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Freedom, collectivism, and quasiparticles: Social metaphors in quantum physics

Fermions are individualists, while bosons are collectivists.[1]

1. FREEDOM AS PROBLEM

WHAT KIND OF freedom do scientists have in mind when they say that an electron or another particle "is free"? The most common model of a system of free particles is an ideal gas, in which atoms are rare and move unfettered, interacting only when they directly collide. Yet some physicists, such as Yakov Frenkel, whose specialty was the quantum theory of matter and whose political views were socialist, observed that in this system, only atoms are free, but electrons are not. They are, on the contrary, enslaved by free atoms. If, however, atoms are packed together closely into a solid body, they lose most of their freedom and become confined to specific loci of a crystal, but in this very same process, electrons gain in freedom as they become liberated from individual atoms.

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The following abbreviations are used: AHQP, Archive for the History of Quantum Physics (Office for History of Science and Technology, University of California, Berkeley); AP, *Annalen der Physik*; BSSP, *The beginnings of solid state physics.* A symposium organized by Sir Nevill Mott, F.R.S. Held 30 Apr-2 May 1979 (London 1980); *FPW* (*Frenkel popular writings*), Ya.I. Frenkel. *Na zare novoi fiziki. Sbornik izbrannykh nauchno-populyarnykh rabot* (Leningrad: Nauka, 1970); *FSW* (*Frenkel selected works*), Ya.I. Frenkel, *Sobranie izbrannykh trudov*, vols. 1-3 (Moscow-Leningrad, 1958-59); OCM, Lillian Hoddeson, Ernest Braun, Jürgen Teichmann, and Spencer Weart, eds., *Out of the crystal maze. Chapters from the history of solid state physics* (Oxford, 1992); *PR*, *Physical review*; *PZSU*, *Physikalische Zeitschrift der Sowjetunion*; *TCW* (*Tamm collected works*), I.E. Tamm. *Sobranie nauchnykh trudov* (2 vols., Moscow, 1975); YIF, Victor Ya. Frenkel. *Yakov Ilich Frenkel. His work, life and letters.* (Basel, 1996); ZhETF, *Zhurnal eksperimental'noi i teoreticheskoi fiziki*; *ZP*, *Zeitschrift für Physik.*

1. M.I. Kaganov, I.M. Lifshits, *Kvazichastitsy,* 2nd. ed. (Moscow, 1989), 14.

Liberated into what state? The answer is not simple. In a metal, electrons transport electric current and, therefore, are apparently free enough to move through the solid body. On the other hand, they are still subject to very strong forces from the atoms of the crystal lattice as well as from other electrons. Some physicists described this complex situation with the help of electrons belonging to their proper atoms and only occasionally switching their allegiances, while others envisioned electrons as almost free, an ideal gas of their own. Frenkel and some similarly minded colleagues felt that neither of these alternative descriptions was close to electrons' real state of freedom, which he referred to with a special word: "collectivist." The idea came from leftist political language and social theory.

Disagreements over the large issue of freedom played a particularly important role during the early formative stages of the quantum physics of the solid, liquid, and plasma states of matter—or condensed matter in the current usage—from the 1920s through the 1950s. At stake was not only the language proper, but the mathematical models and conceptual foundations of an emerging scientific discipline. A variety of specific approaches and theories that existed and competed during that period rested on their authors' conflicting intuitions regarding the freedom of particles. In their attempts to conceptualize these intuitions in physical and mathematical terms, physicists often used social metaphors, implicitly as well as explicitly, consciously as well as unconsciously. These metaphors reflected their varying interpretations—liberal and collectivist, among others—of the general concept of freedom, their political philosophies, and also their personal and often incompatible existential experiences of social life in different countries and regimes.

The present paper studies one line in this debate: the collectivist approach in the early history of condensed matter physics and its corresponding collectivist metaphors.[2] I will follow attempts by socialist-minded physicists to develop methods for the description of the collective behavior of particles, which led them to several new physical models, later united under the general term quasiparticles. As basic objects in virtually all fields of current research on the properties of matter, including some half-dozen Nobel prize-winning works, quasiparticles are familiar to any practicing physicist and, since the 1950s, belong among the most fundamental concepts of physics. Little is known, however, about their historical kinship with collectivism. The relationship dates back to the first half of the century when socialist ideas thrived and when the foundations of the physics of condensed matter were laid. Physicists in the field today much more commonly work for business than for leftist political causes, but they continue speaking collectivist language. Its success is partly related to the fact that its relationship with the by-

2. This approach has not been studied so far in the existing historical literature. For more information on the history of other main approaches, see, in particular, OCM. This paper may be considered an additional chapter for that landmark study.

now largely discredited political movement has become invisible, just like many other legacies of socialism in contemporary life.

"Collectivism," like "freedom," was used and abused so much in political propaganda that it seems necessary to start with clarifications of its meanings. As if in order to remind us that words sometimes have tricky trajectories, "collectivism" as a political term originated with opponents of Marxism. It referred to the theory that the means of production should be owned neither by private individuals nor by the state, but by free associations of laborers. The conflict between Mikhail Bakunin and other proponents of this view with Karl Marx and his followers led to the split of the First International in 1872. The new political movement that formed thereafter accepted collectivism as its program and anarchism as its name. The anarchists were the Marxists' main rivals within the international workers' movement, having strongholds in France, Switzerland, Spain, and Italy. They continued to be a powerful force within the European left until their last important organizations were exterminated in the 1930s, especially during the Spanish Civil War.[3]

Much earlier, however, by 1900 at least, anarchists had lost their monopoly over the term "collectivism." Although they and some others continued to use it in defense of workers' freedom against both private and state property, the word was also appropriated by virtually all socialist factions. Its meaning changed, too, as it began to be used ever more often as a vague synonym for anti-capitalist values, while its critique of étatisme weakened. Socialists accepted collectivism as an alternative to the liberal individualist concept of freedom, noting that the latter often went hand in hand with exploitation and slavery.[4] Collectivism, for them, was the true strategy of liberation for the oppressed and their only way to succeed in the struggle for freedom.

The next major change of meaning occurred owing to collectivization, a violent reform of Soviet agriculture around 1930. Legally, the Soviet kolkhoz was a cooperative of peasants, not a state enterprise, which was a large concession from the point of view of hard-core Marxists. The *kolkhoz* thus had some formal resemblance with the original anarchist program, although it in fact was anything but a free association. The results of collectivization were notoriously disastrous. Among other, more important things, they also damaged the reputation of collectivism, showing that what had been conceived as a liberation concept could also become a method of enslavement. In this, as in a number of other important historical cases, the pursuit of a new type of freedom in the political realm turned into the emergence of a new type of dictatorship. A similar pursuit in the realm of physical models produced a different outcome, leading to the discovery of new kinds of natural objects.

3. On anarchist collectivism see Max Nettlau, *A short history of anarchism* (London, 1996), chapt. 8; George Woodcock, *Anarchism: A history of libertarian ideas and movements* (Cleveland, 1962).
4. On this and other antinomies of freedom see, for example, Zygmunt Bauman, *Freedom* (Minneapolis, 1988).

2. QUASIPARTICLES

New objects started to appear in solid state physics around 1930, when all of the meanings of collectivism discussed above were still in wide circulation. Their current name, quasiparticles, was introduced after World War II. In their early decades, these new objects were most commonly referred to as "collectivized" particles or as "collective excitations." A basic idea indicative of their name may be illustrated by two simple examples. Consider a string of connected atoms, one of which is in an excited state. Since it interacts with neighboring atoms, it can give its energy to one of them; the excitation can thus move from one neighbor to another though the atoms themselves do not move. The excitation's movement along the string can be described mathematically in a fashion very similar to the movement of an ordinary particle, and it received the particle-like name, "exciton." Or consider a crystal lattice with one unoccupied place. If a neighboring atom receives some extra energy, it can jump to the vacancy, leaving behind an empty space into which another atom can move, and so on: the vacancy travels through the lattice like a particle. In this case, actual atoms move, too, but rather than analyzing the behavior of thousands of them, it is much more convenient to describe their collective movement by means of just one, albeit fictional, particle, the "hole."

Besides holes and excitons, there are over a dozen commonly recognized species of quasiparticles, or collective excitations, as well as many other, more specific varieties.[5] Like ordinary particles they carry energy and momentum, possess effective mass and charge, and can scatter, emit, or absorb other particles and quasiparticles. Quantitatively, their behavior can be unusual: some values of energy E can be forbidden, momentum $\mathbf{P}$ is not conserved exactly but can change by a quantum, and the relationship between energy and momentum is often described by a mathematical function more complicated than $E = \mathbf{P}^2/2m$ of the usual mechanics. These features, however, are not considered at all problematic by contemporary physicists, for whom quasiparticles have become familiar and uncontroversial natural objects. They offer an indispensable method of describing processes that involve movements of inconceivably large numbers of particles by means of much more convenient models with relatively few participating constituents. Some physicists have considered quasiparticles, rather than atoms or molecules, as the elementary constituent parts of practically all real bodies in the world surrounding us except rarefied gases and the high vacuum inside particle accelerators and out in interstellar space.

For physicists, the existence of quasiparticles in nature is no less real than the existence of the electron. Indeed, the philosophical criteria of the reality of elec-

5. See updates in the database of *Chemical abstracts service*, under the heading *Quasiparticles and excitations.* URL: http://www.cas.org/vocabulary/18640.html.

trons, for example those formulated by Ian Hacking, equally apply to quasiparticles.[6] They have become so real that some physicists even wonder whether there is a fundamental distinction between quasiparticles and ordinary particles. Those who had thought the matter through concluded that "In all dynamic properties, quasiparticles are just like ordinary particles (although the laws of their movement may be significantly more complicated). However, in contrast to ordinary particles, quasiparticles cannot appear in vacuum; they need a certain medium as the background, because, being elementary units of movement, they are diferent from the elementary building blocks of the medium. This is the main difference between particles and quasiparticles; in all other major characteristics they are the same."[7] In other words, one needs to postulate other particles first in order to construct out of their movements new combinations, or quasiparticles, which are thus explicitly entities of the second ontological order. This solution, however, does not exclude possible doubts about the ontological status of ordinary particles, which may, in the end, also turn out to be artifacts of a medium.

A short version of the history of quasiparticles was told by two physicists driven mainly by the curiosity to find out "who named the -on's" (both quasiparticles and ordinary particles). They did not restrict the inquiry to names, but tried to determine for each particle who was the author of the concept and who invented the name for it. Their findings for quasiparticles are presented in Table 1.[8] Not all of the attributions are beyond doubt, nor is their list of quasiparticles complete, but it gives a useful first approximation to important places and names. All but one name, Bloch, of the pre-1950 names, belong to Soviet physicists. Indeed, the method of collective excitations was developed primarily within the Soviet Union until the late 1950s, when it lost its national specificity and gained worldwide acceptance.

Part I of this study centers on Yakov Frenkel, the pioneer of the entire collectivist approach and the author of the model of collectivized particles, including the hole and the exciton, and Igor Tamm, whose phonon became the paradigm for a different model, collective excitations. The forthcoming Part II will consider contributions by Lev Landau and David Bohm, whose accomplishments and modifications of the collectivist approach were largely responsible for its eventual wide success and recognition. These physicists, three Soviet and one American, had certain things in common. They were all socialists of various kinds, mostly unorthodox, and cared about politics almost as much as about science. All lived through

6. Ian Hacking, *Representing and intervening. Introductory topics in the philosophy of natural sciences* (Cambridge, 1983).

7. I.M. Lifshitz, "Kvazichastitsy v sovremennoi fizike," *Priroda, 5* (1958), 11-20, reprinted in I.M. Lifshitz, *Izbrannye Trudy.* Vol. 2 (Moscow, 1994), 397-407, on 402.

8. Charles T. Walker and Glen A. Slack, "Who named the -On's," *American journal of physics, 38* (1970), 1380-1389; a similar list in M.I. Kaganov and V. Ya. Frenkel, *Vekhi istorii fiziki tverdogo tela* (Moscow, 1981), 28-35, 51-54.

the existential experience of persecution and deprivation, to various degrees, of personal freedom, which left an impact on their thoughts on freedom and the amount of it that could be achieved by people in real life and by particles in real bodies. They believed in collectivism as a political philosophy and introduced collectivist terminology and models into quantum physics.

Table 1. Early quasiparticles and their authors

QUASIPARTICLES	CONCEPT	NAME IN PRINT
Phonon	Tamm, 1930	Frenkel, 1932
Magnon	Bloch, 1930	Pomeranchuk, 1941 Referring to Landau
Exciton	Frenkel, 1931	Frenkel, 1936
Polaron	Landau, 1933	Pekar, 1946
Roton	Landau, 1941	Landau 1941 Referring to Tamm
Plasmon	Bohm and Pines, 1951	Pines, 1956
Polariton	Fano, 1956	Hopfield, 1958

The language of contemporary science includes many phrases and concepts such as "collective excitations," "collective phenomena," "collective coordinates," "collective modes," and "collective oscillations." Their scientific meanings and usage have separated sufficiently from related terms in the political language to receive a separate treatment in some encyclopedic dictionaries.[9] My investigation started with noticing this curious linguistic fact and attempting to find out the historical roots of collectivist ideas in science. It ended up with the conclusion that the development of a new fundamental language in physics and of some of its highly sophisticated mathematical models was enabled by the collectivist conception of freedom. The transfer of metaphors and concepts between scientific and political discourses can thus play an important productive role not only in biological sciences, where it has been studied extensively, particularly in the case of Darwinism, but also in a mathematized hard science like physics.[10]

9. See, for example, "Kollektiv" in *Brockhaus Enzyklopädie*, 19 edn. (24 vols., Mannheim, 1986), *12*, 170.
10. On social metaphors in biology see, for example, Sabine Maasen, Everett Mendelsohn, and Peter Weingart, eds., *Biology as society, society as biology: Metaphors* (Dordrecht, 1995); Robert Young, *Darwin's metaphor: Nature's place in Victorian culture* (Cambridge, 1985); Adrian Desmond, *The politics of evolution. Morphology, medicine, and reform in radical London* (Chicago, 1989); Daniel Todes, "Darwin's Malthusian metaphor and Russian evolutionary thought, 1859-1917," *Isis, 78* (1987), 537-551. On the reverse transfer of metaphors from science into social discourse see Richard Olson, ed. *Science as metaphor: The historical role of scientific theories in forming Western culture* (Belmont, 1971).

3. THE ORIGIN OF THE COLLECTIVIST METAPHOR

Yakov Il'ich Frenkel (1894-1952) grew up in the family of a Jewish revolutionary in the last years of the Russian Empire. His father, Ilia, had been a member of "The People's Will," an underground revolutionary organization that prepared terrorist attacks against leaders of the monarchical regime. After a six-year exile in Siberia, Ilia Frenkel withdrew from active politics and became a small merchant but continued to support illegal revolutionaries.[11] He sympathized with the Socialist Revolutionaries, or SR, a radical non-Marxist political party oriented towards the peasants rather than toward the nascent industrial proletariat. SR envisioned Russia's way to a future socialist society through the *mir*, the traditional communal organization of the Russian village, in which peasant families owned the village land collectively and periodically redistributed plots among themselves. The first national elections after the March 1917 revolution and the fall of the monarchy gave victory to socialist parties in general and to SR in particular, yet the power in the capitals fell to the Marxist Bolshevik party in the November coup. SR's leftist faction formed a coalition with Bolsheviks in the first Soviet government, but revolted later in 1918. Many SR's joined forces with opponents of the Bolshevik regime during the unfolding Civil War.

On the day of the Bolshevik uprising in Petrograd, Frenkel the son was busy there taking his major exam in physics, a formal prerequisite for obtaining the first teaching position at a university. The collapse of the ancien regime allowed local initiative groups to establish dozens of new universities all over Russia. Frenkel was offered a junior position at the first of these post-revolutionary schools, Tauria University in the Crimea, and moved there in early 1918. He shared his father's political values and was critical of the Bolshevik government, but allegiance to the cause of the revolution was more important to him than distinctions among socialists. Although regretting that the revolution came to be headed by Marxists, Frenkel concluded in a letter to his father that it was "late now to struggle with the Bolsheviks; we have to help them diminish the negative results of their policy and enhance the positive ones. On the other hand...I am too far from active politics...and am not at all inclined to exchange my science for it."[12]

In the Crimea, Frenkel combined university teaching with membership in the governing board of the Commissariat of Enlightenment of the local Crimean Soviet.[13] Political power in the south alternated many times during the Civil War. When the Whites made the Crimea their stronghold in summer 1919, Frenkel was jailed for having worked in the Red administration, and only the fact that he was

11. YIF, 1-4.
12. YIF, 20-21.
13. His post, according to one account, was deputy commissar of the enlightenment of the Crimean republic, *FPW*, 8.

an academic, a profession somewhat respected by both sides of the conflict, saved his life. Not knowing yet that he would be so lucky, he tried to comfort his mother: "I am not pining in the least; rather I am occupied with reading Drude and Grave....If one doesn't give oneself up to thoughts about what could be...then it's just like living in clover, like being in a sanitorium. The whole difference is that in a sanitorium there are usually rooms that lock from the inside, and in prison, the cells lock from the outside."[14] The books mentioned here are a textbook on higher algebra by Kiev mathematician Dmitry Grave and the treatise on optics by the German physicist Paul Drude (figure 1).[15]

FIG. 1. Frenkel in the Crimea, shortly after he had been released from jail (self-portrait). Source: V.Ya. Frenkel, Yakov Il'ich Frenkel (Moscow-Leningrad, 1966), 77.

14. Victor Ya. Frenkel, "Yakov Ilich Frenkel: Sketches toward a civic portrait," *HSPS, 27:2* (1997), 197-236, on 204.
15. Paul Drude, *Lehrbuch der Optik* (Leipzig, 1900).

Drude's treatise of 1900 contained his famous electron theory of metals, which rested on the physical assumption that electric current consisted of the movement inside the metal of a gas of free electrons. Drude's model gave a satisfactory quantitative explanation of the ratio between the electrical and thermal conductivity and, in an improved form given by Hendrik Antoon Lorentz a few years later, was the best available pre-quantum theory of metals.[16] Reading Drude's book while sitting behind bars perhaps helped Frenkel to realize that electrons inside lattice cells can hardly be free. (Incidentally, the Russian word for "bars" of a jail and for "lattice" of a crystal is one and the same, *reshetka.*) He verified the idea with a calculation based on the virial theorem, demonstrating that electrons are contained within the body of the crystal by binding stronger than that inside an individual atom. Whether Frenkel developed his model in the Crimea or a couple of years later is hard to document, since he was first able to publish it in 1924, after the Civil War had ended, Russian academic life and publishing had resumed, and Frenkel had returned to Petrograd to work at the newly founded State Physico-Technical Institute.[17]

Frenkel proposed to replace the classical Drude-Lorentz model with a theory based on quantum ideas. Quantum mechanics remained to be formulated; he relied in this first attempt on Bohr's atomic theory, according to which electrons circled around the atomic nucleus on elliptical orbits.[18] In metals, Frenkel calculated, atoms are forced so close to each other that their outermost orbits overlap. Before completing the full ellipse, an electron would come close enough to a neighboring atom to jump over onto an elliptical orbit around another nucleus. In Frenkel's model, the electric current in a metallic body was represented by electrons gliding from one atom to another in a chain, passing from hand to hand like land plots in the Russian village commune. These electrons no longer belonged to individual atoms, as in the gaseous state of matter, but neither did they become absolutely free, as in the ideal gas of the Drude-Lorentz model. Frenkel called their more

16. On the Drude-Lorentz theory see OCM, 27-31; Michael Eckert, "Das 'freie Elektronengas': Vorquantenmechanische Theorien über die elektrischen Eigenschaften der Metalle," Deutsches Museum, *Wissenschaftliches Jahrbuch* (1989), 57-91.
17. J. Frenkel, "Beitrag zur Theorie der Metalle," *ZP*, *29* (1924), 214-240; Ya.I. Frenkel, "Teoriia elektroprovodnosti metallov," *Zhurnal Russkogo Fiziko-Khimicheskogo Obshchestva. Chast' fizicheskaia, 56* (1924), 505-524; *FSW*, *2*, 54-70.
18. Bohr's theory of 1913 managed to arrive in Russia despite the interruption of scientific contacts and literature caused by World War I and the revolutions. Frenkel reviewed it for the journal of the Russian Physico-Chemical Society and used it in his first original paper in 1917. Some scientific journals from Germany arrived in the Crimea during the short period in 1918 when the peninsula was occupied by the German army (*FPW*, 10.) Supplies of foreign scientific literature to Soviet Russia resumed in 1921 and by 1924, when Frenkel was writing his paper, he must have had adequate access to recent journals.

complex state of freedom "collectivist" and he summarized the essence of his model in metaphorical terms borrowed from the language of the revolutionary era: "In this way, valence electrons become 'free' electrons, contributing to the electrical conductivity of metals. It must be noted that they are not free in the real sense of the word. On the contrary, they are bound more strongly to the body of the metal than within isolated atoms. But they have become emancipated from the domination of particular atoms; they no longer belong to individual atoms but to the entire collective formed by these atoms. The quantum character of their motion can only be described, strictly speaking, as 'collectivist'."[19]

The use of metaphors, including far-reaching anthropomorphic ones, characterized Frenkel's scientific creativity. In a student paper on the photoelectric effect in 1913, he described electrons as "emigrating" from the surface of the metal at the same time as he himself, unsure whether the quota on Jewish students would allow him to study at a Russian university, was considering emigration to the U.S.[20] In a letter of 1924 Frenkel referred to "inanimate objects, such as molecules, atoms, and electrons" as "microscopic inhabitants of the animate universe" and praised physics as being "not so much exact science as...a drama or comedy of the life of atoms and electrons."[21] Throughout his career, he developed analogies between phenomena in very distant areas of physics, and not only physics, as long as this helped to make sense of things. Colleagues, especially Landau, were often critical of Frenkel's imaginative visualization, occasional sloppiness in calculations, and promiscuous creation of models, preferring more dry, precise, and consistent work. Some of the critics, however, later acknowledged that, although a number of his metaphors did not survive, others proved to have important value for physics, and praised Frenkel as "a generator of new ideas," even though he often left to others the critical work of checking, perfecting, and justifying them.[22]

19. *FSW*, 57-58. The above is my translation from the Russian version of the paper. In its German version, the same passage reads as: "In solcher Weise werden die Valenzelektronen "freie" Elektronen, welche für die elektrische Leitfähigkeit der Metalle verantwortlich sind. Man muß beachten, daß sie nicht "frei" in eigentlichem Sinne werden. Vielmehr sind sie noch stärker mit dem ganzen Metallkörper verbunden als in isolierten Atomen. Aber sie werden von der Alleinherschaft bestimmter Atome emanzipiert; sie gehören nicht mehr den individuellen Atomen an, sondern dem von diesen gebildeten Kollektiv. Was nun den Quantencharakter ihrer Bewegung anbetrifft, so kann dieser, streng genommen, nur "kollektivistisch" bestimmt werden." J. Frenkel, "Beitrag" (ref. 17), 218-219.
20. YIF, 10, 15.
21. YIF, 66. With these words, Frenkel expressed his admiration for Paul Ehrenfest. However, they say more about his own preferences than about Ehrenfest's style of doing physics.
22. See Tamm's description of Frenkel's controversial style in I.E. Tamm, "Yakov Il'ich Frenkel," *Soviet physics uspekhi, 5* (1962), 173-194, on 174, and A.B. Migdal's belated regret for youthful underestimation of Frenkel, in Ya.I. Frenkel, *Vospominaniia, pis'ma,*

In 1958, the editors of the posthumous edition of Frenkel's selected works acknowledged that his collectivist metaphor of 1924 had found a "profound development in the modern quantum theory of the solid state." They observed further that the "collectivization of valence electrons takes place in all crystals," not only in metals.[23] By that time, collectivist terms in physics had lost their direct political connotations. They had acquired a life of their own in professional parlance, textbooks, reviews, and technical papers. The initial metaphor had undergone, in Sabine Maasen's terms, not only *transfer* from political to scientific discourse, but also *transformation*: it had been furnished in its new setting with language, formalism, and meanings specific to the discipline of physics.[24] This transformation, however, had not been easy or straightforward. Physical models and mathematical apparatus capable of describing the complex collectivist state of freedom were not available at the start, and it took quite some time and effort to develop them.

4. LIBERATED HOLES

In 1926 Frenkel reached from his model of the movement of electrons to the concept of the hole. Even in crystals, atomic ions are not bound absolutely to their positions in the lattice, as appears from diffusion in solids. George von Hevesy had proposed a mechanism for solid diffusion as two (or occasionally more) ions simultaneously exchanging their positions in the lattice (Platzwechsel). In 1923 Abram Joffe put forward a different hypothesis, according to which ions in a crystal enjoyed the greater freedom of occasionally leaving their proper places and wandering within the interatomic space, thus adding an ionic contribution to the total electric current. Frenkel now developed the idea of his Leningrad colleague and institute director one step further, by noting that the "dissociation" of an ion from its proper place would also liberate an "empty space," a vacancy ("ein leerer Platz") in the lattice that would behave like a particle.[25]

Frenkel's liberated empty spaces of 1926 travelled through the lattice in the same way as his collectivist electrons of 1924, by jumping from one atomic posi-

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dokumenty, 2nd ed. (Leningrad, 1986), 216-218. Self-conscious about his use of metaphors, Frenkel drafted a paper in 1931, "The method of analogies in physics," which included such theses as "[g]ood ideas are born in the subconscious sphere, without participation of our will, and come out into consciousness without special effort" and "[a]ll genuinely new theories are more or less irrational," in Zh.I. Alferov and V.Ya. Frenkel, et al., eds., *Voprosy teoreticheskoi fiziki* (St. Petersburg, 1994), 183, 184, 234.

23. *FSW, 2*, 58 and 72.

24. Sabine Maasen, "Who is afraid of metaphors," in Maasen, et al., eds. (ref. 10), 11-35.

25. J. Frenkel, "Über die Wärmebewegung in festen and flüssigen Körpern," *ZP*, 35 (1926), 652-669; *FSW, 2*, 254-268.

tion to a neighboring one, and thus enjoyed a similar freedom. An elementary act in this process can be described either as an ion moving to a nearby vacant place or as a vacancy moving in the opposite direction. Frenkel thus characterized an empty space as a "negative atom," an "ion of the opposite sign." It can travel through the lattice until it meets a liberated wandering ion with which it can recombine into an ion properly fixed in the lattice. In later Russian-language publications he referred to vacancies in the lattice as "*dyrki*" (holes), which by that time was also the Russian term for electron holes, or anti-electrons, of Dirac's famous theory of 1929. The two concepts, one in solid state physics and the other in quantum electrodynamics, have much in common, indeed, and it is also very likely that Dirac had known of Frenkel's holes at least since their conversations on board a steamer in 1928, during the week of the Volga congress of Russian physicists (figure 2).[26]

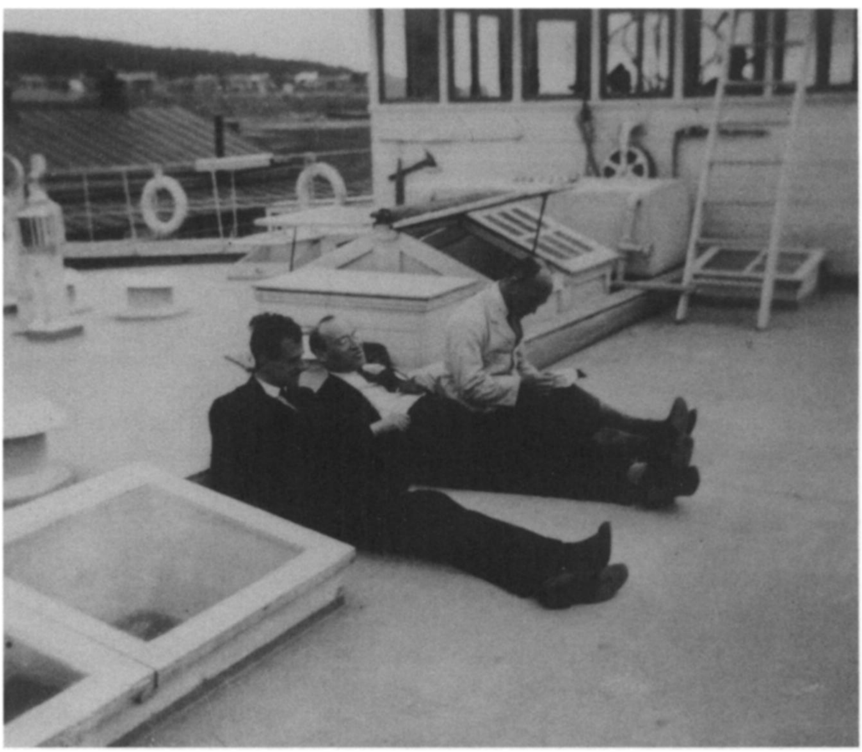

FIG. 2. Frenkel and Dirac on board the steamship, 6th Congress of Russian Physicists, August 1928. Courtesy of the American Institute of Physics/Emilio Segrè Visual Archives.

26. On Dirac's hole theory see D.F. Moyer, "Evaluations of Dirac's electron, 1928-1932," *American journal of physics*, *49* (1981), 1055-1062; Helge Kragh, *Dirac. A scientific biog-*

Having played a heuristic role in the initial development of the idea of holes, the analogy with collectivist movement became less necessary once the concept was in place. Frenkel could operate both with and without the collectivist metaphor when he discussed holes in his multiple papers and books. Dirac was probably unaware of it at all; at least he did not use collectivist terminology in his papers of 1930 on the hole theory, which made the concept widely known, even if not widely accepted, among physicists. Dirac's theory had many opponents, who did not like its postulate of a vacuum filled with an infinite number of negative energy electrons, in which only the vacancies, the holes, were observable. Eventually, the hole model lost its popularity in high energy physics to the mathematically equivalent representation of anti-electrons, or positrons, moving as free particles in empty space. But it became universally recognized in condensed matter physics, where the existence of a medium was obvious.

Although Werner Heisenberg was among the critics of Dirac's approaches to quantum electrodynamics, he appreciated his idea of the electron hole and in 1931 returned the concept to the physics of the solid state. Heisenberg considered holes as vacancies in either electronic shells of an atom or nearly filled electronic bands of a crystal, vacancies that behave like positively charged particles.[27] After Dirac and Heisenberg, the term "hole" has become most commonly, though not exclusively, associated with electronic vacancies. Frenkel's original ionic vacancies, too, have become commonplace in physics, but under a different name. In the 1930s they were incorporated by Friedrich Wilhelm Jost, Carl Wagner, and Walter Schottky into the general theory of defects in solids, in which the pair made of a wandering ion and a vacancy in the lattice is called a "Frenkel defect."[28]

5. THE COLLECTIVIZED ELECTRON AND THE BLOCH ELECTRON

Frenkel's model of electrical conductivity of 1924 offered a solution to the main difficulty of the Drude-Lorentz theory, that of specific heats. Had electrons in metals been free, their thermal motion would have added a significant contribution to the value of specific heat of metals, which was not observed in experiments.[29] Frenkel's electrons passed from one atom to another with velocities much higher than thermal ones and therefore did not have to contribute to specific heats.

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raphy (Cambridge, 1990), 87-105. On his visit to the Soviet Union in 1928, see A.B. Kojevnikov, ed., *Paul Dirac and Igor Tamm. Correspondence, 1928-1933* (Max-Planck-Institut für Physik, Preprint 93-80, 1993).

27. W. Heisenberg, "Zum Paulischen Ausschließungsprinzip." *AP*, *10* (1931), 888-904.

28. Laurie M. Brown, Abraham Pais, and Brian Pippard, eds., *Twentieth century physics* (3 vols., Philadelphia, 1995), *3*, 1528-1529; OCM, 255-264.

29. On this and other problems of the Drude-Lorentz theory see Lillian H. Hoddeson and G. Baym, "The development of the quantum mechanical electron theory of metals: 1900-28," in BSSP, 8-23.

Despite this promising feature, the proposal found little support among physicists. Even Paul Ehrenfest, who was very sympathetic to Frenkel, thought that his paper contained "many clever ideas and a big confusion." Although Arnold Sommerfeld once referred to Frenkel's theory as "well known,"[30] Frenkel himself found exactly the opposite situation when he tried to communicate further developments of his ideas to the cream of the international physics community at the Volta memorial conference held in Como, Italy, in 1927 (figure 3).[31]

FIG. 3. Frenkel talking to Lorentz in Como, probably trying to explain the differences between their theories. Courtesy of the American Institute of Physics/Emilio Segrè Visual Archives.

He started boldly: "In the classical theory of electrical conductivity of metals, the so called 'free' electrons are regarded as particles of gas that move with constant velocities between collisions with positive ions....A few years ago I showed that this conception is totally wrong." After presenting his arguments, Frenkel concluded: "The only type of freedom electrons could obtain under these conditions

30. Ehrenfest to A.F. Joffe, 24 Nov 1924, in *Erenfest-Ioffe, Nauchnaia perepiska* (Leningrad, 1990), 176; A. Sommerfeld, "Zur Elektronentheorie der Metalle," *Die Naturwissenschaften*, *15* (1927), 825-832, on 828.
31. The same congress at which Bohr first presented his complementarity interpretation of quantum theory.

is, so to speak, the freedom to change their master, or the atom to which they belong. While in the gaseous state each electron belongs to its proper atom, in the liquid or solid state it becomes 'the slave of the collective' formed by all atoms, and enjoys a rather relative freedom of constant transition 'from hand to hand,' i.e., from one atom to another."[32]

At the same meeting, Sommerfeld announced a different modification of the Drude-Lorentz theory. He avoided the difficulty of the specific heats by applying to electrons the new quantum statistics of Pauli and Fermi; otherwise, he took over the ideal gas model from the classical theory.[33] Sommerfeld wrote of these electrons as free, even though he admitted that quantum statistics imposed restrictions on them. By banning more than one electron from occupying the same phase cell, it created a relative deficiency of available phase space, thus making electrons "a nation without space," in Sommerfeld's metaphor borrowed from the contemporary ideology of German nationalism.[34] In the following year, Sommerfeld's students and assistants developed and applied his theory to other problems of the solid state. Some of them, however, were troubled by the difficulty about freedom. As Hans Bethe recalled, "Sommerfeld...recognized that Drude's main difficulty, namely the large specific heat of the free electrons, would be eliminated by applying Fermi statistics....However, it was very unsatisfactory that Sommerfeld had to assume completely free electrons. How could the electron be considered as free in the presence of the obviously very strong variations of the potential energy inside the metal? I thought that this was a very major objection against the Sommerfeld theory; Sommerfeld himself seemed to be less concerned. The problem was solved by Felix Bloch in his famous Ph.D. thesis."[35]

32. "Le seul genre de liberté, que les électrons puissent acquérir sous ces conditions—c'est pour ainsi dire la liberté de changer leur maître, c'est à dire l'atome, auquel ils peuvent être censés d'appartenir. Tandis que dans l'état gazeux chaque électron appartient à un atome déterminé, dans l'état solide ou liquide il devient l'esclave du collectif, formé par tous les atomes, juissant de la liberté très relative d'ailleurs de passer incéssamment, 'de main en main' c'est à dire d'un atome à l'autre." J. Frenkel, "Nouveaux développements de la théorie électronique des métaux," in *Atti Congresso Internazionale dei Fisici. Como-Pavia-Roma* (Bologna, 1927) *2*, 65-103, on 66; *FSW, 2*, 71-72.
33. A. Sommerfeld, "Elekronentheorie der Metalle und des Volta-Effektes nach der Fermi'schen Statistik," in *Atti Congresso Internazionale dei Fisici. Como-Pavia-Roma* (Bologna, 1927) *2*, 449-473. See Frenkel's impression of the conference in Ya.I. Frenkel, "Mezhdunarodnyi fizicheskii kongress v pamiat' A.Vol'ty v g. Komo," (1928), repr. in *FPW*, 253-256. His 1928 review and the comparison between his and Sommerfeld's theories was recently translated into English as Ya.I. Frenkel, "Theory of metallic conduction" (1928), *Physics—Uspekhi, 37* (1994), 360-371.
34. "Ein 'Volk ohne Raum.' " A. Sommerfeld, "Zur Elektronentheorie der Metalle," *Die Naturwissenschaften, 16* (1928), 374-381, on 375. On Sommerfeld's theory, see Michael Eckert, "Propaganda in science: Sommerfeld and the spread of the electron theory of metals," *HSPS, 17:2* (1987), 191-233.
35. H.A. Bethe, "Recollections of solid state theory, 1926-1933," BSSP, 49-51. See also R.E. Peierls, "Recollections of early solid state physics," BSSP, 28-38, on 29.

Frenkel and Sommerfeld had initiated the application of quantum ideas to metals, but it was Bloch, in 1928 a student of Heisenberg in Leipzig, who found how to do this consistently, on the basis of the fundamental Schrödinger equation. Bloch's landmark accomplishment explained why electrons can move through the lattice with apparent ease despite the strong internal forces acting on them. The key turned out to be the lattice's periodicity. In the version of his theory of 1927, Frenkel estimated the mean free path of electrons by considering the scattering of corresponding de Broglie waves on an atom. Reasoning once again by analogy (this time with the scattering of light waves), he concluded that in a perfectly periodic crystal electrons would propagate without scattering. Resistance to the current arose only from impurities, defects, and the thermal movement of the lattice ions.[36] Bloch proved this thesis in 1928 by rigorous calculation: "I had gotten the essential idea that a periodic arrangement is not really an obstacle for waves, but it's only the thermal vibrations. Heisenberg was very pleased. I told it to him only in the one-dimensional case, in a very primitive way. And he said, 'That is explained now. Now I understand'."[37]

Sommerfeld's school at first perceived Bloch's approach as "a quantum theoretical analog of Frenkel's theory."[38] This view had some basis, since Bloch's electrons were neither a free ideal gas as in Sommerfeld's model, nor bound to particular atoms as in Heisenberg's theory of ferromagnetism. Bloch distanced himself from both these contrasting alternatives. He referred to his approach as "intermediate," since it took into account at least one kind of strong forces inside the metal: the periodic potential. However, Bloch had no special notion in his vocabulary to characterize this state of intermediate freedom, and he apparently did not accept Frenkel's collectivist terminology and model. The intermediate state was also hard to describe mathematically and Bloch had to resort to rough approximations. He considered two limiting cases: near freedom, with the potential treated as a small perturbation; and tight bonding to a single atom, with the influence of other atoms approximated as small. Although aware that neither of these approximations correspond to reality, he thought that they could be relied upon insofar as they both provided qualitatively similar results.[39]

36. Felix Bloch, "Über die Quantenmechanik der Elektronen in Kristallgittern," *ZP, 52* (1929), 555-600, on 555-556; J. Frenkel (ref. 32). Frenkel followed the development of quantum mechanics at its source while spending the year 1925/6 in Göttingen and Hamburg as a Rockefeller fellow.

37. Felix Bloch, oral history interview conducted by Thomas Kuhn, AHQP (14 May 1964), 21.

38. William Houston reporting to his mentor about Bloch's yet unpublished theory, in Houston to Sommerfeld, AHQP (30 May 1928).

39. Felix Bloch (ref. 36); F. Bloch, "Wellenmechanische Diskussion der Leitungs- und Photoeffekte," *Physikalische Zeitschrift, 32* (1931), 881-886, on 882. Bloch said later, that

Pursuing this approach further, in 1929 Bloch and Rudolph Peierls, another student of Heisenberg, described the strange and counterintuitive (*unanschauliche*) properties of electrons that were neither bound nor free: their momentum **k** was not conserved, but could change by a quantum (*Umklapp* processes), and their kinetic energy E deviated from the usual quadratic function of the momentum (which Peierls used to explain the anomalous Hall effect in metals). Not only were electrons able, in a periodic potential, to jump from one atom to another despite their energies being lower than the potential barrier separating the atoms, but also, as Peierls found further, there were certain regions of higher electron energy above the barrier level within which the electrons, contrary to classical intuitions, were prohibited to move (forbidden bands).[40] Peierls thus formulated his own notion of quantum freedom in a review of the state of the theory in 1932: "The difference between 'free' and 'bound' electrons, which is important in the classical theory and for which it is decisive whether or not the electron's energy suffices to overcome the potential barrier between atoms, is largely erased in quantum mechanics." In his own review, Frenkel welcomed Bloch and Peierls' new achievements from the point of view of his understanding of freedom. To him, they had proved mathematically "that all valence electrons are free with regard to individual atoms...and at the very same time bound with regard to the collective formed by all these atoms."[41]

Meanwhile, in 1929 the word "collectivization" became familiar to everybody in the Soviet Union as the main political slogan of the year of the "Great Break" and of the collectivization campaign in agriculture. While teaching quantum theory, Frenkel presented its unusual concepts in collectivist terms familiar to and popular among his young audience. Students sensed (in their own understanding of collectivism) political connotations of the concept. As one of them, Oskar Todes, recalled: "Frenkel's formulation of the 'collectivization' of free electrons in metals emerged from the events of contemporary political life. It enabled us to remember for our entire lives the main physical ideas about the behavior of these electrons." Todes himself, together with two enthusiastic classmates, organized a student

he "had never understood how anything like free motion could be even approximately true [for electrons in a metal]." F. Bloch, "Memories of electrons in crystals," BSSP, 24-27, on 25.

40. R.E. Peierls, "Zur Theorie der galvanomagnetischen Effekte," *ZP, 53* (1929), 255-266; R.E. Peierls, "Zur Theorie des Hall-effekts," *Physikalische Zeitschrift, 30* (1929), 273-274; R.E. Peierls, "Zur Theorie der elektrischen und thermischen Leitfähigkeit von Metallen," *AP, 4* (1930), 121-148.

41. R.E. Peierls, "Elektronentheorie der Metalle," *Ergebnisse der exakten Naturwissenschaften, 11* (1932), 264-322 , on 265. See also F. Bloch, "Elektronentheorie der Metalle," *Handbuch der Radiologie, 6* (Leipzig 1933),1-226; Ya.I. Frenkel, "Teoriia metallov" (1932), repr. in *FPW*, 174-200, on 182.

kolkhoz for collective work on the curriculum, but the authorities criticized their initiative as a "collective of kulaks," since the three were regarded as the best students in the class.[42]

After several years of use, the notion of "collectivized electrons" was no longer just a figurative metaphor for Frenkel, but the appropriate description of the complex reality within metals and the basis of his understanding of the physics of solids. This conviction led Frenkel in the 1930s into disagreement with further developments in the field, the so-called band theory of solids, and caused his alienation from the mainstream of the solid state community. It also motivated his search for alternative approaches. The one that he eventually found, the exciton, had profited from an earlier proposal of the elastic quantum, or phonon, suggested in 1930 by Frenkel's Moscow colleague, Igor Tamm.

6. THE PHONON AND QUANTUM INDIVIDUALITY

The son of a railroad engineer, Igor Evgen'evich Tamm (1895-1971) was accustomed to moving. Born in Vladivostok in the Far East of the Empire, he grew up in Elizavetgrad, a provincial town in the Ukraine. Like many gymnasium students of the pre-revolutionary decade, Tamm was fond of reading forbidden political literature, which developed for him into a serious interest in politics. He became involved in a Marxist study circle and participated in workers' demonstrations and illegal meetings, which made his parents worry. Trying to distract the boy from politics, they convinced him to go abroad, to a university in quiet Edinburgh rather than politically active London.[43]

Having spent an uneventful year in Edinburgh, Tamm was getting bored when the outbreak of the World War I prevented him from continuing his studies abroad. He transferred to Moscow University, where his academic interests shifted from mathematics and chemistry to physics despite the poor level of physics teaching in Moscow at the time. At twenty, Tamm still hoped and feared that he might live the life of a revolutionary, regarding a possible career in science as philistinism. In 1915 he joined the Social-Democratic Workers Party as a member of its Menshevik faction. During the subsequent years of wars and revolutions, Tamm alternated between Elizavetgrad and Moscow, Kiev and Odessa, between pursuing his academic studies and participating in the turbulent political life, living under alternating political regimes. After the collapse of the monarchy in the capitals in the

42. On O.M. Todes recalling his student years in Leningrad in 1929 in *Ya.I. Frenkel. Vospominaniia, pis'ma, dokumenty,* 2nd ed. (Leningrad, 1986), 94.
43. Tamm's diary specifically mentions his reading of a brochure on "Collectivism" by Jules Guesde, French socialist and one of the founders of the socialist party. See L.Vernskii, "V kabinete i vne ego (Iz razgovorov s dedom i iz semeinogo arkhiva)," in *Vospominaniia o Tamme* (Moscow, 1995), 79-129, on 99-100.

spring of 1917, Tamm turned political agitator and left Moscow for Elizavetgrad to help make the revolution there. In April he was elected a member of the city Soviet and in June represented his home town at the First All-Russian Congress of Soviets in Petrograd. A leftist among Mensheviks, he shared the Bolsheviks' uncompromising opposition to the imperialist war and voted with them on this crucial issue against the new offensive on the front.[44]

Unlike the easy overnight coup in Petrograd, the Soviet takeover of power in Moscow in November 1917 took a week of heavy fighting. Although Tamm, caught in the crossfire, despised the Bolsheviks' "fanaticism," he was not too far from them politically and initially entertained some hopes for a cooperation between leftist Mensheviks and the new regime. With the start of the Civil War in the summer of 1918, however, the Bolsheviks declared all other political parties illegal. By that time Tamm was already concentrating more on his academic studies. He did not fight in the war, although his sympathies were definitely on the Red side, and he managed to graduate in the fall.[45] He spent 1919/20 as an assistant at Tauria University in the Crimea, where his life-long friendship with Frenkel began. Like Frenkel, Tamm experienced arrest and the menace of execution at least once, in summer 1920, when he tried to pass secretly across the front between the Whites and the Reds, from the Crimea to his fiancée in Elizavetgrad. Caught by the Reds with no documents, Tamm was ordered shot as a White spy and escaped death only by proving his identity as a mathematician. To check this, the Red commander, who also happened to be a former mathematics student, demanded that Tamm derive the Taylor series.[46]

In 1922 Tamm returned to Moscow and soon began teaching as a lecturer at Moscow State University. A number of his best friends and former colleagues-in-arms joined the Bolshevik party, but Tamm remained formally unaffiliated. His disagreements with communists were philosophical rather than political: instead of believing in dialectical materialism, Tamm followed Mach and the positivists. He was the first Moscow theoretician to use the new quantum mechanics once it appeared in 1925. Paul Ehrenfest noticed him and invited him to Leyden in early 1928, where Tamm met Paul Dirac, the British genius and one of the leaders of the young quantum generation. Although reputedly unsociable, Dirac developed a close friendship with Tamm, Frenkel, and a few other Soviet physicists. This friendship and Dirac's leftist sympathies made him interested in the Soviet experiment. Almost every year between 1928 and 1936, altogether seven times, Dirac visited the

44. Ibid., 103-105.
45. "I.E. Tamm v dnevnikakh i pis'makh," *Priroda, 7* (1995), 134-160, on 143-145; see also E.L. Feinberg, "Rodoslovnaia rossiiskogo intelligenta," ibid., 12-22.
46. The following detail may give verisimilitude to the story: Tamm confessed that, having struggled all night, he failed to reproduce the full derivation, whereupon the Red leader also admitted that he had forgotten most of his college math and postponed the execution. Vernskii (ref. 43), 105-108.

FIG. 4. P.A.M. Dirac, O.N. Trapeznikova, I.E. Tamm, I.V. Obreimov (left to right), Leyden, Spring 1928. Courtesy of the American Institute of Physics/Emilio Segrè Visual Archives.

Soviet Union. For Tamm, he became the main authority in physics, alongside Leonid Isaakovich Mandelstam, Tamm's mentor and revered colleague at Moscow State University.[47]

Both Mandelstam's and Dirac's influences are evident in the paper of 1930 in which Tamm introduced a new hypothetical particle, later named the phonon. Tamm was following up a discovery by Mandelstam and Grigorii Landsberg, who in early 1928 had observed a new effect while studying the scattering of light in quartz. They found two distinctive additional frequencies in the scattered light, one higher and one lower than the frequency of the incoming light, which they called "molecular" or "combinational" scattering and interpreted as a combination of the original electromagnetic oscillation with the elastic oscillations of the solid body.[48] Tamm complemented Mandelstam and Landsberg's semi-classical explanation with a strict theory based on Dirac's form of quantum mechanics.

47. On Dirac's contacts with Soviet physicists see B.V. Medvedev and A.B. Kozhevnikov, eds., *Pol' Dirak i fizika XX veka* (Moscow, 1990); On Mandelstam: *Akademik L.I. Mandel'shtam (k 100-letiiu so dnia rozhdeniia)* (Moscow, 1979).
48. At about the same time, the effect was observed in liquids by Chandrasekhara V. Raman and Kariamanikkam S. Krishnan in Calcutta and is currently known as the Raman effect. On that history, see I.L. Fabelinskii, "The discovery of combinatorial scattering of light (the

Since the Moscow team understood that the new effect could not be caused by scattering by independent atoms, Tamm considered the solid body "as a whole," as a system bound together by strong interactions between the atoms. Elastic vibrations of these atoms had already been treated in the earlier quantum theories of Einstein, Debye, Born, and von Karman, in which quantization of the energy of vibrations helped to explain the specific heats of solids. Dirac developed more advanced methods of wave quantization in his quantum theory of radiation of 1927. Tamm used these methods in 1930 to describe electromagnetic radiation in his theory and also extended the same methods of quantum electrodynamics to the treatment of the solid state, for the quantization of elastic waves in the crystal. For the physical interpretation of quantized electromagnetic waves, Dirac relied on the corpuscular model of light quanta, or photons. In addition to them, Tamm introduced analogous "elastic quanta," particles corresponding to quantized elastic waves, with their own momentum, direction of propagation, and energy. He thus interpreted the change of light frequency during scattering in the solid as the process of absorption or emission of one particle by another, of an elastic quantum by a quantum of light.[49]

Unlike Frenkel, Tamm avoided using metaphors in his published papers. The analogy with the photon alone was sufficient for him to justify the idea of the elastic quantum in print. Yet the proposal had an additional value-laden meaning related to Tamm's attitude toward Bose-Einstein statistics. In 1926, Tamm had discussed physical interpretations of the new quantum statistics, according to which particles appeared as indistinguishable. In his view, this lack of individuality left two possible choices: either to admit that individuality is fundamentally lost on the microscopic quantum level, or to save individuality by postulating a physical cause, as Einstein had hinted, in an unknown interaction between particles. Tamm expressed his hope that indistinguishability would be found to be only a formally valid, phenomenological description of what at a deeper level of reality would be an ensemble of distinguishable but interacting particles. Having to choose between free particles without individuality and particles with individuality but without absolute freedom, he preferred the latter.[50] The issue of maintaining individuality in a collective with strong interaction had been one of the main principles of Menshevism as political movement. The split of the Russian Social-Democratic

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Raman effect)," *Soviet physics uspekhi, 21* (1978), 780-797; Laurie M. Brown, et al. (ref. 28), *2*, 996-997; G. Venkataraman, *Raman and his effect* (London, 1995).

49. Ig. Tamm, "Über die Quantentheorie der molekularen Lichtzerstreuung in festen Körpern," *ZP*, *60* (1930), 345-363, on 345.

50. I. Tamm, "Novye printsipy statisticheskoi mekhaniki Bose-Einshteina v sviazi s voprosom o fizicheskoi prirode materii," *Uspekhi fizicheskikh nauk, 6* (1926), 112-141; TCW, *2*, 254-286. See also I.E. Tamm, "Elektronnaia teoriia metallov," in *Fizika* 1 (Moscow-Leningrad, 1928), 62-77.

Workers Party in 1903 into Menshevik and Bolshevik factions, which would have so many tragic consequences, occurred on exactly this line. The Bolsheviks insisted on the clause in the party statutes that established strict discipline and subordination of individual members to their party organizations, while the Mensheviks defended a more liberal clause with more room for individual rights and choices.

By 1930 developments in quantum theory definitely favored the conception of photons as free but fundamentally indistinguishable particles. Yet Tamm's proposal of elastic quanta offered a possibility to save individuality. Mathematically they were exactly like photons, an ideal Bose gas of particles, whose number was not conserved, but behind the phenomenology of free, indistinguishable elastic quanta was the reality of strongly connected and collectively oscillating atoms with individuality but without much freedom. Frenkel welcomed the new particles in a paper of 1931, calling them "sound quanta" and "heat quanta,"[51] and in his textbook on wave mechanics of 1932, where he suggested the name "phonon," which became the standard term. He, too, interpreted phonons phenomenologically: they were for him fictive particles, whose very usefulness cast doubt on the physical reality of their close prototype, photons.[52] In his philosophy of physics, Frenkel inclined towards positivism even more strongly than Tamm, and he dared to criticize dialectical materialism openly at a conference in 1931, when it was not safe politically to do so. This public act would not be forgotten by Soviet philosophers and made Frenkel a frequent target of their criticism, which grew especially militant in the late 1940s. Among other charges, attackers cited Frenkel's use of phonons as "fictive particles" instead of "real" sound waves as the proof of his positivistic heresy.[53]

Phonons could be interpreted from many perspectives, which no doubt helped them gain a wide and quick acceptance. If for Tamm and Frenkel they were a phenomenological description of the collective of strongly interacting atoms, for Peierls, who used them in a paper of 1932 under the name *Schallquanta*, they were

51. J. Frenkel, "On the transformation of light into heat in solids. II," *PR, 37* (1931), 1276-1294, on 1289.

52. "It is not in the least intended to convey hereby the impression that such phonons have a real existence. On the contrary, the possibility of their introduction serves to discredit the belief in the real existence of photons." J. Frenkel, *Wave mechanics. Elementary theory* (Oxford, 1932), 267-268; "Phonon" simultaneously appeared in J. Frenkel, "On the elementary derivation of some relations in the electron theory of metals," *PZSU, 2* (1932), 247-253.

53. Positivism, and Mach in particular, was popular not only among non-Marxist Russian socialists (Aleksandr Shreider. *Ocherki filosofii narodnichestva* (Berlin, 1921)), but also among Mensheviks and some less orthodox Bolsheviks, which was why Lenin attacked this philosophy in his *Materialism and empiriocriticism* (1909). On accusations against Frenkel, in particular by the Marxist philosopher Mikhail Omel'ianovsky, see A.S. Sonin, *Fizicheskii idealizm. Istoriia odnoi ideologicheskoi kampanii* (Moscow, 1994), 139. On Frenkel's critique of dialectical materialism, see YIF, 225-227.

merely synonyms for quantized sound waves and, as such, not conceptual novelties. These nuances did not make a serious difference for the mathematical formalism: the formulas were all equivalent and could be easily and fully translated into one another. They did make a difference, however, for the generalization of the concept of the phonon into a broader model of "collective excitations."

Tamm did not publish further on phonons. Having done important work on the solid state in the early 1930s, he returned to quantum electrodynamics, nuclear physics, and particle physics, the fields that interested him the most. He participated in the further development of the concept of quasiparticles mostly indirectly, as a discussant at conferences and seminars, as the mentor of younger students, and through his theoretical colloquium at the Physical Institute of the Academy of Sciences. But other physicists who shared his interpretation of phonons transformed it into a much more general hypothesis: that not only for oscillations of atoms in solid body, but for any kind of collective system with strongly interacting particles, there should exist a phenomenological description in the form of an ideal gas of fictive particles, "collective" or "elementary" excitations. Led by this assumption, these physicists tried to describe strange properties of dense bodies by postulating new kinds of particles that resembled phonons, but possessed novel and strange properties and did not necessarily have well defined classical analogs. As a general strategy, this way of dealing with condensed matter would be advocated and pursued with tremendous success by another Moscow group, Lev Landau and his students, starting in the late 1930s.[54] In a more rudimentary form, a similar generalization of Tamm's elastic quantum helped Frenkel in 1931 to introduce a new hypothetical particle, the 'excitation quantum,' or exciton.

7. SHARED EXCITATION

Frenkel spent the academic year 1930/1 as a visiting professor at the University of Minnesota and anxiously followed political developments at home. Newspapers and letters delivered mixed news: the disappearance of food from the stores and the introduction of rationing, propagandistic accounts about class war and the collectivization campaign in the countryside, and promises of a bright future. In his letters back home Frenkel mentioned the contradictions of the Soviet life—its idealism and cruelty, great successes of industrialization and agriculture and the lack of most basic goods—while approving wholeheartedly the Soviet system in general and, with some reservation, the collectivization of agriculture.[55]

In his major paper written during that year, Frenkel considered another kind of excitation of a solid body: not the displacement of an atom from its equilibrium position that leads to elastic oscillations, but the absorption of a light quantum by

54. See the forthcoming Part II of this study.
55. V.Ya. Frenkel, *Yakov Il'ich Frenkel* (Moscow-Leningrad, 1966), esp. 251.

FIG. 5. Frenkel in Minneapolis, Spring 1931. Courtesy of the American Institute of Physics/Emilio Segrè Visual Archives.

an atom that puts the atom (actually, one of its electrons) into an excited state. In the former case, oscillation of one of the atoms does not remain localized, but spreads across the whole solid in the form of sound waves (classical physics) or phonons (quantum physics), whereby all atoms participate in the collective movement. The same thing, according to Frenkel, must also occur with the excitation of an atom by a light quantum. In a gas, such an excitation remains the property of an excited atom until it either reemits a light quantum, or collides with another atom and transforms the energy of excitation into kinetic energy. But in the solid body, owing to interactions between the atoms, the excitation would not remain localized on one atom, but should be shared by the entire collective. In order to describe this sharing mathematically, Frenkel constructed a wave function for an excited crystal as a superposition of wave functions corresponding to excitations localized at different atoms, and found the stationary states of such a system in the form of "excitation waves." Unlike Tamm's elastic quanta, these did not come about as a result of the quantization of a classical wave: although their classical analog could be found post-hoc, it did not provide so direct a basis for reasoning as sound waves did for phonons.[56]

Frenkel introduced a new particle corresponding to excitation waves, which he called the "excitation quantum," making explicit the analogy with Tamm's "elastic quantum" and describing its important role as the intermediary in the process of the absorption of light by solids and its further transformation into heat. The direct process would have required a simultaneous transformation of a light quantum into hundreds of elastic quanta (because the energy of a photon is typically a hundred times larger than the energy of a phonon), and, according to quantum mechanics, would have had a very low probability of occurrence. The process can take place much more easily through an intermediate excited state, "visualized from the corpuscular point of view as the transformation of the incident light quantum into an excitation quantum having the same energy and momentum," which would then live for some time in the body and gradually dissipate its energy into the energy of elastic quanta, or heat. If realized in nature, Frenkel's excitation quantum or exciton would imply the existence of narrow lines in the absorption spectra of solids.[57]

Experimental physicists had not yet seen these narrow bands. Although Frenkel could point to some experimental data that indirectly supported his proposal, the excitation quantum remained a purely hypothetical entity. Theorists made the first attack on it. While in Minneapolis, Frenkel learned from his wife, Sarra (and she apparently from Peierls, Pauli's assistant, who had come to Leningrad in spring 1931 to marry his fiancée), that Pauli had rejected the excitation quantum in his usual gentle way—"You mention that my long paper in *Phys. Rev.* was severely

56. J. Frenkel, "On the transformation of light into heat in solids. I," *PR*, 37 (1931), 17-44.
57. J. Frenkel (ref. 51), 1284-1285.

criticized in Zurich and they decreed it to be wrong. I believe that this opinion is undoubtedly incorrect—not only on the basis of my own discussion with American theoreticians, but also according to my personal conviction. The fact that Pauli considers my work *Falsch* proves only, in my opinion, that it is not *Trivial*," replied Frenkel.[58]

In Peierls' alternative version of the theory of light absorption in solids, he accepted parts of Frenkel's theory, including phonons and the intermediate excited state of the crystal. He objected, however, to the idea that the excitation would be distributed evenly over the whole crystal, arguing instead that it should be localized in a small area. Mathematically, Peierls managed to treat only the case of such an excitation bound to a particular atom.[59] Until early 1950s, when exciton spectra were observed, Frenkel's proposal found very few supporters. The main problem that hindered its acceptance, however, was not the criticism by Pauli and Peierls, but its perceived incompatibility and rivalry with the emerging mainstream approach in solid state theory, the band theory of free electrons.

8. ELECTRONS FREE AND TRAPPED

In 1931 Alan H. Wilson arrived from Cambridge to study with Heisenberg in Leipzig and tried to make sense of Bloch's far from transparent papers on the theory of metals. Having interpreted them in his way, Wilson extended Bloch's methods from metals to insulators and semiconductors, and explained why these substances differ. For Bloch (and also for Frenkel) the difference had been merely quantitative, electrons in insulators being more tightly bound to their respective atoms than electrons in metals. Wilson, however, understood how to prevent electrons from conducting current without binding them to atoms. If the number of electrons in the body just suffices to fill completely some of the allowed bands in the energy spectrum, these filled bands form "closed shells" of zero net current, with equal numbers of electrons moving in opposite directions. The energy gap between the highest filled band and the next available empty band make the crystal an insulator: only a sufficiently strong excitation or force can make an electron jump across the gap to the empty band of higher energy and thus become a conduction !ectron. In metals, by contrast, one of the allowed energy bands is only

58. Frenkel to his wife, 1 Apr 1931, quoted in B.P. Zakharchenya and V.Ya. Frenkel, "History of the theoretical prediction and experimental discovery of the exciton," *Physics of the solid state, 36* (1994), 469-474, on 470; Pauli to Peierls, 1 Jul 1931, in Wolfgang Pauli, *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a.*, vol. 2, ed. Karl von Meyenn (Berlin, 1985), 89.

59. R. Peierls, "Zur Theorie der Absorptionsspektren fester Körper (Züricher Habilitationsschrift)," *AP, 13* (1932), 905-952, on 916 and 942; R. Peierls, "Über die Absorptionsspektren fester Körper," *PZSU, 1* (1932), 297-298.

partially filled, and its electrons have room to accelerate easily even in a weak electric field.[60]

Heisenberg quickly combined Wilson's concept of filled bands with Dirac's idea of electron holes into a new interpretation of the anomalous Hall effect. Peierls had explained the effect by an unusual relationship between energy and momentum for electrons in the tight-binding approximation, a relationship equivalent to a negative "effective mass." Heisenberg pointed out that the same mathematical formulas could be easily reinterpreted as referring to vacancies in nearly filled Wilson bands, which behave like normal particles but with opposite electric charge, just like Dirac's holes. Bloch suggested further that this combination can also explain the photoelectric current in insulators: the absorption of a light quantum by an electron allows the latter to jump across the gap of forbidden energies. A pair is generated in the process: a conduction electron in the formerly empty band and a hole in the formerly filled one, both of which contribute to the resulting current.[61]

Wilson drew even more profound lessons from his accomplishment. The generalization of the Bloch method allowed him to generalize the notion of quantum freedom, too. According to Wilson, the classical theory confused electrons' freedom with their ability to carry electric current. But in the quantum theory, where all electrons are described as traveling waves in a perfectly periodic lattice, "we cannot assume, as we do in the classical theory, that only valence [conduction] electrons are free." "[A]ll the electrons in a metal are free," as they are also in semiconductors and insulators, regardless of whether or not they transport electric charge.[62] This interpretation constituted an important departure from the attempts by the Weimar physicists of the Heisenberg school to comprehend the unclear situation of a state that was neither bound nor free. Wilson's view that the periodicity of the lattice makes all electrons free in all crystals, whether metals or insulators, was further extended and developed after 1933 into the band theory of solids.

Band theory assumed that abrupt, strong, and very complex forces acting upon an electron in a crystal from all the atoms and other electrons could be accounted for, summarily, by a smooth periodic potential, the effective or self-consistent field, through which the electron could move as a nearly free particle. That this not very realistic model, sometimes called "electrons in a jellium,"[63] could deliver results

60. OCM, 119-123.

61. W. Heisenberg, "Zum Paulischen Ausschließungsprinzip" *AP, 10* (1931), 888-904; F. Bloch, "Wellenmechanische Diskussion der Leitungs- und Photoeffekte," *Physikalische Zeitschrift, 32* (1931), 881-886.

62. A.H. Wilson, "The theory of electronic semi-conductors," Royal Society of London, *Proceedings, A133* (1931), 458-491, on 458-459; *A134* (1932), 277-287.

63. J.M. Ziman, *Electrons in metals. A short guide to the Fermi surface* (London, 1963), 20. On the development of the band theory see OCM, 182-202.

close to the experimental characteristics of real substances was demonstrated by Eugene P. Wigner and Frederick Seitz in 1933 in their prototypical calculation of sodium metal, which became the model for many subsequent studies.[64] Mathematical sophistication and the liberty to choose whichever form of the effective potential worked best allowed band theorists to reproduce the properties of many real materials. The main results of Bloch and Peierls were also reinterpreted and incorporated into the band theory: the Bloch electrons in the loose-binding approximation were accepted as they were, while electrons in the tight-binding approximation were replaced by nearly free holes.

The rise of the band theory coincided chronologically with the geographical transition of the center of the solid state community from Germany. It was developed primarily in the universities of Britain and the United States, with a particularly visible role played by refugees who had fled to free countries from Central European dictatorships. The fact that they were also eager to see electrons in solids as free is a suggestive coincidence that might be worthy of a separate investigation. In the Soviet Union, the reaction to the band theory was ambivalent.

An early report of Wilson's achievement was brought to Leningrad by Ralph H. Fowler from Cambridge in September 1932. He presented it to a conference on the physics of metals together with the new lesson about freedom: "If we discuss quantum mechanically the motion of an electron in a perfect lattice we are forced to conclude that all the electrons in all the atoms are free to move through the lattice—are 'free electrons' in the classical sense—except in so far as they are prevented from moving by Pauli's exclusion principle."[65] The audience included most of the young Soviet quantum theorists who worked on the solid state: Frenkel and Tamm, and D.I. Blokhintsev, M.P. Bronstein, V.A. Fock, L.D. Landau, S.P. Shubin, S.V. Vonsovsky, and a few others. They listened politely to the foreign luminary but deep in their bones they disagreed with Fowler's thesis.

Their community was not coherent, but split on a variety of scientific, political, and personal issues. Only a very few, Frenkel and some of his students, were already using collectivist language and developing corresponding models of solids. Most Soviet physicists initially accepted at least parts of the band theory, albeit with significant reservations. Their varying social experiences had already taught them that not all public declarations of freedom should be taken at face value. As far as electrons in solids were concerned, Soviet theorists knew that the adjective "free" could not be applied there in its true meaning. This attitude was the common denominator of their various approaches and reactions to band theory. Even those who used the models of free or nearly free electrons rarely failed to add a

64. E. Wigner and F. Seitz, "On the constitution of metallic sodium," *PR, 43* (1933), 804-810; *PR, 46* (1934), 509-524.

65. R.H. Fowler, "Report on the theory of semiconductors," *PZSU, 2* (1932), 507-528, on 508; R.G. Fauler, "Teoriia poluprovodnikov," *ZhETF, 3* (1933), 1-15, on 2.

reservation or remark about their basic assumption's limited validity. When referring to the Bloch electron, Frenkel used "free" and "collectivized" interchangeably, the former as a conventional term, the latter as a description of the actual state of affairs. Other Soviet physicists tended either to put "free" in quotation marks or to replace it with other words, such as "conduction," depending on the context.

Their shared intuition about the electron's freedom can be seen in a confused polemic between Tamm and Frenkel in 1931. Frenkel, then in Minneapolis, attacked a new theory of the photoelectric effect in metals by Tamm and his student, Semion Shubin, for allegedly "introducing...the notion of free electrons of two types, completely free 'Sommerfeld electrons' and partially bound 'Bloch electrons,'" which he found incompatible with "the fact that Sommerfeld's 'completely free' electrons simply do not exist and are but an approximation to the more real 'relatively bound' electrons of Bloch." Tamm replied that Frenkel had misunderstood their work. For him, too, Sommerfeld's model was only a rough approximation of restricted applicability, and conductivity electrons were not absolutely free. Indeed, Tamm and Shubin opened their paper with a reference to the "well known fact that the photoelectric effect cannot take place with free electrons in free space," and on this basis criticized as inconsistent an earlier theory by Sommerfeld's student Gregor Wentzel. Frenkel's admission of his mistake ended the confusion.[66]

The sensitivity of Soviet theorists to the limited applicability of band theory's basic assumption motivated them to explore specifically the limits of the formalism. Rather than following the mainstream approach of the theory of free electrons, they studied boundary situations and cases in which electrons become bound or trapped, and from this came their arguably most important contributions to the electron theory of metals during the 1930s. The theory by Tamm and Shubin of 1931 took into consideration two types of binding acting upon the electron in metal—the potential barrier at the surface of the body and the periodic potential inside it—which allowed them to distinguish and describe two different mechanisms for the photoelectric effect. In another paper of the same year, Tamm showed how these two potentials combined can produce new bound states of electrons in a metal. He studied the behavior of Bloch's electrons in a periodic lattice limited (on one side) by the body's surface. Tamm's calculation showed that adding the surface potential allowed the electrons to occupy some of the formerly forbidden energy levels, but these new levels correspond to bound states of electrons trapped near the surface and capable of moving only along the surface. His prediction remained unconfirmed for several decades, until Tamm's levels, as they are currently known in the physics of surface phenomena, were finally observed.[67]

66. Ig. Tamm and S. Schubin, "Zur Theorie des Photoeffektes an Metallen," *ZP*, *68* (1931), 97-113; J. Frenkel, "Some remarks on the theory of the photoelectric effect," *PR*, *38* (1931), 309-320, on 315, 317; Ig. Tamm, "Some remarks on the theory of photoelectric effect in metals," *PR*, *39* (1932), 170-172.

67. Ig. Tamm, "Über eine mögliche Art der Elektronenbindung an Kristalloberflächen,"

9. ARRESTED ELECTRONS AND THE POLARON

A different possibility for the trapping of an electron in a crystal lattice was suggested by Lev Landau in 1933. Landau accepted Wilson's notion of electron bands and considered it to be a mathematically proven theorem that all electrons in a strictly periodic lattice should be able to move without resistance. This, however, did not allow him to declare electrons in solids free, and he consistently refused to use this term in his work. In the 1930s, Landau's favorite approach to electrons in solids was statistical. He described an ensemble of electrons by means of a kinetic equation, always abstained from relating an electron's energy and momentum by the free-particle formula $E=\mathbf{p}^2/2m$, and strictly forbade his students to use this common assumption.[68] At the same time, Landau was also very critical of, and occasionally openly hostile to, many ideas of Frenkel, his former teacher. He disagreed, among other things, with the hypothesis of the excitation quantum and proposed a different excitation scenario instead. Already the part of band theory that Landau accepted enabled him to conclude that a small excitation or deformation of the lattice at some point leads to scattering, but "does not mean yet the electron is trapped at this point." Exploring further the limits of the theory, he suggested that trapping may occur if the deformation is large and distorts the periodicity of the lattice. Landau proposed some materials in which such a trapping of an electron near the distorted area might be observed, and estimated that the formation of these bound states would require an activation energy.[69]

Frenkel replied to Landau's implicit criticism by adding this new scenario to his picture of solids and developing it further. In a paper presented at a conference in Kiev in 1935, he pointed out that trapping can occur even without an activation energy, spontaneously, in the deformation of the lattice caused by the electron itself. He insisted, however, that this combination of an electron with a "trapping" of the lattice disturbance would not remain fixed but could move through the crystal, though much more slowly than a "free" electron. The possible states of an electron in a solid thus included a wide spectrum of complicated situations, from collectivized "free" particles to slowly moving "trapped" ones, but Frenkel consistently avoided the two poles: that of electrons bound to individual atoms and localized in fixed places, and that of electrons free like atoms of an ideal gas.[70]

PZSU, 1 (1932), 733-746; *ZP, 76* (1932), 849-850; I. Tamm, "O vozmozhnoi sviazi elektronov na poverkhnostiakh kristalla," *ZhETF, 3* (1933), 34-35. L.V. Keldysh, "Tammovskie sostoianiia i fizika poverkhnosti tverdogo tela," *Priroda*, 9 (1985), 17-33; B.A. Volkov, "Tammovskie sostoianiia pod tunnel'nym mikroskopom," *Priroda, 7* (1995), 45-47.

68. Oral history interviews with A.I. Akhiezer and M.I. Kaganov.

69. L. Landau, "Über die Bewegung der Elektronen im Kristallgitter," *PZSU, 3* (1933), 664-65; repr. in *Collected papers of L.D. Landau* (Oxford, 1965), 67-68.

70. J. Frenkel, "On the absorption of light and the trapping of electrons and positive holes in crystalline dielectrics," *PZSU, 9* (1936), 158-186; Ya.I. Frenkel, "O pogloshchenii sveta

Several years later, in his book *Kinetic theory of liquids*, Frenkel metaphorically described a trapped electron or electronic hole as "visiting" a lattice cell and "becoming 'self-arrested' during its movement through the atom." The shocking word "arrested" was replaced in the English translation with 'trapped,' but for Frenkel's Soviet audiences, who had behind them the nightmare of the worst years of Stalinist terror, it was a familiar and frequent concept of everyday language, if not of personal experience. Traumatic memories of the 1937/8 purges also paled in their minds in comparison with the even more inhumane conditions of the Great Patriotic War. When he wrote his book during the harsh winter of 1942/3, in Kazan evacuation with the larger part of his institute, Frenkel had already become an indirect witness not only to the pre-war arrests and disappearances of millions including many of his friends and colleagues, but also to the war-time deaths and starvation of millions, in particular in his home city, Leningrad, then in the second year of the tragic siege that virtually exterminated its inhabitants.[71]

To those who had lived through that cruel experience, freedom did not appear as an unproblematic gift and a natural state of life, but neither could they accept its absolute impossibility. Freedom was for them a difficult challenge and a serious problem to be solved by everyone: some portion of it, some complicated state of it, had to be achieved under even the most terrible conditions. Even when "arrested," Frenkel noted, electrons or holes "can liberate themselves again; the liberation, however, requires an increase of potential energy...and can occur after a certain period of time....The freedom obtained on such release will, [however], be of extremely short duration; liberation being followed by a new 'self-arrest' near one of the adjacent atoms."[72]

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i prilipanii elektronov i polozhitel'nykh dyrok v kristallicheskikh dielektrikakh," *ZhETF, 6* (1936), 647-655, in *FSW, 2*, 182-200.

71. Ya.I. Frenkel, *Kineticheskaia teoriia zhidkostei* (1945), *FSW*, *3*, 62-63. In the same book, holes and dislocations in the atomic lattice are called "offenders of order" *("narushiteli poriadka,"* the Soviet militia's term for hooligans), ibid., 25. English translation is J. Frenkel, *Kinetic theory of liquids* (Oxford, 1946), 52.

72. Ibid., 62-63. Incredible as it seems, the phenomenon of "self-arrest" could occur in Stalinist Russia during the insane chaos of the Great Terror. A case of a woman, who, unsure of her own political loyalty, denounced herself to the state prosecutor, is described in Jochen Hellbeck, "Writing the self in the time of terror," in Laura Engelstein and Stephanie Sandler, eds., *Self and story in Russian history* (Ithaca, forthcoming). The cycle of consecutive arrests and releases was a more common occurrence, especially among scientists and engineers who worked in so-called *sharashki*, privileged labor camps for arrested specialists put to work on secret military projects. Frenkel might well have been aware of this social phenomenon, known in the folklore of radio engineers as the "Mints cycle," after Aleksandr L. Mints (1895-1974), who reportedly went through this experience thrice and each time he was in captivity he built another more powerful radio transmitter.

Neither Landau nor Frenkel developed mathematical models for their proposals of "trapped" or "self-arrested" electrons. The solution was found by the war's end, in 1945, by Solomon Pekar, a professor in Kiev and former student of Tamm. Pekar realized that the deformation of the crystal lattice can be described mathematically as the electrical polarization of the lattice by the electron's Coulomb field. He managed to solve the corresponding wave equation and find energy levels for an electron in a polarizable dielectric medium, which had bound-state solutions. Tamm brought Pekar to report his results at Landau's seminar in Moscow, where the new particle was baptized during the discussion as the "polaron," the name that eventually became standard. Pekar's publication of 1946 contained the basic theory as well as the name of the polaron: its movement through the lattice, its dissociation into heat or phonons, and the electron's transitions between "free" and "polaron" trapped states.[73]

10. THE EXCITON

Of all the new particles suggested at the early stage of the collectivist approach, Frenkel's excitation quantum stood apart as the most incompatible with the prevailing band theory. The exciton was the solid-state collectivist analog of what in a gas would have been a bound excited state of an electron, but the band theory explicitly denied the possibility of such states in a periodic lattice. Even its restricted versions accepted by Landau and many other Soviet physicists seemed to leave no room for the excitation quantum state. The concept of filled bands and the energy-gap explanation of the difference between metals and insulators carried with them a model of an excitation of a crystal by a light quantum. An electron, when excited, was supposed to jump from a filled band into an empty one, thus creating a conduction electron and a hole. The absorption of light by an insulator produced carriers of electric current, which explained the phenomenon of photoelectricity. The excitation quantum, on the contrary, had zero electric charge and could not transport any electric current. When explained in these terms, Frenkel's hypothetical mechanism of light absorption seemed to contradict band theory at the level of phenomena available for experimentation and thus "appeared...completely paradoxical" even to most of his Soviet colleagues, both theorists and experimenters, including those at his home institute in Leningrad.[74]

73. S. Pekar, "Avtolokalizatsiia elektrona v dielektricheskoi inertsionno poliarizuiushcheisia srede," *ZhETF, 16* (1946), 335-340; S. Pekar, "Lokal'nye kvantovye sostoianiia elektrona v ideal'nom ionnom kristalle," *ZhETF, 16* (1946), 341-347; S. Pekar, "Local quantum states of an electron in an ideal ionic crystal," *Journal of physics, 10* (1946), 341-346; S. Pekar, "Autolocalization of an electron in a dielectric inertially polarizing medium," *Journal of physics, 1* (1946), 347-350.

74. S.I. Pekar recollection in *Ya.I. Frenkel Vospominaniya, pis'ma, dokumenty* (Leningrad, 1986), 198. On excitons being "practically incompatible" with band theory, see also É.I.

Facing widespread skepticism, Frenkel defended his proposal of the excitation quantum in a paper of 1936, where he also introduced the name "exciton." Not only the name, but also his understanding of the particle had changed in the interim. Frenkel accepted part of Peierls' and Landau's critique and agreed that the excitation would be localized rather than shared uniformly by all atoms of the crystal, but he criticized them in turn, insisting that it would not remain fixed to this location, but could move through the body. "[T]he collectivization of the exciton" in the 1936 version of Frenkel's theory was closer to his "collectivized electrons" of conductivity of 1924 and "empty spaces" of 1926 rather than to Tamm's phonons of 1930: excitons moved in the familiar fashion of successive jumps from one atom to a neighboring one.[75]

On this occasion, Frenkel also publicly presented his criticism of the band theory for the first time. The agreed shared ground was the mathematical model of the Bloch electron in metals, although band theorists called it "free" while Frenkel preferred 'collectivized.' This terminological disagreement about metals, however, evolved into contrasting, physically different approaches to insulators. In insulators, Frenkel insisted, almost all electrons remained "uncollectivized," or more tightly bound to individual atoms than in metals, and therefore could not easily move and transport current. Rather than move, electrons of neighboring atoms exchanged their energy of excitation. The picture of a moving collectivized excitation quantum, or exciton, according to Frenkel, represented processes in non-metallic solids better than the picture of a nearly free moving electron. Applying the latter model to insulators was, for him, "an inexcusable abuse of Bloch's method. It has to be regretted that such an abuse has been practiced by nearly all writers on the electron theory of the solid state, leading them occasionally to wholly erroneous results. One of such mistake...consists in the exclusion of nonconducting excited states of a crystal, i.e., such states which...are characterized by moving excitons."[76] Frenkel's defense of the exciton thus led him so far as to oppose the applicability of band theory to non-metallic crystals and the band-gap explanation of the difference between insulators and conductors, which were then almost universally accepted.

His presentation furnished the qualitative physical picture with only rudimentary basic calculations. In less than a year, John Clarke Slater and William Shockley at MIT and finally Gregory Wannier at Princeton developed a strict and consistent quantum mechanical formalism for the exciton. Without mentioning its collectivist philosophy, they attempted to eliminate, at least partly, the contradiction of the

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Rashba, "The prediction of excitons (On the 90th birthday of Ya.I. Frenkel)," *Soviet physics uspekhi, 27* (1985), 790-796, 792.
75. J. Frenkel (ref. 70).
76. Ibid., 161.

exciton with band theory. "For several years, there have been two competing pictures in use to describe the behavior of electrons in crystals," explained Wannier. "The one adopted in most theoretical calculations and especially successful for metals describes each electron by a running wave, but Frenkel has shown that in many cases the more elementary atomic picture may be the better approximation. This apparent contradiction has been removed by Slater and Shockley, who showed with a simplified model that the two types of states actually coexist in a crystal."[77]

Wannier succeeded in constructing a complete set of orthogonal wave functions for the electron in a crystal that was not limited to the periodic solutions representing Bloch's electrons. Wannier's functions included Frenkel's excitation waves in the lower part of the energy spectrum and another series of solutions for intermediate energies, which corresponded to hydrogen-like states of an electron and a hole bound together by the Coulomb field. The following year Nevill Mott in Bristol favorably reviewed the "collective electron" treatment as a more convenient approach in some problems of the solid state theory.[78] Mott covered Tamm's surface levels, Landau's electron trapped in a lattice distortion, and the bound states of an electron in the Coulomb field of a distant hole. These investigations helped to clarify the difference between two distinctive types of excitons, as they are now known: the original "Frenkel exciton," a tightly localized excited state of the atom, and the "Wannier-Mott exciton," or "mega-exciton," a bound pair of an electron and a hole that can be far from one other inside the crystal.

Even furnished with appropriate mathematical apparatus, the exciton still remained a hypothetical construct and contradicted the most widespread interpretation of the band theory. Only a very few physicists accepted it. But in 1951 the hydrogen-like spectrum it predicted was observed, apparently accidentally, in cuprous oxide by Leningrad spectroscopist Evgenii Gross. Frenkel died in early 1952 of a heart attack and did not have an opportunity to see the first photographs of exciton bands and to learn of the success of his theory. Gross also had to overcome serious opposition from colleagues, both theorists, especially Landau, and experimenters, which caused a one-year delay in the submission of his paper. It took several more years before the exciton was recognized as a natural fact.[79]

77. Gregory H. Wannier, "The structure of electronic excitation levels in insulating crystals," *PR, 52* (1937), 191-197, on 191; J.C. Slater and W. Shockley, "Optical absorption by the alkali halides," *PR, 50* (1936), 705-719.

78. "We find it most satisfactory to treat electrons in the closed shells as belonging to the ions, and reserve the collective electron treatment for the electrons in the conduction band." N.F. Mott, "Energy levels in real and ideal crystals," Faraday Society, *Transactions, 34* (1938), 822-827, repr. in *Sir Nevill Mott. 65 years in physics* (Singapore, 1995), 145-151.

79. E.F. Gross and N.A. Karyev, "Pogloschenie sveta kristallom zakisi medi v infrakrasnoi vidimoi chasti spektra," *Doklady Akademii Nauk SSSR, 84* (1952), 261-264; The same year the exciton spectra was also reported in Masakazu Hayashi and Kiichirô Katsuki, "Hydrogen-like absorption spectrum of cupruous oxide," *Journal of the Physical Society of Japan*, *7* (1952), 599-603. On the initial rejection of the experimental results on excitons and

11. THE COLLECTIVIST ALTERNATIVE TO BAND THEORY

Frenkel, in his paper of 1936, went further than defending the exciton. He summarized the entire collectivist approach, and the sorts of new particles proposed by that time, and presented it as a full-blown alternative to band theory. His synthetic picture shunned either practically free or absolutely fixed electrons, describing instead various processes in solid bodies as movements of particles with varying intermediate states of freedom. The exposition started with an electron liberated from its atom by an incident light quantum to become a "free or collectivized electron" of conductivity that moved by jumping from one position in the lattice to another. The liberated electron left behind a "collectivized positive hole, or positron" (actually a positive ion), which could also move through the lattice by "capturing the missing electron from one of its neighbors, and thus converting the latter into a 'positive hole.'" If the energy of the light quantum was not sufficient to liberate the electron fully into a collectivized state, the electron remained bound to the hole, but the entire complex—an atom in an excited state, or a "collectivized electron and positron pair"—could still travel through the crystal in a similar way and could thus be called a "collectivized exciton."[80] Any "free or collectivized" particle— electron, hole, or exciton—could cause a local deformation of the crystal and become trapped in it. These "trapped" (*prilipshii*) particles would also be able to move through the lattice, though at a much slower pace, and carry the deformation with them. Frenkel suggested that these slowly moving complexes might be observable, pointing in particular to the reports on the apparent trapping of photoelectrons in the experiments of Robert Wichard Pohl and his collaborators in Göttingen.[81]

The collectivist approach formed the basis of Frenkel's lecture course at Leningrad Polytechnic Institute in 1946 and of the resulting textbook, Introduction to the Theory of Metals (1948). By that time, the collectivization of electrons was already to Frenkel an "experimentally proven" fact, demonstrated by X-ray diffraction in metals. The simplest example of collectivization, the sharing of electrons by two atoms in a diatomic molecule, leads to the so-called exchange forces, which Frenkel considered more appropriate than the model of self-consistent field as a mathematical way of describing the collective behavior of particles. He reproduced on his model the main results obtained by Sommerfeld, Bloch, and Peierls in the late 1920s and early 1930s, but he largely ignored the later band theory, whose "level of mathematical complexity is not matched by the level of impor-

difficulties with publication see E.F. Gross, in *Vospominaniia ob A.F. Ioffe* (Leningrad, 1973), 141-153, on 147-148; B.P. Zakharchenya and V.Ya. Frenkel (ref. 58), 473.

80. J. Frenkel (ref. 70), 158-159.

81. Ibid., 171.

tance of the results it delivers." Instead, his picture of solids featured the entire family of "collectivized particles"—electrons, holes, excitons, and polarons—plus the phonon, which belonged to a separate category.[82]

Frenkel included more about band theory in the textbook's second edition in 1950, but also added a new preface with a stronger critique (simultaneously satisfying stricter ideological demands imposed on textbook authors by Cold War hawks) of the "formalistic tendencies of some Western-European and American...physicists, who often diligently develop the theory in its formal mathematical aspect while paying little attention to the question whether or not its basic assumptions correspond to reality." While accepting and interpreting from his perspective some of the results of band theory, he continued to reject as "radical" the idea of "wholesale collectivization," or the thesis that all electrons in all solids, including insulators, are free or collectivized, which did not leave room for the existence of either excitons or polarons. Until the end of his life, Frenkel maintained his quixotic opposition to the band-gap explanation of the difference between metals and insulators.[83]

Frenkel's last years were difficult for him: politically, rising anti-Semitism and ideological accusations of philosophical idealism had hit him hard, while professionally he suffered from the intolerant attitudes of Landau's school. His collectivist crusade in the theory of solid state looked like a one-man struggle. But had he lived a few years more, until the mid-1950s, he would have seen an intensification of criticism of band theory and a strong increase in interest in collectivist models.

New versions of the collectivist approach had been accumulating in the field for a number of years. In the theory of metals, Shubin and Vonsovsky in Sverdlovsk and Edmund Stoner in Leeds developed collectivist theory in the mid-1930s as alternatives to Heisenberg's theories of ferromagnetism that considered electrons as bound to particular atoms. From the late 1930s, Landau with Pomeranchuk and several others in Moscow enlarged Tamm's interpretation of phonons into a much more general method of elementary or collective excitations, which was justified further in the late 1940s by Nikolai Bogoliubov. During the 1940s, Anatoly Vlasov and Landau in Moscow and David Bohm and his graduate students in Princeton formulated new mathematical ways of describing collective interactions among electrons in plasma. Starting in 1950, Ilia Lifshitz with his collaborators in Kharkov treated electrons in metals as quasiparticles. In combination, these efforts pro-

82. Ya.I. Frenkel, *Vvedenie v teoriiu metallov,* 4th ed. (Leningrad, 1972), 8, 124.

83. Ibid., 7, 153. "Wholesale collectivization" was a term in Soviet political language denoting admittedly wrong and violent "excesses" of the collectivization campaign of 1930. Another careless phrase by Frenkel, "forced collectivization of electrons," was critized at the Polytechnic Institute's academic council as mocking the Soviet collective farm system. See R.A. Suris, V.Ya. Frenkel, "Ya.I. Frenkel's studies of the theory of the electric conductivity of metals," *Physics-Uspekhi, 37* (1994), 357-373, on 371.

duced in the mid-1950s a qualitative change in the community of condensed matter physicists and brought the collectivist approach and the method of quasiparticles to recognized success.

The new collectivist models were less explicit politically but better developed mathematically than Frenkel's theories. In the mid-1930s, Shubin and Vonsovsky in Sverdlovsk and Edmund Stoner in Leeds were developing collectivist alternatives to Heisenberg's theory of ferromagnetism that considered electrons as bound to particular atoms. They added new kinds of quasiparticles to the list: rotons, magnons, and plasmons, among others. They involved new meanings of collectivism, which were different from Frenkel's preferred metaphor of shared property. And they also reflected other forms of personal experience, in particular, Landau's phenomenological state of freedom within Stalinist totalitarian society and Bohm's desire to find out how to participate in a collective movement without losing one's individuality.[84]

84. These issues will be discussed in Part II of this study.