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Book Review: The Quantum Theory of Measurement

The Quantum Theory of Measurement, P. Busch, P. Lahti, and P. Mittelstaedt, Springer Verlag, Berlin, 1991

The aim of this book is to give a precise formulation of quantum measurement theory. The problem of measurement is treated in the framework of ordinary Hilbert space quantum mechanics. This well-written book presents an excellent exposition of its subject.

A brief historical account is given in the Introduction. Important questions which a theory of measurement has to answer are: how object systems are brought into well-defined states, how they are prepared, how they are registered by an apparatus, and how observables are measured. A guide to the various interpretations of quantum mechanics is listed in a decision tree at the end of the Introduction.

For Chapter 2, a physical system S is represented by a complex separable Hilbert space H. On H, states T and observables E are defined as positive trace-one operators T on H and positive operator-valued measures E, where the value space of E is usually a Boolean σ-algebra F, arising as a product of real Borel spaces. The minimal interpretation says:

(1) For $X \in F$ the number $E_T(X)$ is the probability that a measurement of E on the system S in the state T leads to a result in X.

Compound physical systems $S+A$ consisting of an object system S and an apparatus A are based on the tensor product K of their associated Hilbert spaces. Reduced dynamics on K and the dynamical unitary group U_t (t: time) yield linear state transformations V_t for states of S, which play an important role in the quantum theory of measurement. Gleason's theorem is formulated for H. Some of its important consequences of the probabilistic structure of quantum mechanics are: irreducibility of probabilities, nonobjectivity of observables, nonunique decomposability of mixed states, and limited applicability of the ignorance interpretation of mixed states.

Chapter 3 contains a systematic treatment of the quantum theory of measurement. A survey on the notion of measurement is given, the objectification problem of isolated systems is described, and the measurement

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coupling is defined by five-tuples (H, P, T, V, f), called premeasurements of an observable E of an object system S, where H is a Hilbert space for the measuring apparatus A, P is a pointer-observable of H which is to be correlated with E, T is an initial state of S in A, V is a (trace-preserving positive linear) state transformation, and f is a measurable function which correlates the value sets of the observables P and E. Premeasurements are defined as producing correlations between E and P such that the probability reproducibility requirement is satisfied. Premeasurements qualify as measurements if they lead to a definite result, which is also called the objectification requirement. Normal unitary premeasurements exist for discrete ordinary observables. Lüders and von Neumann measurements and instruments are defined. The final state of an object system after a Lüders or von Neumann measurement is in general not the same. Concerning (1), two approaches of a statistical interpretation of $E_T(X)$ are discussed: the measurement statistics of Cassinelli–Lahti 1989 and the statistical ensembles of Everett 1957. (Strong) correlations of states and observables and first kind, repeatable, and ideal measurements are studied. Some results are: Quantum mechanics allows for ideal and repeatable measurements. No continuous observable admits a repeatable unitary measurement. Complementary observables do not admit any joint measurement. A classification of premeasurements and the concepts of entropy and information are given for a state. Problems and results on objectification, measurement dynamics, state preparation, and limitations on measurability conclude this chapter.

Objectification and interpretations of quantum mechanics are the theme of Chapter 4. Write PR for "probability reproducibility condition," O for "objectification requirement," U for "unitary measurement coupling," HO for "measurement coupling is generated by an observable," QS for "the object system is a proper quantum system," and CP for "the pointer observable has some classical properties." Logical problems encountered with the measurement problem are:

(MP1) PR, O, U, QS imply CP.
(MP2) U, HO, CP imply $\neg$PR.

Several interpretations are presented: the Copenhagen interpretation, the ensemble and hidden variable interpretations, and without objectification the many-world interpretation and the witnessing and modal interpretation. Some modifications of the usual quantum mechanical axiomatics are necessary with regard to (MP1) and (MP2) in order to explain the effective classical nature of the pointer observable. Within quantum mechanics are discussed: (dynamically induced) superselection rules, an environment approach, and unsharp observables. Some approaches beyond quantum mechanics, using C^*-algebras instead of Hilbert spaces, continuous superselection rules, and operational approaches, are mentioned at the end of this chapter.

In a concluding discussion the obstacles for a language of the quantum theory of measurements are reviewed concerning no-go theorems and objectification. The pertinent references to this material are given at the end of the book.

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