Werner Heisenberg and the beginning of nuclear physics

The advent of quantum mechanics caused a greater transformation in the understanding of physical reality of microscopic phenomena than the change in the understanding of macroscopic phenomena brought about by relativity.

Arthur I. Miller

Great advances in science alter our view of the world. Galileo Galilei's theory of motion, Albert Einstein's theory of special relativity and Werner Heisenberg's invention of quantum mechanics, with its subsequent interpretation by Niels Bohr and Heisenberg himself, spring immediately to mind (figure 1). In exploring these episodes we must recognize that historical narrative without investigation of conceptual transformation is just chronology.

An excellent case study to illustrate the shift in points of view is that of the roots and ramifications of Heisenberg's ground-breaking papers in nuclear theory, "On the Structure of the Atomic Nucleus," published[1] in 1932–33. Investigating the roots of these papers brings into bold relief a fascinating aspect of the development of atomic physics, namely, that for Bohr, Heisenberg and Erwin Schrödinger, among others, conceptual problems were often more critical than considerations of empirical data.

During 1926–27 the most critical fundamental problem of physics was the nature of physical reality on the atomic level. The continuing struggle of physicists such as Bohr and Heisenberg to understand nature at a level beyond sense perceptions, forced them to grapple with problems that cut to the very core of how we construct knowledge: How thoroughly connected are visualization and intuition? How is the intuition that leads to one sort of visualization replaced by another? How did the imagery of subatomic phenomena represented in an analogous fashion to atomic transitions (figure 2) or Yukawa's nuclear force (figure 3) arise? By what process was the first representation replaced by the second, a precursor of Feynman-type diagrams? Probing such problems offers insight into the transformation of the imagery used to describe the atom—from models of the atom viewed as a tiny solar system (figure 4), to the diagrams of energy levels (figure 2), and then to Feynman diagrams (figure 3). The ramifications of replies by Bohr and, particularly, Heisenberg to these problems have set the course of subnuclear physics and altered dramatically our understanding of physical reality in ways that are still not completely understood.

I will proceed as follows: First, I will show that the roots of Heisenberg's nuclear exchange force are found in his June 1926 discovery of the exchange energy in atomic processes. The discussion in early 1927 of the Bohr–Heisenberg interpretation of quantum mechanics completed setting the stage for Heisenberg's introduction, in June 1932, of the nuclear exchange force. Next I will analyze two early ramifications of Heisenberg's exchange force: Enrico Fermi's theory of beta decay (January 1934) and Hideki Yukawa's meson theory of nuclear forces (November 1934). The epilogue connects these developments in nuclear physics with the modern notion of forces transmitted by particles.

New atomic physics

From June 1925 through early 1927 certain longstanding problems in atomic physics, such as the anomalous Zeeman effect and the spectrum of the helium atom, were solved with the new quantum mechanics Heisenberg had invented in June 1925. In this heady period so many stunning results appeared every month, it was as if years were passing. However, the physical

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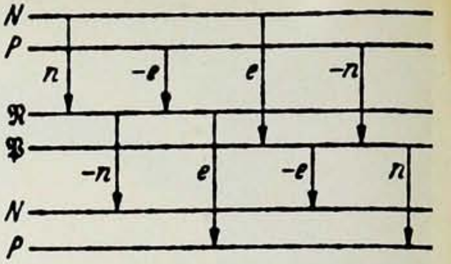
Werner Heisenberg in 1926, one year after he had invented the matrix, or quantum, mechanics. Figure 1

meaning of the intermediate manipulations was unclear, although they produced results that could be compared with experiment: Quantum mechanics lacked correspondence rules for the physical meaning of its symbols. In other words, the mathematical symbols and operations of quantum mechanics (its syntax) did not yet possess unambiguous meanings (semantics). When Bohr and Heisenberg were struggling in Copenhagen to interpret quantum mechanics, Heisenberg wrote[4] to Wolfgang Pauli on 23 November 1926: "What the words 'wave' and 'corpuscle' mean we know not any more."

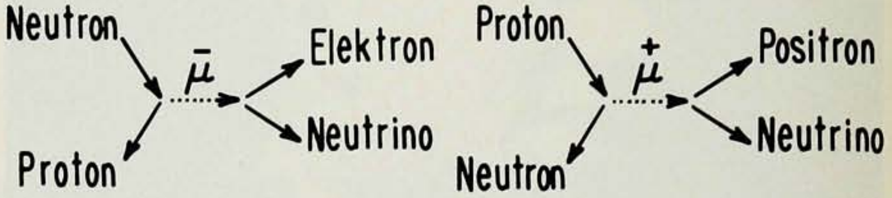
Heisenberg provided[5] an excellent glimpse into their struggles in his November 1926 paper, "Quantum mechanics," where he emphasized that our "customary intuition" (*gewöhnliche Anschauung*) cannot be extended into the atomic domain. This term appears often in the German-language scientific literature of 1923–27. The German usage of this phrase is loaded with subtleties because the notion of intuition (*Anschauung*) as it was used by Bohr, Max Born, Heisenberg, Pauli and Schrödinger is rooted in Kantian philosophy. By "customary intuition" these physicists meant the intuition or mental imagery that is constructed from objects or phenomena that we actually observe in the world of sense perceptions. Examples include the mental imagery of a solar-system atom, with its positively charged nucleus and satellite electrons; light as strictly a wave phenomenon whose properties are abstracted from those of water waves; and electrons that behave like billiard balls. Customary intuition is the mental imagery that is imposed on classical physics. Heisenberg went on to describe how one by one these customary intuitions had to be given up: Data from dispersion had undermined the picture of the solar-system atom, the experiments of Arthur Compton, Hans Geiger and Walther Bothe had forced physicists to consider the light quantum seriously, and according to Einstein's results on the ideal quantum gas, free electrons had lost their individuality. In fact, Heisenberg had been forced to abandon customary intuition to invent the matrix, or quantum, mechanics. In the original formulation of quantum mechanics, Heisenberg characterized the atom with measurable quantities such as its spectral lines. Yet in key scientific papers, Heisenberg and Born, among others, lamented the loss of a directly "intuitive" interpretation of the new atomic physics.

Erwin Schrödinger thought he knew how to bring back customary intuitions—somewhat altered, of course. In a paper of March 1926 on wave mechanics, Schrödinger explained[6] in a highly subjective tone that he had been driven to formulate his theory because he had been "repelled by the methods of transcendental algebra, which appeared very difficult to me and by the lack of visualizability [*Anschaulichkeit*]" of Heisenberg's quantum mechanics. Classical realists, such as Einstein and the venerable Hendrik A. Lorentz, had nothing but praise for Schrödinger's wave mechanics, in which the bound electron was represented as a charged wave surrounding the nucleus.

Heisenberg thought otherwise. On 8 June 1926 he wrote[4] to Pauli that "what Schrödinger writes on the visualizability of his theory . . . I consider trash. The great accomplishment of Schrödinger's theory is the calculation of matrix elements." And it was to this end that Heisenberg exploited[7] what he insisted was only the mathematical equivalence of the two theories in a remarkable paper entitled, "Many-



Beta decay depicted as a "cascade-like" process analogous to the transition between atomic energy levels. N and P denote a neutron and proton, and $\mathfrak{N}$($\mathfrak{P}$) a "hypothetical stationary state" of a neutron and proton, n and – n a neutrino and antineutrino, and e and – e an electron and positron. (From G. Wentzel, *Zeitschrift für Physik* **104**, 34, 1936.) Figure 2



Gregor Wentzel's "schemata" for depicting beta decay as a "two-stage process" that is intermediated by a meson. (From reference 22, German edition.) Figure 3

body problem and resonance in quantum mechanics" completed in June 1926. Heisenberg warned that Schrödinger's "intuitive pictures" should not be imposed on quantum mechanics, whose invention had required their denial in the first place, and that Schrödinger's intuitive pictures should be especially avoided in the many-body problem. In March 1926, Schrödinger had suggested that many-body problems should temporarily be set aside in both wave and matrix mechanics. These theories use classical potential functions for point particles that are actually interpenetrating states of vibration; this causes severe conceptual difficulties for the many-body problem. Heisenberg's direct rebuttal to Schrödinger's pessimistic assessment came in June 1926, in a paper in which Heisenberg *treated* the many-body problem—he writes that we must set limitations "on the discussion of the intuition problem."

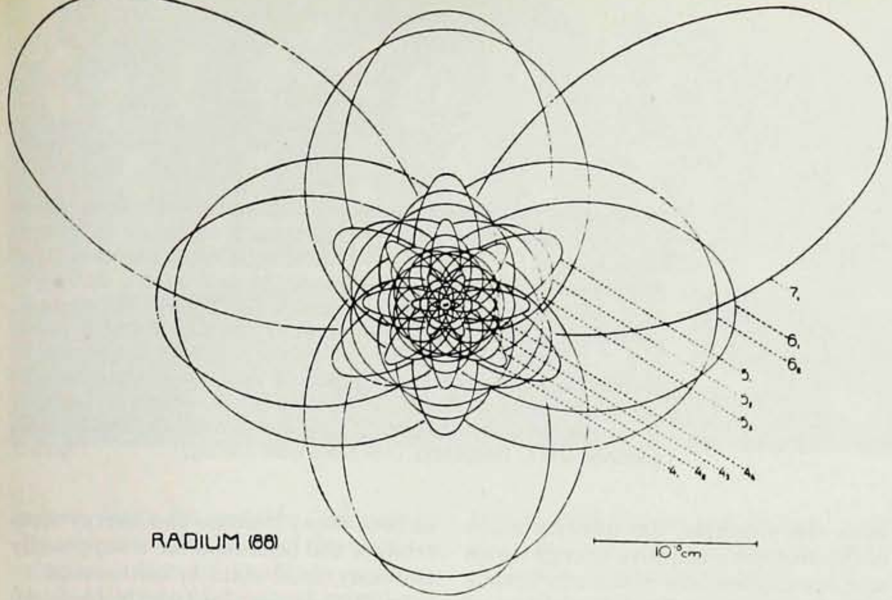
Heisenberg's desire to demonstrate that matrix mechanics could deal with many-body systems was the catalyst for his June 1926 paper. But the results in this paper drew him ever deeper into the "intuition problem." An even more fundamental problem for him was the connection of matrix mechanics with Bose–Einstein statistics and Pauli's "prohibition against equivalent orbits." At first sight, in either matrix or wave mechanics, atoms should obey classical statistics. So Bose–Einstein statistics seemed to contradict these theories. Yet, for example, only the ortho and para states of the two-electron helium atom are possible. Also Pauli's prohibition against equivalent orbits seemed not to fit into the mathematics of matrix or wave mechanics.

It suffices here to sketch how Heisenberg set the stage for the many-body calculations that followed. He analyzed the spectrum of two identical systems coupled through an interaction that is symmetrical in the coordinates of both systems. The total energy of the unperturbed total system is degenerate. Using first-order perturbation theory Heisenberg demonstrated that the symmetrical interaction breaks the degeneracy. The resulting energy spectrum contains two series of energy levels, one higher than the other. Each energy level contains a contribution that can be interpreted as the result of two systems exchanging places, that is, as a resonance, or exchange, energy.

Applying these results to the helium atom, and including the electron's spin for which there was then no mathematical formulation, Heisenberg reached the following conclusions: The reduction of the statistical weight to one, that is, the number of possible states of the two-electron system to only the totally antisymmetric state, was an example of Bose–Einstein counting. This choice satisfied automatically "Pauli's prohibition against equivalent orbits." Consequently, concluded Heisenberg, Bose–Einstein statistics and Pauli's prohibition against equivalent orbits are consistent with quantum mechanics. Owing to the indistinguishability of electrons (which Heisenberg assumed to be a consequence of Bose–Einstein statistics), any depiction of the exchange energy "makes no sense physically." To Heisenberg these results augured further restrictions on the "reality of corpuscles," and hence on their depiction. Heisenberg went on to extend his results to a system of N identical spin-½ particles. He recognized that the statistics of spin-½ particles go "beyond the Bose–Einstein" statistics for reasons that may reside in the "phase relations between the component systems or particles." As he wrote in his sequel paper "Quantum mechanics," of November 1926, one would like to determine to "what extent Pauli's prohibition of equivalent orbits makes necessary a modification of the Einstein statistics."

Independent of Heisenberg, P. A. M. Dirac was also investigating[8] the symmetry properties of systems composed of identical particles. Using a more general approach, Dirac concluded that of all possible wavefunctions for systems of identical particles, only the symmetric and antisymmetric combinations are acceptable. He showed that the symmetric combination is associated with Bose–Einstein statistics and that the antisymmetric is associated with spin-½ particles. The vanishing of the antisymmetric wavefunction when two electrons are in the same state "is just Pauli's exclusion principle." Up to this point Heisenberg's and Dirac's results are the same, as Dirac himself wrote in a footnote mentioning that Born had just notified him of Heisenberg's "many-body" paper. But Dirac went on to use an ideal gas to prove that antisymmetric wavefunctions are associated with a new statistics *intrinsic* to spin-½ particles.

Heisenberg recalled[9] in an interview (25 February 1963) that the many-body paper was "full of excitement for me because so many new things came up [that] for quite a considerable time I did mix up Bose statistics with Fermi–Dirac statistics." So, on the way to solving the matrix mechanics for the spectrum of helium, Heisenberg found it necessary to invent new concepts such as the exchange energy and, independently, the Fermi–Dirac statistics. Courage to persevere in solving a problem by overcoming obstacles through inventing new concepts, and an intuitive feel for which obstacles



Bohr's atomic theory. This rendering of the radium atom from Bohr's theory depicts what Max Born wrote of in 1923 as "a remarkable and alluring result of Bohr's atomic theory [that] the atom is a small planetary system . . . the thought that the laws of the macrocosmos in the small reflect the terrestrial world exercises a great magic on mankind's mind."[2] (Figure from reference 3.) Figure 4

should be bypassed for the moment, are trademarks of Heisenberg's style of research. We recall that in the 1925 quantum-mechanics paper, he was undeterred by his lack of understanding why xy does not equal yx, that is, by his ignorance of matrix algebra. This style would stand him well while working with Bohr during 1926–27, and again during the 1930s, when he invented the exchange force in nuclear physics despite having to deal with "Bose" electrons. We next turn to this work.

Restricted metaphors

After the heroic struggles of late 1926 through early 1927 in Copenhagen, Bohr and Heisenberg arrived independently at apparently separate resolutions for the paradoxes posed by the wave–particle duality of light and matter.

In the 1927 paper on the uncertainty principle, Heisenberg further explored[10] the concept of intuition and, in fact, entitled the paper "On the intuitive [*anschaulich*] content of the quantum-theoretical kinematics and mechanics." Focusing exclusively on his own quantum mechanics, with its unvisualizable particles, and encouraged by the redefinitions of macroscopic physical reality required by special and general relativity, Heisenberg proposed that in the atomic domain a revision of our usual kinematical and mechanical concepts "appears to follow directly from the fundamental equations of the quantum mechanics." In this way Heisenberg boldly demarcated the notion of "to be understood intuitively" from the visualization of atomic processes. He permitted the syntax of quantum mechanics to determine the restrictions on such perception-laden symbols as position and momentum. These restrictions are the uncertainty relations. Consequently, Heisenberg redefined the concept of intuition through the theory's mathematics and separated intuition from visualization. The paper on the uncertainty principle was, therefore, a turning point in Heisenberg's view of the nature of physical reality. In later years Heisenberg recalled Pauli's response to the uncertainty principle paper as, "*Es wird Tag in der Quantentheorie*" ("Day is breaking over the quantum theory").

Bohr disagreed with Heisenberg. The dilemma, in Bohr's view, was that whereas images constructed from our customary intuitions had to be separated from the laws of physics, we are forced to phrase these laws in a language tempered by sense perceptions because it is the only language we have. By September 1927 Bohr found[11] that he could grasp both horns of the dilemma with the principle of complementarity, which he took to be rooted in the wave–particle duality of matter and radiation. In the atomic domain this principle separates intuitive pictures from the actual development of atomic systems in space and time: The development is governed by physical laws that require a "departure from visualization in the usual sense."

Heisenberg agreed that the complementarity principle placed restrictions on metaphors from the macroscopic world, that is, from ordinary perceptions. But he remained wary of these metaphors, owing to their previous disservices. In fact, in a letter of 16 May 1927 to Pauli, Heisenberg wrote[4] that there are "at present between Bohr and myself differences of opinion on the word 'intuitive'."

To summarize thus far: By 1929 Heisenberg and most other physicists realized that in the atomic domain visualization and visualizability are mutually exclusive. Visualization results from the cognitive apparatus of our mind acting on sense data to produce, somehow or other, the sort of mental imagery that until 1923 physicists had imposed cavalierly on all physical theories. So visualization is what Heisenberg referred to in his 1926 paper, "Quantum mechanics," as the "customary intuition" that could not be extended into the atomic domain. Visualizability, on the other hand, concerns the intrinsic characteristics of atomic entities that are not open to our perceptions—the electron spin, for example. In classical physics, visualization and visualizability are synonymous. In the 1927 paper on the uncertainty principle, Heisenberg permitted the mathematics of quantum theory to decide the meaning of the theory's symbols, that is, the intrinsic properties of subatomic particles are revealed through the mathematics of quantum theory. But he still resisted any imagery of atomic phenomena. Thus, for Heisenberg, as of 1927, in the atomic domain visualizability and intuition did not yet possess a depictive or visual component. (In Kant's philosophy *Anschaulichkeit*—visualizability—is less abstract than *Anschauung*—intuition. For example, a typical definition of *Anschaulichkeit* that may be found in a German-language philosophical dictionary is: "the immediately given . . . the readily graspable in the *Anschauung*." In 1927 Heisenberg found it necessary to invert the Kantian notions of *Anschauung* and *Anschaulichkeit*, no mean feat.)

The nuclear exchange force

In 1932 Heisenberg introduced the depictive component of visualizability in another virtuoso performance, Part I of his nuclear physics papers published in the *Zeitschrift für Physik*. In these papers we can glimpse—as perhaps

1933 Solvay Conference. Some of the *dramatis personae* discussed here appear among the participants sitting (left to right): E. Schrödinger, I. Joliot, N. Bohr, A. Joffe, M. Curie, P. Langevin, O. W. Richardson, E. Rutherford, T. De Donder, M. de Broglie, L. de Broglie, L. Meitner and J. Chadwick. Standing (left to right): E. Henriot, F. Perrin, F. Joliot, W. Heisenberg, H. A. Kramers, E. Stahel, E. Fermi, E. T. S. Walton, P. A. M. Dirac, P. Debye, N. F. Mott, B. Cabrera, G. Gamow, W.Bothe, P. M. S. Blackett (at back), M. S. Rosenblum, J. Errera, E. Bauer, W. Pauli, J. E. Verschaffelt, M. Cosyns (at back), E. Herzen, J. D. Cockcroft, C. D. Ellis, R. Peierls, A. Piccard, E. O. Lawrence and L. Rosenfeld. (AIP Niels Bohr Library) Figure 5

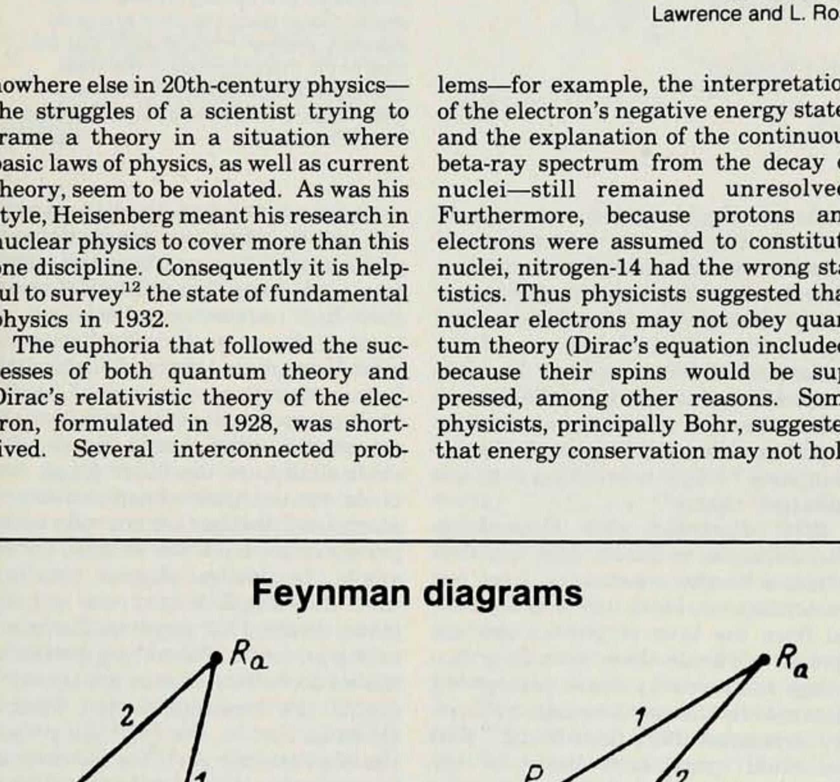
nowhere else in 20th-century physics—the struggles of a scientist trying to frame a theory in a situation where basic laws of physics, as well as current theory, seem to be violated. As was his style, Heisenberg meant his research in nuclear physics to cover more than this one discipline. Consequently it is helpful to survey[12] the state of fundamental physics in 1932.

The euphoria that followed the successes of both quantum theory and Dirac's relativistic theory of the electron, formulated in 1928, was short-lived. Several interconnected problems—for example, the interpretation of the electron's negative energy states and the explanation of the continuous beta-ray spectrum from the decay of nuclei—still remained unresolved. Furthermore, because protons and electrons were assumed to constitute nuclei, nitrogen-14 had the wrong statistics. Thus physicists suggested that nuclear electrons may not obey quantum theory (Dirac's equation included) because their spins would be suppressed, among other reasons. Some physicists, principally Bohr, suggested that energy conservation may not hold in beta decay because the energy spectrum of the beta rays for a supposedly two-body final state is continuous.

In 1932 James Chadwick's discovery of the neutron led, as Heisenberg wrote[1] in Part I of his paper, to an "extraordinary simplification for the theory of the atomic nucleus." In addition to settling the problem of statistics, the neutron suggested to Heisenberg a way to relate the problems of beta decay to the form of the attractive force that binds the nucleus. As Heisenberg wrote[13] to Bohr on 20 June 1932, "The basic idea is to shift the blame for all principal difficulties [of fundamental physics] onto the neutron and to refine quantum mechanics in the nucleus."

To explain the statistics of nitrogen-14, Heisenberg assumed that the neutron is a particle with spin $\frac{1}{2}$. (However, in Part III of the paper he expressed[1] reservations even on this point.) Next Heisenberg had to decide whether the neutron is a composite particle, consisting of a proton and electron, or a fundamental particle. The conception of the neutron as a bound state, or as a collapsed hydrogen atom, had been proposed by Ernest Rutherford in 1920 and was advocated by Chadwick. However, a non-elementary neutron required the nuclear electron to obey incorrect statistics. So Heisenberg wrote, "it does not seem appropriate to elaborate further on such a picture." Yet, Heisenberg proposed, if under the proper circumstances a fundamental neutron decays into a proton and electron, then the "conservation laws of energy and momentum are probably no longer applicable." At this time Heisenberg had not yet accepted Pauli's hypothesis of a neutrino and he straddled the fence regarding Bohr's proposal that energy conservation may be violated in beta decay. In fact, Heisenberg continued[1] in Part I to use energy conservation for discussing the energetics of beta decay. In Part III he wrote that pushing the "energy law beyond its validity is

Feynman diagrams



Heisenberg approved of Feynman diagrams as "intuitive" in accordance with the new meaning of "visualizability" (reference 23). He recalled (reference 9) on 13 February that the diagrams in the Kramers–Heisenberg paper of 1925 (*Zeitschrift für Physik* **31**, p. 681) that resulted from photon–atom scattering were suggested by the mathematics of this late version of atomic physics, and so were like Feynman diagrams: "We drew these pictures. First you go from this level to that and then from that level to here. Then one could easily see that in going from here to here you can go by different ways. That's like Feynman diagrams nowadays." In this representative term diagram from the Kramers–Heisenberg paper, R_a, R_b, R_c, Q and P are levels in an atom from which light is scattered. The incident light causes the atom to make transitions from a state P to a state Q via the intermediate states R. Energy need not be conserved in the intermediate transitions. (Figure from W. Heisenberg, H. Kramers, *Z. Phys.* **31**, 681, 1925.)

indeed logically possible throughout (e.g., the strong validity of the classical selection rules in quantum mechanics)." Although Heisenberg considered that the idea of a fundamental neutron was far more satisfactory, owing principally to the problem of where the electrons originated in beta decay, he dealt also with a composite neutron. In fact, in his 1932–33 papers on nuclear physics, Heisenberg tried in every way to include electrons in the nucleus.

The force between a charged proton and a neutral neutron cannot be of the same sort as that between two charged particles, and any proposed form for the nuclear force must yield the property of saturation. Thus Heisenberg drew the "analogy" of the attractive force between a proton and neutron and the exchange force that is the dominant factor for the stability of H_2 and H_2^+ molecules. The failure of the old Bohr theory to account for the stability of the H_2^+ ion had been taken as an indicator of fundamental problems. In 1927 Fritz London and Walter Heitler extended the concept of exchange energy (and thereby quantum mechanics too) into chemistry and formulated the theory of the homopolar bond. They discovered that the ion's stability is due to the exchange energy. No visualization of the exchange force is possible because it cannot be developed from intuitions constructed from the world of sense perceptions (see box, page 66, a and f). Rather, the visualizability for the exchange energy is given by the quantum mechanics, although it defies depiction, thus frame f is empty. In the solution to the problem of the H_2^+ ion, a strictly quantum-mechanical contribution to the ion's energy can be described metaphorically as the two protons sharing the single electron. The exchange contribution to the helium atom and the H_2 molecule arises through the indistinguishability of the electrons, and so, as Heisenberg himself cautioned[7] in his many-body paper of 1926, any depiction of this force "makes no sense physically." In 1928 Heitler had written[15] that it is as "yet incomprehensible what exchange in reality means."

As if in response to Heitler, in 1932 Heisenberg extended the concept of exchange energy to the nucleus in a way that offered a depictive component of visualizability through the mathematics of the theory, and thus, in this case, to an understanding of what the exchange energy "in reality means."

Modern nuclear physics begins with this passage[1] in Heisenberg's "On the structure of the atomic nucleus I":

> Suppose we bring the neutron and proton to a separation comparable to nuclear dimensions; then in analogy to the H_2^+ ion, the negative charge will undergo a migration [*Platzwechsel*], whose frequency is given by a function $J(r)/h$ of the separation r between the two particles. The quantity $J(r)$ corresponds to the exchange [*Austausch*], or more correctly, migration integral [*Platzwechselintegral*], of molecular theory. The migration can again be made more intuitive by the picture of electrons that have no spin and follow the rules of Bose statistics. But it is surely more correct to regard the migration integral $J(r)$ as a fundamental property of the neutron–proton pair, without intending to reduce it to electron motions.

Yet as we shall see, Heisenberg went on to discuss nuclear electrons that "follow the rules of Bose statistics." This was necessary for him to relate beta decay to the neutron–proton force. Heisenberg played all ends against the middle in this theoretical free-for-all, which offered him the "arbitrariness [in seeking] a formulation that will not lead sooner or later to internal difficulties."

Heisenberg's change of terminology from "exchange" to "migration" signals a new concept to follow. With this switch from exchange to migration, Heisenberg's visualizability of the migration of the electron in the neutron–proton force is, however unintentionally, the ingredient required to draw figure g in the box on page 66. In this figure the quantity $J(r)$ is the attractive force between a fundamental nuclear proton and a composite nuclear neutron. The attractive force operates through the "migration" of charge from the neutron to the proton, which, capturing the Bose electron, becomes a neutron. In Heisenberg's nuclear exchange force the neutron and proton do not merely change places. The metaphor of motion is of the essence here, and that is why I rendered "*Platzwechsel*" as "migration."

The mathematics of Heisenberg's nuclear theory offered a new intuition, or mental imagery, for the atomic and subatomic domains. The reason is that the graph in frame g, and as we shall discuss in a moment, frames h, i and j as well, in the box on page 66, could not have been conceived without quantum mechanics. Needless to say, owing to our cognitive apparatus all graphs must be drawn with the usual figure and ground arrangement—that is, with continuity and discontinuity side by side.

In the subsequent literature most physicists referred to the quantity $J(r)$ as an "exchange force." The exchange force was a center of attention at the 1933 Solvay Conference on nuclear physics (figure 5). To a first approximation, Heisenberg assumed that the exchange forces between neutrons and protons are static and central. Because $J(r)$ is a short-range force, the expressions most frequently used for it were

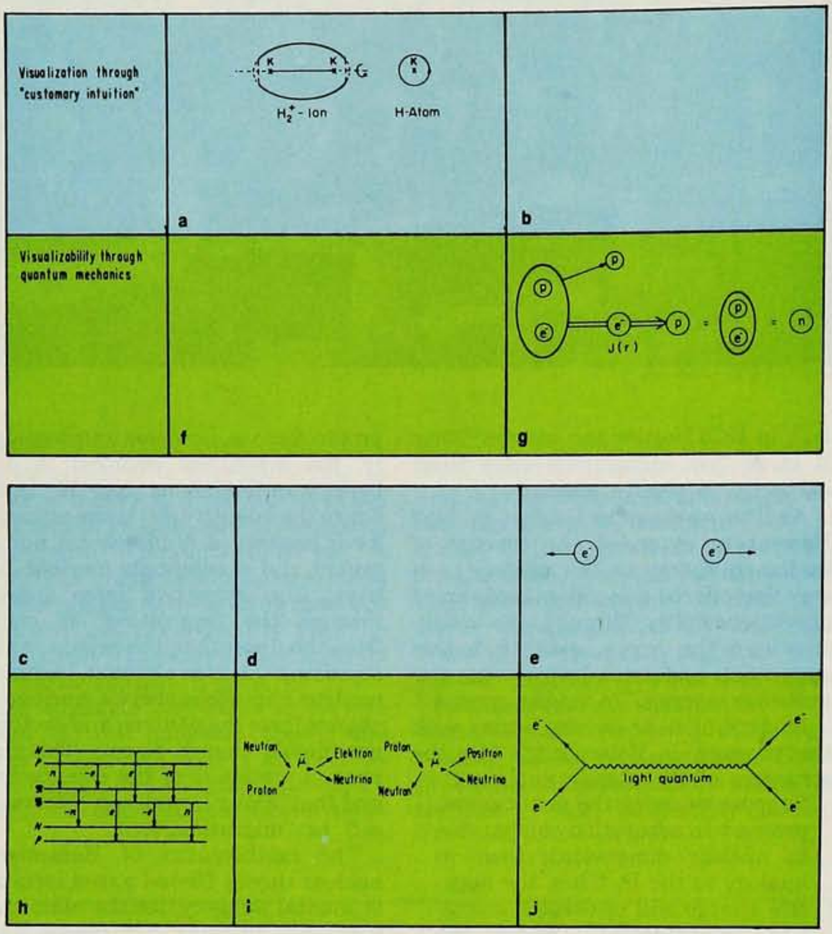
$$J(r) = ae^{-br}$$
$$J(r) = ae^{-(br)^2}$$

where a and b are parameters that can be adjusted to fit, for example, the binding energies of nuclei.

Ramifications

Other sorts of exchange forces were proposed that agreed with available data better than Heisenberg's. These

Visualization and visualizability



The changing notions of physical reality that began with Heisenberg's extension of the exchange concept from molecular physics to nuclear physics are in frames **g** through **j**. Frames **a**, **b**, **c**, **d** and **e** contain visualizations according to pictures constructed from objects actually perceived—that is, customary intuition. Until 1923 customary intuition was imposed on all theories. Frame **a** is from Pauli's unsuccessful attempt in 1922 to deduce a stable H_2^+-molecule ion from Bohr's theory of the atom with its solar-system imagery of atoms and molecules; K denotes a "positive center," or proton. Frames **f**, **g**, **h**, **i** and **j** depict visualizability according to quantum mechanics. Thus frames **b**, **c**, and **d** are empty. By a new mode of intuition is meant that the graphs in frames **g**, **h**, **i** and **j** could not have been conceived of without quantum mechanics. Frame **f** is empty. Frame **e** is the anthropomorphic, or intuitive, representation for the Coulomb repulsion between two electrons. Frame **j** is a Feynman diagram for the new visualizability, or intuition, for the repulsive interaction between two electrons in which they exchange a light quantum. Today the words exchange and migration are synonymous. (Frame **a** is from reference 13.)

forces did not require inappropriate migratory electrons. But Heisenberg's visualizability of a nuclear exchange force with something exchanged turned out to be fruitful. It was instrumental in Enrico Fermi's thinking towards his 1934 theory of beta decay,[16] whose success, wrote[17] Heisenberg in 1935, was "proof of the existence of exchange forces" in nuclei. Fermi's theory was referred to as an "intuitive theory"—in the new interpretation of the term intuitive—because the theory's mathematics permitted an analogy of the electromagnetic transition in a two-level atomic system to the redefined intuition or mental image. Here a neutrino and an electron are emitted instead of the photon in the transformation of a neutron into a proton when an atom decays (compare figures c and h in the box above).

In 1934 Igor Tamm elaborated[18] and further generalized Fermi's intuitive theory of beta decay. Tamm assumed that the neutron and proton result from the splitting of a degenerate state by the exchange energy that originates in the neutron's emission of the electron and neutrino, or inversely, the proton's emission of a positron and neutrino. The splitting of the energy levels is analogous to what occurs in molecules. So far Tamm offered nothing really new. But next he generalized the mental imagery in Fermi's theory of beta decay as follows: "The role of light particles (ψ - field) [electrons and neutrinos] providing an interaction between heavy particles corresponds exactly to the role of the photon (electromagnetic field), providing an interaction between electrons. . . ." Using suitably modified methods of quantum electrodynamics Tamm went on to show that the interaction energy from Fermi's beta-decay theory was too small to explain the binding energies of neutrons and protons in nuclei. Thus, contrary to the hopes of Heisenberg and Fermi, a theory of beta decay could not cover the neutron–proton force as well.

Directly following on Tamm's paper, and similar in thrust, is a paper[19] by D. Iwanenko. Like Tamm, Iwanenko compared Heisenberg's "interaction *exchange* energy . . . between proton and neutron [to] the birth and absorption of a photon in the case of two electrons." It is noteworthy that Iwanenko used the term exchange even though he compared the mechanism of the neutron–proton force to the Coulomb interaction mediated by a photon. It is tempting to suggest here that Iwanenko, like most other physicists at that time, missed the purpose of Heisenberg's change of terminology from exchange to migration. Hideki Yukawa did not. In November 1934 Yukawa considered[20] the exchange force between the neutron and proton to be a "migration force describable with a *Platzwechselintegral* [migration integral]."

Yukawa set out to modify the theory of Heisenberg and Fermi by changing the analogy of the field of "light particles" transmitting the neutron–proton force to the exchange of a single, new "heavy particle." The "interaction between the elementary particles," continued Yukawa, "can be described by means of a field of force, just as the interaction between charged particles is described by the electromagnetic field. . . . This field should be accompanied by a new sort of quantum just as the electromagnetic field is accompanied by the photon." Yukawa found that he could write a Hamiltonian for his theory that was equivalent to Hei-

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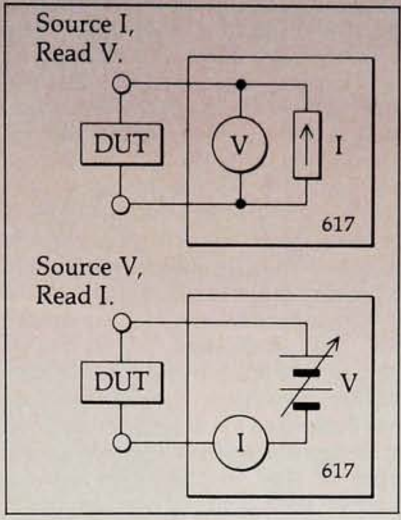

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senberg's Hamiltonian (reference 1, Part I) if one takes for the migration integral

$$J(r) = g\,\frac{e^{-ur}}{r}$$

for describing the exchange of a legitimate Bose particle, where g is a coupling constant and u is the inverse of the range of the nuclear force associated with the exchanged particle. Yukawa's choice for $J(r)$ stands in stark contrast with earlier choices, which were almost arbitrary exponentials chosen for expediency in comparing theory with empirical data. We may conjecture with confidence that Yukawa's explicit use of the German word *Platzwechselintegral* in his English-language paper was to signal that he meant not a metaphorical exchange, or *Austausch*, but a real "migration." And thus did Heisenberg's metaphor of motion become physical reality.

Epilogue

The scientific literature supports Gregor Wentzel's recollection[21] that Yukawa's "ingenious idea ... was not received, wherever it became known, with immediate consent or sympathy." This situation changed in 1937 when physicists believed Yukawa's meson had been discovered in cosmic-ray phenomena. So it would seem reasonable to expect in the 1937 literature some sort of diagrammatic representation of particles transmitting forces. After all, the proper verbal descriptions abounded in the literature and, with hindsight, such suggestive mathematical formalisms as those proposed by E. C. G. Stueckelberg. But no diagrams of exchange particles can be found from that time. In fact a conceptualization from Dirac's 1927 quantization of the electromagnetic field of the Coulomb force transmitted by a photon played little, if any, role in subsequent work on electromagnetic processes such as electron–electron scattering. Nor have I found in the correspondence I have studied thus far diagrams depicting the transmission of forces by particles. In the published literature there are depictions of beta decay like the one in figure 2. But figure 2 was, after all, the sort of diagram that was the basis of Fermi's intuitive theory of beta decay.

An interesting development occurred in 1943, when Wentzel proposed a "didactic" device for depicting Yukawa's treatment of beta decay as an "indirect" process that is mediated by a virtual meson (compare figures d and j in the box on page 66. In Heisenberg's original conception, the exchange force was transmitted by a real electron with incorrect properties. These "schemata," wrote[22] Wentzel, depict the "beta-decay process as a two stage transition." Wentzel's figure (see figure 3) depicts the nuclear exchange force that had been first proposed by Heisenberg with no analogy to the photon as an intermediary of the interaction between two electrons. We recall that Iwanenko and Tamm did make the photon analogy, although without any diagram. Yukawa's more successful theory of the nuclear exchange force was formulated directly along the lines proposed by Heisenberg, namely, by introducing a "migration integral" for describing the nuclear force. It was Yukawa's ingenious idea to propose a "migration integral" that described the actual "migration" of a proper particle, that is, a proper boson and not a Bose electron. But Yukawa offered no depiction of this process.

In the 1949 preface to the English edition of his book, Wentzel wrote that extensive changes were necessary only in the section where his figure (figure 3) appeared, and "here it was easy to modernize the text and to adapt it to the present state of knowledge." Wentzel's book became a valuable stop-gap until the publication of up-to-date books such as *Mesons and Fields* (Row, Peterson, Evanston, Illinois, 1955) by Hans Bethe and Frederic de Hoffmann. But the transition from Wentzel's schematics of 1943 to the Feynman diagrams of 1949 required further transformations of what constitutes physical reality and its accompanying mental imagery.

By 1943 the mental imagery of most physicists had already undergone several transformations, for is it not true that figure 3 is another way of "seeing" the energy levels in figure 2? In turn, figure 2 is a descendant of the energy-level representations in atoms that replaced the customary intuition of the solar-system atom that the intuitive (in the pre-1927 meaning of this word) language of classical physics had imposed on the Bohr theory (figure 4). Analysis of these transformations of mental imagery, which resulted in Feynman diagrams (compare figures e and j in the box on page 66), is beyond the scope of this article.[23]

Clearly, as we have seen, fundamental progress in science is accompanied by transformations of mental imagery. Heisenberg's nuclear exchange force was another step on a path that reached back to scientific work that he had accomplished in 1926. This path reaches even further back, because it is defined by a culturally based mode of mental imagery—customary intuition—that had been of importance to philosopher–scientists such as Ludwig Boltzmann, Albert Einstein and Hermann von Helmholtz, who emphasized this mode of visual thinking. Despite the advances that resulted from their scientific research, their mental imagery remained based in customary intuition. On the other hand, Heisenberg's scientific research forced him to liberate his mental imagery from customary intuition. His results set the course of subnuclear physics.

By and large, research on the frontiers of physics continues on the path taken by Boltzmann, Einstein, Helmholtz and Heisenberg. A hallmark of a well-developed and fruitful scientific theory in the 20th century is some sort of mental imagery. As Heisenberg recalled[9] on 25 February 1963 of his style of research: "The picture changes over and over again, and it's so nice to see how such pictures change."

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