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YAKOV IL'ICH FRENKEL

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Following a resolution by the Physics and Mathematics Division U.S.S.R. Academy of Sciences, the present issue is devoted to the memory of the outstanding Soviet theoretical physicist Yakov Il'ich Frenkel .

The editors

YAKOV Il'ich Frenkel was not only a great theoretical physicist, but a striking person in many other respects.

Following the classification proposed by W. Ostwald in the book "Great Men," Frenkel was in his scientific makeup a typical representative of the scientific "romanticists," whom Ostwald contrasted with the scientific classicists. According to Ostwald's description, the latter cooperate little with their colleagues, concentrate on a small number of basic problems in science, but their ideas, on the other hand, influence in decisive fashion the development of these problems.

Frenkel, on the other hand, combined a passionate fondness for science with extraordinary versatility, breadth of interest, striking theoretical productivity, and an abundance of new original scientific ideas. As is characteristic of "romanticists," the very abundance of new ideas has caused some of them not to be fruitful or correct. But the need for later re-evaluation is barely significant compared with the fact that very many of his ideas have led to essentially new physical concepts and served as a starting point for the development of several important branches of science.

I shall mention here only three examples, although many more could be readily found. The idea of applying quantum (or, using the term employed in the late twenties, "wave") mechanics to the electron theory of metals is due to Frenkel, who first formulated the basic concepts of the quantum theory of electric conductivity and showed the way out of the difficulties of the classical theory.

In the theory of nuclear reactions, Frenkel first introduced the concept of the temperature of an excited atomic nucleus and the treatment of its decay as "evaporation" of elementary particles from a "heated" nucleus.

The question of the origin of terrestrial magnetism was in a hopeless state for so long a time, and the number of unsuccessful attempts to solve this problem was so large, that it became customary among scientists to refer to it as a typical example of hopeless scientific confusion. Frenkel became interested in terrestrial magnetism while still in secondary school, when he developed some new theory for its origin; some thirty years later he succeeded in pro-

posing a new idea, the so-called "dynamo principle," according to which terrestial magnetism is produced by unipolar induction currents flowing when the earth's liquid conducting core rotates relative ot its out layers. After Frenkel's death the known British scientist E. Bullard revived this idea and developed it quantitatively and mathematically. There is now every reason for assuming that Frenkel's hypothesis has finally solved this complicated problem.*

The unfortunate failure of the new generation of physicists to appreciate sufficiently Frenkel's contributions to modern physics is also connected with the "romantic" makeup of his scientific daring. He rarely subjected his new ideas to a detailed and deep analysis. This was far from due to insufficient mastery of mathematical techniques or lack of mathematical talent, but merely to the breadth and variety of his scientific interests. He contributed the principal parts —new ideas and new concepts. These ideas and concepts were seized upon by other scientists, who developed them in detail, subjected them to thorough mathematical analysis, and consequently proved their validity (and sometimes refuted them). The names of these scientists are known to all specialists in the corresponding field, while the decisive role of Frenkel's idea is too frequently left in the shadow (although his name is mentioned in the first papers of the "founders" of these fields).

We cannot speak of Frenkel and confine ourselves only to the scientific aspect of his activities. He was vivacious, sociable, easily carried away, and exceedingly versatile. Along with his work in science, he found time to play the violin and to draw (many very good drawings and portraits of friends and acquaintances have been preserved); he not only had great charm, which won over even persons who did not know him well, but had exceeding warmth and was an exceptionally good man in the truly best sense of this word. This was very well described by A. F. Ioffe: "One cannot fail to recall the active help that Yakov Il'ich rendered to all those who turned to him or to all those whom he deemed worthy of help. Unusual goodness, love, and respect for anyone whom he would presume to have good intentions and a desire for knowledge were such an inseparable part of his bright personality, that he frequently seemed naive, trusting even those unworthy of trust. The very thought of deceit was strange to him, so remote was his mental world from any unworthy thought."

In spite of the importance and great size of his scientific inheritance (in 35 years of work he published about 300 articles and more than 20 books), I will not confine myself to his scientific activity only, and will attempt as much as possible to recall the image remembered by his friends and fellow workers. This task has been made easy by the fact that his son, Viktor Yakovlevich, has put in order and arranged the abundant correspondence left by his father, and many hundreds of letters addressed to his wife and parents which were preserved by the family (he was also most helpful in other parts of this article). These letters, which I cite abundantly throughout, cover the period from 1906 through approximately 1941. Particularly interesting are the letters written at the start of the revolution, during the civil war, and during his prolonged stays abroad. These letters bring to life the image of a man devoted to the best ideals of the revolution, a man who lived a splendid life: he was abundantly endowed with talent, worked in a field he loved, and was happy in his family life.

* * *

Yakov Il'ich was born on 10 February 1894 in Rostov on Don. His father, Il'ya Abramovich Frenkel, participated actively in the People's Freedom movement in his youth, for which he was arrested and sent to Berezov in Siberia, where he spent about seven years.* Returning to the fatherland in 1892, I. A. married Rozaliya Abramovna Batkina; Ya. I. was their oldest son.

"In my childhood," writes J. I. in his autobiography in 1946, "I showed a proficiency in painting and music; this induced my parents to arrange for lessons in violin (from the age of eight) and painting (from the age of 12). Both occupations have been my favorite relaxations to this very day."

In 1909 the Frenkel family moved to St. Petersburg, the city where Frenkel spent all his life (with a few interruptions). His interest in physics and especially mathematics manifested itself approximately at that time, when he was in the sixth class of the secondary school. This interest was not merely passive, but active, for along with reading the special literature he himself started to test his ability in this direction and engaged in the theory of infinite series. The work took possession of him; whereas at first his father encouraged his activities in every way and stimulated them by sending him the appropriate literature, by 1911 the opposite tendency appeared. Frenkel became so attracted by his occupation and devoted so much time to it, that his parents became disturbed and dissatisfied. At the same time, Frenkel himself was dissatisfied with the rate of his progress. In July 1911 he wrote his father:

" . . . my paper will thus not be finished. I shall be glad if I write the first part (the most important and difficult of the suggested three parts), and I shall attempt to get through with it, come what may, before I go away. The reason I am delayed just where I least expected it is my inability, more so, my incapacity to formulate and particularly systematize the results obtained. In short, I do not like and I am unable to write finished copy, and this is precisely what needs to be done now. At the same time I

*E. Bullard, Priroda No. 12, 80(1960).

*In his last years of his life, 1935, I. A. Frenkel started to write his memoirs, "Passage to Prison and Siberia," which covered this time of his life but remained unfinished and unpublished.

feel that until this is done I cannot devote myself completely to anything else; I cannot occupy myself seriously "in between."

The paper referred to by Frenkel was entitled by him "Progressive Calculus," and was shown at the end of 1911 to Professor Uspenskiĭ, who recognized in it the principles of the calculus of finite differences, which was developed shortly before that by Academician A. A. Markov.

In 1913 Frenkel was graduated from the secondary school with a gold medal and was matriculated in the same year in the Mathematics Division of the Physics and Mathematics Department of the St. Petersburg University.

At that time practically no theoretical physics was taught in the university. The pertinent courses (on a rather low level) were taught by Prof. N. A. Bulgakov. Frenkel recalled this with a smile; Bulgakov was a very absent minded and eccentric person. He started to read his lecture while still in the corridor, and continued to speak as he entered the auditorium; only three or four students were in attendance, in rotation, so as not to cause the course to be discontinued. Yet Bulgakov saw Frenkel's outstanding abilities and actively recommended that he be retained at the university to prepare for professorial activity.

In October 1916 Frenkel was graduated, within three years, from the physical-mathematical department of the university (the "Mathematics Division"); his diploma thesis was devoted to the structure of the atom in light of its radioactive emission (it was subsequently published as a series of articles in the Jornal of the Russian Physical and Chemical Society). On the recommendation of Professors Khvol'son, Bulgakov, and Rozhdestvenskiĭ, Frenkel was retained by the St. Petersburg University "to prepare for professorial and teaching activity"; he worked there until the start of 1918.

Frenkel thus studied theoretical physics by himself. In the cited autobiography he writes:

". . . After acquiring some superficial knowledge of electron theory I developed, while still in the secondary school (in 1912), a new theory for the origin of terrestial magnetism, which I related to the magnetic action exerted by the sun as a result of its positive charge (due to electron emission), and its axial rotation. I attempted to present in the same paper a theory of atmospheric electricity, which, however, was quite naive (I call attention to these problems because they have become the subject of later work in 1944–1945 which have led me, it seems to me, to the important idea that the earth's magnetism is due to the presence of a liquid metallic core in the earth, which I treat as a self-excited dynamo).

I showed this paper in 1912 to Professor A. F. Ioffe, who was gracious enough to read it in spite of its size (250 pages), and commented on it kindly and critically; at that time, however, I decisively rejected his criticism. The acquaintance with Professor Ioffe turned later into friendship and collaboration.

Professor Ioffe, being an experimental physicist, was not my teacher, and I continued my self-education in theoretical physics without any guidance whatever.

In the fall of 1916 Professor Ioffe organized a physics seminar at the Polytechnic Institute and enrolled in it several young persons interested in the latest developments in physics. Among these were P. Kapitza, N. Semenov, P. Lukirskiĭ, Ya. G. Dorfman, the late M. Kirpicheva, Ya. Shmidt, and myself. Ioffe's interests determined the choice of material, and his stimulating discussions exerted a deep influence on all the young participants of the seminar, including myself. The result of this stimulating influence was my first serious work—on the electric double layer on the surfaces of liquids and solids, in which I developed for the first time the theory of contact potentials and surface tension of metals."[2]

Ya. G. Dorfman, recalling this period, writes: "Even then Frenkel was outstanding in his many-sided erudition. I wish to note in particular his wonderful good nature and patience, and his sharing his extensive knowledge with the younger participants in the seminar. This remarkable feature distinguished him throughout his life."*

It is difficult to overestimate the tremendous role played in the development of physics in our country by A. F. Ioffe himself and by the group of young people organized under Ioffe's guidance—they were the true pioneers of modern physics in the Soviet Union. In spite of the existence of individual top-notch scientists such as P. N. Lebedev, both physics teaching and physics research were on the whole on an extremely low level in pre-revolutionary Russia. To understand why Frenkel had to be self-taught it is sufficient to cite two characteristic examples. When I attended the Moscow University in 1914—18, Maxwell's theory was not mentioned by Professor Stankevich in his physics course, since this theory was deemed too complicated to be treated in lectures.†

A second example was told to me by A. F. Ioffe. When he started to work in the St. Petersburg University after spending some time with Roentgen in Germany, physics professor I. I. Borgman asked him what research he intended to follow. When Ioffe outlined his plans, Borgman asked who did this research already and where. Hearing that no one had worked on this subject, the professor was amazed: "You certainly are an opinionated young man" he told Ioffe, "we should not attempt to seek anything new; it would be very well if we were able to duplicate correctly in our country the measurements made abroad!"‡ It is precisely to the Leningrad school of physicists that we are greatly indebted for the fact that such statements now sound simply absurd.

It is interesting that Frenkel's first printed paper

*Ya. G. Dorfman. Introductory article to the second volume of "Selected Works of J. I. Frenkel," Moscow, AN SSSR, 1958. p. 4.

†To be sure, it was taught in a special "elective" course by Lecturer A. Bachinskiĭ, but I was given a top grade in the examination on this course only because in deriving formulas on the blackboard I used the symbol for the vector product and knew its meaning; no other questions were asked of me at all.

‡Ioffe related this episode in his book "Encounters with Physicists," Moscow, Fizmatgiz, 1960, p. 127.

was entitled "The Mechanical Operating Conditions of the Differential" and published in the Russian journal "Avtomobil" [3] (Automobile). The cause of this paper was his friendship with N. V. Fausek, a gifted designer, who worked after the revolution in the aviation industry, and whose original designs were frequently described in "Avtomobil." It is obvious that Frenkel carried out this work at his request.

Frenkel worked very hard in the winter of 1916–1917. He frequently spoke at Ioffe's seminars, at the university, and at the sessions of the Physical Society. Along with the strictly physics work mentioned above [1,2] he started an article, never finished or published, entitled "The General Character of Living Processes." In this article he attempted to determine the main difference between animate and inanimate nature. He saw the difference in the fact that inanimate bodies tend to assume a stable equilibrium state, any deviation from which, produces a counteracting force tending to decrease the deviation. "The normal state of any inanimate system is stable equilibrium," wrote Frenkel, "whereas the normal state of any live system, no matter from what point of view it is viewed (mechanical or chemical), is that of unstable equilibrium maintained by the life."

The fall of tsarism in February 1917 was enthusiastically greeted by Frenkel. Many letters to his father dating back to that time have been preserved. I cite a few extracts from these letters, as interesting evidence of the time when the revolution developed and history was made, and as a description of Frenkel's early revolutionary views.

"6 March 1917.

Long live freedom and those to whom we owe it! This is the first Russian freedom, attained by the third Russian revolution. The first (1825) was the revolution of an army without people, the second (1905) was a revolution of a people without an army, and finally the third is a revolution of an army of people and a people's army merged into one. This is why it struck with lightening speed, with a powerful and friendly spirit, and dispelled the frightful ghost of the old government. The nation, long under the yoke of this government, has realized with inexpressible amazement that it had been afraid of a ghost whose entire strength lay in the people's disunity; uniting, it swept away those miserable and mean persons who while frightening it with the old ghost attempted to subject it to a new one; the ghosts then disappeared in the fog, leaving the people to forge freedom with their own forces.

. . . The revolution has not yet extended to the front, but as soon as this is done I am certain that it will also cross the Austrian and German fronts into these countries, and will bring an end to the war even before the gathering of the Constituent Assembly. Thus, long live freedom and the future democratic republic. Long live and flourish the Russian people!

18 April 1917 (1 May by the new calendar)

Dear Father,

Volodya described in detail what used to be called the "first of May disorders," but which now has turned into a holiday of order, freedom, and international solidarity. I shall add only a few words about my own experiences and activities.

At ten in the morning we left the house and went to the Alexander Square–the assembly point of the Rozhdestvenskiĭ region. There were many speeches, good and bad. The public showed its characteristic response. Individual expressions of disapproval were immediately suppressed and the dissatisfied person advised to state his objections from the platform and not to interrupt the speaker. The slogan "freedom of speech" acted like a charm.

I could not stand the nonsense expounded by one of the orators (of course, a member of the "intelligentsia") and for the first time in my life assumed the role of an orator-agitator. I convinced the public that one must not confuse the people with the ruling classes or the government; that the German people had as little desire for war as the Russians, that it was betrayed through being convinced that "it was attacked," and that in order to conclude the peace as soon as possible it is necessary to convince the German people that not only the Russian nation but the Russian government have no warlike tendencies; for the latter it is necessary to address immediately the enemy and the Allied Governments with an official peace program, etc.

At first somebody cried "down," but was silenced, and then the people started to shout "that's right." One officer reported that not a single exchange of shots occurred in the Carpathians between the Germans and the Russians for several months; the Germans were on the peaks, and the Russians some 50–100 paces below. The Germans could immediately shoot down all the Russians if they wished, "like partridges." Instead, they played on the harmonica and exchanged friendly banter with the Russians. When the Germans received an order to advance (after the revolution), they warned the Russians and asked them to leave.

At two o'clock I went to the Cinzelli Circus for a meeting of the social-revolutionaries; what I saw and heard there you already know from Volodya's letter. From the Cinzelli Circus I went to the "Modern" Circus, but on the Mars Field I was attracted by the sight of a large crowd, and wished to share news and ideas with it, which I did eventually. A revolting speech was made by one student (of the university, of course) who announced that this war is waged by the German people against the Slavs, that the Germans must be crushed, etc. After my speech (which apparently was heard with great interest by the public), I was surrounded by some twenty persons with whom I discussed current political topics for an hour and a half."

In the fall of 1917 Frenkel published the already mentioned article on the double electric layer on the surface of solids and liquids (we note that in view of its importance it was included in the second volume of his Collected Works). This work was very highly valued by Russian physicists, particularly by O. Khvol'son, under whom Frenkel prepared to take the Master's examination.

He started out to take the first of his examinations in the morning of 26 October (old style), but could not get farther than the Dvortsovoĭ Bridge, where he was stopped by a patrol of revolutionary sailors. When a few days later Frenkel explained the reason for his absence to one of the members of the examination commission, the professor angrily said: "Young man, for men of science there are no revolutions whatever."

Here is an extract from a letter of 14 November 1917:

" . . . I am writing this at five in the morning on the front stairway of House No. 4 of Metinskaya Street, which I must guard

by myself from 3 to 6 AM, I know not against whom. These watches on the front stairways are to be modified the day after tomorrow. I am glad of this opportunity, however, since I use it to write many letters, while in the daytime I have little time. Thus, yesterday I passed my first Master's examination. This was held in Khvol'son's apartment, who was slightly ill. Rozhdestvenskiĭ and Bulgakov were there.

In general this examination is pure formality, or, if you wish, like all examinations, a preface to work. While in the sense of new or added knowledge these two weeks were not spent in vain, nevertheless I am sorry for the lost time! There is only a month to Christmas and I have to take three more examinations."

On 12 December Frenkel passed all his mathematics tests in one session—the examiner was Academician Steklov—and thus overcame the Master's degree barrier within a record short time.

By that time the question of organizing a university in Yalta, in the building of the former Tsar's (Livadiĭskiĭ) Palace was finally resolved (this was raised by the Grand Council of the Tavra Province as early as in 1916). Wishing to join his family, which moved to Crimea in January 1917, Frenkel decided to work in this university as instructor, and in the beginning of 1918 he left Petrograd for Crimea. By that time the civil war already started in the country. Together with his brother Vladimir Il'ich, then a medical student, and another companion Frenkel reached Simferopol' with difficulty and from there he proceeded to Yalta on foot. Somewhere in the Alushta region they ran across a division of soldiers. Wishing to know how far it was to Alushta, Frenkel started his question with the greeting "Comrades," to which he became accustomed in Petrograd. This was almost fatal, for they were White guards. Fortunately, the incident was smoothed down, and the Frenkels successfully reached Alushta (which two days later was occupied by the revolutionary seamen of the Black-Sea fleet), and then Yalta.

Frenkel's Crimean stay lasted three years. These were difficult years, when Crimea was first occupied by German and then by the "Allied" forces. Particularly difficult was the occupation by Denikin's and Vrangel's forces (June 1919—November 1920).

The Crimean University was opened in May 1918 in Yalta, but was moved to Simferopol' in the fall of that year. The operating conditions are well illustrated by a resolution of the Council of the University, dated October 1920, in which it is stated that "the staff members of the University are down to an extreme degree of starvation."*

The teaching staff of the University was essentially reactionary, but included also worthy and talented people, later well known. Frenkel became friendly with many of these, and the friendship continued in later years. This pertained above all to Nikolaĭ Mitrofanowich Krylov, who headed the "Mathematics Laboratory" of the University. Krylov gathered in his faculty many talented persons, particularly Mikhail Lyudvigovich Frank (the father of I. M. and T. M. Frank, later professor of the Polytechnic Institute in Leningrad), N. S. Koshlyakov, and L. A. Vishnevskiĭ, Somewhat later the same faculty was joined by Vladimir Ivanovich Smirnov. At the end of 1919 I came to Simferopol' and started work as an assistant in the Physics Laboratory. My first acquaintance with Frenkel dates back to that time, and by the end of the 1920's it turned into a strong friendship.

Frenkel also established close relationships with the biologists working in Simferopol', where the University soon moved, and above all with Aleksandr Gavrilovich Gurvich. The discussions with him, and also with Professor S. I. Metal'nikov, who later went to France, exerted a strong influence on him and strengthened his interest in biology. As is well known, Frenkel turned to this field many times and published many papers on biophysics. One of these (in 1943) was written in collaboration with A. G. Gurvich [4] (during the time of the evacuation to Kazan', Frenkel painted an exceedingly good portrait of Gurvich). In 1920, Frenkel delivered at Gurvich's seminar a paper "The Contrast between Animate and Inanimate Processes," which was a development of the already-mentioned work of 1916.

The staff of the physics faculty, to which Frenkel belonged, was exceedingly small and at first included only Professor L. I. Kordysh of Kiev and Frenkel himself. Later, in 1920, several assistants were added; for this group of assistants Frenkel gave a course on the theory of crystals, which was the first draft of the book which he published three years later when already in Petrograd.

In the fall of 1918 Frenkel started to teach a course in general physics to the students of the first and second years; his listeners were for the most part medical students. These lectures were published as individual brochures. In a letter dated February 19, 1919, Frenkel wrote his parents in Yalta:

". . . Our university has turned in remarkable fast time into an ordinary shabby temple with ordinary priests to guard the ancient order. It was literally born covered with dust and mold of the past. Not a single live stream, not a single novelty—everything in the old fashion! A comparison with an old hurdy-gurdy comes involuntarily to mind! Incidentally, the burden of routine bears heavily not only on the university, but on all the institutions that vegetate in the 'abundant' south of Russia. The printing of my lectures has been temporarily delayed for lack of funds in the Students' Publishing Commission. Thus, I don't have to worry about writing my course. Nikolaĭ Mitrofanovich (Krylov—I. T.) advises me to start on my dissertation, and perhaps I shall follow his advice."

In a second letter written in the same time we read:

". . . I wish to engage in some real work. Unfortunately, the scientific journals are hopelessly delayed in Kharkov. Thus, I

*See "History of Crimean Pedagogical Institute" by F. S. Zagorodskikh et al. Krymizdat 1960, p. 8.

have nothing to read in my specialty except lectures and there is no one to listen to them. Incidentally, this pertains only to the second-year students. . . The physical equipment is beginning to take shape here, and soon we shall also be able to organize a machine shop."

Work on getting the physical equipment together was carried out essentially by Frenkel's brother, Sergeĭ Il'ich, who at that time was 19 years old and, being a student of the university, served simultaneously as an assistant in the physics faculty. He was, according to Frenkel, an exceedingly gifted youth, and died tragically at the beginning of 1920.

In April 1919, the "Allies" were expelled from Crimea, and the Soviet regime installed in Simferopol'. Frenkel, continuing his teaching activity, was also in charge of the Division of Higher Schools in the Crimean Commissariat for National Education. In an outline devoted to the history of the Crimean Pedagogical Institute,* we read:

"Among the university professors and instructors were also active fighters against the interventionists and the White Guard. Thus, for example, lecturer Ya. I. Frenkel (later Corresponding Member of the U.S.S.R. Academy of Sciences) was held to account by Denikin's forces for agitating against the White Guard bands in a brochure which he published during the short Soviet domination of Crimea in April-June 1919."

Immediately after Denikin's occupation of Simferopol', Frenkel was imprisoned. In a letter to his mother, couched in a language to set his relatives at ease, he writes:

". . . I spend enough time reading Drude and Grave. I started to write my article; now I expect to receive my lectures, which have not yet been delivered to me. I play chess with home-made chessmen with Rabinovich and Krasnoperov (who were in the same cell—I. T.). This is a forbidden activity in the prison, and yesterday the assistant warden, inspecting the cell while drunk, took away our "board," which we replaced with another. We discuss, as usual, political and personal topics. Thus, I repeat, I am not at all bored. I am freed of worry by optimism and a philosophical mood, as I have already written. If I do not succumb to thoughts of what could happen if, etc., something I try not to do, then I can live in clover, like in a sanatorium. The only difference is that in a sanatorium you get a room that you lock from the inside, and in a prison the room is locked from the outside."

Energetic intercession on the part of Frenkel's friends in the University resulted in his being released in the custody of a group of instructors, but he was forbidden to teach at the university for half a year.

The late Torichan Pavlovich Kravets, who was at that time professor at the Kharkov University, related that he received through the rector's office a document, in which a certain member of Denikin's counter espionage enquired whether it was true that the "Bolshevik agitator" J. I. Frenkel was indeed the physicist he claimed to be. In reply to this question, T. P. wrote that Frenkel was the author of, in his opinion, one of the most outstanding papers published of late in the Journal of the Russian Physical-Chemical Society (he referred to the paper on the double layer). Kravets recalled this episode shortly before the war, when he, Frenkel, and a few other physicists returned from a conference on the nature of the latent photographic image. Kravets's paper evoked certain objections on the part of Frenkel, and Kravets said jokingly: "You know, I was at one time a much less severe critic of your work," and then related the story.

Soon after he resumed work at the university, the Council of the Physics and Mathematics Faculty recommended that Frenkel be appointed lecturer. This is what he wrote on this subject to his parents:

"Simferopol', 6 May 1920

My dears,

At this evening's session of the Council I was "blackballed," 23 against 16. Obviously my enemies carried on as strong an agitation as my friends. The formal reason against my election was the lack of three-years' service (which, however, did not prevent the election of Vishnevskiĭ and Koshlyakov). This service term will be completed only in the fall. In spite of an emotional and apparently even pathetic speech made by Nikolaĭ Mitrofanovich (Krylov—I. T.), which was supported by Vishnevskiĭ and Bunge, our obscurantists, without making real objections but merely mentioning the lack of this required length of service, stating that I am being provided for in the sense of delivering the required course and the resultant rights and privileges, and also recalling my past crimes,* quite unanimously "voted me out."

I am afraid, my dears, that you will be more mortified by this than I am. I assure you that personally this result troubles me very little.

Furthermore, the election at the University Council has not completely settled the matter; the final approval is made in Sevastopol' by the "Chief of National Education." It is quite possible that this higher office would not only fail to confirm me as a lecturer, but would even force me to resign as instructor."

And here is another excerpt from a letter of 8 May 1920:

". . . All my friends are terribly disturbed and apparently much more mortified than I am by my failure, seeing in it clear proof of inadmissible predominance of purely personal and political considerations over academic ones. Incidentally, Nikolaĭ Mitrofanovich tells me that after the results of the ballot were made known, Gel'vig† told him and Nikolaĭ Ivanovich (Kuznetsov, professor of botany—I. T.): "I was so afraid of this result!" without blinking an eye, although he not only blackballed me, but used most inadmissible agitation procedures against me before the elections. Thus, for example, he ordered to display in the office, two weeks before the elections, alone with my application, curriculum vitae, list of papers, also a note by Malinin (?) concerning my removal " . . . for the call to war against the White Guard bayonets,"—and in a most prominent place, to boot."

At the end of November 1920, after Vrangel's defeat, a Soviet government was established in Crimea.

*Page 9; see the preceding footnote.

*That is, Frenkel's activity in the Commissariat for Education—I. T.

†Professor Gel'vig was at that time the rector of the university (I. T.).

The last week before the liberation of Simferopol' Frenkel, warned in time of his impending arrest, was hidden by friends. Immediately after the reestablishment of the Soviet government, Frenkel assumed charge of the division of higher and professional-technical education of the Crimean People's Council for Education. On 8 December 1920 he wrote his mother:

"I spend the hours from 10 or 11 to 4 at the Division for the People's Education; incidentally, three times a week I steal a few hours for lectures. Were it not for the mass of minute details (admission of late students, issuance of protective charters, passes, etc.), I would be satisfied with my work. I already carried out and continue to carry out reforms in the university life, and as far as I know, my colleagues not only have no complaints against me, but would hate to see me go. As regards the gist of the reforms, so far they reduce to the following. First, the faculties and the council of the university have been somewhat reorganized (all those who instruct students independently have been given equal rights, and representatives of the other instructors and the students have been admitted—one from each course, each faculty, or each division). Next, some reorganization, although very slight, in the humanities faculties, with creation of a faculty of social sciences with law, economics, and history divisions. Study schedules have been introduced and, in connection with them, a tutoring system to check on the students and to help them, (i.e., special assignments with small groups for each subject, the tutors being the most advanced students of the senior classes). Finally, in so far as possible, provision for the social needs of the students, i.e., for the time being, organization of a dining room and the distribution of bread. The disorganization of the student body greatly delays the realization of these measures, and I, having called a general meeting of the students (at which, incidentally, I explained all questions connected with the reform of the university), suggested that they reorganize on a new and more business-like basis.

In addition, I am preparing for the January opening of a workers faculty at the university, intended exclusively for workers, of course those who have somehow received an adequate education.* You can find reports on all these subjects in the copies of the newspapers which I am enclosing.

In addition to the university, I am also in charge of professional-technical education, on which, incidentally, I have not had to spend much time so far."

At the end of December 1920, Frenkel married Sara Isaakovna Gordina, at that time a student at the biology department of the university. A very clever, tactful, and sympathetic woman, Sara Isaakovna played an important and beneficial role in Frenkel's life; their warm love and real friendship lasted throughout their life.

In early 1921, at the invitation of A. F. Ioffe, Frenkel and his wife left Crimea for Petrograd (in December 1918 Frenkel was chosen an active member of the newly organized X-ray Institute, the president of which Ioffe was). Immediately after his arrival, Frenkel was also appointed instructor at the Polytechnic Institute, where he started to teach a course on electrodynamics and where he did some practical work in mathematics for some time.

At the beginning of March 1921 Frenkel met M. Gor'kiĭ and asked his help in improving the difficult material conditions of the instructors and students of the Crimean University. This help could not be rendered at that time, since the fuel crisis and the resultant transport difficulties had resulted in breakdown of the transportation to Crimea.

In Petrograd Frenkel buried himself in his work. In less than five years he published five books. In the foreword of the first of these ("The Structure of Matter," published in 1922—1924 in three parts), Ioffe wrote: "The book by J. I. Frenkel is more than a valuable contribution to the general literature of physics. Nowhere in the contemporary literature has the structure of matter been subjected to such a complete theoretical analysis.

In 1923 Frenkel published his "Theory of Relativity," based on lectures delivered in the summer semester of 1922 at the physico-mechanical faculty of the Polytechnic Institute. This was, as noted by Frenkel himself, the first (Russian) "non-popular manual" on this subject.

In 1924 he published his "Electron Theory of Solids," written at the suggestion of A. F. Ioffe. This book reflects in part Frenkel's ideas concerning thermal motion in solids, which later served as a basis for further original work.

During 1925 two of his books were published: "Electricity and Matter," a popular revision of the "The Structure of Matter," and "A Course of Vector and Tensor Analysis with Applications to Mechanics," based on his lectures. Along with these published books, Frenkel completed in the spring of 1924 his "Electrodynamics," which the Gosizdat (State Publishing House) then rejected, because in the opinion of the director this book would not gain a large circulation.

At the same time, Frenkel published during that time more than fifty original papers in the Journal of the Russian Physical and Chemical Society and in Zeitschrift für Physik. These papers—on the theory of electric conductivity of metals, on the theory of the condensation and adsorption phenomena, on the electron theory of solids—made Frenkel one of the outstanding physicists of the Soviet Union and made his name known far beyond the borders of our country.

In September 1924 Frenkel delivered five papers at the Leningrad Physics Congress. Attending this Congress was T. S. Ehrenfest, who highly praised Frenkel's work. On 19 September 1924 Frenkel wrote to his father:

" . . . I was quite successful at the Congress and in general attained a position which I would consider myself to be unworthy

*The workers faculty of the Crimean University was organized at Frenkel's initiative. I do not know whether faculties of the same type were created at that time in Leningrad and in Moscow, but Frenkel knew nothing about them—I. T.

of, were it not for the well-known proverb that "among the blind a one-eyed man is king." Yet, the Congress disclosed that the USSR is completely "devoid of birds" when it comes to theoretical physics, and as a result I proved to be the "nightingale." Incidentally, this was due for the most part to Ehrenfest, who tried to advance me in every way possible. He spoke to me on the third day of the Congress about the trip abroad, and it turned out that the conditions that I must leave the family in Russia or some other place, a condition which Ioffe told me was imposed by the Rockefeller Foundation, was really due to him. He told me: "You can send all your money to the family and live on black bread alone, this is your business; but you must spend these six months without a family, so as to use your time properly." According to Ehrenfest, I could find an excellent appointment abroad even without his intervention, but he is ready to offer his collaboration only under the above condition. And I assume that he is correct."

In the next letter to his father, Frenkel presents a strikingly clear and accurate description of P. S. Ehrenfest, splendidly bringing to life his fascinating image:

". . . I must tell you that Ehrenfest won the heart of all our youths, and perhaps also the older persons. Here is a man combining simplicity and directness of a child with an extraordinary love for persons, exceedingly sharp wit, and the brain of a great and acute researcher. Through his mouth, inanimate objects such as molecules, atoms, and electrons converse with each other (in a language which although broken in the sense of endings, cases and genders, is yet a precise Russian), they love and hate each other, and generally come to life and become microscopic residents of an animated universe. For Ehrenfest, or more accurately with Ehrenfest, physics is not so much a precise science as an artistic drama or comedy from the life of the atoms and the electrons. You can see from the foregoing description the extent to which I am under the spell of Ehrenfest's personality. I do not know whether this spell is connected with his friendliness to me; I believe, however, that there are no selfish motives here, for nobody can look at Ehrenfest, and particularly listen to him, without a smile of satisfaction in response to the humor and good nature that flow from him."

Wishing to gladden his mother with his success, Frenkel wrote her at the end of September 1924:

"At the end of our conversation Ehrenfest said the following: "I do not know whether you ever learned anything from me, but in any case I learned very much from you."

So large a scientific activity was due above all (disregarding native ability) to the environment in which Frenkel worked. The X-ray Institute has gathered an exceedingly friendly and talented staff. Its core comprised P. L. Kapitza, N. N. Semenov, P. I. Lukirskiĭ, Yu. B. Kharitin, Ya. G. Dorfman, V. M. Kondrat'ev, G. A. Grinberg, and many others —indirect or direct students of A. F. Ioffe. In addition, in those years Frenkel converted into kinetic and creative energy the potential energy, in the form of knowledge and accumulated pedagogical experience, which he "stored up" during his three-years stay in the Crimea.

One might think that such a colossal amount of work could be performed only by an ascetic scientist, locked up in his office and having no other interests. But Frenkel did not stop his music and painting, and was a constant participant in merry parties, frequently organized by the staff members of the X-ray Institute. In general it was difficult to imagine a more lively and social person than Frenkel.

In 1925, at Ehrenfest's recommendation, Frenkel received a fellowship from the Rockefeller Foundation, and in the fall he left for a year's stay in Germany. He was accompanied by his wife and oldest son, who settled in Nice, when Frenkel came to visit from Hamburg and from Göttingen. The year he spent in Germany coincided with the time of foundation of quantum mechanics; Frenkel was able to become acquainted and collaborate with many of its founders, primarily with W. Pauli and M. Born. He lived in Göttingen during that idyllic time, about which many write now and which is called the "the Göttingen period" of the development of physics. His stay abroad and the possibility of such contacts exerted a great influence on Frenkel's further work.

Both the environment in which he worked abroad and the character of his own activity are best illustrated by the foregoing extracts from his numerous letters to his parents (the correspondence with his wife was not preserved).

Berlin, 20 November 1925.

Today from 12 to 2, I was at Einstein's. I went up the stairs in Einstein's house with certain trepidation, which incidentally disappeared immediately as soon as I saw him "in the flesh." He turned out to be an unusually pleasant man (he combines Ioffe's softness with Ehrenfest's directness and sincerity). I spoke about physics exclusively, for the most part developing my own concepts. He approved those concepts fully, and particularly my theory of metals, which will be reported in the seminar at the university on Wednesday evening. We also touched on other problems connected with quantum theory, and Einstein summarized his own relationship to the latter in the following manner: The situation is desperate, nothing is understandable!

The meeting was held in Einstein's study; he had a rather proletarian appearance in a knit vest without a jacket, in rather worn trousers, and in the sandals which are now so popular in Leningrad.

Berlin, 26 November.

Were it not for Einstein's accidental departure for Leyden, I would probably stay another month and work with him (not on relativity theory). My meeting with Einstein has resulted in his expressing if not a desire at least an agreement to take me under his guidance.

At the university colloquium, on the day before yesterday in the presence of Einstein, Planck, Nernst, Laue, and a few other top notchers (including Ioffe), the discussion concerned, among other things, my theory of electric conductivity of metals; the lecturer Becker disagreed with me in one very important question, but Einstein responded quite energetically and announced that he "believes my arguments to be perfectly correct, and their results quite remarkable." I must say without false modesty that I never

expected so high an estimate of the work, which seemed to me quite modest both qualitatively and quantitatively. There were discussions at the colloquium, and Herr Geheimrat Nernst himself (whom, to the shock of all present, I dared call Professor), asked certain questions; I answered in a German which, in Ioffe's opinion, could hardly be understood by many. I shall try to master spoken German as soon as possible.

Hamburg, 2 December.

. . . These days I am quite busy, trying not so much to expand as to deepen my knowledge. I spend every day, from about 11 or 12 to 5, at the library of the Physics Institute. In the evening, from 7 to 8, I am usually at home and stay up to late at night—about 2 in the morning. I have decided to give up this miserable habit, since as a result I get up at 10 and I do not feel sufficiently awake. The reason for my night watch is in part the article, which I wrote three evenings ago and finally finished last night. This article pertains to work on viscosity of liquids, which I did last year, but so far remained unpublished. In the nearest future, at the request of Professor Stern, I shall report this work to the local seminar on theoretical physics.

Hamburg, 24 January.

Thank you for the letters which I obtained last night and this morning. I read them with satisfaction. In particular, I read not without satisfaction the news of being appointed Professor. Yesterday I started to rewrite my new article (No. 2), which seems intersting to me.* The corresponding work was successfully completed only a few days ago. My stay in Hamburg, i.e., my scientific contacts with Pauli and in part with Stern, as well as my intense activity, begin to be reflected in a rise in my knowledge and in a broadening of my horizons.

. . . I am completely immersed in physics and, as already reported to you, I leave it only for correspondence and for music. I must confess, incidentally, that such a monastic way of life is dictated not only by my thrist for knowledge, but in part by lack of financial resources.

. . . My limited means do not hinder my studies at all; to the contrary, it is a very favorable factor, since nothing distracts me from work. The only thing I regret is that I am unable, under these conditions, to become better acquainted with my comrades in science. All—Stern, Pauli, Wentzel, Minkowski—are bachelors (quite some boys) and meet each other outside the Institute only in restaurants, cafes, motion picture theaters, and the like, places which I do not frequent.

Hamburg, 14 March.

Since yesterday I have a guest—Yu. A. Krutkov, whom my landlady installed in the next room. I am very glad he arrived, we spend the time quite pleasantly and usefully. Yesterday we read, discussed, and in part analyzed further Heisenberg's new article on quantum mechanics until late in the evening. This morning, because it was Sunday and the weather was good, we visited Hagenbeck. We dined in a restaurant, as behooves substantial professors, and again discussed physics, which has occupied us until this instant, i.e., until 11 in the evening. Krutkov is exceedingly pleasant; during the one day of our joint stay in Hamburg I have learned to know him better than during the five years of living together in Leningrad. From the middle of April to the start of August we shall, at any rate, work together in Göttingen. We both suffer from laziness, and the "collectivism" is in this case the best countermeasure. In addition, discussion of many problems is frequently an essential supplement to an individual analysis.

*He refers to[5]—I. T.

Hamburg, 22 March.

. . . Yesterday unfathomed some "secret of science" (as my father is wont to say), namely the question of the so-called "elastic limit" of solids. This question greatly interested Ioffe, who investigated it experimentally and who was assigned 500 rubles to pay for my theoretical investigation. But then, two years ago, I was unable to accomplish anything, and after receiving 100 rubles, I refused to take the rest. Now, however, i.e., last night, after a discussion with one physicist, who also worked experimentally on this problem, I apparently solved the problem.* Incidentally, not apparently but undoubtedly. I already had an opportunity to speak about it with Stern, who found my arguments quite correct (but was scared of the large number of formulas).

Hamburg, 25 March.

During the last week and a half I finished two projects; one I already reported to you, and the other was more or less completed only last night (with the aid of Pauli). Because of the good weather, good work, and the good relations that have been established between myself and Pauli and other colleagues, I am leaving Hamburg with a feeling of a certain regret. Will it be better at Göttingen?—We shall see.

Nice, 17 April.

My departure from Nice is scheduled for the 20th. In Paris I plan to see Langevin and to have a more detailed chat with him concerning one of his latest papers, in greater detail than last time. I just today received a proof of a preliminary report on this work, and observed three days ago that the theory developed in it, in spite of Pauli's opinion and my own initial ideas, does not settle this problem.

Last time I saw Langevin only briefly. He just returned from a short tour of France, devoted to pacifist propaganda. He is an exceedingly pleasant person and one of the most enlightened representatives of the modern French intelligentsia.

Göttingen, 1 May

As before, I am fully delighted with Göttingen. It has been long since I have lived in a small town and the contrast with the large cities is most favorable. In addition, Göttingen has charming surroundings. Half an hour's walk or even less and you're already outside the city, on hills covered with linden and other trees, filling the air with intoxicating aroma of spring's bloom. From the hills, each topped by an unavoidable Bismarckturm or Bismarckstein, one sees a charming view of the city, sunken in green (except for the small central part). In the city itself there are neither streetcars nor automobiles (practically), only bicycles and pedestrians, at least half of them students in colored caps of various corporations and burgerschafts.

Göttingen 4 May

Today at last I met Born. I liked him exceedingly well. He is somewhat more than forty, but looks quite young. He is short, thin, clean shaven, with graying hair and blue eyes. In one word, I like the boss just as much as I liked Göttingen.

Göttingen, 9 May

Born and his wife are apparently very musical, for in a tremendous room adjoining Born's study and serving at the same time as a living room there are two grand pianos next to each other.

In Göttingen there are several Americans who are anxious to join the world of new truth as taught by Born. Unfortunately, the truths are pronounced by him so rapidly, that most of the listeners fail to get them. And although the audience, consisting predom-

*See [6]—I.T.

inantly of German students, stomps lively with their feet to show their approval of the lecturer ("stomping" is used in Germany in place of applause), it is nevertheless beginning to thin out.

Göttingen, 15 May

My life flows evenly with little variety, mostly bicycle rides, hikes, and regular attendance at the movies (twice a week). The scientific work goes quite well, although for the time being I have not thought of anything new.

Yesterday, at the theoretical seminar headed by Born and by the famous mathematician Hilbert, I delivered a small paper on one of my Hamburg projects. I found out that when necessary I can speak German quite fluently, although with an accent that differs considerably from the customary one, and also with a systematic mutilation of the genders. In the last fact I consider myself innocent and I am placing the blame for the senseless assignment of masculine and feminine sexes to inanimate objects on the Germans themselves.

Göttingen, 30 May

Recently I have been making quite good progress with my electrodynamics,* and may even finish it in the beginning or at the very latest in the middle of July. As regards my new ideas, they are beginning to take some shape. I am thinking about new problems, for the most part during my evening walks, which last week, I can say, have become part of my schedule. At 11 in the evening the streets of Göttingen are practically empty and to walk through them is a sheer pleasure. Particularly attractive is the rampart surrounding the central part of the city, at one time a fortification wall, now just a high avenue, densely planted with beautiful branchy trees. Thus, walking alone over this rampart, and also over other Göttingen byways, I think of quanta, relativity, and the connection between the two still separated fields. I think that I am on the right path, and I am not losing hope of reaching my goal. Incidentally, it is still premature to write about this. . .

. . . Soon to arrive in Göttingen are Bursian, Lukirskiĭ, and Semenov with his wife. In a word—a Russian, or more correctly an X-ray Institute occupation of this city, German from times immemorial, is impending. In addition, in the middle of June, Ehrenfest and a host of his co-workers are expected, including the Ceylon parrot, which Ehrenfest taught to pronounce the following phrase: "Aber meine Herren, das ist keine Physik." This parrot is being nominated by Ehrenfest to chair the impending discussions on the new quantum mechanics.

Göttingen, 29 June

I can finally state that my book is finished. Some inconsequential trifles remain. I am fully justified in being proud of this work. First, so to speak, quantitatively. To the 150 pages which I wrote in Hamburg, I added an additional 400 during the last month and a half, of which 300 were done during the last month. As to the qualitative aspect, I hope that this book will have many advantages and few shortcomings. And this is all that can be expected. I brought my manuscript to Born today and explained to him in a friendly and prolonged discussion first the reasons compelling my literary activity, and then the contents of my book. He still wants to see it himself. Tomorrow I shall get from him a letter of recommendation to Springer and the day after tomorrow I shall go to Berlin for a few days to fortify the won positions.

Incidentally, Born is now working on an exceedingly interesting and clever theory, which casts light on many of the problems that still remain unexplained. I wish you knew how simply and modestly he speaks about his work. I like him very much not only as a physicist but as a man.

Berlin, 2 July

Springer received me very cordially and after looking through Born's letter, immediately took possession of the manuscript. Born's letter read as follows: "Having become acquainted with Professor Frenkel's book, I find that it is a very good and original work, which furthermore is very timely, since there are at present no texts on electrodynamics worthy of attention, except the obsolescent book by Abraham. I am convinced that Professor Frenkel's work will gain wide distribution. I myself can learn much from it. . ." My book will go into print immediately and in October, i.e., even before I leave for home, it will be published. Very pleasant!

Göttingen, 22 July

Galleys of my book have started to arrive in large numbers. I am reviewing them immediately and turn them over for further polishing to Krutkov and Bursian.

This evening I attended a concert of new music with Ehrenfest and Born. Tomorrow I plan to play Grieg's second sonata with Natasha Semenova.

Less than a year after returning from Germany, Frenkel participated in a congress devoted to the memory of Volta, held in Como (Italy). At this congress he delivered a paper in which he first formulated the main premises of quantum theory of electric conductivity. Frenkel indicated that the anomalously large free path of the conduction electrons in metal (compared with the lattice constant) is due to the wave nature of the electron. An ideal regular crystal lattice is transparent to the electron waves, which are scattered only by lattice inhomogeneities (including inhomogeneities due to thermal oscillations). These premises served as basis of modern theory of electron conductivity, subsequently developed by F. Bloch. The content of the entire paper was communicated by Frenkel to Einstein in Berlin, on his way to Italy. In Italy he met Sommerfeld. He wrote his wife on 26 September 1927 from Naples.

". . . I traveled to Naples with Sommerfeld. We talked much on the way, naturally, about physics. He is no longer a young man (58); he acts very simply and pleasantly. Too bad that I could not study with him ten years ago. Almost all the most talented theoreticians (in Germany and in part in other countries) have been his students."

During 1927—1929 Frenkel published more than 20 papers, mostly on the theory of metals. Simultaneously, he completed the second volume of "Electrodynamics," and published his "Introduction to Wave

*At the end of 1925 the Springer scientific publishing house in Berlin undertook to publish the text book "Electrodynamics," which Frenkel wrote in 1924. As already mentioned, the Gosizdat refused to print this book. Frenkel worked hard on the translation and revision of this book in Hamburg, and especially in Göttingen. Later on, this book together with its second part, which was written later, was published in both German and in Russian and became one of the basic books on modern theory of electricity in the world literature. It is sufficient to state that it was accepted as a standard text in many European and North American universities—I. T.

Mechanics"—one of the first textbooks on this newly created science. Both books were written in Russian, but were first published abroad (in Germany).

Frenkel was always an active participant in physics conventions. One of these, the convention of 1928, was organized quite uniquely: The delegates traveled along the Volga on a steamer, and the plenary sessions of this convention were held in cities on the way. On 15 August 1928 he wrote from Saratov:

"... Time passes on the steamer quickly and lively. There are so many interesting persons with whom it is useful or pleasant to chat or discuss things; many merry youths, in whose company one stays up late at night, or more accurately into the early morning.

Today, a few hours ago, the congress ended. Summarizing the eleven days since its opening, it must be recognized that Ioffe's ideas of having a traveling convention was on the whole fully justified. While there were some shortcomings, these were due to unsuccessful choices of papers at the "provincial" sessions, particularly in Nizhni and in part in Saratov.

In open sessions aimed at large audiences the lectures must be made popular or semi-popular. Papers of any complexity remain perfectly unintelligible to a tremendous majority of such an audience. On the other hand, closed sessions on a steamer are exceedingly interesting and useful for the "active" membership of the convention. There were 200 of us on the steamer (most of whom remained in Saratov). Active among these—together with the foreigners—not more than 50 persons."

At the end of the 1920's Frenkel's work gained widespread recognition and fame. These works can be subdivided into three principal groups.

The first pertains to the theory of metals and dates back to the already mentioned paper [2] in which he developed the theory of contact potentials and surface tension of metals. In 1924 he published an article [7] in which he expounded the theory of "wandering" electrons. In this paper he established the main premise of modern electron theory of metals, namely that the kinetic energy of the conduction electrons in metals is practically independent of the temperature (in spite of the main position of Drude's classical theory), and is determined by quantum conditions. Applying Bohr's theory to the description of the electrons, Frenkel showed that condensation of the metallic vapor in a crystal is accompanied by "collectivization" of the valence electrons, which lose their host and become capable of "wandering" in the metal. These electrons are indeed responsible for the electric conductivity characteristic of metals. Frenkel showed that his theory leads to all the experimentally confirmed results of Drude's theory (the Wiedemann-Frantz law, etc.), and at the same time eliminates the intrinsic contradictions of the classical theory, which have led to the well-known "specific heat catastrophe."

We have already mentioned the electric conductivity theory reported at the congress in Como. Another very important idea of Frenkel's (which, as he noted, arose in discussions with Ya. G. Dorfman), was the first explanation he proposed for the nature of ferromagnetism, the gist of which is that, by virtue of exchange interaction between the electrons, a corresponding part of their electrostatic interaction depends on the mutual orientation of their spins, i.e., on their resultant magnetization. It is precisely this electric interaction energy that causes the great difference between the energies of the magnetized and unmagnetized states of ferromagnets, a difference which cannot be explained outside the scope of quantum theory. Heisenberg's classical work, in which the same idea was independently developed more completely and more rigorously, was published a few months after Frenkel's paper. The same group includes the well-known articles [11] (written with Ya. G. Dorfman), where the authors presented a theory of the Weiss domains in ferromagnetic bodies and indicated the dependence of the dimensions of these domains on the total dimensions of the specimen.

Frenkel developed the theory of a degenerate relativistic gas and applied it to the problem of the internal structure of stars. He showed that the mass of a stable star, which is in a degenerate state, cannot exceed a definite maximum, somewhat larger than the mass of the sun. Finally, he presented the now standard textbook derivation for the zero-point energy of a degenerate Fermi gas.

Later, in 1946, in a review article [12] devoted to the theory of metals, we find an interesting evaluation of his own work; in this article Frenkel formulates his views on problems of physical theory as follows:

"The more complicated the system considered, the more simplified must its theoretical description be. One cannot demand that a theoretical description of a complicated atom, and all the more of a molecule or a crystal, have the same degree of accuracy as of the theory of the simplest hydrogen atom. Incidentally, such a requirement is not only impossible to fulfill, but also essentially useless... An exact calculation of the constants characterizing the simplest physical system has essential significance as a test on the correctness of the basic principles of the theory. Once, however, it passes this test brilliantly, there is no sense in subjecting it to further tests as applied to more complicated systems. The most ideal theory cannot pass such tests, owing to the practically unsurmountable mathematical difficulties unavoidably encountered in applications to complicated systems. In this case all that is demanded of the theory is a correct interpretation of the general character of the quantities and laws pertaining to such a system. The theoretical physicist is in this respect like a cartoonist, who must depict the original not in all details, like a photographic camera, but simplify and schematize it in a way as to disclose and emphasize the most characteristic features. Photographic accuracy can and should be required only of the description of the *simplest* systems. A good theory of complicated systems should represent only a good "caricature" of these systems, exaggerating the properties that are most difficult, and purposely ignoring all the remaining inessential properties."

Although I personally cannot agree with the statement that there is no sense in applying a qualitatively tested theory to complicated systems, nevertheless

Frenkel emphasized in this citation very successfully the need for singling out and "overemphasizing" the main qualitative laws of complicated systems, which were always of prime interest to him.

The same period marks the start of Frenkel's work in a new direction, to which he refers to in his autobiography as follows: "Although I have engaged in a great variety of problems in physics, physical chemistry, and geophysics, my favorite subject has been the structure of matter, particularly the structure of solids and liquids."

We shall stop to discuss here only two investigations. The first[13] was devoted to the theory of adsorption and explains the critical temperature of condensation of a molecular beam on the surface of a solid, together with the notion of the "creeping" of adsorbed molecules [some twenty years later Frenkel extended these notions to include adsorption by a crystal of not foreign but so to speak its "own" atoms (molecules)]. This investigation was made in close contact with N. N. Semenov and Yu. B. Khariton and its results were reported somewhat later in a joint article.[14]

A second paper[15] presented the theory of motion of atoms and ions in crystals, destined to win a firm position in science. Frenkel pointed out that along with the evaporating from the surface of a crystal lattice into the surrounding space, atoms can evaporate uniquely from equilibrium positions into interstitial space (the ions in the interstices, as noted by A. F. Ioffe, play a decisive role in the electric conductivity of ionic crystals; Ioffe, however, paid no attention to the empty sites, formed when an atom (ion) goes into the interstitial space). This kind of dissociation of the crystal lattice into atoms (ions) in the interstices and vacant sites (holes) leads to the formation of what is now called in the literature a "Frenkel defect." The hole (or vacant lattice site) can move through the crystal independently of the atom that has left the site. It can, in particular, "evaporate," and emerge to the surface.* The atoms in interstices, together with the vacant sites (holes), do indeed make up the pattern of a real crystal.

In the same work, Frenkel obtained a theoretical expression for the electron conductivity of ionic crystals and introduced the notion of vibrational-translational motion of molecules in liquids and in amorphous bodies in general. Along with this, Frenkel developed the notion of "roaming" motion of liquid molecules and calculated the average time of their "settled" life. This notion turned out to be exceedingly fruitful and was used in the very same article for a theoretical analysis of diffusion processes and for the construction of a quantitative theory of viscosity of liquids. Calculations with electronic computers made recently to explain the character of particle motion in liquids fully confirmed the notions presented by Frenkel.*

The third group of works pertained to fundamental problems connected with elementary particles. Paper [5] was devoted to the relativistic theory of the rotating electron.

Although this problem was ultimately solved only in Dirac's later papers, Frenkel's work constituted appreciable progress. In particular, Frenkel first introduced the description of the magnetic moment of the particle not in terms of the vector μ_α but the antisymmetrical tensor $\mu_{\alpha\beta}$, the temporal components of which ($\alpha = 4$ or $\beta = 4$) determine the electric moment of the particles (they vanish in its rest frame). This is precisely the tensor that characterizes in modern relativistic theory the possible additional (i.e., not purely spin) magnetic moment of the particle. In 1928 Frenkel proposed[6] an equation which, in his opinion, should describe the motion of the electron with allowance for the postulates of relativity. It turned out later that this equation introduced by Frenkel can be used to describe the motion of vector mesons (with spin 1) and is identical with the Proca equations (1936).

All these papers (totaling 60 by the end of 1920) along with the books published here and abroad, established Frenkel as one of the world's leading theoretical physicists. In 1929 he was elected corresponding member of the Academy of Sciences of the U.S.S.R.

In the fall of 1930 Frenkel left for a year's stay in the U.S.A. as a visiting professor of the University of Minnesota in Minneapolis. The letters he wrote from America to his wife and parents depict clearly his exceeding capacity for work, contain many interesting observations of the American scene of that time, and at the same time show the zeal and energy with which Frenkel attempted to acquaint the Americans with the ideals of the Soviet system in numerous discussions and addresses.

We present below a series of extracts from Frenkel's letters of that time.

New York, 29 September 1930

I just visited Columbia University, where I met some of the local physicists. Somehow it is pleasant to meet in America with a reception evidencing respect and appreciation. Incidentally, the physicists form a narrow caste, the members of which are well known to each other in all parts of the world, but are at times perfectly unknown even to their neighboring fellow countrymen.

Minneapolis, 2 October 1930

. . . This morning after a two-day's trip in Pullman cars I arrived safely at my temporary post, where I was very cordially received by Professor Erickson, the chairman of the Physics Department, and Dr. Hill, my assistant. Both are very pleasant, as are incidentally all the Americans whom I met here. Erickson, a Swede by descent (most residents of Minneapolis fall in this category) is tall and thin, like a skyscraper. Hill is small and agreeable. I hardly had a chance to get settled in my quarters (where

*We note that this evaporation of holes, and of lattice defects in general, is used at present to obtain ideal defect-free crystals.

*See in this connection the review by I. Z. Fisher, UFN 69, 349 (1959), Soviet Phys. Uspekhi 2, 783 (1960).

some of the single professors and instructors live) and barely had time to read your letters before I proceeded to my first lecture.

My duties consist of delivering three hourly lectures a week. The rest of the time is fully at my disposal.

Mineapolis, 8 October

... Today I delivered my fourth lecture. I feel that it was less successful than the earlier ones. Nothing lost–I shall make it up to my listeners next time. I am about to report on some of my own work at the local seminar.

Professor Erickson promised to lend me his violin and I, at the same time, already talked with some of my new friends about quartet playing.

Minneapolis, 12 October

My audience consists of 25 persons, of whom 14 are students and the rest professors and instructors. The students have little preparation (something like our third-year students) but make a very good impression.

... The female sex, as I have already reported, has heretofore not been represented in my audience, but at the last session such a representative appeared for the first time (attracted obviously by my fame as a lecturer). But who do you think it was? ... A nun! And this with thousands of pretty American students outside my audience. Where this nun came from, the devil only knows. I hope that she runs away soon and does not annoy me with her gloomy appearance, emphasizing the unpopularity of my subject among the members of the fair sex.

... I read with pleasure in the American press increasingly frequent, sympathetic, and informative notes and articles on the USSR. The Americans begin to believe in the success of the "Russian experiment" and, in particular, in the realization of the five-year plan. I am planning to write on this subject and on America in general a small article for "Izvestiya."

Minneapolis, 12 October 1930.

I have an opportunity to speak quite frequently of Russia, interest in which has greatly increased in America in recent times. You know that abroad our success is felt even more acutely than at home, where it is frequently obscured by our failures and difficulties, and I carry my Soviet citizenship with pride.

Minneapolis, 19 October 1930.

Tomorrow morning I shall resume my artistic activities and studies, under the guidance of a known local artist right here at the university (in the architecture department).

I am starting to be gradually drawn into work, which goes crescendo, but so far has only reached mf (or perhaps only p), having started with ppp. I am now completing my first article, and as soon as it is finished I shall begin a second. These are two old projects, left unfinished in Leningrad, where I was too busy in the last days to work on this.

23 October

Recently the students' paper published an interview headed "Frenkel Sees Prosperity for Russia Under Soviet." Today the editor of the journal "Technolog," published by the group of engineering departments, asked me for an article concerning the latest technical and industrial accomplishments in Russia. I need material for this article (preferably illustrated). Please contact Fakidov or Braude at the X-ray Institute on this subject and ask them to obtain and send to me these materials as soon as possible (it would be desirable in the future to supply me regularly with illustrated journals devoted to problems of this kind).

Minneapolis 3 November

... Today I finished my painting–a portrait of some old man. Incidentally, I am not worried too much about physics either. I need only some external pressure to guarantee the desired tempo of work. Such a pressure is provided by my talks in Urbana, and also at the physics convention to be held in Chicago on 28–29 November. As a result, my tempo has accelerated...

7 November

I received from Amtorg at my request several illustrated publications (some in English) on Russia, which I use for my articles and speeches. So far I have not refused requests of this kind, since I consider it my duty to use every opportunity for "Soviet propaganda." In the nearest future I shall have to talk on Russia at one of the faculty clubs, where I was invited to become a regular member (this is considered to be quite flattering here), then at the students' international club, and still in some other city club. Usually these addresses are combined with lunch or dinner, and thus take up very much of my time.

I am planning to intensify my work and complete my article on the absorption of light in solids.* I was able to clear up all the difficulties and now I think that the work will proceed rapidly.

Minneapolis, 15 November

... Today was my first public talk on Russia at the so-called Saturday Lunch Club, to an audience of about 150, representing, at the assurance of the directors of the club, the flower of the local intelligentsia. Among my listeners was one senator, two members of Congress, several professors, many teachers, and all kinds of businessmen. I spoke more than an hour, well and convincingly I thought, and then answered questions for about an hour. I built my entire talk around the topic that Russia is presently at war not with an external enemy, but with nature and with the old order, war aimed not at destruction but at creation, where sweat flows instead of blood and where heroism of labor is cultivated instead of heroism of death; a war the front of which extends not along the state boundaries but cuts across and along the entire territory of the country; a war carried on in the name of creation of socialism not for the coming generations, but for the very participants in the war during the coming years. These wartime stresses explain the apparent contradictions in the facts concerning Russia: the tremendous success in industrialization and agriculture and lack of food and consumer's goods, idealism and cruelty, etc.

In answering questions I touched upon religion, nationalities, etc. The Americans were particularly interested in whether Russians can save money, either to spend it later or to leave it to their children. They could not get the idea that the tendency towards capitalistic accumulation cannot occur in our country.

18 November

I just returned from a club, where I made my (n + 1)-st talk on Russia (the n-th was given this morning, and the (n–1)-st on Saturday, i.e., three days ago). All were quite successful. But these talks begin to tire me, particularly that of this evening. I presented tonight's talk quite differently from the preceding ones, describing to my listeners the impressions which they would gain as tourists, and then supplementing these impressions with more lofty considerations. Incidentally, I am sending a distorted and abbreviated interpretation of my Saturday talk as published in a newspaper.

I feel very tired now. I both spoke long and spent much time answering questions.

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*Frenkel refers here to his article on excitons[17]–I. T.

The Americans' increasing interest in Russia, which only this year became quite real, is greatly due to the present crisis in America. This crisis has shaken (for the time being) not so much the Americans' economic institutions as their minds In newspapers and conversations one encounters doubts, quite new to the Americans, about the sanctity of the principle of private property. In connection with these doubts, the Americans begin to be more and more interested in the results that can be attained—and have been actually attained in Russia—by eliminating or limiting private property. This probably explains the popularity of my lectures on Russia.

24 November.

I have worked quite a lot recently and as a result I am completing my article today. It has not been easy, but on the other hand I am very satisfied with it and consider it to be one of my best works on quantum theory.* I now have many ideas on further work, partly in the same direction (absorption of light in solids), and partly in others. I am so busy that I practically read no books or journals, all the more since the contents of the latter are not brilliant.

Minneapolis, 27 November

Today is Thanksgiving Day in America, a holiday commemorating the thanks given by the pilgrims 300 years ago for the fruit of their labor. For this reason I was invited to the Ericksons for dinner, after which I played music for two hours with Mrs. Erickson, performing with great success my usual repertoire: Wieniawski's Legend, Vieuxtemps' Ballad and Polonaise, the Berlioz Scene du Bal, Tartini's Devil's Trill, and part of Sarasate's Gypsy Airs. The audience, in the person of Professor Erickson, was most satisfied with the concert, which I offered as interest on the loan of the violin.

Minneapolis, 1 December.

... Incidentally, in Chicago I ran several times across perfectly well dressed young people (one of whom would certainly be regarded in Russia as belonging to the bourgoisie) who asked for help timidly: "Sir, have you some money; I am unemployed, dead tired, and hungry." And this at a time when around me the stores are bursting with abundance and no one knows what to do with the goods. How fortunate for Russia that it skipped the bourgoisie order.

13 December, on board the train (Iowa City—New York)

I am still under the impression of my visit in Iowa City. I spent two days there in practically continuous conversations, for the most part scientific or semi-scientific, but at any rate interesting, in the company of exceedingly pleasant and cultural people. Professor Stuart cordially invited me to stay with him. He is a real American and of the best type at that, full of the joy of living, energetic, and very straightforward... He related in detail about his work, which was most interesting to me (I did not know him before). In speaking about his x-ray research on the structure of liquids, he used the following expression: "I like to play that." His results on the close similarity between liquids and solids agree with the ideas which I myself have been adhering to in the last few years (I first advanced them in the X-ray Institute in 1925), and which I plan to develop in greater detail in the nearest future.

... Yesterday evening, after my second lecture (on the application of wave mechanics to the theory of viscosity of gases), I was honored with a dinner at the University Club, and after dinner I made another speech on Russia (number 12!), seemingly more successful than all the preceding ones. There were about 30—40 people, mostly physicists and their wives.

*This refers to article[17]—I. T.

New York, 15 December

I now must get to work on the long promised article on Russia, so that it can appear in the January issue of the Minnesota Technolog.

Next on my New York program is the revision—more correctly rewriting—of the first chapter of "Wave Mechanics."

I am very glad, my dears, that an improvement is taking place in your living conditions. I myself am firmly convinced that within a few years our country will be the happiest in the world.

New York, 17 December

Yesterday I went to Columbia University. I was very pleasantly received, shown the laboratories, and informed of the work done there. The Physics Institute of Columbia University is a rather imposing 13-story building. But its interior does not fully match the exterior, at least with respect to the research work. In this respect Columbia University differs little from the universities in Minnesota, Illinois, or Iowa. Theoretical physics is taught by Mr. Rabi, a very famous young man, recently returned from Europe, where he worked for a year with Stern and Born. Another university in the city of New York engaged this year a very talented theoretician, Breit, an emigrant from Russia, who incidentally has lived in America for a long time. Tomorrow evening the New York theoreticians are gathering at a seminar where I will be the guest and lecturer.

20 December.

Yesterday evening I presented a rather detailed lecture on my last two papers* to the local theoreticians and persons more or less close to theory, at the theoretical seminar of Columbia University. In attendance were Rabi, Breit, Halpern (from Vienna, now an assistant professor under Breit), and others, a total of about 25. I met Breit only yesterday evening. He is an exceedingly talented theoretical physicist and a very sympathetic young man of about thirty.

My lecture aroused great interest, confirming my own impressions of the success of my two American investigations. The last of these raises many new and incidentally very interesting problems, to the solution of which, already sketched in general outlines, I hope to devote three more papers in the future. I would like to finish them in time for the next meeting of the Physics Society, which will be held on 28 February in New York.

I started to work, gradually developing crescendo. Today I proceeded for the first time to a revision of my book (you yourself know how difficult it is to start any project of considerable size).

Minneapolis, 20 January 1931

I returned from Rochester only a few hours ago, where yesterday evening I devoted some three and a half hours to a talk on the USSR to some 50 persons—for the most part on the staff of the Mayo Clinic, and also some representatives of the local intelligentsia. I already lost count of my addresses. Yesterday's I think was the 16th or the 18th. Fully successful. I convinced the Americans 100 per cent. I convinced not only the Americans, but myself, or more accurately, I got so wound up, that I felt an unsurmountable urge to go back to the socialist fatherland,—let alone you, the children, and the relatives— and I read the New Year's Soviet papers that I received with a deep emotion, such as I have not experienced for a long time. My only regret is that I must address small, although select audiences, and the useful effect of my propaganda activity is greatly decreased thereby.

Mayo Clinic is indeed a grandiose establishment. It is sufficient to say that it treats some 80,000 patients annually. It is amazingly equipped. The plant is tremendous (the main building has 20 stories and is connected by underground corridors to a

*He refers, in particular, to [17, 18].

multitude of auxiliary buildings) and exceedingly beautiful. The organization is a model of its kind.

The clinic is connected with several guest houses and sanatoria, which complement it to some extent. In one of those guest houses I was given a luxurious room, naturally with bath and a million of towels, and furthermore... with a bible.

I reached the Institute of Experimental Medicine at the end of an operation on two unfortunate dogs and the start of an operation on a no less unfortunate rabbit. And although this sight did not give me pleasure (I even felt queasy towards the end), nevertheless, I was very pleased with my visit, owing to discussions on the effect of snake poison on the living organism, on the regeneration of the liver in animals from a small remnant (unlike in the hyman body), etc. Physiology is an unusually interesting science; what a pity that it cannot be developed by purely theoretical means, like theoretical physics, or at least supplemented by bloodless experiments. Naturally, one can get used to anything, particularly to bloody operations. But nonetheless I am glad that I do not have to perform them.

2 February

The last week and a half I was busy principally in "self education," i.e., I studied (with great enthusiasm) Dirac's book. I am now getting ready to study a few more books and to read some long postponed articles, and then return to attempts to move science. It's been long since I have read anything properly and I believe that time spent to catch up is not wasted. I am planning to expand the scope of my reading in the future to include the electrotechnical and biophysical literature. I feel cramped in a single field... Tomorrow I hope to finish Erickson's portrait, after which I will put my brushes away for a while in favor of music.

This Sunday I will again play with my pianist and in addition take part in a trio on one occasion and probably play Bach's Concerto for Two Violins (with Hill) on another.

Minneapolis, 1 April 1931

... Incidentally, you remember that my long paper in Physical Review (on excitons, Phys. Rev., 1931–I. T.) was criticized in Zurich, where it was claimed to be incorrect. I believe this opinion to be unconditionally in error, not only on the basis of my discussions with the American theoreticians, but also from inner conviction. The fact that Pauli believes my work to be "falsch," proves only, in my opinion, that it is not "trivial."* Incidentally, a sequel will be published soon, proving and supplementing this paper considerably (Phys. Rev., 1931–I. T.) Before leaving America I hope to write still another one or two articles developing this subject further.

I am now, incidentally, completely absorbed in my book. During my stay in New York, including the trip back and forth, I wrote about a hundred pages. I hope to finish the entire work within three or three and a half weeks. Unfortunately, I have a feeling that "social obligations" (not at all in the Soviet meaning of this word), will detract me from this work quite frequently, i.e. unavoidable visits, dinners with arriving visitors (incidentally, a splendid custom, which we should take over from the Americans), etc. Today I was at a dinner in honor of the British scientist, political economist, and socialist, Laski. After dinner he, as is customary, gave his impressions of the state of Western Europe. His impressions are very gloomy; he believes it quite probable that a war will break out in Europe in the near future.– I debated this, proving that Russia is now the only hope of peace in Europe. If war does not break out this year or next (God forbid!), then no government would dare to start one because it would immediately turn into a communist revolution in the West...

Minneapolis, 3 April

I was just interviewed by a correspondent from one of the Minneapolis newspapers. I talked a whole hour with him, and I believe that I have convinced him with my propaganda a hundred per cent. Let us see what he writes!...

*W. Pauli, while an outstanding scientist, was distinguished for his extremely skeptical relations to new physical ideas; he is credited for a statement that most papers are "entweder falsch oder trivial" (i.e. either incorrect or trivial). In particular, his first reaction was negative both to Frenkel's excitons and to Uhlenbeck and Goudsmit's idea that electrons have spin–I.T.

The first part of "Wave Mechanics" was printed in England in 1932 and soon (1936) a second edition was published. The second part was written by Frenkel after his return to the fatherland (it was published in England in 1934). In 1933–1935 Russian editions of both volumes of "Electrodynamics" and "Wave Mechanics" were published. Frenkel found it easy to express his thoughts on paper. He was an exceedingly fast writer, equally fluent in Russian and in foreign languages (English, French, and German). In spite, however, of his speed and facility, the writing of books, and also technical work connected with their publication, occupied much of his time. Consequently Frenkel never stopped his work in the summer during the vacations. In July 1935 he wrote his father from Zhelezo—the painters' rest home on the shore of the Luga river, where he frequently vacationed with his family:

"... I even practically seldom walk. Strange as it may seem, there is not enough time. Before dinner I work; today, for example, I wrote 18 large pages. In the evening I regularly play the violin with Sergeĭ Federovich Vasil'ev or with Prof. Bauer–also a violinist (I brought a large number of duets). And after supper, i.e., after nine in the evening, I "chatter" or write letters, as for example now. For the time being I do not have time for painting. I shall probably get to it only after I finish the book.* I hope that this will happen by the 25th. Then I shall again go to Leningrad to deliver my book to the publishing house. Unfortunately, after finishing the book I still will not be completely free; I have to write two articles and edit translations. I don't remember a summer when I was fully free of literary obligations!"

Frenkel liked to use the method of analogies† in developing physical problems, a method about which he wrote in the foreword of the Russian edition of the first volume of "Wave Mechanics":

"From didactic considerations I made extensive use in exposition of the method of analogies, which is sometimes superficial, but has, on the other hand, the merit of being illustrative. This includes the analogy between matter and light, the limited character of which is observed in a deeper study of the connection existing between them. An analogy, if treated with sufficient cau-

*He refers to the second volume of "Electrodynamics."

†In 1931 in the USA, and later in Russia, he delivered a lecture on this subject "On the Method of Analogy in Physics"; part of the manuscript of this lecture was preserved.

tion, is the simplest and most understandable path from the old to the new; it is merely necessary not to forget that any analogy, unless it be an actual identity, has definite limits. The old never contains anything that is truly new, and in recognizing the laws of nature we should learn to see not so much the old in the new, as the new in the old, regarding the latter as being an approximate form of the former."

Frenkel wrote his books and scientific articles in pictorial, simple, and clear language. Max Born wrote to Frenkel (in March 1947): "I thank you for a reprint of your article on 'Fission'*. I read it with great interest, although I am not a specialist in nuclear physics. You always write so clearly and simply, that it is very easy to follow your thought."

In the early 1930's, a policy was initiated, destined to play a very important role in the development of physics in our country. This consisted of separating several laboratories from the Leningrad Physicotechnical Institute (LFTI), led at that time by Academician A. F. Ioffe, and organizing them into individual institutes, both in Leningrad and other cities (Kharkov, Sverdlovsk, Dnepropetrovsk, Khomsk, etc.). For several years Frenkel, along with being in charge of the theoretical division of the LFTI, was also the head of the theoretical division of the Institute of Chemical Physics (also separated from the LFTI). He frequently traveled for consultation and lectures to the new institutes, and also to Kiev, Odessa, and Rostov, greatly contributing to the organization of physics departments in the provincial cities of the Soviet Union. Here are a few excerpts from Frenkel's letters of that time:

"Kiev, 15 May 1935

... I hardly stepped into the building of the Academy of Sciences when I ran across Nikolaĭ Mitrofanovich (Krylov–I.T.), with whom I spent several hours in lively discussion. ... In spite of his eccentricity, he still remains a splendid friend and a most interesting person. Tomorrow the participants of the conference will leave and I shall remain alone with my Kiev students, whom I shall teach daily from 5 to 9, until May 20th, when I go to Odessa for the same purpose.

Odessa, 30 May 1935

... I successfully concluded my Odessa activities yesterday with a two and a half hour lecture on "Matter and Energy." Today and tomorrow I am completely free; today I have kept busy since morning (I wrote a third article; two are all ready for press). The day after tomorrow I go to Dnepropetrovsk (by air–3-1/2 hours), where I shall lecture the very evening.

Rostov, 4 September 1936

... I must deliver two lectures daily, one from 8:30 to 10:30 in the morning, and the other from 5 to 7 in the evening. In addition, they persuaded me to deliver three or four lectures to the students of the Pedagogical Institute. Yesterday's lectures, particularly the evening one, devoted to the question of the theory of the liquid state, had a very large audience (some 500 persons). Let us see what happens. I started to work: I am writing a supplement to my English book."

In the 1930's Frenkel worked with exceptional energy. In this decade he published about 100 articles and had ten books printed (or reprinted).

In 1930-1931, during his stay in the USA, Frenkel worked on the absorption of light in solids [17,18] and showed that if the electron of any atom in the body becomes excited after absorbing a quantum of light, this excitation can be transferred from atom to atom (at a definite speed). Such a mobile excited state, which he called "exciton" behaves like a particle (and can be described by suitable excitation waves). There is no transfer of electric charge here, however. The hole formed as a result of excitation of the electron in the normally filled band of the energy spectrum of the electrons of the body, together with the electron to whom this hole owes its existence, form a unique "exciton atom," characterized by its own energy spectrum.

A spectrum of this kind was observed in the experiments by E. F. Gross and his co-workers at the end of 1951; since that time the number of papers devoted to the theory and experimental investigation of excitons has been increasing from year to year, and the concept of exciton has become so familiar that it has lost almost all connection with its originator.

Many articles written in those years were devoted to electron theory; one of these, in particular, is a further development of the theory of excitons, [19] and in another [20] (written together with A. F. Ioffe) the rectification on the contact between a metal and a semiconductor is discussed.

During those years Frenkel developed his ideas concerning the similarity between the properties of liquids and solids. [21-23]

In [24] he developed the concept of the so-called orientational melting of liquids, which reduces to an elimination of the long-range order in the distribution of the equilibrium orientations of the dipole molecules of the liquid (and not to a transition from rotational swings to free rotation), with retention of the short-range order and the associated character of thermal motion, i.e., rotational swings. The presence of such an orientational melting is used to explain the experimentally known anomaly of specific heat and the jump in electric polarization in crystals of hydrogen-halide compounds (such as hydrogen chloride or hydrogen bromide). The work of V. N. Tsvetkov with liquid crystals (anisotropic liquids), carried out a few years later, has confirmed Frenkel's theoretical predictions on the existence of orientational melting, occurring at a temperature higher than the ordinary melting temperature (he derived for the orientation-melting temperature a formula analogous to the cor-

*He refers to the paper "On Certain Features of Fission of Heavy Nuclei," Journal of Physics USSR, 10, 533-539 (1946).

responding expression for the Curie temperature of ferromagnets).*

At the already mentioned March 1936 session of the Academy of Sciences, in a discussion of my own article on the theory of atomic nuclei, Frenkel proposed his own statistical model of the nucleus [25] (which he called not too appropriately "solid" in his article [26]). Speaking of N. Bohr's theory of the compound nucleus (published in "Nature" two weeks before that date †), Frenkel indicated that the very complexity of nuclear structure, to which this theory is applicable, makes it possible (as is always the case) to introduce simplifications in the theory.

Frenkel likened the atomic nucleus to a solid or liquid body consisting of a large number of particles bound to one another. The energy carried into such a system by a captured neutron should be regarded as the thermal energy of this nucleus, and the process of neutron capture should be regarded as a unique adsorption accompanied by the heating of the (compound) nucleus with subsequent "evaporation" of a neutron, proton, or alpha particle from the compound nucleus. On the basis of this analogy, Frenkel introduced the concept of the temperature of the nucleus and in subsequent articles cast his ideas in mathematical form. These ideas were recognized and further developed, in particular, by N. Bohr himself (together with Calcar), ‡ where a special section is devoted to an exposition of Frenkel's results, and also in the papers by Landau** and Weisskopf and Bethe.*** Frenkel himself two years after publishing the cited article, [26] devoted to the development of his theory his article "On the Statistical Theory of the Decay of Atomic Nuclei." [27]

A summary of these papers would take too much space. We therefore confine ourselves only to a very brief description of the most important of these.

First is Frenkel's classical paper on electrocapillary fission of heavy nuclei by slow neutrons. [28] In this paper he develops an analogy between an atomic nucleus and a drop of charged liquid ("liquid drop model of the nucleus"). The electric charge tends to stretch and break the drop, while the nuclear binding forces between the particles prevent this and create a surface tension in the drop of "nuclear" liquid. Equilibrium of these two forces determines the maximum electric charge of the stable heavy nuclei, and instability of a nucleus that receives energy (for example, from a neutron) is due to the occurrence of vibrational motion in the nucleus upon capture of a neutron, particularly capillary waves. When the intensity of these waves is sufficient, the nucleus "splits" into two drops of smaller size. In the same paper Frenkel indicated that a nucleus of nonspherical (ellipsoidal) shape can be stable.* A more detailed similar representation of the mechanism of nuclear fission was advanced a few months later and quantitatively developed by Bohr and Wheeler. † These two papers, by Frenkel and by Bohr and Wheeler, contain the first formulation of the principles of modern theory of fission of heavy nuclei.

In the same year, 1939, Frenkel completed two other papers on molecular physics. One pertained to the theory of heterophase fluctuations and pre-transition phenomena. [30] In it he indicates that any phase contains the nuclei of a new phase, owing to fluctuations connected with the thermal motion of the particles. He treats the nuclei of the new phase, which appear in the initial phase at temperatures both higher and lower than the temperature of the macroscopic transformation, as particles of a certain "dissolved" substance, the concentration of which is determined on the basis of the general theory of dissociation in dilute solutions. Frenkel uses the results obtained to explain quantitatively the "pre-melting" (anomalous increase in specific heat and the coefficient of thermal expansion of crystals near the melting temperature), and also the kinetics of crystallization.

In 1939, Frenkel together with S. E. Bresler completed a basic paper on the thermal motion of long molecular chains. [31] It was shown in this paper that the thermal motion of a macromolecule of the polymer is made up of individual torsional oscillations of the links of the chain. As a result, the macromolecule moves and bends like an elastic steel rod, whereas heretofore it was regarded as perfectly free and "soft" like a thread. The results of this work turned out to be in good agreement with the experiments of Debye and Zimm, and served as a starting point for a large number of theoretical and experimental works.

Another important paper, written by Frenkel (together with T. A. Kontorova) during the same 1938–1939 period, [32] deals with the nature of plastic deformation. In this paper is proposed for the first time a microscopic theory of plastic deformation, in which plasticity is regarded as a special type of motion in the solid—a compatible collective displacement of entire groups of atoms, and certain regularities pertaining to this type of motion are predicted (in particular, a formula is derived for the rate of displacement of such a deformation).

Frank and Eshelby ‡ have approached the same problem, in several papers published ten years later, from the "macroscopic" point of view and obtained, starting on the basis of the fundamental equations of the theory

*See also the work by Zimm at al., Ann. Revs. of Phys. Chem., 4, 220 (1953).

†N. Bohr, Nature, 29 February 1936.

‡N. Bohr and F. Calcar, translated in UFN 20, 1, (1938).

**L. D. Landau, JETP 7, 819 (1937).

***V. Weiskopf, Phys. Rev. 52, 295 (1937); H. Bethe, Phys. Rev. 57, 1125 (1940).

*By now the existence of a whole class of nonspherical atomic nuclei has been established beyond any doubt.

†See N. Bohr and J. A. Wheeler, Phys. Rev. 56, 426 (1939).

‡F. C. Frank, Proc. Phys. Soc. 62, 131 (1949); J. D. Eshelby, Proc. Phys. Soc. 62, 307 (1949).

of elasticity, precisely the same results as Frenkel.

Along with active scientific work, Frenkel taught every year a course in theoretical physics at the Physico-mechanical department of the Leningrad Polytechnic Institute, where, continuing to head the department of theoretical physics, he also became head of the department of technical electronics (after the death of Professor T. S. Tartakovskiĭ).

In 1933, on the basis of one of the courses he delivered, Frenkel published his "Statistical Physics," and in 1940 he published his "Course of Theoretical Mechanics Based on Vector and Tensor Analysis."* Thus, by 1940, Frenkel completed a series of texts on theoretical physics, including, in addition to the foregoing books, the two-volume "Electrodynamics" and "Wave Mechanics."

During the first months of the second world war Frenkel completed a study [33] aimed at preventing trolley sparking. This problem arose when streetcar sparks made it impossible to camouflage Leningrad in the summer nights of 1941. At the end of August of 1941 Frenkel and his family were evacuated to Kazan', where the main Physics Institutes of the Academy of Sciences were then concentrated. Along with his work at the Leningrad Physico-technical Institute, Frenkel undertook the chairmanship of the department of theoretical physics in the Kazan' University, where he came in contact with the Kazan' physicists, including E. K. Zavoĭskiĭ. In evaluating the work of the latter, Frenkel noted in particular that the experimental curve that Zavoĭskiĭ obtained for paramagnetic absorption in a solution is a branch of a resonance curve, and presented a theory of relaxation losses due to paramagnetic resonances [34] in both solutions and solids. The extent to which this phenomenon is now used in both physics and in chemistry is well known.

In 1942—1945 Frenkel frequently visited Sverdlovsk, where his ties with the workers of the Sverdlovsk Metal Physics Institute became even closer than in the pre-war years. In Kazan', at the end of 1943, he again turned to problems in geophysics (theory of atmospheric electricity and terrestial magnetism); this activity was stimulated by the interest which his work evoked among the co-workers of the Institute of Theoretical Geophysics, particularly the director of this institute, O. Yu. Schmidt. In 1944 Frenkel became an associate of this institute and worked there for several years.

In Leningrad, where Frenkel frequently visited in 1943 (and where he ultimately returned in 1944), he acted as consultant on several projects in the Main Geophysical Observatory where he was quite active.

At the end of 1942, Frenkel started to write his "Kinetic Theory of Liquids" (rewarded with a first-degree State Prize in 1947). He wrote the book under the difficult wartime and evacuation conditions, when his "office" at the Physico-technical Institute was a corner fenced off by several file cabinets in the hall of the Ethnographic Museum of the Kazan' University (this hall housed several laboratories of the Physico-technical Institute, separated by plywood partitions which did not reach the ceiling). Incidentally, some of the exhibits of that museum were used at that time for their original purpose; in particular, one of the staff members of the Institute used a primitive grain mill of an Indian tribe to mill some rye which he managed to acquire. Naturally, Frenkel had likewise no office at home, using his landlady's laundry room as a working place. This laundry room, of course, had no table, which was replaced by a plywood board held on the knee. Under these conditions Frenkel wrote in the summer and fall of 1943 his "Kinetic Theory of Liquids," one of his best books (by his own estimate). This book summarized twenty years of work on the theory of liquids and real crystals. There are few examples in the history of science where a physicist developed such an extensive branch of science with so much use of his own ideas and work. It is typical of Frenkel that in this book, as incidentally everywhere else, he exhibited originality even in explaining work done by others, and this book goes far beyond the scope of the ordinary review.

A year after the publication of the Russian edition, the book was published by the Oxford University Press (1946); in working on its translation, Frenkel revised and expanded the exposition in many places.*

During the war years Frenkel published many articles on the theory of viscosity of liquids, [35] and an important paper on statistical theory of brittle strength (together with T. A. Kontorova), [36] in which he developed a theory that explained the so-called "scale factor"—the dependence of the strength of the body on its dimensions—established and investigated principally by A. P. Aleksandrov and S. N. Zhukov.†

In 1943 he published in the Vestnik of the Academy of Sciences of the USSR an article "Problems of Modern Physics," [37] which contains his own ideas of a program for physical research plan for many years ahead. Since I cannot present the content of this article in detail, I confine myself to the following extract:

"... Of greatest interest in physics are problems dealing with either extreme or intermediate properties of material bodies.

*The last book is the third completely revised edition ot the two others ("Course of Vector Analysis with Applications to Mechanics," GIZ, 1925 and "Analytic Mechanics," Kubutch, 1925).

*In 1955 an American edition of the book was published, and in 1959 it was published as the third volume of his collected works. This last edition contained corrections and addenda from the English version of the book.

†See, for example, A. P. Aleksandrov and S. N. Zhukov, Yavlenie khrupkogo razryva (Phenomenon of Brittle Fracture), Moscow, Gostekhizdat, 1933.

This is true not only of physics but of other sciences as well. Moreover, the most urgent problems pertain not to phenomena dealt with in certain fully developed and established sciences, but to "intermediate" or borderline phenomena. This is quite natural, since it is precisely these intermediate or borderline phenomena that are not only the most complicated, but at the same time the least studied. This is true, in particular, of problems in biophysics, the inclusion of which in physics is long past due.

Until recently physics was used for the solution of biological problems principally by biologists; physicists showed no particular interest in these problems (apart from physiological optics and acoustics). I am inclined to think that this situation ought to change radically in the nearest future, and that especially on this sector of the front of science the greatest battles for new advances in science should develop. I shall not list here the problems in biophysics, for they are uncountable."

Frenkel's prediction was wholly confirmed, and the present-day relentless and accelerating penetration of physics into biology and the striking advances of so-called molecular biology are well known.

We note that Frenkel himself worked on several biophysical researches. Thus, as long ago as in 1938 he applied the theory of polymers to the mechanism of muscular contraction, starting with the notion that this contraction is brought about by a process analogous to vulcanization of rubber and due to the release of ions in the chemical reactions that accompany the stimulation of the muscle.[38]

In 1940 he developed the theory of electrical phenomena connected with cavitation due to ultrasonic oscillations in a liquid,[39] which manifest themselves, for example in the case of water, in the appearance of experimentally observed electrical discharges (sparks) during propagation of ultrasonic waves. Such discharges occur in the cavitation space, according to Frenkel, because of fluctuations in the distribution of the extraneous ions dissolved in the water on the walls of the cavitation space. Frenkel developed these ideas of his in May of 1939 in a paper read at a Leningrad conference devoted to the biological action of radiant energy, as applied to the effect of ultrasound on living organism [see abstract of this paper in Arkhiv biologicheskikh nauk (Archives of Biological Sciences) 55, No. 3, 124 (1939)]. In particular, Frenkel points out in this paper the possibility of using ultrasound to destroy tumors, in view of the ability of focusing ultrasound in a desirable (internal) region.

We note, finally, that for several years Frenkel was interested in the mechanics of live organisms (i.e., movements of humans, animals, and insects). After the war, in consultation with one of the staff members of the Institute of Prothesis, Frenkel suggested an original design of an artificial leg which could be freely bent in the place corresponding to the knee joint.

In 1944 Frenkel was fifty years old. Quite typically, he spent his birthday in the train from Moscow to Gor'kiĭ, being invited by the Gor'kiĭ University to consult on one of its projects. This is excellent evidence of the extent to which any ostentation and flashiness were foreign to him.

After the end of the war, Frenkel's work developed in three principal directions, geophysics, molecular (especially experimental) physics, and field theory.

Without stopping to describe the main results he obtained in the field of terrestrial and atmospheric physics,* we mention here only the recognition recently gained by his theory of the origin of the earth's magnetic field (developed by Frenkel in the article[40,41]), which we already mentioned at the beginning of the present article.

One of Frenkel's characteristic features was that, along with a predilection towards the fundamental problems of physics he retained an acute and live interest in specific physical experimentation. He was always in close communication with experimenters working in many varied fields of physics.

The door of Frenkel's office in the Physico-technical Institute opened into the assembly hall, and in days when there were no assemblies, a unique queue formed outside the entrance to his room (like in a doctor's waiting room), consisting of theoreticians and experimenters, staff members of the Leningrad Physico-technical Institute and visitors from other Leningrad and foreign institutes, wishing to report on their work and to consult with him.

Frenkel frequently thought of organizing his own experimental laboratory. This desire could not be realized within the Leningrad Physico-technical Institude, where this idea was apparently regarded as some idiosyncracy. In Moscow, however, at the All-Union Institute for Aviation Materials (VIAM), where Frenkel was a consultant on several projects, they readily accepted this suggestion, and such a laboratory was organized at the beginning of 1948. Frenkel soon started work in this laboratory, and already in 1948, along with dealing with special problems, he started to experiment on friction, interaction between liquid films or drops and surfaces of solids, and related problems, which are of interest in themselves and have also purely applied technical character. The results were published in various journals. Without dwelling on the details of all the work done in this laboratory by Frenkel and his co-workers, it is appropriate to mention those dealing with the behavior of liquid drops (or bubbles) on solid surfaces. In a theoretical paper devoted to this problem,[42] Frenkel derived a formula for the maximum angle that the surface of a drop assumes before the drop starts rolling.

His next paper[43] (written with Ya. Aron), reports

*A detailed analysis of these papers (the number of which reaches 20) is given in the introductory article of the selected geophysical papers, published in the third volume of his collected works.

experiments on the dependence of the critical rolling angle of a drop (mercury or water) on its mass and also on the dependence of the angle at which air bubbles will roll on different surfaces. The results of the experiments proved to be in good agreement with the formulas proposed by Frenkel. On the basis of these investigations, particularly the research on the motion of drops flattened between two surfaces [44] Frenkel proposed in 1950, in a letter to the editor of ZhTF (Journal of Technical Physics), [45] the idea of replacing balls in bearings by drops of a liquid that is incapable of wetting the corresponding bearing surfaces and has low viscosity (mercury or Wood's alloy in the liquid state), particularly when the forces that press these surfaces to each other are relatively small.

Also related to this group of researches are two theoretical papers written immediately after the war. [46,47] The notions of viscous flow in crystalline bodie, developed by him in [47], serve as a recognized theoretical basis for the sintering of metal powders (powder metallurgy).

According to Frenkel, the sintering of a compressed powder proceeds in two stages. The first is the "coalescence of the drops" and consists of the grains of the metal powder coming together and an increase in their contact area; as a result, additional voids (pores) are produced in the compressed mass. The "streaming in" of these pores comprises the second phase of the sintering process; both phases are produced under the action of surface tension forces, based on viscous flow. These investigations, in conjunction with the earlier ones concerning diffusion and self diffusion in solids, have served as the starting point for many recent investigations by Ukrainian physicists (primarily B. Ya. Pines and his co-workers).* During the course of these researches, a detailed study was made of the occurrence of additional porosity during uneven partial hetero-diffusion of atoms in solids. The vacancies that then remain in the crystal lattice at the sites of the atoms of the more rapidly diffusing component form a supersaturated solution, and the decomposition of this solution, i.e., the separation of the excess vacancies, does indeed lead to the formation of the pores. This phenomenon has been named the Frenkel effect, being compatible only with the vacancy diffusion mechanism indicated by Frenkel, and confirming this mechanism.

The last group of Frenkel's researches dealt with general problems of quantum mechanics—field theory of matter. Devoted to these problems are four printed [48,49,50,51] and several unpublished articles, on which Frenkel worked during the last two or three years of his life.

In these articles, the general physical problems considered by Frenkel border on the philosophical. In this connection, interesting material was found in his files on a book headed "Epistemology of Physical Sciences." The file contains also the plan of this book, the foreword, and the beginning of the first chapter.* I think it is appropriate to present this plan here.

Plan of the Book

I. Similarity and Difference

1. Cognition and recognition. 2. Physical analogies. 3. Formal (mathematical) analogies. 4. Structure of a physical theory and its relation to experiment (direct and indirect experiments). 5. Relation between mathematical theory and physical reality.

II. Cause and Effect

1. Coexistence and succession of causes and effects in mechanics and electrodynamics. 2. Reciprocity of cause and effect and stability in physical phenomena. 3. Instability in living phenomena. 4. Anthropomorphism of causality and its replacement by regularity. 5. Regularity and randomness in statistics and mechanics (statistical regularity; randomness).

III. Change and Constancy

1. Constants of variation and laws of conservation. 2. Invariant things and relationships.† 3. Covariance and relativity 4. Variance and uniformity. 5. Understanding as a reduction to constancy and uniformity.

†Note. Elimination of subjective aspects by invariance or symmetry (loss of identity).

IV. Macroscopic and Microscopic Considerations

1. Microscopic theory of macroscopic phenomena. 2. Macroscopic theory of microscopic phenomena. 3. Model representations and the nature of matter. 4. Continuity and discontinuity. 5. Role of observer and quanta of action.

Along with the foregoing multifaceted work, Frenkel, as always, continued to carry out vigorous pedagogical activity. The result of this was in particular the publication of the second expanded edition of "Statistical Physics" (1948) and "Introduction to the Theory of Metals" (editions of 1950 and 1951; posthumous edition 1958). The last book, incidentally, went through four editions abroad.

In 1946 Frenkel published a small book on "Release of Atomic Energy," which he soon republished in greatly expanded form under the title "Principles of Theory of Atomic Nuclei" (1950; posthumous edition 1955).

In his last year of life, Frenkel proceeded to prepare a new edition of "Wave Mechanics," having rewritten many of its sections, and was planning to republish his "Electrodynamics" (a plan for the new edition was also left among his papers). A week before his death Frenkel was notified that the Academy of Sciences Press planned to publish his "Kinetic Theory of Liquids" (which he intended to revise com-

*B. Ya. Pines, UFN 52, (4), 601 (1954); B. Ya. Pines and A. F. Sirenko, I. Self-induction and Hetero-diffusion in Inhomogeneous Body; II. The Direct and Reverse Frenkel Effects, ZhTF 28 1748 (1958), Soviet Phys.–Tech. Phys. 3, 1612 (1959). III. Manifestation of Frenkel Effects and Kirkendahl Effects in the Sintering of Specimens Made of Mixtures of Mutually Diffusing Metal Powders, ibid, 29, 653 (1959), translation 4, 582 (1959).

*The work on this book dates back to the end of the 1940's and the beginning of the 1950's.

pletely under the title "Kinetic Theory of Solids and Liquids").

Frenkel was an exceptionally healthy man and was never sick: Only a man of strong health could withstand the tremendous and stressed work which carried on all his life. However, in the last two or three years of his life his health started to fail; the summer vacation, in his words, no longer relieved the fatigue accumulated over the year.

In October 1951, Frenkel's health forced him to interrupt his work and spend two months in a resort. After returning to Leningrad, he continued to work until the last day of his life.

He died on the night of 23 January 1952.

I hope that in this article I was able to describe with sufficient relief, although in only general outlines, the importance of Frenkel's contribution to the development of modern theoretical physics. I wish to emphasize in conclusion the tremendous role that Frenkel played in the development of theoretical physics in our country. It was not by accident that he had to be self-taught in his youth: In our theoretical physics he played the role of a pioneer in many important branches that have come into being in our century; he not only developed creatively these branches of physics, but was the first to present them to our young students and to our main scientific ranks of physicists.

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Translated by J. G. Adashko