Everything is quantum: what I measure, my detector, myself!

Since the first formulation of quantum mechanics, Nature has been divided into two categories: the classical world (that of tennis balls) and the quantum world of atoms and photons. The transition between the two is made by the wave function collapse during the measurement process. From the multitude of possible measurement results included in the wave function, only one value comes out, the one actually measured, corresponding to a particular state of the wave function. This is an irreversible process, quite different from the (reversible) evolution of the system just before the measurement according to the Schrödinger equation. Two worlds and two types of dynamics... too complicated! Another approach is possible by considering that everything is of a quantum nature: the system studied, the measuring apparatus, the observer and even the watch that marks the time of the measurement. A researcher of the team Clusters and surfaces under intense excitation (ASUR acronym in French) of the INSP has shown that, with this approach, the probability function of the measurement results is simple and unique. Moreover, it is valid for tennis balls as well as for photons.

Let us suppose that the system we want to study follows the rules of quantum mechanics. Let us also suppose that the measuring device follows the same rules, but also the person who measures, his brain and his watch which gives him the time of measurement. We then have chains of quantum systems entangled with each other and linked by unitary reversible interactions, i.e., compatible with the Schrödinger equation, without any collapse. Nothing new until then; Everett had already considered this scenario in 1957 and several authors have rediscovered or repeated it afterwards. But how to get out predictions and probabilities from these networks of relations? If everything is quantum, all the ingredients considered (measured system, measuring apparatus, observer, clock, etc.) can be described in an abstract space, called kinematic Hilbert space. The dynamics of the system and its observation are now included in the global wave function, which extends in time and describes everything. In this framework, formulated for the first time by Page and Wootters in 1983, a clock is just an additional quantum system, consisting for example of a spin in precession, with the time defined by the orientation of the spin at the moment of its measurement.

If the system under study, the observer and its clock can be all described in a unique Hilbert space, each measurement can be associated to an operator that lives in such a space. We show [1] that the form of the associated probability is then univocally defined by a mathematical theorem (Gleason-Bush theorem). The expression of probability function, including the associated conditional probabilities resulting from an intermediate measure, is then well defined. This allows to describe also confusing cases like the Wigner's friend scenario where one person observes another person and both measure apparently contradictory things (see figure). The obtained unambiguous expression of the probability for a particular a result underlines on the contrary the relative aspect of the measurements. Wigner sees his friend as being in a quantum superposition but also the friend sees Wigner in a superposition state. No paradoxical situation appears.

Figure
Artistic illustration of the case of Wigner's friend. Wigner's friend makes a measurement on a system which can give as a result «up» or «down». Wigner measures the system as well and, at the same time, the result of the friend's measurement, but with a different basis: «left» or «right». Therefore, Wigner and his friend have a different perception of the same system studied; hence the apparent paradox.

If our probability function is unique, how is it possible to apply the same rule to the classical world as to the quantum world? Indeed, for tennis balls that pass through two slits, A or B, and are then detected by a detector D, the probability of passing through A or B is equal to the probability of passing through A plus the probability of passing through B. At the quantum level, the world of atoms and photons, this simple sum rule is no longer valid (with the appearance of interference phenomena). An accordance can be found if we generalize the definition of probability even more. The standard approach to define the probability of a measurement is to associate it with an operator in the associated Hilbert space. An equivalent formulation can be obtained by defining the probability as a quantitative measure (between 0 and 1) that a proposition such as “I measured x at time t0” is true, like Bayesian probabilities. With this approach, we show [2] that the sentence “I measured A and D or B and D” is no longer equivalent to “I measured A or B and D”. In the first case, we have the probability of tennis balls because we can in principle follow their trajectory, which consists of the propositions “A and D” or “B and D”. In the second case, the intrinsic ignorance of “A or B” causes the possible presence of interference. In both cases, it is always the Gleason-Bush theorem that dictates the unique form of the probability. In the more specific framework of Rovelli’s relational quantum mechanics (1996), such a definition reduces its postulates from three to two [3].

In 1951, Richard Feynman, one of the fathers of quantum electrodynamics, wrote “The concept of probability is not altered in quantum mechanics... What is changed, and changed radically, is the method of calculating prob- abilities”. This work demonstrates that this is not necessarily true. The probability function is universal. It emerges unambiguously and naturally when all the systems involved, including the observer and the clock, are considered as quantum systems. What should not be considered valid is the distributive property of the arguments (and of the logical operators «and» and «or») of the probability function. The transition from tennis balls to photons is only a question of measurement accuracy and of the entanglement between the system under study, the measuring apparatus and the observer.

References

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