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BOOK REVIEW

Alain Aspect, *Einstein and the Quantum Revolutions*

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Alain Aspect's *Einstein and the Quantum Revolutions* is a republication and translation (by Teresa Lavender Fagan) of a 2019 volume in the CNRS (National Centre for Scientific Research) series The Great Voices in Research, presenting the work of CNRS gold medalists. The book offers a bird's-eye view of the development of quantum physics. Written for a general audience, it is similar to Carlo Rovelli's short books on physics; at the same time, it is relevant for historians of science for its unique vision of the history of quantum physics from a cutting-edge Nobel Prize-winning experimental, rather than theoretical, physicist.

By the second sentence, in which the quantum revolution is equated to the industrial one, it is clear that we are reading an experimentalist's views on quantum mechanics. Aspect then nods to the Baconian goal of changing society through scientific theories. But his vision goes further: according to Aspect, there were two quantum revolutions. Historians have focused on the first, of the early twentieth century. The second is equally acute as a theoretical development, but potentially more important in its applications. It started with a focus on one of the trickiest quantum puzzles – quantum entanglements – but steadily led to groundbreaking experimental work, including Aspect's, and to quantum computing. The crux of the book's concise analysis is its identification of a feedback loop between quantum theory, experiments and applications, all of which have probed the limits of the physical world.

Aspect narrates the first quantum revolution in a conventional way, taking a compressed walk through emergence of quantum theory and quantum mechanics, from Planck's considerations of black-body radiation and his unconventional idea of handling it via discrete energy exchange of radiation, to Albert Einstein's idea of constitutive radiation packets (photons) and the dependence of their energy on frequency rather than intensity, to wave–particle duality and the formal (matrix and wave) duality that captured it, to Dirac's formal unification of theory in the 1930s. What stands out as a theoretically daring insight among many from the first revolution, according to Aspect, is Einstein's vision of radiation composed of discrete units, since the insight went against the entire nineteenth-century construction of radiation as a continuous-wave phenomenon.

A brief historical account of wave–particle duality is followed by discussions of Aspect's experiments with Philippe Grangier testing it using individual photons. The beam splitting produced interference patterns, even when individual photons were emitted from the source. Any doubt that wave–particle duality would hold at the level of individual particles vanished. The experimentalist's perceived choice between whether the apparatus would measure the wave or particle feature of the splitting beams was reformulated by John Wheeler as the hypothesis of the 'choice' of a beam, or an individual particle, that could be tested with a delay. Wheeler's suggestion was realized in 2007 at the Institute of Optics at Orsay. Findings showed that the individual split beam can be switched to one or another feature-measuring apparatus within twenty nanoseconds, while the related choice cannot be signalled because the signal from the splitter has insufficient time (if travelling at the speed of light) to reach the detector. The results cemented the duality, even in such conditions.

The success of quantum mechanics as a founding theory for particle physics led to unprecedented experimental precision in ever-more powerful colliders. However, the seeds of the second quantum revolution were sewn already at the tail end of the first revolution, in the famous dialogue between Einstein and Niels Bohr. Einstein argued for an upper limit for correlations between quantum systems. These apparent quantum entanglements of particles suggested to him that quantum mechanics was incomplete. Aspect refers to Bohr's successful countering of Einstein's point as resulting from Bohr's prestige, rather than from the strength of his argument. This has been conventional wisdom for a long time, but in fact Bohr was siding with experimentalists (as I have argued elsewhere): Einstein's challenge was fine but it was in dire need of a truly novel experiment that would test it directly; the existing ones did not support it. Aspect himself realized such an experiment, but was preceded by a more poignant formulation of the Einstein–Bohr dilemma provided by the so-called Bell inequalities, which set an upper limit of correlations of quantum phenomena.

John Stuart Bell's 1964 result went virtually unnoticed by physicists, but it caught the eye of the astute experimentalist. Aspect realized that polarization experiments could resolve a long-standing philosophical dispute. His now famous Nobel Prize-winning experimental apparatus, as well as those of his co-laureates Anton Zeilinger and Nicola Gisin, enabled quantum correlations at distances that, due to the speed of light, prevented signalling from one entangled state to another while the states were randomized and measured at the precision of a few nanoseconds. The result demonstrated non-local correlations violating Bell's inequalities, as any possibility of local correlation prior to or during the experiments was eliminated.

The third phase of the second quantum revolution is an application phase uniting the theoretical insights into non-local quantum correlations and the experimental manipulation of individual components (electrons and photons) of entangled states. It may prove to be the most impressive one. If an entangled state is treated as a piece of information, a quantum bit of 1 and 0 (a qubit), then the process of quantum entangling of qubits can potentially be treated as a computer run by algorithms. If the initial state of a system is well set, the entangled 'mixture' of potentially millions of qubits may provide the useful computing output, something a regular computer could not do within a reasonable period, as it lacks the parallel computing channels enabled by quantum entanglement 'cheating'. Even though quantum physics does not prohibit this, it is easier said than done, as any 'perfect' entangled qubit is violated by hundreds of undesired ones. Aspect tackles this challenge and summarizes the others he is currently in the process of solving.

Aspect ends this readable book with a chapter on quantum cryptography. In the spirit of his historical take on quantum physics, he encapsulates the loop that started with a philosophical debate on quantum entanglements and which may enter our daily lives: 'If we observe a violation of the Bell inequalities, we can be sure there isn't a spy online.'

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