"Human, All Too Human:" On the concept of quantum state, from Bohr's atom to quantum automata

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Bohr's 1913 atomic theory is well known for several radical ideas, at the time even more radical than those, quite radical already, of his main predecessors, Planck and Einstein. One of these ideas, arguably most radical conceptually, is often overlooked or underappreciated. This idea could be sketched as follows, in part courtesy of Laurent Freidel's argument. The classical electron theory of H. Lorentz and his followers considered the probability of finding a moving electron in a given state, under the underlying realist assumptions, in particular that of (causally) representing the motion of electrons in terms of oscillators. Bohr's theory was instead concerned with the probabilities of transitions between stationary states, thus essentially defining quantum discreteness, without assuming the possibility of representing these transitions and, as a result, abandoning causality as well. This change of attention toward transition probabilities between quantum states was central to Einstein's remarkable 1916 treatment, using Bohr's theory, of spontaneous and induced emission and absorption of radiation, and then to Heisenberg's discovery of quantum mechanics, which abandoned any attempt at a mechanical (orbital) representation of even stationary states, as well as of transitions between them. As he wrote to R. Kronig, "What I really like in this scheme is that one can really reduce all interactions between atoms and the external world ... to transition probabilities [between states]." Note that one no longer thinks so much in terms of discrete quantum objects, such as electrons, but rather of discrete states of these objects, object that are no longer physically described, and probabilities of predicting these states. It follows that there is not, or in any event there may no longer be, either any underlying continuity or any underlying causality of quantum processes left, the probabilities of transitions between allowed stationary states, or by implications quantum states in general.

Taking this concept, which I assume to be crucial for all quantum theory, as a point of departure, this paper considers the concept of quantum state, both physical, to which and only to which the preceding description referred, and mathematical, as a vector (for which the name state may well be misleading) in the Hilbert-space formalism of quantum mechanics and then quantum field theory, and the relationships between both. I then argue that both concepts and the relationships between them underwent another revolutionary change with quantum electrodynamics and quantum field theory. The nature and implications of this change, specifically for the concept, physical and mathematical, of quantum field are far from fully explored and even understood even now, nearly a century since the theory was introduced by Dirac. I close by considering the implications of this situation for quantum information theory and, in part, via quantum information theory, quantum gravity.