Einstein und Bohr Verschränkten

Einstein and Bohr were the dominant figures in the conceptual foundations of quantum measurement in the early to mid-20th century. They were both exceptionally conceptual and deductive thinkers. The thirty-five-year long series of disagreements over thought-experiments constituting the Bohr-Einstein debates were the sounding chamber for the clarification of the central issues of quantum measurement and to which the various other players reacted and responded. These debates began essentially when they first met in 1920 and carried on at various levels until Einstein's death in 1955. Particularly prominent were the disagreements at the 5th and 6th Solvay conferences in 1927 and 1930, respectively and with the EPR paper in 1935. Einstein initially attempts to undercut quantum mechanics by demonstrating the possibility of intrinsic violations of Heisenberg's uncertainty principle and Bohr finding the often subtle flaws in Einstein's schemes. Einstein eventually lowers his sights with the goal of showing quantum theory to be incomplete rather than incorrect. However, more recently there has been the acknowledgment that both Einstein and Bohr unmistakably appreciated early on that *entanglement* was the principle feature of quantum theory that needed to be confronted, though they may not have always used the term. The evidence for this has been particularly emphasized by Howard [3]. For Bohr, entanglement was the underlying enforcer of complementarity. For Einstein, entanglement was the impediment for his view that real states of spatially separate objects are independent of each other. Their joint recognition of entanglement ultimately overrode other concerns over science and that led to their being themselves intertwined or *entangled – verschränkten* – and in disagreement over quantum theory for over three decades. And as demonstrated and emphasized in this book, entanglement is the key to defining and resolving the measurement problem. Einstein and Bohr were the key players in defining the issue of quantum measurement.

As discussed in the section *Planck's Fortunate Guess*, Einstein had mentioned in a 1909 letter to Lorentz that it would be problematic if his proposed light-quanta behaved as independent particles, since "A light ray divides, but a light quantum indeed cannot divide without an alteration of frequency." For Einstein, this was the source of the infection, the first inkling that nature would not conform to a view where separate parts of space have an independent real existence. The conspiracy involving the ingredients "nondeterminism", "whole photon or nothing," "exact conservation for individual events," and "entanglement" appeared to be built-in features of nature. However, yet another factor entered with Bose statistics in 1924 so that Einstein's light quanta must be bosons, further reinforcing the lack of corpuscular independence for photons but also necessary for Planck's black-body formula. Bose and Fermi statistics thus also enter into Nature's conspiracies and thereby the measurement problem. Wave-particle duality is intrinsic in the proceedings of quantum theory. Bohr's rethinking of an ordinary space-time description was given another jolt four years later with the failure of the 1924 BKS theory after the Compton-Simon and Bothe-Geiger experiments showing exact conservation for individual events. The conspiracies that Nature required to implement the quantum of action into the universe were closing in on both Einstein and Bohr. Over the succeeding three years, with the complete theory of quantum mechanics and in particular Heisenberg's indeterminacy principle, Bohr's thinking moved inexorably toward complementarity.

In the 1927 Solvay conference, Einstein's single slit (i.e. beam splitter) thought-experiment had brought out aspects of nonlocality, incompleteness and energy conservation, Figure 5.15. A more celebrated photon-box thought-experiment occurred at the 1930 Solvay conference. Einstein envisioned a mirrored box that could contain a photon for an arbitrary lapse of time. A precisely timed shutter mechanism allows accurate timing of the photon emission from the box. The box is suspended by a spring so that it can be weighed before and after the photon emission and thus finding the photon's energy by the mass-energy equivalence relation of relativity and apparently violating Heisenberg's time-energy uncertainty principle; i.e., weigh the box to fix the energy and open the box to check the clock. According to Bohr's 1949 retelling of the story [503], after a sleepless night of being stumped, Bohr realized that the weighing of the box requires vertically moving the box in the gravitational field and that Einstein's theory of relativity predicts that this will change the rate that the clock ticks. A calculation showed that this introduced just the uncertainty in the clock's rate to save Heisenberg's indeterminacy. Thus, Einstein was defeated in yet another debate.

However, Einstein explained later to Ehrenfest that he also had another purpose in mind for his photon box [111]. In this variation, the emitted photon is allowed to be reflected back from a mirror at an arbitrarily long space-like separated distance. At the time of the photon's distant reflection, we can make a choice to either weigh the box or check the clock. Einstein argued that this choice can have no effect on the distant photon so it will be identical whenever it returns. However, quantum mechanics would ascribe a different state depending on the choice. Therefore, Einstein had concocted yet another argument for him to claim that quantum mechanics is incomplete. And once again, Einstein had devised an example that intrinsically involves what would come to be known as entanglement. Einstein's own 1949 comments point to Einstein's and Bohr's mutual appreciation of entanglement's role in quantum mechanics [504, p. 681],

> *...Niels Bohr seems to me to come nearest to doing justice to the problem. Translated into my own way of putting it, he argues as follows: if the partial systems A and B form a total system which is described by its* Ψ*-function* $\Psi(A, B)$*, there is no reason why any mutually independent existence (state of reality) should be ascribed to the partial systems A and B viewed separately, not even if the partial systems are spatially separated from each other at the particular time under consideration. The assertion that, in this latter case, the real situation of B could not be (directly) influenced by a measurement taken on A is, therefore, within the framework of quantum theory, unfounded and (as the paradox shows) unacceptable.*

Albert Einstein, Remarks to the Essays Appearing in this Collective Volume, p.663 in Albert Einstein: Philosopher-Scientist, Schilpp, Paul Arthur (Editor), Cambridge University Press 1949.

Even noninteracting systems that are spatially separated cannot always maintain mutual independence. And this applies when such systems involve an observed subject and a measurement apparatus, leading to inevitable correlations. As Bohr had explained in 1928 [442, p. 78],

> *…in order to make observation possible we permit certain interactions with suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word. The very nature of the quantum theory thus forces us to regard the space-time co-ordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description…*

S. Petruccioli, Atoms, Metaphors and Paradoxes, Niels Bohr and the construction of a new physics, Cambridge University Press 1993.