UNCERTAINTY: EINSTEIN, HEISENBERG, BOHR, AND THE STRUGGLE FOR THE SOUL OF SCIENCE BY DAVID LINDLEY

Reviewed by Richard A. Blasband, M.D.

If you are mathematically challenged, as am I, but still wish to understand how quantum mechanics and the uncertainty principle came about, as am I, then this slim, wonderfully written volume is for you. David Lindley, an astrophysicist, science journal editor, and author of several books on various aspects of the history of science, has given us here an extremely well written, well referenced and annotated history of the development of scientific thinking beginning with Robert Brown's discovery of what came to be called "Brownian motion" in plant seeds and ending with Werner Heisenberg's discovery of the uncertainty principle in modern physics. Along the way he wittingly and perceptively tells us of the main players in this quest to understand how nature works, of their triumphs, foibles, and their battles with each other over the "soul" of physics, that is whether nature is continuous in its changes from one state to another and thoroughly deterministic or whether it is discontinuous and probabilistic. Anyone interested in science will find ***Uncertainty*** wonderfully informative and a magnificent read. In this review I have paraphrased and borrowed extensively from Lindley with the intention of presenting his view as accurately as possible.

The story begins with the Scottish physician and clergyman, Robert Brown, who in 1827, saw through a microscope that pollen grains of the wildflower, Clarkia Pulchella, endlessly jiggled about although there was no obvious reason why they should do so. Interestingly, the plant was named by its discoverer, Meriweather Lewis, in 1806 for his co-discoverer of the Northwest Passage, William Clarke. Make of this possibly synchronistic pairing of the two discoveries what you will. Who knew?

In the early 1800s the atomic theory which had been extant since Democritus and Leucippus first propounded it in 400 BC, was in flux. Atoms as the cause of how things worked was believed by some scientists, doubted by others. In 1863, however, Ludwig Christian Weiner, described how the movement of atoms could readily account for Brownian motion, which, within another couple of decades was observed in any material of sufficiently small size in solution. However, calculations indicated that the movement of atoms of the solution was hundreds of times faster than what was being observed in the "jiggling" of the microscopic particles. The apparent solution to the puzzle came with the formulation at the end of the 1800s by Louis-Georges Douey of a statistical understanding of atomic movement: it is the mean impact of atoms on the particles that results in their jiggle. While not formulated as such at the time, however, Douey's view was to become a thorn in the side of the thoroughly deterministic view of nature that had been propounded since the work of Isaac Newton.

The Scottish physicist, Clerk Maxwell, "arguably the most eminent theorist of the nineteenth century," believed that if the Brownian particles were submitted to a more powerful microscope they would settle into a repose: the apparently spontaneous nuisance would go away. The Marquis de Laplace, one of the leading eighteenth century developers of Newtonianism, declared that, in essence, if we knew all the forces that animate nature, nothing would be uncertain and all would be predictable. On the other hand most physicists knew that it would be absurd to think that one could calculate the individual behavior of every atom or molecule in a volume of gas. Statistical descriptions were obviously essential. Later the Austrian physicist, Ludwig Boltzman demonstrated his belief in an atomic theory when he, according to Lindley, wrote that, "The observed motions of very small particles in a gas may be due to the circumstance that the pressure exerted on their surfaces by the gas is sometimes a little greater, sometimes a little smaller", which Lindley took to mean that, "because a gas is made of atoms, and because these atoms dance around in an erratic way, a small particle within the gas will be jostled unpredictably back and forth". Einstein, who allegedly knew nothing of Brownian motion, undertook calculations to ascertain the cause of the movement of hypothetical suspended particles, thus establishing the first quantitative treatment of the bombardment of the particles by atoms in the solution. In 1908 his theory was confirmed by detailed measurement of particles in solution by the physicist, Jean Perrin. From this point on the atomic theory was accepted by most physicists and statistical thinking became an intrinsic aspect of physical theorizing.

With the introduction of probability the classical Newtonian hope for perfectibility as expressed by the mathematician, LaPlace, was seriously challenged.

As Lindley states it:

> *Until this time a theory was a set of rules that accounted for some set of facts.*

> *Between theory and experiment there existed a direct, exact two-way correspondence. But that was no longer the case. Theory now contained elements that the physicists were sure existed in reality, but which they couldn't get at experimentally. For the theorist, atoms had definite existence and had definite positions and speeds. For the experimenter, atoms existed only inferentially, and could be described only statistically. A gap had opened up between what a theory said was the full and correct picture of the physical world and what an experiment could in practice reveal of that world.*

The discoveries of x-rays by Roentgen in1896 and radium in 1898 by the Curies got the objective reality pot to boil, so to speak, adding considerable challenges to the comfort zone of scientists, who remained committed to a stable deterministic universe. Madame Curie wrote in 1898 that "radioactivity is an atomic property" and two years later that, "… the spontaneity of the radiation is an enigma, a subject of profound astonishment." This put a glitch in the classical operation of cause and effect. And, since radioactivity releases energy, where did the energy come from? This problem was solved chiefly by Ernest Rutherford, who, with Frederick Soddy, proposed a theory of the transmutation of atoms within elements via radioactive decay to account for the multiplicity of radioactive elements. Rutherford found that each radioactive element had a half-life. But, as Lindley states it, ". . . who is to say which atoms decay and which do not?" Perhaps, as many physicists thought, there were internal components to atoms, "sub-atoms," that caused the atom to disintegrate? It was at this point that Niels Bohr came onto the scene.

Bohr, initially a student of Thomson in Cambridge, began to study with Rutherford in Manchester, England in 1912. By then Rutherford, through experimentation with alpha particles had discovered that the interior of the atom had something that alpha particles bounced off of, something dense, which he defined as the nucleus of the atom. A problem, however was how to conceive of the relationship between what seemed to be a "cloud" of electrons in the atom and the atom's nucleus. Bohr realized that in some way the nucleus of the atom held the complement of electrons in hand by some restraining force imagined by Bohr to be like a ball on a spring, vibrating back and forth. Bohr proposed that the electrons could not vibrate with just any amount of energy, but could only carry energy in multiples of some basic "quantum."

The idea of the quantum had been proposed ten years previously by Max Plank in 1900 in an attempt to solve certain problems of emitted radiation. It seemed that when material bodies emitted energy they radiated it in discrete quanta. The idea remained mysterious, but was in the air when Bohr formulated his atomic theory. The quantum atomic theory proved of almost instant help in solving the problem of the basis for the frequencies of spectroscopic lines displayed by hydrogen, the "Balmer" series. Now, in Bohr's imagination electrons orbited the nucleus much as planets orbit the sun. But, the orbiting electrons cannot have any energy they like, but must take on only a limited set of values. The model worked beautifully in many situations, although no one knew why it worked. Which inspired Rutherford to ask of Bohr, "How does an electron decide with what frequency it is going to vibrate and when it passed from one stationary state to another? It seems to me that you would have to assume that the electron knows beforehand where it is going to stop." Radioactive decay and the electron hopping from one orbit to another were spontaneous events in the same way. In neither case is there any special time when the change happens––it just happens and for no evident reason. There is no known physical cause.

The metaphysical implications of this theory of spontaneous energy emission were largely ignored by scientists at the time but some, such as the theoretical physicist, Arnold Sommerfeld, embraced Bohr's atomic theory and augmented it so well that many physicists came to speak of the "Bohr-Sommerfeld" atom. In the meantime Albert Einstein had achieved fame in 1905 for four seminal papers on physics including a paper on relativity and one where he argued that Plank's argument about little packets of energy should be treated at face value, as if they were bona fide discrete little objects. By applying standard statistical methods many of the established properties of electromagnetic radiation were readily demonstrated. By asserting that light was "quantized", Einstein was able to explain previously puzzling details of the photoelectric effect, where voltage is generated by light striking certain metals. Of course the quantum theory went against Maxwell's classical wave theory of the electromagnetic field where waves behaved smoothly, gradually, and seamlessly. Light quanta, however, came and went abruptly without apparent cause. As much as Einstein believed in the latter, when it later came to accepting the notion of spontaneity in nature, he vigorously rebelled.

In 1918 and 1920, respectively, Wolfgang Pauli and Werner Heisenberg, both brilliant young men, came to Munich to study in the Department of theoretical physics with Arnold Sommerfeld who was attempting to find some patterns that could be interpreted as quantum rules in the hope of deepening physical theory. He put Pauli and Heisenberg to work on it. The Bohr-Sommerfeld atom of those days was, to Heisenberg, a "peculiar mixture of incomprehensible mumbo-jumbo and empirical success." Heisenberg did not play by the rules. Searching for something wholly new, something radical, he developed a theory of the half-quantum to account for the spectroscopic anomalies. Developing his formulation further, Heisenberg found that it worked although there was no natural-scientific basis for its doing so.

At one of Bohr's lectures at a conference in Gottingen, Germany; Heisenberg, who was meeting Bohr for the first time, asked what quantum theory meant, what was the underlying conception, the true physics of it all? According to Lindley:

> *Bohr did not insist on the need for classical models that could be translated systematically into quantum terms. Rather, he told Heisenberg, the point of models was to capture as much as one could hope to say about atoms, given the inadequacies of the ideas with which physicists were fumbling along. "When it comes to atoms," Bohr concluded enigmatically, "language can be used only as in poetry. The poet, too, is not nearly so concerned with describing facts as with creating images and establishing mental connections."*

Nevertheless Bohr insisted that despite the fact that quantum physics did not follow classical rules, the language of classical physics remained indispensible. There existed an overarching idea Bohr called the "correspondence principle," which said that the quantum theory of the atom ought to seamlessly match the classical analyses of atomic behavior, when the latter are known to work. This was, apparently, easier said than done, except in Bohr's mind, which operated in a highly intuitive, yet fruitful way.

Bohr, steeped in classical wave theory, felt that the idea of the existence of discrete quanta of light to be untenable and with his students he inveighed against it. However, when John Slater, a Harvard graduate visiting Copenhagen in 1923, told Bohr of his idea that a classically derived radiation field might guide light quanta in their interaction with atoms, Bohr got excited. Bohr, Slater, and another student, Hendrik Kramer, developed the idea and published what became known as the BKS theory which described in purely qualitative terms a new kind of radiation field that surrounds atoms, influences their absorption and emission of light, and also transports energy between them. In addition, electrons were now to be seen not as orbiting nuclei in the atom, but as "virtual oscillators," each one corresponding to a particular spectroscopic line. However, contrary to classical physics, in this system energy was not absolutely conserved because the emission and absorption of energy ran according to rules of probability: it can disappear from one place and reappear somewhere else without the event being strictly connected by old-fashioned cause and effect. Apparently the radiation field would account for any discrepancies in energy balance in the short run, although the sums always added up in the long run. According to Pauli, however, Einstein thought the whole business to be "Quite artificial" and by 1925, experiments by Compton demonstrated that the BKS theory was false. Despite this, according to Lindley, "The BKS proposal marks…a turning point. Depending on one's interpretation of what the theory actually was, it was either the last gasp of attempts to rest quantum theory on some sort of classical foundation or else the first proof that all such efforts were doomed." What was conserved from the BKS theory was the use of virtual oscillators as a means to talk about how an atom emitted and absorbed light. It fell to Heisenberg to transform this innovation into a wholly new theory of physics.

Max Born, the head of the department of theoretical physics at the university at Gottingen, laid the groundwork for

Heisenberg with a paper calling for a new system of "quantum mechanics," that is, a structure of quantum rules obeying their own logic, not necessarily following the dictates of classical, Newtonian mechanics. Born also abandoned the use of traditional calculus which was incapable of dealing with phenomena that were discontinuous, abrupt, and spontaneous. Heisenberg suggested that the characteristic frequencies of the proposed oscillators, not the position and velocity of the electrons, would be the basic elements of the atomic physics and the motion of electrons would be expressed only indirectly. This was revolutionary. Heisenberg developed a new and strange mathematics, which yielded a consistent result for the energy of a system-but only so long as that energy was one of a restricted set of values. According to Lindley, Heisenberg's new form of mechanics was, in fact, a quantized form of mechanics.

In the meantime the French physicist, Louis DeBroglie wondered whether Einstein's particles of light might display some of the properties of waves if they could act in a stream of particles. Combining Planck's quantization rule for radiation with Einstein's $E=mc^2$ for moving objects, DeBroglie proposed that the speed of a particle yielded a certain wavelength, the faster the speed, the smaller the wavelength. He then calculated that an electron circling a nucleus would have a wavelength equal to the orbit's circumference. For an electron in the next outermost orbit the circumference was twice the electron's wavelength, and so on. In other words, the allowed orbits of the Bohr atom were those for which a whole number of electron wavelengths fit around the orbit's circumference.

In 1925, influenced by de Broglie's concepts, the Viennese physicist Irwin Schrodinger enlarged on de Broglie's electron wave concept, suggesting that particles are not really particles at all, but were "whitecaps" of an underlying wave field. An equation described a field governed by a mathematical operator that embodied a kind of energy function. When applied to an atom the equation yielded a limited number of solutions in the form of static field patterns, each one representing a state of the atom with some fixed energy. It was also possible to understand a quantum jump, a transition from one state to another, not as an abrupt and discontinuous change but as a fluid transformation of one standing wave pattern into another with the wave reconfiguring itself rapidly but nonetheless smoothly. Classical order had been restored!

Born, reviewing Heisenberg's math, realized that a mathematical system already existed within which quantum mechanics worked: it was known by a small group of mathematicians and was called matrix algebra. Soon it would be called matrix mechanics. Born supplied the mathematics to Heisenberg's physics. Together with Born's assistant, Pascual Jordan, they refined and extended matrix mechanics. Unfortunately it was very complex stuff that seemed to be largely a formal achievement, albeit one that well explained many of the puzzling propositions inherent in quantum theory. Pauli, initially skeptical, and as was his wont, scathing in his criticism of matrix mechanics, nevertheless was able to us it to derive the Balmer series of spectral lines for hydrogen. It was a tour de force of mathematics, one which, however, few could follow. To add to the mix, Paul Dirac, a young physicist at Cambridge, in 1925, presented a paper wherein he explained his own rigorous mathematization of quantum mechanics similar to that of Born, Jordan, and Heisenberg. Now, quantum mechanics could be explained by two systems with different foundations! Schroedinger, like so many others, found it quite arcane and difficult. When his wave equation appeared in early 1926, it was gratefully received, consisting as it did of old-fashioned differential equations. In his Nobel Prize lecture from 1933, he spoke of his desire through the wave equation to save "the soul of the old system" of mechanics.

Heisenberg, however, objected. At a lecture given by Schrodinger, he asked how wave mechanics could explain the photoelectric effect or Compton scattering, both of which provided direct experimental evidence for the proposition that light came in discrete, identifiable packets? Then, in the spring of 1926 Schrodinger found that wave mechanics and matrix mechanics were not fundamentally different after all: they were, in effect, the same theory presented in different mathematics. The problem was in understanding how two such different views of nature could arise from the same source.

Einstein and Heisenberg continued to object. Max Born used wave mechanics to describe how the collision of two particles resulted in waves corresponding to the rebound particles spread out something like ripples on a pond, ". . . smeared out in all directions." But a particle had to be somewhere; it couldn't disperse uniformly throughout space. The end result of a collision had to amount to two distinct particles moving off in well-defined directions, what happened in the Compton effect. Born resolved the problem by proposing that the spreading waves leaving the collision site described not actual particles but their probabilities: where the wave was strong in a certain direction this is where the rebounding particles were less likely to be seen. Schroedinger's equation, thus, generated not a classical wave, but rather the chance of finding an electron here, there, or somewhere else in an atom. This harmonized with Heisenberg's matrix mechanics, wherein the physical presence of an electron was a function of various things it might be *doing*, rather than some specific indication of *where it was.* What Born showed, according to Lindley, was that ". . . the recognition of wave mechanics as dealing with probability didn't just clarify what Schrodinger's equation meant. It also fleshed out the physical as opposed to the purely mathematical connection between wave mechanics and matrix mechanics. Probability had slipped into physics in a new form.

Born wrote in 1926 that it was no longer possible to say what the specific outcome of a collision would be. You could only specify the probabilities of a range of outcomes. "Here the whole problem of determinism arises, . . .In quantum mechanics there exists no quantity which in an individual case determines the result of a collision . . . I myself am inclined to give up determinism in the atomic world." But not Einstein, who repeatedly and famously said "I for one am convinced that He(God) does not throw dice." As Lindley wrote, "If probability were to replace causality, then as far as Einstein was concerned the rational basis for constructing theories of physics had been swept away."

Bohr and Heisenberg in Copenhagen butted heads daily, the former arguing for a totally new physics, the latter trying to save classical continuity. Dirac, also in Copenhagen at that time, 1927, was working on the mathematics of translating quantum problems into classical form. But, he found, try as he might, he could not describe both the position of a particle and its momentum simultaneously: it was as if the position-based account and the momentum–based account were somehow depicting two different quantum systems, not the same one in different ways. Pauli found the same thing, as did Heisenberg. There was no way to force a quantum system to yield up a description that would make unambiguous sense in classical terms. In an attempt to resolve the matter practically by measuring position and momentum, Heisenberg came up with what became a famous example involving the collison between an electron and a photon. He concluded that the more an observer tried to extract information about the electron's position, the less it was possible to know about its momentum and vice versa. There would always be an "inexactness." To Bohr, however, the inexactness was a manifestation of the contradictory roles that particles and waves play in quantum events. As usual the two argued incessantly, but finally resolved their disagreement and went to press using the word that Bohr preferred, "uncertainty", instead of "inexactness."

Bohr, meanwhile, had developed his new philosophy of "complementarity" according to which both the wave aspect and the particle aspect of quantum objects had necessary but contradictory roles to play. Einstein, with his students Podolsky and Rosen (EPR), found a way to invalidate the quantum uncertainty concept, that physical properties are fundamentally indefinite until measured. Particles, they insisted, have definite properties: quantum mechanics is only a partial theory, an incomplete portrayal of the underlying physical truth. Bohr responded in his usual careful, ponderous, opaque way showing how the EPR argument begins with a certain definition of physical reality, and then shows that quantum mechanics doesn't stack up. The key is in the definition of physical reality, which Bohr indicates is inadequate to understand the phenomenon with which quantum mechanics is concerned. The observer's choice of what to measure, not yet acted on, will affect how the particles reveal themselves later. In 1964, the physicist, John Bell, proposed certain experiments on suitably arranged pairs of particles designed to test the EPR argument. Two decades later the experiment was carried out and it proved quantum mechanics to be wholly correct.

Heisenberg left Copenhagen to teach in Leipzig, leaving Bohr to bring the uncertainty principle onto the international scientific stage. Bohr's correspondence principle was the vehicle whereby the quantum world would transform seamlessly into our classical world. No matter what system is under investigation, *measurement* will disturb what is being measured and in measuring one aspect of a system the doors will be closed on what else you might find out. This was the "Copenhagen interpretation" of quantum mechanics.

Einstein tried mightily to argue against quantum mechanics, but in vain. Whereas he lectured on the need for a synthesis of conflicting views and thus, hopefully make the underlying conflicts go away, Bohr's complimentarity reveled in contradiction. Einstein could not tolerate this, continuing to insist that beneath the apparent discontinuities and spontaneities determinism rules. His attempts to undermine quantum mechanics by "thought experiments" invariably failed.

The Nobel Prize in physics was awarded to Heisenberg in 1932, to Schrodinger and Dirac in 1933, and to Born in 1954. This was, however, not the end of the controversy pitting Einstein and Schrodinger against Bohr and Heisenberg. The latter were challenged often by the former, the most famous example being that of Schrodinger's half-dead, half-alive quantum cat, whom Bohr dismissed as, "just silly." Bohr became the principle spokesman of quantum mechanics and indeterminancy, speaking on psychology, philosophy and applying his complimentarity principle to the nature of life. In the 1950s the physicist, David Bohm provided an alternative interpretation of quantum mechanics, which claimed to restore determinism by means of what were called "hidden variables." According to Lindley, Einstein found Bohm's work unimpressive and "cheap." As Lindley indicates, Bohr's complimentarity principle developed little traction in physics, but the uncertainty principle became famous in many realms outside of physics, including literary deconstruction and even the television series, *The West Wing*.

Heisenberg visited Einstein in Princeton in 1954 a year before the latter's death. Einstein told Heisenberg, "I don't like your kind of physics. There's consistency, but I don't like it." Bohr and Heisenberg had a complete break in friendship in 1941. Heisenberg was allegedly involved in Germany's attempt to make use of nuclear power and was shunned after the war by many physicists. Heisenberg slowly worked his way back into the scientific community becoming director of the Max Planck Institute in Munich where he died in 1976. The reader of ***Uncertainty*** will come away from the book realizing to what extent uncertainty in the form of intuition plays a part, not only in the objective quantum universe, but in the scientific process. Obviously in the present case it played a huge roll, especially in Niels Bohr's creativity. It is almost as if the mathematization of Bohr's intuitively-derived concepts was but a device to confirm what was already known. And, with respect to the function of quantum processes, per se, it is my view, admittedly as one who is not expert in physics or mathematics, but who has spent his rather long professional life studying anomalous events and theory, that quantum processes are not the rock-bottom foundation of our physical world, but exist at the borderline of that place where the "intangible physical domain" meets the "tangible physical domain".[1]

• • •

CORRESPONDENCE: Richard A. Blasband, M.D. • The Center for Functional Research, Sausalito, CA.

REFERENCES & NOTES

1. R.G. Jahn & B.J. Dunne, A Modular Model of Mind/Matter Manifestations (M5), *Journal of Scientific Exploration* **15**, 3 (2001), pp. 299-329.

∞ ∞ ∞