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From the History of Physics

*LEV DAVIDOVICH LANDAU (1908–1968)**

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VERY little time has passed since the death of Lev Davidovich Landau on 1 April, but fate wills that even now we view him at a distance, as it were. From that distance we perceive more clearly not only the greatness of this scientist, the significance of whose works becomes increasingly obvious with time, but also his greatness as a large-souled human being. He was unusually just and benevolent. There is no doubt that therein lie the roots of his popularity as a scientist and teacher, the roots of that indivisible love and esteem which his direct and indirect students felt for him and which were manifested with such exceptional strength during the days of the struggle for saving his life following the calamitous accident.

To him fell the tragic fate of dying twice. The first time it happened was six years ago on 7 January 1962 when on the highway, en route from Moscow to Dubna, his car collided with a truck coming from the opposite direction. The epic story of the subsequent struggle to save his life is primarily a story of the selfless labor and skill of numerous physicians and nurses. But it also is a story of a remarkable feat of solidarity. The unfortunate accident agitated the entire community of physicists, arousing a spontaneous and instant response. The hospital in which Landau lay in a coma became a center to all those—his students and colleagues—who strived to make their own strenuous contributions to help the physicians in their desperate struggle to save Landau's life.

"Their feat of comradeship commenced on the very first day. Illustrious scientists who, however, had no idea of medicine, academicians, corresponding members [of the scientific academies], doctors, candidates, men of the same generation as the 54-year Landau as well as his students and the youthful students of his students—they all volunteered to act as messengers, chauffeurs, intermediaries, suppliers, secretaries, members of the watch and, lastly, stretcher carriers and laborers. Their spontaneously established headquarters was located in the office of the Chief Physician of Hospital No. 50 and it became a round-the-clock organizational center for an unconditional and immediate implementation of any instruction of the attending physicians.

"Eighty-seven theoreticians and experimenters took part in this voluntary rescue team. An alphabetical list of the telephone numbers and addresses of any one and any institution with which contact might be needed at any instant was compiled, and it contained 223 telephone numbers! It included other hospitals, motor transport bases, airports, customs offices, pharmacies, ministries, and the sites at which consulting physicians could most likely be reached.

"During the most tragic days when it seemed that 'Dau is dying'—and there were at least four such days—8–10 cars could be found parked at any time in front of the seven-story hospital building....

"When everything depended on the artificial respiration machine, on 12 January, a theoretician suggested that it should be immediately constructed in the shops of the Institute of Physics Problems. This was unnecessary and naive, but how amazingly spontaneous! The physicists obtained the machine from the Institute for the Study of Poliomyelitis and carried it in their own hands to the ward where Landau was having difficulty breathing. They saved their colleague, teacher, friend.

"However you may put it, this was a real fraternity of physicists...."*

And so, Landau's life was saved. But when after three months he regained consciousness, it was no longer the same man whom we had known. He was not able to recover from all the consequences of his accident and never again completely regained his abilities. The story of the last six years is only a story of prolonged suffering and pain.

* * *

Lev Davidovich Landau was born on 22 January 1908 in Baku, in the family of a petroleum engineer who worked on the Baku oilfields. His mother was a physician and at one time had engaged in scientific work on physiology.

He was graduated from school at the age of 13. Even then he already was attracted by the exact sciences, and his mathematical ability manifested itself very early. He studied mathematical analysis on his own and later he used to say that he hardly remembers a time when he did not know differentiation and integration.

His parents considered him too young to enter a university and for a year he attended the Baku Economic Technicum. In 1922 he enrolled at the Baku University where he studied simultaneously at two departments: Physico-mathematical and Chemical. Subsequently he did not continue his chemical education but he remained

*This article was written for the two-volume Sobranie Trudov L.D. Landau (Collected Works of L.D. Landau) which soon will be published by Nauka Press. A bibliography of Landau's works, taken from the Sobranie, is presented at the end of this article. It includes nearly every scientific article published by Landau (Editors)

*D. Danin, "Comradeship," Literaturnaya Gazeta (Literary Gazette), 21 July 1962 interested in chemistry throughout his life.

In 1924 Landau transferred to the Physics Department of the Leningrad University. In Leningrad, that main center of Soviet physics at the time—he first made the acquaintance of genuine theoretical physics, which was then going through a turbulent period. He devoted himself to its study with all his youthful zeal and enthusiasm and worked so strenuously that often he became so exhausted that at night he could not sleep because he was still turning over formulas in his mind.

Later he used to describe how at that time he was entranced by the incredible beauty of the general theory of relativity (sometimes he even would declare that such a rapture on first making one's acquaintance with this theory should in general be a characteristic of any born theoretical physicist). He also described the state of ecstasy to which he was brought on reading the articles by Heisenberg and Schrödinger signaling the birth of the new quantum mechanics. He said that he derived from them not only delight in the glamor of genuine science but also an acute realization of the power of the human genius, whose greatest triumph is that man is capable of apprehending things beyond the pale of his imagination. And of course, such things are precisely the curvature of space-time and the principle of indeterminacy.

In 1927 Landau was graduated from the university and enrolled for postgraduate study at the Leningrad Physicotechnical Institute where even earlier, in 1926, he had been a part-time research student. These years are associated with his first scientific works. In 1926 he published the theory of intensities in the spectra of diatomic molecules,[1]* and as early as in 1927, a study of the problem of deceleration in quantum mechanics, which had first introduced a description of the state of a system with the aid of the density matrix.

His fascination in physics and first achievements as a scientist were, however, at the time beclouded by a painful diffidence in his relations with others. This trait caused him a great deal of suffering and at times —as he himself confessed in later years—led him to despair. The changes which occurred in him with years and transformed him into a buoyant and gregarious individual were largely a result of his characteristic self-discipline and feeling of duty toward himself. These qualities, together with his sober and self-critical mind, enabled him to grow spiritually and evolve into an individual with a rare ability—the ability to be happy. The same sobriety of mind enabled him always to discern between what is true in life and what is humbug and thus also to retain his mental equilibrium during the difficult moments which had occurred in his life too.

In 1929, on an assignment from the People's Commissariat of Education, Landau traveled abroad and for one and one-half years worked in Denmark, Great Gritain and Switzerland. To him the most important part of his trip was his stay in Copenhagen where, at the Institute of Theoretical Physics, theoretical physicists from all Europe gathered round the great Niels Bohr and, during the famous seminars headed by Bohr, discussed all the basic problems of the theoretical physics of the time. This scientific atmosphere, magnified by the charm of the personality of Bohr himself, decisively influenced Landau in forming his own view of physics and subsequently he always considered himself a disciple of Niels Bohr. He visited Copenhagen two more times, in 1933 and 1934. Landau's sojourn abroad was associated, in particular, with his works on the theory of the diamagnetism of an electron gas[6] and the study of the limitations imposed on the measurability of physical quantities in the relativistic quantum region ([5], in collaboration with Peierls).

On his return to Leningrad in 1931 Landau worked in the Leningrad Physicotechnical Institute and in 1932 he moved to Khar'kov, where he became head of the Theoretics Division of the newly organized Ukrainian Physicotechnical Institute, an offshoot of the Leningrad Physicotechnical Institute. At the same time he headed the Department of Theoretical Physics at the Physics and Mechanics Faculty of the Khar'kov Mechanics and Machine Building Institute (the counterpart of the Leningrad Physics and Mechanics Department) and in 1935 he became head of the Department of General Physics at the Khar'kov University.

The Khar'kov period was for Landau a time of intense and varied research activity.* It was there that he began his teaching career and established his own school of theoretical physics.

Twentieth-century theoretical physics is rich in illustrious names of trailblazing creators, and Landau was one of these creators. But his influence on scientific progress was far from exhausted by his personal contribution to it. He was not only an outstanding physicist but also a genuinely outstanding educator, a born educator. In this respect one may take the liberty of comparing Landau only to his own teacher, Niels Bohr.

The problems of the teaching of theoretical physics as well as of physics as a whole had first attracted his interest while still a quite young man. It was precisely there, in Khar'kov, that he first began to work out programs for the "theoretical minimum"—programs of the basic knowledge in theoretical physics needed by experimental physicists and separately by those who wish to devote themselves to professional research work on theoretical physics. In addition to drafting these programs, he gave lectures on theoretical physics to the co-workers of the Ukrainian Physicotechnical Institute as well as to students of the Physics and Mechanics Faculty. Being absorbed by the ideas of reorganizing instruction in physics as a whole, he accepted an appointment as head of the Department of General Physics at the Khar'kov State University (and subsequently, after the war, he continued to give lectures on general physics at the Physicotechnical Faculty of the Moscow State University).

*He did not know, however, at the time that these results had been already published a year earlier by Hoenel and London

*The extent of Landau's scientific activities at the time can be grasped from the list of studies he had completed during the year 1936 alone: theory of first-order phase transitions [28,29] theory of the intermediate state of superconductors [30], the kinetic equation in the case of Coulomb interaction, [23] the theory of monomolecular reactions, [22] properties of metals at very low temperatures [24] theory of the dispersion and absorption of sound, [21,27] theory of photoelectric effects in semiconductors. [20]

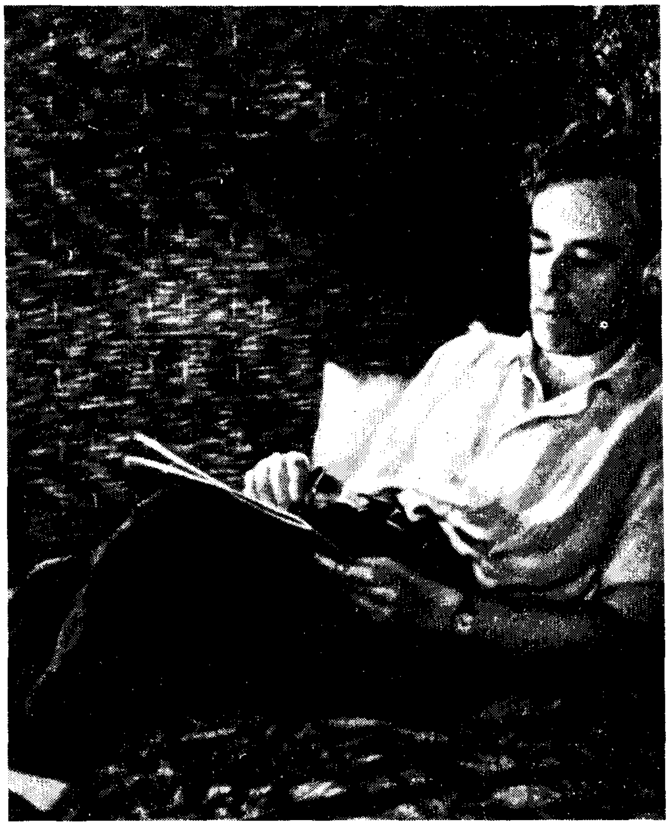
It was there also, in Khar'kov, that Landau had conceived the idea and began to implement the program for compiling a complete Course of Theoretical Physics and Course of General Physics. All his life long, Landau dreamed of writing books on physics at every level—from school textbooks to a course of theoretical physics for specialists. In fact, until his fatal accident, nearly all the volumes of Teoreticheskaya fizika (Theoretical Physics) and the first few volumes of the Kurs obshcheĭ fiziki (Course of General Physics) and Fizika dlya vsekh (Physics for Everyone) had been completed in his lifetime. He also had been completed in his lifetime. He also had drafted plans for the compilation of textbooks on mathematics for physicists, which should be "a guide to action," should instruct in the practical applications of mathematics to physics, and should be free of the rigors and complexities superfluous to this course. He did not have the time to begin to translate this program into reality.

Landau generally attached great importance to the mastering of mathematical apparatus by the theoretical physicist. The degree of this mastery should be such that, insofar as possible, mathematical complications would not distract attention from the physical difficulties of the problem—at least whenever standard mathematical techniques are concerned. This can be achieved only by sufficient training. Yet experience shows that the current style and programs for university instruction in mathematics for physicists often do not assure such training. Experience also shows that after a physicist commences his independent research activity he finds the study of mathematics too "boring."

Therefore, the first test which Landau gave to any one who desired to become one of his students was a quiz in mathematics in its "practical" calculational aspects.* The successful applicant could then pass on to the study of the seven successive sections of the program for the "theoretical minimum," which includes basic knowledge of all the domains of theoretical physics, and subsequently take an appropriate examination. In Landau's opinion, this basic knowledge should be mastered by any theoretician regardless of his future specialization. Of course, he did not expect any one to be as universally well-versed in science as he himself. But in this he manifested his belief in the integrity of theoretical physics as a unified science with unified methods.

At first Landau himself gave the examination for the "theoretical minimum." Subsequently, after the number of applicants became too large, this duty was also divided between his closest associates. But Landau always reserved for himself the first test, the first meeting with each new young applicant. Any one could meet him—it was sufficient to call him up and request him for an interview.

*The requirements were: ability to evaluate any indefinite integral (in terms of elementary functions) and to solve any ordinary differential equation of the standard type, knowledge of vector analysis and tensor algebra as well as of principles of the theory of functions of complex variable (theory of residues, Laplace method). It was assumed that such fields as tensor analysis, group theory, etc. will be studied together with fields of theoretical physics to which they apply.



Of course, not every one who began to study the "theoretical minimum" had sufficient ability and persistence to complete it. Altogether, between 1934 and 1961, 43 persons passed this test. The effectiveness of this selection can be perceived from the following facts alone: of these persons 7 already have become members of the Academy of Sciences and an additional 16, doctors of sciences.

In the spring of 1937 Landau moved to Moscow where he became head of the Theoretics Division of the Institute of Physics Problems which had not long before been established under the direction of P. L. Kapitza. There he remained to the end of his life; in this Institute, which became a home to him, his varied activity bloomed into maturity. It was there, in a remarkable interaction with experimental research, that Landau created what may be the fundamental accomplishment of his scientific life—the theory of quantum fluids.

It was there also that he received the numerous outward manifestations of the recognition of his contributions. In 1946 he was elected Active Member of the USSR Academy of Sciences. He was awarded a number of orders (including two Orders of Lenin) and the honorific title of Hero of Socialist Labor—a reward for both his scientific accomplishments and for his contribution to the implementation of important practical State tasks. He was awarded the State Prize three times and in 1962, the Lenin Prize. There also was no shortage of honorific awards from other countries. As far back as in 1951 he was elected member of the Danish Academy of Sciences and in 1956, member of the Dutch Academy of Sciences. In 1959 he became member of the British Physics Society and in 1960, Foreign Fellow of the Royal Society of Great Britain. In the same year he was elected to membership in the National Academy of Sciences of the United States and the American Academy of Arts and Sciences. In 1960 he became recipient of the F. London Prize (United States) and of the Max Planck Medal (West Germany). Lastly, in 1962 he was awarded the Nobel Prize in Physics "for his pioneering studies of the theory of the condensed state of matter and particularly of liquid helium."

Landau's scientific influence was, of course, far from confined to his own students. He was deeply democratic in his life as a scientist (and in his life as a human being, for that matter; pomposity and deference to titles always remained foreign to him). Any one, regardless of his scientific merits and title, could ask Landau for counsel and criticism, on one condition only: the question must be businesslike instead of pertaining to what he detested most in science: empty philosophizing or vapidity and barrenness cloaked in scientifically sounding sophistries. He had an acutely critical mind; this quality, along with his approach from the standpoint of profound physics, made discussion with him extremely intriguing and useful.

In discussion he used to be ardent and incisive but not impolite; witty and ironic but not sarcastic. The nameplate hanging on the door of his office at the Ukrainian Physicotechnical Institute bore the inscription:

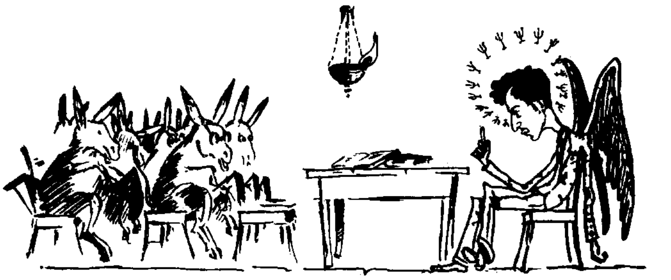
L. Landau
Beware, he bites!

With years his character and manner mellowed somewhat, but his enthusiasm for science and his uncompromising fundamental attitude toward science remained unchanged. And, at any rate, his harsh exterior concealed a scientifically impartial attitude, a great heart and great humanity. However harsh and unsparing he may have been in his critical comments, he was just as intense in his desire to contribute with his scientific counsel to another man's success, and his approval, when he gave it, was just as ardent.

These traits of Landau's personality as a scientist and his talent in practice elevated him to the position of a supreme scientific judge, as it were, over his students and colleagues.* There is no doubt that this side of Landau's activities, his scientific and moral authority which exerted a restraining influence on improperly or hastily conceived research, had also markedly contributed to the lofty level of our theoretical physics.

His constant scientific contact with a large number of students and colleagues also represented to Landau a source of knowledge. A unique aspect of his style of work was that, ever since long ago, since the Khar'kov years, he himself almost never read any scientific article or book but nevertheless he was always completely au courant with the latest news in physics. He derived this knowledge from numerous discussions and from the papers presented at the seminar held under his direction.

*This position is symbolized in A. A. Yuzefovich's well-known friendly cartoon, "Dau said," reproduced here



Dau said . . . .

This seminar was held regularly once a week for nearly 30 years, and in the last years its session acquired the nature of gatherings of theoretical physicists from all Moscow. The presentation of papers at this seminar became a sacred duty for all students and coworkers, and Landau himself was extremely serious and thorough in selecting the material to be presented. He was interested and equally competent in every aspect of physics and the participants in the seminar did not find it easy to follow his train of thought in instantaneously switching from the discussion of, say, the properties of "strange" particles to the discussion of the energy spectrum of electrons in silicon. To Landau himself listening to the papers never was an empty formality: he did not rest until the essence of a study was completely elucidated and any trace of "philology"—unprovable statements or propositions made on the principle of "why might it not"—there in were eliminated. As a result of such discussion and criticism many studies were condemned as "pathology" and Landau completely lost interest in them. On the other hand, articles that really contained new ideas or findings were included in the so-called "gold fund" and always remained in Landau's memory.

In fact, usually it was sufficient for him to know just the guiding idea of a study in order to reproduce all of its findings. As a rule, he found it easier to obtain them on his own than to follow in detail the author's reasoning. In this way he reproduced for himself and profoundly thought out most of the basic results obtained in all the domains of theoretical physics.* This probably also was a factor in his phenomenal ability to answer practically any question concerning physics that might be asked of him.

Landau's scientific style was free of the—unfortunately fairly widespread—tendency to complicate elementary things, to obfuscate (often on the grounds of generality and rigor which, however, usually turn out to be illusory). He himself always strived toward the opposite—to simplify complex things, to uncover in the most lucid manner the genuine simplicity of the laws underlying the natural phenomena. This ability of his, this skill at "trivializing" things as he himself used to say, was to him a matter of special pride.

The striving for simplicity and order was generally an inherent part of the structure of Landau's mind. It manifested itself not only in serious matters but also

*Incidentally, this explains the absence of certain needed references in Landau's papers, which usually was not intentional. In some cases he did leave out a reference on purpose, if he considered the corresponding question too trivial he had his own rather high standards.

in semi-serious things as well as in his characteristic personal sense of humor.* Thus, he liked to classify everyone, from women according to the degree of their beauty, to physicists according to the significance of their contribution to science. This last classification was based on a five-grade system on the logarithmic scale: thus, a second-class physicist supposedly accomplished 10 times as much as a third-class physicist ("pathological types" were ranked in the fifth class). On this scale Einstein occupied the median class while Bohr, Heisenberg, Schrödinger, Dirac and certain others were ranked in the first class. Landau modestly ranked himself for a long time in the 2 ½ class and it was only comparatively late in his life that he promoted himself to the second class.

He always worked hard (never behind a desk, always semi-recumbent on a divan). The recognition of the results of his work is to a greater or lesser extent important to any scientist; it was, of course, also essential to Landau. But it still can be said that he attached much less importance to questions of priority than is ordinarily the case. And at any rate there is no doubt that his drive for work was inherently motivated not by desire for fame but by an inexhaustible curiosity, an inexhaustible passion for exploring the laws of nature in their large and small manifestations. He never omitted a chance to repeat the elementary truth that one should never work for extraneous purposes, work merely for the sake of making a great discovery, for then nothing would be accomplished all the same.

The range of Landau's interests outside physics also was extremely wide. In addition to the exact sciences he loved history and was well-versed in it. He was also passionately interested in and deeply impressed by every genre of fine arts except, however, music (and ballet as well).

Those who had the good fortune of being his students and friends for many years knew that our Dau, as his friends and comrades† nicknamed him, did not grow old. In his company boredom vanished. The brightness of his personality never grew dulled and his scientific power remained strong. This makes all the more senseless and frightful the accident which put an end to his brilliant activity when it was at its zenith.

* * *

Landau's articles, as a rule, display all the features of his characteristic scientific style: clarity and lucidity of physical statement of problems, the shortest and most elegant path toward their solution, no superfluities. Even now, after many years, the greater part of his articles does not require any revisions.

The brief review below should provide only a tentative idea of the abundance and diversity of Landau's works as well as clarify the place occupied by these works in the history of physics, a place which may not always be obvious to the contemporary reader.

A characteristic feature of Landau's scientific creativity is its almost unprecedented latitude, its great breadth which encompasses the entire theoretical physics, from hydrodynamics to the quantum field theory. In our century, which is a century of increasingly narrow specialization, the scientific paths of his students also have been gradually diverging, but Landau himself unified them all, always retaining a truly astounding interest in everything. It may be that in his person physics has lost one of the last great universalists.

Even a cursory examination of the bibliography of Landau's works shows that his life cannot be divided into any lengthy periods during which he worked only in some one single domain of physics. Hence also the bibliography of his works is listed not in the chronological order but, insofar as possible, in thematic order. We shall begin with the works devoted to the general problems of quantum mechanics.

These include primarily several of his early works. In the course of his studies of the bremsstrahlung problem he was the first to introduce the concept of incomplete quantum-mechanical description accomplished with the aid of quantities which were subsequently termed the density matrix.[2] In the article[2] the density matrix was introduced in its energy representation.

Two articles[6,7] are devoted to the calculation of the probabilities of quasiclassical processes. The difficulty of this problem stems from the fact that, by virtue of the exponential nature (with a large imaginary exponent) of the quasiclassical wave functions, the integrand in the matrix elements proves to be a rapidly fluctuating quantity, which greatly complicates even an estimate of the integral; in fact, until Landau's work all studies of problems of this kind proved to be erroneous. Landau was the first to provide a general method for the calculation of quasiclassical matrix elements and also he applied it to a number of specific problems.

In 1930 Landau (in collaboration with R. Peierls), published a detailed study of the limitations imposed by relativistic requirements on the quantum-mechanical description;[5] this article in its time caused lively discussions. Its basic result lies in determining the limits of the possibility, in principle of measuring the particle momentum within a finite time (in addition to determining more precisely the question of the individual uncertainty of the coordinate). This implied that in the relativistic quantum region it is not feasible to measure any dynamic variables characterizing the particles in their interaction, and that the sole measurable quantities are the momenta (and polarizations) of free particles. Therein also lies the physical root of the difficulties that arise when methods of conventional quantum mechanics, employing concepts which are now becoming meaningless, are applied to the relativistic domain. Landau returned to this problem in his last published article,[98] in which he expressed his conviction that the ψ-operators, as carriers of unobservable information, and along with them the entire Hamiltonian method, should disappear from future theory.

One of the reasons for this conviction was the results of the studies of the principles of quantum electrodynamics which Landau carried out during 1954–1955 (in collaboration with A. A. Abrikosov, I. M. Khalatnikov and

*It is characteristic, however, that this trait was not a habit of Landau in his, so to speak, everyday outside life, in which he was not at all pedantically accurate and a "zone of disorder" would quite rapidly arise around him.

†Landau himself liked to say that this name originates from the French spelling of his name: Landau = L'âne Dau (the ass Dau)

I. Ya. Pomeranchuk).[76-79,83] These studies were based on the concept of the point interaction as the limit of "smeared" interaction when the smearing radius tends to zero. This made it possible to deal directly with finite relations. Further, it proved possible to carry out the summation of the basic terms of the entire series of perturbation theory and this led to the derivation of asymptotic relations (in the presence of large momenta) for the principal quantities of quantum electrodynamics —Green's functions and the vertex part. These relations, in their own turn, were used to derive the relationship between the true charge and mass of the electron, on the one hand, and their "bare" values. Although these calculations proceeded on the premise of smallness of the "bare" charge, it was convincingly argued that the formula for the relation between true and bare charges retains its validity regardless of the magnitude of the bare charge. Then analysis of this formula shows that at the limit of point interaction the true charge turns to zero—the theory is "nullified."* (A review of the pertinent questions is provided in the articles [82,86]).

Only future will show the extent of the validity of the program planned by Landau for constructing a relativistic quantum field theory.[98] He himself was intensely working in this direction during the last few years prior to his accident. As part of this program, in particular, he had worked out a general method for determining the singularities of the quantities that enter in the diagram technique of the quantum field theory.[96]

In response to the discovery in 1956 of parity nonconservation in weak interactions, Landau immediately proposed the theory of a neutrino with fixed helicity ("two-component neutrino"),[90]† and also he suggested the principle of the conservation of "combined parity," as he termed the combined application of spatial inversion and charge conjugation. According to Landau, by the same token, the symmetry of space must be "saved"—asymmetry is transferred to the particles themselves. This principle indeed proved to be more widely applicable than the law of parity conservation. As is known, however, in recent years processes not conserving combined parity also have been discovered; the meaning of this violation is at present still unclear.

A 1937 study by Landau[31] pertains to nuclear physics. This study represents a quantitative embodiment of the ideas proposed not long before by Bohr: the nucleus is examined by methods of statistical physics as a drop of "quantum fluid." It is noteworthy that this study did not make use of any far-reaching model representations, contrary to the previous practice of other investigators. In particular, the relationship between the mean distance between the levels of the compound nucleus and the width of the levels was established for the first time.

The lack of model representations characterizes also the theory of proton-proton scattering developed by Landau (in collaboration with Ya. A. Smorodinskiĭ). The scattering cross section in their study was expressed in terms of parameters whose meaning is not restricted by any concrete postulates concerning the particle interaction potential.

The study (performed in collaboration with Yu. B. Rumer) of the cascade theory of electron showers in cosmic rays[36] is an example of technical virtuosity; the physical foundations of this theory had been earlier formulated by a number of investigators, but a quantitative theory was essentially lacking. That study provided the mathematical apparatus which became the basis for all subsequent works in this domain. Landau himself took part in the further refinement of the shower theory by contributing two more articles, one on the particle angular distribution[41] and the other, on secondary showers.[42]

Of no smaller virtuosity was Landau's work dealing with the elaboration of Fermi's idea of the statistical nature of multiple particle production in collisions.[72]* This study also represents a shining example of the methodological unity of theoretical physics in which the solution of a problem is accomplished by using the methods of a seemingly completely different domain. Landau showed that the process of multiple production includes the state of the expansion of a "cloud" whose dimensions are large compared with the path of particles through it; correspondingly, this stage should be described by equations of relativistic hydrodynamics. The solution of these equations required a number of ingenious techniques as well as a thorough analysis. Landau used to say that this study cost him more effort than any other problem that he ever had solved.

Landau always willingly responded to the requests and needs of the experimenters, e.g., by publishing the article[54] which established the energy distribution of the ionization losses of fast particles during passage through matter (previously only the theory of mean energy loss had existed).

Concerning Landau's work on macroscopic physics, we will begin by examining several articles representing his contribution to the physics of magnetism.

According to classical mechanics and statistics, a change in the pattern of movement of free electrons in a magnetic field cannot result in the rise of new magnetic properties of the system. Landau was the first to elucidate the character of this motion in a magnetic field for the quantum case, and to show that quantization completely changes the situation, resulting in the appearance of diamagnetism of the free electron gas ("Landau diamagnetism" as this effect is now termed).[4] The same study qualitatively predicted the periodic dependence of magnetic susceptibility on the intensity of the magnetic field when this intensity is high. At the time (1930) this phenomenon had not yet been observed by any one, and it was experimentally discovered only later (the De Haas-Van Alphen effect); a quantitative theory of this effect was presented by Landau in a later study.[37]

A small article published in 1933[11] is of a signifi-

*In connection with the search for a more rigorous proof of this statement, article [98] contains the assertion, characteristic of Landau, that "in view of the shortness of our lifespan we cannot afford the luxury of considering questions which do not promise new results."

†Simultaneously and independently, this theory was proposed by Salam as well as by Lee and Yang.

For a more detailed exposition of this study and elaboration of the pertinent details see the review article [85] (written in collaboration with S. Z. Belen'kiĭ) cance greatly transcending the problem stated in its title—a possible explanation of the field dependence of the magnetic susceptibility of a particular class of substances at low temperatures. This article was the first to introduce the concept of antiferromagnetism (although it did not use this term) as a special phase of magnetism differing in symmetry from the paramagnetic phase; accordingly, the transition from one state to the other must occur at a rigorously definite point. This article concretely examined the model of a layered antiferromagnet with a strong ferromagnetic coupling in each layer and a weak antiferromagnetic coupling between the layers; a quantitative investigation of this case was carried out and the characteristic features of magnetic properties in the neighborhood of the transition point were established. The method employed here by Landau was based on ideas which he had subsequently elaborated in the general theory of second-order phase transitions.

He carried out one more work on the theory of ferromagnetism. The idea of the structure of ferromagnetic bodies as consisting of elementary regions spontaneously magnetized in various directions ("magnetic domains," as the modern term goes) was expressed by P. Weiss as early as in 1907. However, there was no suitable approach to the question of the quantitative theory of this structure until Landau (in collaboration with E. M. Lifshitz)[17] showed in 1936 that this theory should be constructed on the basis of thermodynamic considerations and determined the form and dimensions of the domains for a typical case. The same study derived the macroscopic equation of the motion of the domain magnetization vector and, with its aid, developed the principles of the theory of the dispersion of the magnetic permeability of ferromagnets in an alternating magnetic field; in particular, it predicted the effect now known as ferromagnetic resonance.

A small communication published in 1933[9] expressed the idea of the possibility of the "autolocalization" of an electron in a crystal lattice within the potential well produced by virtue of the natural polarization effect of the electron. This idea subsequently provided for the so-called polaron theory of the conductivity of ionic crystals. Landau himself returned once more to these problems in a later study (in collaboration with S. I. Pekar')[65] dealing with the derivation of the equations of motion of the polaron in the external field.

Another small communication reported on the results obtained by Landau (in collaboration with G. Placzek) concerning the structure of the Rayleigh scattering line in fluids or gases.[13] As far back as in the early 1920s Brillouin and Mandel'shtam showed that, owing to scattering by sound vibrations, this line must split into a doublet. Landau and Placzek drew attention to the attendant necessity of the existence of scattering by entropy fluctuation, not accompanied by any change in frequency; as a result, a triplet should be observed instead of a doublet.*

Two of Landau's works pertain to plasma physics. One of these two was the first to derive the kinetic equation with allowance for Coulomb interaction between particles;[23] the slowness of decrease of these forces rendered inapplicable in this case the conventional methods for compiling kinetic equations. The other work, dealing with plasma fluctuations,[59] showed that even under conditions when collisions between particles in the plasma can be disregarded, high-frequency oscillations will still attenuate ("Landau damping").†

His work to compile one of the successive volumes of the Course of Theoretical Physics was to Landau a stimulus for a thorough investigation of hydrodynamics. Characteristically, he independently pondered and derived all the basic postulates and results of this science. His fresh and original perception led, in particular, to a new approach to the problem of the onset of turbulence and he elucidated the basic aspects of the process of the gradual development of unsteady flow with increase in the Reynolds number following the loss of stability by laminar motion and predicted qualitatively different alternatives possible in this case.[50] On investigating the qualitative properties of supersonic flow around bodies, he arrived at the unexpected discovery that in supersonic flow there must exist far from the body not one—as had been the conventional assumption—but two shock waves, one following the other.[58] Even in such a "classical" field as the jet theory he had succeeded in finding a new and previously unobserved exact solution for an axially symmetric "inundated" jet of a viscous incompressible fluid.[49]

In Landau's scientific creative accomplishments an eminent position is occupied—both from the standpoint of direct significance and in terms of the consequent practical applications—by the theory of second-order phase transitions;[28,29] the first outline of the ideas underlying this theory is already contained in the communication.[16]‡ The concept of phase transitions of varying order had first been introduced by Ehrenfest in a purely formal manner, as a function of the order of magnitude of thermodynamic derivatives which could undergo a discontinuity at the transition point. As to the question of exactly which of these transitions can exist in reality and wherein lies their physical nature, it had remained open, and previous interpretations had been fairly vague and unsubstantiated. Landau was the first to point to the profound relationship between the possi-

*Roughly a year earlier Néel's (whose work was unknown to Landau) had predicted the possibility of existence of substances which, from the magnetic standpoint, consist of two sublattices with opposite moments. Néel, however, did not assume that a special state of matter is involved here, and instead he simply thought that a paramagnet with a positive exchange integral at low temperatures gradually turns into a structure consisting of several magnetic sublattices.

*A detailed exposition of the conclusions and results of this study was somehow not published in article form. It is partly presented in the book, Élektrodinamika Sploshnykh Sred (Continuum Electrodynamics), Sec. 96 (M., Fizmatgiz, 1959).

†It is interesting that this work was carried out by Landau as his response to the "philology" present, in his opinion, in previous studies dealing with this subject (e.g., the senseless replacement of diverging integrals by their principal values). It was to prove his rightness that he occupied himself with this question.

‡To Landau himself belongs the credit for applying this theory to the scattering of x-rays by crystals [32] and—in collaboration with I. M. Khalatnikov—to the absorption of sound in the neighborhood of the transition point. [80]

bility of existence of a continuous (in the sense of variation in the body's state) phase transition and the jump-like (discontinuous) change in some symmetry property of the body at the transition point. He also showed that far from just any change in symmetry is possible at that transition point and provided a method which makes it possible to determine the permissible types of change in symmetry. The quantitative theory developed by Landau was based on the assumption of the regularity of the expansion of thermodynamic variables in the neighborhood of the transition point. At present it is clear that such a theory, which fails to allow for possible singularities of these variables at the transition point, does not reflect all the properties of phase transition. The question of the nature of these singularities was of great interest to Landau and during the last years of his activity he worked a great deal on this difficult problem without, however, succeeding in arriving at any definite conclusions.

The phenomenological theory of superconductivity developed in 1950 by Landau (in collaboration with V. L. Ginzburg)[71] also was constructed in the spirit of the theory of phase transitions; subsequently it became, in particular, the basis for the theory of superconducting alloys. This theory involves a number of variables and parameters whose meaning had not been completely clear at the time it was originally developed and has become understandable only after the appearance in 1957 of the microscopic theory of superconductivity which made possible to provide a rigorous substantiation of the Ginzburg-Landau equations and to determine the region of their applicability. In this connection, the story (recounted by V. L. Ginzburg*) of an erroneous statement contained in the original article by Landau and Ginzburg is highly instructive. The basic equation of the theory, defining the effective wave function Ψ of superconducting electrons, contains the field vector potential **A** in the term

$$\frac{1}{2m}\left(-i\hbar\nabla-\frac{e^*}{c}\mathbf{A}\right)\Psi,$$

which is completely analogous to the corresponding term in the Schrödinger equation. It might be conceivable that in the phenomenological theory the parameter e^* should represent some effective charge which does not have to be directly related to the charge of the free electron e. Landau, however, refuted this hypothesis by pointing out that the effective charge is not universal and must depend on various factors (pressure, composition of specimen, etc.); then in an inhomogeneous specimen the charge e^* would be a function of coordinates and this would disturb the gauge invariance of the theory. Hence the article stated that "...there exist no grounds for regarding the charge e^* as being different from the electron charge." We now know that in reality e^* coincides with the charge of the Cooper electron pair, i.e., $e^* = 2e$ and not e. This value of e^* could, of course, have been predicted only on the basis of the idea of electron pairing which underlies the microscopic theory of superconductivity. But the value 2e is as universal as e and hence Landau's argument in itself was not valid.

Another of Landau's contributions to the physics of superconductivity lies in elucidating the nature of the so-called intermediate state. The concept of this state was first introduced by Peierls and F. London (1936) to account for the observed fact that the transition to superconducting state in a magnetic field is gradual. Their theory was of a purely phenomenological nature, however, and the question of the nature of the intermediate state had remained open. Landau showed that this state is not any new state and that in reality a superconductor *existing in that state consists of successive thin* layers of normal and superconducting phases. In 1937[30] Landau considered a model in which these layers emerge to the surface of the specimen; using an elegant and ingenious method he succeeded in completely determining the shape and dimensions of the layers in such a model.* In 1938 he proposed a new variant of the theory, according to which the layers repeatedly branch out on emerging to the surface; such a structure should be thermodynamically more expedient, given sufficiently large dimensions of the specimen.†

But the most significant contribution that physics owes to Landau is his theory of quantum liquids. The significance of this new discipline at present is steadily growing; there is no doubt that its development in the last few decades has produced a revolutionary effect on other domains of physics as well—on solid-state physics and even on nuclear physics.

The superfluidity theory was created by Landau during 1940–1941 soon after Kapitza's discovery in 1937 of this fundamental property of helium II. Prior to it, the premises for understanding the physical nature of the phase transition observed in liquid helium had been essentially lacking and it is not surprising that the previous interpretations of this phenomenon at present even seem naive.‡ The completeness with which the theory of helium II had been constructed by Landau from the very beginning is remarkable: already his first classical article on this subject[44] contained practically all the principal ideas of both the microscopic theory of helium II and of the macroscopic theory constructed on its basis —the thermodynamics and hydrodynamics of this fluid (with the article [51] also being devoted to its hydrodynamics).

Underlying Landau's theory is the concept of quasiparticles (elementary excitations) constituting the energy spectrum of helium II. It was exactly Landau who was the first to pose the question of the energy spectrum or a macroscopic body in such a most general form, and it was he, too, who discovered the nature of the spectrum for a quantum fluid of the type to which liquid helium (He^4 isotope) belongs—or, as it is now termed, of the Bose type. In his 1941 work Landau assumed that the spectrum of elementary excitations consists of two

*Cf. Usp. Fiz. Nauk 94, 181 (1968) [Sov. Phys.-Usp. 11, 135 (1968)]

*Landau himself wrote concerning this matter that "amazingly enough an exact determination of the shape of the layers proves to be possible." [30]

†A detailed description of this project was published in 1943. [47]

‡Thus, Landau himself in his work on the theory of phase transitions [29] considered whether helium II does not represent a liquid crystal, even though he emphasized the dubiousness of this assumption.

branches: phonons, with a linear dependence of energy ϵ on momentum p, and "rotons," with a quadratic dependence, separated from the ground state by an energy gap. Subsequently he found that such a form of spectrum is not satisfactory from the theoretical standpoint (as it would be unstable) and careful analysis of the more complete and exact experimental data that had by then become available led him in 1946 to establish the renowned spectrum containing only one branch in which the "rotons" correspond to a minimum on the curve of ϵ(p). The macroscopic concepts of the theory of superfluidity are widely known. Basically they reduce to the idea of two motions simultaneously occurring in fluids —"normal" motion and "superfluid" motion which may be more graphically considered as motions of two "fluid components."* Normal motion is accompanied by internal friction, as in conventional fluids. The determination of the viscosity coefficient represents a kinetic problem which requires an analysis of the processes of the onset of an equilibrium in the "gas of quasiparticles"; the principles of the theory of the viscosity of helium II were developed by Landau (in collaboration with I. M. Khalatnikov) in 1949.[67,68] Lastly, yet another work (carried out in collaboration with I. Ya. Pomeranchuk) dealt with the problem of the behavior of extraneous atoms in helium;[62] it was shown, in particular, that any atom of this kind will become part of the "normal component" of the fluid regardless of whether the impurity substance itself does or does not display the property of superfluidity—contrary to the incorrect view previously held in the literature.

The liquid isotope He^3 is a quantum liquid of another type—the Fermi type as it is now termed. Although its properties are not as effective as the properties of liquid He^4, they are no less interesting from the standpoint of basic theory. A theory of liquids of this kind was developed by Landau and presented by him in three articles published during 1956–1958. The first two of these articles[87,88] established the nature of the energy spectrum of Fermi liquids, considered their thermodynamic properties and established the kinetic equation for the relaxation processes occurring in these liquids. His study of the kinetic equation led Landau to predict a special type of vibrational process in liquid He^3 in the neighborhood of absolute zero, which he had termed zero sound. The third article[93] presented a rigorous microscopic substantiation of the kinetic equation, whose earlier derivation had contained a number of intuitive assumptions.

Concluding this brief and far from complete survey, it only remains to be repeated that to physicists there is no need to emphasize the significance of Landau's contribution to theoretical physics. His accomplishments are of surpassing significance and will always remain part of science.

*Some of the ideas of the "two-component" macroscopic description of liquid helium were introduced independently of Landau by L. Tisza (although without providing a clear physical interpretation of them). His detailed article, published in France in 1940 was, owing to wartime conditions, received in the USSR as late as in 1943 and the small 1938 notice in the Comptes rendus of the Paris Academy had unfortunately remained unnoticed. A criticism of the quantitative aspects of Tisza's theory was provided by Landau in the article [64].

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