An approach to the measurement problem based on a detailed consideration of quantum ensembles

Two main ingredients are sufficient to account for all properties of ideal quantum measurements, including the uniqueness of the outcome of each individual run: (i) Describing by means of quantum statistical mechanics the dynamical behavior of the apparatus coupled with the tested system, not only for the full density matrix associated with an ensemble of runs, but also for its decompositions. (ii) Introducing, only for the macroscopic pointer variable, an interpretation in terms of sub-ensembles of the mathematical expressions thus obtained at the final time.

New "weak" postulates

Although quantum mechanics is our most universal and successful theory, its foundations still raise questions, especially about quantum measurements. When one wishes to show that the description of measurements as dynamical processes that couple the tested system S and an apparatus A, treated as a quantum object, is consistent quantum mechanics, one faces the celebrated "measurement problem". One should understand why successive runs of a repeated measurement yield different but well-defined outcomes, although quantum theory assigns to the compound system S+A a density operator that describes only globally the large ensemble of runs.

In classical statistical mechanics, probabilistic information about individual systems would readily be derived from the probability distribution that describes their ensemble; however, in quantum mechanics, Schrödinger's ambiguity for the decomposition of mixed density operators impedes such a step. The quantum formalism must therefore be supplemented by some principles (postulates) which relate theory to observational facts, and thus allow to make statements about individual objects. Our aim is to impose the weakest postulates, weaker than the Copenhagen ones.

Thermodynamic equilibrium

The recent approach of Allahverdyan, Balian and Nieuwenhuizen [1] aims at introducing a minimal set of such principles needed to explain measurements, after having drawn from the abstract formalism of quantum statistical mechanics the strongest possible conclusions about the process. As the apparatus is macroscopic, the states of S+A are represented by density operators which encode "q-probabilities", "q-correlations" or "q-expectation values", without interpretation yet. The expected final state of S+A is first recognized to be a thermodynamic equilibrium state with broken symmetry, and the ideal measurement process appears as a relaxation towards it.

Many models, reviewed or worked out in [2], have exhibited the mechanisms that ensure this relaxation, which encompasses the creation of correlations between the tested system and the pointer in the diagonal blocks of the density matrix of S+A, and the disappearance of its off-diagonal blocks. Moreover [1, 2], non-trivially due to Schrödinger's ambiguity, the latter two properties are shown to hold not only for the state describing a large ensemble of runs but also for a more detailed description by means of states describing its sub-ensembles; the proof relies on a new mechanism, the poly-microcanonical relaxation, which involves only the apparatus near the end of the measurement. The set of sub-ensembles contains “pure” sub-ensembles for which every member produces the same pointer indication, hence connecting to individual measurements.

Assigning probabilities

When evaluating q-expectation values in the final state of the process (for both the full ensemble of runs and its sub-ensembles), the observable associated with the macroscopic pointer is shown to behave as if it commuted with any other observable of S+A. This suggests to introduce a principle restricted to the pointer variable near the end of the measurement: The q-probabilities assigned by the abstract quantum formalism to the possible outcomes are identified with ordinary probabilities of occurrence for the physical indications.

This limited interpretation of ideal measurements, introduced only for the macroscopic pointer, is sufficient to ensure that the uniqueness of the outcome of an individual run is consistent with quantum mechanics, and to produce Born’s rule and von Neumann’s reduction. Using this approach to understand other types of measurement raises open questions. An alternative understanding of the measurement problem might also arise from a deeper consideration of quantum states.

References

[1] A.E. Allahverdyan, R. Balian, T.M. Nieuwenhuizen, A sub-ensemble theory of ideal measurement processes, Annals of Physics 376C (2017) 324–352.

[2] A.E. Allahverdyan, R. Balian, T.M. Nieuwenhuizen, Understanding quantum measurement from the solution of dynamical models, Physics Reports 525 (1) (2013) 1–166.

Affiliations: Armen E. Allahverdyan (Yerevan Physics Institute, Yerevan, Armenia), Roger Balian (Institut de Physique Théorique, CEA Saclay, France), Theo M. Nieuwenhuizen (Institute for Theoretical Physics, University of Amsterdam, Netherlands and International Institute of Physics, Natal, Brazil).