SOME STEPS ON THE WAY OF THE FORMATION OF PLASMA TURBULENCE THEORY

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I was lucky in my life. I heard the course of lectures by N.N. Bogoliubov in the second half of the 1940s given by him for future physicist-theorists at the Faculty of Physics of Moscow State University. This course was based on his book "Problems of Dynamical Theory in Statistical Physics" published in 1946. I was under the especially strong impression of the solution of the problem of irreversibility of the kinetic description. As well known, N.N. Bogoliubov transferred this problem from the Boltzmann kinetic equation onto the boundary condition of the weakening of correlations of many-particle distribution functions. In this case, the boundary condition by N.N. Bogoliubov is subordinated to the statement of problems concerning the study of the future, which introduces the irreversibility – an increase of the entropy. I note that a change of such boundary condition for the application it to studying the past simply replaces the sign of the Boltzmann collision integral in the derivation of the Boltzmann equation. All the said by N.N. Bogoliubov rendered an indelible influence on my student's mind loaded by the history of the discussion which accompanied the appearance of the Boltzmann equation. Since that time, a number of my results were explicitly and implicitly connected with the N.N. Bogoliubov's approach to the substantiation of physical kinetics.

In the present communication, I should like to pay attention to the expediency to use the Bogoliubov's approach to the substantiation and the development of kinetic theory in such a trend of physics as the theory of plasma turbulence. There, as it seems to me, a lot of questions remained outside of the field of researchers' attention. In order to promote the awakening of the interest in this branch of science advanced in the USSR, I restore some steps of the history of its formation. I am sure that it is actual today, because the experimental discovery of the plasma turbulence was the result of efforts of physicists in Moscow and Khar'kov. It is the example which is worthy to be imitated in our time period of the complicated geopolicy.

Sufficiently many years were over, but I well remember the pleasant reminiscence of the latest (but old now) news about that E.K. Zavoiskii who left Kazan for Moscow to work at I.V. Kurchatov Institute of Atomic Energy named earlier the Laboratory of Measuring Devices of the AS of USSR (LIPAN in common parlance among Russian physicists) became to study the heating of plasma. It seemed to me that my exceptionally theoretical interest in plasma did not correspond completely to the circle of problems considered by the mode legislators in the field of controlled thermonuclear fusion which were leaders in Moscow. However, this point did not hamper me to create the own intellectual world which was closer to real experiments in some aspects than the world of ideas of FIAN's experimenters (FIAN stands for the Russian short name of Lebedev Physical Institute of the RAS). The possibility of such a freedom was characteristic of the staff of the theoretical department of the FIAN, which was a reference point for other departments. My stay in the plasmocracy, as well as the term to seek for sufficiently profound experimental results, was else short in time. This explains why the news about E.K. Zavoiskii was significant for me.

His name was very weighty among the comparatively young (at that time) physicists. I can surely assert that he was already a man-legend. Of course, the experimental discovery of electron paramagnetic resonance by him made the position of Evgenii Konstantinovich Zavoiskii in the Soviet physics heroic. His legendariness was also supported, for example, by the defense of his doctoral dissertation which was associated with the initial negative attitude to his work. However, when he repeated the results included into his dissertation at the institute guided by P.L. Kapitsa, the dissertation was accepted for the defense and then was successfully defended. At that time, the physical youth was collecting, by maturing, its divine pantheon. E.K. Zavoiskii had already occupied the deserved place in this pantheon. He had already been considered the experimenter of God, though this term can seem unnatural for the practically fully atheistic young physicists in the second half of the XX-th century. But it was just so.

I note that the staff of researchers in the field of controlled thermonuclear fusion at the Kurchatov Institute, where E.K. Zavoiskii found himself, was considered leading in the USSR. However, their experimental scientific results which were met initially with enthusiasm turned out too far from the desired aim. Therefore, any outsider could see no tragic element in the invitation of E.K. Zavoiskii by I.V. Kurchatov to take participation in works on the peaceful thermonuclear fusion. But such an element did be, and I.V. Kurchatov as a highly experienced man would understand it. The matter was in the presence of a compact energetic group of researchers of the thermonuclear fusion at the Kurchatov Institute. This group supported its leaders, L.A. Artsimovich and M.A. Leontovich, in their comprehension of the essence of plasma physics studied by them for a significant period. Their results obtained certain recognition in the USSR and abroad. In this situation, it seemed that the appearance of a "novice" changes almost nothing. However, the abovementioned news was related to the time when E.K. Zavoiskii had worked at the Kurchatov Institute (i.e., at the LIPAN) for several years. By antedating, one can say that the group engaged in the controlled thermonuclear fusion was separated into two clans, respectively Artsimovich' clan and Zavoiskii's clan, with ordinary interclan trifles and the permanent gradual development of science. For an external observer, all things were good. But the estimate of an internal (at the LIPAN) observer was different. I cite the article by S.V. Mirnov in "Collection of Reminiscences about Academician E.K. Zavoiskii. The Magician of Experiment" (Nauka, Moscow,1993): "Clans of Artsimovich and Zavoiskii were definitely in opposition to each other as for the thermonuclear fusion ... The department of Artsimovich suffered painfully from the intrusion into its kitchen-garden".

Eventually, the delayed-action bomb had exploded. In his annual survey, the leader of the Division of Physics and Astronomy of the AS of the USSR L.A. Artsimovich declared the discovery of the turbulent heating of plasma by the group of E.K. Zavoiskii. However, then at an all-Moscow seminar held at the Kurchatov Institute in 1965, A.I. Karchevskii made communication bearing the unmasking character. He asserted that he repeated the experiment made by E.K. Zavoiskii's group, and the new results indicate that only a small part of the whole plasma volume is heated, whereas the remaining part is not. E.K. Zavoiskii answered at once that A.I. Karchevskii could not measure the heating of the main part of the plasma volume, because the diamagnetic effect was not registered. But the leadership hurried and approved a commission for the consideration of technical details. The Moscow plasmocracy boiled up. The commission reported about the inaccuracy of previous measurements and expressed its doubt about the turbulent heating. Fortunately, then A.I. Karchevskii increased the voltage on his condensers and obtained the turbulent heating. However, the words, which were "heretical" for admirers of E.K. Zavoiskii who occupied his place in the pantheon by right, were already pronounced.

The support of E.K. Zavoiskii appeared in Khar'kov at the Khar'kov Physico-Technical Institute. At the beginning of the 1960s, V.A. Suprunenko, E.D. Volkov, and E.A. Sukhomlin discovered that the resistance of a hard-current gas discharge increases at its heating. The Khar'kov physicists had heard that E.K. Zavoiskii was developing, in Moscow, a method of heating of plasma with electric current which is based on the use of "collective interactions". By the way, the role of collective effects in the interpretation of the experiments of the V.A. Suprunenko's group was indicated by Ya.B. Fainberg. E.K. Zavoiskii himself followed just this idea of collective oscillations.

Decisive for lessening the tense situation concerning the role of collective processes in the heating of plasma was the fact that the Zavoiskii–Suprunenko contact turned out characteristic of Evgenii Konstantinovich; namely, it was noble. V.A. Suprunenko wrote about the behavior of Evgenii Konstantinovich Zavoiskii: "he not only did not hamper us, but, on the contrary, he rendered the huge moral and even material support". Further, he wrote: "Evgenii Konstantinovich shared his ideas and plans of subsequent experiments with me, prompted some top-priority tasks, and even permitted his co-workers to give us some very necessary details. Since that time for at least one decade, our small Khar'kov collective worked in a close contact with the laboratory of E.K. Zavoiskii". (See the article of V.A. Suprunenko in "Collection of Reminiscences about Academician E.K. Zavoiskii. The Magician of Experiment" (Nauka, Moscow,1993).

One of the results of this work is discovery No. 112: Phenomenon of turbulent heating and anomalous resistance of plasma – Claim OT-7595 on 30.03.1970. The discovery priority on 9.09.1961. Published on 23.10.72. The authors: M.V. Babykin, E.D. Volkov, P.P. Gavrin, B.A. Demidov, E.K. Zavoiskii, L.I. Rudakov, V.A. Skoryupin, V.A. Suprunenko, E.A. Sukhomlin, Ya.B. Fainberg, S.D. Fanchenko. In what follows, we will use the term discovery No. 112.

We emphasize that the 1960s were years when the intent attention of physicist-theorists from the plasmocracy was given to the plasma turbulence which was sometimes mentioned as collective processes in plasma. In our case, we mean the following. As long ago as in the first half of the XX-th century, the American physicists I. Langmuir and L. Tonks discovered specific plasma oscillations, in which many particles of plasma take participation and cause them. By the middle of the XX-th century, a lot of collective oscillations were found. The magnetoacoustic and ion-acoustic branches of collective plasma oscillations were sufficiently well known. Just these branches of oscillations were related to the results of experiments on the anomalous heating of plasma made by the group of E.K. Zavoiskii in Moscow and on the anomalous resistance of plasma made by the group of V.A. Suprunenko in Khar'kov resulted in the abovementioned discovery. For example, the first work on the anomalous heating of plasma considered magnetoacoustic waves [M.V. Babykin, P.P. Gavrin, E.K. Zavoiskii, L.I. Rudakov, and V.A. Skoryupin, Zh. Eksp. Teor. Fiz. **43**, 411, (1962)], and then the ion-acoustic turbulence was taken into account [see the review: E.K. Zavoiskii and L.I. Rudakov, Plasma Physics – Collective Processes in Plasma and Turbulent Heating (Znanie, Moscow, 1967)].

Let us now turn to the theory. In 1961–1962, three theoretical works [1] were published, in which the equation named quasilinear was proposed for the description of a nonlinear interaction of waves and particles of plasma. We note that one of the works lay in the portfolio of the Editorial Board of Zh. Eksp. Teor. Fiz. one year, being reported verbally else earlier. The necessity of the quasilinear equation (though such a term was not used by the authors of the first of these three articles which attracted the attention of many researchers) for the comprehension of the discovery made by E.K. Zavoiskii was obvious. However, the quasilinear approximation was in poor agreement with experimental data of the works initiated by discovery No. 112. Namely, the main difference consisted in that the high-intensity ion-acoustic fluctuations arising in plasma with a current have a rather wide spectrum.

However, somewhat later on, it was proposed [2] one more equation. As distinct from the quasilinear equation based on the Cherenkov effect, it involves the simulated scattering of fluctuating ion-acoustic waves on ions, by describing their balance. This new equation allowed one to obtain a comparatively wide spectrum of fluctuations of ion-acoustic waves in plasma positioned in a constant electric field. This spectrum was confirmed experimentally in many works, because the followers of the authors of discovery No. 112 appeared in a number of countries of the world. The spectrum was called the Kadomtsev–Petviashvili spectrum.

It is worth to note that, despite a definite success, the theory of the turbulence spectrum related to discovery No. 112 turned out unfinished in the sense that no angular distribution of turbulent fluctuations was calculated, though the mathematical tools for the description of the physical phenomenon itself were available. At that time, I traced attentively the development of the theory of discovery No. 112, but I was retained from the work on the necessary theory by the scandalous atmosphere associated with this problem. Therefore, the facts that E.K. Zavoiskii changed the direction of his studies and then left the Kurchatov Institute seemed to me natural. The victory costed him very much. His brilliant report at the International conference on controlled thermonuclear fusion at Culham (Great Britain) in 1965 produced a strong impression on the international audience and led to the development of a separate trend in plasma physics. In the world physics, the Zavoiskii name sounded very weighty. But in his Motherland, the undercarpet play deprived him of the possibility to present the scientific reports at foreign conferences. Moreover, this was realized in the most impudent form. To go through such a situation is especially painful for delicate persons. I note that Evgenii Konstantinovich was one of the most delicate men. This delicacy removed him from science and then from life. The civil funeral rites occurred at the FIAN which is positioned on the side of Moscow opposite to the Kurchatov Institute.

On those sad days, no exhaustive interpretation of discovery No. 112 was available yet. But the time was passing. During some years, the emotions decreased or disappeared together with their carriers. The plasmocracy continued to be engaged in its matter, but the memory of discovery No. 112 was alive. This memory required the comprehension from science.

In 1982, a theoretical work was published in Zh. Eksp. Teor. Fiz. [3]. Its authors decided on the construction of a theory of ion-acoustic turbulence which considers simultaneously the Cherenkov turbulence-generating interaction of electrons with plasma and the simulated scattering of ion-acoustic waves on ions of plasma, which stabilizes the ion-acoustic turbulence by Kadomtsev and Petviashvili. So, such a theory included both plasma effects which were used separately for the explanation of discovery No. 112 in the time when E.K. Zavoiskii was living.

The authors of the mentioned article worked at the FIAN and were not afraid to publish long formulas in their works following the natural traditions of I.E. Tamm's school. That is, a comparatively awkward theory was an "ordinary" thing for the FIAN's theorists, though it was ostracized in datzybaos at the Kurchatov Institute. In brief, we have constructed a relatively involved theoretical model and confirmed, in fact, the distribution over frequencies obtained by Kadomtsev and Petviashvili. We also calculated the angular distribution of turbulent pulsations, being naturally free from the divergence – "infinity" – obtained by L.I. Rudakov and L.V. Korablev [4]. It becomes clear that the earlier proposed elements of a model of ion-acoustic turbulence are consistent and allow one to formulate the single physical theoretical model.

However, it was not a finish. Sometimes, by flying in an aircraft and by remembering the latest conference on plasma, I thought suddenly: the Kadomtsev–Petviashvili model is suitable only for a plasma with ions of one sort and, strictly speaking, is not proper even for deuterium-tritium plasma. In 1992, S.A. Uryupin and I published the theory of ion-acoustic turbulence of a plasma with ions of two sorts [5].

The found similarity and difference of the results concerning the spectrum of ion-acoustic turbulence in the model of plasma with ions of two sorts at solving a number of problems, as compared with the results of the model with ions of one sort, strengthen our assurance in the significance of our theory. At the same time, it became clear that the turbulence related to discovery No. 112 is the phenomenon potentially very rich for the study. I mention that discovery No. 112 was met by the leading plasmocracy very coldly without, simply speaking, a due respect to experiment. But it is quite obvious now that discovery No. 112 involves undoubtedly the properties of the plasma turbulence which have not attracted the proper attention till now. This is seen from the potentialities of the modern theory used for its comprehension. Therefore, we may surely think that the scandal at the LIPAN in the middle of the past century will else more enrich the plasma science and will recall about the delicate style of the great worker of science who turned out redundant at the LIPAN, Evgenii Konstantinovich Zavoiskii, who was called "the magician of experiment" and was an extraordinary person in the Soviet physics. Without any doubt, his human properties became the base of the fruitful collaboration of E.K. Zavoiskii's Moscow school and V.A. Suprunenko's Khar'kov school which had led to discovery No. 112 and awakened theorists' thoughts.

In conclusion, I emphasize that I would hope for that the use of N.N. Bogoliubov's approach to the theoretical clarification of properties of the plasma turbulence will play its role.

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