Einstein's Ghost Field

Einstein's 1905 paper signaled that a foundational result of 19th century physics, the wave character of light, must be reexamined. By 1908 or early 1909 he realized that independent light quanta are not the whole story of radiation by deriving Equation (5.7) from the Planck radiation law, simply viewed as an empirical relation, to see what lurks below the surface. Since both terms are necessary to reproduce the Planck law, this implied that the localized quanta must somehow interfere with one another. In the previously mentioned letter to Lorentz expressing his doubts about the notion of independent light-quanta, he went on to say further [3]:

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

This was the beginning of Einstein's idea of using guiding or *ghost fields* to somehow deal with the unavoidable but mysterious influence at a distance between light quanta. As early as 1920, Einstein had written to Born:

> *That business about causality causes me a lot of trouble, too. Can the quantum absorption and emission of light ever be understood in the sense of the complete causality requirement, or would a statistical residue remain?*
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> Max Born, The Born-Einstein Letters, MacMillan and Co. Ltd. 1971, reproduced with permission of Palgrave Macmillan.

However, Einstein did speculate about a probabilistic interpretation of Maxwell's equations to link the wave and particle concepts, using his *ghost-field* concept, a precursor to Born's 1926 probabilistic interpretation of the wave function of quantum mechanics. Although discussed with a number of physicists, he never published a paper regarding this concept [436, p. 382]. In Einstein's ghost-field, a wave of interference radiation of vanishingly small amplitude and which carries no energy prepares the way for the radiation of energy in the form of light quanta. This consists of indivisible quanta of magnitude $h\nu$, which follow the path prescribed by the interference radiation. In Born's extended paper on collision processes in 1926, he states [4, p. 163] [181]:

> *In this, I start from a remark by Einstein on the relationship between the wave field and light quanta; he said, for instance, that the waves are there only to show the corpuscular light quanta the way, and in this sense he talked of a 'ghost field'. This determines the probability for a light quantum, the carrier of energy and momentum, to take a particular path; the field itself, however, possesses no energy and no momentum.*
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> G. Bacciagaluppi and A. Valentini, Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference, Cambridge University Press, 2013.

Einstein continued to think along the lines of the ghost-field idea in the 1920s, though again without publishing a detailed theory. In 1925, one year before Born's collisions papers, Einstein gave a colloquium in Berlin where he discussed the idea that every particle was accompanied by a ghost or guiding field [437, p. 441] [3, p. 72]. According to Eugene Wigner (1902-1995), who was present at the colloquium, Einstein realized that it conserves energy and momentum only on average and violates conservation principles for individual trials. When a light quantum and an electron collide, both would follow a guiding field. However, guiding fields give only the probabilities of the directions in which the light quantum and the electron will proceed and so they follow their directions independently, giving only statistical energy and momentum conservation. This difficulty could be overcome by the introduction of a guiding field in configuration space as was done in a theory by Louis de Broglie (1892-1981), and later by David Bohm (1917-1992), that determined probabilities for all particles collectively. In Einstein's approach, each particle had its own guiding field and so entanglement was precluded [4, pp. 200-201]. This led to a sort of complementarity between exact conservation laws and entanglement. For Einstein, exact conservation was sacred but he could not tolerate entanglement. This predicament meant Einstein would eventually go his way and the gap between him and the physicists developing quantum theory continued to widen in the following decades. For Einstein, "indeterminacy was but a symptom; entanglement was the underlying disease" [111, p. 67]. In addition to indeterminacy and entanglement, a third essential ingredient in understanding quantum theory turned out to be nonlocality. Einstein struggled for the rest of his life to fit together this triumvirate of puzzle pieces into his view of the universe.

Einstein's ghost field work was one of several related efforts that were never published. He had made many other attempts to understand the quantum. In May 1927, Einstein had read a paper before the Prussian Academy of Sciences in Berlin, entitled "Does Schrödinger's Wave Mechanics Determine the Motion of a System Completely or Only in the Sense of Statistics?" [438]. This was Einstein's attempt at a deterministic hidden-variable completion of quantum mechanics with the aim of showing that Schrödinger's wave mechanics completely determines the motion of a system. Einstein was able to use the methods of non-Euclidean geometry familiar to him from his development of his theory of gravitation, General Relativity, to specify n unique initial conditions at each point in the n-dimensional configuration space that completely determine the system's dynamics. These n degrees of freedom would in effect serve as hidden variables leading to a deterministic version of Schrödinger's equation. However, after submitting the paper to the journal of the Prussian Academy, Einstein noticed the possibility of solutions in which non-local correlations exist between subsystems which was not satisfactory for a physical system. He was not allowed to have it both ways. Therefore, he requested to the editor that the paper be withdrawn before publication. Yet again, the appearance of nonlocality had blocked Einstein's way.

These issues would smolder in the background for Einstein as quantum theory developed further, including Bohr's atomic models beginning in 1913. Although primarily working on his theory of gravitation, Einstein still managed to make important contributions to quantum theory. In dealing with a gas of particles in thermal equilibrium with radiation, Einstein applied statistical considerations to Bohr's stationary states and succeeded in arriving at a simple deduction of Planck's radiation law but only if the transition is given by Bohr's atomic transition hypothesis $E_m - E_n = h\nu$. In 1916, Einstein's published arguments derived the "A and B coefficients" regarding rates of spontaneous and stimulated emission. These arguments set down the principles that decades later would be utilized in the operation of the laser, which relies on stimulated emission. Einstein's work on spontaneous emission sets the scale for all radiative transitions and manifests the fundamental interaction of matter with the vacuum. However, he was concerned that his theory could not predict the direction in which a light-quantum moves after spontaneous emission thereby violating causality. A further major innovation of the 1917 paper was that the momentum as well as the energy of light quanta were included so that the excitation of an electron is accompanied by momentum transfer. This was a crucial step allowing the proper coupling of light-quanta to matter.