Teaching ideal quantum measurement: from dynamics to interpretation

The interpretation of quantum mechanics has been subject of debate since its inception in 1925. This leads not only to philosophical debates, but also to questions in teaching at various levels.

Given that a measurement is the only point of contact between quantum formalism and the reality in a laboratory, Armen Allahverdyan (Yerevan), Roger Balian (Saclay) and Theo Nieuwenhuizen (Amsterdam) have taken, in a decades long collaboration, the viewpoint that one should model theoretically what happens in a laboratory, and draw the interpretation from that. This led them to introduce in 2003 the "Curie-Weiss model for quantum measurement", write a review paper on models for quantum measurement with an extensive analysis of the Curie-Weiss model in 2013 and an interpretational paper in 2018.

In the Curie-Weiss model, a spin 1/2 is measured by an apparatus which consists of a magnet and a bath. The magnet consist of many spins 1/2, coupled to each other in the z-direction. Its magnetization in the z-direction is the macroscopic pointer of the measurement, which can be read off. The bath is a large set of harmonic oscillators, coupled to each component of each spin of the magnet. As a whole, the system is closed.

The approach is to first solve the dynamics of the measurement and then provide an interpretation for the loose ends. The dynamics reduces to the evolution of the magnet in the various sectors of the tested spin (up-up, up-down, etc.) There appear two regimes: the off-diagonal elements of the density matrix (the so-called "Schrödinger cat" terms) vanish quickly, first by decoherence, and are later washed out, for instance by decoherence due to the bath. The diagonal terms relate to registration, whereby the magnet goes from its initial metastable (paramagnetic) state to one of the of the stable ferromagnetic states. Its initial magnetization is zero, and its final one is upwards or downwards, which can be read off.

– Due to the unitary motion, one might think that a measurement is in principle impossible. However, it is important to look at conditions of practical interest. While the dynamics is in principle subject to Poincaré recurrences, on timescales of practical interest the magnet relaxes from its initial non-magnetized initial state to one of the magnetized final states, which can be read off within a reasonable time.

– Born's rule emerges technically from the dynamical conservation of the tested variable in an ideal experiment. Born probabilities relate to the indications of the macroscopic pointer, and only indirectly to the microscopic system.

– The "measurement problem", here: the fact that each individual run of the experiment yields a defined outcome, cannot be solved within the quantum formalism, which does not describe individual processes. It is dealt with by means of a postulate that complements this formalism and makes it compatible with experimental macroscopic evidence. This allows to describe theoretically, among the large set of tested systems described by the mere quantum formalism, the subsets characterized by a common pointer value.

– Consideration of simultaneous, non-commuting experiments leads to "quantum" concepts such as quantum-probabilities and quantum-correlations, that are analogous to physical probabilities and correlations, but cannot always be identified as such.

All in all, the analysis supports various viewpoints known in the literature. The wave function (in general: the density matrix) codes our best knowledge about the set of systems to be measured (Bohr's catalog of knowledge); the "collapse of the wavefunction" is an update of the description after having read off the pointer and selected the systems accordingly. Most revealing is that the Born probabilities, coded in the initial state, are conserved dynamically so as the determine the probabilities in the final sate.

This and much more is now summarized in a paper meant for teachers of quantum mechanics, as well as for advanced students, at various levels.

Armen E. Allahverdyan, Roger Balian and Theo M. Nieuwenhuizen
Teaching ideal quantum measurement: from dynamics to interpretation
Comptes Rendus Physique (2024).