Pilot wave theory, Bohmian metaphysics, and the foundations of quantum mechanics

A graduate lecture course by Mike Towler (University of Cambridge, Lent term 2009)

Course web page : `www.tcm.phy.cam.ac.uk/~mdt26/pilot_waves.html`

All lectures on Wednesday afternoons at 3pm in the TCM Seminar Room (top floor, Mott building), Cavendish Laboratory.

Lecture 1 : 21st January - *An introduction to pilot wave theory*

Lecture 2: 28th January - *Pilot waves and the classical limit. Derivation and justification of the theory*

Lecture 3: 4th February - *Elementary wave mechanics and pilot waves, with nice examples*

Lecture 4: 11th February - *The theory of measurement and the origin of randomness*

Lecture 5: 18th February - *Nonlocality, relativistic spacetime, and quantum equilibrium*

Lecture 6: 25th February - *Calculating things with quantum trajectories*

Lecture 7: 4th March - *Not even wrong. Why does nobody like pilot-wave theory?*

Lecture 8: 11th March - *Bohmian metaphysics : the implicate order and other arcana*

- Final lecture to be followed by a GENERAL DISCUSSION "*What is this nonsense?*"

Course summary

Someone once memorably said: 'It is not clear what quantum mechanics is about.' and he wasn't wrong. The overabundance of quantum 'interpretations' is confusing even to professionals and - as presented in the mainstream media - the quantum theory is inevitably a mystical and bizarre subject involving splitting universes and superimposed cats in which objects do not exist until a conscious mind looks at them, and so on.

What is not widely understood, even amongst physicists, is that a belief in the mystical aspects of the theory is a *choice* that one makes, rather than something inevitable. One formulation of quantum mechanics - long ignored or derided by just about everyone - which makes this particularly clear is the *pilot wave theory* (also known as Bohmian mechanics, de Broglie-Bohm theory, the causal or ontological interpretation of QM). In this theory, wave particle duality is explained through the startlingly sensible notion of having both waves *and* particles (think about how that makes the double slit experiment intelligible!). So unlike in orthodox QM - where the wave function is all there is - the particles have an objectively real existence and they move along trajectories, guided by the waves. In such a formalism the standard paradoxes related to measurement, observation or wave function collapse (Schrödinger's cat, and so on) simply evaporate. The classical limit emerges out of the theory, rather than being presupposed. All the 'talk' is replaced by sharply-defined mathematics, it becomes possible to 'visualize' the reality of most quantum events, and - most importantly - the theory is completely consistent with the full range of QM predictive-observational data.

Amazingly, we will see that as early as 1924 (before the discovery of the matrix mechanics and Schrödinger theory) Louis de Broglie had the essence of the idea, and in fact he subsequently presented the more-or-less complete mathematical theory at the famous Solvay conference in 1927. How he ended up being beaten into the ground by the Heisenberg/Pauli/Bohr axis, abandoning his theory until Bohm took it up again the 1950s, is a fascinating story which we shall explore. As is the fact that Bohm was in his turn ignored and misinterpreted until an exploration of his work led Bell to his famous inequality which - contrary to popular belief - can be taken as evidence *for* the pilot-wave theory, rather than as a disproof of it. Even today, relatively few people have even heard of the theory.

Strictly speaking, pilot-wave theory is not really an 'interpretation' of anything, but a mathematical formulation of quantum mechanics with essentially the same status as Feynman's path-integral method. As such it can be used to do calculations with quantum particles following trajectories. In addition to looking at the pilot wave theory in terms of the foundations of QM, we shall therefore try to understand whether such calculations are likely to be of any use to us, either here in the TCM group or elsewhere.

In the last few decades of his life, Bohm began to devote more energy to metaphysical thinking and spent time 'hanging out with Indian gurus' (yet another reason why many refused to take his physics seriously). He explored the idea common in Indian philosophy that (to quote Valentini) 'material objects are somehow illusions and projections from something deeper, that things emerge from this deeper level and disappear into this deeper level again. So Bohm tried to adopt an interpretation of the wave as a manifestation of a deeper level, perhaps associated with consciousness. He called the wave an implicate order and the particle an explicate order.' Although it is true that these concepts were not directly connected to physics in any meaningful way, we shall for completeness - since many people mistakenly think them a fundamental part of the pilot-wave theory - look at these ideas in the final lecture.

It is a fact that many people do not appreciate that today it is simply untenable to regard the views of Bohr and Heisenberg expressed in the Copenhagen interpretation as in any sense standard or canonical. The 'meaning' of quantum theory is still a completely open question. However over the last ten or fifteen years, it seems that many people are starting to take pilot-wave ideas seriously and it might be said that the work of de Broglie and Bohm is finally beginning to bother the mainstream. As this is clearly not the case in the Cavendish, I hope that in this course we shall have a great deal of fun exploring the possibility that they were right.

Did I mention the two-slit experiment? But Feynman said this was '*..a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains the only mystery..*' and '*How does it really work? What machinery is actually producing this thing? Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a description of it.?*' Hmmm...