Wolfgang Pauli | Encyclopedia.com

(*b*.Vienna, Austria, 25 April 1900; *d*. Zurich, Switzerland, 14 December 1958)

physics.

Wolfgang Pauli's father, a distinguished and original scholar, was professor of colloid chemistry at the University of Vienna and was also named Wolfgang. Thus his son, in his early work, called himself Wolfgang Pauli, Jr. The child was baptized a Catholic, his godfather being Ernst Mach, the physicist and critical philosopher. Pauli went to school in Vienna. Toward the end of his high school studies he became acquainted with Einstein's general theory of relativity, which at that time was completely new. He read it secretly during dull classroom hours. He was truly proficient in higher mathematics, for he had previously studied Jordan's *Cours d' analyse* in the same manner. Einstein's papers had made a deep impression on him. It was, he said, as if scales had fallen from his eyes; one day, so it appeared to him, he suddenly understood the general theory of relativity.

After finishing high school Pauli decided to study theoretical physics. He went to Arnold Sommerfeld in Munich, who was then the most imposing teacher of theoretical physics, in Germany or elsewhere. Many outstanding theoreticians were his pupils, including Heisenberg and Bethe. Here Pauli further perfected his analytical skills, which he later again and again masterfully put to use. Felix Klein was then publishing the *Encyklopädie der mathematischen Wissenschaften*, a monumental compilation that was to examine the current state of science from all sides. Leading scholars—mathematicians and physicists—were contributors. Klein had requested Sommerfeld to write an article on relativity theory for the Encyklopädie. Sommerfeld ventured to entrust the task to Pauli, who although scarcely twenty years old had published several papers on the subject. (Sommerfeld revealed admirable courage and insight in letting a student in his fourth semester write this important article.)

Pauli soon completed a monograph of about 250 pages, which critically presented the mathematical foundations of the theory as well as its physical significance. He took thorough account of the already very considerable literature on the subject but at the same time clearly put forth his own interpretation. Despite the necessary brevity of discussion, the monograph is a superior introduction to the special and general theories of relativity; it is in addition a first-rate historical document of science, since, together with H. Weyl's *Raum, Zeit, Materie*("Space, Time, and Matter"), it is the first comprehensive presentation of the mathematical and physical ideas of Einstein, who himself never wrote a large work about his theory.

Sommerfeld was elated by this performance and wrote to Einstein that Pauli's article was "simply masterful"—and so it has remained to the present day. Pauli showed here for the first time his art of presenting science, which marks everything he wrote.

In Sommerfeld's institute Pauli also became acquainted with the quantum theory of the atom. He wrote in his Nobel lecture:

While, in school in Vienna, I had already obtained some knowledge of classical physics and the then new Einstein relativity theory, it was at the University of Munich that I was introduced by Sommerfeld to the structure of the atom, somewhat strange from the point of view of classical physicist, accustomed to the classical way of thinking, experienced when he came to know of Bohr's "basic postulate of quantum theory" for the first time.

It is a modest expression when Pauli speaks of "some knowledge of classical physics and the… Einstein relativity theory." This must be taken into account to understand what it means for a "physicist, accustomed to the classical way of thinking, " to experience a shock from Bohr's postulate. There were, to be sure, few students scarcely twenty years of age who had penetrated the classical way of thinking as deeply as Pauli had. At this age the shock must have been great.

In 1922 Pauli obtained the doctorate with the thesis "Über das Modell der Wasserstoffmolekülions". Soon thereafter he began to work on the anomalous Zeeman effect. as he reports in his Nobel lecture, these studies finally culminated in the discovery of the exclusion principle, announced in "Ueber den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren" (*Zeitschrift für physik*.**31** [1925], 765). The markedly complicated title shows that here Pauli had solved an intricate problem. Landé, Sommerfeld, and Bohr among others believed, particularly in the case of the alkali metals, that the atomic core around which the valence electron moved possessed an angular momentum and that this was the cause of the magnetic anomaly. Why the atomic core should possess a halfintegral angular momentum and a magnetic moment was, to be sure, unclear. Even more incomprehensible was the situation regarding the alkaline earths which possess both a singlet and a triplet system; these two systems should also be explained from the properties of the core. Indeed, the core should always possess the same electron configuration; but in the two cases it would interact differently with the valence electrons. No one could say how this would happen; and Bohr spoke of a *Zwang*, or constraint, which had no mechanical analogue. Now because the core, the closed noble gas configuration, should possess such peculiar properties, it was further believed that the core could not be characterized by the quantum numbers of the individual electrons: the "permanence of the quantum numbers" would have to be given up.

Pauli now proposed that the magnetic anomaly be understood as a result of the properties of the valence electron: in it appears, as he wrote, "a classically nondescribable two-valuedness in the quantum-theoretic properties of the electron." The atomic core, on the other hand, possesses no angular momentum and no magnetic moment. This assumption meant that the "permanence of the quantum numbers, " Bohr's *Aufbauprinzip*, could in principle be described by quantum numbers. In addition to the already known n, l, and m, one now needed a fourth, which is denoted today by the spin quantum number s. After such a strong foundation was laid, Pauli went on to study the structure of the core, which had previously been considered by E. C. Stoner (*Philosophical Magazine*, **48** [1924], 709).Pauli was able to explain Stoner's rule by means of his famous exclusion principle:

There can never be two or more equivalent electrons in an atom, for which in a strong field the values of all the quantum numbers n, k_1, k_2 and m are the same. If an electron is present, for which these quantum numbers (in an external field)have definite values, then this state is "occupied".

In this formulation the atom is first considered in a strong external field (Paschen-Back effect), since only then can the quantum numbers for single electrons be defined. However, on thermodynamic grounds (the invariance of the statistical weights during an adiabatic transformation of the system) the number of possible states in strong and weak fields must, as Pauli observed, be the same. Thus the number of possible configurations of the various unclosed electron shells could now be ascertained.

The discovery of the exclusion principle builds the crowning conclusion to the old quantum theory based on the correspondence principle, which Pauli described in *Handbuch der Physik*, XXIII (1926). When the article was published, new developments had already occurred; in rapid succession the fundamental work of Heisenberg, Dirac, and Schrödinger appeared, leading to a proper, mathematically consistent quantum mechanics.

Following Dirac's precedent, Jordan, Heisenberg, and Pauli developed the relativistic quantum electrodynamics. This theory occupied physicists for a good twenty years before it became clear that, in spite of all the doubts and disappointments, one of the most precise physical theories had been discovered. Disappointment and doubt had arisen primarily from the following circumstances: It was known for a long time that in the quantum theory of light and the electron, the Sommerfeld fine structure constant $e^2/hc = \alpha$ plays an exceptional role: α is a dimensionless quantity and has the value 1/137. In it three areas of theoretical physics are symbolically united: electromagnetism, which is represented by e; relativity, represented by c; and quantum theory, represented by h. It was therefore believed that if a relativistic quantum electrodynamics was successfully developed, it would at the same time yield a theory of α Thereby, so it was further hoped, a natural solution would be found for the problem of the infinite self-energy of the electron, an insurmountable problem in the classical electron theory. These hopes have not been fulfilled.

In order to accommodate the new developments, Pauli wrote an article on wave mechanics for the second edition of the *Handbuch der Physik* (XXIV, pt.1 [1933]), "Die allgemeinen Prinzipien der Wellenmechanik." A student at the time, the author well remembers meeting Hermann Weyl on the street and his saying, "What Pauli has written on wave mechanics is again completely outstanding!" This judgment of a connoisseur is still valid today: the same article, twenty-five years later, was used unchanged in the new handbook (1958). Pauli's presentation was thoroughly modern and well thought out, considering that such articles frequently become outdated after only a few years.

While the work on the Pauli principle and the first *Handbuch* article—"the Old Testament"—was done in Hamburg, the second article—"the New Testament"—was written in Zurich. After finishing his thesis under Sommerfeld's guidance, Pauli had gone to Göttingen as an assistant to Max Born. Here he met Niels Bohr, who invited him to Copenhagen. From there he soon went to Hamburg, where he held an assistantship under Wilhelm Lenz and gave his inaugural lecture as *Privatdozent*. In 1928 the Swiss Board of Education appointed him Debye's successor as professor at the Eidgenössische Technische Hochschule, where he remained until his death in 1958. At the same time Schrödinger had left the University of Zurich, where wave mechanics was developed, and he was succeeded by Gregor Wentzel. Both professors were very young and brought a rich and active scientific life to Zurich. For many years Pauli and Wentzel organized a seminar together, in which the more important new work from practically all areas of theoretical physics was critically discussed.

By today's standards facilities at both schools were at that time rather limited. At the Technical University, Pauli was the only lecturer for theoretical physics, and students specializing in this field were practically nonexistent. But Pauli—in contrast to Wentzel at the university—did have an assistantship at his disposal. This was a research position, and he always filled it with someone who had already attained the doctorate. These assistants became his true pupils: R. Kronig, Rudolf Peierls, H. B. G. Casimir, and V. F. Weisskopf were his assistants during his first ten years in Zurich, and all were scholars who later became well-known in the field.

Pauli was never what one would call a good lecturer. He mumbled to himself, and his writing on the blackboard was small and disorganized. Above all, though, he had the tendency during the lecture to think over the subject at hand—which, as Wilhelm

Ostwald remarked in *Great Men,* hinders teaching. And so his lectures were difficult to understand—but nevertheless his students were fascinated and greatly stimulated. On the whole he radiated a very strong personal force. One was immediately impressed by his sharp and critical judgment. In discussions he was in no way willing, and perhaps completely unable, to accept unclear formulations. He seemed hard to convince, or he reacted in a sharply negative manner. Thereby he forced his partner in discussion to selfcriticism and to a more logical organization of his thoughts. If, however, one succeeded in convincing Pauli of an idea, then at the same time one's own thoughts were brought to a greater clarity. In this sense he was a truly Socratic teacher who helped in the birth of the ideas of others.

The great influence that Pauli exerted on students and colleagues cannot be ascribed to his imposing critical understanding alone. Nor did the respect that one had for him originate solely from his often caustic way of jumping at his discussion partner, which put many into disarray. Such attacks, although occasionally malicious, were not intended to be mean and had a humorous, ironic side. It was the daemon of the man that one sensed. Theoretical physics surely appears quite rational, but it rises from irrational depths. And so it rests on a daemonic background that can lead to serious conflicts. Pauli had experienced and endured this deep within himself. He had, as few others, earnestly endeavored to master this conflict rationally. Since mathematics and theoretical physics are creations of the human soul, and since they come out of the structure of the soul, he took up the ideas of C. G. Jung in order to better understand the meaning of scientific activity. The results of these efforts are numerous essays and lectures, and particularly his study "Der Einfluss archetypischer Vorstellungen auf die Bildung naturwissenschaftlicher Theorien bei Kepler." It appeared—and Pauli attached importance to this—in the book *Naturerklärung und Psyche* (1952), which he published with C. G. Jung.

It appears that Pauli's colleagues did not always understand how earnestly he wrestled with the philosophical foundations of science and how strongly he experienced their irrational origin. But in some obscure manner they felt it and realized it in outward experiences. These experiences took form in the strange phenomena known as the "Pauli effect": Pauli's mere presence in a laboratory would cause all sorts of misfortunes. So believed critical scholars, such as Otto Stern, who was friendly with Pauli, and so Pauli himself believed. The great impression that his personality made on all who came in contact with him can be correctly assessed only when this mysterious side of his complex being is taken into account.

One of Pauli's most significant accomplishments in physics while in Zurich is the neutrino hypothesis. With it he correctly explained the continuous β spectrum, at that time ver puzzling. In a lecture before the Naturforschende Gesellschaft in Zurich in 1957 he presented the history of this discovery. Niels Bohr was of the opinion that in the case of β decay the conservation of energy should be only statistically valid. If this were conceded, then the conservation of angular momentum and the statistical laws for particles of spin 1/2 would be violated. In the early days of the development of atomic theory, Bohr was ready to sacrifice the *Aufbauprinzip* and the permanence of the quantum numbers and to introduce a mechanically unexplainable *Zwang;* and he was now also prepared to give up the classical conservation laws. He was always "ready and willing" to discover the unexpected in the realm of atomic dimensions. Pauli, on the other hand, resolved only with great difficulty to let fall natural laws that had previously been confirmed everywhere. Just as he held on to the permanence of the quantum numbers in his theory of the closing of shells in atoms, which led him to the exclusion principle, so it appeared to him right to retain the conservation laws. Thus he proposed in a letter of 4 December 1930 to Lise Meitner and associates "the continuous β-spectrum would be understandable under the assumption that during β-decay a neutron is emitted along with the electron…"

Since the letter was written before Chadwick had discovered the neutron in the nucleus, the discussion here involved another particle, which Fermi then christened "neutrino." At the Solvay Congress in 1933, Pauli again extensively justified his proposal, which was published in the Congress report. Shortly thereafter, in 1934, Fermi worked out his theory of β decay, which, in spite of unsolved basic difficulties, has been confirmed amazingly well.

During the war Pauli was active at the Institute for Advanced Study in Princeton; but later, after careful consideration, he returned to Zurich. He lived happily with his wife in Zollikon, near great forests that invited meditative strolls. Consistent as he was, he now earned Swiss citizenship.

This article has intentionally avoided giving even an approximately complete review of Pauli's scientific work, for there is practically no area of theoretical physics in which he did not decisively take part. The aim has been to make clear, in connection with his most important contributions, the manner in which he worked. A last example to be mentioned is his important work on discrete symmetries in field theory. He dedicated it to Niels Bohr on his seventieth birthday under the title "Exclusion Principle, Lorentz Group and Reflection of Space-time and Charge." Starting from investigations by Schwinger and Löders, Pauli showed that every Lorentz invariant Lagrangian field theory is invariant under the operation CTP, whereas C, T, and P separately do not have to be symmetries of the theory. This study had greatly occupied him, as he occasionally told nee, and I guessed that he had hidden thoughts about the matter which he did not express. So I asked him if in this work there was not in fact another problem between the lines and if he might not say something about it. But he denied my conjecture: he was interested in these symmetries in their own right.

Not much later it was discovered that in weak interactions-for example, in β decay-the parity (P) is not conserved (Lee and Yang, 1956). Pauli was greatly stirred by this discovery. It seemed to him at first extraordinarily repugnant that in nature right and left should not enjoy equal status. But then he realized that the symbolic, to some extent naturalphilosophic, concept which he saw in this symmetry did indeed remain: for as he had made clear one year earlier, CTP must be a valid symmetry if only the natural laws are Lorentz invariant. Thus, guided by his own genius, he had meaningfully prepared for the coming developments.

Just as Pauli received a shock when, as a student, he first became acquainted with the strange laws of quantum theory, so did he receive a shock from the nonconservation of parity. For it was always his hope that physics would indicate the mysterious harmony of God and Nature. This hope was not illusory. Precisely in his most important work he had shown how apparently paradoxical phenomena could be explained through a harmonious extension of the previously confirmed theory. And so theoretical physics since Kepler, Galileo, and Newton appeared to him as a great house the foundations of which, despite many changes, would never be shaken. It was because he felt this way, and because he considered himself a representative of a great tradition, that he reacted so sharply against obscure arguments and superficial speculation. He expressed himself thus concerning his position to a colleague: “In my youth I believed myself to be a revolutionary; now I see that I was a classicist.”

In December 1958, Pauli became violently and seriously ill, and on December 14 he died. At the funeral Viktor Weisskopf said he was “the conscience of theoretical physics.” This is truly the shortest statement that can render the impression which this rare man made on all who knew him.

BIBLIOGRAPHY

A complete list of Pauli’s books, articles, and studies is *in Theoretical Physics in the Twentieth Century, a Memorial Volume to Wolfgang Pauli* (New York, 1960). Collections include his scientific papers (New York, 1964) and *Aufsätze und Vorträge üiber Physik and Erkenntnistheorie* (Brunswick, 1961).

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