BKS Showdown over Quanta

By the 1930s, Bohr, had finally accepted the idea of light-quanta. In his earlier work on atomic structure, Bohr had discussed emission and absorption of light in atomic transitions, without examining the mechanisms for these processes nor the nature of light itself. Quantum phenomena had initially cast doubts on classical theory but, apparently these had only to do with interactions between matter and radiation, not with radiation itself. However, there was also the question of conservation of energy and momentum. In 1923, Arthur Compton (1892-1962) observed a change in frequency when light is scattered by electrons, thereafter called the *Compton effect*. The results could be explained by assuming the light beam behaves as light-quanta and that energy and momentum are conserved. However, Bohr found a way of using Einstein's approach without also using the light-quantum hypothesis by reinterpreting the principles of energy and momentum conservation as *statistical* principles. The conservation laws had the status of a fundamental law since the mid-19th century but would not be tested experimentally at the level of individual microscopic processes such as atomic transitions or collisions of electrons until 1925. Thus, it was in 1924 that Bohr, Kramers and Slater published a provocative description of the interaction of matter and electromagnetic interaction, historically known as the BKS paper that combined quantum transitions and electromagnetic waves with energy and momentum being conserved only on average. BKS tried to take [441] the duality between particle and wave-models as the starting point for the interpretation of quantum theory. The waves would play the role of a probability field, even though this forces energy conservation for individual processes to be abandoned. BKS correctly noted that the Compton experiments had actually only demonstrated conserved energy-momentum averaged over many individual processes.

Energy and momentum are conserved exactly within the formalism of Schrödinger's equation; however, Schrödinger's equation allows entanglement. For strict validity of the conservation laws, Bohr expected a breakdown of the space-time description that is incompatible with the properties of mechanical models [441]. In 1925, Walther Bothe (1891-1957) and Hans Geiger (1882-1945) developed counter-coincidence techniques to verify that in the Compton effect the secondary photon and electron are produced simultaneously as required by causality, disproving the BKS theory. Secondly, Compton and Alfred Simon studied the Compton effect in cloud chamber experiments, enabling them to demonstrate that energy-momentum was conserved in individual events. Soon after the results became known, Bohr wrote [442, p. 126]:

> *It seems …that there is nothing else to do than to give our revolutionary efforts as honorable a funeral as possible.*
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> S. Petruccioli, Atoms, Metaphors and Paradoxes, Niels Bohr and the construction of a new physics, Cambridge University Press 1993.

However, BKS had also led to deeper discussions and renewed attention to the difficulties in the foundations of quantum theory and subsequently influenced

Heisenberg, Kramers and Born to explore mathematics that strongly inspired the development of Heisenberg's matrix mechanics in 1925.

This immediate shift in point of view illustrates the character of Bohr's deductive approach to research when he readily accepted the experimental results disproving BKS. However, Bohr returned to the possibility of violation of energy and momentum conservation again in the crisis of *β-decay* due to experiments carried out in 1929 [9, p. 364]. With the deductive approach, it's important to emphasize that all possibilities logically remain under consideration even if they had failed in other situations. In α-decay, the α particles emitted by any given species of atoms all have the same energy and the final two particles emerge with equal and opposite momenta. The result is that a particular α-particle momentum corresponds to a particular energy. In contrast, the β-spectrum is continuous so that it is either a two-body process which violates energy and momentum conservation or else β-decay is not a two-body process and additional unobserved particles are involved that account for the conservation laws. In this case, Bohr once again proposed non-conservation as a possibility, but the additional particle interpretation ultimately turned out to be correct as suggested by Pauli and modeled by Fermi. This led to the important discovery of the neutrino though it took until 1956 to finally detect it due the weakness of the interaction of the neutrino with matter. Although Bohr's preference failed once again, it must be emphasized that it is important to keep all consistent options under consideration.

When Bohr finally accepted Einstein's light-quanta in 1925, the developments in quantum theory were in full tilt. This included de Broglie's proposal for matter waves in 1924, extending wave-particle duality to matter. However, a special case of matter wave-particle duality had appeared in 1909 when Einstein derived a version of Equation (5.7) for matter when he studied the *Gibbs paradox* [3]. Pauli formulated the exclusion principle in 1925 and the mathematical theory of spin in 1927. In 1927, Dirac developed the relativistic equation for the electron which incorporated Pauli's theory of spin and predicted the existence of anti-matter. That indistinguishable particles have two types of counting statistics for allowed energy states was developed by Bose and Einstein in 1925 for one class now called *bosons* (which includes light-quanta or photons) and by Fermi and Dirac in 1926 for the second class, now called *fermions*.

Heisenberg discovered the uncertainty relations of Equation (1.2) in 1927. Although the derivation of the uncertainty between position and momentum can be extended to any conjugate pair of Hermitian operators, Pauli noticed that the semi-boundedness required for the stability of any Hamiltonian implies that there is no time operator in quantum mechanics to allow the uncertainty relations to be extended to energy and time. Although other methods were later developed to justify time-energy uncertainty relations, Bohr gave a very simple argument in his 1927 Como paper where he had also introduced complementarity [9, p. 312]. For a particular wave-packet with finite extension Δx, he considered the time interval Δt during which the bulk of the wave-packet passed a particular point and the frequency interval $\Delta\nu$ where the relevant frequencies lie along with the corresponding interval for inverse wave length $\Delta(1/\lambda)$. Then from the known theory of the resolving power of optical instruments, he could write:

$$\Delta t \Delta \nu \geq 1, \ \Delta x \Delta(\frac{1}{\lambda}) \geq 1 \, . \tag{5.8}$$

From the wave-particle duality of Einstein or de Broglie for either photons or matter, we have:

$$E = h\nu, \ p = h/\lambda \, . \tag{5.9}$$

Combining Equations (5.8) and (5.9) immediately gives the uncertainty relations, Equations (1.2) for both position-momentum and energy-time. So, Bohr's acceptance of light-quanta could be used in stimulating ways.

Pauli also visited Bohr's Copenhagen Institute in June 1927 and joined in mediating the disparate views of Bohr and Heisenberg on the uncertainty relations. From this time on, Bohr, Heisenberg and Pauli shared a somewhat common set of views, sometimes known as the *Copenhagen interpretation* of quantum mechanics. Heisenberg's uncertainty paper and Bohr's complementarity paper were the two basic pillars, and it was further summarized in Pauli's 1933 *Handbuch der Physik* article [443]. The interpretation included the uncertainty principle, wave-particle duality for photons, electrons, and other particles, Born's probabilistic interpretation of the wave function, the correspondence between eigenvalues and measured values, and the correspondence principle. However, the Copenhagen interpretation was not necessarily coincident with Bohr's epistemology which he continually refined although it was not always widely understood or appreciated.

The new Copenhagen interpretation also created the climate for a consensus on the issue of quanta for both light and matter. The next stage in understanding involved delving into the issue of entanglement, which is the central issue for the measurement problem. As discussed, both Einstein and Bohr had been conceptually dealing with entanglement in various forms decades before Schrödinger coined the term in 1935. For the next two decades, this issue mainly involved debates between Einstein and Bohr along with other important supporting characters, taking place at Solvay Conferences, during private discussions, in correspondence, and several important journal articles. Following Einstein's death in 1955 and Bohr's in 1962, the issue of entanglement would then become re-energized after the formulation of the Bell inequalities in the 1960s and their supporting experiments. This would continue up to the present day with the development of quantum information and new experimental techniques to manipulate entangled states of photons and atoms.