Einstein's Quandary

A conflict of views on the nature of quantum mechanics emerged in the first half of the 20th century, with researchers such as Bohr, Born, Heisenberg, Jordan, and Pauli embracing nondeterminism, each with subtle differences in their positions, while Einstein, Planck, Schrödinger, and de Broglie were inclined towards determinism though for differing reasons [320, p. 18]. De Broglie tried to maintain determinism within a picture of waves piloting particles of well-defined position. Schrödinger despaired of the quantum jumps of particles but an acceptable wave picture seemed to him out of grasp after he had uncovered the inevitability of entanglement in 1935 [424] [425] [426]. Einstein put forward a series of *gedanken experiments* to first test the consistency of quantum theory and later its incompleteness while taking the long-term view that the field approach of his gravitational theory held the seeds to also include the quantum. However, not being able to find a way, his thoughts remained conflicted as he grasped at other possibilities. In a 1935 letter to Paul Langevin, Einstein wrote [427]

> *In any case one does not have the right today to maintain that the foundation must consist of a field theory in the sense of Maxwell. The other possibility, however, leads in my opinion to a renunciation of the time-space continuum and to a purely algebraic physics. Logically this is quite possible… Such a theory doesn't have to be based upon the probability concept…*
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> John Stachel, The Other Einstein: Einstein Contra Field, Science in Context 6, 275-290 Cambridge University Press (1993).

However, the situation remained murky. The issue was clarified further in a 1929 paper [428] by Nevil Mott (1905-1996), a future Nobel laureate, for work in magnetic and disordered systems. Mott used quantum mechanics to analyze the probabilities of exciting atoms at successive positions in a cloud chamber and found that the probability is negligible unless they lie on a linear track. Heisenberg did a similar analysis the same year in his Chicago Lectures [429, p. 66]. From these analyses, there is a set of potential linear tracks pointing in different directions, but with the set of potential tracks still maintaining the spherical symmetry of the incoming spherical wave of the α-particle. The issue then arises as to how one particular linear track is picked out of the infinitely many potential linear tracks, Figure 5.8. This is where the measurement problem is seen—during a measurement which is consistent with only one of the lines of ionization probabilities. This issue clearly has interesting similarities with the issues of *potentiality* and *actuality* that were considered by

Aristotle as discussed in the section *Backstory to Deductive Thought*.

The logical possibilities and pitfalls of following the paths of quanta were explored in Chapter 1, and it was seen that there is always a price to pay for any attempted tampering with wave-particle duality. The formulations of quantum mechanics by Heisenberg, Schrödinger, and Born, give a correct description of wave-particle duality, with knowledge that either the system evolves like a delocalized unitary wave evolution or as a localized particle via Born's rule when measurement has occurred. In addition to the Heisenberg and Schrödinger formations of quantum mechanics, a third way was found in 1948 by Richard Feynman (1918-1988) in terms of a sum over all possible paths of a particle, the summation represented mathematically by a path integral. In contrast to the wave picture of Schrödinger, Feynman's picture has

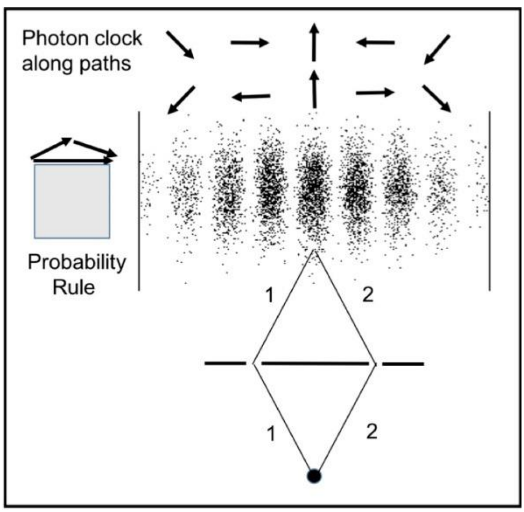

Figure 5.13: Photons interfering as particles via Feynman's sum-over path picture, with clock hands rotating along each path at the photon frequency rate and interference given by a head-to-tail probability rule.

localized particles moving along the paths but the particles are also able to endow the paths with the ability to interfere with each other to produce the quantum properties. At first glance, this may appear as another suspicious tampering of wave-particle duality, but Feynman could show that his scheme is equivalent to the Heisenberg and Schrödinger formulations. For photons moving along paths, Feynman's method can be visualized in a remarkably simple way [430] to unveil what properties localized light quanta need to exhibit correct wave-particle duality. Feynman explained that the machinery of his sum-over paths method implies that the photon essentially carries along a "clock" as it moves along each path, which can be thought of conceptually as an arrow rotating at the rate of the photon's frequency as shown schematically in Figure 5.13 for two photon paths in a double-slit experiment. The clock arrow will point in different directions as the photon moves along a path and the directions will generally be different for different paths. However, the paths can interfere with each other as they have a square probability rule for the sum over paths: the clock arrows are added head to tail and the resultant arrow is squared to give the probability of finding the photon at that location. As seen in Figure 5.13, the arrows add at interference maxima and cancel at minima. This method has been successfully applied to experiments in photon optics and in explaining the limit of how classical lenses and gratings function.

After Feynman had developed the sum-over-paths method, Feynman's professor, John Wheeler (1911-2008), thought this intuitive depiction might sway Einstein's view of quantum mechanics [431]:

> *"Visiting Einstein one day, I could not resist telling him about Feynman's new way to express quantum theory. "Feynman has found a beautiful picture to understand the probability amplitude for a dynamical system to go from one specified configuration at one time to another specified configuration at a later time. He treats on a footing of absolute equality every conceivable history that leads from the initial state to the final one, no matter how crazy the motion in between. The contribution of these histories differs not at all in amplitude, only in phase…This prescription reproduces all of standard quantum theory…Doesn't this marvelous discovery make you willing to accept quantum theory, Professor Einstein?" He replied in a serious voice, "I still cannot believe that God plays dice. But maybe," he smiled, "I have earned the right to make my mistakes.""*
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As seen in all three of the quantum formulations, a picture of localized quanta must also possess subtle additional features in order to exhibit correct wave-particle duality. The history of this begins with Einstein. Planck's discovery of the quantum of action led Einstein to take a further step beyond Planck and consider light-quanta in his miracle year of 1905. Even before Planck did so himself, Einstein had realized that Planck's radiation law meant that a new kind of physics was called for. Einstein said it was [339]

> *as if the ground had been pulled out from under one, with no firm foundations of physics to be seen anywhere, upon which one could have been built.*
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> Albert Einstein, Autobiographical Notes in Albert Einstein: Philosopher-Scientist, Paul Arthur Schillp (Ed), Cambridge University Press 1949, pp. 2-49.

However, in 1905 Einstein treated the light-quanta as independent particles with no wave-particle duality yet in sight. Einstein had previously developed expertise in calculating fluctuations in ensembles of molecules, such as in the Brownian motion paper [432], and these were the tools he had at hand for the theory of light quantization. In doing so, he remarkably was able to infer from the macroscopic properties of heat radiation their corresponding microstructure in terms of a fluctuating quantity. Unlike the molecules in his previous fluctuation work where the number of molecules was fixed, most processes of heat radiation are not fixed. However, Einstein focused on the volume fluctuations, essentially the only process of heat radiation that does not alter the number of quanta, and thus could utilize his previous methods to show that the energy E of the heat radiation can be identified with N independent spatially localized quanta of magnitude $h\nu$ [433] (see Appendix 5.A).

In response to Arnold Sommerfeld's (1868-1951) inquiry in 1912 about the status of Einstein's work on the quantum, Einstein wrote [434, pp. 1-2]:

See the print edition of The Quantum Measurement Problem for quotation.

Already in 1907, he published an article, *The Principle of Relativity and Its Consequences*, in which he suggested the equivalence between a gravitational field and an accelerated frame of reference, the *Equivalence Principle* that would become the basis for his theory of gravitation, *General Relativity*. This focus on relativity reflected his deepest views on how a physical theory should be approached and would influence his views concerning the meaning of quantum theory for decades to come. In his *Autobiographical Notes* of 1949, Einstein put his views on quantum theory into perspective [339]:

> *It is my opinion that the contemporary quantum theory by means of certain definitely laid down basic principles, which on the whole have been taken over from classical mechanics, constitutes an optimum formulation of the connections. I believe, however, that this theory offers no useful point of departure for future development. This is the point at which my expectation departs most widely from that of contemporary physicists…At this point it is my experiences with the theory of gravitation which determine my expectations. These equations give, from my point of view, more warrant for the expectation to assert something* ***precise*** *than all other equations of physics…I have learned something else from the theory of gravitation: No ever so inclusive collection of empirical facts can ever lead to the setting up of such complicated equations…Equations of such complexity can be found only through the discovery of a logically simple mathematical condition which determines the equations completely.*
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> Albert Einstein, Autobiographical Notes in Albert Einstein: Philosopher-Scientist, Paul Arthur Schillp (Ed), Cambridge University Press 1949, pp. 2-49.

Einstein's theory of relativity comprised causal deterministic trajectories within the structure of space-time that extended the classical world-view of Newton. From Bohr's perspective, the first important extension to the depiction of our reality occurred with the physics of Galileo and Newton followed by the field theories of Faraday and Maxwell [435, p. 118]. The introduction of relativity closed this line of development. In contrast, quantum phenomena must refer to observations obtained under circumstances that take into account the details of the experimental apparatus. A question naturally emerges as to how precisely does *space-time* differ from *quanta*?