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*A tribute to the memory of
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5. THE INTERPRETATION OF QUANTUM MECHANICS REVISITED

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The foundations and meaning of quantum theory became a central issue to Albert Einstein and Niels Bohr since the onset of their impassioned debate in the 1920s, enriched by the contributions of many other distinguished scientists and philosophers. The questions are not settled down at all, despite the great achievements of the theory, its impressive accordance with experiment and predictive power. The fundamental and technological applications range from cosmology to biology, with the development of invaluable instruments and the design of new materials.

Is quantum mechanics a complete or an incomplete theory? Is there an objective reality independent of the observer or is the reality created by the measurements? Are hidden-variable theories justifiable? Is there a quantum theory founded in a local-causal and non-linear approach that formally contains the orthodox linear theory as a special case? Can such a formulation unify classical and quantum physics? Are Heisenberg's uncertainty relations valid in all cases?

Here, the subject is addressed as an adaptation of our contribution to the Colloquium "*Quantal aspects in Chemistry and Physics. A tribute in memory of Professor Ruy Couceiro da Costa*" held at Academia das Ciências de Lisboa, November 27, 2009.

Ruy Couceiro da Costa (1901-1955), University of Coimbra, was one of the first professors and researchers to apply and teach quantum mechanics at Portuguese universities. The above questions presumably crossed his mind as they do pervade, presently, the minds of teachers and researchers interested in the interpretation, philosophy and epistemology of quantum theory.

5.1 Introduction

The roots of quantum theory, originated in the 19th century by Gustav

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Kirchoff's challenge on the black body radiation, were definitely launched between 1900 and 1925. Experiments and first theoretical models on the behaviour of light and material particles recognized that: (i) light is emitted or absorbed, and constituted, by photons of energy $E = \hbar\omega$ (Planck - Einstein's relation), where \hbar is the reduced Planck constant and ω the time frequency; (ii) atomic energies are quantized, *i.e.*, when an atom "jumps" from an energy level E_i to another E_f it emits or absorbs a photon, $E_f - E_i = \hbar\omega$ (Bohr-Sommerfeld models); (iii) to a photon or material particle with momentum, p , is associated a wave number (space frequency) $k = 2\pi/\lambda$, such that $p = \hbar k$ (de Broglie's relation); (iv) some atomic emission lines split, in the presence of a magnetic field, into well distinct lines (Zeeman's effect); and (v) each electron "orbit" can contain only two electrons (early form of Pauli's exclusion principle underlying the Periodic Table structure).

Classical wave theory and classical mechanics are unable to rationalize the evident wave-particle duality either for light or material particles. The Bohr-Sommerfeld models, though remarkable steps forward, are essentially based on classical mechanics with the introduction of rather *ad hoc* quantum rules, and do not describe most of the atomic and molecular properties. Thus, a well-founded theory was needed to reproduce all known experimental results in such a way that quantum numbers and rules turned out naturally, *i.e.*, without *ad hoc* assumptions.

Since 1925 many quantum formulations were achieved, starting with Heisenberg, Born, Jordan's *matrix mechanics* (1925) and Schrödinger's *wave mechanics* (1926) which, apparently different, were proved to be equivalent by Schrödinger and, independently, by Dirac. However, these formulations are spinless, not fully explaining Zeeman's effect and other spectroscopic details.

Pauli introduced the *spin matrices* (1927) into Schrödinger's time dependent equation, though well-aware that the introduction of spin in such a way was rather *ad hoc*. It is noteworthy that Ralph Kronig firstly, and Uhlenbeck and Goudsmit later, had anticipated the existence of electronic spin in 1925. Curiously, Kronig was much discouraged on the proposal by Pauli who later

regretted it.

Between 1928 and 1933, Dirac, based on special relativity, developed a *relativistic quantum theory*, from which spin came out naturally, reproducing Zeeman's effect. Besides, the positron was predicted whose real existence Carl Anderson confirmed experimentally by 1933.

These achievements constitute what is known as the *first quantization*. Yet, an extension to a *second quantization* was still needed to account for the interaction of matter and radiation that Dirac's theory was unable to accommodate. It requires the quantization of fields so that particles turn out as the *quanta of non-classical fields*, allowing the creation and annihilation of quanta in different types of interaction. This is the scope of *quantum field theories*, particularly of *quantum electrodynamics* (Bethe, Tomonaga, Schwinger, Feynman, Dyson, ...) developed since 1948, a very successful theory that reproduces the experimental value of the "g-factor", for example, with an outstanding accuracy.

Further on, *gauge and renormalization group theories* (Yang, Mills, Glashow, Salam, Weinberg, Kadanoff, Fisher, Wilson, Gell-Mann, ...) extended quantum field formulations to atomic nuclei (with their "coloured" quarks and gluons), giving birth to *quantum chromodynamics* aiming at the understanding of a myriad of elementary particles and the unification of fundamental forces.

Despite all these great achievements, the gravitation problem still remained. Presently, *superstrings theory* (Green, Schwarz, Witten, ...) appears as the "jewel of the crown" for it attempts the full unification of quantum mechanics and general relativity as well as of the whole physics, what underlies the "dreams of a final theory".

Quantum theories gave rise to a remarkable progress in chemistry and physics, predicting, with great accuracy, the properties of molecules, atoms, nuclei, elementary particles, chemical and nuclear reactions. The mechanisms of the universal forces are unravelled by means of their mediating "particles" and symmetries. The fundamental and technological applications range from cosmology to biology, with the development of invaluable instruments and the design of new materials.