

If You Ask a Physicist from Any Country*

—A Tribute to Yacov Il'ich Frenkel

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If you ask a physicist from any country: “Have you heard about vacancies in crystals, quantum theory of conductivity, excitons, exchange interaction leading to spontaneous magnetization of the ferromagnetics and their domain structure?” He definitely will say: “Yes! These are basic physics. Everybody knows.”

If you ask a material scientist: “Do you know that apparent stiffness of a metal is many orders lower than its theoretical value?” You will get the same answer: “Of course I know. It is a common knowledge.”

If you ask a chemist: “What do you think about the definition of temperature for a single molecule?” He will answer: “Oh, it is one of the most important ideas in the theory of reaction of gases.”

If you ask an astronomer: “Do you know that if a star has a mass slightly larger than our Sun, it can become unstable and collapse into a neutron star?” The astronomer will tell you: “Of course! It is basic astronomy.”

If you ask a geophysicist: “Do you know that the Earth’s magnetic field is mostly generated by the movement of electrically conducting liquid in the melted part of Earth mantle?” He will definitely say: “Sure, we all know that as the Earth’s Dynamo.”

However, if you ask a western scientist: “Who introduced all these ideas in science?” You will get, perhaps, many great names such as Dirac, Heisenberg, Pauli, Chandrasekhar, Bullard, among others. It is improbable that somebody will give you the answer: one person introduced all these ideas—the brilliant Russian scientist Yakov Il'ich Frenkel.

Yakov Frenkel was born on February 10, 1894 in the southern Russian city Rostov-on-Don. Since his early years he showed a talent in music, fine arts, and science. Being a student in the May Gymnasium at St. Petersburg, Ya. Frenkel wrote a 100-page mathematical paper, which was sent to Jacov Viktorovich Uspenskii, then a student of the famous Andrei Andreyevich Markov, for comment. Uspenskii found that the young Frenkel had rediscovered many results of the calculus of finite differences, which was not a part of his Gymnasium education. Later Frenkel wrote a 300-page exposition paper on the origin of the Earth’s magnetism and atmospheric electricity. The paper was shown to Abram Fedorovich Ioffe, then a professor at St. Petersburg Polytechnic Institute, and the two met for the first time. In 1913 Frenkel graduated from gymnasium with the highest honor (Gold Medal).

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Worrying that he might not be admitted to the university (in tsar's time, admission quota existed for persons of the Jewish religion), he briefly toured the US for the opportunity in North American universities. Fortunately, he was accepted by the Physics and Mechanics Department at the St. Petersburg University, where he completed the six-year course study in three years.

Before the Revolution of 1917, physics in Russia was not strong. Only a small group of physicists worked in St. Petersburg and Moscow at that time. However, they were first-class scientists—Petr Nikolaevich Lebedev, who proved experimentally the light pressure, and Nikolai Alekseevich Umov, who developed in 1874 the theory of propagation of wave energy and introduced the differential form of energy conservation law for continuum media. The physics school in St. Petersburg was associated with the name of A. F. Ioffe, who was an excellent scientist, teacher, and scientific manager—he was “Daddy Ioffe” as the first generation of Russian physicists after the Revolution affectionately called him.

In 1916, Ioffe organized the first of the seminars that later became the trademark of Russian physics. Other famous seminars that came later included the Landau Seminar on Theoretical Physics, and the Moscow Seminar of Vitaly L. Ginsburg (2003 Nobel Prize in Physics). Frenkel took part in the Ioffe seminar from its very beginning together with Lev Davidovich Landau (1962 Nobel Prize in Physics for the theory of liquid helium), Nikolai Nikolayevich Semenov (1956 Nobel Prize in Chemistry for the theory of chain reactions), and Pyotr Leonidovich Kapitsa (1978 Nobel Prize in Physics for the physics of low temperatures).

Right after the Revolution, in 1918, Frenkel left St. Petersburg and took part in the organization of Tavrichesky University in Yalta, Crimea. It is amazing how fate can gather talents at one place and one time. The “father” of Russian atomic bomb Igor Kurchatov was Frenkel's student there, and Igor Yevgenyevich Tamm (1958 Nobel Prize in Physics) was his assistant and friend. The next office was occupied by Nikolai Mitrofanovich Krylov—the Russian mathematician, academician, famous for his work on nonlinear mechanics and the theory of stability of ships, and in the future, father-in-law of P. Kapitsa. Also in the same building was Mikhail Lyudvigovic Frank, the father of Il'ja Mikhailovich Frank (1958 Nobel Prize in Physics) and G. M. Frank, one of the founders of Russian biophysical school.

Living conditions in Crimea at that time were terrible. Excellent climate of Crimea could not compensate for the deprivation of war and hunger. Professor of the University was rationed 200 grams (less than ½ pound) of bread per day and a “free lunch”—one plate of “kasha.” Frenkel was jailed for two months during that time for political reasons. His younger brother Sergei, also a brilliant scientist, was drafted by the army and was killed in an accident. It was devastating for Frenkel and his family because of the five Frenkel siblings, only two remained alive. However, Frenkel worked intensively. He published in 1919 the paper in which he developed the theory of intermetal contact potential and the theory of metal surface tension. He was married in 1920 to Sarra Isaakovna, a biology student he met at the university.

In 1921 Frenkel returned to St. Petersburg and started to work in St. Petersburg Polytechnic Institute. In the university he taught lectures in electrodynamics and

mathematics. Between 1922 and 1925 he published five monographs. The first of them, *The Structure of Matter* was in 3 parts, published in 1922 and 1924. In 1923 he published the first Russian monograph on relativity, *The Theory of Relativity*. In 1924, he published *Electrical Theory of Solid Bodies*. In 1925 he published a popular science book *Electricity and Matter* and then the textbook *Course of Vector and Tensor Analyses*. Five books in four years! He was merely thirty years old at that time. During these years he also published about fifteen papers in the *Journal of Russian Physico-Chemical Society* and *Zeitschrift für Physik*, devoted to the theory of electroconductivity of metals, adsorption and evaporation, and the general electron theory of solid bodies.

Frenkel published in 1924 the first paper devoted to quantum theory of metals. In this paper, before the discovery of the Pauli principle, Frenkel showed that contrary to the classic theory, the kinetic energy of electrons in metals is independent of the temperature, and is dependent on the quantum character of the electron movement. He showed that during the condensation of metals in a crystal, the collectivization of valence electrons occurs, and only these electrons are responsible for the metal conductivity. He demonstrated that his theory not only was consistent with all experimental results supported by the classic theory, but also eliminated a crucial contradiction of the classic theory, called the “thermal capacity catastrophe” by Paul Ehrenfest.

In the same year, while developing the physical theory of adsorption, Frenkel introduced the idea of lateral movement of atoms and molecules along the substrate surface and suggested the two-dimensional phase transition in the adsorbate layer. About 20 years later, he generalized the notion of “adsorption” of foreign atoms to the atoms of the crystal itself, and presented the idea of self-diffusion of atoms along the crystalline surface. He successfully applied this theory for the explanation of the critical temperature of condensation of molecular beam on metal surface.

In those years living conditions were still very hard in Petrograd (St. Petersburg). There was a general shortage in food and fuel. Not only Yacov’s, but also Sarra’s parents depended on the couple for support. These made Frenkel’s productivity even more amazing.

In November, 1925, upon the recommendation of Ehrenfest, Frenkel was awarded a scholarship by the Rockefeller Foundation to visit Western Europe. He spent almost a year in Germany, France, and England. He worked with Max Born in Göttingen and was acquainted with Einstein in Berlin. It was also during this time that he published the first volume of his two-volume book *Electrodynamics*. A Russian scientist reminisced that when he visited Munich in 1928, he encountered a few students in Arnold Sommerfeld’s electrodynamics class. To his surprise, he found that to prepare students for the examination, Sommerfeld required his students to study Frenkel’s book, rather than his own!

In 1927 Frenkel was one of the participants in the International Physics Congress in Como, Italy. He presented his work on the quantum theory of electroconductivity of metals, which became an important part of the modern solid state physics. He argued that the metal’s ability to pass an anomalously large amount of electrons with little resistance was attributed to the periodicity of metal lattice. He claimed that the ideal periodic lattice was transparent to electrons, and electrons could freely pass through it. The only reason

that one observed electrical resistance was due to the scattering of electrons by the inhomogeneities of the lattice (particularly the inhomogeneities caused by temperature fluctuations). Later these ideas were further explored by Felix Bloch.

Frenkel in 1927 also calculated the theoretical stiffness of metals from its crystalline structure and showed that the stiffness was orders of magnitude greater than that of real metals. He explained this discrepancy by the polycrystal structures of real metals.

One of the major successes of Frenkel during these years was the explanation of the effect of spontaneous magnetization of ferromagnetic materials and the development of the theory of magnetic domain (together with Ya. G. Dorfman).

In 1926 Frenkel introduced the key idea of defects of crystalline structure. He showed that the “evaporation” of atoms (or ions) from their equilibrium states occurred under finite temperature and introduced the idea of moving holes that could propagate through crystals independent of the movement of the atom that left it. These defects are known as *Frenkel defects*. On the base of this idea he calculated the electric conductivity of ion crystal and developed the theory of vibrational-translational movement of molecules in liquids and amorphous bodies, and particularly the theory of diffusion and viscosity of liquids and amorphous bodies.

Soon after Pauli formulated his famous exclusion principle, and Fermi and Dirac developed the Fermi-Dirac statistics, Frenkel introduced and calculated the degeneracy pressure of Fermion gas. He applied this theory to star stability. It was completely a new vocabulary in astronomy at that time.

During these years, Frenkel was also interested in the theory of elementary particles. Many of the ideas he developed at that time had been re-vitalized by later investigators. In 1928 he published the second volume of *Electrodynamics*.

In 1929 Frenkel was elected to be a Corresponding Member of the Academy of Sciences of the USSR, together with Semenov and Kapitsa. They were among the first group of young scientists admitted to the Academy after the Revolution.

In 1930, Frenkel received an invitation from the University of Minnesota to spend a year in the US as a Visiting Professor, again recommended by Ehrenfest. In 1930–31, during his visit to the US, Frenkel developed the theory of light absorption in solid bodies. In these papers he introduced the idea and the term “exciton” for the description of the waves of excitation. The term became so common in modern physics that few people remembered the name of the scientist behind the idea.

Frenkel published in 1932 the first volume of his book *Wave Mechanics*, and the second volume followed in 1934, both by Oxford University Press. An earlier version in German was published in 1929. In these books, one found the first use of the term “tunnel effect,” which today is called quantum tunneling. In between 1932 and 1934, he also published the first part of the book *Statistical Physics*. Other books he published around this time included *Theory of Solid and Liquid Bodies* (1934), *Analytical Mechanics* (1935), and *Courses of Theoretical Mechanics on the Basis of Vector and Tensor Analysis* (1940).

In 1935–36 Frenkel was developing an analogy between the structure of liquids and solids and introduced the idea of “orientational melting,” during which the crystal lost its long-range order in the orientation of molecules, while maintaining its short-range order. This idea formed the physical background for the understanding of the liquid crystal state and its isotropic-nematic phase transition.

Frenkel in 1936 introduced the original theory of fission of atomic nuclei. He proposed to consider the energy of neutron as “heat,” the process of neutron capturing by the nucleus as “absorption,” and finally the emission of secondary neutron, proton or alpha-particle as “evaporation.” These ideas had been used later by many physicists, starting from Niels Bohr, to Landau, Victor Weisskopf, and Hans Bethe.

In 1939, several months ahead of Bohr and John Wheeler, Frenkel proposed the so called “drop model” of the atomic nucleus. He developed the theory of electrocapillary fission, introduced the role of vibrational and “capillary” waves in the nucleus partition, and showed that the stable shape of the nucleus could be ellipsoidal, rather than spherical. For a long time, these ideas formed the background of nuclear physics.

Also in 1939, Frenkel published several papers that had strong influence on the development of molecular and polymer physics. First, he developed the ideas of the theory of heterophase fluctuation near the point of phase transition. He claimed that in each phase the fetuses of the other phases existed due to temperature fluctuations. As Frenkel suggested, one could consider the collection of these fetuses in the major phase as a dilute “solution” of “foreign particles” and could use the general theory of dissociation to calculate their equilibrium concentration. He applied this idea to the quantitative explanation of the anomalous increase in heat capacity and the coefficient of heat expansion of crystals in the neighborhood of melting point. Later, these theories were further developed by Yacov Zeldovich and many other investigators.

In the same year he published a key work (together with S. E. Bresler) devoted to the study of the heat movement and thermodynamics of long molecular chains. He also proposed the first quantitative theory of plastic deformation of solid bodies based on the idea of self-consistent movement of atomic ensembles and obtained the expression for the velocity of deformation. Ten years later the results of Frenkel were replicated from macroscopic point of view by F. C. Frank and J. D. Eshelby.

In the fall of 1941, after the invasion of German troops into Russia, Frenkel and his family were evacuated to Kazan’. In 1941 he developed a theory of relaxation losses related to paramagnetic resonances in solvents and solid bodies. It provided the theoretical foundation for practical applications of paramagnetic resonance in fields such as chemistry, geophysics, medicine, and many others.

During 1942-1943 Frenkel finished one of his best books: *Kinetic Theory of Liquids*. During the years of war (1941-1945), Frenkel published several papers devoted to the theory of liquid viscosity, and developed the statistical theory of brittle destruction of solids and the associated scaling effects.

One of the major developments in physics in those days in Russia was the creation of nuclear weapons. Frenkel was kept out of that development partly because he was a Jew. However, in 1945, he presented to his former student Kurchatov, who headed

the project, an extended memorandum in which he proposed the use of atomic explosion for the initiation of the fusion reaction in deuterium.

Although Frenkel's main scientific interests were in theoretical physics, his intellect would not allow him to miss the problems of other natural sciences. He conducted several significant works in theoretical biophysics. Perhaps the most original and important work in this field was the theory of muscle contraction developed by him in 1938. He applied the theory of polymers and suggested a process similar to resin vulcanization. He proposed that muscle contraction was caused by "ion bridges" formed between ions separated during the chemical reactions following muscle excitation.

In 1939 he authored an Academy of Science special report devoted to the biological effects of ultrasound on living organisms. Particularly, he proposed the use of ultrasound for the destruction of cancer tumors. In 1940 he developed the theory of electrical and optical phenomena related to the cavitation during the propagation of ultrasound waves.

Geophysics was a field of Frenkel's early interest. We already mentioned his work on atmospheric electricity and the first physically consistent theory of Earth's magnetic field generation. Starting in 1944, Frenkel's interest returned to geophysics. He frequently visited the Institute of Theoretical Geophysics in Moscow traveling from Kazan'. In the Institute, he became interested in the work of A. G. Ivanov, who had discovered in 1939 that the propagation of seismic waves in soil was accompanied by the appearance of a potential difference between electrode probes inserted into the ground. Ivanov considered the phenomenon as being caused by the pressure difference between two points in wet soil resulting from the propagation of longitudinal waves.

Frenkel took a different view. He correctly recognized the need to model the wet soil as a two-phase material. He formulated the continuum mechanical theory; and by mathematical analysis set up the characteristic equations. He then stated [1], "*We shall not write down the expressions for its roots and shall only remark that . . . one of them corresponds to waves with a very small damping, and the other—to waves with a very large damping.*" Hence Frenkel discovered the existence of the second compressional wave. However, Frenkel's interest was in the seismoelectric effect; hence he dismissed the mechanical effect as unimportant by stating that "*The waves of the second kind are thus really non-existent*" because it would not propagate to a large distance.

For the electrical effect, Frenkel recognized the presence of electrolytes in liquid, which created electric double layers on the interface of soil particles and the liquid. The second wave, despite its non-propagating nature, allowed the solid and fluid phases to move relative to each other. The relative movement of electrical charges created local electrical currents, whose variation in turn caused the emission of electromagnetic waves. The formulae from this theory were in good agreement with the experimental data; and in particular, it explained the dependence of this effect on soil porosity and the frequency of elastic waves.

Frenkel's 1944 paper "*On the theory of seismic and seismoelectric phenomena in moist soil,*" [1] inspired Maurice Biot, who in 1941 presented the quasi-static theory of poroelasticity [2]. Biot in 1956 published a pair of papers [3, 4] to expand his theory to dynamics. Biot investigated the second-type wave in greater detail. He introduced a

conceptual capillary flow model that accounted for the fluid viscous dissipation at higher frequencies. As a consequence, a characteristic frequency at which the visco-inertial attenuation reached its maximum was predicted. Based on these contributions, the second longitudinal wave, first theoretically predicted by Frenkel in 1944, has been called the *Biot second-type wave* in the western literature. In Russia, however, the poroelasticity theory is generally referred to as the *Biot-Frenkel theory*.

Both the static and the dynamic versions of the poroelasticity theory have been widely applied. Large number of papers have been published in areas of prospecting geophysics, sediment acoustics, architectural acoustics, composite materials, seismicity, soil and rock mechanics, groundwater, land subsidence, petroleum engineering, biomechanics, as well as seismoelectric and seismoelectromagnetic applications.

After the war, Frenkel returned to Leningrad and resumed his teaching and research at the Polytechnic Institute. In 1945, the 220th anniversary of the Academy of Sciences was held, which was also an occasion to celebrate the returning to peace and the reconnection of the Russian scientific community with the international community. Frenkel were able to meet a number of old friends, including F. Joliot-Curie, I. Langmuir, and M. Born. During the sessions Frenkel was honored, along with other scientists, with the Labor Red Banner Order. Two years later, his *Kinetic Theory of Liquids* was awarded the First Grade State Prize.

However, even at that time there existed the first hint of a change in the socialism policy; and the first gust of cold wind reached Frenkel soon after the anniversary. The ensuing political persecution affected not only Frenkel, but also many other prominent scientists. Frenkel's work was criticized for not contributing to the construction of the society of great socialism. His contributions in quantum mechanics and the theory of relativity were labeled as servility to Western science. His publications in the Western journals were unpatriotic. Several of his best books were published in German and English before they became available in Russian. To his accuser, these testified that Frenkel was in a hurry "to help the Americans use the achievements of Soviet Science in the interest of monopolistic capitalism." He was even accused by his colleagues and the director of the Institute that his use of terms like "forced collectivization of electrons" and "collectivization under pressure" was a derision of soviet collective farms. Frenkel's work was greatly affected and his health deteriorated toward the end of his life. He died in 1952, not quite 58 years old.

In 1994, the Physico-Technical Institute of the now St. Petersburg Polytechnic State University, where Frenkel worked from 1921 to 1952, celebrated his centennial. Frenkel's memorial plaque now adorns the wall of the main building of the Institute.

General Reference

Frenkel, V.Ya., *Yakov Ilich Frenkel, His Work, Life and Letters*, Birkhäuser Verlag, 1996.

References

1. Frenkel, J., "On the theory of seismic and seismoelectric phenomena in moist soil," *J. Phys.*, **8**, 230-241, 1944. (Republished in this issue)
2. Biot, M.A., "General theory of three-dimensional consolidation," *J. Appl. Phys.*, **12**, 155-164, 1941.
3. Biot, M.A., "Theory of propagation of elastic waves in a fluid-saturated porous solid, part I: low frequency range," *J. Acoust. Soc. Am.*, **28**, 168-178, 1956a.
4. Biot, M.A., "Theory of propagation of elastic waves in a fluid-saturated porous solid, part II: higher frequency range," *J. Acoust. Soc. Am.*, **28**, 179-191, 1956b.



Yacov Il'ich Frenkel (1894–1952)