PACS numbers: **01.10. – m**, 01.10.Fv

The 100th anniversary of the birth of I M Lifshitz
(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 18 January 2017)

DOI: https://doi.org/10.3367/UFNe.2017.01.038043

On 18 January 2017, a scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held at the conference hall of the P N Lebedev Physical Institute, RAS, in honor of the 100th anniversary of the birth of I M Lifshitz.

The following reports were put on the session agenda as posted on the PSD website http://www.gpad.ac.ru:

(1) **Grosberg A Yu** (New York University, USA) "Ilya Mikhailovich Lifshitz and physics of biopolymers";

(2) **Pastur L A** (B I Verkin Institute for Low Temperature Physics & Engineering, National Academy of Sciences of Ukraine, Kharkiv) "Disordered fermions";

(3) **Volovik G E** (L D Landau Institute for Theoretical Physics, RAS, Moscow; Aalto University, Finland) "Exotic Lifshitz transitions in topological materials";

(4) **Krapivskii P** (Boston University, USA) "Lifshitz–Slyozov–Wagner theory and social dynamics";

(5) **Gorsky A S** (Institute for Information Transmission Problems, Moscow) "New critical phenomena in random networks and multiparticle localization";

(6) **Nechaev S K** (P N Lebedev Physical Institute, RAS, Moscow; Interdisciplinary Scientific Center Poncelet, Moscow) "Rare event statistics and hierarchy: from Lifshitz tails to modular invariance".

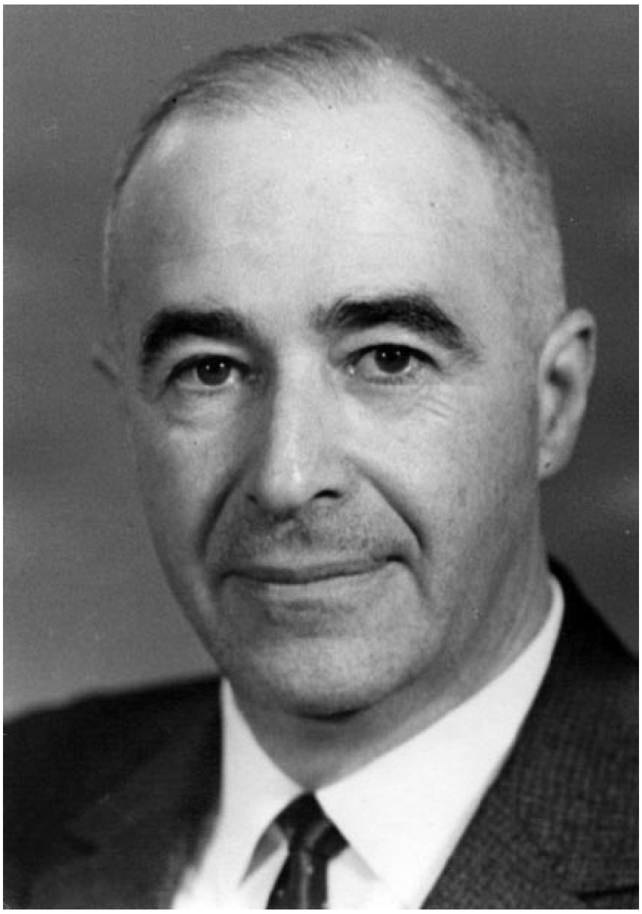
Papers based on oral reports 1, 3, and 6 are given below.

Uspekhi Fizicheskikh Nauk **188** (1) 89 – 112 (2018)
DOI: https://doi.org/10.3367/UFNr.2017.01.038043
Translated by E G Strel'chenko, G E Volovik, S K Nechaev, and K Polovnikov; edited by A Radzig

PACS numbers: **01.60. + q**, **01.65. + g**
DOI: https://doi.org/10.3367/UFNe.2017.01.038041

Ilya Mikhailovich Lifshitz — 100th birthday anniversary

A Yu Grosberg



Ilya Mikhailovich Lifshitz
(13.01.1917 – 23.10.1982)

The 13th of January 2017 marked the 100th anniversary of the birth of Ilya Mikhailovich Lifshitz, one of the founders of the modern theoretical physics of condensed matter. Ilya Mikhailovich was born in Kharkiv, Ukraine and lived there until 1969. There, he received his education, graduating from Kharkov University, and then taught in the same University and held a position at the Ukrainian Institute of Physics and Technology. In the late 1960s, following the invitation by P L Kapitza, he moved to Moscow to head the Theoretical Department of the Institute for Physical Problems after Landau's death, leaving behind a highly reputable (and still active and successful) scientific school of physics. Still a few years before this move, Ilya Mikhailovich followed the

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Received 20 December 2016
Uspekhi Fizicheskikh Nauk **188** (1) 89 – 94 (2018)
DOI: https://doi.org/10.3367/UFNr.2017.01.038041
Translated by E G Strel'chenko; edited by A Radzig

invitation from I G Petrovskii, Rector at Lomonosov Moscow State University (MSU), to organize the program in theoretical solid state physics at the Quantum Theory Department, then under M A Leontovich, and to join M A in leading a seminar at the MSU Faculty of Physics.

Detailed biographies of I M have been published and are available elsewhere [1, 2]. However, considering that 100 years is a long time, and even 35 posthumous years is also quite a while; considering further that not only I M's students but indeed their students are no longer that young and that it is, in fact, his scientific grand grandchildren who are at the top of their careers today; and remembering, finally, that his name belongs to history, it seems appropriate to take a look at the historical context, development, and current status of the ideas that Ilya Mikhailovich contributed to the many fields of physics, where he worked.

While the first third of the twentieth century witnessed an unprecedented revolution in physics, the middle of the century started a systematic expansion into other fields — not only high energies and the depths of the microworld, not only farther into the Universe and its history, but also substances, media, materials, and systems of ever increasing complexity that exist around us, of natural, artificial, and living origin. And in this extension of horizons the role of I M Lifshitz is difficult to overestimate.

One of the earliest successes in quantum mechanics was to explain why some crystals are dielectrics, while others are conductors (F Bloch, 1928). But why do different metals differ? And they certainly do — and quite considerably so, especially at low temperatures and in a magnetic field — a fact supported by a huge body of experimental evidence accumulated by the mid-twentieth century. Attempts were made to explain the energy spectra of electrons in various crystals by drawing constant energy surfaces in the Drude–Lorentz–Sommerfeld model, but the surface looked monstrous and seemed to give no hint whatsoever as to how they possibly relate to any observable properties of metals. If, as Sir Rutherford famously said, "All science is either physics or stamp collecting" (is not it amusing to quote this joke when speaking of the avid stamp collector Ilya Mikhailovich Lifshitz!), then the collecting of the constant energy surfaces of metals definitely was not regarded as physics by most physicists. But not so by Ilya Mikhailovich. As time went, it became first clear from his work and later from the work of his students that the thermodynamic properties of metals are determined by the geometry of their Fermi surfaces. Later on, the same was found to be true for the kinetic properties of metals. I M Lifshitz and his students developed a geometric language in which the 'proper name' of each metal is its Fermi surface; this is called 'fermiology' in the current literature.

The first step on the way to fermiology was the idea of I M Lifshitz's and L Onsager's (who, incidentally, knew nothing of each other's work) to treat an electron moving in a crystal quasiclassically, i.e., as a classical particle but with the energy depending in an unusual way on the momentum (quasimomentum) — rather than the familiar law $\varepsilon = p^2/(2m)$. While this dispersion law is in itself of a quantum nature and should, in principle, be found by a comprehensive quantum calculation for each specific metal, many properties can be determined by considering an electron with an arbitrary dispersion law: $\varepsilon = \varepsilon(p)$. The dynamic characteristics of an electron are then linked in a natural way to the geometry of the Fermi surface.

The first success of such geometrization was the theory of the de Haas–van Alphen effect in metals (magnetic susceptibility oscillations periodic in $1/H$, where H is the magnetic field strength). I M Lifshitz and L Onsager showed independently that the dominant contribution to the magnetic susceptibility comes from the extremal Fermi surface cross sections perpendicular to the applied magnetic field, and it is this fact which leads to an expression for the oscillation period (1950–1952). While L Onsager stopped there, I M Lifshitz went further. The complete theory he developed in 1953–1955 in collaboration with A M Kosevich related the temperature dependence of the oscillation amplitude to the electron velocity and clarified the role of dissipative processes. Further development of the galvanomagnetic theory by I M Lifshitz, M Ya Azbel', M I Kaganov, and V G Peschanskii in 1956–1960 also revealed that the geometry and topology features of the Fermi surface influence not only the thermodynamic but also the kinetic properties of metals in a magnetic field. One of the most notable 'fermiologic' achievements was the discovery that electromagnetic fields in metals placed in a static magnetic field can exhibit complex structures, including undamped electromagnetic waves and various kinds of resonances (of which the most studied is the one sometimes called the Azbel'–Kaner resonance after Ilya Mikhailovich's two students).

Fermiology not only explained the diversity of the properties of metals, but also has become the most reliable tool to learn about electronic energy spectra. It is due to fermiology that we now know in detail the energy spectra of all metals and many intermetallic compounds. Using geometric language enabled I M Lifshitz to predict the so-called Lifshitz transition (or, in Russian terminology, the electron-topological or two-and-a-half-order transition). Such a transition occurs, for example, when the metal Fermi surface changes its topology (connectivity) or develops individual split-off bubbles or broken thin cross connections under an applied pressure.

Predominantly developed by I M Lifshitz and his students, fermiology is currently an integral part of any serious course on the theory of metals, no less necessary than the Bardeen–Cooper–Schrieffer theory of superconductivity or the Landau theory of Fermi liquids.

Broadening the view from metals to solid state theory in general, the formulation and solution of two inverse problems are credited to I M Lifshitz. First, how, in principle, can we determine the shape of the Fermi surface, i.e., restore the spectrum of fermion excitations? Second, how to retrieve the spectrum of boson excitations? For the boson spectrum, the answer is that it can be done in a unique way by utilizing pure thermodynamic heat capacity data, whereas in the fermion case, data on oscillations in a magnetic field are necessary (and sufficient), as I M Lifshitz and A V Pogorelov showed.

Nor should mention be omitted here of the quantum diffusion of defects, a field in which Ilya Mikhailovich contributed no less essentially to the very foundations of solid state physics. Prior to A F Andreev's and I M Lifshitz's 1969 paper, it was taken for granted that the number of sites in a crystal equals the number of atoms. It then turned out — and indeed, after their paper 'it became commonly known' — that even at zero temperature crystal vacancies (for example, in He-4) can move by quantum tunneling, are naturally interpreted as Bose quasiparticles, and can form a superfluid condensate. This new state of matter is usually called a supersolid (a quantum crystal in Russian terminology). To the author's knowledge, whether this state is observable remains an open, controversial, and much addressed question even today, forty (!) years after its prediction.

Incidentally, I M Lifshitz's paper on quantum diffusion is one of his most cited works. But the most cited one is his 1958 paper co-authored with V V Slyozov on the kinetics of the first-order phase transition at the nuclei coalescence stage. Although this process, so-called coarsening (Ostwald ripening), had been known for a long time, it was I M Lifshitz's and V V Slyozov's characteristically beautiful mathematical analysis that gave remarkable insight into the physics of the phenomenon. Their law for how the average nucleus size grows in time, $\sim t^{1/3}$, is recognized as classic.[1] In the same context, mention should be made of I M Lifshitz's and Yu M Kagan's pioneering work on the quantum kinetics of the first-order phase transition, in which nuclei form via quantum subbarrier tunneling.

While the first full manifestation of I M Lifshitz's creative potential was in the physics of metals, it is perhaps the physics of disorder which was his constant preoccupation and interest, something like a thread through the whole of his career. Chronologically, the first research area to which he applied his creative skills in the late 1930s was the physics of real (i.e., nonideal) crystals (note that he was only 24 when he passed his doctoral dissertation defense). At the time, the theoretical knowledge of solids did not extend beyond perfect (i.e., perfectly ordered) crystals. While impurities were, of course, universally recognized to exist, their only assumed role was that of a hindrance, scattering centers responsible for electrical resistance. Amorphous states were completely beyond the scope of theoretical physics. As it turned out, impurities are not only scattering centers: they also give rise to local vibrational modes — with the result that the heat capacity of a solid differs from that predicted by Debye and is impurity-dependent.

While I M Lifshitz's research in the 1940s focused on the disorder of the lattice, the late 1950s witnessed a decisive shift to the electronic properties of disordered materials. It would not be exactly correct, though, to say that he turned to this research area; as things really were, it was he, together with P Anderson and N Mott, who opened it up. Of course, interest in this subject was kindled by the engineering applications of doped semiconductors, but this does not at all downplay his intellectual leadership. Among his achievements is the famous optimum fluctuation method and its associated concept of so-called I M Lifshitz tails. I M's often used word when explaining the concept of disorder was 'memory', which referred to the fact that, for example, a certain distribution of impurity atoms that arises during the preparation of a sample is 'remembered' — in the sense that it remains unchanged by the subsequent thermal motion of the system. If the simplest model of a regular crystal is the motion of a particle in a spatially periodic potential, a disordered system can, in the simplest case, be thought of as a set of random-depth potential wells located at the sites of a regular spatially periodic lattice (the so-called Anderson model) or as a set of equal-depth wells located at random points in space (the Lifshitz model).

In another development, I M Lifshitz conducted a remarkably simple analysis of how this frozen or 'remembered' disorder affects the spectrum of possible electronic energy states. The idea is that the appearance of an energy level at a certain distance from the boundary of the band gap in the spectrum of a periodic system is possible only if a certain number of impurities come together or if deeper or more closely separated wells exist and, as Ilya Mikhailovich showed, the probability of such a level appearing is dominated by quite specific disorder realizations, which were called optimum fluctuations according to his readily accepted suggestion. In 1963–1964, I M Lifshitz's analysis of these fluctuations led him to conclude that the probability of finding relevant energy levels exhibits an exponential decay, a result which entered physics under the name 'Lifshitz's tails'. The remarkable universality of I M Lifshitz's results and his deep insight into the problem already show up in the now firmly established fact that Lifshitz's tails occur not only in the Lifshitz model but also in the Anderson model and indeed in many other systems. These and other related results were summarized by I M Lifshitz, S A Gredeskul, and L A Pastur in their *Introduction to the Theory of Disordered Systems*, which was first published in Russian in 1982, just shortly before I M Lifshitz's death.

The inherent logic of advancing the physics of disordered systems naturally ushered Ilya Mikhailovich into the field of polymers. The context within which this occurred involved the revolution in biology and the emergence of molecular biology. Starting in the early 1960s, Ilya Mikhailovich participated in the famous School of Molecular Biology in Dubna and considered problems in biopolymer physics to be a challenge to the theoretical physics of condensed matter, or more precisely, to the physics of disordered systems. He was one of, if not THE first to realize that the 'information content' of biological molecules and the 'frozen disorder' in physical systems are surprisingly closely related concepts and more often than not are just different names for the same thing.

Here, I M Lifshitz again applies the idea of 'memory': both polymer chain sequences and the impurity arrangement in a solid are created during the preparation (synthesis) procedure and thereafter remain unaffected by thermal motions. This realization became the starting point of his work on polymers. Ilya Mikhailovich was, of course, fully aware of the serious difference between these two kinds of phenomena: whereas disorder in physical systems usually results from some more or less random processes, a chain sequence (in, say, a protein molecule) is generated by a highly organized biosynthesis process in a cell on a ribosome — and in this sense the application of the term 'disorder' to proteins looks somewhat frightening and disorienting. Still, similarity does exist and is important, and this is the possible reason why Ilya Mikhailovich insisted on the use of the term 'memory' — adding the definition 'linear' in the case of polymers (linear memory). While this term did not take root, the idea itself has by now been fully accepted — to the point indeed that no one remembers the name of its author.

It should be noted that at about the same time, in the mid-1960s, a kind of revolution — or a change in paradigm — occurred in the field of polymers in the West, associated principally with the names of P-G de Gennes and S F Edwards. I M Lifshitz's and later his students' work on polymer physics became a natural and integral part of this revolution — a revolution which by now has turned polymers into one of the

[1] C Wagner obtained analytical results independently of I M Lifshitz and V V Slyozov. The duo's first paper was published in *Zh. Eksp. Teor. Fiz.* in 1958, and its more detailed English version appeared three years later in *J. Phys. Chem. Solids* (1961), at the same time as Wagner's paper; hence, the commonly used term Lifshitz–Slyozov–Wagner theory.

building blocks of an important new field, the physics of 'soft' condensed matter.

There is a noteworthy feature to 'I M Lifshitz's polymer physics program' — a program which already showed up in his first paper (1968) on polymers. He noted at the very outset that if even simple liquids of small molecules are not amenable to a theoretical description unless with some uncontrollable approximations, then there are no chances at all to develop a theory for a by far more complex system of small molecules tied into a long chain. Acting with his characteristic elegance, he approached the problem the other way around by asking: supposing that we know the thermodynamic functions of a simple liquid of disconnected monomers; how can the properties of polymers be expressed in terms of them? In retrospect, one cannot help noticing the conceptual similarity between 'an arbitrary system of broken chains' and 'an electron with an arbitrary dispersion law'.

The most important achievement of I M Lifshitz in polymer physics is the formulation of concept and development of the theory of the coil–globule transition. First, in 1968, came a prototypic theory of such a transition for the most fundamental case of a single homopolymer (its summary can be found in I M Lifshitz's 1978 review, also one of his most cited papers). Later on, a huge collection of other transitions of this type was gathered, mainly through the efforts of I M Lifshitz's students. A sufficient example is genome folding, a recently emerging active field of research which is concerned with how a 2-meter long DNA filament turns out to be packed into a 10-μm nucleus in each cell of the human body. That the genome has a globular nature can by now be considered a generally accepted fact, and the numerous discussions concerning this subject focus on the exact aspects of this globule, such as its degree of equilibrium, how many knots it has, what its fractal properties and dynamics are, etc.

Theoretical work on the folding of proteins and related molecules provides another good illustration of the current status of the globule concept. The central idea here is that of design — an artificial process allowing 'constructing' sequences with certain desired properties (folding uniqueness, stability to mutations, etc.) and estimating their number, i.e., the corresponding entropy.

Other examples are readily available of how fruitful I M Lifshitz's polymer ideas are. Whereas, prior to I M Lifshitz's work, the dominant polymer research tools were the one-dimensional approach (rotation isomer model, etc.) or P Flory's empirically based theories or else P-G de Gennes's scaling concept, Ilya Mikhailovich in fact opened up a whole new field of research which was previously virtually ignored by polymer physicists and which also turned out to be of crucial importance for numerous applications, including biological research.

Chronologically, I M Lifshitz's shift to polymers coincided with his move to Moscow. His very first undergraduate lecture course on the theory of polymer chains given at the MSU Faculty of Physics turned out to have far-reaching consequences. First came students, then came a seminar on polymer physics, a center of attraction and a unifying venue for polymer and biopolymer theorists not only from Moscow but also from other Soviet cities. The seminar then grew into a Chair of Polymers and Crystals at the MSU Faculty of Physics, later to develop into a major scientific and education center.

Along with successes, setbacks (if minor) occur in the career of great scientists, and in this sense, the history of I M Lifshitz's 1973 work on the 'melting' of heteropolymer DNA is instructive. While relatively rarely cited, the work presents an absolutely correct and, as always with I M Lifshitz, mathematically very elegant analysis of melting curves for a random ('frozen') disordered sequence of nucleotides. The key idea of the work was to use the measured fine structure of melting curves to solve the inverse problem of 'reading' the sequence. Thus, the goal was extremely ambitious, and the problem considered was very important and timely addressed and involved Ilya Mikhailovich's two favorite subjects, frozen disorder and inverse problems. The only reason why this work can be considered a failure is because in time totally different DNA sequencing techniques were developed — in huge industrial numbers, in fact. Importantly, though, Ilya Mikhailovich addressed the problem decades before it became fashion. Does it not resemble of how he turned to the electronic properties of disordered systems before doped semiconductors became a common interest?

Returning to where we began, the question can be properly asked: today, 35 years after I M Lifshitz's death, can we say which of his numerous specific achievements are in the golden treasury of theoretical physics? There are many phenomena and/or theories that are named after him, including the Lifshitz–Slyozov–Wagner theory, Lifshitz's tails, the Lifshitz transition, and the Lifshitz–Kosevich formula.[2] But it is more interesting perhaps to look at those research areas where his name is now not always mentioned for the reason that 'it is well known'. Noteworthy here are the idea that the electronic properties of a metal are determined by the geometry of its Fermi surface; the frozen disorder and optimum fluctuation ideas; polymer globules; the coil–globule transition, and quantum crystals — a very impressive list indeed. The development of theoretical physics over the past 35 years also illustrates and gives us an idea of the depth of I M Lifshitz's intuition — indeed, the theory of disordered systems, amorphous materials and glasses, the theory of biopolymers and the physics of living matter ('true biophysics', to use his term), i.e., precisely the areas of physics that were at the center of his interest — are currently among the most rapidly developing research fields.

Now, taking a different perspective on I M Lifshitz's legacy, which of his results deserved citation in L D Landau's and E M Lifshitz's 10-volume course of theoretical physics? It turns out that, in addition to the already-mentioned coalescence theory, the Lifshitz–Onsager quantization, the theory of the de Haas–van Alphen effect in metals, and the theory of galvanomagnetic phenomena, his 1952 theory of the heat capacity of highly anisotropic crystals is also included in this '*Encyclopedia of Theoretical Physics*'.

At a still deeper level, his unity of style is noteworthy, the first style features coming to mind being virtuosity in generalizing isolated extreme cases into a general picture, sophisticated analysis of the physics imparting spirit and life to the mathematics used, and approaching problems in terms of functionals, with maintaining the generality–specificity balance (as in fermiology and in a system of broken chains).

To conclude, one cannot help but admire I M Lifshitz's deep intuition. Time and again, he identified and developed

[2] The Google-suggested term 'Lifshitz point' refers to Evgenii Mikhailovich Lifshitz, Ilya Mikhailovich's brother.

research avenues that held neither interest nor promise for most theoretical physicists (disordered systems in the 1940s–1960s, metals in the 1950s, polymers in the 1960s and 1970s) but after two decades (!) it invariably turned out that Ilya Mikhailovich had looked more deeply and seen farther than most of his colleagues; he was never a fashion follower — rather a fashion creator.[3] It was more than once that a field that before him was altogether inaccessible to any systematic study became, thanks to him, a subject of theoretical physics — a sufficient reason in itself that today, 100 years after his birth and 35 years after his death, we are confident to conclude that the court of history will place him among the truly prominent theoretical physicists of the 20th century.

The friendly criticism and helpful comments from S A Gredeskul, M I Kaganov, A R Khokhlov, and especially D E Khmel'nitskii are gratefully acknowledged.

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[3] Here again, Rutherford comes to mind. A colleague of his once said in his presence, "Lucky fellow, Rutherford, always on the crest of a wave." "Well, I made the wave, didn't I?" was Rutherford's answer.