The Scientific Method
Einstein and the Quantum Revolution

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Albert Einstein (1879 – 1955) is undoubtedly one of the greatest of scientists of all times and his contributions to physics have been acclaimed worldwide. Einstein's greatest contribution to physics is his theory of special and general relativity in which he revolutionized our understanding of space and time; Einstein replaced Newton's law of gravitation by showing that mass creates curvature of space and time which in turn appears as a gravitational force[1].It is widely known that, after his initial enthusiasm and contribution to the development of quantum physics, Einstein became one of the most incisive critics of the idea of the quantum and never accepted quantum physics as being a satisfactory theory of nature. We briefly analyze this historical episode in physics in order to emphasize certain general aspects of the scientific method.

The Quantum Hypothesis

Classical physics was established by such luminaries as Galileo, Newton and Maxwell. In classical physics, the world is very much like what one observes in daily life. Objects occupy unique positions and have definite paths when they move. Newton introduced the concept of force to explain the motion of objects: force is the cause of motion and the effect is the path followed by the object. Maxwell further developed classical physics by demonstrating that light, and electromagnetism in general, requires the concept of a field -- a physical entity spread throughout space and time. It will be seen that quantum physics in time would overturn the very foundations of classical physics.

The quantum revolution starts in 1900 when Max Planck made the epoch making quantum hypothesis that energy in nature comes in discrete packets, or quantum. Planck was led to this hypothesis from his studies of electromagnetic radiation.

Planck obtained an expression for the spectrum of radiation emitted by a black body at temperature T. Consider a cavity (hollow enclosure) with a small opening; if the cavity is heated to temperature T, the radiation emitted from the opening of the cavity is black body radiation. See Figure 1.

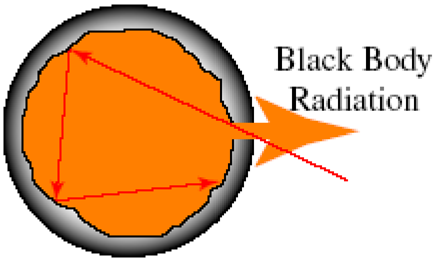

Figure 1. Radiation from a black body can be considered to be the radiation emitted from a cavity that is at temperature T.

In Planck's derivation he assumed that the walls of the cavity were made of atoms that carry electric charge and the atoms were to be regarded as harmonic oscillators. Since the atoms carry charge, the oscillators emit radiation as they oscillate back and forth. The oscillators and radiation are in thermal equilibrium at temperature T, and the radiation that is produced is black body radiation.

In deriving the spectrum of emitted black body radiation Planck made a crucial assumption - which has no basis in classical physics - that an oscillator with frequency f is only permitted to have energy nhf, where h is Planck's constant and $n = 0, 1, 2, \ldots \infty$; n is the quantum number of the oscillator. All other values of energy for the oscillator are forbidden. The energy of single

[1]*Subtle is the Lord* … by A. Pais, Oxford University Press (1982).

quanta is *hf*, and the allowed quantum of energy for the oscillator is

$$E = nhf \; : \; n = 0, 1, 2, \ldots \; \infty \, ;$$

Einstein's Contribution to the Quantum Revolution

In 1905 Einstein showed that Planck's formula could be understood in a much simpler manner. Planck had quantized only the motion of the atoms but had considered the radiation field to be a continuous field. Einstein proposed that the radiation field consists of discrete packets of energy, called photons. An electromagnetic wave of frequency *f* was considered by Einstein to be a stream of discrete photons; depending on it's intensity, the wave would have a discrete number of photons given by integer *n* with the energy of the wave being given by *nhf*.

In 1922 A.H. Compton showed that the photons had momentum in addition to the energy attributed to them by Einstein.

When atoms oscillate, they can only excite a finite number of photons. Electromagnetic waves inside the cavity travel in all directions and can be considered to be a gas of photons at temperature *T*. It was only in 1925 that the idea of the photon gas could be made precise by Einstein and S.N. Bose; they applied statistical mechanics to the gas of photons and obtained Planck's formula for the spectrum of black body radiation.

The development of quantum physics proceeded in two different directions. Niels Bohr and co-workers addressed the quantum nature of the atom -- why the atom should have only discrete states as was shown by Planck's derivation as well as other independent experimental observations. The other direction was to understand the discrete nature of the electromagnetic field.[2]

Heisenberg's Matrix Formulation

In 1925 W. Heisenberg re-examined the very concept of what is observed in an experiment. In classical physics measurable quantities like position, velocity, energy and so on are represented by real numbers. To account for the behaviour of the quantum world Heisenberg postulated that all physically observed quantities needed to be represented not by ordinary numbers but by more complicated mathematical objects such as matrices, and in general by non-commuting operators.[3] Heisenberg states his guiding thoughts quite candidly "The present paper seeks to establish a basis for theoretical quantum mechanics founded exclusively upon relationships between quantities which in principle are observable."[4]

In 1926 P.A.M. Dirac introduced his *q* and *c* numbers and gave a mathematical and abstract formulation to Heisenberg's ideas. Heisenberg was able to derive the result that the hydrogen atom has only discrete quantum states. Heisenberg could compute the spectrum of radiation resulting from the discontinuous 'jumps' (transitions) of the hydrogen atom from one state to another -- without specifying how it got from one state to the other.

Einstein's discomfort with quantum physics starts with Heisenberg's formulation in which there is no underlying description of the physical system. Heisenberg is silent on what is the object by itself and addresses only the question of what happens to the object when it is experimentally observed. Einstein rejected this notion and demanded of Heisenberg, " 'You don't seriously believe that none but observable magnitudes go into a physical theory?' and Einstein further stated that "it is theory that decides what we can observe'. "[5]

Heisenberg relates the following discussion he had with Einstein in 1926; we quote at length to give a flavor of the sort of objections that Einstein had. "He (Einstein) pointed out to me that in my

[2] It was only in 1949 that the quantization of the electromagnetic field was understood and resulted in what is known as quantum electrodynamics. The quantization of a classical field leads to the discipline of quantum field theory. Einstein's objections to quantum field theory were even more strenuous than his objections to non-relativistic quantum mechanics, and that Einstein "did not believe in any of the consequences of quantum field theory."p.463 *Subtle is the Lord* … by A. Pais, Oxford University Press (1982).

[3] It was not clear at that time exactly what were the mathematical objects introduced by Heisenberg so we speak with hindsight.

[4] *Einstein Defiant* by E.B. Bolles, p. 232 Joseph Henry Press (2004).

[5] p. 232 ibid.

mathematical description the notion of 'electron path' did not occur at all, but that in a cloud chamber the track of the electron can of course be observed directly. It seemed to him absurd to claim that there was indeed an electron path in the cloud chamber, but none in the interior of the atom. .. I defended myself to begin with by justifying in detail the necessity for abandoning the path concept within the interior of the atom. I pointed out that we cannot, in fact, observe such a path; what we actually record are frequencies of light radiated by the atom, intensities and transition-probabilities, but no actual path...To my astonishment, Einstein was not at all satisfied with this argument. He thought that every theory in fact contains unobservable quantities".[6]

The path that one sees of an electron in a cloud chamber is the result of the device used in the experiment. In quantum mechanics, an observation of a quantum particle requires that the experimental apparatus must greatly **magnify** the effect being observed by some irreversible process. In the case of the cloud chamber the single electron being observed creates an avalanche of electrons resulting in 10^7-10^8 electrons being released from the material constituting the detector, and it is these electrons that are seen making a track in the cloud chamber. The electron being observed does not directly appear in the tracks in the cloud chamber. Indeed according R.P. Feynman's formulation of quantum mechanics, made much later in 1949, the electron being observed does not have a unique path; instead the path of the electron is **random**: the electron takes -- in a virtual sense and with different likelihood -- all possible paths simultaneously.

Schrodinger's Wave Formulation

In 1924 L.V. de Broglie proposed that the electron can be considered to be a `matter wave'. The electron wave provided an explanation of the semi-classical model of the atom that Bohr had developed. De Broglie's bold and drastic postulate was strongly supported by Einstein.

In four papers from January to June 1926, E. Schrodinger obtained the equation that de Broglie's matter wave satisfies. The famous Schrodinger equation replaces Newton's equation of motion and forms one of the cornerstones of quantum mechanics. In Schrodinger's formulation a physical system is described by a wave function ψ, which is a continuous wave defined on space and time.

Einstein was delighted that one could explain the quantum properties of atoms using a continuous formulation and wrote to Schrodinger, "Professor Planck pointed your theory out to me with well justified enthusiasm, and then I studied it with the greatest enthusiasm ... The idea of your article shows real genius."[7] Expressing his disapproval of the Heisenberg approach in a second letter to Schrodinger in 1926 Einstein wrote "I am convinced you have made a decisive advance with your formulation of the quantum condition, just as I am equally convinced that the Heisenberg-Bohr route is off the track."[8]

Einstein felt that Schrodinger formulation had restored the central position of space and time in describing a quantum system. Einstein's expectation of the correct formulation of the quantum principle rested heavily on the work of Schrodinger and he wrote in May 1926 "Schrodinger has come out with a pair of wonderful papers on the quantum rules"[9]. This was last time that Einstein would make an unambiguously enthusiastic remark regarding the quantum revolution.

But what is the electron's matter wave? Every time the electron is observed, it is seen to occupy a definite position, is seen to be a point, whereas a wave is spread over space. So where is the electron wave? In June 1926 Max Born made one of the most radical and greatest strides in science; he stripped ψ, the wave function of Schrodinger, of any physical reality and gave it a purely mathematical meaning. The Schrodinger wave function ψ is a statement of **probabilit**y: if a system is observed, the likelihood of finding the system in a particular state is given by $|\psi|^2$. According to quantum mechanics what `causes' the system to end up in a particular final state can

[6] *Encounters with Einstein* by W. Heisenberg, p. 113 Princeton University Press (1983).

[7] p 225. ibid

[8] p. 230 ibid.

[9] *Subtle is the Lord* …by A. Pais, p.442 Oxford University Press (1982).

never be answered: all that one can observe and predict are the likelihood of different outcomes.

Cause and effect are no longer simply linked in quantum mechanics. A system prepared in an identical manner will show different final states every time it is observed; in other words the same cause gives a multiplicity of effects with varying likelihood. In one deft stroke

In classical physics a single observation shows the state of the particle, say its position. In quantum mechanics a collection of observations is required to deduce the statistical behaviour of the particle. In the case of the tracks in a cloud chamber, the same experiment has to be repeated many times, and each time the electron must start from the same initial state. It is seen that although each time the electron starts from an identical initial state its path is different every time the experiment is performed. Quantum mechanics can then predict the **likelihood** of the electron taking a particular path.

Max Born destroyed forever the deterministic world of every day experience, and of classical physics.

The statistical formulation of quantum theory was the last straw for Einstein; in a letter written to Born, Einstein states, "You believe in God playing with dice and I in perfect laws in the world of things existing as real objects".[10] Bohr's response to this statement of Einstein was that "But still, it cannot be for us to tell God, how He is to run the world."[11]

'Quantum Mechanics is a Complete Theory'

In February 1927, Heisenberg obtained his celebrated Principle of Uncertainty (Bohr preferred the term indeterminacy). This principle states that physically observed quantities like position and velocity come in complementary pairs: if one observes one of the quantities say position, then this puts a limit on how precisely one can measure the other of the pair, which for position is velocity.

By 1927 Heisenberg, Dirac and W. Pauli had removed from quantum mechanics all the vestiges of classical physics that was present in Bohr's formulation of the atom. Furthermore, Dirac and others had demonstrated the equivalence of Heisenberg's 'Matrix Mechanics' and Schrodinger's 'Wave Mechanics' by combining the two approaches into a single mathematical formalism: measurable quantities are represented by Heisenberg's operators that act on the Schrodinger wave function, which describes the state of a physical system.

The Solvay Meeting in 1927 was one of the greatest ever gatherings of physicists. At the meeting Heisenberg and Bohr announced that the formulation of quantum theory was complete. They stated "We maintain that quantum mechanics is a complete theory; its basic physical and mathematical hypotheses are not further susceptible of modifications."[12] It is should be noted that these were indeed prophetic words. Quantum mechanics till today has passed all the (innumerable) tests that it has been subjected to. Quantum mechanics has been able to explain a stunning range of phenomena far beyond it's origins in atomic physics – from subnuclear particles to semiconductors and on to large objects like neutron stars. Furthermore there has been no change in the mathematical formulation of quantum mechanics and neither of its physical hypotheses. Quantum phenomena are described by operators and probabilities and its mathematical formulation is the one that has been laid down by Heisenberg, Schrodinger and Dirac.

Starting with the Solvay Conference of 1927 Einstein's scepticism and doubts regarding quantum mechanics took a more serious turn. "He (Einstein) became defiant, refusing to bow before claims of completeness, finality and unmodifiability ... And the notion that something must forever be undiscoverable was offensive to him."[13] Einstein chose to attack the implications of the probabilistic interpretation of quantum mechanics and of Heisenberg's Principle of Uncertainty; Einstein never questioned the mathematics of quantum mechanics but rather always thought up ingenious *gedanken* (thought) experiments to show that the formulation of quantum mechanics was defective. All of

[10]p.252 ibid.
[11]*Encounters with Einstein* by W. Heisenberg, p. 117 Princeton University Press (1983).

[12]p.267 ibid.
[13]p.268 ibid.

Einstein's criticisms were answered by Bohr, Heisenberg, Pauli and Dirac. P. Ehrenfest has the following to say of the debates at the 1927 Conference, "It was delightful for me to be present during the conversations between Bohr and Einstein. Like a game of chess, Einstein all the time with new examples … to break the Uncertainty Relation. Bohr from out of philosophical smoke clouds constantly searching for the tools to crush one example after another"[14]

Einstein's Last Public Debate on the Quantum

The last time that Einstein publicly debated the correctness of quantum mechanics was at the Solvay Conference in 1930. At this conference, he proposed a *gedanken* experiment in which the Heisenberg Uncertainty Principle that relates time and energy would apparently fail; the Principle states that if one measures the energy of an object very precisely then one is limited as to the accuracy of the time at which this measurement is made. Put differently, Heisenberg's Principle states that one cannot simultaneously measure the energy of an object and the time at which the energy measurement is made. If one measures the energy with great precision one cannot fix the time at which this measurement is made.

Einstein proposed the following experiment. Consider a box with a shutter containing photons; the box has a clock attached to it and it is hanging by a balance in a gravitational field. See Figure 2. Suppose at some instant t the shutter is opened and a photon with energy E escapes. The change in the weight of the box will be measured to yield, from the principle of relativity, a change in mass equal to $m = E/c^2$. Hence it would seem one had measured the energy of the photon and the time at which the photon is emitted with arbitrary precision -- and in effect violating Heisenberg's Uncertainty Principle.

It is reported that Bohr spent a very long and sleepless night before coming up with his solution. Ironically the resolution of this apparent paradox lies in Einstein's theory of gravitation. When the photon leaves the box, it does so in a random direction.

[14]p.275 ibid.

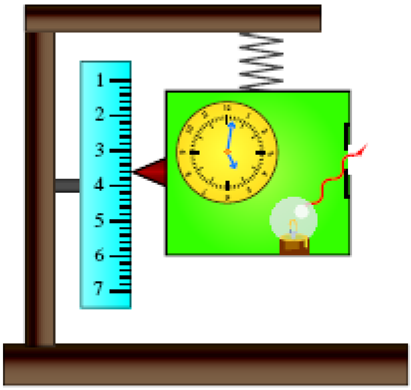

Figure 2. Photons in a box of with a shutter, containing a clock, and attached to a weighing balance. If the time the photon is emitted and the weight of the box can be simultaneously measured, Heisenberg's Uncertainty Principle would be violated.

Due to momentum conservation, the box recoils in a random direction by an amount Δx and hence balance measuring the mass as well as the clock are moved away from their original position. This displacement causes an error on the scale measuring the mass and yields an error of ΔE in the measurement of energy. From Einstein's theory of gravitation it is known that time flows more slowly when one is nearer to the gravitating mass; hence displacement by Δx of the clock induces an uncertainty of Δt in the time of measurement. It was then shown by Bohr, with Einstein willingly helping him with the calculations, that the uncertainties obey $\Delta E \Delta t > \hbar$ precisely as Heisenberg's Principle requires.[15]

The Scientific Method

From our discussion we can conclude that Einstein did not accept the construction of physical reality that emerges from quantum mechanics. Many explanations have been proposed as to why a great scientist like Einstein could 'not move with the times'. It is thought that in creating the theory of special and general relativity, the concepts of causality and continuity were carried over by Einstein from classical physics -- ideas that Einstein refused to discard even though they were no longer valid in quantum mechanics. Einstein

[15]*Discussion with Einstein on Epistemological Problems in Atomic Physics* by Niels Bohr http://www.emr.hibu.no/lars/eng/schilpp
Einstein, Physics and Reality by J. Mehta p. 70 World Scientific (1999).

felt that in quantum mechanics 'reality' was permanently hidden away since the object is always behind a quantum 'veil' -- one cannot know what the object is doing only what it does when we observe it. Einstein felt that 'the Lord is .. not malicious"[16] and would not 'hide' the reality of nature from us human beings.

The idea of a unique and 'objective' universe independent of the observer seems to have been an underlying assumption that Einstein was not willing to give up. Einstein's very success seems to have blinded him to other ways of thinking. ".. the purity of Einstein's relativity theory had a blinding effect on him. He almost said so himself: 'To the discoverer ... the construction of his imagination appear so necessary and so natural that he is apt to treat them not as the creation of his thoughts but as given realities'. His insistence on objective reality is a perfect example of such a mental process." [17]

It is worth noting that the 'quantum veil' does not hide 'objective' reality – rather, one needs to *enlarge* one's concept of reality, which consists of the observed state and the unobservable virtual realm. The quantum veil is necessary for separating the actual physically observed world from its (the world's) virtual state. If not for the quantum veil the virtual realm would not exist. Apparently Einstein did not accept or grasp the significance of this expanded view of reality that quantum physics requires.

From the point of view scientific methodology it is clear that the ideas that Einstein held onto, like deterministic causality in the microscopic realm or the path of an electron inside the atom, had no empirical basis. Of course, scientists have to believe in their intuition and hold onto unpopular and unaccepted ideas if they are to pioneer new ways of thinking. But from the example of Einstein, it is clear that one also has to know when one should accept the empirical evidence that at some point becomes incontrovertible. To hold onto to one's subjective and personal views in the face of convincing experiments pointing to the contrary contains the seeds of failure.

Nature can do whatever it chooses to do; nature is forever beyond the ken of mankind and whatever ideas we have of nature can never fully encompass of fully explain nature's laws. Einstein's conception of a unique and 'objective' universe whose state is independent of observation is simply a human construct based on our five senses -- there is no reason that nature has to be this way. It is finally experiment, and not a priori human ideas, that is the ultimate guide to the empirical behaviour of nature. In the empirical sciences, nature is the 'king' and it is experiment that (in the empirical sciences) is the most faithful messenger of the king!

Einstein was one of the greatest of physicists of all time. He contributed greatly to onset of the quantum revolution. But when the time came, in 1927, to make a radical and permanent break with classical concepts, for reasons discussed above he was either unwilling or unable to do so. "In course of scientific progress", writes Heisenberg "it can happen that a new range of empirical data can be completely understood only when the enormous effort is made to enlarge [their philosophical] framework and to change the very structure of the thought process. In the case of quantum mechanics Einstein was apparently no longer willing to take this step, or perhaps no longer able to do so."[18]

Einstein's encounters with the quantum revolution shows that even the greatest of scientific minds must submit to nature.

About the Author

Belal E. Baaquie is an Assoc. Professor at NUS Physics Department. His training is in theoretical physics with specialization in quantum field theory. He has a long standing interest in science and physics education. His research is currently focused on applying theoretical physics to finance.

[16] p.301 ibid.

[17] p.463 *Subtle is the Lord* … by A. Pais, Oxford University Press (1982).

[18] p.253 ibid.