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In memoriam Wolfgang Pauli (1900–1958)

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1. Prologue

Infant prodigy, 'god's whip' [1], Einstein's spiritual son, Wolfgang Pauli had the extraordinary qualifications to be considered 'the living conscience of theoretical physics' [1] of his time. But although he had been one of the young revolutionary geniuses of early quantum mechanics, towards the end of his life, 25 years ago, Pauli concluded in retrospect that he still had been a classicist rather than a revolutionary [2].

This observation may be at the origin of a certain lack of popularity of Pauli as compared to his equally famous contemporaries Bohr, Heisenberg, etc. [3]: He was seeking truth by analysing the given rather than by persuing the new.

In this attitude his natural way of communication was by discussion and, even more, by correspondence [4, 5]. Today we may wonder what he would say seeing the bloom of new ideas and the spread of computer-aided methods all across physics. But would his voice be heard in the noise of the modern information explosion?

In the following I wish to take a look at Pauli's way of thinking by following the main stations of his scientific life [6, 7].

2. The early works on relativity

Wolfgang Pauli was born into a Viennese intellectual environment on 25 April 1900. His father Wolfgang Joseph, of Jewish origin, was a medical doctor and made an academic career at the University of Vienna. There he became a professor and later director of a new institute of medical colloïd chemistry. There also he met his illustrous friend Ernst Mach, professor of philosophy and positivist physicist.

Mach became the godfather of Wolfgang son who was baptised catholic and was given the second name Ernst [8] which, however, he never used. Mach had a marked influence on both, father and son Pauli. Later Wolfgang son described this influence by the label 'of anti-metaphysical descent' adding, however, that afterwards he had undergone 'larger spiritual transofrmations' [9].

In 1918 Wolfgang graduated from the humanistic section of the gymnasium at Döbling, a district of Vienna, with a 'class of geniuses' [6]. At this time he was already in full possession of the mathematical and physical knowledge enabling him to publish three papers on general relativity which attracted the attention of the famous mathematician Hermann Weyl.

In the third paper Pauli criticised Weyl's use of the notion of field strength in the interior of the electron which, he said, is unobservable because the electron is the smallest test particle. Here Mach's influence becomes apparent, but in spite of his anti-metaphysical label Pauli could not be called a positivist.

The following year Pauli went to Munich to learn theoretical physics from Arnold Sommerfeld who, with Niels Bohr in Copenhagen, was one of the exponents of the quantum theory of the atom which Pauli later liked to call the 'Old Testament' in distinction to the 'New Testament' of quantum mechanics [10], founded since 1925 by the rising generation of Heisenberg, Dirac, Schrödinger and Pauli.

Although Pauli did not attend regularly the lecture courses of Sommerfeld he kept an attitude of devotion toward his teacher during his lifetime. It was on the suggestion of Sommerfeld that Pauli published at the age of 21 the famous review article on relativity theory which evoked the admiration of Einstein himself. Apart from the supplementary notes added by Pauli in the last year of his life this article has survived to this day.

The same year 1921 Pauli obtained his doctorate 'summa cum laude' from the University of Munich with a thesis on the Hydrogen molecule ion. In this one-electron but two-center problem Pauli pushed the old Bohr-Sommerfeld theory to its limits. This time at Munich was also the beginning of his friendship with Werner Heisenberg who, one year younger than Pauli, was also a pupil of Sommerfeld.

3. The exclusion principle

His research in the domain of the old quantum theory begun with his thesis led Pauli to the most active centers of Europe in this domain. During the winter of 1921–1922 he was assistant of Max Born in Göttingen and, after a summer in Hamburg, he spent one year in Copenhagen on the invitation by Niels Bohr. This was also the starting point of his occupation with atomic spectroscopy and, most importantly, with the anomalous Zeeman effect. This research led Pauli in January 1925 to the formulation of the exclusion principle for which he was awarded the Nobel prize of 1945, by realizing that energy and orbital angular momentum do not suffice to characterize an electronic state in the atom but that the electron exhibits a 'classically non-describable two-valuedness'.

This cautious expression, of course, means nothing else than the orientation of the electron spin, an idea that Pauli admitted only reluctantly because of its classical content. Much has been written on the history of this dramatic episode [6, 11, 12]. But once converted Pauli added his own mark by introducing the spin matrices and by calculating the low-temperature paramagnetism of conduction electrons.

Pauli's role in the elaboration of the new quantum mechanics initiated by Heisenberg in 1925 was in the first place that of a clear-sighted arbiter and of a 'master of criticism' [13]. This role is marvellously put in evidence by the abundant correspondence Pauli had with his colleagues, mainly with Bohr and

Heisenberg [5]. But Pauli also made his own contributions, the most important being his brilliant matrix-mechanical solution of the hydrogen atom. In 1933 he summed up the state of the new quantum theory in a review 'The general principles of wavemechanics' whose celebrity and durability are at least comparable to those of the review on relativity of 1921.

4. The neutrino

After spending five years at Hamburg as private docent and as assistant of W. Lenz, himself a pupil of Sommerfeld, Pauli became professor of theoretical physics at the Federal Institute of Technology (ETH) at Zurich in 1928. This was an eventful period marked by a passing marriage [14] and by his encounter with the famous psychiatrist C. G. Jung, professor at the University of Zurich. This was also the moment when Pauli's interest focussed on the theory of quantized fields and of elementary particles. Associated to the chair at ETH was a post-doctorate position which in the course of the years attracted the most brillant young theorists: R. Kronig, F. Bloch, R. E. Peierls, N. Kemmer, H. B. G. Casimir, V. F. Weisskopf, M. Fierz, R. Jost.

At this time, more precisely before 1932, when the only known 'elementary' particles were the photon, the electron and the proton, Pauli had the boldness to postulate a new one which he called 'neutron' and which, following a suggestion by Fermi, became known as 'neutrino'. It was his deep belief in the fundamental role of symmetries in the laws of physics that led Pauli to do this, rather than to accept that energy conservation should be violated in the radioactivity of the nucleus of Radon (Radium-Emanation) by emission of an electron [15].

But although the experimental detection of the (anti-) neutrino in 1956 was a personal triumph for Pauli, this particle still kept some surprise in store for him. Indeed, less than six months later, different experiments revealed the existence of an intrinsic left helicity for the neutrino, in manifest violation of parity invariance. One understands that it was a shock for Pauli to admit that 'god is just left-handed' [16].

5. Spin and statistics

In 1934 the year of his marriage with Franca Bertram, his devoted spouse for the rest of his life, Pauli, in collaboration with his assistant Weisskopf, obtained the result that charged particles of spin zero admitted antiparticles of opposite charge. This result which was perfectly analogous to the case of the electron and the positron, discovered in 1932, is of historical interest because it applies directly to the pi-mesons, discovered somewhat later.

More importantly, however, Pauli and Weisskopf noticed that their theory was compatible only with the Bose-Einstein statistics of symmetric states but not at all with the Fermi-Dirac statistics of the exclusion principle. This was the first indication of the relation between spin and statistics which Pauli proved in all generality in 1940, according to which integer and half-integer spin values are always associated with Bose-Einstein and Fermi-Dirac statistics, respectively. Later he generalized the particle-antiparticle symmetry (*C*) into the CPT theorem which states that the product of C, parity P and time reversal T is an absolute symmetry.

Pauli had completed the work on spin and statistics at the Institute for Advanced Study in Princeton where he had joined Einstein in 1940 in order to escape from Nazism which menaced Switzerland. It was at this institute also that the news of his nomination for the Nobel Prize of 1945 reached Pauli and where on 10 December 1945 a dinner was given to celebrate this distinction. At this dinner the old Einstein offered a toast [17] in which he designated Pauli as his successor at the institute and called him his spiritual son [18]. This dinner was also a farewell gathering since shortly afterwards Pauli left for Europe where he decided to return to his professorship at ETH left vacant during the war.

6. The essay on Kepler

Two men have influenced Pauli's 'larger spiritual transformations' mentioned above: Sommerfeld and Bohr. From his teacher he had inherited the sense for the pythagorean harmonies based on the natural numbers which had revealed Kepler his laws of the planetary orbits but which, according to Sommerfeld, manifest themselves also in the period lengths of the periodic system of elements: 2, 8, 18, 32, . . . , [19] the latter being a direct consequence of the exclusion principle.

From Bohr came an incessant inspiration during all their 'common pilgrimage since the year 1922, in which so many stations are involved' [20]. The central idea of this inspiration was 'complementarity' which in quantum mechanics made possible a synthesis of contradictory terms such as wave-particle, but which had been generalized by Bohr into a new philosophical notion, to the extent that Pauli saw in it 'the germ of a progress in direction towards a unified global conception of the world, in which the natural sciences are only one part' [21].

A better understanding of the last aspect combined with the pythagorean elements so dear to Sommerfeld led Pauli to direct his attention towards Johannes Kepler 'since his ideas represent a remarkable intermediary stage between the former [i.e., pre-17th century] magic-symbolic and the modern quantitative-mathematical description of Nature' [22]. This essay analyses the role of the unconscious in the discovery of the laws of Nature which for Kepler is symbolized by the notion of archetype, a terminology which, independently was also introduced by C. G. Jung in his psychology of the unconscious. It is then not astonishing to find united under the same cover of the book 'Naturerklärung und Psyche' an essay by Jung alongside the mentioned paper by Pauli (see Ref. 21). This book which appeared in 1952, in fact marks the culmination in the relation between Pauli and Jung.

The depth of Pauli's philosophical views incited Arthur Koestler to remark that Pauli 'perhaps had a deeper knowledge of the limits of the natural sciences than most of his colleagues' [23]. One of these limits which disturbed Pauli during all his scientific life was the duality between the electric field strength and the means to measure it be its action on a charge mentioned in Section 2. The disturbing aspect is that the precision of such a measurement is limited by the atomicity of electric charges as given by Sommerfeld's finestructure constant 1/137 which has not yet been explained. This number 137 symbolized for Pauli the connection with the magic world of the alchemists which had much fascinated him. By a coincidence which might be called 'cabbalistic' [24], Wolfgang Pauli died in room 137 of the Red Cross Hospital in Zurich on 15 December 1958 [6].

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