The Knight of the Quantum: On the Contribution of D.I. Blokhintsev to Quantum Physics[1]

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Abstract

A concise survey of the contribution of D.I. Blokhintsev to the quantum physics, including solid state physics, physics of metals, surface physics, statistical physics and optics is given. These achievements have been considered in the context of modern development of these fields of physics.

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. 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. In the beginning of his distinguished academic career [1, 2], D.I. Blokhintsev has worked in the field of quantum solid state physics and statistical physics, as well as in the field of quantum physics [1]. The aim of my talk is to recall these quite interesting and important works and correlate them with corresponding modern directions in condensed matter physics and quantum physics [3]. D.I. Blokhintsev entered the Physics Faculty of Moscow State University in 1926. At that time L.I. Mandelstam was the head of the Department of theoretical physics and optics and I.E. Tamm was professor of theoretical physics of that Department. Blokhintsev considered L.I. Mandelstam, S.I. Vavilov and I.E. Tamm his teachers. I.E. Tamm become his Ph.D. promotor in postgraduate studies. 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. Blokhintsev was certainly influenced strongly by Mandelstam and learned a lot from him, 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 later, "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

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parts of Moscow." Mandelstam delivered his famous lectures on the principles of quantum mechanics (the theory of indirect measurements) in spring of 1939. 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 famous book written by J. von Neumann. Later, this program was realized by Blokhintsev.

It was time when quantum mechanics had acquired a certain maturity [4]. In the book by Gurney [5], 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". Blokhintsev joined the realization of a program of reconsideration of atomic and solid state physics in their entirety on the basis of new quantum physics 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" [1]. At that time, solid state physics, in particular, the theory of metals, attracted great attention. In 1932, the work "Temperature Dependence of the Photoeffect on Pure Metals" of D.I. Blokhintsev was published. The next paper was "The Work Function of Electrons from Metals" (1933) (jointly with I.E. Tamm). In the monograph [6] this study by Tamm and Blokhintsev was cited together with other basic works on the problem. Thus, from the very beginning, his works were at the highest level of quality. The early works of D.I. Blokhintsev have manifested also his talents of clear vivid presentation of the subject, transparent style, concreteness, the ability to point out most significant things and, most important, emphasis on the *physical meaning*. In a large work by Blokhintsev in 1933 "Theory of Electron Motion in a Crystal Lattice", the F.Bloch theory of motion of tight binding electrons was generalized for the many bands case and for the electron motion in a crystal which is bounded by surface. The next work was the paper "Theory of Anomalous Magnetic and Thermoelectric Effects in Metals"(1933) coauthored with L.W. Nordheim (1899-1985). In this work, the consistent theory of thermoelectric and galvanomagnetic effects in metals was constructed. Unlike earlier works, the case of $s-p$ band metals was considered. The authors studied the behavior of divalent metals in a magnetic field (Thompson and Hall effects). To make their equations compact, Blokhintsev and Nordheim introduced a new notion, the tensor of reciprocal effective masses. In the book of Mott and Jones [6], the priority of Blokhintsev and Nordheim in the creation of this fundamental notion was established. The achievement made by Blokhintsev and Nordheim was that they showed that the concept of effective mass was much more general and workable 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. It turned out that the notion of effective mass is extremely useful in the theory of conductivity and other fields of solid state physics, nuclear physics, etc. The concept of effective mass became widely applied, especially in semiconductor physics and the physics of semiconductor devices, the polaron theory, semiconductor superlattices, microelectronics and physics of nanostructures.

A few word should be said about Blokhintsev's coauthor Lotar Wolfgang Nordheim (1899-1985). Nordheim belonged to the Gettingen 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 Jammer's book [4], 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 student, 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 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, etc. 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.

In 1933, Blokhintsev published "Theory of the Stark Effects in a Time-Dependent Field". In this paper Blokhintsev showed that the atomic levels move under influence of variable electric field (Stark modulation). The picture of light scattering depends nonlinearly on the intensity of the incident light. This work was one of the first in the field of physics, which was latter called *nonlinear optics*.

In 1934, Blokhintsev published paper on the theory of phosphorescence. According to the author, "An attempt was made to explain the phenomenon of phosphorescence in the so called Lenard phosphors on the basis of quantum mechanical ideas of the electron motion in the crystal lattice" [1]. Blokhintsev assumed that duration of the phosphorescence 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 impurities. Then he estimated the time of reciprocal recombination of these states. Thus, the theory of localized states made it possible to qualitatively (and, partially, quantitatively) interpret the big duration of the phosphorescence. This point of view was included in textbooks on optics. This and subsequent works by Blokhintsev, 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 same approach was used by Blokhintsev in the work "Quantum Mechanical Theory of Adsorption" (1934) (co-authored with Sh. Shekhter). This work is a very useful and clear survey of the problem as a whole. The paper of the same authors "Lifetime of Particles in Adsorbed State" (1934) was devoted to the calculation of the lifetime of particles in the adsorbed state. In that paper it was demonstrated how the quantum mechanics provides one with the microscopic picture of phenomenon. The authors obtained the correct qualitative behavior of the average lifetime of the adsorbed molecule on the surface, which demonstrated once more the effectiveness of the quantum mechanical approach. In 1934, Blokhintsev presented his Ph.D. thesis to the Institute of Physics of the Moscow State University, entitled *Selected Problems of the Solid State Theory, Especially Metals*. As a result of the high level of the work, he received a degree of Doctor of Science. At the time, Blokhintsev was 26 years old.

In 1935–1936, Blokhintsev continued his work on the theory of light absorption in heteropolar crystals, the theory of phosphorescence, and the theory of dyed crystals. It is interesting to note that in the paper "Theory of Dyed Crystals" (1936), Blokhintsev, in certain sense, anticipated the concept of the *polaron*, which was formulated later by S.I. Pekar (1917-1985). S.I. Pekar wrote this story in his well known monograph [7] in 1951: "In 1936, Blokhintsev attempted to find out in which crystals autolocalization of electrons pointed out by Landau should be expected on the basis of the approximation of tight-binding electrons...". As is well known, S.I. Pekar coined the very term, *polaron*, in 1946. The main idea was that "excess" electron in ionic crystal polarizes the 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 may 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. These states of the crystal with the polarization well in which the electron is localized were termed *polarons* by Pekar. The contribution made by Blokhintsev in 1936 to this direction of researches was mentioned later by a few other investigators. The main point was the formulation of the problem of autolocalized electronic states on the basis of approximation of tight-binding electrons. This approximation (LCAO) [3] later become widely used in condensed matter physics, especially for the description of localized states of different nature and disordered systems. The investigation of localized states in the framework of the tight-binding approximation bringed Blokhintsev to the point, namely to the need to describe the interaction of the electron with the lattice vibrations accordingly to the spirit of tight-binding approximation. This was carried out much later (see for details Ref. [3]).

In 1938, Blokhintsev prepared 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 [8] in 1949. Later on, the following was written [9]: "Already in early works by Blokhintsev, 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 cutoff. 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 described by Blokhintsev himself [1]. "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 presenting the affair in this light...". The **Lamb shift** is indeed related to quite remarkable and interesting effects of quantum physics [10]. Lamb and his colleagues performed very precise, thorough, and elegant experimental studies 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. Blokhintsev wrote about his calculations in [1]: "As a result of them, the following expression is obtained for the frequency shift:

$$\delta\omega_0 = k(\frac{e^2}{\hbar c})^3 \frac{Z^4}{n^3} R \lg\left(\frac{\mu c^2}{\Delta E_{av}}\right), \tag{1}$$

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 cutoff, the coefficient k and the values of ΔE_{av} differ somewhat from exact values obtained using the method of electron mass renormalization (note that (1) 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 $\delta\omega_0/\omega = 2.8 \cdot 10^{-8}$ 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. Experimental investigations of the Lamb shift continue. It was reported not long ago that two-loop corrections to the Lamb shift were first measured in strongly ionized atoms of heavy elements using the ion trap technique [11]. The history of theoretical calculation of the Lamb shift value is quite interesting. It is known from firsthand accounts and has been well described in many papers and books [12, 13]. According to V. Weisskopf [12], "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 Retherford 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 Retherford. What's the moral of this story? You have to believe in what you do."

In 1939, Blokhintsev published his work "Hydrodynamics of an Elecron gas". 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 $\rho(x)$, was considered. Blokhintsev maintained that since a many-particle problem could not be solved exactly, an approximate solution should be sought. It is known 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 with this exchange taken into account. There exist a large number of works on this method both with and without the exchange account. Blokhintsev wrote in his work 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. 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 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 using a different method.

It is appropriate to note here that the work "Hydrodynamics of an Electron Gas" 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 reconstructing, 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 obtained interesting and deep development, connected with the concept of the "*quantum* *protectorate*." In a work with a remarkable title, "*The Theory of Everything*" [14], authors R. Laughlin and D. Pines discussed the most fundamental principles of the description of matter in a wide sense. The authors put forward the question what the "Theory of Everything" should be. In their opinion, "it describes the everyday world of human beings - air, water, rocks, fire, people, and so forth". The answer given by the authors was that "this theory is nonrelativistic quantum mechanics," or, more precisely, the equation of nonrelativistic quantum mechanics, which they wrote in the form

$$H\psi = -\frac{\hbar}{i}\frac{\partial \psi}{\partial t}. \tag{2}$$

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 "Less immediate things in the universe, such as the planet Jupiter, nuclear fission, the sun, or isotopic abundances of elements in space are not described by this equation, because important elements such as gravity and nuclear interactions are missing. But except for light, which is easily included, and possibly gravity, these missing parts are irrelevant to people-scale phenomena. Eq.(2) is, for all practical purposes, the Theory of Everything for our everyday world. However, it is obvious glancing through this list that the Theory of Everything is not even remotely a theory of every thing. We know this equation (2) is correct because it has been solved accurately for small numbers of particles (isolated atoms and small molecules) and found to agree in minute detail with experiment. However, it cannot be solved accurately when the number of particles exceeds about 10. No computer existing, or that will ever exist, can break this barrier because it is a catastrophe of dimension. If the amount of computer memory required to represent the quantum wave function of one particle is N then the amount required to represent the wave function of k particles is N^k." According to R. Laughlin and D. Pines, "The emergent physical phenomena regulated by higher organizing principles have a property, namely their insensitivity to microscopics, that is directly relevant to the broad question of what is knowable in the deepest sense of the term. The low energy excitation spectrum of a conventional superconductor, for example, is completely generic and is characterized by a handful of parameters that may be determined experimentally but cannot, in general, be computed from first principles. An even more trivial example is the low-energy excitation spectrum of a conventional crystalline insulator, which consists of transverse and longitudinal sound and nothing else, regardless of details. It is rather obvious that one does not need to prove the existence of sound in a solid, for it follows from the existence of elastic moduli at long length scales, which in turn follows from the spontaneous breaking of translational and rotational symmetry characteristic of the crystalline state. Conversely, one therefore learns little about the atomic structure of a crystalline solid by measuring its acoustics. The crystalline state is the simplest known example of a quantum protectorate, a stable state of matter whose generic low-energy properties are determined by a higher organizing principle and nothing else. There are many of these, the classic prototype being the Landau fermi liquid, the state of matter represented by conventional metals and normal ^3He... Other important quantum protectorates include superfluidity in Bose liquids such as ^4He and the newly discovered atomic condensates, superconductivity, band insulation, ferromagnetism, antiferromagnetism, and the quantum Hall states. The low-energy excited quantum states of these systems are particles in exactly the same sense that the electron in the vacuum of quantum electrodynamics is a particle:

They carry momentum, energy, spin, and charge, scatter off one another according to simple rules, obey Fermi or Bose statistics depending on their nature, and in some cases are even "relativistic," in the sense of being described quantitatively by Dirac or Klein-Gordon equations at low energy scales. Yet they are not elementary, and, as in the case of sound, simply do not exist outside the context of the stable state of matter in which they live. These quantum protectorates, with their associated emergent behavior, provide us with explicit demonstrations that the underlying microscopic theory can easily have no measurable consequences whatsoever at low energies. The nature of the underlying theory is unknowable until one raises the energy scale sufficiently to escape protection."

The existence of two scales, low-energy and the high-energy, in the description of magnetic phenomena was stressed by Kuzemsky (see Refs. [15, 16, 17]) upon comparative investigation of localized and itinerant quantum models of magnetism. The concept of quantum protectorate was applied to the theory of magnetism in paper [17]. 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.

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 L. I. Mandelstam and K.V. Nikol'skii. Nikol'skii's book *Quantum Processes* [18] is mentioned many times in his papers. In the work "Correlation of a Quantum Ensemble with a Classical Gibbs Ensemble" (1940), the limiting transition from quantum equations of motion for the density matrix to the equations of motion for the classical distribution function was studied. 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 was used. Blokhintsev shown in that paper that there does not exist any distribution function depending on (q,p) which could describe the quantum ensemble. In the next work on the topic (1940), the problem of the conditions of approximation of quantum statistics by classical statistics was considered. It was shown that there is no limiting transition ($h \to 0$) 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 $\Omega \gg \hbar$. Thus, in these works, a new direction of physics was initiated: quantum mechanics in the phase space [19].

The title of the next work written by Blokhintsev (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. 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 survey [20].

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". This short 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 is 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". 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".

In 1947, Blokhintsev published the work "The Atom under an Electron Microscope". 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 scattering. 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 scattering necessary for obtaining an image of the atom consists of a series of scattering related to objects from different quantum ensembles. This seems to be a unique case of such a situation."

Since physicists, chemists, metallurgists, and biologists needed improved microscopes, this problem always stirred interest. It should be noted that remarkable works were performed by Mandelstam on the theory of the microscope. 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 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". 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 greatly and is being extensively developed now.

Blokhintsev's name is closely related to the problem of **interpretation of the quantum mechanics** [21]. Blokhintsev recollected [1] 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." A large number of his books [22, 23, 24] and papers [25, 26] were devoted to this problem. His views of the problem changed and evolved with deepening and perfection of arguments. 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 wave function. The variety of opinions concerning the interpretation of quantum mechanics increased with time. Blokhintsev wrote [1]: "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".

As a result of longterm research and reflections, Blokhintsev developed his own approach to interpreting quantum mechanics, which included ideas put forward by J. von Neumann, L.I. Mandelstam, and K.V. Nikol'skii. It was called the interpretation of quantum mechanics on the basis of quantum ensembles. He wrote in a summary work [24], "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; also Nikol'skii contributed considerably to our 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". 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. Blokhintsev's approach to the interpretation of quantum mechanics became widely known. De Witt and Graham [27] in their survey of different approaches to interpreting quantum mechanics wrote about Blokhintsev's books: "...they are both very well written and informative. The departure from orthodoxy occurs, in fact, only in certain attitudes and choice of words, while the general presentation of quantum mechanics is refreshing...; [the second book] contains an excellent account of measurement theory". Blokhintsev's approach to interpreting quantum mechanics is a constituent part of the scope of ideas of various researchers. One of the authoritative historians of quantum mechanics, Hooker [28], noted that "...Einstein and his co-workers Podolsky and Rosen, Blokhintsev, Bopp, de Broglie, Popper, Schrodinger, Lande, and most recently Ballentine constitute a small group of physicists and philosophers, who are determined to treat quantum theory as a species of statistical mechanics, many of them hoping ultimately to reinstate the classical conception of reality." A detailed survey of the interpretation of quantum mechanics on the basis of quantum ensembles can be found in [29]. The interpretation of quantum mechanics on the basis of quantum ensembles is one of many in existence. 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. Interpretation of quantum mechanics on the basis of quantum ensembles was considered in detail by Ya.A. Smorodinskii (1986). The conclusion he made is quite remarkable [30]: "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" (see also recent book [31]).
We conclude this paper with the words by Max 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, may be in slightly different words. In these notes and in the extended review [3] we 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. We have tried to show that Blokhintsev's book *Quantum Mechanics* [22], 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 background on which the book *Quantum Mechanics* stands, and it continues to describes the world using the **language of a quantum**!
In this work due to the lack of space, not all the topics and problems that I wanted to discuss are here. 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 in Moscow. A more detailed discussion of modern approaches to interpreting quantum mechanics can be found in paper [3]. The full details and precise References are given in paper [3] as well.

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