CERN 79-03
28 March 1979

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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LEV D. LANDAU: HIS LIFE AND WORK

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*) Colloquium given at CERN in June 1978.

Lev Davidovich Landau, the great Soviet theoretical physicist, born on 22 January 1908, became immortal during his lifetime. He died twice: on 7 January 1962, as a physicist, and six years later, on 1 April 1968, as a man.

Landau was a very unusual personality, both as a physicist and as a man. In science as well as in life he liked to provoke, to break up canons, to arouse public interest or indignation.

Certainly, Landau belongs to the dozen most well-known theoretical physicists of the first half of the 20th century [I]. In a 5-decade logarithmic scale that he himself invented for the classification of theoretical physicists, he adjudged himself class $2\frac{1}{2}$. (A physicist in class 1 did ten times more in physics than a physicist in class 2. The class $\frac{1}{2}$ had been created by Landau for Einstein only; Bohr, Heisenberg, Dirac, Schrödinger and a few others were assigned class 1.) Only later, when he had finished his work on the phase transitions of second order, did he modestly transfer himself to class 2. No doubt, he was the best "second-class" physicist ever known!

The German chemist Ostwald once divided men of science into two groups: classicists and romantics. The classicists know their own fields of science very profoundly and often devote their entire lives to working out or founding one scientific discipline or problem. Their thinking is inertial; it is a rare and difficult process for them to pass from one sphere to another. Romantics, on the other hand, have an encyclopaedic knowledge in various fields, often very different ones, and they exhibit a lively interest in the border regions of science. They literally boil over with ideas and thoughts, which they usually do not work out in detail. Their discoveries and logics and thinking processes are distinctive, intuitive, and often derived from remote associations. Their thinking is almost without inertia -- they fly from one thing to another like birds, and often glide from one scientific field to another.

Since Landau was, no doubt, a typical scientific romantic, the description of his scientific activities is a very complicated task. He made quite important and essential contributions to so many fields of modern theoretical physics, that merely listing them all would take up a great part of my talk.

Lev Davidovich Landau was born on 22 January 1908, in Baku. His father was chief engineer of an oil company, his mother a midwife.

Little Lev was a singular, determined, and immensely obstinate child prodigy, although he later declared that he never was a "Wunderkind". He soon mastered perfectly elementary arithmetic and, instead of games, played with numbers, which he added, subtracted, multiplied and divided in different ways. Later, he said about himself rather sarcastically that he could not remember a time when he did not know differential and integral calculus. That is certainly somewhat exaggerated but at the same time there is an element of truth, since he was entirely at home with mathematical methods -- he mastered them almost as safely and surely as a person masters walking or the movements of his hands. He did not therefore need to think about them or devote to them much of the time or energy which he could use to get directly to the physical essence of a problem; in this lay Landau's style (or more precisely, one aspect) and in this lay part of his success.

It was almost impossible to force little Landau to do something he did not consider to be useful. In an essay about Tatyana in "Eugene Onegin" he wrote just one sentence -- that

she was on the whole a boring person; when asked what the poet wanted to say in his book "A Hero of Our Times", he replied that only Lermontov could answer that. To his father he defended his own special brand of philosophy by saying that he would be ashamed to get a better mark than a pass for some subjects, e.g. literature.

At twelve, when he passed his matriculation examination, he knew practically the whole of higher mathematics. At fourteen, he entered the university in Baku, where he began to study at two faculties simultaneously: physics-mathematics and chemistry. Although he did not complete his chemical studies, his friends used to say that his contact with the Faculty of Chemistry marked him for life, and it was to this that he owed his dislike of alcoholic drinks!

After studying for a year at Baku, Landau left for Leningrad and there continued at the Leningrad State University, which in the twenties was regarded as the centre of Soviet science in general and of physics in particular.

In Leningrad Landau studied with great intensity and began to take shape as a scientist. A group of young scientists began to collect around the older and more experienced physicists there; an active member of this group was Landau, and it also included a number of other theoretical physicists who are today outstanding and many of whom have become Academicians. It was at that time that Landau obtained his nickname Dau (from D. Ivanenko, from whom he later completely dissociated himself). This nickname accompanied him throughout his life; not only his friends and collaborators but also his wife addressed him thus.

Before finishing at the university, when he was 18, Landau published his first scientific paper, devoted to quantum mechanics, which was just emerging. In his second paper, on bremsstrahlung, he introduced the incomplete quantum mechanical description and the conception of density matrix in quantum mechanics, simultaneously with Bloch[1].

Two days before his 19th birthday, Landau completed his studies at Leningrad University and became a post-graduate student at the Leningrad Physical Technical Institute of the Academy of Sciences of the USSR, the organizer and director of which was the Nestor of Soviet physicists, Abram Ioffe.

At the end of 1928 Landau went to Europe for a year and a half to continue his studies in physics. In Germany he met Albert Einstein; the young Landau, however, did not succeed in convincing the "old" man of the correctness of quantum mechanics. In Zürich he worked with Pauli, in England with Dirac. But he stayed longest in Copenhagen with Niels Bohr. At that time Bohr's institute was just becoming the Mecca of theoretical physicists, who went there not only to learn but also to teach others. "From the very beginning", wrote Bohr later, "we got a deep impression of his (Landau's) power to penetrate to the root of physical problems and his strong views on all aspects of human life, which gave rise to many discussions ..." [II]. In Copenhagen Landau immediately became one of the most active members of Bohr's seminar, so active that Bohr continually had to remind him: "Landau, do not grumble but criticize. And now let me say a few words myself."

A cartoon even exists from that time of Landau sitting in Bohr's seminar with a gag in his mouth and tied to a chair -- so that the lecturer could get a word in edgeways. Incidentally, Landau never agreed with this interpretation of the situation and said that Bohr always behaved like that, that he spoke most of all and when anyone tried to interrupt him, he complained that he was not allowed to get a word in.

Landau's European trip was fruitful: In Copenhagen he and Peierls published papers on quantum electrodynamics[2]) and on the uncertainty principle in the relativistic quantum theory[3]). In Cambridge he had published a very important paper on the theory of metals[4]). Landau had shown, and in this respect corrected Pauli, that the degenerated ideal electron gas in metals should not be treated classically, but quantum mechanically, and that, owing to quantum effects, the ideal electron gas has diamagnetic susceptibility (Landau's diamagnetism).

After his return from abroad Landau again worked in the Physical Technical Institute in Leningrad, where he succeeded in pointing out the theoretical incorrectness of a paper on electrical insulation by means of very thin (molecular) films[5]). Academician Ioffe had thought highly of his idea and had expected much from it (just imagine the savings in the national economy!). Ioffe finally had to admit the correctness of the conclusions reached by the young theoretician (later confirmed also by experiment), though he remained inwardly offended and made this clear to Landau at the first opportunity that arose. After listening to one of Landau's talks, he declared that he saw no point in such work. Landau reacted immediately, in front of everybody and in his characteristic manner: "Theoretical physics", he told Ioffe, "is a complicated science and not everyone is able to understand it." Ioffe was naturally deeply offended and Landau had to leave Leningrad. In 1932, he went to Kharkov, where he became head of the Department of Theoretical Physics and somewhat later also head of the Theoretical Department of the newly founded Kharkov Physical Technical Institute. Landau's transfer to Kharkov was natural -- Kharkov at that time was the second centre of Soviet modern physics and particularly of nuclear physics; Bohr, Pauli, Weisskopf, Peierls, and many others spent various periods of time there.

In Kharkov, Landau began to realize his talents as a teacher: He started to lecture on the whole of theoretical physics. Landau's lectures in Kharkov attracted students not only by their masterly address and perfectly conceived and presented material, but also by their witty and original presentation. At his first lecture in Kharkov, Landau turned up in sloppy linen trousers, blue jacket and sandals without socks -- even at that time in Kharkov regarded as a challenge to public taste. To the end of his life he preserved his liking for an extraordinary way of dressing -- he could most often be seen in a checked open-necked shirt and sandals which he changed for something more *comme il faut* only on special occasions, for example, when he was presented with the Nobel Prize.

It was in Kharkov that Landau formed the idea of writing a large book on theoretical physics, which would contain an interpretation of all branches of this subject conceived as a whole and using the same methods. Thirty years later, this work, consisting of eight large volumes, became one of the best textbooks and monographs in the whole of theoretical physics and it has been translated (in part or as a whole) into ten languages.

In Kharkov, too, Landau created his famous theoretical minimum (it was later called Landau's barrier), which was a collection of tests from theoretical physics that contained everything a good theoretical physicist should know. The barrier comprised nine tests. The first two were in mathematics and at the same time played the role of a sort of entrance examination. Landau did not require the candidate in mathematics to know "much": He had to be able to solve an arbitrary ordinary differential equation and calculate an arbitrary indeterminate integral which could be expressed in elementary functions. Further mathematical

subjects (e.g. group theory, special functions, tensor analysis, etc.) were contained in the individual theoretical tests. The seven remaining tests covered roughly the whole of Landau's textbook -- candidates usually had "only" to solve a few of the problems in order

Landau's Theoretical Minimum

Entrance examination in mathematics:

1. *Solve an arbitrary, ordinary differential equation.*
2. *Calculate an arbitrary, indeterminate integral expressible in elementary functions.*

Examinations in physics:

1. *Theoretical mechanics.*
2. *Thermodynamics and statistical physics.*
3. *Theory of fields (including the special and general theory of relativity).*
4. *Non-relativistic quantum mechanics.*
5. *Relativistic quantum mechanics, quantum electrodynamics, theory of fields, theories of elementary particles.*
6. *Electrodynamics of continuous media.*
7. *Mechanics of continuous media (hydrodynamics, theory of elasticity).*

to prove they had actively mastered the material. But these problems -- for example, of the anomalous Zeeman effect or of radiative corrections to some process treated in quantum electrodynamics -- had to be calculated to the very end.

By the end of Landau's life only 43 physicists had surmounted his barrier. Of these at least seven are today members of the Academy of Sciences of the USSR, and at least 16 doctors of science or professors.

One could speculate about the effectiveness and productivity of such a comprehensive and universal examination. It was very difficult to pass, especially since Landau neither asked questions, nor discussed the theories or their interpretation with the candidate examined. He just gave him a problem, placed him in his home studio, and left him for many hours to solve the problem.

One could easily imagine that penetrating Landau's barrier was for some of his students such a tremendous task, and required such efforts, that they had to use all their energy and abilities just to pass these examinations, so that afterwards they were exhausted and thus unable to do anything important in physics. In fact, several of those who had successfully passed the theoretical minimum disappeared for ever from the world of physics.

When examining, Landau was very informal. He did not pay any attention to the official requirements stipulated by the Soviet law concerning the number of examinations, their duration, and the commission which should be present at the examination, etc. And he never made any notes about the examinations -- he remembered by heart all his students and their progress in penetrating the barrier.

Landau was a strict examiner and in some questions was absolutely implacable and without mercy. The first examination of the minimum could be taken three times, but nobody could talk Landau into testing someone for the fourth time. Once in Kharkov he threw almost a whole class out of the examination room, because the students did not know some basic rules in algebra. The head of the faculty, in order to avoid a scandal, entrusted the examinations to another teacher with somewhat more modest requirements.

In 1934 Landau was awarded his Doctorate in Physics and Mathematics without having to defend a thesis. According to a joking curriculum vitae written by his colleagues on the occasion of Landau's fiftieth birthday, the commission was said to "have had a feeling of understanding for the difficulties of the young scientist who was incapable of writing a thesis and therefore awarded him the title without presenting one". His friends were referring here to Landau's proverbial dislike of putting pen to paper -- most of his papers and books were written in cooperation with someone: Landau's contribution was "merely" the idea, the derivations, the calculations, the plan, and the manifold criticism and profound reworking of the manuscript. "The pen was mine, the ideas belong to Dau", answered Evgenij Lifshitz [Lifshits]*) (with whom Landau wrote the course), when asked once who actually wrote the "Course of Theoretical Physics".

In addition to teaching in Kharkov, Landau continued intensive scientific research. He began investigations on the theory of phase transitions of second order[6,7] (many years later he said, to one of his friends, that he devoted more effort and time to this question than to any other) and published a series of fundamental works on the theory of ferromagnetism.

Landau was the first to introduce antiferromagnetism as a special phase of magnetics. He also created the theory of domain structure of ferromagnetics and the theory of ferromagnetic resonance[8,9]. In Kharkov, Landau started his theoretical investigations of superconductivity. In a number of papers, published between 1937 and 1957, he made an essential theoretical contribution to this complicated phenomenon. He proposed a theory of an intermediate state of superconductors, in which the superconductor consists of shifts of normal and superconducting phases[10,11]; he introduced the surface tension between the normal and superconducting phases. Later he developed the quasimacroscopic theory of superconductivity[12], which appears to be a special case of the microscopic theory of superconductivity of Bardin, Cooper and Shrieffer.

Landau did not remain very long in Kharkov -- the rector called him one day and complained about his testing physics students in material which was taught at the Philological Faculty, for example asking them: "Who wrote Eugene Onegin?". From a pedagogical point of view, he said, this was not allowed. "I've never heard of anything so stupid in my life",

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*) The international transliteration of a name has been added in square brackets in those cases where the more common English form has been used in the text.

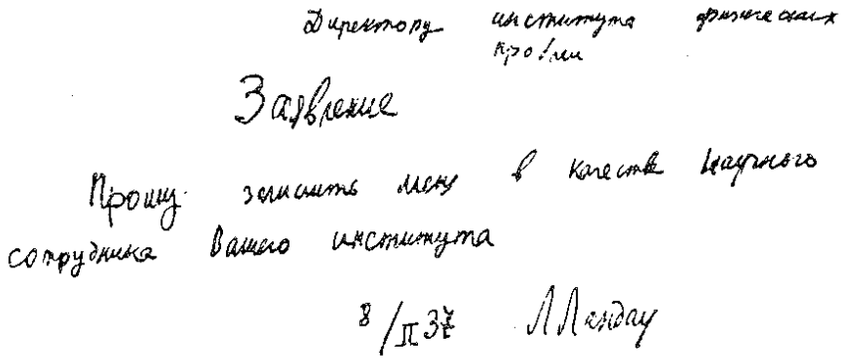
answered Landau. The rector was offended and asked Landau to apologize or he would throw him out of the university. Landau said the rector had no formal right to do so. And indeed the rector really had no formal right to dismiss a full professor -- this could only be done by a minister. But Landau received his notice from the university the same day. The offended pride of people who are narrow-minded and therefore insufficiently tolerant usually passes all bounds. But Landau did not resist or argue. He did not try to defend himself -- he was only too well aware of how much he would lose in the quarrel and how much the university; he gathered up his belongings and left for Moscow.

In a few weeks his friends and colleagues learnt that Landau had begun work in the Institute of Physical Problems in Moscow. Kharkov had thereby lost one of the greatest Soviet theoreticians. Moscow had gained. In time all Landau's most talented pupils and colleagues followed him to Moscow, since Kharkov without Landau had ceased to be attractive.

The Institute of Physical Problems in Moscow, where Landau started to work, was founded and built in 1935 for the Soviet physicist, Academician Piotr Kapitza [Kapitsa]. Kapitza was for many years working in the Cavendish Laboratory with Rutherford and was one of his closest collaborators. In 1934, Kapitza, as usual, went to Moscow to see his friends and relatives. Suddenly, the Soviet authorities refused to allow him to return to Cambridge. As a compensation, Kapitza was offered a new institute to be built in Moscow according to his own plans and ideas. Rutherford, who was very unhappy about the loss of Kapitza (who had been considered as his successor), tried for a long time to get Kapitza back. Finally, when Rutherford realized that all his efforts had been in vain, he made a beautiful gesture: he sent to Kapitza the first-class equipment which Kapitza had built up before his departure from the Mond Laboratory.

In building up the new institute, and later when he was directing it, Kapitza had almost unlimited financial and administrative power at his disposal. In the institute grounds an English-type house was built for Kapitza and a row of small houses for his colleagues. Kapitza was able to build up not only a first-class, and at the same time comfortable, institute but also to select good colleagues -- Rutherford's pupil had a special feeling for scientific talent.

In February 1937, Kapitza received a short application. It read:



Директору института физических проблем

Заявление

Прошу зачислить меня в качестве научного сотрудника Вашего института

8/II 37 Л. Ландау

To the Director of the Institute of Physical Problems:

Application

Please accept me as a scientist in your institute.

8/2/37 L. Landau

Kapitza knew Landau from Cambridge and he granted his application without more ado. Compared with other scientific institutes in the Soviet Union, Kapitza's was an exceptional one, and the exceptional Landau found work there and also the conditions under which his personality would not give rise to new conflicts -- on the contrary, he won recognition and space; without further internal obstacles and difficulties Landau could do the work for which his talent and abilities had predestined him.

Immediately after his arrival in Moscow, he worked on a number of new and important problems: phase transitions[6,7], the statistical theory of atomic nuclei[13], the cascade theory of electron showers[14], etc. In Moscow, Landau started one of his most important works, the theory of the superfluidity of liquid helium II (a phenomenon which Kapitza had discovered in 1937 in his laboratory). Landau realized very soon that this new phenomenon -- superfluidity -- required for a theoretical understanding and description, a completely new approach: helium II must be treated entirely as a quantum system -- as a kind of quantum liquid. Landau's theory of superfluidity gave not only the correct and full explanation of all observed effects, but also predicted several new effects[15,16], which lately have been confirmed in experiments.

The theory of superfluidity did not come into being without difficulties. In the spring of 1938, Landau was arrested for suspected espionage for Germany. This period of Landau's life is covered with great shyness in Soviet official publications. Kapitza, in his book "Experiment, Theory, Practice" [III], writes about this period of Landau's life in the following words: "At the Institute of Physical Problems Landau was working until the end of his life. Only in 1938, a year's interruption of his job occurred ...". I would like to devote a few lines to this "year's interruption".

Landau himself devoted to this tragic period a few lines written at the end of the fifties, during the thaw of Krushchev's rule: "... today such an accusation seems to be quite laughable -- at that time, however, believe me, it was obvious that I would not hold out more than another half-year: I was simply dying. Kapitza came to the Kremlin asking for my release, otherwise he would leave his institute. I was released. I need not emphasize that such a deed at that time required great courage, great humanity and a character of crystal purity of a man".

It is less known that it was not only Kapitza who had intervened on behalf of Landau. In the archives of Niels Bohr in Copenhagen is a copy of a very strong and extremely well formulated letter from Bohr to Stalin, where he is asking Stalin to use his influence to release Landau. Bohr wrote

> "... Während vieler Jahre habe ich die grosse Freude gehabt, mit Prof. Landau in sehr enger Verbindung zu stehen und regelmässig mit ihm über wissenschaftliche Probleme, die uns beide aufs tiefste interessieren zu korrespondieren. Auf meine letzten Briefe habe ich jedoch zu meiner grossen Besorgnis keine Antwort empfangen, und soviel ich weiss hat auch keiner der vielen anderen ausländischen Physiker, die seine Arbeit mit grösstem Interesse verfolgen, Nachrichten von ihm erhalten. Durch eine Anfrage an die Sowjet-Akademie der Wissenschaften, deren Mitglied zu sein ich die Ehre habe, habe ich auch versucht, mit Prof. Landau in Verbindung zu kommen; aber die Antwort des Präsidenten der Akademie, die ich soeben erhielt, enthält keinerlei Auskunft über Aufenthalt oder Schicksal von Prof. Landau.

"Hierüber bin ich tief bekümmert, besonders deshalb weil neuerdings Gerüchte von einer Verhaftung Prof. Landau mich erreicht haben. Ich hoffe noch immer, dass diese Gerüchte jeder Grundlage entbehren; sollte aber Prof. Landau wirklich verhaftet worden sein, so bin ich davon überzeugt, dass es sich um ein unseliges Missverständnis handeln muss; denn ich kann mir nicht vorstellen, dass Prof. Landau, der sich immer ganz der wissenschaftlichen Forschung widmete und dessen aufrichtige Persönlichkeit ich aufs höchste schätze, irgendetwas getan haben könnte, was eine Verhaftung rechtfertigen würde.

"In Anbetracht der grossen Bedeutung dieser Angelegenheit sowohl für die Wissenschaft in der USSR wie für die internationale wissenschaftliche Zusammenarbeit wende ich mich an Sie mit der dringenden Bitte, eine Untersuchung über das Schicksal von Prof. Landau zu veranlassen, sodass, wenn wirklich ein Missverständnis vorliegen sollte, dieser so ausserordentlich begabte und erfolgreiche Wissenschaftler wieder die Gelegenheit bekommt, an dem für den Fortschritt der Menschheit so wichtigen Forschungswerk teilzunehmen." [IV].

Landau was very lucky, indeed, to be released. At that time, many of his colleagues disappeared (e.g. M.P. Bronshtejn, N.I. Vavilov, etc.) or, as Yu.B. Rumer, had to spend many years in concentration camps.

In 1940, after being released from prison, Landau broke with the "great principle" of his youth and married. He again broke with one of his principles in 1946, when a son, Garik, was born to him. Up till then he had asserted that people should not have children because they interfered with their work.

Landau had a unique attitude to marriage. Edward Teller writes well about it: "Landau liked to make statements that would shock members of a bourgeois society. When we were together in Copenhagen I got married. He approved my choice (and played tennis with my wife). He once asked us how long we intended to remain together. When I answered that certainly for a very long time and that we actually had no intentions of breaking up our marriage, he got excited and said that only a capitalist society could force its members to spoil a basically good thing by exaggerating it in such a way." [II].

During the second world war Kapitza's institute was evacuated to Kazan. Together with other physicists Landau took part in solving problems raised by the war. Official records are silent as to what he did and Landau too was silent and only smiled mysteriously when asked directly. Equally "mysterious" was the awarding of the title of Hero of Socialist Labour that Landau received on 4 January 1954 -- his biographers can only hazard a guess at what he did or consult the calendar of important scientific and technical events in the USSR.

At the end of the war Landau began to write his Mechanics of Continua. Gradually a number of scientific papers appeared in this field, some of which are of basic and others of practical significance. This work concerned problems in relativistic hydrodynamics, the theory of shock waves[17], the theory of burning[18], the theory of turbulence[19], the theory of the detonation of explosives[20], etc. In connection with this cycle of scientific papers, work was also done on the theory of plasma [the theory of oscillations in plasma[21]], which later found application in experiments on controlled thermonuclear reaction.

In 1946 Landau was elected as a full member of the Academy of Sciences of the USSR. This meant recognition and fame. But Landau did not change. As before, anyone could go to him at any time and discuss with him or be examined. His days were filled with work, discussions, and debates. Thursdays were reserved for seminars (Fig. 1), which began exactly at 11 a.m.

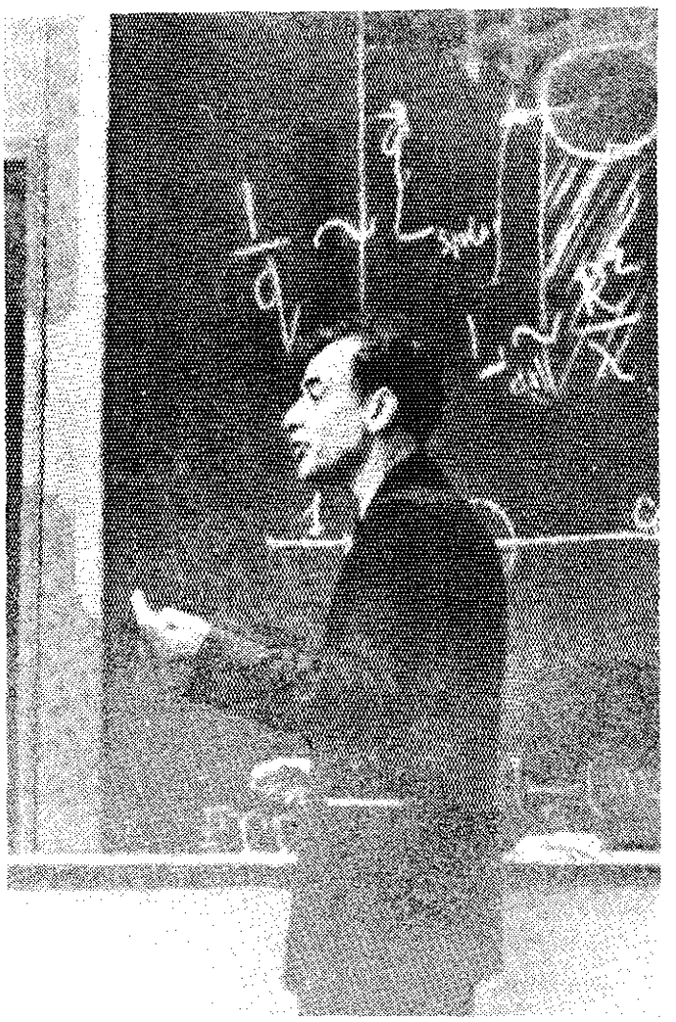


Fig. 1 L.D. Landau at a seminar

In 1946 Landau was elected as a full member of the Academy of Sciences of the USSR. This meant recognition and fame. But Landau did not change. As before, anyone could go to him at any time and discuss with him or be examined. His days were filled with work, discussions, and debates. Thursdays were reserved for seminars, which began exactly at 11 a.m.

The only time Landau's seminar was interrupted was in connection with a lecture on Heisenberg's non-linear theory, which created a sensation, and a special Kapitza evening seminar was devoted to it on the Wednesday; so many physicists went to it that the lectures and discussions had to be relayed by amplifier to the courtyard. Next morning, at Landau's Thursday seminar, someone read a letter from W. Pauli to M. Danish, in which Pauli announced

the complete collapse of the non-linear theory: the numerical solution of Heisenberg's non-linear equation was leading to a very large fine-structure constant. The letter made a great stir and almost all who took part in the discussion admitted that the new theory had not appealed to them very much and that they had actually not believed in it too much. Only Academician Pomeranchuk doubted Pauli's arguments. He wondered, how a theoretician like Pauli could go straight to the computer without trying some more theoretical means, e.g. asymptotical solutions of the non-linear equations. The criticism of Heisenberg's theory continued until someone noticed that the first letters of the paragraphs formed the Russian word "duraki" (fools). The letter was a fake -- a practical joke of Academicians A. Migdal and B. Pontecorvo (who objected to the uncritical spirit of the Wednesday seminar). For the first time Landau was unable to calm the seminar and induce those present to get on with normal business.

In the postwar period we witnessed a real eruption of scientific activities of Landau. He published a series of papers on the development of the theory of superfluidity and on the viscosity of helium II [22-25]. In the fifties he started, together with some of his collaborators, a very fundamental investigation and critical re-evaluation of quantum electrodynamics, quantum field theory and the theory of elementary particles[26-34]. In the fifties, Landau also created one of his most important contributions to theoretical physics -- the Theory of the Fermi liquid[35-37].

By the end of the fifties, an enormous work was almost finished -- a "Course of Theoretical Physics", which Landau wrote together with his closest colleague, Evgenij Lifshitz. The Course consisted of eight*) large volumes of about 4,000 pages of text and is indeed an encyclopaedia of modern theoretical physics, written moreover in a uniform approach and style, which without exaggeration we can call the style of modern theoretical physics.

"Course of Theoretical Physics"**) by L.D. Landau and E.I. Lifshitz
- Mechanics (1940, 1958, 1965)***)
- Field Theory (1941, 1948, 1960, 1967)
- Quantum Mechanics (1948, 1963)
- Relativistic Quantum Mechanics I (1968)†)
- Relativistic Quantum Mechanics II (1971)††)
- Statistical Physics (1938, 1940, 1951, 1964)
- Mechanics of Continuous Media (1944, 1954)
- Theory of Elasticity (1965)
- Electrodynamics of Continuous Media (1959).

Landau was one of the most outstanding theoreticians of our century. He was a theoretician body and soul, a theoretician *par excellence*, who was able to apply the methods of modern theoretical physics to any branch of physics. He has achieved unfading merit by his creation of a modern theoretical style. Complete mastership of the methods of theoretical physics enabled him to work in a very broad field. He was unique in being able to get to

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*) The number of pages and volumes and also their sequence vary in different editions.

**) In brackets are given the years of the first edition and of revised editions of importance.

***) The first edition was written with I. Pyatigorskij.

†) Published after Landau's death with V.B. Berestetskij and L.P. Pitaevskij.

††) Published after Landau's death with L.P. Pitaevskij.

the theoretical essence of any scientific problem and then to solve it "by the method of theoretical physics". He could easily disengage himself from the ideas of others, rid himself of their influence; he could simplify a problem and make it trivial. Landau was, as he used to say, "one of the very few physicist-Universalists (encyclopaedists)". After Fermi's death he remarked sadly: "Now I am the last physicist-Universalist ...".

Besides the "Course of Theoretical Physics", Landau published also a number of other books, among them a colourfully written "Physics for All" [V] (together with A.I. Kitajgorodskij), "Lectures on Nuclear Theory" [VI] (together with Ya.A. Smorodinskij), "What is the Theory of Relativity?" [VII] (together with Yu.B. Rumer), the first volume of a "Course in General Physics" [VIII], etc. Landau's philosophy in writing books (as we have already mentioned, Landau himself actually "wrote" very little) was characteristic: "To publish a silly book is no great tragedy, it does not hurt anyone. It is better to publish ten imperfect books than to risk not to publish one good one."

Landau had created the most important and influential Soviet (and not only Soviet) school of theoretical physics. It is difficult to overestimate its importance and role in Soviet physics. However, looking back from some distance and from outside, Landau's role sometimes seems somewhat controversial.

His intellectual superiority was beyond doubt. It was stimulating to work with Landau, but sometimes his superiority mixed with sarcasm had a depressing effect.

Landau himself was a strange and unique mixture of simplicity and democratic behaviour (rather unknown in the Soviet Union at that time), unlimited intolerance and self-confidence. Especially his lack of tolerance was quite a characteristic feature of Lev Landau. I may illustrate this by giving some examples.

In 1931, Niels Bohr got a cable from Landau in England, in which young Landau had summarized his impressions of the Dirac talk, where Dirac was trying to find an interpretation of his equation in terms of particle-holes (positrons as holes in the infinite sea of electrons). The particle-hole conception appears to be one of the most fruitful conceptions in modern physics -- both modern nuclear physics and solid state physics would hardly exist without it. Landau's cable was short and categorical [IV]:

QUATSCH*) .

Of course, it was not easy to understand this new conception and to accept it. In 1933, for example, commenting on Dirac's talk at the 1st All Union Conference on the Atomic Nucleus (Leningrad) [IX], V.A. Fock said: "I have to confess that I am experiencing extraordinary confusion when trying to understand this basic assumption (about the infinite large mass and charge of the negative sea of electrons, which does not manifest itself at all physically) of the theory, and I think that I am not alone in having such feelings."

Fortunately, Landau's opinion did not have any great influence on Dirac and his colleagues at that time, and he himself changed his idea of this subject quite soon.

Landau had invented a special word for condemning theories or physics he did not like:

PATHOLOGY .

*) QUATSCH means "rubbish" in German.

When, in the late thirties, he was not allowed to travel abroad any more, he expressed in a letter to Niels Bohr his fears, that his isolation might develop pathologies in himself, since he considered contacts with foreign scientists and exchange of ideas and scientists (to use the formulation of the Helsinki document) as a very essential constituent of science: "Ich habe gehört Sie kämen in nächster Zeit in die Union. Das wäre sehr schön! Mit meinen Reiseplänen scheint nichts zu werden und ich kriege allmählich Angst, dass ich mich in trauriger Einsamkeit zu einem Patologen entwickeln könnte" (Kharkov, 10.11.1936) [IV].

The impact of his categorical judgements can be illustrated by two episodes. It is quite interesting to consider a histogram of Landau's scientific publications as a function of time. It is based on his collected scientific papers, published in two volumes, selected for publication during his life. One can easily explain the minima in the histogram (Fig. 2) by the interference of external influences like prison, war, campaigns against

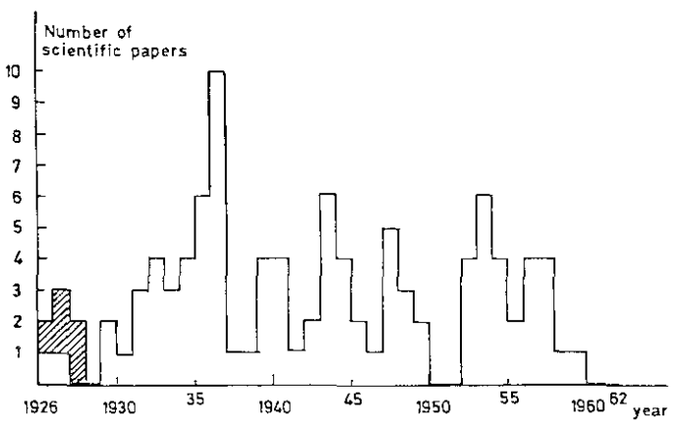

Fig. 2 Histogram showing the number of Landau's scientific papers as a function of time, according to his collected works [X]

cosmopolitanism and Jews, etc. But I am going to concentrate myself on the first part of the histogram. The shadowed part indicates the publications that Landau himself has excluded from his collected papers. All five papers that he had published with Ivanenko are among the excluded ones. The reason? It is difficult to say. Most probably this strange censorship is related to the fact that Ivanenko had been transferred from the group of Landau's (or Dau's) best friends to that of the most pathologist physicists, who were never allowed to participate in Landau's seminars. If you would dare to mention to Landau that Ivanenko had done some nice investigation or had published an interesting paper, you would spoil completely your own relations with Landau.

Landau's intellectual superiority, lack of tolerance, and absolute judgements could sometimes have harmful consequences, for example in the case of I.S. Shapiro, from Moscow. In 1956 Shapiro had been very actively investigating the so-called τ-θ problem, which had been puzzling physicists for a long time. Shapiro came to the conclusion that the only possible explanation could be the parity non-conservation in this decay of mesons. Since this decay belongs to weak interaction, he predicted and calculated some other phenomena, which could testify about the parity non-conservation in beta decay, such as longitudinal polarization of electrons, circular polarization of internal bremsstrahlung and correlation beta-gamma-circular polarization. He even speculated about the possible explanation of

parity violation and tried to attribute it to the structure of space at distances characteristic of weak interactions, i.e. 10^{-17} cm (discussed in another connection by a Canadian mathematician, Coish). Landau, when Shapiro presented him the paper, laughed at such an idea -- without Landau's holy consent Shapiro's paper could not be published*). It remained on his desk, where I saw it many months before Lee and Yang submitted their paper for publication. So, because of Landau, Soviet physics lost one Nobel prize.

Once, lecturing in Moscow during his last visit to the USSR, Niels Bohr was asked how he had succeeded in creating such a famous and first-class school of theoretical physics. He answered: "Probably because I have never been ashamed of admitting to my students that I am a fool."

Bohr's lecture was translated into Russian by Landau's closest collaborator, E. Lifshitz, who translated it: "Probably because I have never been ashamed to tell my students that they are fools."

Lifshitz's mistranslation caused a lot of laughter among the listeners. Lifshitz became aware of his mistake, corrected himself, and apologized. Kapitza, who was present, remarked that this mistranslation had not been accidental at all: "Precisely here lies the difference between Bohr's and Landau's schools of theoretical physics."

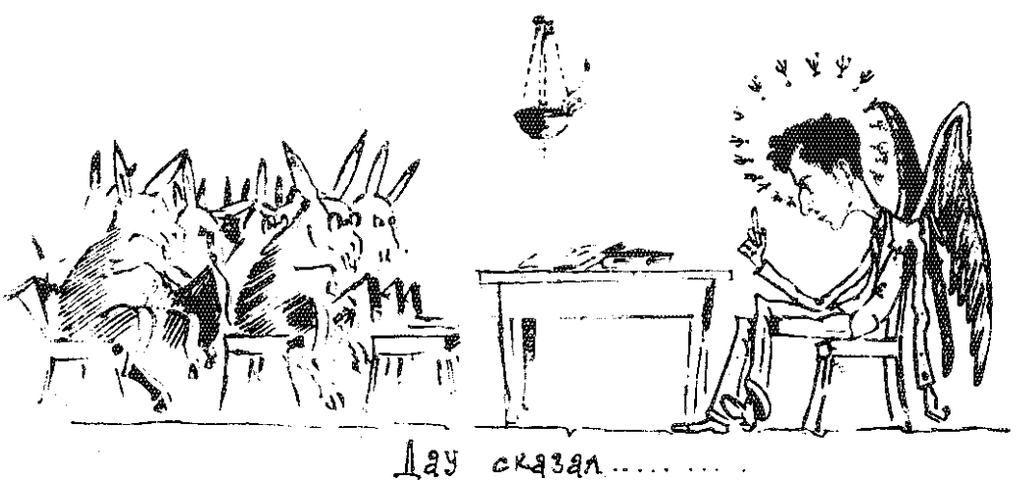

Fig. 3 "Dau said ...". Caricature by A. Yusefovich [X]

In Landau's last years, perhaps from the end of the second world war, he was more and more non-political, avoiding public activities and engagements. His original admiration of the revolution and the radical changes the revolution brought along, cooled down. He was more balanced, critical, sceptical. (Similar scepsis could be observed among the majority of the Soviet physicists.)

*) A similar case is reported by Landau's closest collaborator, A.A. Abrikosov [XI]. Landau's negative attitude to Abrikosov's theory had delayed the discovery of superconductivity II for about four years.

Landau remained a Russian (or Soviet) patriot. His admiration was, however, directed towards Soviet science, some Soviet art, and Russian classical literature. His public activities were strictly limited to science, pedagogy and participation in discussions concerning the reforms of the Soviet school system*).

It is difficult to judge whether Landau's non-political attitude was the result of "a year's interruption" (the euphemism used in his biography), his experiences in the thirties or fifties, or of his preoccupation with science.

It is, however, a fact that Landau, at least during the last 10-15 years of his life, did not lend his name to any political declaration or condemnation of anything or anyone, and that he never became a member of the communist party.

In the postwar period, in spite of his high reputation and fame, he was never allowed to travel abroad. To Landau this was a heavy burden, although he did not show it in public -- it was not his life style -- but in private, among his friends, he sometimes complained bitterly of not being allowed to travel abroad, not even to the East European countries ... .

Being a recognized and celebrated Soviet scientist (and the social status of Soviet scientists at that time was much higher than it is nowadays in the USSR), Landau was sometimes forced to comment or give his judgement on some "genial" discoveries, which were being presented to the Academy of Sciences or other governmental organizations in the USSR. He usually tried to avoid such time-wasting duties, but when forced to comment, his remarks were hard: "I have to tell you that your manuscript is of no interest at all. Modern physics is an immense science, based first of all on a great amount of experimental facts. Obviously you are totally ignorant of science and try to explain in empty words the laws of physics which you hardly know. This can lead nowhere. If you have a serious interest in physics, you should not try to make discoveries, but to learn the subject at least a little bit."

Landau gave the impression that he was a person who could do anything easily, blindfold, that he was such a genius that he did not even have to work. He must have made this impression even on his close colleagues -- V.L. Ginzburg once told him that he thought that with his talent, technique and style Landau could do much more. Landau immediately answered, as though he had already thought about such a question, "No, that is not true. I have done what I could."

His last scientific paper, "Fundamental Problems"[38], deals with nullification of electrical charge in elementary particles, a problem Landau and his collaborators had been working on during the past few years. The paper is characteristic of Landau, and I will allow myself to quote from it:

> "It is with the deepest sorrow that I send this article written in the honour of the sixtieth birthday of Wolfgang Pauli to a volume dedicated to his memory, which will always be cherished by those who had the good luck of knowing him personally.

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*) Since, according to Soviet canons and ethics, the principal duty of every Soviet citizen is to be involved in public activity, the Soviet intelligentsia has invented a self-protecting theory: Pedagogical activity has the highest priority in public affairs and, therefore, scientists who are lecturing and teaching should not be forced to do anything else.

"It will be impossible now to know his opinion about the ideas expressed in this article but I am still encouraged by the thought that his views on the subject would not be very different ... .

"... The correctness of "nullifying" the theory has often been called in question. The Lee model is a very special one, considerably differing in several respects from physical interactions; and the validity of Pomeranchuk's proofs has been doubted. In my opinion such doubts are unfounded. For example, Källén has several times put forward the view that unusual properties of the series to be summed are involved, but he has never given reasons to support this view. By now, the "nullification" of the theory is tacitly accepted even by theoretical physicists who profess to dispute it. This is evident from the almost complete disappearance of papers on meson theory, and particularly from Dyson's assertion that the correct theory will not be found in the next hundred years -- a piece of pessimism which would be impossible to understand if one supposed that the present meson theory leads to finite results which we are yet unable to derive from it. It therefore seems to me inopportune to attempt an improvement in the rigour of Pomeranchuk's proofs, especially as the brevity of life does not allow us the luxury of spending time on problems which will lead to no new results ..."

(Underlined by F.J.)

As I have mentioned in the beginning, it is extremely difficult to give a short survey of Landau's scientific activity, which covers quantum mechanics, quantum field theory, elementary particle physics, nuclear physics, thermodynamics and statistical physics, continuum mechanics, and many different parts of solid state physics.

It may be that the most appropriate and correct way to perform this task is to mention here the "Ten Commandments of Landau", in which his friends and collaborators tried to summarize his scientific activity on the occasion of Landau's fiftieth birthday. The "Ten Commandments of Landau" were presented to him, engraved on two stones [XII] (Fig. 4).

During the postwar period, Landau became a member of many academies and scientific societies (*inter alia*, the Danish, Dutch, and American Academies and the Britsh Royal Society, etc.) and received several Soviet and foreign awards*). The highest, the Nobel Prize for Physics, however, he received after his accident.

The telegram telling Landau he had been awarded the Nobel Prize said:

"Stockholm, 1 November 1962. The Royal Swedish Academy of Sciences has decided to award you the Nobel Prize for Physics for pioneering theories for condensed matter, especially liquid helium. Details follow in letter.
Erik Rudberg, Permanent Secretary."

For the first time in history the Nobel Prize for Science was not accepted from the hands of the Swedish king in Stockholm; it was handed over by the Swedish ambassador in Moscow, in the hospital where Landau lay.

On 7 January 1962, Landau, the physicist, was fatally hurt in a car accident. The terrible and senseless accident ended the life of one of the greatest theoreticians of our century in the midst of his creative work. Landau was travelling with some colleagues to

*) e.g. the Lenin Prize (1962), F. London Prize (1960), Max Planck Medal (1960).

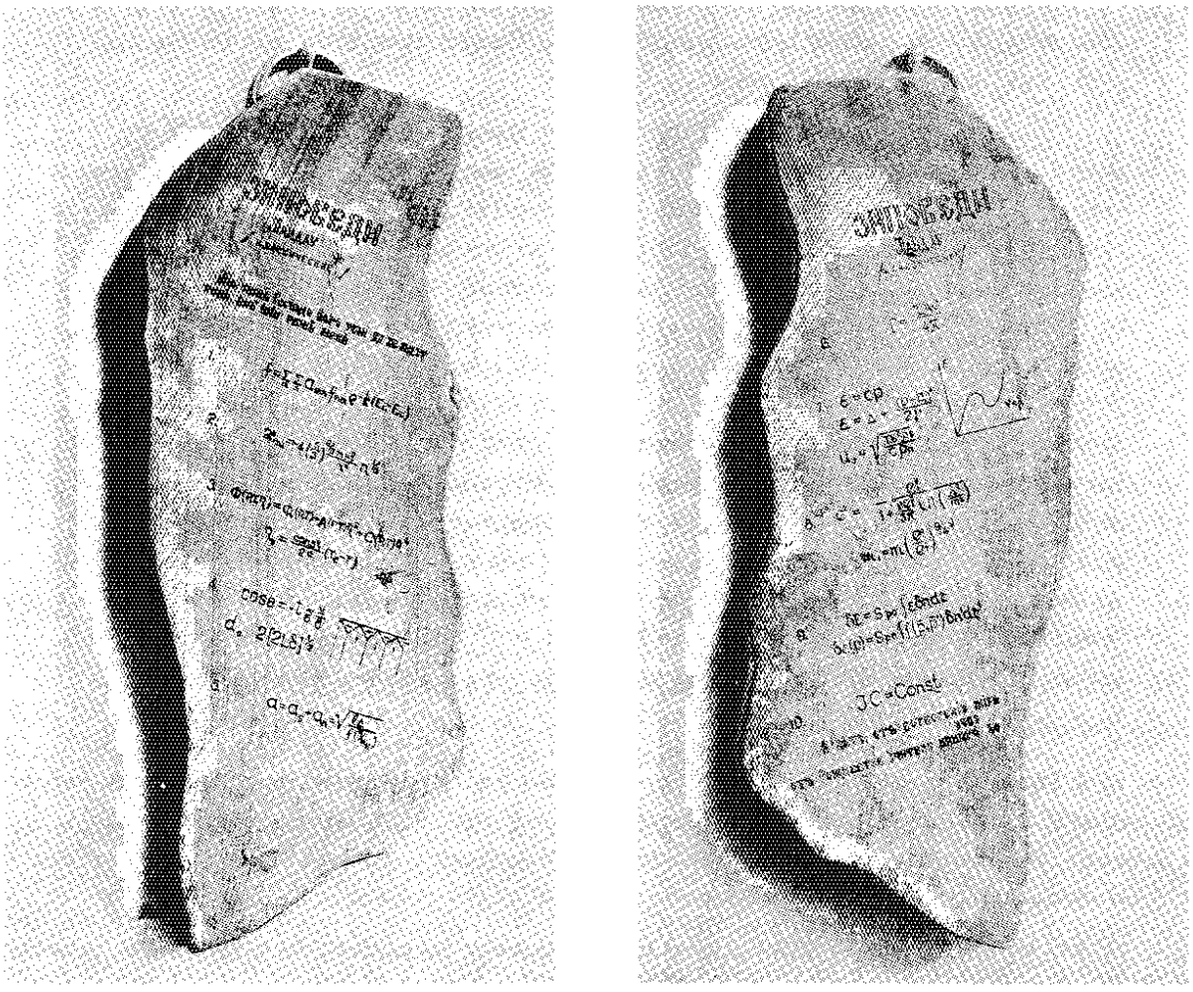

Fig. 4 "Ten Commandments of Landau"

"Ten Commandments of Landau"

1. The density matrix in quantum mechanics and statistical physics (1927) [1].
2. Quantum theory of diamagnetism of free electrons (1930) [4].
3. Phase transitions of second order (1936-37) [6,7].
4. The domain structure of ferromagnetics; interpretation of antiferromagnetism (1935) [8,9].
5. The theory of an intermediate state of superconductors (1943) [10,11].
6. The statistical theory of the atomic nucleus (1937) [13].
7. Quantum theory of superfluidity of helium II (1940-41) [15,16].
8. The nullification of electrical charge of elementary particles (1954) [31].
9. Quantum theory of the Fermi liquid (1956) [35,36,37].
10. Combined parity in weak interactions (1957) [39].

Fig. 5 L.D. Landau with his wife during the Nobel ceremony in Moscow

Dubna. It was icy and, on the outskirts of Moscow, the driver -- Landau's friend and also a theoretical physicist -- braked, skidded, and crashed into an oncoming lorry. Landau was the only one hurt. Not even the eggs taken to Dubna were broken.

Landau's injuries were serious, so serious that he was taken to hospital almost in a state of clinical death.

The catastrophe shook the world of physics. Moscow physicists immediately formed a team to do everything, even the impossible, in the shortest possible time. Day and night several physicists were on duty at the hospital and several cars waited outside, whose drivers -- also physicists -- were prepared to drive immediately anywhere and organize everything. They literally carried resuscitation equipment into the hospital, and this dragged Landau from the jaws of clinical death. In a few hours foreign colleagues had helped to get some rare medicine to Moscow -- a plane was held up in London for an hour because of it. An international concilium of the world's best specialists arrived in Moscow, amongst whom was Professor Z. Kunc from Prague.

The doctors, half jokingly, half seriously, declared that Landau owed 33% of his salvation to the doctors, 33% to the physicists, 33% to his own organism and 1% to God.

On 8 April Landau said his first words: "Thank you." On 14 April he began to speak in Russian and in foreign languages. On 3 May he remembered that he had a son, Garik, and wanted to see him. On 6 May a post-graduate student of his began to put him questions on physics -- Landau answered correctly and intelligibly.

It was a miracle that Landau survived such severe injuries to his brain. But it was a miracle helped on by all those around him, because nothing was left to chance. For months Landau's food was prepared by his old friend, A.I. Shal'nikov; every day, according to the doctors' prescription, he measured out exactly the quantities of the freshest meat, eggs, fruit, and butter in sterilized pots (and the word exactly has quite a different significance for a physicist than for an ordinary cook or dietician). Fresh food was brought to Shal'nikov's flat by professors and doctors of science, and the ready meals were then taken personally to the hospital by Shal'nikov, Corresponding Member of the Academy of Sciences of the USSR.

Physically, Landau gradually got better. He began to walk, he revised physics and mathematics with his son -- but he himself did not do any physics. It even seemed as though he were afraid of physics. The serious damage to his brain had led to a loss of immediate memory. Landau remembered nothing of what was said to him. He was unable to remember anything new in physics. Although he remembered that he had had a phenomenal memory, he felt this weak point and therefore preferred to avoid talking about physics. It was tragic to watch him. At first glance it was the same Landau, but in reality it was somebody quite different. He was able to react normally, joke, chat, and walk -- but he, best of all, realized that the injury to his head had deprived him of the qualities that had made him Landau.

Landau the man outlived Landau the physicist by six years.

On 24 March 1968, Landau suddenly had a relapse. A desperate operation was performed. He improved slightly but on 1 April he was worse again. "I shall not outlive this day", he said in the morning. As so many times in his life, he was right. He was dying, and he knew it. His last words were: "I haven't lived badly. I was always successful in everything.

A Selected List of L.D. Landau's Scientific Papers

(A complete list can be found, for example, in [X])

1) Das Dämpfungsproblem in der Wellenmechanik, Z. Phys. 45, 430 (1927).

2) (With R. Peierls) Quantenelektrodynamik im Konfigurationsraum, Z. Phys. 62, 188 (1930).

3) (With R. Peierls) Erweiterung des Unbestimmtheitsprinzips für die relativistische Quantentheorie, Z. Phys. 69, 56 (1931).

4) Diamagnetismus der Metalle, Z. Phys. 64, 629 (1930).

5) (With L. Rozenkevich) Über die Theorie des elektrischen Durchschlags von A. Joffe [A. Ioffe]*), Z. Phys. 78, 847 (1932).

6) Zur Theorie der Phasenumwandlungen I, Phys. Z. Sowjet. 11, 26 (1937).

7) Zur Theorie der Phasenumwandlungen II, Phys. Z. Sowjet. 11, 545 (1937).

8) Eine mögliche Erklärung der Feldabhängigkeit der Suszeptibilität bei niedrigen Temperaturen, Phys. Z. Sowjet. 4, 675 (1933).

9) (With E. Lifshitz [E. Lifshits]*)) On the Theory of the Dispersion of Magnetic Permeability in Ferromagnetic Bodies, Phys. Z. Sowjet. 8, 153 (1935).

10) Zur Theorie der Supraleitfähigkeit, Phys. Z. Sowjet. 11, 129 (1937).

11) On the Theory of the Intermediate State of Superconductors, J. Phys. (USSR) 7, 99 (1943).

12) (With V.L. Ginzburg) On the Theory of Superconductivity, Zh. Eksp. & Teor. Fiz. 20, 1064 (1950) (in Russian).

13) Zur statistischen Theorie der Kerne, Phys. Z. Sowjet. 11, 556 (1937).

14) (With G. Rummer [Yu.B. Rumer]*)) The Cascade Theory of Electronic Showers, Proc. Roy. Soc. A166, 213 (1938).

15) On the Theory of Superfluidity of Helium II, J. Phys. (USSR) 5, 71 (1941); Zh. Eksp. & Teor. Fiz. 11, 592 (1941) (in Russian).

16) On the Hydrodynamics of Helium II, J. Phys. (USSR) 8, 1 (1944); Zh. Eksp. & Teor. Fiz. 14, 112 (1944) (in Russian).

17) On Shock Waves at Large Distances from the Place of their Origin, J. Phys. (USSR) 9, 496 (1945).

18) On the Theory of Slow Burning, Zh. Eksp. & Teor. Fiz. 14, 240 (1944) (in Russian); Prikl. Mat. Mekh. 9, 286 (1945) (in Russian).

19) On the Problem of Turbulence, Dokl. Akad. Nauk SSSR 44, 339 (1944) (in Russian).

20) (With K.P. Stanyukovich) On the Detonation of Condensed Explosive Materials, Dokl. Akad. Nauk SSSR 46, 399 (1945) (in Russian).

21) On the Vibrations of the Electronic Plasma, J. Phys. (USSR) 10, 25 (1946); Jz. Eksp. & Teor. Fiz. 16, 574 (1946) (in Russian).

22) On the Theory of Superfluidity of Helium II, J. Phys. (USSR) 11, 91 (1947).

23) On the Theory of Superfluidity, Phys. Rev. 75, 884 (1949); Dokl. Akad. Nauk SSSR 61, 253 (1948) (in Russian).

*) The international transliteration of a name has been added in square brackets in the References in cases where a different form was used in the quoted work.

24) (With I.M. Khalatnikov) The Theory of Viscosity of Helium II. 1. Collision of Elementary Excitation in Helium II, Zh. Eksp. & Teor. Fiz. 19, 637 (1949) (in Russian).

25) (With I.M. Khalatnikov) The Theory of Viscosity of Helium II. 2. The Calculation of the Viscosity Coefficient, Zh. Eksp. & Teor. Fiz. 19, 709 (1949) (in Russian).

26) (With A.A. Abrikosov and I.M. Khalatnikov) On the Removal of Divergences in Quantum Electrodynamics, Dokl. Akad. Nauk SSSR 95, 497 (1954) (in Russian).

27) (With A.A. Abrikosov and I.M. Khalatnikov) The Asymptotic Expression of the Green Function of the Electron in Quantum Electrodynamics, Dokl. Akad. Nauk SSSR 95, 773 (1954) (in Russian).

28) (With A.A. Abrikosov and I.M. Khalatnikov) The Asymptotic Expression of the Green Function of the Photon in Quantum Electrodynamics, Dokl. Akad. Nauk SSSR 95, 1177 (1954) (in Russian).

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30) On the Quantum Theory of Field, *in* Niels Bohr and the Development of Physics (ed. W. Pauli) (Pergamon, London, 1955), p. 52.

31) (With I.Ya. Pomeranchuk) On the Point-Interaction in Quantum Electrodynamics, Dokl. Akad. Nauk SSSR 102, 489 (1955) (in Russian).

32) (With A.A. Abrikosov and I.M. Khalatnikov) On the Quantum Field Theory, Nuovo Cimento Suppl. 3, 80 (1956).

33) (With A.A. Abrikosov, A.D. Galanin, L.P. Gorkov, I.Ya. Pomeranchuk, K.A. Ter-Martirosyan) On the Possibility of the Formulation of the Theory of Strongly Interacting Fermions, Phys. Rev. 111, 321 (1958).

34) On Analytical Properties of Vertex Parts in Quantum Field Theory, Zh. Eksp. & Teor. Fiz. 37, 62 (1959) (in Russian).

35) The Theory of Fermi Liquid, Zh. Eksp. & Teor. Fiz. 30, 1058 (1956) (in Russian).

36) The Vibration of Fermi Liquid, Zh. Eksp. & Teor. Fiz. 32, 59 (1957) (in Russian).

37) On the Theory of Fermi Liquid, Zh. Eksp. & Teor. Fiz. 35, 97 (1958) (in Russian).

38) On Conservation Laws in Weak Interactions, Zh. Eksp. & Teor. Fiz. 32, 405 (1957) (in Russian).

39) Fundamental Problems, *in* Theoretical Physics in the Twentieth Century, A Memorial Volume to Wolfgang Pauli (ed. M. Fierz and V.F. Weisskopf) (Interscience, New York, 1960).

A Selected List of Books and Articles about or by L.D. Landau

[I] F. Hund: Geschichte der physikalischen Begriffe (Bibliographischerches Institut, Mannheim, 1972).

[II] J. Pellam: Lev Landau, Physics Today 14, No. 3, 42 (1961).

[III] P.L. Kapitza: Experiment, Theory, Practice (Nauka, Moscow, 1977) (in Russian).

[IV] Niels Bohr Archives, Copenhagen.

[V] L.D. Landau and A.I. Kitajgorodskij: Physics for All (Nauka, Moscow, 1965) (in Russian).

[VI] L.D. Landau and Ya.A. Smorodinskij: Lectures on the Theory of the Atomic Nucleus (Gosudarstvennoje Izdatelstvo Nauchnoj Literatury, Moscow, 1955) (in Russian).

[VII] L.D. Landau and Yu.B. Rumer: What is the Theory of Relativity (Sovetskaja Rossija, Moscow, 1959) (in Russian).

[VIII] L.D. Landau, A.I. Akhiezer and E.M. Lifshitz: Course of General Physics, Mechanics and Molecular Physics (Nauka, Moscow, 1965) (in Russian).

[IX] Atomnoje Jadro (Ed. M.P. Bronshtejn) (Gosudarstvennoje Tekhniko-teoreticheskoje Izdatelstvo, Leningrad-Moscow, 1934).

[X] L.D. Landau, Sobranie Trudov (Collected Works) (Nauka, Moscow, 1969) (in two volumes -- in Russian). Also Collected Papers (Ed. D. Ter Haar) (Pergamon, Oxford, 1965) (in English).

[XI] A.A. Abrikosov: My years with Landau, Physics Today 26, No. 1, 56 (1973).

[XII] M. Bessarab: Stranicy zhizni Landau (Moskovskij Rabochij, Moscow, 1971).

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[XIII] V.B. Berestetskij: L.D. Landau, Uspekhi Fiz. Nauk 64, 615 (1958) (in Russian).

[XIV] A.A. Abrikosov: Akademik L.D. Landau (Nauka, Moscow, 1963) (in Russian).

[XV] V.L. Ginzburg: L.D. Landau, Uspekhi Fiz. Nauk 94, 181 (1968) (in Russian).

[XVI] F. Janouch: Lev Landau I, Czech. J. Phys. A22, 400 (1972);
F. Janouch: Lev Landau II, Czech. J. Phys. A22, 451 (1972).

[XVII] A. Livanova: L.D. Landau (Znanie, Moscow, 1978) (in Russian).

[XVIII] A. Dorozynski [A. Dorozhinskij]: The Man They Wouldn't Let Die (Secker & Warburg, London, 1965).