gave an early report on this work at the International Ornithological Congress of 1910. Over the course of more than two decades, the Heinroths proceeded to rear nearly all the bird species of Central Europe in isolation. The results of this work were detailed in their four-volume classic, *Die Vögel Mitteleuropas in allen Lebens- und Entwicklungsstufen photographisch aufgenommen und in ihrem Seelenleben bei der Aufzucht vom Ei ab beobachtet* (1924–1933).

Heinroth's studies, in the opinion of the distinguished German ornithologist Erwin Stresemann, constituted the first great step toward closing the long-standing gap between avian systematics and avian biology, the two major branches of ornithology. At first Heinroth's work attracted few disciples or emulators. At the beginning of the 1930's, however, Heinroth was sought out by the young Austrian naturalist Konrad Lorenz, and over the next decade they developed a strong friendship, and exchanged observations and ideas. This interaction was of great importance for the subsequent history of ethology. Heinroth's love of animals and concern with establishing the study of animal behavior on a firm inductive foundation were shared by Lorenz, though the younger man proved significantly less reluctant to generalize about animal behavior than Heinroth had been.

It was primarily Lorenz, first with Heinroth's encouragement and then with the very able support and collaboration of the young Dutch naturalist Nikolaas Tinbergen and others, who between 1935 and 1960 played the leading role in establishing ethology, the comparative study of behavior, as a modern scientific discipline.

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RICHARD W. BURCKHARDT, JR.

HEISENBERG, WERNER KARL (*b.* Würzburg, Germany, 5 December 1901; *d.* Munich, Federal Republic of Germany, 1 February 1976), *quantum theory, nuclear physics.*

Heisenberg was the younger son of August and Anna Wecklein Heisenberg. His father taught ancient languages at the Altes Gymnasium in Würzburg and Greek philology at the university. In 1910 he moved his family to Munich, where he had been appointed professor of Greek philology at the university. Heisenberg attended primary school in Würzburg and Munich. He began piano lessons early, and by the age of thirteen he was playing master compositions. He remained an excellent and avid player throughout his life. On 29 April 1937 Heisenberg married Elisabeth Schumacher, daughter of the noted Berlin professor of economics Hermann Schumacher. They had seven children.

In 1911, Heisenberg entered the Maximilians-Gymnasium, of which his maternal grandfather was rector. There he displayed an outstanding talent for mathematics. By the time of his final examinations (*Abitur*), he had taught himself calculus, had explored the properties of elliptic functions, and had attempted to publish a paper on number theory. Heisenberg entered the University of Munich in 1920, intending to study pure mathematics. Following the refusal of mathematics professor Ferdinand von Lindemann to admit Heisenberg to his seminar for advanced students, Heisenberg's father arranged an interview with the professor of theoretical physics, Arnold Sommerfeld, who tentatively accepted the ambitious student into his advanced seminar. Heisenberg received his doctorate under Sommerfeld in 1923—over the objections of Wilhelm Wien, the professor of experimental physics, who found the candidate deficient in his field. Heisenberg's dissertation involved an approximate solution of the complicated equations governing the onset of hydrodynamic turbulence.

When Heisenberg entered the University of Munich, theoretical physics, although it had attained recognition through the efforts of the older generation, was overshadowed by the work of experimentalists like Wien. Sommerfeld's institute was one of the few, mainly in Germany, where theoretical atomic physics was pursued, and the only German institute concerned with the entire quantum theory of atomic spectroscopy.

By 1920, atomic structure, the properties of light, and spectroscopy had become focuses of research on quantum atomic theory. This theory, formulated by Niels Bohr in 1913, regarded atomic motions as governed by integral quanta of energy and momenta. Transitions between quantum states involved the emission or absorption of monochromatic radiation of frequency proportional to the change of energy. During the early 1920's the mechanical properties of quantized models of atoms and molecules consisting of more than two particles disagreed with observed properties, and atomic spectra and their behavior in applied electric and magnetic fields displayed numerous inexplicable regularities and anomalies. The discovery of the Compton effect at the end of 1922 lent support to the light-quantum hypothesis, contradicting the well-established wave theory of light and raising the wave-particle dualism to a fundamental problem.

During his studies and research at Munich, and subsequently at Göttingen with Max Born and at Copenhagen with Niels Bohr, Heisenberg became familiar with each of the above difficulties, as well as with the limitations of quantum theory and of the methods employed by each of his mentors. He also made the acquaintance of such young and brilliant theoretical physicists as Wolfgang Pauli, Enrico Fermi, and Paul Dirac, who would dominate atomic physics for at least a decade. Heisenberg, a leading representative of this group, is best known scientifically for his contributions to the creation and development of quantum mechanics.

As early as his first semester at Munich, Heisenberg displayed the audacity, optimism, and independence of thought and action that characterized his physics as well as his personal life during and immediately following World War I. While his father, a reserve infantry officer, was away from home for nearly the entire war, his sons were left increasingly on their own. A severe shortage of fuel and food forced the occasional closing of school and encouraged Heisenberg to educate himself. Weak from lack of food, he helped to bring in the harvest with schoolmates on a Bavarian farm in the summer of 1918.

The loss of the war and the abdication of the monarchy caused revolutionary unrest throughout Germany. In Bavaria a socialist republic came to power in 1918, then was replaced in 1919 by a Bolshevik-oriented republic that was suppressed by troops dispatched from Berlin. During the sometimes heavy street fighting and the subsequent restoration of democratic socialist rule, Heisenberg supported the invading forces as part of a unit composed of boys from his gymnasium. Soon after the restoration of democratic socialism, Heisenberg was elected leader of a small group of younger boys from the earlier unit who became associated with the Bund Deutscher Neupfadfinder (New Boy Scouts). The New Boy Scouts strove for a renewal of supposedly decadent German personal and social life through the direct experience of nature and the uplifting beauties of Romantic poetry, music, and thought. Heisenberg's comrades from these years remained among his closest friends throughout his life, and outdoor activities, together with music, remained among his favorite pastimes.

During his studies with Sommerfeld, Heisenberg became acquainted not only with Wolfgang Pauli, a fellow student who thereafter was his closest collaborator and severest critic, but also with the intricacies of the anomalous Zeeman effect, the inexplicable splitting of atomic spectral lines into more than the expected three components in a magnetic field. In his first semester, Heisenberg offered a classification of the anomalous lines using thoroughly unorthodox half-integral quantum numbers. In 1922 he publicly displayed his audacity—and his intuition—in his first published paper, which offered a model for the Zeeman effect that described all of the known data in terms of the couplings between valence electrons and the remaining atomic "core" electrons. The model, however, violated many of the basic principles of quantum theory and classical mechanics. It thus served both as the basis for most of the subsequent work on the Zeeman effect until the advent of electron spin and as the first indication of the radical changes required for solving the quantum riddle.

The core model brought its author to the attention of established theoreticians. Sommerfeld had already written to his colleagues about Heisenberg's work when, in June 1922, he brought his student to Göttingen for a series of lectures on quantum atomic physics presented by Bohr. Heisenberg's audacious criticism of one of Bohr's assertions and a subsequent confrontation between the two over the core model resulted in a mutual admiration and the beginning of a lifelong collaboration that was as important for Heisenberg as his collaboration with Pauli.

During the Göttingen meeting Sommerfeld arranged for his students to continue their studies at Göttingen with Max Born while Sommerfeld traveled. A lecture on the core model, delivered soon after he arrived in Göttingen for the winter semester of

1922–1923, brought Heisenberg a private assistantship with Born.

Except for semester-long visits to Munich and Copenhagen, Heisenberg remained in Göttingen until May 1926. The period was one of his most productive scientifically. With his colleagues there, he developed the matrix form of quantum mechanics, progressed toward an interpretation of the new formalism, and applied the quantum theory, along with electron spin, to the Zeeman effect, the helium atom, and other old problems. In July 1924 Heisenberg qualified to teach on the university level by presenting to the Göttingen faculty a modification of the quantum rules for the Zeeman effect. The modification foreshadowed the notions of what Born was now calling a future "quantum mechanics."

After Pauli had indicated the inadequacy of quantum theory for the hydrogen molecule ion in 1922, attention turned to an exact calculation of the orbits of helium. While Pauli grew increasingly skeptical of any approach that assumed the existence of electron orbits in atoms, Born and Heisenberg managed to support Bohr's building up of the periodic table, which explicitly assumed the existence of orbits. But the celestial mechanics of atoms clearly failed to reproduce the properties of helium, and in 1923 Born and Heisenberg officially pronounced the premises of quantum atomic theory inadequate.

During a seven-month visit to Bohr's institute at Copenhagen beginning in the fall of 1924, Heisenberg turned to the nature of light. Earlier in 1924 Bohr, Hendrik A. Kramers, and John C. Slater had attempted to resolve the wave-particle duality by assuming the statistical conservation of energy and momentum in the absorption and emission of radiation. The proposal was already in doubt and was soon refuted, but it indicated again the belief that radical change was necessary. With Bohr and Kramers, Heisenberg attempted to account for optical fluorescence and dispersion by a "sharpened" version of Bohr's correspondence principle between classical and quantum physics. In the Kramers-Heisenberg scheme, which has proved fruitful ever since, emission and absorption were treated as if they occurred via quantized harmonic oscillators whose frequencies and amplitudes were related to the Fourier components of the supposed electron motions in atoms. From his visit to Copenhagen, Heisenberg also gained an appreciation of what Pauli called Bohr's "philosophical thinking," a concern for the physical and conceptual nature of the difficulties in quantum theory, in addition to their mathematical expression. All of these elements contributed to his discoveries soon after his return to Göttingen in 1925.

In May 1925, Heisenberg took on a new and difficult problem, the calculation of the line intensities in the hydrogen spectrum. Just as he had done with Kramers and Bohr, Heisenberg began with a Fourier analysis of the electron orbits. When the hydrogen orbits proved too difficult, he turned to the anharmonic oscillator. With a new multiplication rule relating the amplitudes and frequencies of the Fourier components to observed quantities, Heisenberg succeeded in quantizing the equations of motion for this system in close analogy with the classical equations of motion.

A severe attack of hay fever in early June forced Heisenberg's retreat to the island of Helgoland. There he completed the calculation of the anharmonic oscillator, determined the constants of motion, and obtained from his multiplication rule the Thomas-Kuhn summation rule for spectral lines. After nearly two weeks on Helgoland, Heisenberg returned to Göttingen, where he drafted his fundamental paper "Über die quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen," which he completed in July. In this paper Heisenberg proclaimed that the quantum mechanics of atoms should contain only relations between experimentally observable quantities. The resulting formalism served as the starting point for the new quantum mechanics, based, as Heisenberg's multiplication rule implied, on the manipulation of ordered sets of data forming a mathematical matrix.

Born and his assistant, Pascual Jordan, quickly developed the mathematical content of Heisenberg's work into a consistent theory with the help of abstract matrix algebra. Their work, in collaboration with Heisenberg, culminated in their "three-man paper" that served as the foundation of matrix mechanics. Confident of the correctness of the new theory, Heisenberg, Pauli, Born, Dirac, and others began applying the difficult mathematical formalism to the solution of lingering problems. But most physicists soon welcomed a rival theory propounded by Erwin Schrödinger in 1926.

Schrödinger offered a quantum "wave mechanics" that purported to replace electron orbits, banish quantum jumps, and require only the familiar methods of partial differential equations. His recognition of the mathematical equivalence of the rival theories and his claim that his theory superseded matrix mechanics caused a flurry of activity among the matrix mechanicians.

In May 1926 Heisenberg succeeded H. A. Kramers as Bohr's assistant in Copenhagen. The acceptance of electron spin, Born's interpretation of the square of Schrödinger's wave function as a probability density, and the formulation of the Dirac-Jordan transformation theory led to intensive studies in Copenhagen of the "perceptual content" of the rival quantum formalisms. In extensive correspondence with Pauli, Heisenberg analyzed the measurement of individual quantum events in the context of transformation theory. This led him in early 1927 to the formulation of his principle of uncertainty, or indeterminacy, the contribution for which Heisenberg is perhaps best known.

According to Heisenberg, the precise, simultaneous measurement of canonically conjugate variables, such as the position (q) and the momentum (p), or the energy (E) and time (t), of a particle, are excluded in principle. Instead, reciprocal relationships exist between the indeterminacies in the measurements of position (Δq) and momentum (Δp), or energy (ΔE) and time (Δt). These can be represented by Heisenberg's famous uncertainty relations:

$$\Delta p \cdot \Delta q \approx h$$
$$\Delta E \cdot \Delta t \approx h,$$

where h is Planck's constant. The implications were enormous. Heisenberg declared in particular that traditional notions of causality are weakened by the indeterminacy formula, since all initial conditions of a particle's motion cannot be known with enough precision to predict its subsequent motion with certainty. The difficulty was one of principle, not of technique. Strict determinism, he insisted, will never be reestablished.

Heisenberg formulated his principle in Copenhagen, where he was teaching, after long conversations with Bohr. Bohr was not satisfied with Heisenberg's formulation, among other versions, because it did not adequately treat the simultaneous use of the physical pictures of particles and waves. Bohr's views, expressed in the principle called "complementarity," provided a deeper understanding of the uncertainty principle in terms of the actual measuring processes in any experiment. These two principles combined with Born's probabilistic interpretation of the wave function to form the basis of the "Copenhagen interpretation" of quantum mechanics. Although this interpretation, despite its revolutionary implications for measurement, causality, and objectivity, was soon accepted by the majority of physicists, a vocal minority that included Einstein, Schrödinger, and Planck was never fully reconciled to it. Physics that renounces knowledge of objective processes in principle cannot, they argued, be a complete account of physical reality.

In 1927, as Heisenberg, Bohr, and Born presented the Copenhagen interpretation, Heisenberg accepted a call to Leipzig as professor of theoretical physics, at the age of twenty-five Germany's youngest full professor.

Heisenberg and his Leipzig colleagues transformed the Physics Institute into a leading center for research on atomic and quantum physics. Among Heisenberg's early students and collaborators were Felix Bloch, Rudolf Peierls, Edward Teller, Peter Debye, Frederick Hurd, and Carl Friedrich von Weizsäcker. Heisenberg traveled widely during his early Leipzig years, carrying the message of quantum mechanics to the United States, Japan, India, and Italy.

Heisenberg's research in Leipzig concentrated upon applications and extensions of quantum mechanics. In 1928 he showed that a quantum-mechanical exchange integral that had played a crucial role in his earlier solution of the helium problem could account for the strong molecular magnetic field in the interior of ferromagnetic materials. Bloch, then Heisenberg's assistant, supplemented the theory with his notion of spin waves, and Peierls offered a theory of the anomalous Hall effect.

Heisenberg also explored the philosophical implications of quantum theory. With Weizsäcker and Grete Hermann, a student of Kantian philosophy, he considered the problems of language in quantum theory and the applicability of neo-Kantian notions of causality. With Bohr, Heisenberg pushed the Copenhagen view into chemistry, biology, and even into social and ethical phenomena. To many lay persons, however, the new ideas seemed as strange and disturbing as the revisions in world view brought about earlier by the relativity theory. Consequently, Heisenberg addressed himself increasingly to popular audiences. As theoretical physics and physicists fell into increasing disfavor with the rise of Hitler, the task of popularization became more pressing.

Heisenberg's foremost scientific concern after 1927 involved the search for a consistent extension of the quantum formalism that would yield a satisfactory unification of quantum mechanics and relativity theory. This required the formulation of a covariant theory of interacting particles and fields that accounted for elementary processes at high energies and small distances. In 1929, drawing upon the work of Dirac, Jordan, Oskar Klein, and others, Heisenberg and Pauli succeeded in formulating a general gauge-invariant relativistic quantum field theory by treating particles and fields as separate entities interacting through the intermediaries of field quanta.

The formalism led to the creation of a relativistic quantum electrodynamics, equivalent to that developed by Dirac, which, despite its puzzling negative energy states, seemed satisfactory at low energies and small orders of interaction. But at high energies, where particles approach closer than their radii, the interaction energy diverged to infinity. Even at rest, a lone electron interacting with its own field seemed to possess an infinite self-energy, much as it did in classical electrodynamics. Attention was directed to the resolution of such difficulties for more than two decades.

Soon after the discovery of the neutron in 1932, Heisenberg developed a neutron-proton model of the nucleus by introducing the concept of the nuclear exchange force and the formalism of isotopic spin. Nonrelativistic quantum mechanics could be applied to the nucleus, Heisenberg showed, as long as one did not consider the structure of nucleons. Heisenberg's work served as the basis for contemporary nuclear physics, much of which was pursued by his assistants, especially Weizsäcker. Heisenberg preferred to continue the search for a consistent quantum physics of fields. In 1935 Heisenberg and his assistant Hans Euler discovered that nonlinear interactions in positron theory, which yielded photon-photon scattering, could be represented by treating the electron as possessing a minimum size, below which the interferences predominated.

These studies were slowed by the deterioration of German politics. The takeover of German student bodies, such as Leipzig's, by Nazi students preceded the Nazi control of German society. Heisenberg was thirty-one when Hitler came to power in 1933. At the end of the year Heisenberg was awarded the Nobel Prize for physics (for 1932) for his contributions to quantum mechanics. His scientific renown and his ties to leading members of the older generation of German quantum physicists—Max Planck, Max von Laue, Arnold Sommerfeld—rendered the young man a leading spokesman for German physics.

It needed defense. The attack upon academic professions, including physics, had three phases before the outbreak of war: the dismissal of Jewish and leftist teachers and professors, the dismissals of those protected during the first round of dismissals, and an attempt to force the remaining Germans and German institutions into acquiescence with, if not overt support of, the dictatorship. Heisenberg's response was perhaps typical of many educated Germans. There was little chance that he would emigrate voluntarily, despite numerous opportunities and invitations to do so. The reasons included his attachment to Germany, his agreement with its resurgence as a nation, and his perceived duty to his profession, made more acute by the unsavory politicians in control. As for many Germans, nation and politics were separable for Heisenberg, and, like many, he believed the Nazis would not be in power long.

Planck, Heisenberg's main political mentor, counseled optimism for the future and quiet diplomacy for the present. Public protest or direct confrontation was not compatible with their temperaments or their strategy of administrative diplomacy. At no time, however, was Heisenberg an overt supporter of Nazi ideals; nor do Nazi party records show that he was ever a member. He was a man dedicated to his country and to the preservation of the best of its culture, even at personal risk. His were the dilemma and the tragedy of many German scientists under Hitler.

Heisenberg found support and protection in his efforts to counter the effects of the regime through circles of numerous friends and colleagues of like mind, extending from his family acquaintances to the university faculty, to the Saxon Academy of Sciences in Leipzig, to the entire non-Nazi academic community of Germany. Optimism, perseverance and attempts to utilize bureaucratic channels characterized Heisenberg's early efforts on behalf of colleagues dismissed in 1933. The dismissal of four Jewish veterans of World War I from the Leipzig science faculty two years later occasioned perhaps the strongest verbal protests from the Leipzig physicists and an implied threat to resign. A strong reprimand of the Leipzig physicists resulted, but the four victims were never reinstated.

Beginning in 1936, antiscientific political attention focused upon theoretical physics and upon Heisenberg in particular. Sommerfeld, who had by then reached retirement age, wanted Heisenberg as his successor in Munich. That touched off a campaign by Nazi physicists against the theoretical physics establishment. Early in 1936 the Nobel Prize–winning physicist Johannes Stark and his followers unleashed a newspaper assault against "Jewish [that is, theoretical] physics" and contrasted it with a supposedly experimentally oriented "German physics." Heisenberg responded in the same party newspaper with a defense of teaching and research in contemporary theoretical physics. With the experimentalists Max Wien and Hans Geiger, he authored and circulated a petition among German physicists protesting the attack and the effects of Nazi policy on teaching and research. It was submitted to the Reich Education Ministry with seventy-five signatures. Although the petition did have some immediate effect, it exerted little influence upon the overall political course of the regime or its policies.

While engaged in this political fight, Heisenberg vigorously pursued his search for a consistent quantum field theory. His tenacious adherence to what he believed to be the beginning of a new quantum revolution is in part attributable to his concern for the vitality of German research. In 1935 Heisenberg's research began to focus on high-energy collisions of elementary particles in cosmic rays, the highest-energy phenomena then known. Examining the Fermi (weak) interaction in early 1936, Heisenberg discovered a mathematical minimum length, about the size of elementary particles, that appeared to trigger the onset of "explosion showers" of cosmic rays. The minimum length, a notion that he had earlier considered in the context of quantum electrodynamics, marked, he believed, the boundary of quantum mechanics and the frontier of a wholly new and revolutionary physics.

Heisenberg's revolutionary notions were challenged soon afterward by the alternative quantum electrodynamics of "cascade showers," generated by *Bremsstrahlung* and pair production. A controversy ensued, mainly between Heisenberg and several American physicists, over the existence of explosion showers and over allegiances to the two types of theories and their implications for the future course of physics. Fermi's weak-field theory soon proved inapplicable to the problem, but in 1939 Heisenberg extended his notions to Yukawa's (strong) meson theory of nuclear forces, revitalizing the controversy into the war years. A universal minimum length remained a permanent feature of Heisenberg's physics. Although explosion showers, later called "multiple processes," were discovered after the war in cosmic-ray events, the invention of renormalization techniques and the experimental confirmation of quantum electrodynamics to the highest energies left Heisenberg's physics with only minority support.

In 1937 a new attack in the Nazi press interrupted Heisenberg's work on quantum field theory. When Heisenberg accepted a renewed call to succeed Sommerfeld in Munich, *Das Schwarze Korps*, the journal of the S.S., published an article signed by Stark declaring that Heisenberg and other theoreticians were "white Jews." It accused Heisenberg in particular of actions amounting to overt opposition to the totalitarian regime. Not only was Heisenberg's appointment canceled, but his personal safety and future ability to work and teach in Germany seemed endangered. With the support of his colleagues, he decided to write directly to the head of the S.S., Heinrich Himmler, requesting an official disavowal of the charges and a termination of the campaign against him and his physics. A year of investigations and interrogations, some in the Berlin office of the S.S., brought partial relief. Himmler disavowed the charges and placed the proponents of "German physics" on the defensive, but Heisenberg never did succeed his former teacher.

The outbreak of world war in September 1939 profoundly affected Heisenberg and his career. Still of military age, he was ordered to report to the Army Weapons Bureau (Heereswaffenamt) in Berlin. There the authorities asked him and other leading German nuclear physicists to investigate whether nuclear fission, discovered in Berlin a year earlier, could be used for large-scale energy production. Within two months Heisenberg completed a comprehensive report on the theory of chain reactions and their uses, including their use in an atomic bomb. The report made Heisenberg the leading specialist on nuclear energy in Germany.

In order to continue the promising research, the Army Weapons Bureau designated the Kaiser Wilhelm Institute for Physics in Berlin the center of German fission research. After the departure of the institute's Dutch director, Peter Debye, who chose emigration over German citizenship, Heisenberg was named adviser, and later acting director, of the institute and its nuclear research. At the same time, Heisenberg supervised preliminary reactor experiments in Leipzig. He also continued with high-energy interactions. In papers written between 1942 and 1944, Heisenberg developed a theory of particle collisions based, as in 1925, only upon the observable properties of the colliding particles. The resulting "S-matrix" theory of particle scattering, especially in its later analytic forms, enjoyed considerable attention after the war, then again during the 1960's, but renormalized field theories eventually found more followers.

Heisenberg consciously pursued his assumed role of protector of German physics after 1938. The chance that he might emigrate accordingly declined, despite the various offers and pleas from his American colleagues during his tour of the United States a year later. Heisenberg was later much criticized for his decisions to remain in Germany and to work on nuclear energy under Hitler. He always responded that Germany needed him.

The aims of German nuclear research have also been debated. The theoretical possibility of an atomic bomb was known among nuclear physicists before the outbreak of the war. In 1942 a decision was made at a meeting between German government officials and atomic scientists, calling for the construction of a reactor, the first step toward atomic energy and, if so desired, an atomic bomb. During a private meeting a year earlier between Bohr and Heisenberg in German-occupied Copenhagen, Bohr received the distinct impression that the Germans were indeed aiming for a bomb. Heisenberg later insisted that a misunderstanding had occurred; however that may be, a very disturbed Bohr conveyed his impressions to Allied scientists when he fled Denmark in 1943.

The German reactor effort never succeeded. Technical and scientific errors, lack of financial and material support, and the effects of Allied bombing prevented the Germans from achieving a chain reaction. By war's end the German project and its scientists had moved to small towns in southern Germany in order to escape the bombing of the larger cities. The ALSOS Mission, a secret American intelligence unit, captured Heisenberg and nine other atomic scientists there during the last chaotic days of the war. Heisenberg and his colleagues were eventually turned over to the British, who held them for six months at a country estate near Cambridge.

The British returned the German scientists to Göttingen in early 1946. In addition to developing themes of superconductivity, hydrodynamic turbulence, and particle physics, Heisenberg set out to revitalize German science. While reestablishing in Göttingen the Kaiser Wilhelm Institute for Physics, renamed the Max Planck Institute and placed under his direction, Heisenberg devoted enormous energy to realizing his conception of government science policy. He sought a direct role for the new West German federal government in forming a national science policy and a direct role for science advisers to the chancellor. Such conceptions found expression in 1949 in the German Research Council (Deutscher Forschungsrat), composed of fifteen leading scientists, including Heisenberg as president. With the support of the scientific establishment and of Chancellor Konrad Adenauer, the German Research Council represented German science in international affairs and directly in the chancellor's office. Among the council's successes were the acquisition of Marshall Plan money for German research, the admission of the Federal Republic into the International Union of Scientific Councils, and the statement of federal responsibility for science in the West German constitution.

As head of both the research council and the leading West German physics institute, Heisenberg became a leading spokesman for German science in the international arena. Seeking to reestablish international relations, he headed (beginning in 1953) the Alexander von Humboldt Foundation for the support of foreign scholars in the Federal Republic, and he traveled and lectured widely abroad. In 1954 Heisenberg served as the West German delegate to the conference Atoms for Peace in Geneva. After the founding of the European Council for Nuclear Research in 1952, Heisenberg, as head of the German delegation, participated in the decision to locate the European research center for high-energy physics (CERN) in Geneva and later served as chairman of its scientific policy committee.

But at home Heisenberg's research council went against the German tradition that support for science fell to the cultural minister of each state. The research council thus came into increasing conflict with the Emergency Association of German Science (Notgemeinschaft der Deutschen Wissenschaft), revived in 1949 by the cultural ministers and the university rectors. In order to avoid further friction, Heisenberg reluctantly allowed the amalgamation of the research council with the emergency association in 1951 to form the German Research Association (Deutsche Forschungsgemeinschaft). Representation of German science was assumed by the senate of the new body, composed mainly of the old research council. Heisenberg became a member of the presidential committee of the research association and chairman of its committee for atomic physics, which coordinated nuclear research.

Heisenberg's influence and that of his colleagues is evidenced by their twofold impact on the important field of West German nuclear policy: support of nuclear energy and opposition to nuclear weapons. In 1955 the Western allies granted the Federal Republic full sovereignty and full membership in the NATO alliance, removing all restrictions upon West German research. Heisenberg and his colleagues immediately launched a public campaign for a crash program in nuclear energy development. Under Heisenberg's direction, Germany's first nuclear reactor, a research model, was set up at Garching (near Munich) in 1957. At the same time, a major nuclear research section was established at Heisenberg's Max Planck Institute under the direction of Karl Wirtz; it eventually relocated in Karlsruhe.

While Heisenberg energetically argued for nuclear energy production, he equally energetically opposed Adenauer's plans to equip the West German army with tactical nuclear weapons. With strong support from an aroused public, Heisenberg and other leading German scientists launched a broadly based political campaign against nuclear weapons. It culminated in 1957 in a public declaration, formulated mainly by Weizsäcker and Heisenberg, and signed by seventeen prominent nuclear scientists opposed to research on or possession of nuclear weapons by West Germany. This time the effort met with success; the West German army has remained nonnuclear.

Despite the enormous demands of his political involvement, Heisenberg continued to pursue his search for a consistent quantum field theory. After an unsuccessful attempt at a nonlocal theory, he turned in 1952 to the investigation of nonlinear field equations in which the mathematical state space was extended beyond that used in quantum mechanics. Heisenberg and his collaborators discovered that with these equations, results could be obtained without the introduction of supplementary subtraction or renormalization techniques. After demonstrating the consistency of the theory in 1957, Heisenberg entered into an extremely intense collaboration with Pauli that a year later yielded a nonlinear spinor equation designed to describe the properties and the behavior of all known elementary particles. The resulting equation, dubbed the "world formula" by journalists, caused immense excitement among physicists, but Pauli, ever the critic, withdrew his support later that year.

Saddened by Pauli's renunciation and by his death soon afterward, Heisenberg nevertheless continued research on the nonlinear spinor theory after moving his institute to Munich from Göttingen in 1958. A year later he and his colleagues published a long paper enunciating the new theory and obtaining its resonance states, one of which, a new particle (the eta-meson), was discovered in 1960. Although the theory did not enjoy wide popularity, Heisenberg retained his belief in it to the end of his life. In his view the prevailing method of inventing ever more elementary material objects, such as quarks, missed the main objective of a fundamental theory: to explain the very existence and behavior of matter itself by fields. In Heisenberg's opinion, his theory agreed with Plato's representation of the structure of matter by simple geometrical forms. The symmetries of Heisenberg's field equation seemed to him to be analogous to Plato's forms. Matter and its properties would follow from the symmetries of the nonlinear field equation and the conditions imposed upon it. While attempting to realize this plan in the complicated mathematics of nonlinear equations, Heisenberg extended his Platonic notions to the rest of his world view, merging it in his later years with his views on the philosophy of physics, on religion, on society, and on his role in the history of quantum physics.

Heisenberg continued to work tirelessly into the 1970's on his nonlinear spinor theory, on philosophy, on international relations, and on the direction of his Max Planck Institute. In the middle of 1973 he fell seriously ill. He slowly improved and appeared to have fully recovered, but in July 1975 he suffered a severe relapse. He died six months later.

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I. ORIGINAL WORKS. Heisenberg published over 500 independent works, of which some 100 may be considered original scientific contributions. The others concern philosophical, cultural, political, and popular subjects. All of Heisenberg's published writings have been reissued in facsimile in *Werner Heisenberg: Gesammelte Werke/Collected Works*, 9 vols., Walter Blum, Hans-Peter Dürr, and Helmut Rechenberg, eds. (Berlin, Munich, and New York, 1984–). The volumes are divided into three series issued by two publishers. Series A (Berlin and New York, Springer-Verlag) contains the original scientific writings, which are arranged by topic with an introductory survey by a distinguished figure in the field. Series B (Munich: Piper-Verlag) contains review articles, lectures, and books. Series C (Munich: Piper-Verlag) contains the philosophical, political, and popular writings. The *Collected Works* also contains a number of significant, previously unpublished items, among them a long manuscript titled (by the editors) "Ordnung der Wirklichkeit" (1942) and all available wartime nuclear research reports authored or coauthored by Heisenberg. A complete bibliography, including references to subsequent reprintings, translations, and excerpts, has been compiled by David Cassidy and M. Baker, *Werner Heisenberg: A Bibliography of His Writings* (Berkeley, 1984). References to translations of Heisenberg works cited below are in the *Bibliography*.

Heisenberg summarized his own physics in various periods in series of lectures that were subsequently published as textbooks. The most important of these include *Die physikalischen Prinzipien der Quantentheorie* (Leipzig, 1930, repr. Mannheim, 1958), trans. by Carl Eckart and Frank C. Hoyt as *Physical Principles of the Quantum Theory* (New York, 1930); *Kosmische Strahlung*, which Heisenberg edited (Berlin, 1943; 2nd ed., 1953), translated by T. H. Johnson as *Cosmic Radiation* (New York, 1946); *Die Physik der Atomkerne* (Brunswick, 1943; 2nd ed., 1949), also in English, *Nuclear Physics* (New York, 1953); and *Introduction to the Unified Field Theory of Elementary Particles* (New York, 1966).

Nearly all of Heisenberg's nontechnical writings originated as lectures. Some of the more widely distributed collections, published before the *Collected Works*, include *Wandlungen in den Grundlagen der Naturwissenschaft* (Leipzig, 1935; 11th ed., Stuttgart, 1980); *Das Naturbild der heutigen Physik* (Hamburg, 1955; 2nd ed., 1961); *Physics and Philosophy: The Revolution in Modern Science* (New York, 1958; repr. 1962); *Schritte über Grenzen: Gesammelte Reden und Aufsätze* (Munich, 1971; 2nd ed.,

1973); and *Tradition in der Wissenschaft: Reden und Aufsätze* (Munich, 1977).

Extensive unpublished interviews of Heisenberg, focusing mainly upon his contributions to quantum physics, were conducted in the early 1960's by the Sources for History of Quantum Physics (SHQP). Transcriptions are available in the repositories of the project. Heisenberg's memoirs, written largely as a series of dialogues, appeared as *Der Teil und das Ganze: Gespräche im Umkreis der Atomphysik* (Munich, 1969), trans. by Arnold J. Pomerans as *Physics and Beyond: Encounters and Conversations* (New York, 1971).

Portions of Heisenberg's extensive correspondence have been published in *Wolfgang Pauli: Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a.*, I, Armin Hermann *et al.*, eds. (New York, 1979), II, Karl von Meÿenn, ed. (New York, 1984); in *Niels Bohr: Collected Works*, 10 vols., Erik Rüdinger, general ed. (Amsterdam, 1972–); and in many other places, for which see Bruce R. Wheaton and John L. Heilbron, *An Inventory of Published Letters to and from Physicists 1900–1950* (Berkeley, 1982).

Heisenberg's unpublished papers and correspondence are considerable, although many early items were not preserved or were lost during World War II. The main body of material, currently in Munich, at the Werner Heisenberg Archives in the Werner Heisenberg Institute of the Max Planck Institute for Physics and Astrophysics, will be deposited in the library and archives of the Max Planck-Gesellschaft, Berlin. The papers include administrative documents, lecture course notes, and extensive correspondence. A survey of all of the available extant archival papers through 1950 is provided by the Inventory of Sources for History of Twentieth-Century Physics, Office for History of Science and Technology, University of California, Berkeley. Some of the scientific correspondence and manuscripts are available on microfilm in the SHQP repositories. Copies of German wartime documents, interviews, and other materials pertaining to the fission project, many of which refer to Heisenberg, are preserved in David Irving's collection *Records and Documents Relating to the Third Reich*, group 2, microfilms DJ-29 to DJ-31 (East Ardsley, Wakefield, England, 1966).

II. SECONDARY LITERATURE. There is, as yet, no comprehensive account of Heisenberg's life and work in print. Surveys are provided by Armin Hermann, *Werner Heisenberg in Selbstzeugnissen und Bilddokumenten* (Reinbek bei Hamburg, 1976) and *Die Jahrhundertwissenschaft: Werner Heisenberg und die Physik seiner Zeit* (Stuttgart, 1977). Appreciations of Heisenberg's life and work by his friends and colleagues are in the *Collected Works*, ser. A, and in Fritz Bopp, ed., *Werner Heisenberg und die Physik unserer Zeit* (Brunswick, 1961); Hans-Peter Dürr, ed., *Quanten und Felder: Physikalische und philosophische Betrachtungen zum 70. Geburtstag von Werner Heisenberg* (Brunswick, 1971); Heinrich Pfeiffer, ed., *Denken und Umdenken: Zu Werk und Wirkung von Werner Heisenberg* (Munich, 1977); and Carl-Friedrich von Weizsäcker and Bartel L. van der Waerden, *Werner Heisenberg* (Munich, 1977).

Heisenberg's political life is treated in Elisabeth Heisenberg, *Das politische Leben eines Unpolitischen: Erinnerungen an Werner Heisenberg* (Munich, 1980), translated by S. Cappellari and C. Morris as *Inner Exile: Recollections of a Life with Werner Heisenberg* (Boston, 1984); Sir Nevill Mott and Sir Rudolf Peierls, "Werner Heisenberg, 5 December 1901–1 February 1976," in *Biographical Memoirs of Fellows of the Royal Society*, **23** (1977), 213–251; and Samuel A. Goudsmit, "Werner Heisenberg (1901–1976)," in *Year Book of the American Philosophical Society for 1976* (1977), 74–80, which revises Goudsmit's evaluation in *ALSOS* (New York, 1947; 2nd ed., 1983). A history of the "Heisenberg affair" and the broader problems of academic physicists in the Third Reich is offered by Alan D. Beyerchen, *Scientists Under Hitler: Politics and the Physics Community in the Third Reich* (New Haven, 1977).

Portrayals of Heisenberg's participation in German wartime nuclear research include Jost Herbig, *Kettenreaktion: Das Drama der Atomphysiker* (Munich, 1976); Robert Jungk, *Heller als tausend Sonnen: Das Schicksal der Atomforscher* (Bern, 1956), translated by James Cleugh as *Brighter Than a Thousand Suns: A Personal History of the Atomic Scientists* (New York, 1958); David Irving, *The German Atomic Bomb: The History of Nuclear Research in Nazi Germany* (New York, 1967, repr. 1983); and Mark Walker, "The German Quest for Nuclear Power, 1939–1949" (Ph.D. dissertation, Princeton University, 1987). Studies of postwar science policy, especially nuclear policy, with reference to Heisenberg include Armin Hermann *et al.*, *History of CERN*, I, *Launching the European Organization for Nuclear Research* (New York, 1987); Joachim Radkau, *Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975* (Hamburg, 1983); Hans Karl Rupp, *Ausserparlamentarische Opposition in der Ära Adenauer: Der Kampf gegen die Atombewaffnung in den fünfziger Jahren* (Cologne, 1970); Thomas Stamm, *Zwischen Staat und Selbstverwaltung: Die deutsche Forschung im Wiederaufbau 1945–1965* (Cologne, 1981); and Kurt Zierold, *Forschungsförderung in drei Epochen: Deutsche Forschungsgemeinschaft. Geschichte, Arbeitsweise, Kommentar* (Wiesbaden, 1968).

Historical and philosophical studies of Heisenberg's physics differ widely in interpretation, methodology, and use of sources. Some of the better-known works include Mara Beller, "The Genesis of Interpretations of Quantum Physics, 1925–1927" (Ph.D. dissertation, University of Maryland, 1983), and "Matrix Theory Before Schrödinger: Philosophy, Problems, Consequences," in *Isis*, **74** (1983), 469–491; Joan Bromberg, "The Impact of the Neutron: Bohr and Heisenberg," in *Historical Studies in the Physical Sciences*, **3** (1971), 307–341; David C. Cassidy, "Cosmic Ray Showers, High Energy Physics, and Quantum Field Theories: Programmatic Interactions in the 1930s," *ibid.*, **12** (1981), 1–39; Olivier Darrigol, "Les débuts de la théorie quantique des champs (1925–1948)" (doctoral dissertation,

University of Paris I [Panthéon-Sorbonne], 1982); Peter Galison, "The Discovery of the Muon and the Failed Revolution Against Quantum Electrodynamics," in *Centaurus*, **26** (1983), 262–316; Patrick A. Heelan, *Quantum Mechanics and Objectivity: A Study of the Physical Philosophy of Werner Heisenberg* (The Hague, 1965); John Hendry, *The Creation of Quantum Mechanics and the Bohr-Pauli Dialogue* (Hingham, Mass., 1984); Herbert Hörz, *Werner Heisenberg und die Philosophie* (Berlin, 1968); Max Jammer, *The Philosophy of Quantum Mechanics: The Interpretations of Quantum Mechanics in Historical Perspective* (New York, 1974); Edward MacKinnon, "Heisenberg, Models, and the Rise of Matrix Mechanics," in *Historical Studies in the Physical Sciences*, **8** (1977), 137–188, and *Scientific Explanation and Atomic Physics* (Chicago, 1982); Jagdish Mehra and Helmut Rechenberg, *The Historical Development of Quantum Theory*, II–IV (New York, 1982–1987); and Daniel Serwer, "*Unmechanischer Zwang*: Pauli, Heisenberg, and the Reception of the Mechanical Atom, 1923–1925," in *Historical Studies in the Physical Sciences*, **8** (1977), 189–256. Further references are in John L. Heilbron and Bruce R. Wheaton, *Literature on the History of Physics in the 20th Century* (Berkeley, 1981).

DAVID C. CASSIDY

HEISKANEN, WEIKKO ALEKSANTERI (*b*. Kangaslampi, Finland, *ca*. 23 July 1895; *d*. Helsinki, Finland, 23 October 1971), *geodesy*.

The ninth and youngest child of Heikki Heiskanen and Riikka Jurvanen, Heiskanen grew up on a small farm in eastern Finland. He was exceptionally energetic, generous in his opinions of others, and of a deep religious faith. In 1922 he married Kaarina Levanto; they had one daughter. From 1933 to 1936 Heiskanen was a member of the Finnish Diet, where he worked to improve the legal status of the Finnish language (Swedish was still the dominant language in some quarters). He also translated and wrote popular works on astronomy with the intent of widening the cultural sphere of his Finnish-speaking countrymen. His work in geodesy was recognized by memberships in seven different academies of science, including the American Academy of Arts and Sciences, and he was an honorary member of the Council of the International Association of Geodesy. The University of Bonn, the Helsinki University of Technology, the University of Uppsala, and Ohio State University awarded him honorary doctorates.

After three years of study, Heiskanen graduated with an M.S. degree from the University of Helsinki in 1919, with top honors in physics, mathematics, astronomy, political economy, and theoretical philosophy. With opportunities more promising in geodesy than in astronomy, his first love, he joined the Finnish Geodetic Institute in 1921 and produced a doctoral dissertation under Ilmari Bonsdorff, "Untersuchungen über Schwerkraft und Isostasie," in 1924. Bonsdorff's own studies on the isostatic equilibrium of the earth's crust may well have provided the initial inspiration that led Heiskanen to become an expert in isostasy and a major figure in physical geodesy.

Heiskanen's computational gravity calculations contributed to the development of methods for the isostatic reduction of gravity measurements, which were then used to compute the undulations of the geoid and eventually a worldwide geodetic system, the Columbus geoid. Outside of geodesy his work was important to the successful inertial guidance of the first United States satellites and missiles, which depended upon detailed knowledge of the gravity field, and important to geophysical studies of the structure of the earth's crust. Heiskanen's scientific career may be divided into three phases: his computations in the 1920's in connection with the international gravity formula; his development and application of the Airy-Heiskanen hypothesis in isostasy in the 1930's and 1940's, most notably associated with the Isostatic Institute in Helsinki; and his program for the creation of a worldwide geodetic system, carried out after 1950 at Ohio State University.

The calculation of the geoid—the equipotential surface of the gravity field—was the central problem of classical geodesy. The reference surface was provided by the ellipsoid approved by the International Association of Geodesy in 1924, and the comparison of observed gravity values with it was based on the international gravity formula approved at the Stockholm congress of the association in 1930. Heiskanen first achieved international recognition when his value for gravity at the equator, $\gamma = 978.049\,(1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 2\phi)$ cm./sec.^{2}, was adopted by the congress as the first term, or idealized constant, of the formula. He had arrived at this figure on the basis of several thousand isostatically reduced gravity stations in all parts of the world.

From the beginning Heiskanen advocated the importance of the isostatic correction of gravity stations. His development of G. B. Airy's less-favored hypothesis, according to which land masses float on a fluid base, like icebergs in the ocean, was to prove immensely fruitful in his own work; and present seismological findings would suggest that the Airy-Heiskanen hypothesis prevails.

In 1928 Heiskanen began a twenty-one-year as-