Ruward

Exam "Foundations of Quantum Mechanics"
29 January 2015, 9.00-12.00 a.m.

Please write your name and registration number on every sheet!

1. According to the philosopher Immanuel Kant it is part and parcel of the *concept* of an "object" that an object is something always possessing definite values for a given set of applicable physical quantities.
   a) Discuss whether or not this Kantian notion of an object is in accordance with the conceptual framework of classical mechanics.
   b) Discuss this same question in the context of quantum mechanics, and comment on the relevance of the Kochen and Specker theorem (explain what this theorem says).

2. Consider the following variation on the EPR experiment. We have three spin ½ particles, at very large distances from each other. It is given that the spin part of their total quantum state is given by $1/2\sqrt{2}\ \{|\uparrow\uparrow\uparrow\rangle - |\downarrow\downarrow\downarrow\rangle\}$, in which $|\uparrow\uparrow\uparrow\rangle$ stands for the three-fold tensor product of spin up states in the z-direction, etc. This is a state in which there is a strict correlation between spins in the z-direction: if one of the particles shows spin up (down), the other two will do the same.
   a) Construct a variation of the EPR argument to argue that the three particles in this state must each possess a well-defined spin value in the z direction, independent of measurement.

   b) It turns out that the above three-particle spin state predicts the certain value +1 for the product of the results of an x-spin measurement on any one of the particles and y-spin measurements on the others. Adapt the EPR-like argument to argue that the three particles must have definite spin values in all three directions x, y and z.

   c) Finally, it turns out that the above quantum state predicts with certainty that the product of the results of three x-spin measurements will be -1.
   Show that this prediction cannot be reproduced by a hidden variables theory à la EPR.

3. Bohm has shown that hidden variables are possible in quantum mechanics.
   a) Explain what the hidden variables are in Bohm's theory.
   b) Suppose we are going to measure the values of these hidden variables. Will we find the values that were present before the measurement? Explain your answer, and illustrate it with an example. Is there a relation here with no-go theorems like the one by von Neumann or the one by Kochen and Specker? Explain.

4. Suppose that an object system O enters into an interaction with a measuring device M that has been designed to measure observable **A**.
   a) Explain how this measurement interaction should be described in quantum mechanics, according to von Neumann.
   b) Explain why and how the final state of this interaction gives rise to the "measurement problem".

c. In what way is this problem accommodated by the standard postulates of quantum mechanics? Do you think that this standard solution is adequate?

5. It is often claimed, in the secondary literature, that Einstein's problem with quantum mechanics was first and foremost the indeterministic character of the theory (viz. "The Old One (i.e. God) does not play dice"---"Der Alte würfelt nicht"). But Einstein was actually very explicit that his main problem was different (e.g., in conversations with Pauli, as reported in Don Howard's article). Explain what Einstein's real problem was, and relate this problem to the concept of an "entangled state". Finally, attempt to relate this problem to the difference between pure states and mixed states, and the interpretation of mixed states.