. S. Stenholm, Phys. Rep. **6**, 1 (1973).
318. S. Bloom and H. Margenau, Phys. Rev. **90**, 791 (1953).
319. A. L. Kuzemsky and K. Walasek, Lett. Nuovo Cimento. **2**, 953–956 (1971).
320. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **17**, 814–817 (1947).
321. K. Valyasek and A. L. Kuzemsky, Teor. Mat. Fiz. **4**, 267–276 (1970).
322. D. I. Blokhintsev, Zh. Eksp. Teor. Fiz. **17**, 924–929 (1947).
323. E. Schrodinger, *What is Life? The Physical Aspect of the Living Cell* (Atomizdat, Moscow, 1972; DIAS, Dublin, 1955).
324. P. A. Florenskii, "Continuation of Our Sensities," in *Work Collection in 4 vols* (Mysl, Moscow, 1999), Vol. 3(1), p. 383 [in Russian].
325. G. Binning and H. Rohrer, Helv. Phys. Acta **38**, 726 (1982).
326. J. Tersoff and D. R. Hamann, Phys. Rev. B **31**, 805 (1985).
327. *Atoms from the Electron "Point of View"* (Znanie, Moscow, 1988) [in Russian].
328. F. Studer, M. Hervieu, J.-M. Constantini, and M. Toulemonde, Nucl. Instrum. Methods B **122**, 449 (1997).
329. G. Binnig and H. Rohrer, Rev. Mod. Phys. **71**, S324 (1999).
330. G. A. Fiete and E. J. Heller, Rev. Mod. Phys. **75**, 933 (2003).
331. M. F. Crommie, C. P. Lutz, and D. M. Eigler, Phys. Rev. B **48**, 2851 (1993).
332. B. G. Levi, Phys. Today **51** (4), 17 (1998).
333. C. Day, Phys. Today **53** (2), 17 (2000).
334. C. J. Humphreys, Nature **401**, 21 (1999).
335. M. Varela, S. D. Findlay, A. R. Lupini, et al., Phys. Rev. Lett. **92**, 095502 (2004).
336. I. N. Serdyuk, N. R. Zaccai, and J. Zaccai, *Methods in Molecular Biophysics. Structure, Dynamics, Function* (Cambridge UP, Cambridge, 2007).
337. A. A. Grib, "Metodological Importance of Quantum Theory for Psychology" in *Quantum Mechanics and the Theory of Relativity* (Leningr. Univ., Leningrad, 1980), pp. 130–145 [in Russian].
338. R. Penrose, *Shadows of the Mind* (IKI, Izhevsk, Moscow, 2005; Oxford Univ., Oxford, 1994).
339. M. B. Menskii, Usp. Fiz. Nauk **177**, 415 (2007).
340. M. B. Menskii, *The Person and Quantum World. Stranges of Quantum World and the Secret of Consciousness,* Ser. The Science for Everyone (Fizmatlit, Moscow, 2007) [in Russian].
341. D. Bouwmeester, J.-W. Pan, K. Mattle, et al., Nature **390**, 575 (1997).
342. V. V. Belokurov, O. D. Timofeevskaya, and O. A. Khrustalev, *Quantum Teleportation as a Normal Wonder*, (RDKh, Izhevsk, 2000) [in Russian].
343. L. D. Landau and E. M. Lifshits, *Quantum Mechanics* 4-th ed. (Nauka, Moscow, 1989) [in Russian].
344. C. Cohen-Tannoudji, B. Diu, and F. Laloe, *Quantum Mechanics* (Wiley, New York, 1977), Vols. 1, 2.
345. E. Merzbacher, *Quantum Mechanics,* 3rd ed. (Wiley, New York, 1997).
346. P. A. M. Dirac, *The Principles of Quantum Mechanics* (Fizmatlit, Moscow, 1960; Clarendon, Oxford, 1958).
347. C. Piron, *Foundations of Quantum Physics* (Benjamin, New York, 1976).
348. A. Böhm, *Quantum Mechanics: Foundations and Applications* (Springer, Berlin, 1986).
349. R. Shankar, *Principles of Quantum Mechanics*, 2nd ed. (Plenum, New York, 1994).

350. A. I. Panchenko, *Logical Gnoseological Problems of Quantum Physics* (Nauka, Moscow, 1981) [in Russian].
351. A. S. Kholevo, *Probabilitical and Statistical Aspectes of Quantum Theory* (Nauka, Moscow, 1980) [in Russian].
352. V. E. Tarasov, *Quantum Mechanics* (Vuzovskaya Kniga, Moscow, 2000) [in Russian].
353. A. Peres, *Quantum Theory: Concepts and Methods* (Kluwer, New York, 2002).
354. O. V. Kuznetsova, *Investigations in the Hystory of Physics and Mechanics. 1991–1992* (Nauka, Moscow, 1997), p. 66 [in Russian].
355. V. d'Espagnat, *Veiled Reality. An Analysis of Present-Day Quantum Mechanical Concepts* (Addison-Wesley, New York, 1995).
356. D. Dieks, "The Formalism of Quantum Theory: An Objective Description of Reality?," Ann. Physik (Leipzig) **7**, 174 (1988).
357. G. F. R. Ellis, Phys. Today **58** (7), 49 (2005).
358. B. Richter, Phys. Today **59** (10), 8 (2006).
359. L. G. Antipenko, *The Problem of Physical Reality* (Nauka, Moscow, 1973) [in Russian].
360. O. V. Kuznetsova, "Quantum Mechanics and its Interpretation," in *Physics of XX Century and Its Connection with Other Sections of Natural Sciences*, Collected volume, Ed. by G. Idlis (Yanus-K, Moscow, 1997), p. 86 [in Russian].
361. M. Born, Brit. J. Phil. Sci. **4**, 98 (1953).
362. M. Born, *The Physics in the Life of My Generation* (Inostrannaya Liter., Moscow, 1963) [in Russian].
363. V. A. Fok, *Quantum Physics and the Structure of Matter* (GTTI, Leningrad, 1965) [in Russian].
364. M. A. Markov, *On Three Interpretations of Quantum Mechanics* (Nauka, Moscow, 1991) [in Russian].
365. E. P. Wigner, "Interpretation of Quantum Mechanics," in *Quantum Theory and Measurement*, Ed. by J. A. Wheeler and W. H. Zurek (Princeton UP, Princeton, 1983), p. 260.
366. H. D. Zeh, Found. Phys. **18**, 723 (1988).
367. V. P. Demutskii and R. V. Polovin, Usp. Fiz. Nauk **162**, 147 (1992).
368. R. Omnes, *Interpretation of Quantum Mechanics* (Princeton Univ., Princeton, 1994).
369. M. B. Menskii, Usp. Fiz. Nauk **168**, 1017 (1998) [Phys.-Usp. **41**, 923 (1998)].
370. J. Bricmont, Phys. Today **52** (8), 82 (1999).
371. M. B. Menskii, Usp. Fiz. Nauk **170**, 631 (2000) [Phys.-Usp. **43**, 585 (2000)].
372. M. B. Menskii, Usp. Fiz. Nauk **171**, 459 (2001) [Phys.-Usp. **44**, 438 (2001)].
373. A. I. Golokhvastov, Usp. Fiz. Nauk **172**, 843 (2002) [Phys.-Usp. **45**, 783 (2002)].
374. J. T. Cushing, *Quantum Mechanics: Historical Contingency and the Copenhagen Hehemony* (Chicago Univ., Chicago, 1994).
375. D. I. Blokhintsev, Usp. Fiz. Nauk **95**, 75 (1968) [Phys.-Usp. **11**, 320 (1968)].
376. D. I. Blokhintsev, Usp. Fiz. Nauk **122**, 745 (1977) [Phys.-Usp. **20**, 683 (1977)].
377. D. I. Blokhintsev, *Quantum Mechanics. Lections on Selected Questions* (Atomizdat, Moscow, 1981) [in Russian].
378. D. I. Blokhintsev, *Principal Questions of Quantum Mechanics*, 2-nd ed. (Nauka, Moscow, 1987) [in Russian].
379. D. V. Shirkov, Usp. Fiz. Nauk **124**, 197 (1978).
380. *Phylosofical Questions of Modern Physics*, Collected Volume, Ed. by M. E. Omeljanovskii (Politizdat, Moscow, 1958) [in Russian].
381. *Phylosofical Questions of Modern Physics*, Collected Volume, Ed. by I. V. Kuznetsov and M. E. Omeljanovskii (Politizdat, Moscow, 1958) [in Russian].
382. *Phylosofical Questions of Modern Physics*, Collected Volume, Ed. by L. G. Antipenko (Nauka, Moscow, 1970) [in Russian].
383. I. S. Alekseev, *Conception of Additivity. Hystoricsl Metodological Analysis* (Nauka, Moscow, 1978) [in Russian].
384. R. Feynman and A. Hibbs, *Quantum Mechanics and Path Integrals* (Mir, Moscow, 1968; McGraw-Hill, 1965).
385. G. Ya. Myakishev, *Dynamical and Statistical Laws in Physics* (Nauka, Moscow, 1973) [in Russian].
386. D. I. Blokhintsev and Ch. M. Briskina, Vestnik MGU **10**, 115–118 (1948).
387. M. Gell-Mann and J. B. Hartle, Phys. Rev. D 1993. **47**, 3345 (1993).
388. P. Paradoksov, Usp. Fiz. Nauk **89**, 707 (1966) [Phys.-Usp. **9**, 618 (1966)].
389. Z. Onyszkiewicz, Am. J. Phys. **52**, 817 (1984).
390. M. Jammer, *Philosophy of Quantum Mechanics* (Wiley, New York, 1974).
391. B. S. De Witt and R. N. Graham, Am. J. Phys. **39**, 724 (1971).
392. C. A. Hooker, "The Nature of Quantum Mechanical Reality: Einstein Versus Bohr," *The Pittsburgh Studies in the Philosophy of Science* (Pittsburgh Univ., Pittsburgh, 1972), Vol. 5, p. 67.
393. D. Home and M. A. B. Whitaker, Phys. Rep. **210**, 223 (1992).
394. F. Rohrlich, Found. Phys. **17**, 1205 (1987).
395. K. R. Popper, *Quantum Theory and the Schism in Physics* (Logos, Moscow, 1998; London, 1982).
396. L. E. Ballentine, Rev. Mod. Phys. **42**, 372 (1970).
397. L. E. Ballentine, Found. Phys. **3**, 229 (1973).
398. Z. Maki, Prog. Theor. Phys. **79**, 313 (1988).
399. M. Namiki, "Quantum Mechanics of Macroscopic Systems and Measurement Processes," in *Microphysical Reality and Quantum Formalism*, Ed. by A. Van Der Merwe et al. (Kluwer, Dordrecht, 1988), p. 3.
400. H. Everett, Rev. Mod. Phys. **29**, 454 (1957).
401. *The Many-Worlds Interpretation of Quantum Mechanics*, Ed. by B. S. De Witt and R. N. Graham (Princeton Univ., Princeton, 1973).
402. D. Böhm, *Causality and Chance in Modern Physics* (Inostrannaya Liter., Moscow, 1959; Routlege, London, 1984).
403. D. Böhm, Found. Phys. **1**, 359 (1971).
404. D. Böhm, Found. Phys. **3**, 139 (1973).

405. S. Goldstein, "Bohmian Mechanics and the Quantum Revolution," Synthese **107**, 145 (1996).
406. S. Goldstein, Phys. Today **51** (3), 42 (1998).
407. S. Goldstein, Phys. Today **51** (4), 38 (1998).
408. P. Mittelstaedt, Int. J. Theor. Phys. **22**, 293 (1983).
409. P. Mittelstaedt, *Quantum Logic* (Kluwer, Dordrecht, 1978).
410. U. Lamb, Usp. Fiz. Nauk **99**, 719 (1969); W. Lamb, Phys. Today **22** (4), 23 (1969).
411. G. C. Ghirardi, "The Quantum Worldview: Its Difficulties and an Attempt to Overcome Them," in *Bridging the Gap: Philosophy, Mathematics and Physics,* Ed. by G. Corsi et al. (Kluwer, Dordrecht, 1993), p. 175.
412. J. G. Cramer, Rev. Mod. Phys. **58**, 647 (1986).
413. R. Healey, *The Philosophy of Quantum Mechanics: An Interactive Interpretation* (Cambridge Univ., Cambridge, 1989).
414. R. Healey, Found. Phys. Lett. **6**, 307 (1993).
415. S. Kochen, "A New Interpretation of Quantum Mechanics," in *Symp. on the Foundations of Modern Physics*, Ed. by P. Lahti and P. Mittelstaedt (World Sci., Singapore, 1985), p. 151.
416. B. C. van Fraassen, *Quantum Mechanics: An Empiricist View* (Oxford, 1991).
417. P. E. Vermaas and D. Dieks, Found. Phys. **25**, 145 (1995).
418. R. K. Clifton, "The Properties of Modal Interpretation of Quantum Mechanics," Brit. J. Phil. Sci. **47**, 371 (1996).
419. Y. Aharonov, J. Anandan, and L. Vaidman, Phys. Rev. A **47**, 4616 (1993).
420. B. B. Kadomtsev, *Dynamics and Information* (UFN, Moscow, 1997) [in Russian].
421. R. Omnes, Rev. Mod. Phys. **64**, 339 (1992).
422. R. B. Griffith, Phys. Rev. A **54**, 2759 (1996).
423. R. B. Griffith, *Consistent Quantum Theory* (Cambridge Univ., Cambridge, 2003).
424. Z. Onyszkiewicz, "Immaterial Interpretation of Quantum Theory in the Context of Quantum Cosmology," in *New Developments on Fundamental Problems in Quantum Physics*, Ed. by M. Ferrero and A. van der Merwe (Kluwer, Dordrecht, 1997), p. 285.
425. A. Ya. Khinchin, *Mathematical Bases of Quantum Statistics* (GTTI, Moscow, 1951) [in Russian].
426. D. Bohm and B. J. Hiley, Phys. Rep. **144**, 323 (1987).
427. M. Tegmark, "The Interpretation of Quantum Mechanics: Many Worlds or Many Words," in *Fundamental Problems in Quantum Theory*, Ed. by M. H. Rubin and Y. H. Shin (Kluwer, Dordrecht, 1998), p. 74.
428. R. Omnes, *Quantum Philosophy: Understanding and Interpreting Contemporary Science* (Princeton Univ., Princeton, 1999).
429. M. B. Menskii, *Quantum Measurements and Decogerention* (Fizmatlit, Moscow, 2001) [in Russian].
430. W. H. Zurek, Rev. Mod. Phys. **75**, 715 (2003).
431. M. Tegmark, Nature **448**, 23 (2007).
432. A. Aspect, Nature **446**, 866 (2007).
433. M. Roukes, Nature **443**, 154 (2006).
434. Ya. A. Smorodinskii, "On Quantum Ansambles," in *Proc. of Science Seminar Devoted to 75 Year from Birthday of D. I. Blokhintsev, Dubna, 23 Jan., 1983* (OIYaI, Dubna, 1986), pp. 92–97.
435. A. Yu. Khrennikov, *Nonkolmogorov's Probability Theories and Quantum Physics* (Fizmatlit, Moscow, 2003) [in Russian].
436. Yu. I. Alimov and Yu. A. Kravtsov, Usp. Fiz. Nauk **162**, 149 (1992) [Phys.-Usp. **35**, 606 (1992)].
437. A. A. Pechenkin, "Strasburg's Factor in the Creation of L.I. Mandelshtam and its School," in *Physics of XX Century and its Connection with Other Sections of Natural Sciences*, Collected Volume, Ed. by G. M. Idlis (Yanus-K, Moscow, 1997), pp. 199–223 [in Russian].
438. A. Ya. Khinchin, Usp. Fiz. Nauk **9**, 141 (1929).
439. S. Petrov, *Beginnings of Probability Interpretation of Wave Function,* in *Theory of Knowledge and Modern Physics*, Ed. by Yu. I. Sachkov (Nauka, Moscow, 1984), pp. 260–274 [in Russian].
440. L. Cohen, Found. Phys. **18**, 983 (1988).
441. R. G. Newton, Am. J. Phys. **48**, 1029 (1984).
442. D. J. Vellemans, Am. J. Phys. **66**, 967 (1998).
443. A. Cassinello and L. S. Sanchez-Gomez, Found. Phys. **26**, 1357 (1996).
444. E. T. Jaynes, *Probability Theory: The Logic of Science* (Cambridge Univ., Cambridge, 2003).
445. G. Weihs, Nature **445**, 723 (2007).
446. C. W. Chou, H. de Riedmatten, D. Felinto, et al., Nature **438**, 828 (2005).
447. I. V. Bargatin, B. A. Grishanin, and V. N. Zadkov, Usp. Fiz. Nauk **171**, 625 (2001) [Phys.-Usp. **44**, 597 (2001)].
448. B. Kennedy, Phys. World **3**, 52 (1994).
449. *Physics and Probability: Essays in Honor of Edwin T. Jaynes*, Ed. by W. T. Grandy and P. W. Milloni (Cambridge Univ., Cambridge, 1993).
450. E. T. Jaynes, *Papers on Probability, Statistics and Statistical Physics*, Ed. by R. D. Rozenkranz (D. Reidel Publ., Dordrecht, 1983).
451. T. L. Fine, The "Only Acceptable Approach" to Probabilistic Reasoning," SIAM News **37** (2), 723 (2004).
452. N. V. Fock, *Investigations on the History of Physics and Mechanics. 1998–1999*, Ed. by G. M. Idlis (Nauka, Moscow, 2000) [in Russian].
453. K. V. Nikolskii, Z. Physik **62**, 677 (1930).
454. K. V. Nikolskii, Sow. Phys. **2**, 447 (1932–1933).
455. K. V. Nikolskii, Usp. Fiz. Nauk **16**, 930 (1934).
456. G. E. Gorelik, "Prehistory of FIAN and G. A. Gamov," Preprint IIET No. 41 (IIET AN SSSR, Moscow, 1990).
457. G. E. Gorelik, "Moscow, Physics, 1937 Year," in *Tragical Fates: Repressed Scientists of Science Academy of USSR* (Nauka, Moscow, 1995), pp. 54–75 [in Russian].
458. N. F. Mott, *Wave Mechanics and Nuclear Physics* (ONTI, Moscow, 1936) [in Russian]; "The Wave Mechanics of α-Ray Tracks," Proc. Roy. Soc. A **128**, 79 (1929).
459. K. V. Nikolskii, Usp. Fiz. Nauk **16**, 537 (1936).
460. V. A. Fock, Usp. Fiz. Nauk **17**, 552 (1937).
461. K. V. Nikolskii, Usp. Fiz. Nauk **17**, 554 (1937).
462. V. A. Fock, Usp. Fiz. Nauk **19**, 139 (1938).

463. A. A. Pechenkin, "The Last Word," in K. R. Popper, *Quantum Theory and the Schism in Physics* (Logos, Moscow, 1998; London, 1982).
464. V. A. Fock, Usp. Fiz. Nauk **45**, 3 (1951).
465. V. A. Fock, Usp. Fiz. Nauk **62**, 461 (1957).
466. D. I. Blokhintsev, "The Answer to Academic V. A. Fock," Vopr. Filos. **6**, 171–175 (1952).
467. V. A. Fock, "Hydrogen Atom and Non-Evclide Geometry," Izvestiya AN SSSR, Ser. Fiz. **2**, 169 (1935).
468. M. G. Veselov, "Science Work of V. A. Fock," in *Quantum Mechanics and Theory of Relativity* (Leningr. Univ., Leningrad, 1980) [in Russian].
469. I. A. Malkin and V. I. Manko, Pisma Zh. Eksp. Teor. Fiz. **2**, 230 (1965) [JETP Lett. **2**, 146 (1965)].
470. M. Bander and S. Itzykson, Rev. Mod. Phys. **38**, 330, 346 (1966).
471. K. V. Nikolskii, Usp. Fiz. Nauk **24**, 534 (1940).
472. K. V. Nikolskii, Usp. Fiz. Nauk **24** (8), (1940).
473. J. W. Gibbs, *Elementary Principles in Statistical Mechanics Developed with Especial Reference to the Rational Foundations of Thermodynamics* (OGIZ, Leningrad, Moscow, 1946; Yale Univ., New Heaven, 1902).
474. B. N. Finkelshtein, Usp. Fiz. Nauk **33** (10), (1947).
475. S. I. Vavilov, *Essays and Memories* (Nauka, Moscow, 1981) [in Russian].
476. S. I. Vavilov, A. A. Maksimov, and V. F. Mitkevich, *Materialism and Empirical Criticism of Lenin and the Modern Physics* (SOTsEKGIZ, Moscow, 1939) [in Russian].
477. A. A. Grib, *The Problem of Non-Invariant of Vacuum in Quantum Field Theory* (Atomizdat, Moscow, 1978) [in Russian].
478. A. B. Migdal, *Quantum Physics*, Bibl. "Kvant", vol. 75 (Nauka, Moscow, 1989) [in Russian].
479. D. I. Blokhintsev and F. M. Galperin, Pod Znamenem Marksizma **3**, 97 (1934).
480. D. I. Blokhintsev and F. M. Galperin, Antireligioznik **3**, 10 (1936).
481. L. L. Maksimov, *Intoduction into Modern Learning about Matter and Motion* (OGIZ, Moscow, 1941) [in Russian].
482. B. M. Bolotovskii, Yu. N. Vavilov, and A. N. Kirkin, Usp. Fiz. Nauk **168**, 551 (1998) [Phys.-Usp. **41**, 487 (1998)].
483. S. G. Suvorov, "On So-Called Physical Conception of Matter," Usp. Fiz. Nauk **44**, 485 (1951).
484. N. O. Losskii, *The Matter in the System of Organical World View* (Leman i Sakharov, Moscow, 1918) [in Russian].
485. J. C. Maxwell, *Matter and Motion* (Gosizdat, Moscow, 1924; London, 1873).
486. Te. Svedberg, *The Matter. Its Investigations in the Past and Future* (Gosizdat, Moscow, 1924; Berlin, 1919).
487. M. A. Markov, *On the Nature of Matter* (Nauka, Moscow, 1976) [in Russian].
488. V. Ya. Komarova, *Formation of Phylosophycal Materialism in the Ancient Greece* (Leningr. Univ., Leningrad, 1975) [in Russian].
489. G. E. Gorelik, *Investigations on the History of Physics and Mechanics. 1998–1999,* Collected Volume, Ed. by G. M. Idlis (Nauka, Moscow, 2000), p. 50 [in Russian].
490. D. I. Blokhintsev*, Reflections on Problems of Perception and Creation and Laws of Development Processes,* in *The Theory of Knowledge and Modern Physics*, Ed. by Yu. I. Sachkov (Nauka, Moscow, 1984), pp. 53–74 [in Russian]
491. D. I. Blokhintsev, *Preconditions of Scientific and Technical Progress,* in *Modern Problems of Physics* (Znanie, Moscow, 1976), pp. 4–18 [in Russian].
492. G. Caglioti, *On the Dynamics of Polisemantic and Violations of Symmetry in the Science and Art* (Fazis, Moscow, 2000; Vieweg, Braunschweig, 1990).
493. P. N. Lebedev, *Work Collection* (MFO im. Lebedeva, Moscow, 1913) [in Russian].
494. D. I. Blokhintsev, M. A. Leontovich, I. E. Tamm, et al., Izv. AN SSSR, Ser. Fiz. **3**, 425 (1937).
495. D. I. Blokhintsev, M. A. Leontovich, I. E. Tamm, and Ya. I. Frenkel, Izv. AN SSSR, Ser. Fiz. **3–4**, 591 (1938).
496. A. V. Andreev, "Alternative Physics in USSR: 20th–40th Years," in *Physics of XX Century and Its Connection with Other Sections of Natural Sciences*, Ed. by G.M. Idlis (Yanus-K, Moscow, 1997), pp. 241–263 [in Russian].