The Marvel and the Mystery of Quantum Mechanics – Some Reflections*

N Mukunda

The creation of quantum mechanics is one of the most dramatic developments in the physics of the 20th century. After the period 1900–1924, during which the Law of Black Body Radiation, wave particle duality for light and for matter, the general quantisation of energy and stability of matter and the laws of spectroscopy had begun to be understood, the mathematical structure of quantum mechanics was discovered amazingly rapidly in just under two years, 1925–1927. On the other hand, the physical interpretation and meaning of this structure required an enormous effort, in which the uncertainty and complementarity principles, the Born probability interpretation and rule and the wave function collapse idea, all played important roles. While quantum mechanics has all along been amazingly successful in numerous applications, many puzzling questions about interpretation remain and continue to be pursued till today, though the focus has shifted from wave particle duality to entanglement and its signatures and consequences. This article gives an impressionistic account of these developments, accompanied by comments on the origins of human intuition and the meaning of human understanding of nature [1].

October–December 1900

Quantum theory was born in the evening hours of Sunday, 7th October 1900, in the home of Max Planck in Berlin. It came out of his effort to explain the energy density of black body radiation as a function of frequency and temperature. That evening he found a formula, the Planck Law, involving a new fundamental constant of Nature, Planck's constant, which agreed and continues to agree very well with experiment. A few weeks later he presented an attempt at a derivation, in which the idea of energy quantisation was first introduced.

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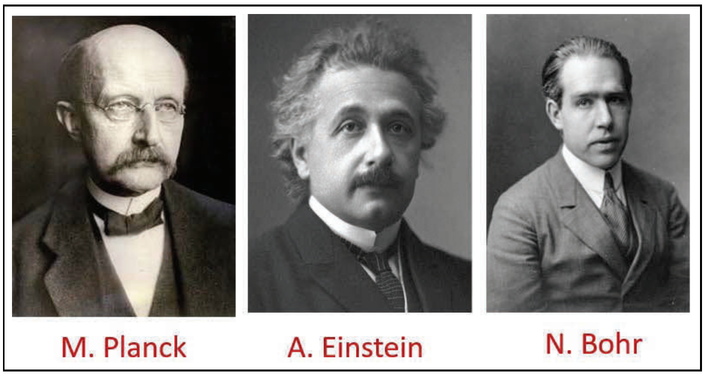
The Old Quantum Theory: 1900–1924

Quantum mechanics was discovered over the two-year period 1925–1927. From 1900 till then, the period of the Old Quantum Theory, the effort was mainly led by Albert Einstein, joined after 1913 by Niels Bohr. The focus was largely on understanding the statistical properties of radiation; and in Bohr's work based on Rutherford's model of the nuclear atom, the origins of spectroscopy and stability of matter. The main aim was to somehow graft Planck's constant on to the theoretical framework of classical physics. In hindsight there was a sense of adhocness in all this, though the problems were extraordinarily difficult. Many fundamental insights were gained – the photon concept for light, wave particle duality for light and then for matter, and a preliminary understanding of the laws of spectroscopy and the structure of the Periodic Table of elements.



Quantum Mechanics: 1925–1927

The two-year period 1925–1927 saw one of the most dramatic developments in the history of physics with the appearance of quantum mechanics. It came from an amazing creative outburst. The first breakthrough came from Werner Heisenberg, followed very soon after by Paul Dirac and Erwin Schrödinger. These three are the joint creators of quantum mechanics. As a recent article said, paraphrasing Winston Churchill from World War II [2],

"Never in the history of physics has so much been achieved by so few in such a short time".

Every serious student of quantum mechanics is always left wondering – how could it have been discovered at all?

The drama of Heisenberg's breakthrough is best conveyed by an eloquent passage from his later writings. He was Sommerfeld's student, Max Born's assistant, Kramers' collaborator, and a close associate of Bohr. In late May 1925 he spent two weeks on the grass-less island of Helgoland recovering from hay fever, and then [3]:

" ... one evening I ... was ready to determine the individual terms ... in the energy matrix, by... an extremely clumsy series of calculations. When the first terms seemed to accord with the energy principle, I became ... excited, and began to make countless arithmetical errors. ... it was almost three o'clock in the morning before the final result of my computations lay before me. The energy principle had held..., and I could no longer doubt the mathematical consistency and coherence of the kind of quantum mechanics to which my calculations pointed. ... I had the feeling that, through the surface of atomic phenomena, I was looking at a strangely beautiful interior, and felt almost giddy at the thought that I now had to probe this wealth of mathematical structures nature had so generously spread out before me."

This passage has inspired and been quoted by so many over the years.

Mathematical structure ahead of physical interpretation

With the arrival of quantum mechanics, a new situation in physics arose. The mathematical structure was found first, but with no clear cut physical interpretation to begin with. This had to be built up later with great effort. In brief the problem was this: while in classical physics every property of a system is treated as a number with some value at each time, in quantum mechanics this is not so. Physical properties are represented by more abstract mathematical objects, not numbers any more. The description of states of a system also becomes more subtle and abstract than earlier. But when a measurement is made in an experiment, the result has to be a number. How does this transition take place? This was the problem, and it is still not fully resolved.

The key components of the interpretation, put together over 1926–1927, are: the Born probability interpretation and rule for results of measurement, the Uncertainty Principles of Heisenberg and Complementarity Principle of Bohr, both formulated in 1927. But what seemed so difficult to accept were the lack of pictures to 'see what was going on' in phenomena described by the equations of quantum mechanics; and the finding that probabilities are essential to the interpretation, and are irreducible. Both these aspects deeply troubled Einstein right from the beginning.

On the first aspect Dirac wrote as early as in 1930 [4]:

"... nature works on a different plan. Her fundamental laws do not govern the world as it appears in our mental picture in any very direct way, but instead they control a substratum of which we cannot form a mental picture without introducing irrelevancies."

A few years later he expanded on this [5]:

"The main object of physical science is not the provision of pictures, but is the formulation of laws governing phenomena and the application of these laws to the discovery of new phenomena. If a picture exists, so much the better, but whether a picture exists or not is a matter of only secondary importance. In the case of atomic phenomena no picture can be expected to exist in the usual sense of the word 'picture', by which is meant a model functioning essentially on classical lines."

Since mental pictures and classical ways of thinking are mentioned so often, let me mention a related aspect pointed out by Konrad Lorenz and Max Delbruck [6]. It is that our abilities and capacities to deal with the world have been fashioned by evolution guided by natural selection in interaction with a limited range of phenomena, just the part relevant for evolution. This is referred to by Delbruck as 'The World of Middle Dimensions' and is the domain of classical physics, so when we move away from it we face great difficulties. But that, as the bartender said, is another story.

In spite of these deep problems, in the initial decades most physicists were busy with the practical applications of quantum mechanics. It could handle pretty much all of atomic and molecular physics, condensed matter physics, and then nuclear physics and the emerging field of elementary particles. As for quantum chemistry, as soon as quantum mechanics came Linus Pauling declared,

"There is no part of chemistry that does not depend, in its fundamental theory, upon quantum principles."

Einstein's concerns

Let me now turn to Einstein's concerns with the interpretation of quantum mechanics offered by Bohr, Heisenberg, Dirac and company. In passing I may mention that some later writers refer to his objections in a condescending way, which seems unfortunate and unnecessary. At first Einstein felt that quantum mechanics was internally inconsistent; in this spirit he attacked the Uncertainty Principles. This is at the level of wave particle duality, which he himself had discovered for both light and matter, respectively in 1909 and 1924. In the case of matter it was also suggested independently by de Broglie in late 1923. The mathematics of quantum mechanics is perfectly adequate to handle these dualities. In a humourous vein it is said that

"To the question 'Is the electron a particle or is the electron a wave?', quantum mechanics gives the triumphant answer: 'Yes!'."

After this Einstein changed his attitude: he felt quantum mechanics is correct, so far as it goes, but is incomplete. Something is missing in the description it gives of natural phenomena. The final expression of these ideas came in the EPR – Einstein, Podolsky, Rosen – paper of 1935 [7]. This was followed up by Schrödinger [8], and all together they highlighted a 'new' feature of quantum mechanics – the property of entanglement for general states of composite systems. Actually, on account of the Superposition Principle, it was already known that most states of composite systems are entangled. EPR introduced two key ideas or requirements which seemed very reasonable to them – realism and locality.

Realism is the idea that under certain conditions specified by them, we can say in advance of measurement that certain physical properties of a system have definite numerical values. Locality is the idea that the state and properties of a subsystem cannot be influenced by operations on another subsystem located far away. The two together constitute 'local realism'. They then presented an example of a two-particle system where their ideas led to consequences not describable by quantum mechanics, so the latter must be incomplete. They expressed the hope that quantum mechanics could be extended in some way, involving so-called hidden variables, to meet their requirements.

Of course Bohr responded immediately, refuting all their arguments [9].

Today it is clear that the quantum revolution comes in two parts – wave particle duality, dealt with by about 1930; and entanglement, emphasized by EPR in 1935, picking up steam in the 1960's as we will see, and still the focus of intense study. It is amusing that in his justly famous lectures, Feynman says that wave particle duality is the only mystery of quantum mechanics! [10]

The Second Quantum Revolution – von Neumann, Bohm and Bell

Now to the second quantum revolution. Based on certain assumptions, in 1932 von Neumann proved that there is no way to embed quantum mechanics in a larger theory more classical in nature, while retaining all the predictions of quantum mechanics [11]. Neither EPR nor Bohr refer to this in their 1935 papers. In 1952, motivated by EPR and earlier ideas of Louis de Broglie, David Bohm presented a classical realist interpretation of non-relativistic quantum mechanics, apparently contradicting von Neumann's Theorem [12]. This situation was examined in two brilliant papers by John Stewart Bell in 1964 [13]. He pointed out that von Neumann's main assumption was physically unjustified and unnecessarily strong. He then proved that any local realist extension of quantum mechanics along the lines of EPR's hopes would contradict quantum mechanical predictions at the statistical level. (In particular the Bohm Theory is spectacularly nonlocal). Thus the EPR ideas could be studied experimentally.

Einstein, Pauli and Heisenberg did take notice of Bohm's work, and responded. In 1952 Einstein said in a letter to Max Born: 'that way seems too cheap to me'. Both Pauli and Heisenberg also viewed Bohm's attempt negatively since it violated a formal symmetry between position and momentum present in standard quantum mechanics. Bohm responded in detail to all these criticisms [14]. In retrospect one sees that Bohm's work did play an important role in the development of the subject, since it inspired Bell to examine critically its 'violation' of von Neumann's theorem.

Starting from Aspect's experiments in the 1980's [15] to very recent and much more sophisticated ones, all the results have ruled in favour of standard quantum mechanics.

David Bohm J. S. Bell

Bell was a very strong critic of the standard interpretation of quantum mechanics, and often wrote almost scathingly about it [16]. It is said that he was angry with Bohr for never stating clearly the nature of the boundary between classical and quantum mechanics; and never writing down the details of the 'Copenhagen' interpretation of quantum mechanics. Unfortunately he did not work out his own comprehensive view of the subject either, as (it is said) he could not solve the relativistic measurement problem. Still his work inspired countless others.

After Bell's work, many other possible hidden variable extensions of quantum mechanics, based on weaker assumptions, were tried. Some did not involve statistical features at all. New concepts, such as contextuality, were added to realism and locality. But quantum mechanics would never yield, just more and more impossibility theorems got proved. There is no way to force quantum mechanics to become part of a larger more classical looking framework. The cures were all worse than the perceived diseases [17].

A Change in Attitude

These findings led to a changed attitude: accept the standard version of quantum mechanics, especially entanglement, then see how to combine it with Shannon's 1948 classical theory of information. This is an amazing piece of work which showed how to measure information quantitatively, in the classical sense, and gave rise to the information and communication revolutions of recent decades [18]. This has led to the fields of quantum information science and quantum computation [19]. Some famous results are the no-cloning theorem, quantum teleportation, and the Grover and Shor algorithms. Within quantum mechanics, some major developments are the idea of weak measurements, new terms in the Schrödinger equation, the micro structure of the process of measurement and the Born rule, to mention a few.

Concluding remarks

To draw towards a conclusion – using a double negative, not everyone is convinced that there are no problems in understanding quantum mechanics. There is still work remaining. In 1964 Feynman wrote [10]:

'I think I can safely say that nobody understands quantum mechanics'.

The fact is that over half a century later, Steven Weinberg makes rather similar comments. In a recent article [20] he says:

'Today, despite the great successes of quantum mechanics, arguments continue about its meaning, and its future, ...There is no argument about how to use quantum mechanics, only how to describe what it means, so perhaps the problem is merely one of words.'

He concludes that there seem to be two main options for a resolution, either the instrumentalist approach or the realist one, but each has problems. The instrumentalist approach takes the standard interpretation to be final, and accepts that quantum mechanics involves probability notions in an intrinsic manner. Recall here what Wolfgang Pauli said about probability [21]:

'The mathematical concept of probability is the outcome of an endeavor to give as objective a shape as possible to a subjective notion'.

As Weinberg says, this road can end up with saying that human consciousness is necessary to interpret quantum mechanics. How else can probability be understood and judged? Eugene Wigner had said this long ago [22]:

"...it was not possible to formulate the laws of quantum mechanics in a fully consistent manner without reference to the consciousness",

and Weinberg quotes this, though it is said Wigner later changed his mind. But it is unnerving to go along this road.

The realist approach abandons the probability interpretation of quantum mechanics, and declares that all the possible events with different probabilities described by quantum mechanics are actually realised, but each in a different world. All possibilities become actualities but not in the same world. This is the many worlds interpretation of Hugh Everett [23], but it seems intellectually too extravagant for words.

In another famous paper in 1985 by Anthony Leggett and Anupam Garg [24], they refer to

"... the genuine adherents of the relative-state ("many worlds") and mentalistic ("reduction-by-consciousness") interpretations of quantum mechanics".,

but guess that their numbers are small. That may depend on how far you push them.

Weinberg ends his article with a line from Shakespeare's 'Twelfth Night':

Viola: 'O time, thou must untangle this, not I'.

Let me conclude this impressionistic account of our subject by turning to J. B. S. Haldane to characterize the mystery aspect:

"...my own suspicion is that the Universe is not only queerer than we suppose, but queerer than we can suppose."

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References and footnotes

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