The legacy of Werner Heisenberg

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W. Heisenberg, *Gesammelte Werke/Collected Papers.* **(Eds.) W. Blum, H. P. Dürr, and H. Rechenberg,** Springer-Verlag, Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, 1985–1989. Series A. Parts AI and AII. Original Scientific Papers/Wissenschaftliche Original Arbeiten. Series B. Scientific Review Papers, Talks, Books. / Wissenschaftliche Übersichtsartikel, Vorträge und Bücher.

Can a poet avoid being mirrored in his work as a person, as a character, as a nature—in a word, as a personality! Of course, not, because the very ability to depict phenomena of reality without any reference to oneself, is again an expression of the poet's nature. (V. G. Belinskiĭ "A glance at Russian literature of 1847")

Eight volumes have been published of the collected works of Werner Heisenberg—one of the great natural scientists who have radically changed the physical picture of the world. The difficult work on bringing together and editing this collection was carried out by the scientists of the Max Planck Institute for Physics and Astrophysics in Munich—H. P. Dürr who for many years had worked with Heisenberg and who succeeded him as the director of the institute, H. Rechenberg[1] a talented historian of science, and L. Blum.

The planned and almost completed collection has been divided into three series. Series A contains scientific articles, Series B contains reviews, talks and books, Series C contains popular articles. In Series A two volumes AI and AII have already been published (apparently, the last volume AIII is still in press). Series B consists of a single volume (already published). Series C includes five volumes (which have all been published already by Piper Verlag).

In this review we shall deal with the first volumes (AI, AII, B). Series C deserves a separate discussion.[2] For those who have been following the publications of Heisenberg we note that the collection contains (B p. 346–358) the previously unpublished report prepared for the 1939 Solvay Congress which did not take place due to the war that had begun. Moreover volume AII includes 20 previously unpublished papers relating to reactor physics. These papers were in secret storage and after the defeat of Germany were brought to the USA. Now they (together with other material) have been returned to Germany. The last of these papers is dated 3 January 1945. There still remains a hope that also other papers relating to the uranium project may become known.

The war left a deep and very painful trace in the life and scientific output of Heisenberg. His role in the "project," his position in the scientific life of Nazi Germany posed for him unusually difficult moral problems. Books and articles[3] have been devoted to an analysis of those years. But this, naturally, goes beyond the framework of this review.

Let us return to physics. In the collected works of W. Heisenberg the articles are divided according to subject matter; within a given subject the order of the articles is chronological.

Series A opens with a scientific biography written by Cassidy and H. Rechenberg (it is also repeated in Volume B). In addition each subject-matter group of papers is preceded by an introduction. The high level of the authors of the introductions guarantees a description of the required historical background against which appeared the articles of Heisenberg and his coauthors.

Probably there is not a physicist on this earth who does not know at least in general outline about the role played by Heisenberg. The maxima of the fundamental activity of Heisenberg (the time of his maximum influence) fall in 1925 (quantum mechanics, the Heisenberg–Jordan algebra) and in 1929–1930 (quantum electrodynamics). But his other papers also would be an object of pride for any physicist.

Here is probably not the place (more accurately, space is lacking) to review Heisenberg's scientific life, but it is useful to call attention to its beginning.

After brilliant graduation from secondary school in 1920 Heisenberg entered the University in Munich and very soon became involved in the work of the seminar conducted by Arnold Sommerfeld where he became acquainted, in particular, with Wentzel and Pauli. Discussions at the seminar led him to work on the quantum theory of the anomalous Zeeman effect, the results of which he submitted already on 17 December 1921 to Zeitschrift für Physik.[4] This marks the beginning of Heisenberg's scientific life. But his interest in the Zeeman effect did not restrict the activity of the young man. In September of the following 1922 year he submitted a second article on von Karman's vortices.[5] In the same year he gave his first report at a conference in Innsbruck, and in less than a year, in September 1923, Heisenberg completed his dissertation.

Thus Werner Heisenberg entered into physics to share with Niels Bohr, Wolfgand Pauli and Paul Dirac leadership in the development of physics of the new era.

The accumulated data on spectra which did not fit into the paradoxical (as it then appeared to contemporaries) Bohr model became natural in the new (and still more paradoxical) quantum mechanics.

At the beginning of this century the development of the physics of atoms did not proceed along the path of logic. Logic was violated by Bohr by his "contrived" rules for electrons and atoms. After Bohr Heisenberg did the same by discovering noncommutativity (according to Dirac's terminology) of coordinates and momenta. It is surprising how rapidly and almost without opposition these "mad" ideas conquered the world and found followers of genius stature. This is a manifestation of a "miracle" in science. The time comes when "mad" ideas become fundamental ones. Is this transformation due to some complicated algorithm to which human thought is subject, or should we here make reference

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to something which we call the unconscious?

The work of 1922 opens up a new branch in Heisenberg's creative output. These are magnificant papers on hydrodynamic stability and turbulence (the introduction to these articles was written by S. Chandrasenkhar). The papers on satistical turbulence would undoubtedly have played an even greater role, had they not been (as he learned only after the war) exceeded by the publications of A. N. Kolmogorov.

The fundamentals of quantum mechanics and turbulence fom the content of Volume AI.

Volume AII begins with two famous articles written together with W. Pauli which formed the basis of quantum electrodyamics.

These two papers (accompanied by an introduction by R. Haag) associated with the quantization of the electromagnetic field (second quantization) concluded the first stage of quantum theory. The predecessors of these papers were P. Jordan, E. Wigner, but only after Heisenberg and Pauli could the problem have been regarded as solved.

The next section (the introduction has been written by A. Pais) contains articles associated with the Dirac equation and the positron problem. In the last of the articles written in 1935 together with his pupil Euler (AII p. 714) he discusses such new effects as scattering of light by light. This effect was calculated by Euler and Kockel, also a pupil of Heisenberg, in the same year 1935. Together with Euler he notes divergences in higher orders (in the fourth order in the compton-effect and in the sixth order in the scattering by light).

The construction of an effective Lagrangian for the electromagnetic field must be regarded as the principal result of this paper. This was the first encounter with a nonlinear equation in quantum theory. Pais notes that in letters to Pauli in 1936 Heisenberg discusses the equation $\psi = \lambda\psi\psi^*\psi$, for which he had great hopes (here we should refer to the as yet unpublished volume AIII).

The next group is devoted to the structure and properties of the nucleus (two introductions have been written by C. Weizsäcker, L. Brown and H. Rechenberg). Here the operator for the proton–neutron transition appears: the first step in the theory of isotopic spin.

Having dealt in his publications with all sides of quantum theory Heisenberg did not leave out the difficulties encountered along the way. In connection with the Dirac theory he discusses the problem of mass. The attempts to ascribe to mass an electromagnetic nature led him to the necessity of introducing "cutoff"—an elementary length. Such a solution did not satisfy him and he tried to find a way out in a nonlinear equation. Heisenberg's deep thoughts were not able to become a real theory; the physicists still knew too little to invent a suitable model. Heisenberg took up a model which was too simple to lay claim to be a description of real phenomena.

Heisenberg's last two reviews (B p. 917–927) "On the nature of elementary particles" [6] and "Cosmic rays and the fundamental problems of physics" [7] reflect both the wisdom and the perplexity of the aging genius.

The multiple production of parlticles in cosmic rays was for a long time an enigma for Heisenberg. In the articles of the section "Phenomena in cosmic rays and the limits of quantum field theory" (the introduction has been written by E. Bane) he discusses the nature of such production. The review of Heisenberg and Euler (B p. 261–330), which can be regarded as a summarizing one, has been studied for a long time by all those who had anything to do with high energy physics.[8] Since in 1938 pions had not yet been discovered (only the muon was unsuccessfully playing the role of the mediator of nuclear forces), the articles of this group have now been relegated to history.

Finally we have arrived at the articles on the uranium project (the introduction has been written by Wirtz) which we have already mentioned. An impression remains that not everything that was being worked on in Germany during the war has found reflection in the published articles and that the German specialists knew more than that. This will probably become clear in the near future. One should note that the history of atomic investigations in Nazi Germany is not well known in our country. Much that is incorrect also has been said about the role played by Heisenberg. There is no doubt that he did not take part in the Nazi movement, but attempting to preserve (and even increase) the role to be played by Germany in the science of the future postwar Europe he often found himself in an ambiguous position. This subject, as we have already noted, requires a separate analysis.

During the war years, finding himself practically in isolation, Heisenberg returned to his old idea which led him to matrix mechanics. The idea consisted of the fact that the theory must deal with quantities which approach as closely as possible to the quantities measured experimentally. The difficulties in field theory (divergences of integrals) Heisenberg attempted to relate to the overly detailed description of physical processes with the aid of the wave equation. In developing this idea Heisenberg introduced a new object—the S matrix—which describes the transition from the initial to the final state omitting the "history" of this transition.

The theory of the S matrix (or of its phase the η matrix) is described in the articles on the theory of scattering matrix (the introduction was written by R. Oehme). This section ("Observable quantities in the theory of elementary particles") contains three articles which in their time attracted many physicists.[9]

The theory of the S matrix in the form in which Heisenberg wanted to construct it did not succeed. But the S matrix became an important element in modern field theory.

In the case of a great author even failures lead to progress!

In concluding our discussion of the volume AII (articles up to 1946) one can say that Heisenberg after the defeat of Germany in the war immediately took part in the worldwide development of the physics of the microworld and continued his attempts to overcome its difficulties. Two ideas seemed to him capable of saving the situation—the theory of the S matrix and nonlinear equations. History has shown (history is almost always cruel!), that both ideas are too primitive. The microworld turned out to be richer in its inhabitants, and the theory turned out to be more complex and more "aristocratic" from the mathematical point of view. But a discussion of this "last chapter of the novel" will be more appropriate after the appearance of volume AIII.

It now remains to say a few more words concerning volume B. This thick volume contains 68 articles which in the form of reviews and books summarizes both what has been accomplished by Heisenberg (and his school) as well as

general views on the development of physics (up to the middle of the 1970's). In these articles one can study the history of the development of the concept of the structure of matter as seen by the eyes of Heisenberg in his own co-moving coordinate system.

Without attempting to recapitulate the articles and reviews we shall mention only books included in this volume. First of all this is the book "Physical Principles of Quantum Mechanics" a translation of which was published by D. D. Ivanenko in 1932. Since then the book has not been republished, and there are few of those now who have read it (and that is a pity!).[10]

The second book is based on lectures given in Chicago and the collection incudes its translation into English. Further in this volume we find articles from the collection "Cosmic Rays" published with Heisenberg as editor. This is followed by "Two lectures" (Elementary particles and Superconductivity). And finally a book on nonlinear equations, a translation of which was published in our country.[11]

One more book on the theory of the nucleus has been transferred to the five volume series C. Apparently, it was accidently omitted by the compilers.

The development of physics is impetuous. Articles and monographs age rapidly. Young natural scientists learn from ever newer books. But the monuments of science do not disappear; their time comes and they will be read and studied just as we read the diaries of travellers of old times. Books—monuments—do not perish just as the acient tragedies did not perish; they will remain as standards of beauty along the complex path of humanity's acquisition of knowledge about nature. "In exact sciences, just as in art, beauty is the most important source of light and clarity."[12]

I conclude these remarks by one more equation (CI, p. 96–101): "Along the path of new knowledge it is necessary to return to the position of Columbus who had sufficient courage, disregarding the old lands, to set sail with an irrepressible hope in search of new lands lying somewhere beyond the ocean."

[1]Coauthor of a multi-volume history of quantum mechanics (together with Mehra, whose name the present reviewer regrets to have earlier incorrectly transliterated into Russian): cf. the review in Usp. Fiz. Nauk **158**, 747 (1989), Erratum **159**, 747 (1989) [Sov. Phys. **32**, 734 (1989), Erratum **32**, 1117 (1989)].

[2]We note here only the titles of the volumes: CI-CIII—"Physics and Knowledge" (1927–1955, 1956–1968), CIV—"Biographical Material and Nuclear Physics", CV-"Science and Politics".

[3]We note here those that, in our opinion, are the most objective ones: E. L. Feĭnberg, Znamya, 1990, No. 3, M. Walker, German National Socialism and Quest for Nuclear Power (1939–1949)—Cambridge University Press, 1989; cf. discussion in Physics Today, May 1991, p. 13; C. F. von Weizsäcker, Bewusstseinswandel, Dutsche Taschenbuch Verlag, Munche, 1991, 6 Kapitel.

[4]Zur Quantumtheorie der Linienstruktur und der anomalen Zeemaneffekt, Z. Phys. **8**, 273–297 (1927).

[5]Die absolute Dimension der Karmanschen Wirbelbewegung, Z. Phys. **23**, 363–366 (1922).

[6]Physics Today, March 1976, pp. 32–39. The article was published already after 1 February—the day the author died.

[7]Naturwissenschaften **63**, 63–67 (1976).

[8]Ergeb. exakten Naturwiss. **17**, 1–69 (1938) [Russ. transl., Usp. Fiz. Nauk **21**, 130 (1939)].

[9]The third paper became known in our country only after the war.

[10]5000 copies were printed. This number was quite sufficient for the market, but its price was 5r.75kop.: at that time this was expensive.

[11]Cf. W. Heisenberg, *Introduction to the Unified Field Theory*, Interscience, N.Y., 1966 [Russ. transl., Mir, M., 1968].

[12]W. Heisenberg. *The significance of beauty in the exact sciences*, Report at the Bavarian Fine Arts Academy, 17 November, 1953; cf. Russ. transl. in the book W. Heisenberg, *Steps Beyond the Horizon*, (In Russian), Progress, M., 1987, p. 268.

Translated by G. M. Volkoff