Exact Conservation with Whole Photon or Nothing

As discussed in the section *Einstein's Ghost Field*, since the early 1920s Einstein had been investigating the formulation of quantum mechanics using "ghost fields," guiding fields that give probabilities of the directions in which particles will proceed, and so they follow their directions independently, giving only average energy and momentum conservation. At the same time, de Broglie was developing his own version of a hidden-variable theory, which utilized the entire configuration space and presented it at the 1927 Solvay Conference [4]. Einstein's familiarity with these issues prompted him to comment on the action at a distance feature of his Figure 5.15(a) thought experiment,

> *It seems to me that this difficulty cannot be overcome unless the description of the process in terms of the Schrödinger wave is supplemented by some detailed specification of the localization of the particle during its propagation. I think M. de Broglie is right in searching in this direction. If one works only with Schrödinger waves the Interpretation II of* $|\psi|^2$*, I think, contradicts the postulate of relativity.*
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> G. Bacciagaluppi and A. Valentini, Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference, Cambridge University Press, 2013.

With his by now hands-on knowledge of conservation laws and nonlocality, Einstein also emphasized in the Solvay Discussion the implications of his Interpretation II regarding conservation,

> *It is only by virtue of II that the theory contains the consequence that the conservation laws are valid for elementary processes; it is only from II that the theory can derive the result of the experiment of Geiger and Bothe, and can explain the fact that in the Wilson [cloud] chamber the droplets stemming from an* α*-particle are situated on very nearly contiguous lines.*
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> G. Bacciagaluppi and A. Valentini, Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference, Cambridge University Press, 2013.

From this statement would emerge the beginnings of a struggle over the next fifty years to ascertain theoretically and experimentally the nature and interrelations of nondeterminism, entanglement, exact conservation laws and the corpuscular aspects of photons. These would be the ingredients needed to characterize the quantum measurement problem.

Recall from the discussion in the section *BKS Showdown over Quanta* that the Bohr-Kramers-Slater (BKS) theory for electron-radiation scattering had predicted energy conservation only on average but this was refuted by the experiments of Compton-Simon in 1925 demonstrating exact energy and momentum conservation and Bothe-Geiger in 1926 also demonstrating coincidence between the produced photons and electrons. This led to the acceptance of Einstein's light quanta with its "whole photon or nothing" property though Einstein still struggled to find an acceptable way to understand quantum theory. Schrödinger had been skeptical of the reality of discontinuities in quantum theory since he had complained to Bohr about "all this damned quantum jumping" during his visit to Copenhagen in 1926. In his series of Wave Mechanics papers in 1926, he introduced characteristic frequencies as the basic properties of interacting systems and explained dynamics as a resonance phenomenon that maintains space-time continuity. His attitude was that [449],

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

Schrödinger had also been quite sympathetic to BKS with its adherence to continuity and did not object to violation of exact conservation laws for individual events. His fourth Wave Mechanics paper also developed a treatment of radiation scattering with continuous waves which conserved energy and momentum only on average [450]. However, Schrödinger retreated from publicly discussing his original interpretation following the pressure from Bohr and the results of the photon-electron scattering experiments that clinched the validity of exact conservation laws for every individual interaction [451]. However, he returned to exploring his earlier views in the 1930s after his discovery of quantum entanglement and also possibly encouraged by new experiments of Shankland [452] that apparently conflicted with the earlier Compton-Simon and Bothe-Geiger results. This provoked a flurry of letters in *Nature* by Dirac, Peierls, and others discussing the startling implications if this turn of events was valid. This included a letter by Bohr and a report by Jacobsen from Bohr's Copenhagen Institute who reported his new scattering measurements that did support exact conservation laws [453] [454]. However, there were still lingering doubts in some circles which were finally put to rest in 1950 with experiments by Cross and Ramsey [455] and Hofstadter and McIntyre [456] verifying exact conservation and coincidence, employing modern electronic counting methods. In contrast, the Bothe-Geiger experiments of 1926 were laborious and time-consuming, employing two opposing needle counters and X-rays passing between them. One of the counters responded only to photons and the other only to recoil electrons. The deflections of the counters were recorded on silver bromide film that moved at high speed between the counters to record the timing of the particles from the collisions. The recording of coincidences of the joint impact of a photon and recoiling electron would indicate the conservation of energy at the atomic level. It took Bothe and Geiger almost a year to develop, dry, and analyze the results from the three kilometers of 1.5 cm wide film it took to accomplish this in order to obtain the statistically convincing results that the photon and electron counter were coincident to within 10^{-4} sec. These intense efforts might even be viewed as a prefiguring of the Bell-type correlation experiments. On Einstein's recommendation, Walter Bothe shared the 1954 Nobel Prize with Max Born, Hans Geiger having died in 1945 [457] [458].

Still harboring doubts, Schrödinger persuaded Ádám, Jánnosy, and Varga [459] [460] to carry out Heisenberg's version of Einstein's thought-experiment to test whether light at the half-silvered mirror would always respond as a particle or a wave, Figure 5.15(b) [461]. However, the result was effectively a null experiment due to insufficient detector efficiency at that time. It was not until 1974 that Clauser finally demonstrated the “whole photon or nothing” property that photons do not split at a half-silvered mirror and that true single photons are not measured at both detectors simultaneously [462]. Only one detector clicks. This experiment used a light source based on atomic cascades in mercury atoms to produce heralded single photons and two joint intensity measurements performed at the outputs of the beam splitter. If the photon is indivisible, detectors 1 and 2 are never triggered simultaneously so that there is an anti-correlation effect, $< \hat{n}_1 \hat{n}_2 >= 0$, i.e., *photon antibunching*. Clauser’s experiments on the “whole photon or nothing” photon antibunching also confirmed the exact point-wise conservation of energy in QED, further confirming this aspect of the Compton-Simon and Bothe-Geiger experiments. A calcium atomic cascade source was used by Grangier et al. to also observe antibunching as well as wave interference effects in a Mach-Zender interferometer configuration [72]. Einstein’s concern about action at a distance was finally addressed by Guerreiro et al. with the experimental observation of single-photon anti-bunching in which the detectors are separated by space-like distances, confirming that in each round of the experiment only one detector clicks [463].