Personalia

WOLFGANG PAULI

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In December 1958 world science suffered a heavy loss — the death, in Zurich, of Wolfgang Pauli, one of the most outstanding theoretical physicists of our time.

Pauli's scientific work, like that of most other major theorists, began very early. His first paper, devoted to the general theory of relativity, goes back to 1918. At that time the eighteen-year-old physicist was a student at the University of Munich. Like almost all of the outstanding theorists of his generation, Pauli was a student of A. Sommerfeld.

The majority of Pauli's papers, however, are closely connected with quantum theory, on which he began his work in 1923, while still in Munich. The first problem to which he applied his powers was that of the anomalous Zeeman effect. His enthusiasm about this difficult problem has been colorfully described by Pauli himself: "When my friends in Munich would ask me, 'Why do you look so unhappy?' I always answered, 'Can anyone look happy when he's thinking about the anomalous Zeeman effect?' "

Pauli did not solve the entire problem of the anomalous Zeeman effect; indeed it could not be solved at that time, before the creation of wave mechanics. Pauli was, however, led by his studies of the anomalous Zeeman effect to a correct explanation of the phenomenon of the fine structure of spectral lines. He was the first to understand that the fine structure is the manifestation of a completely new physical property of the electron, which has no analogy in classical mechanics. To explain the fine structure Pauli ascribed to the electron a new quantum number, which takes two values. He called this number "a double-valuedness that cannot be described classically." The existence of this quantum number and the correctness of the explanation given by Pauli were brilliantly confirmed later by the discovery of the spin of the electron, which, according to quantum mechanics, takes on two values.

It is interesting that Pauli did not at once accept the interpretation of the spin as a mechanical angular momentum of the electron. To him, with his excellent understanding of the purely quantum character of the "two-valuedness" of the electron, such an interpretation seemed too classical. It was made fully acceptable to him only when Bohr showed the impossibility of a classical measurement of the spin of a free electron, and consequently of giving it a purely classical interpretation.

The discovery of the new quantum number was an important step in preparation for the appearance of Pauli's most important and famous paper — the paper in which the principle that bears his name was formulated. This principle, which states that if we adjoin to the quantities defining the state of the electron the new quantum number, then not more than one electron can be in each state, was formulated by Pauli in 1925, after he had carefully studied the papers of Bohr (with whom he worked for about a year in Copenhagen) on the quantum-mechanical interpretation of the Mendeleev periodic system of the elements. Now, many years later, when the Pauli Principle is a well known fact, it is already hard to conceive the boldness of a hypothesis that even particles between which there are no forces at all affect each other so strongly that they cannot be in the same state.

There is little need for any detailed remarks on the importance of the Pauli Principle, which is one of the basic laws of nature. The Pauli Principle was first stated by its author in the terminology of the old quantum theory of Bohr. After the development of quantum mechanics, the Pauli Principle became one of its most important basic features.

After 1925 Pauli took an active part in the development of quantum mechanics in its formative stages. In particular, an important part was played at this time by a paper in which he used the apparatus of quantum mechanics in its matrix form, before the invention of wave mechanics, to determine the energy levels of the hydrogen atom. The solution of this problem in the matrix form was very complicated and required great ingenuity.

In 1927, after the spin of the electron had been discovered, Pauli showed how the spin must be introduced into the mathematical apparatus of quantum mechanics. It is significant that Pauli's paper devoted to this problem is so clearly and simply written that even now one need scarcely change even a word of the author's exposition.

From this same time we have one of the few papers Pauli wrote on macroscopic physics, in which he calculated that part of the magnetic susceptibility of an electron gas that is due to the magnetic moments of the electrons (the Pauli paramagnetism).

The boldness of Pauli's scientific thought appeared again in 1931, when he predicted the existence of the neutrino. As is well known, until the appearance of Pauli's hypothesis it had seemed that for the explanation of the phenomenon of β decay there would have to be a radical modification of the existing physical concepts, since the continuous β-ray spectrum seemed to be a direct proof of a violation of the law of conservation of energy in the decay. Pauli's hypothesis, that part of the energy is carried away by a particle that has only an extraordinarily weak interaction with matter — the neutrino — seemed at that time very artificial and implausible. To appreciate fully the boldness of this hypothesis, we have only to remember that in 1931 only two elementary particles were known, the electron and the proton, and the very possibility of the existence of a new elementary particle, to say nothing of one with such strange properties, seemed altogether incredible. It is not surprising that Pauli's hypothesis was met with great disbelief, which was abated only after it was shown that there exists an upper limit of the energy of β-decay electrons.

A considerable number of papers by Pauli are devoted to various problems of relativistic quantum mechanics. As early as 1927 (sic), in collaboration with Heisenberg, he shaped into a system the formal apparatus of quantum electrodynamics, which theorists used thereafter for about twenty years, right up to the invention of the new invariant perturbation theory.

One of the problems in this field that most interested Pauli was that of the connection between spin and statistics. From 1936 to 1940 he published several papers on this topic. In these papers it was shown that particles with integral spin obey the Bose-Einstein statistics, and those with half-integral spin obey Fermi-Dirac statistics — i.e., they obey the Pauli Principle.

Somewhat apart from Pauli's other papers stands one published in 1938, on the exact theory of the diffraction of electromagnetic waves by a conducting wedge.

Later on, in the 1940's, Pauli took an active part in the development of the new quantum field theory, based on the so-called theory of renormalization. Together with Villars he developed a method which played an important part in the early stages of the development of the theory.

Later, when serious difficulties began to appear in quantum field theory in its present form, Pauli was one of a few physicists who understood that for the strong interactions the apparatus of the present theory leads to the vanishing of the whole interaction. Significant in this connection is his paper with Källen, in which this proposition was proved for the case of one special model of interacting fields, the so-called Lee model.

Pauli's last achievement is the very curious Lüders-Pauli theorem, which states essentially that in virtue of certain purely formal transformation properties of fields all equations must remain invariant under the combined transformations of change of sign of the space coordinates, change of sign of the time, and replacement of all particles by their antiparticles. This theorem has taken on special significance quite recently, when the discovery of parity nonconservation in weak interactions has revealed that in nature one does not have invariance with respect to each of these transformations taken separately.

Besides a large number of original scientific papers, many more, of course, than we have mentioned here, Pauli wrote several papers of a survey character. Among them Soviet readers are well acquainted with "The Theory of Relativity," "General Principles of Wave Mechanics," "Relativistic Theory of Elementary Particles," and "The Meson Theory of Nuclear Forces." All of these books, the first of which was written while the author was still in his student years, are distinguished by the exceptional clarity, brevity, and depth of the exposition. It is now a long time since most of them were written, but only the slightest fraction of the material in them seems outmoded; this is without doubt due to the author's exceptional intuition.

It is interesting to note that in the very small space of the second part of "General Principles of Wave Mechanics" space was still found for an exposition of the properties of the two-component equation for particles with mass zero and spin $\frac{1}{2}$. Earlier this equation was rejected, since it did not satisfy the law of conservation of parity. After the discovery of parity nonconservation, however, it has turned out that the neutrino is described by precisely this equation.

In this article we have commented briefly on Pauli's scientific papers. But Pauli's role in science was not confined to the work that he did in person. Theoretical physics was enormously influenced by Pauli's personality, the exceptional clarity of his thought, and his style in research and in the exposition of scientific questions, which was marked by the effort to distinguish sharply what was most general and essential and to express it without superfluous words and lengthy arguments.

The writer of these lines, in repeated encounters with Pauli, always felt the fascination and power that radiated from this remarkable person.

Pauli was always greatly interested in the basic problems of physics and had a clear grasp of them. Along with this he hated with all his heart every sort of scientific showiness, deeply despised those papers in which the absence of real content is concealed behind learned definitions and "rigorous" arguments, and ridiculed their authors with extraordinary venom, calling them "basic thinkers" and "new-foundation layers."

Pauli retained a deep understanding of the problems confronting theoretical physics and a capacity for work until the last day of his life. It cannot be doubted that if it were not for his untimely death, further new developments in theoretical physics would again and again be associated with the name of Pauli.

List of the Main Writings of W. Pauli

1. Über die Gesetzmässigkeiten des anomalen Zeemaneffektes, Z. Physik **16**, 155 (1923); Über den Einfluss der Geschwindigkeitsabhängigkeit der Elektronenmasse auf den Zeemaneffekt, Z. Physik **31**, 373 (1925).
2. Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren, Z. Physik **31**, 765 (1925).
3. Über Gasentartung und Paramagnetismus, Z. Physik **41**, 81 (1927).
4. Zur Quantenmechanik des Magnetischen Elektrons, Z. Physik **43**, 601 (1927).
5. Zur Quantendynamik der Wellenfelder (with W. Heisenberg), Z. Physik **56**, 1 (1929); **59**, 168 (1929).
6. The Neutrino Hypothesis. Rapport du Congrés Solvay, 1933.
7. Connection between Spin and Statistics, Phys. Rev. **58**, 716 (1940).
8. Relativistic Field Theories of Elementary Particles, Revs. Modern Phys. **13**, 203 (1941). (Russ. Transl., IL, Moscow, 1947).
9. On the Invariant Regularization in Relativistic Quantum Theory (with F. Villars), Revs. Modern Phys. **21**, 434 (1949). [Russ. Transl., in collection, Сдвиг уровней атомных электронов (Shift of Energy Levels of Atomic Electrons), IL, Moscow, 1950].
10. On the Mathematical Structure of T. D. Lee's Model of a Renormalizable Field Theory (with G. Källen), Dansk. Mat.-fys. Medd. **30**, No. 7 (1955). [Russ. Transl., Usp. Fiz. Nauk **60**, 425 (1956).]

Books

1. Relativitätstheorie, Teubner, Leipzig, 1921. (Russ. Transl., Gostekhizdat, Moscow-Leningrad, 1947.)
2. Die allgemeinen Prinzipien der Wellenmechanik, Handbuch der Physik **24/1**, 2nd edition, Berlin, 1933, pp. 83-272. (Russ. Transl., Gostekhizdat, Moscow-Leningrad, 1947.)
3. Meson Theory of Nuclear Forces, New York, 1946. (Russ. Transl., IL, Moscow, 1947.)

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