BOOKS

HEISENBERG'S COLLECTED WORKS: HIGH PEAKS AND PANORAMIC VIEWS

Heisenberg: Gesammelte Werke [Collected Works]

Edited by W. Blum, H.-P. Dürr and H. Rechenberg

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Reviewed by Valentine L. Telegdi and Victor F. Weisskopf

Being presented with Heisenberg's collected papers is like suddenly being shown a panoramic view of the Himalayas. Just as everybody has heard of Everest, K2 or perhaps even Annapurna, every physicist associates Heisenberg's name with matrix quantum mechanics (and the corresponding state representation), the uncertainty principle and a certain model of ferromagnetism. Older physicists, or the more scholarly among the young, may recall Heisenberg's pioneering model of nuclear structure (which first introduced exchange forces and isotopic spin) or perhaps even his solution of the profound riddle of the helium spectrum. But there are many other peaks—quite a few that become visible only from the Everest of quantum mechanics—each opening new breathtaking vistas. Heisenberg climbed them all, often alone; in preparing many ascents, Wolfgang Pauli was his sherpa.

The Collected Papers constitute eight volumes in three series. The first series, A, consisting of volumes AI and AII, contains reprints of Heisenberg's original scientific papers grouped into 14 sections, each of which is preceeded by an extensive "annotation" analyzing the material and establishing its position in the proper historical setting. (So far only ten sections have appeared: Volume AIII is promised for next year.) These papers are, in terms of the analogy evoked above, guidebooks to specific regions of the Himalayas, each clearly describing the difficulties of the first ascents. In physics, like in mountaineering, these difficulties are often hard to understand in retrospect. Series B consists of one large volume that contains Heisenberg's scientific reviews, his talks on physics and reprints of his books on physics. The five additional volumes, series C, contain his books, articles, talks, book reviews and obituaries directed to nonexperts, covering physics in a more popular manner, in particular quantum mechanics, philosophy, politics and public affairs.

One general criticism of this publication of Heisenberg's collected research papers is the fact that they are mostly reproduced in German. Today that language is no longer the *lingua franca* of physicists, as it was in the 1920s and 1930s. Such works are meant primarily for reference libraries (their price is prohibitive for individuals), and the extra cost of translation into English would have enormously increased their usefulness.

The editors, Walter Blum, Hans Peter Dürr and Helmut Rechenberg, have been extremely fortunate in their choice of authors for the annotations to the scientific papers. Their list includes Heisenberg's contemporaries and coworkers (Erich Bagge, Friedrich Hund, Bartel L. van der Waerden, Carl Friedrich von Weizsacker and Karl Wirtz), some of his students (Rudolph Haag, Reinhard Oehme and Rechenberg), historically inclined physicists (Laurie M. Brown, Abraham Pais, Charles Enz) and last but not least one expert "outsider" (S. Chandrasekhar).

The topic of the first section in series A (admirably annotated by Chandrasekhar), namely hydrodynamic stability and turbulence, actually occupied Heisenberg for the longest period of time (1922–48). This might come as a surprise to many readers. It is in this field that he wrote (in his fourth semester at the university!) his second paper and his doctoral thesis (one year later), presumably because his teacher, Arnold Sommerfeld, considered the topic of

Valentine Telegdi and **Victor Weisskopf** were participants in the development of modern physics. Telegdi, an experimental physicist, currently shares his time between CERN and the California Institute of Technology. Weisskopf, who recently retired as professor of physics from Massachusetts Institute of Technology, was in close personal contact with Heisenberg.

his first paper (on the anomalous Zeeman effect in the "old" quantum theory) too speculative. Chandrasekhar in his annotation describes the expanded version of Heisenberg's thesis as "an important and fundamental contribution to the subject." The combination of mathematical ability and physical insight displayed therein clearly established Heisenberg as a prodigy. On the controversial results of that paper Heisenberg was fully vindicated almost 30 years later, when accurate numerical solutions became available. One aspect of hydrodynamics kept pervading Heisenberg's lifelong work in several fields: nonlinearity.

The sections on atomic and molecular structure in series A (1922–25) and on the applications of quantum mechanics (1926–33) are in some sense complementary. The first covers attempts to understand, in the framework of "old" quantum mechanics, such mysteries as the anomalous Zeeman effect, the helium spectrum, relativistic doublets and so on. These papers would be largely incomprehensible to a modern physicist were it not for the annotations of Hund. The second of these sections presents the solutions to such riddles, obtained after "real" quantum mechanics was formulated; it is ably annotated by Enz, Pauli's last assistant.

The section on quantum mechanics, commented upon by van der Waerden and Rechenberg, brings the least surprise to the reader, because Heisenberg's road to matrix mechanics, constituting a consistent refinement of Niels Bohr's correspondence principle and an extension of his work with Hendrik Kramers on the dispersion formula (with its mysterious virtual oscillators corresponding to transitions rather than to actual oscillations), has been analyzed in many texts.

Among those in this fundamental section, the least-quoted paper is "Many-Body Problems and Resonance in Quantum Mechanics," written in June 1926. With brilliant intuition, Heisenberg succeeds in going from an analogy between two (semiclassical) coupled harmonic oscillators to the discovery of noncombining (symmetric and antisymmetric) states in quantum mechanics. Although in the first part of this paper he exhibits a certain aversion to the wave mechanical approach, he subsequently uses it to conjecture that Pauli's exclusion principle corresponds to selecting antisymmetric states among the possible ones. He makes several references to Bose–Einstein statistics, misses the correspondence to symmetrical states and seems to be altogether unaware of Fermi's degenerate gas (the grand synthesis was given by Dirac barely two months later). This paper was almost immediately followed by Heisenberg's quantitative explanation of the He spectrum (by then Heisenberg was wholeheartedly using the Schrödinger approach). In a second paper on the N-body problem (December 1926) Heisenberg attacks it with less intuitive means, making in fact an appeal to the theory of the permutation group! Few people will remember this foray of Heisenberg's because of the independent and more extensive work of Eugene Wigner.

The work on the many-body problem illustrates well how a genius can draw the right conclusions, unshackled by the strict rules of logic by which others are bound. Another famous illustration is given in the section on the structure and properties of nuclei (annotated by von Weizsacker, and by Brown and Rechenberg). Heisenberg correctly guesses that neutron–proton forces have an exchange character, but still seems to retain the notion that the neutron is a proton–electron compound. That this is incompatible with the spin of the neutron (that is, the spins of nuclei) was surely clear to him, but in 1932 he (and Bohr!) thought that inside the nucleus somehow "things were modified." Heisenberg is also the originator of isotopic spin, but he missed the possibility of charge-independent forces.

Heisenberg and Pauli jointly laid the foundation of Lagrangian quantum electrodynamics in two very long papers (annotated by Haag) in 1929, a time when the hole theory of positrons was not yet born and hence its problems not yet realized. Looking at these papers today it seems surprising that the quantization of electrodynamics was such a difficult task. The two authors try in the first paper to overcome the fact that the scalar potential has no conjugate momentum. Only in the second paper do they discover the way to solve the problem using gauge invariance. Enrico Fermi produced a more compact approach to the problem of the Coulomb gauge (also used by Heisenberg and Pauli in their second paper) and—partly because of his pedagogical skills—that approach won out (see, for example, Walter Heitler's 1936 book *Quantum Theory of Radiation*).

Heisenberg's papers on the Dirac theory of the electron and positron (1929–1936) are presented with a very lucid annotation by Pais. Heisenberg, like other theorists, including Pauli, did not like the first formulation of positron theory by "holes" in a vacuum filled with electrons in the negative energy states. He already had some expertise with this problem from his attempt in 1931 to describe the "holes" in a closed atomic shell by positive electrons. He published in 1934 a reformulation of Dirac's positron theory, after similar attempts by Vladimir Fock (1933) and by Wendell Furry and J. Robert Oppenheimer (1934). His formulation of quantum electrodynamics is very close to the form we use today. The charge symmetry of the theory is clearly demonstrated.

In that period Heisenberg, like many others, worried about divergences that appeared in higher orders of an expansion in powers of the fine-structure constant. These divergences caused the mass and charge of an electron to become infinite, although only as the logarithm of the highest frequency of the interacting photons, a frequency that should tend towards infinity when fields in the immediate neighborhood of the electron are considered. These difficulties were solved (perhaps partly) only after 1945 by the renormalization procedure, whose physical basis may be the fact that electrodynamics is no longer valid at distances on the order of the Planck length. There was no reason why the renormalization procedure could not have been introduced in the 1930s by Heisenberg or other theorists. But the small effects explained by that procedure, such as the Lamb shift and a tiny correction to the magnetic moment of the electron, had not yet been discovered.

It is strange that Heisenberg did not take part in the development of the renormalization procedure after the war; it provided a reasonably satisfactory way of eliminating all divergences and thus created a useful theory of what Heisenberg started in 1934. He had already left the field at that time and launched a "revolutionary approach" to particle physics with his S-matrix program.

From 1932 to 1939 Heisenberg wrote roughly ten original papers on cosmic rays and related phenomena (these are annotated by Bagge). With characteristic pioneering spirit he abandoned nuclear physics soon after writing his fundamental papers on nuclear forces, turning to cosmic rays (the high-energy physics at that time) for deeper insight into fundamental phenomena. Starting from a now-forgotten ($e\nu$)-exchange theory of nuclear forces, he predicted the occurrence of multiparticle production in single collisions. Although the observed showers could later be explained by standard electromagnetic phenomena and the ($e\nu$)-exchange was superseded by Hideki Yukawa's meson exchange, Heisenberg was on the right track. He insisted that mesons could be produced multiply (as opposed to plural production in a chain of successive collisions) and was involved in a lengthy controversy with Heitler. His intuition was fully vindicated by one of the earliest Cosmotron experiments in 1954.

A particularly valuable section is the one presenting Heisenberg's classified wartime papers concerning the construction of a nuclear reactor. These papers, perhaps representing only an incomplete set, show us Heisenberg from a new angle: evaluating experiments and proposing new ones. They roughly correspond to Fermi's classified reports (available in volume II of his collected papers) from Columbia University, thereby illustrating the comparatively modest scope of the German *Uranverein* undertaking. Heisenberg's wartime papers are ably annotated by Wirtz. It is interesting to note that Wirtz's commentary throws little light on why Heisenberg's group discarded a graphite moderator in favor of heavy water (allegedly because the graphite showed too much absorption, being contaminated with boron—a fact that was not realized by the German experimenters).

Series B contains only one heavy volume. It also deals with physics but is directed towards a wider group of physicists. If the collection of the original papars in series A presents detailed descriptions of Heisenberg's various ascents to the peaks of the Himalayas, series B contains beautiful travelogs written in retrospect, after the mist covering those peaks had dissolved (often through discussions with others). We find a large number of survey articles and review papers about almost all of the subjects Heisenberg has worked upon. Several topics are covered here for which the corresponding original papers await publication in volume AIII. One unpublished paper first presented in volume B has particular historic interest, namely a report entitled "The General Properties of Elementary Particles," which Heisenberg had prepared for the October 1939 Solvay Conference—one that never took place. Pauli's part of the same report was published in *Reviews of Modern Physics* in 1941. In series B the editors often include with the lectures of Heisenberg transcriptions of the subsequent discussions. For example, the incisive criticisms of Pauli after Heisenberg's talk on his unified theory at the 1958 "Rochester" Congress in Geneva made it clear why Pauli detached himself—after a lengthy collaboration—from that theory.

Volume B also contains the full text of several books, some in English, such as *The Physical Principles of Quantum Theory*, written in 1930. There are the two editions of *Cosmic Radiation* (in German), the first published in 1943, the second in 1952. The progress of that field was so fast that the second edition is an altogether different book. Finally, we find in that volume *Introduction to the Unified Field Theory*, in English, a book that appeared in the US in 1966. It contains a detailed description of Heisenberg's heroic but unsuccessful attempt to construct a "world formula," the solution of which should describe all observed particle physics.

Series A and B are published by Springer-Verlag (New York) whereas series C is published by Piper (Munich). The five volumes in series C, a collection of writings addressed to a wider audience, are of a different character. They are concerned with philosophy—in particular Heisenberg's views of the philosophical consequences of quantum mechanics, with science politics in post-war Germany and with attempts to make modern physics understandable to the public. Volume CII includes the Gifford Lectures (1956) in German translation (they appeared first in English under the title "Physics and Philosophy"). In volume CIII we find *Der Teil und das Ganze*, written in 1969, which appeared in English under the title *Physics and Beyond*.

Among Heisenberg's philosophical and popular writings, volume CIV is from a historical point of view the most interesting. It contains the laudations and obituaries devoted to his older contemporaries (Einstein, Hilbert, Planck, Schrödinger and others), his main teachers (Sommerfeld, Born and Bohr) as well as some of his close associates (including Pauli, Rudolph Peierls and von Weizsacker). Here it is particularly regrettable that but for one piece—"The Significance of Sommerfeld's Work Today" (1968)—all these masterful biographical sketches are in German. (On the other hand, Heisenberg used his language with the highest literary skill, and it will be hard to find an adequate translator.) Incidentally, this volume contains also some surprising literary exercises, including a travel account written by Heisenberg when he was a Boy Scout "eagle" and a humorous parody entitled "Nuclear Mechanics" contributed for Born's 50th birthday.

About his education Heisenberg is supposed to have said, "From Sommerfeld I learned optimism, from the people in Göttingen mathematics and from Bohr physics." Certainly Bohr's influence was the greatest. Describing one of his earliest discussions with Bohr (1922), Heisenberg quotes him as saying: "Of course we are greatly impressed by the fact that the present quantum theory is able to explain, for example, in the case of the Stark effect, so many details, but mathematics has only a limited number of forms which we can adapt to Nature, and it can happen to one that he finds the right forms by formulating entirely wrong concepts. But then the whole thing is still in a state of total mess and can thus not be extended to constitute a closed theory." This point of view accompanied Heisenberg throughout his life, and he in fact always found confirmation of Bohr's opinion: Clearing up concepts is even more important than a mathematical formalism that represents experiment correctly!

Heisenberg's own credo as a theoretical physicist is stated most clearly in his laudation of Peierls (given when Peierls received the Planck Medal in 1963). There he says, "I am using the term 'theoretical physics' with a very specific meaning, in a certain sense as contrasted with two apparently cognate types of physics, namely with either mathematical physics or with the phenomenological description of experiments.... I would like to circumscribe this approach with a few words: This kind of theoretical physics occupies in a remarkable way the middle ground between mathematical physics and a purely phenomenological description. The compelling power of statements in this [type of] theoretical physics does not stem from the fact that they can be proved. And it is also not merely based on experimental evidence. As far as proofs are concerned, I would like to quote Pauli, with a sentence from a discussion between him and a friend, the eminent mathematician John von Neumann. As von Neumann said to him 'Listen, I can prove that.' Pauli replied: 'Well, if the essence of physics was giving proofs, then you would be a great physicist.' In the case of theoretical physics, as we learned it primarily from Bohr, the essence neither consists of proofs nor in the mathematical description of experiments. Rather the convincing power of the mathematics employed comes from what one calls physical insight or physical interpretation. The supreme requirement of this type of physics is to understand every formula that one writes down physically both as to its intellectual content and to its context."

Pauli was not only Heisenberg's fellow student in Münich, but his lifelong critic. The two men were, notwithstanding their fundamentally different characters and roles during the war, very close. After Pauli's death, Heisenberg summarized Pauli's philosophy brilliantly: "Pauli was an unusually penetrating, critical and productive physicist. Throughout his life he conserved the power to grasp most subtle connections intuitively, although he always focused that power with sharp, unforgiving critical spirit into a limited domain.... He was aroused by those mysterious structures of natural phenomena which can be seized intuitively long before they enter consciousness as rational images, but nevertheless he gave his confidence only to a rational formulation that was clear down to the last detail."

Much but perhaps not enough is found in these volumes about the problems that Heisenberg had to face during the Nazi period with the persecution of the Jews. Although the Nazi concept of Jewish physics was condemned by Heisenberg, he had to be prudent during the Nazi regime and he was not a heroic fighter, as were Wolfgang Gentner and Johannes Jensen. One could have wished a more explicit condemnation of the Nazi crimes in his articles written after the end of the war. In a talk given at the consecration of a bust of Einstein in the German Museum in Münich in 1958, he emphasized Einstein's role as a world citizen, but also ascribed some traits of Einstein's character to his birth in Ulm, Germany. Einstein wrote: "Another sort of application of the principle of relativity will amuse the reader. Today I am called in Germany a 'German savant' and in England a Swiss Jew. If I may come to be regarded as a *bête noire*, I shall become a Swiss Jew for the Germans and a German scientist for the English."

The Mathematics of Projectiles in Sport

Neville de Mestre
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In his preface, Neville de Mestre writes that the first seven of the eight