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ONE HUNDRED YEARS OF QUANTUM PHYSICS ITS IMPACT ON SCIENCE AND TECHNOLOGY

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We are conmemorating the first Centennial of the publication in december 1900, of Planck's paper. "A Theory of the Energy Distribution Law in the Normal Spectrum" (Zur Theorie des Gesetzes der Energieverteilung im Normalspektrum), that can be considered as the first landmark or birth of quantum physics (QP). Few papers have had a long term impact, not only on Physics, but in all sciences,in technology, in philosophy, even in society in general, as Planck´s paper. Most interesting, Planck, like many other innovators, could not foresee the magnitude of the revolution, in Thomas' Kuhn´s sense, that he had just started, that eventually led to a revision of the concepts of particles and fields at the fundamental level.

If I am asked what is the most important features of the 20th. Century, that is coming to a close, I would not hesitate to say that it is the extraordinary advance in our understanding and manipulation of matter and radiation, made possible because of the emergence of QP and the development of elaborate techniques (detectors, accelerators, etc.) for exploring and acting on matter and radiation at its most fundamental level, in other words, a unique combination of science and technology, providing a paradigm of the microscopic world quite different from our view of the macroscopic world. But what is even more important from the social point of view, we live surrounded by technological developments based in one way or another on QP, with applications in fields so diverse as medicine, biology, control and communications, materials, space exploration, image processing, etc, that would be too many to mention in detail.

MICRO, MESO AND MACROPHYSICS

At the level of microphysics, we have identified the most relevant components of matter and recognized how those components interact, and we have developed a coherent formalism or methodology, Quantum Physics, to deal with those components and interactions. This has led to the formulation of a paradigm or "story line" of Physics of great simplicity, as shown in Table 1, that has allowed us to have a unified view of how the universe functions. This conceptual unification is perhaps the most important contribution of QP, that is not a static science, but continues evolving. Thanks to QP we know how to calculate with great precision the properties of molecules, atoms and nuclei, and explain the properties of many materials such as conductors and semiconductors. Thanks to the development of the quantum field theory (QFT) we know how to analize the interaction between EM radiation and matter and found the notion of particles and fields (not waves) can be correlated. A standard model of particles (leptons and quarks) has unified the explanation of many high energy processes. And so on.

This conceptual unification based on QP also had an important impact on our understanding of the world at the macroscopic or sensorial level, that is systems composed of a large number of units, of the order of 10^{23}. Up to 1900 the approach to the understanding of the physical world was based mostly on our sensorial experiences and grew in a haphazard fashion, by aggregation, that blurred any possible conceptual unity at that level, and resulted in several independent sciences according to the phenomenology: Biology, Chemistry, Physics. In turn, Physics became divided according to our sensorial experience into the "classical " branches : mechanics, heat, acoustics, optics and electromagnetism. Although the prevailing mechanistic view of the universe was a sort of unifying principle, and still it is taught in that way. But those sciences, and in particular the "classical" branches of Physics, have been affected by QP, and we talk about quantum biology, quantum chemistry, quantum optics, quantum theory of solids or condensed matter, quantum electrodynamics,etc, that deal with the phenomenology at the fundamental levels, whose explanation requires the formalism of QP.

Today we know taht all those "classical" or sensorial branches of Physics deal with phenomena that are consequence of the structure of matter and radiation at the fundamental level. Therefore macro- and micro-physics are closely related, something that began to be recognized at the end of the 19th century. However it was the advent of QP at the beginning of the 20th. Century what made possible to develop that relation in a precise and quantitative way during this century. Thus we should not divide any more Physics into "classical" and "modern", because "modern" is already one century old. Instead we must talk of "micro", "meso" and "macro" physics, as three broad levels of analyzing nature, depending on the size of the system dealt with and the level of resolution at which we analyze it. The role of QP is different at each level: it is fundamental at the micro, not so much at the meso, and rather diffuse at the macro.

PHYSICS IN 1900

To fully understand the scientific and technological impact of QP it is important to keep in mind the situation of Physics at the turn of the 19th century, when it had been accepted by the society that science is a bona fide quest for knowledge. Let us recognize that we interpret all phenomena at the macro level in terms of the notions of "localization" and "extension", for which the concepts of "particles" and "fields" are used. Newton, with his famous three laws, provided the scientific methodology for dealing at the macroscopic level with the notions of "particles" under the action of "forces", including gravitation, and Maxwell developed a coherent scientific macroscopic "field" theory of electromagnetism, that in its time dependent version included electromagnetic "waves", that is EM fields that propagate in space with a well defined velocity, without distortion.

Other wave phenomena of "mechanical" macroscopic nature, such as elastic waves and waves in fluids, were also known. All had in common that they obeyed the same type of differential equation of second order, $\frac{\partial^2 u}{\partial t^2} = v^2 \nabla^2 u$ where v is the velocity of propagation of the field, although other equations of first order in time, such as $\frac{\partial u}{\partial t} = f(u) + D\nabla^2 u$, admit "wavefront" solutions. However, it must be understood that not all time dependent fields obey that type of equation and propagate as a wave, even if we can associate with them a wavelength or a frequency as a result of their Fourier analysis. Newton-Maxwell view of the universe in terms of "particles" and "fields" has proved to be must succesful and it is still at the core of the 20th century physics, having been incorporated into QP, but in a different way, based on the quantum theory of fields (QFT).

To be precise, I will indicate the meaning in QP of the notions of "particles" and "fields". A quantum "particle" is a physical entity localizable in space-time, that is characterized by certain parameters (charge, mass, spin, parity), the motion is governed by a dynamical law, obeys certain symmetries, and is associated with a quantum "field". In turn a quantum "field" is a physical entity described by a function extended over space and time, obeys a dynamical law, has certain transformation properties and symmetries, and its components are quantum operators that "create" or "annihilate" the "particles" associated with the "field". Whether in QP one uses the notions of "particles" or "fields" depends on the particular situation or process being considered.

Another aspect of 19th century physics is taht most phenomena were described by linear differential equations, that admit precise deterministic solutions, although a few physicists, such as Stokes, Rayleigh, and later Poincare, were beginning to recognize that more complex equations might be needed in some cases (fluid motion, sound, planetary motion,etc). However in1900 the conceptual edifice of physics seemed to be complete and many, rather naively, advanced the idea that the only new things to be expected in the next century was a refinement in the measuring, observational and computational techniques. And this is precisely what happened, with profound conceptual and practical consequences, as we are going to point out in what follows. Rather than presenting a systematic history of the development of QP. I will highlight only the most critical conceptual issues related to QP, that affected our view of the universe, omitting the details and many related developments, because you all know them very well.

THE BEGINNINGS

As it is well known, since the 1850's the spectral distribution of energy in the blackbody radiation, that is EM radiation confined to a cavity and in equilibrium by exchanging with the atoms of the cavity, had been measured experimentally by Kirchoff and others, but still remained to explain how the atoms in the cavity maintained the equilibrium with the EM radiation. The problem interested Max Planck, at that time professor of Physics at the University of Berlin, and in October of 1900, based on recent measurements by Rubens and using Maxwell-Boltzmann statistics, obtained empirically an expression for the spectral distribution of energy in the blackbody radiation, that in current notation is $\rho(\nu,T) = (8\pi h\nu^3/c^3)(\exp h\nu/kT - 1)^{-1}$, where the constant h is known as Planck's constant, the notorius symbol of QM, and $k = R/N_A$ is Boltzmann constant, that Planck introduced. The world is immersed in a cosmic radiation, remnant from the Big Bang, with a blackbody spectrum corresponding to a temperature of 2,7K.

The next task for Planck was to provide a theoretical justification of this expression, compatible with thermodynamics and the concept of entropy.

That he did in a few days and in December of 1900 he submitted a paper with his theoretical analysis. The method followed by Planck, based on Boltzmann´s statistical definition of entropy, S = k ln W, is well known and I do not need to elaborate on it. The important point is that Planck, "in an act of desperation" as he confessed later on, found that the only way to reproduce the empirical spectral distribution of the blackbody radiation was to assume that the atoms of the cavity walls behave as oscillators that could absorb or emit EM radiation only in amounts proportional to the frequency of the radiation, that is $\Delta E = h\nu$. The obvious consequence is that the energy of the oscillators must be $nh\nu + E_0$ where E_0 is a zero point energy, that Planck assumed to be zero to make sure his model gave a finite total energy. We know now that this is not correct, that $E_0 = \frac{1}{2} h\nu$, but that does not matter because we also know that Planck´s derivation is not satisfactory. The correct derivation was obtained by Einstein years later.

As it is well recognized, the most important aspect of Planck's idea was the "quantization" of the energy of the atomic oscillators. Quantization existed in the Newton-Maxwell physics but in a different way. It appeared whenever a wave motion had to be confined to a certain region, resulting standing waves with a discrete spectrum of frequencies (vibrating strings and plates, organ pipes, wave guides and cavities, etc). Or more rigorously, as a consequence of the boundary conditions imposed on the differential equation satisfied by a field, whenever the field was confined to a finite region. Nothing in Newton mechanics led to such quantization of the energy of a particle, whose motion was not described by any partial differential equation. For that reason Planck´s idea was not accepted enthusiastically, although it was recognized as a clever "ad hoc" mathematical way of deriving the blackbody energy spectrum, and the need to justify, based on some new principles, why the energy of the oscillators was quantized, remained. However the similarity of energy quantization and standing waves had a profound influence on the future development of QM, particularly on Schrodingers´s work, although to a certain extent it also led to many confusions or misconceptions. (I should note in passing that in 1906, in what was the first application of Qp to solid state physics, Einstein, and shortly after Debye, used Planck' s ideas of quantization of the energy of oscillators combined with Maxwell-Boltzmann statistics to explain successfully the variation of the heat capacity of solids with temperature, thus reinforcing the idea of energy quantization).

A second important consequence of Planck' s idea was the need to revise the EM radiation interacts with matter. Planck's never questioned Maxwell theory of EM radiation, but how the energy was exchanged with the oscillators remained an open question. The crucial step in this direction was taken by A. Einstein. In March of 1905 Einstein published a paper entitled "On a heuristic point of view concerning the generation and conversion of light" in which he studied blackbody radiation in a new way. Without questioning the validity of Planck's formula for the energy distribution of the radiation, Einstein went beyond Planck's ideas, and proposed that EM radiation is carried in energy "quanta" and stated his revolutionary "heuristic principle": "if monochromatic radiation behaves as a discrete medium consisting of energy quanta of magnitude hv, then this suggests an inquiry s to wether the laws of generation and conversion of light are also constituted as if light were to consist of energy quanta of this kind ". In other words, what Einstein was proposing was to re-examine how EM energy is carried in space and how it is absorbed and emitted by matter. In fact, in 1910 Einstein reiterated that "the properties of elementary processes makes it almost inevitable to formulate a truly quantized theory of radiation".

In the same paper, as a follow up to his proposal that radiation energy is carried in quanta, Einstein proposed an explanation of the photoelectric effect, a subject of active research at the time. Einstein's suggestion was that the electrons absorbed energy from the EM radiation in bundles or quanta with energy hv, and introduced the famous relation $E_k = h\nu - E_0$, to fit the observed kinetic energy of the electrons emitted vs. the frequency of the radiation. This relation has been verified experimentally with great precision with many materials and EM radiation of different frequencies, confirming that h is the same constant used by Planck for blackbody radiation. In spite of the initial resistance to his ideas, Einstein was awarded the 1922 Nobel physics prize for his work on the photoelectric effect. Needless to say Einstein's theory of the photoelectric effect has induced a multitude of important applications, and has been extended to the atomic and nuclear photoelectric effect and to chemical and biological processes.

Of course the energy quanta proposed by Einstein, called "photons" by G. Lewis in 1926, were not particles in the same sense as the elctrons. Since they moved with the speed of light, they had to have zero mass, and therefore according to Einstein's theory of relativity, the relation between their energy and momentum had to be E = pc. It took until 1923, when A.H. Compton derived the relativistic kinematics for the scattering of photons by free electrons and verified them with his experiment on the scattering of X-rays by electrons, to confirm that photons carried a momentum hv/c. Thus it finally became accepted that theEM radiation behaved as particles when it interacted with matter, that implied using two conflicting, or perhaps complementary, models for the radiation, because physicists were thinking of particles and EM waves in a sensorial way. Consequently the big issue became how it is possible that if EM radiation is a wave phenomenon, its energy can come in bundles or quanta or be absorbed in finite amounts proportional to the frequency. This dual representation of EM radiation as waves and particles was incomprehensible in 1905, would appear again in QM a few years later as the "wave – particle duality", and prompted Einstein to recognize in 1909, as a result of his analysis of energy fluctuations in a cavity filled with thermal EM radiation, the need of a "theory of light that can be interpreted as a sort of fusion of the wave and quanta theories".

A third landmark in the early development of QP, that can be considered as the beginning of quantum dynamics or mechanics, occured in 1913, with the publication of N.Bohr's three papers "On the Constitution of Atoms and Molecules". Bohr's aim was to justify the stability of the nuclear model of the atom, developed by E.Rutherford in 1911 as a result of his experiments on the scattering of α-particles or He nuclei, proposed to quantize the angular mometum of the atomic electrons according to the rule $L = nh/2\pi$. In this way Bohr could determine which electronic orbits were allowed or stable, that he called "stationary states", a concept that has been extended to molecules, nuclei and fundamental particles. Bohr then calculated the energy of the stationary states of the H atom using Newtonian dynamics for the electron motion, and advanced the idea that in a transition between two stationary states of energies E and E' the atom emitted or absorbed radiation with frequency ν given by $E - E' = h\nu$, expression that is known as Bohr's relation. In this way Bohr calculated Balmer constant for the H spectrum, an astonishing success.

A few years later it was recognized that, due to momentum conservation, Bohr's equation needs to take into account the recoil energy of the emitter or absorber. Thus depending on whether it is emission or absortion, is $E - E' = h\nu \pm p^2_{(recoil)}/2M$, with $p_{(recoil)} = h\nu/c$ and M the mass of the recoiling atom or nucleus. The recoil energy is negligible in radiative transitions in atoms ($h\nu << M_{(atom)}c^2$), but it may be important in radiative transitions in nuclei ($h\nu \sim M_{(nucleus)}c^2$), though again it is negligible if the nucleus is embedded in a crystal ($h\nu <<< M_{(crystal)}c^2$) (Mossbauer effect); however its experimental verification reinforces the idea of a photon as a "particle" with energy and momentum.

As we know, Bohr's quantization of the angular momentum is not correct and must be replaced by $L = \sqrt{l(l+1)}h/2\pi$, but due to a particular degeneracy, called dynamical or accidental, that assigns the same energy to states with different l but same n for motion under Coulomb forces, that Bohr did not know but we do now, his calculation of the energies of the stationary states proved to be correct (to the first order of approximation) and he was able to derive Balmer formula for the spectum of the H atom in terms of well known constants (e,m.h,c.). Bohr's method was soon extended by A. Sommerfeld by quantizing the phase integrals, based on Ehrenfest principle of adiabatic invariance, and could explain quantitatively the Stark and Zeeman effects as well as incorporate relativistic corrections.

Bohr's idea of energy levels and stationary states was extended to the vibration and rotation of molecules, and all the suddenly atomic and molecular spectroscopy, from microwave to X-ray spectra, interpreted as radiative transitions between energy levels became a quantitative science that allowed to obtain very relevant data about atoms and molecules, of importance not only for physics but also for chemistry, medicine, material science, etc. The idea of energy levels and of radiative transitions between stationary states was extended years later to nuclei to explain the nuclear γ-rays spectra and the particles "resonances", in spite of the great disparity of the energies involved, and was a guiding principle for Schrödinger. Thus it must be considered an important landmark in QP.

Soon two major difficulties became apparent and motivated a lot of discussions: (1) how and when an electron determines to change from one stationary state to another, and (2) what happens to the electron and the EM field "during" the transition between two stationary states. The second question is meaningless in QM because we do not need to describe in detail the electronic motion, as Bohr was trying to do using Nerwtonian mechanics. In fact we know now that we must renounce to that detailed description. During the transition there is an adjustment of the wave function or matter field describing the state of the electron, with the simultaneous creation or annihilation of a quantum of EM radiation or photon. The first question found its explanation years later in QM, but in a somewhat different context, with the notions of transitions probabilities, that can be calculated precisely using QM. However Einstein was again a pioneer by introducing in 1916 the notion of spontaneous and induced radiative transitions, assigning certain coefficients to relate the stationary states involved, that later on were identified with the transition probabilities. By incorporating Bohr's relation into his calculation Einstein obtained the expression for the energy spectrum of blackbody radiation, thus linking Planck's ideas with those of Bohr. However Einstein was not fully happy with the situation and stated that "it is a weakness of the theory that it leaves time and direction of elementary processes to chance". Besides those concerns, spontaneous and induced transitions are the theoretical foundation of lasers, whose technological applications in communications, medicine signal processing, etc, are used extensively.

Another idea with long term impact, introduced in this first stage of the development of QP, was Bose-Einstein statistics originally proposed by S.N.Bose and refined by Einstein in 1924.B-E applies to system of non-interacting identical "indistinguishable" particles, that later became known as "bosons". Today we asume that all the carriers of interactions are bosons. In general, as required by the connection between spin and statistics established in1940, we recognize that all particles with integer spin are bosons and that aggregates of bosons must be described by symmetric wave functions. Bose and Einstein showed that when the number of bosons is not constant, Planck's law for blackbody radiation results, not surprising since photons have spin 1(are described by a transverse EM vector field) , leading to the idea of a photon gas. I should note that the idea of indistinguishable particles, that has been incorporated into Fermi-Dirac statistics, proposed by Fermi in 1928 and used by Dirac to determine the symmetry of the wave function of systems of particles, is fundamental in QM, being a natural consequence of QFT, since all "particles" resulting from the quantization of a given "field" must be identical and thus indistinguishable.

Einstein also applied B-E statistics to mono-atomic ideal gases, but what really showed Einstein's physical insight was his statement that a bosonic gas composed of N particles in volume V should experience a partial condensation (a ground state of zero energy) below a critical temperature $T_c = (h^2/2\pi mk)(N/2.612V)^{2/3}$, the fraction condensed at a lower temperature T being $N/N_0 = 1-(T/T_c)^{3/2}$ which as recognized later, amounted to a phase transition. B-E condensation is possible because although the bosons are assumed non-interacting, they are coupled by the symmetry of the collective wave function. B-E condensation has been the subject of intense experimental research, being associated with HeI-HeII phase transition discovered in 1928, and finally confirmed beyond doubt in 1955 by C.Wieman and E. Cornell. B-E condensation may have many implications in areas such as superfluidity, with potential technological applications. It has even been insinuated that in the primordial universe the B-E condensation of the Higgs bosons (if they exist), gave rise to the mass of the other particles. It must be pointed out that the B-E condensation is a good example of physics at the mesoscopic level.

THE COMING OF AGE

By 1925 it had been realized that a quantum theory of atomic structure based on Bohr's model was not fully satisfactory. In the first place Bohr could not go beyond the H atom. Even in that case Bohr's theory could not explain the fine structure of the H spectrum and several ad hoc adjustments were necessary to reproduce experimental results. This led W. Pauli, among others, to propose around 1925, that electrons carry an "intrinsic" angular momentum or spin ½ $(h/2\pi)$, which implied an intrinsic magnetic momentum $eh/2\pi mc$, as verified experimentally by G.Uhlenbeck and S. Goudsmit. Later on it has been found that all "particles" have an intrinsic angular moment or spin that is either an integer or half-integer of $h/2\pi$, called respectively "bosons" (integer spin) and "fermions" (half-integer spin). But what has been most important from the conceptual point of view, is to recognize that the spin of particles can not be associated with the rotation of the particle as a ball, since as I indicated earlier, we do not describe particles as geometric objects, but according to the nature of the "field" associated with the particle: scalar, spinor, vector, tensor. This is another conceptual landmark of QP, showing that we can not transfer to the microscopic world our macroscopic notions.

Pauli made in 1925 another important ad hoc contribution to explain the stability of atomic structure: the "exclusion principle" for electrons, that, in simple terms, states that no two atomic electrons can have the same set of quantum numbers n, l, m, m_s. This led to the shell model of the atom, that combined with empirical "selection rules" explained the periodic table, atomic and molecular spectra and the origin of characteristic X-rays, allowed to explain the properties of the so-called "rare-earth" elements, clarified the chemical notion of "valence",etc. When QM emerged shortly after, it became clear that the exclusion principle implies that the wave function of a set of electrons must be anti-symmetric in the quantum numbers, including spin. This important idea has been extended by Dirac to all systems composed of indistinguishable identical particles with half-integer spin, that is fermions, and shortly after led to the formulation in 1928 of Fermi-Dirac statistics for fermions. I do not think it is necessary to elaborate on the long range importance of the exclusion principle in its QM formulation, but it must be pointed out that it marked the emergence of a model of the world, composed of two kinds of particles, bosons and fermions, having integral and half-integral spin, obeying two different statistics, B-E and F-D, thus exhibiting two opposite kinds of symmetry, and described by different kinds of fields, another QP landmark.

1925 also marks the birth of QM, first with the work of Heisenberg, Born and Jordan on the matrix version, in which the emphasis was on dynamical variables, represented by matrices that might not be commuting. An alternative treatment, with the emphasis on the stationary states, was elaborated in the nine seminal papers published by E. Schrödinger between Jannuary 1926 and June 1927, in which he presented the formalism that he called "wave-mechanics", that would eliminate the consideration of "micro-mechanical" motions of atomic electrons. Four papers dealt with "Quantizations as a Problem of Proper Values", and the rest dealt with several particular problems. It is interesting to note that Schrödinger confessed that after finishing each paper he had no clear idea of what he was going to elaborate in the next paper. However the amazing result was a theoretical formalism based on the differential equations "in configuration space",that carry his name, that he called "wave or vibration" equation, to determine the state of a system. In those papers Schrödinger successfully applied the equation to the hydrogen atom, the harmonic oscillator and a few other problems, including the method of perturbations, the Stark effect and the non rigid rotator. In one paper he proved his method included the matrix formulation and introduced the idea of associating the operator $\partial/\partial q$ with the momentum p_q to justify Heisenbergs commutation rules. Schrödinger's method, in the form refined by Dirac, has been adopted as the standard form of QM. However a few comments are desirable because of their long term implications.

It is important to remember that Schrödinger was looking for a method for which quantization did not have to be an ad hoc assumption and thought that standing "vibrations" was the answer. He started with Hamilton-Jacobi equation, $H(q,\partial S/\partial q) = E$, and by making $S = K \ln \psi$, and using a variational procedure he obtained the time independent equation $-(K^2/2m)\nabla^2\psi + V\psi = E\psi$. Note that Schrödinger first called ψ a "mechanical field scalar". By inserting for V the Coulomb potential, imposing the proper boundary conditions that restrict the values of E, and making $K = h/2\pi$ he obtained Bohr's formula for the H energy levels. Schrödinger was emphatic that "the equation is stated for purely periodic vibrations *sinusoidal* with respect to time". Thus in his second paper he introduced the relations $v = E/h$ and $\lambda = h/\sqrt{2m(E-V)} = h/mv$ for a standing wave system associated with the motion of the particle, that would oscillate according to a "sine" law, $\sin 2\pi Et/h$, that is $\psi(x,t) = \psi_E(x)\sin 2\pi Et/h$.

Consequently Schrödinger wrote the "wave" equation $\nabla^2\psi - 2m[(E-V)/E^2][\partial^2\psi/\partial t^2] = 0$ for the "mechanical field scalar" ψ. It had to be of second order in time to repeat the sinusoidal time factor, that could be separated for standing vibrations. He saw the logical difficulties with his equation and in his fourth paper , in an interesting heuristic reasoning, replaced it by $-(h^2/8\pi^2 m)\nabla^2\psi + V\psi = i(h/2\pi)\partial\psi/\partial t$, in the current notation; this is the standard time-dependent Schrödinger equation for his scalar "mechanical field"' still in use, but this time he called ψ a "wave function". This adjustment had two momentous consequences that influenced the future development of QM. One is that the equation is of first order in time and therefore does not describe a scalar field that can propagate as a traveling wave. Unfortunately the name "'wave equation" has remained in use. The second is that the scalar field ψ is complex, depending on time as $\exp 2\pi i\, Et/h$, that is $\psi(x,t) = \psi_E(x)\exp 2\pi i\, Et/h$, and therefore is not an observable; this originated an intense discussion that was settled by M. Born probabilistic interpretation of $|\psi|^2$, that I do not need to discuss here, and led, as Schrödinger had already insinuated in his papers, to accept that we can not describe the dynamics of an atomic electron in terms of Newtonian orbits, as Bohr and Sommerfeld had attempted years earlier.

It is interesting to note at this point that Schrödinger acknowledged in his first paper that he had been inspired by de Broglie's original idea, expressed in his Thesis of 1924, of a "pilot wave"of wavelength $\lambda = h/mv$, that would guide the atomic electrons in their motion around the nucleus, but he also pointed out that while de Broglie was thinking of "progressive" waves, his idea was of stationary proper "vibrations" in the atom, described by the field ψ, "which more nearly approach reality than the electronic orbits...existence of which is being very much questioned". In his sixth paper Schrödinger stated the need "to ascribe to ψ a physical, namely electromagnetic, meaning" so that "a ψ-distribution in configuration space is interpreted as a continuous distribution of electricity...in actual space".

This was the origin of the famous and controversial "wave-particle"' duality for "particles", that became incorporated into QM. This has been most unfortunate because the correct statement should be "dual field particle description", since all "particles" have a field associated with them, and depending on the process we must use the "particle" or the "field" approach. Only particles with zero mass, as is the case of the photon, are described relativistically by a true "wave" equation and thus exhibited dual wave-particle behavior. The situation became more confusing when in 1927 C.J. Davisson and L.H. Germer in the U.S.and G.P.Thompson in G.B. obtained with electrons difracction patterns similar to those with x-rays, that were interpreted as showing wave-like behavior of electrons, ignoring that the distortion of a free electron field of defined energy, and thus definite frequency, may show that kind of pattern, even if strictly it is not a wave.

Up to this point QM had developed almost by trial and error. It was P.A.M. Dirac who in 1927 gave QM a formal and beautiful structure, based on what he called transformation theory, using operators to represent observables and his famous ket $|\alpha>$ and bra

$<\alpha|$ vectors for designing the states in configuration (Hilbert) space. In this formulation Schrödinger's equations and field ψ appear naturally when the q-representation is used. Dirac's formal theory is now universally accepted as the methodological foundation of QM, and placed QM on the same footing at the microscopic level as the Newton-Maxwell formalism had done at the macroscopic level.

Dirac's formulation, in 1928, of the relativistic quantum equation of an electron, that in the presence of an EM field is $\left[\sum_u \gamma_u(p_u + (e/c)A_u) - imc\right]\psi = 0$, where $p_u = -(ih/2\pi)\partial_u$, and A_u is the 4-vector potential, was the next crucial development in QP. As is is well known, Dirac's guiding principle was to obtain a relativistic equation of first order in the time derivative, in order to preserve the dynamical law $H\psi = i(h/2\pi)\partial\psi/\partial t$, for which it had to be also of first order in the momenta p_u. This required to introduce the non commuting fourth order matrices γ_u and the field ψ had to be a spinor. With the field ψ and the γ matrices he could form bilinear forms that under a Lorentz transformation behaved like a scalar, a vector, a tensor, an axial vector and a pseudo-scalar. Dirac's formalism has become essential in QP of particles and fields, that requires that all equations be invariant under a Lorentz transformation. Besides Dirac obtained the correct value for the electron spin and magnetic moment, the spin-orbit interaction and the relativistic H energy levels, though radiative corrections had to be added later on. There is much to say about Dirac's formalism, and one of its first applications was to obtain the energy spectrum of the electrons in β-decay, a theory first formulated by Fermi in 1934, that led to the introduction of a new particle, the neutrino, to assure energy conservation, and implied the existence of a "weak" interaction, different from EM. There is no question in my mind that Schrödinger and Dirac contributions are two of the most significant landmarks in the evolution of QP.

An unexpected result from Dirac's equation was the existence of negative energy states, that could not be ignored for mathematical consistency, but posed a difficulty: negative energy states of free particles are not observed. In 1930 Dirac proposed the vacuum was a condition in which all negative energy states are occupied by electrons, that were unobservable, but if an electron was raised to a positive energy state it left behind a "hole" that behaved like a positive electron or "positron", a particle first observed in 1934 by C.D. Anderson. Positrons are emittedby many radiactive nuckei and have found many applications such as in "positron emitters tomography" (PET) used in hospitals and are used in accelerators such as CERN's Large electron Positron (LEP) collider, now about to be closed down. Positrons are also called "antiparticles", a name introduced by de Broglie in 1934. It is accepted that all particles have an anti-particles except that in some instances the particles and anti-particles are identical, as is the case with the photon.

To express in terms of the QP formalism the interaction of EM radiation and charged particles, Dirac using ideas proposed earlier by Born, Heisemberg and Jordan, proceeded to formulate what has become to be known as quantum electrodynamics (QED), and more generally the quantum field theory (QFT), that has shaped the evolution of QP since, and even more, how we model the functioning of the universe at the fundamental level. QFT hs been developed over the years by many creative physicists such as Feynmann, Dyson, Weinberg, Salam,etc. In a nut shell, the basic ideas are the following: (1) all "particles" are associated with "fields", and presumably the converse is also true; (2) the "fieldes" are represented by operators that obey commutation relations, that depend on wheter the associated "particles" are bosons or fermions; (3) the "fields" are expressed by a Lagrangian equation that contains some or the parameters associated with the "particles", such as the mass; (4) the "field" operators can create or annihilate "particles", allowing for the many processes we observe; (5) to describe the fundamental processes occurring in nature, "fields" must interact with each other; (6) the interaction is carried by "virtual" field particles. For example the Lagrangian describing the interaction between electrons and the EM field contains the spinor fields related to the electrons, the vector field related to EM, and a coupling term involving both fields, and the Lagrangian of two electrons contains coupling terms with the spinors of the two particles, the interaction being carried by "virtual" photons. This model has been represented very effectively by Feynman's diagrams that can be used as guide for calculating a process. It is this coupling that really contains the physics of the problem and makes the theory very interesting.

QFT, and in particular QED, has been extraordinarily successful describing with extraordinary precision high energy processes. For example QED has permitted to calculate the radiative corrections to the H energy levels (Lamb-retherford shift, discovered in 1947) and the ionization energy of He with an error of 10^{-9}, and the magnetic moment of the electron with an error of 4×10^{-12}. Other processes such as electron-positron production by photons and their annihilation into photons, Compton scattering (Klein-Nishina), etc, have been calculated precisely. In spite of its successes, QED still has some problems, such as the need to appeal to renormalization procedures, a methodology initiated in 1948 to take care of some divergences that appear in the perturbation calculations. However QED is accepted as a well established theory and its basic ideas have been extended to QFT in general. A similar theory to explain the quark structure of hadrons, quantum chromodynamics (QCD), to which I will refer later on, has been developed since the introduction in 1964 of the standard model of particles. Therefore I think it is safe to say that presently we can consider that the fundamental entities in QP are the "fields", that in their quantized form give rise to "particles", and all fundamental processes can be explained in terms of the "interactions" among the fields. Find the interaction and you have the solution to the problem.

We can affirm that thanks to Dirac, and several other physicists (Feynman, Wigner, Schwinger, Tomonaga,etc.) by the end of the 1950's QM had become a formal theory with great predictive capability that could reproduce with extraordinary precision many experimental results and explain the main features of atomic and molecular structure and even of large aggregates of atoms or molecules. Perhaps the most spectacular related aspect of QM has been the application of band theory to explain the electric properties of solids, particularly conductors and semiconductors. That marked the beginning of what has become known as solid state physics, and more recently as condensed matter physics. This is the area where QP has had more technological impact after the development of transistors and compact integrated circuits called "chips" the essential components for any gadget that needs to process signals and data. Our lives are fully dependent on chips: computers, radios, TV, cameras, cars, phones, imaging devices, etc., that depend on the quantum structure of solids. However at the end af the 1950's QM was not a closed theory, and remained open to new ideas.

PARALLEL DEVELOPMENTS

While QM mechanics proved to be highly successful in explaining atomic, molecular and solid structure and radiative processes, it proved more difficult to explain nuclear structure. Several developments related to nuclear structure and processes took place since Rutherford's experiments in 1911. After J. Chadwick experiments in 1932, it was accepted that nuclei were composed of protons and neutrons, called "nucleons" since 1941, and a lot of empirical properties about nuclei was gathered, but QM formalism in terms of Schrödinger equation was not able to fully explain in terms of a potential, the simplest of all nuclei, the deuteron, a two-body system, even less complex nuclei, that are many-body systems with no dominant central force. It was accepted that the nuclear interaction was much stronger that the EM interaction and that it was of short range but no potential could be found for it.

In fact several empirical potentials were tried to explain the deuteron and nucleon-nucleon scattering: potential wells, with and without hard core, Yukawa potential, a tensor interaction coupling the spins of the two nucleons, even velocity dependant potential, to be inserted in the Schrödinger equation. Some concrete results were obtained but no general theory emerged. Much later it became recognized that the "nuclear" interaction is a "residual" force from what is now called the "strong" interaction, that exists between some particles, now called "hadrons", similar to the residual electric interaction between molecules. The inevitable conclusion was that the "strong" interaction could not be treated by using a potential function, as had been done for charged particles, and that Schrödinger equation was not adequate for that interaction. This was not a failure for QP, but of the formalism used to deal with the strong interaction, as it had happened earlier with the weak interaction.

Nonetheless several ideas based on QM for explaining some features of nuclear structure, were put forward. C.V. Weiszacker proposed in 1935 an empirical equation for the binding energy of nuclei, that proved very useful for discussing nuclear fission. In 1939 N. Bohr and J.A. Wheeler suggested that nuclei could be treated as liquid drops and applied the model to explain the nuclear fission of the U isotopes, a result that was crucial for the development of the nuclear bomb, and later for the controlled release of nuclear energy in nuclear reactors. Between 1948 and 1955 M. G. Mayer, J.H.D. Jensen and others elaborated a nuclear shell model similar to the atomic shell structure but with a strong spin-orbit interaction of opposite sign, so that the nuclear states were designed by n, l, j. The model, elaborated later on in more detail by I. Talmi and A. de Shalit, and still in use, could reproduce fairly well the spin and energy level distribution in many nuclei, including the "magic numbers" or more stable nuclei, and the EM spectrum associated with single nucleon transitions, but it lacked a general explanation of how to calculate the energy levels. Besides many nuclei in between magic numbers, such as the rare earths, showed a spectrum very similar to that corresponding to the vibrational and rotational molecular spectra, and exhibited large electric quadrupole moments, suggesting that those nuclei were deformed and experienced collective vibrations and rotations, but not necessarily as rigid bodies. This idea was developed in great detail in 1952/53 by A. Bohr and B. Mottelson. Shortly after, it was recognized that the shell model, that assumes independent particles states, and the collective model, that implies collective degrees of freedom of strongly coupled particles, are complementary, resulting in a unified model, for which the techniques of QM were necessary. However, in spite of all those developments, still no satisfactory quantum theory of the strong interaction was yet available.

During the same period of time that physicists struggled with nuclear theory. Laboratories for dealing with nuclear and particles experimental physics were established in several parts of the world

(US, Europe, Soviet Union, Japan). Cosmic rays were a source of new particles and led to the discovery of pions and muons. New particle accelerators (synchrotrons, synchrocyclotrons, linear accelerators), each with more energy and luminosity or beam intensity, were built. Several particle detectors (emulsions, bubble chambers, spark chambers, particle calorimeters) were designed, nuclear reactors became strong sources of neutrons. The existence of neutrinos was confirmed experimentally by Cowan and Reines in 1950. Pion-muon decay was first observed in cosmic rays in 1947, and explained using a theory similar to that for β-decay. Antiprotons and anti-neutrons were observed in 1955 and 1956 respectively and produced in the laboratory. And more than 100 of new unstable "particles", later on called "resonances", most having extremely short half-lifes, were produced in the accelerators or identified in cosmic rays. The role of symmetries in all these results, in the context of the CPT theorem, was closely analyzed for possible violations and several empirical rules were proposed for explaining the observed processes. This was a very exciting period in need of new ideas. Needless to say QM techniques were most useful for analyzing those experimental results.

NEW IDEAS

Since 1960 several important ideas have been introduced, aimed mostly to incorporate the weak and strong interactions into the scheme of QFT and particle physics, and to formulate a "grand" unified fields theory (GUT) of the three interactions: EM, weak and strong. Because their conceptual impact. I will review them without entering into great details. In the first place it became clear that there was a big difference between the masses of particles, that became grouped into "baryons", "mesons", and "leptons", term introduced in 1946. Second, it became also clear that only some particles (baryons and mesons) were susceptible to the "strong" interaction, and in 1962 they were called "hadrons". Third, to be consistent with QFT, it was necessary to identify the bosons responsible for the weak and strong interactions, as the photons are for the EM. And what was more exciting: after experiments such as deep inelastic scattering of electrons by protons, it was concluded that hadrons were not so elementary and might have a structure, that could explain the resonances spectrum, while the leptons were structureless particles, not affected by the strong interactions.

Beside the extraordinary progress in experimental techniques since 1960, the two major and closely related conceptual developments of QP, that contributed most to a simpler and coherent model of matter at the fundamental level, were the formulation, based on group theory considerations, of the quark model of hadrons, by M. Gell-Mann and G. Zweig in 1964, and of the electro-weak fields theory (EWFT) that blended EM and weak interactions, using the Lagrangian formalism of QFT, by S.L.Glashow, A. Salam and S. Weinberg in 1968. Eventually these two developments led to the emergence in 1977 of the Standard Model of elementary particles, that asserts that the world is made up of "elementary" fermions interacting through fields, of which they are the sources, by means of the exchange of bosons, thus providing a coherent view of the world at the fundamental level based on QFT. The conceptual and practical importance of the Standard Model for understanding the world is comparable to that of the nuclear model of the atom developed about 60 years earlier. Most of the tenets of the Standard model have been verified experimentally.

In a nutshell, the Standard Model assumes that the electric and weak interactions between fermions are carried by four vector bosons of spin 1: the photon, with no mass, and the W^+, W^- and Z^0 bosons with masses of the order of 90 GeV, as required by the short range, about 10^{-3} fm, of the weak interaction, (recall the relation $\Delta E \Delta t \approx h/2\pi$, and make $\Delta E = Mc^2$ and $\Delta x = c\Delta t$), while the strong interaction is carried by eight "gluons" of zero mass, and thus infinite range, and spin 1. In turn the basic fermions are six leptons: electron e^- muon μ^-, and tau τ^-, and their corresponding neutrinos, ν_e, ν_μ ν_τ (see Table), and six "flavors" of quarks (up, down, charm, strange, top and bottom) with fractional "electric" charge ± 2e/3 and ± e/3 (see Table), and three kinds of "strong charge" or "color" called "red", "green" ~~and~~ "blue". The "color" is carried by the gluons, that have the additional property of "confinement" because the quark/gluon interaction increases at distances above 1 fm, making virtually impossible to observe free quarks and gluons, that have to be recognized by their "signatures", as it happened in 1995 with the top quark at Fermilab. Also at distances less than about 0.2 fm the interaction is so small that quarks and gluons can be considered approximately free particles; this is called "asymptotic freedom". To the above list we must add the anti-particles. This may be seen very elaborate but the beauty is that it provides a rather simple view of the universe at the fundamental level, that explains most fundamental processes and is subject to quantitative analysis and experimental verification. For completeness I will elaborate some of the features of the model, without going into great detail, because the subject is well known.

First, all systems composed of quarks, are hadrons, that can be of two kinds, baryons and mesons. Baryons are composed of three quarks and mesons are composed of a quark and an antiquark, in combinations that are colorless (the stable combinations must be colorless in the same sense that atoms are electrically neutral) held together by the exchange of colored gluons. Two colorless hadrons feel practically no strong force except when they are very close, in which case they experience a "residual force", which is of short range (this is similar to interatomic and intermolecular forces, that are residual electrical forces). Second, quarks are arranged in hadrons in a form similar to the shell structure of atoms and nuclei. Excited states of hadrons, in which the quarks are in higher energy shells give rise to all resonances that have been observed. Third, the hadrons are actually clusters or soups containing the quarks, the gluons that jump among them, and several "virtual" pairs of particles that appear and disappear very fast. It is this rather dynamical structure of hadrons that gives rise to the richness of particle physics processes. An interesting result of the Standard Model is that it has brought the quark energy levels in hadrons in line with the nucleonic energy level in nuclei and the electronic levels in atoms, molecules and solids, although we are dealing with highly different energy levels, from eV up to GeV.

TABLE 1

IS THERE A 'STORY LINE' IN PHYSICS ?

YES at the MICRO-level

NO at the MACRO-level

Basic Assumptions

1) The world is composed of distinguishable "units", called "particles", with well defined properties.
2) There are a few fundamental "interactions" (4 or less?)
3) Interactions are described by means of "fields", that in General are time-dependent, and some propagate in space as "waves".
4) Interactions "conserve"certain physical magnitudes.
5) Conservation laws are related to "symmetries" observed in the Universe.

I do not want to leave the impression that the SM is only descriptive. To allow quantitative analysis, the SM has been framed into the format of QFT using the gauge theories. While a QFT for the electro-weak interaction field theory (EWFT) has been developed, the strong interaction requires a new gauge field theory, called Quantum Chromo-dynamics (QCD). The mathematical procedure to transform the phenomenological electroweak and strong interactions into a QFT has been to developed relativistic and gauge invariant quantum Lagrangians for particles with mass, that contain an interaction part and are renormalizable, for wich the pioneering work on non Abelian gauge theories by C. N. Yang and R.L. Mills in 1954, and the idea of symmetry breaking based on the mechanism proposed by P.Higgs in 1964 (although P.W. Anderson had suggested a similar mechanism in 1963) were fundamental.

For the sake of those not familiar with Higgs mathematical procedure for breaking the symmetry of the vacuum I will illustrate a particular simple case. Let us start with a Lagrangian with a scalar complex field Φ and mass m, $L = \partial_\mu \Phi^+ \partial^\mu \Phi - V(\Phi^+\Phi)$. Usually $V = m^2\Phi^+\Phi$ so that the vacuum state for this Lagrangian is $\Phi = 0$, but then the Lagrangian is not renormalizable. Suppose we make $V = (m^2/2\Phi_0^2)[\Phi^+\Phi - \Phi_0^2]^2$, where ϕ_0 is a real adjustable parameter. The state $\Phi = 0$ is not stable because the field energy density $1/2m^2\Phi_0^2$ is a maximum. Instead the minimum energy or stable vacuum state corresponds to $\Phi^+\Phi = \Phi_0^2$, that in the Φ complex plane is a circle of radious Φ_0, making the vacuum a stable but degenerate state. The degeneracy is broken locally if we chose a ground state $\Phi(\phi_0, 0)$, which is equivalent to a local symmetry breaking. To allow moving out of the vacuum we expand Φ around this point by adding a field h, that is $\Phi = \phi_0 + h/2^{1/2}$ where h is a symmetry breaking field, generically known as the Higgs field or H-field, and insert this Φ into the Lagrangian. The result is a renormalizable Lagrangian with a scalar spin-zero boson of mass $2^{1/2}$m, the Higgs boson, associated with the H-field. If we add in the Lagrangian a massless vector gauge field A_μ, with a coupling coefficient q, the result is a new Lagrangian corresponding to a spinless scalar boson of mass $2^{1/2}$ m and a vector boson of mass $2^{1/2}q\phi_0$.

The important aspect of Higgs mechanism is that it allows particles with mass in a renormalizable Lagrangian, as proved by G.t'Hoff in 1971. In the EWFT it is said that the H-field is responsible for the mass of the $W^\pm$ and Z^0 bosons, and in QCD the H-field gives mass to the quarks. The search for the scalar H-boson, whose mass is assumed to be larger than 100 GeV, has been going on for many years with no succes. Just on Nov.2 CERN authorities decided to stop the search for the H-boson in their LEP collider, that will be dismantled and replaced by a large hadron collider (LHC) to be built in the same place, though the search will continue at Fermilab.

MORE NEW IDEAS

However QFT is not closed and there are still many open ends that are areas of active research, that hopefully will find answers in the 21th century. Physicists, in the quest for simplicity, unity and symmetry, are looking for a Grand Unification Theory (GUT), that will merge the EWFT and QCD into a single unified theory with a higher order of symmetry. GUT implies new quantum properties of particles, such as photon decay, whose half-life is estimated at 10^{31} years, much longer than the estimated age of the universe, X-gluons that would convert quarks into leptons and conversely, several Higgs fields, monopoles, spaces with more than four dimensions, etc. Some progress has been made in this direction but still is an open question.

Another open end question is the inclusion of Gravitation into the format of QFT. A QFT of gravitation that is GQFT, would require the existence of a "particle" or boson with spin two, the "gravitation", to carry the gravitational interaction. This boson has not been observed. However there are good reasons to believe that there are gravitational waves, since any disturbance in a gravitational field must propagate in space. Moreover, Einstein's field theory of gravitation is not renormalizable. More challenging is to try to unify gravitation with the other interactions, that is, unify GQFT with GUT, thus reducing the diversity of forces to a single fundamental unifying force. Many interesting ideas for such super-grand unification, such as the possibility of transforming fermionic fields into bosonic fields and conversely, giving rise to a single "superfield", resulting what is called supersymmetry. Of course to reproduce the observed world, the supersymmetry has to be broken by super-Higgs fields. A constellation of new fields and particles (gravitinos, leptinos, photinos, quarkinos, higgisinos,etc.) have been proposed. However no concrete results have been obtained yet. Again, this is a problem for the 21th Century.

Personally I have the feeling that gravitation can not be incorporated into QFT for the simple reason that, according to the general theory of relativity, gravitation is expressed in terms of a distortion in the metric of space-time due to the mass distribution, the dynamical consequence being "gravitational" forces extremely small compared with the three other interactions. Only, at energies of the order of Planck's energy $(hc^5/2\pi G)^{1/2} \approx 10^{19}$ GeV and distances of the order of Planck's lentgh $(hG/2\pi c^3)^{1/2} \approx 10^{-35}$m, as may have existed at the time of the Big Bang and may be possible in the vicinity of massive objects such as black holes, gravitation can become comparable to the other interactions and a quantum field theory of gravitation might make sense. But again I leave that problem for the next generation of physicists. As a footnote, it may be recalled that since the 1920's until his death in 1955, Einstein tried unsuccesfully to unify gravitation and electromagnetism.

OTHER QUESTIONS

During the 100 years of development of QP many interesting questions, that perhaps may be considered "philosophical", have been raised and continue to be raised, motivated perhaps because some try to look at the tenets of QM in a macroscopic context. I will briefly mention three of them because of their special interest. However, personally I should say I am quite happy with QP as a rather successful paradigm for describing the world at the fundamental level and thus avoid that kind of philosophical considerations, that though important are not necessary for dealing with concrete problems related to matter and radiation.

One of the most critical issues raised at the beginning of QM was the meaning of the "wave function" ψ, that Schrödinger assumed originally represented a sort of stationary vibrations in the atom. However ψ is a complex function and is not an observable. In 1926 M. Born proposed that $|\psi|^2$ corresponds to the probability of finding an electron around point x,t. This suggestion was accepted and combined with Heisenberg's uncertainty principle led to the probabilistic interpretation of QM, that has been the source of many discussions. The fact is that QM is deterministic in its own probabilistic way, which is not the same as the probability of random events, and causality takes its own form in QM.

Another issue, still considered by many, is what is the "meaning" of QM, or in other tems, what "reality" is described by QM. This issue began in 1927 with a discussion between Einstein and Bohr, reached a climax in 1935 with the Einstein-Podolski- Rosen paradox (that is not a paradox), and has continued until now. I have no time to elaborate on this issue, that requires to define first what is understood by "reality" in physics. I would like to point out that I consider there are three "physics" "realities": an "objective" reality independent of the observer, the "observed" reality, which is the result of observations and measurements, that may change as observations techniques improve, and the "perceived" reality, which is our mental construct or interpretation of observations and measurements, and often depends on previous perceived realities. The problem is that for the "perceived" reality we use sensorial or macroscopic notions, that may not be applicable at the microscopic fundamental level, but even so we have been able to develop a formalism, QM, that is adequate for the description of nature at the fundamental level based on the "observed" reality. However from a rigorous point of view we can not ignore the role of the observer, that in the quest for an "observed" reality may affect the state of the observed system and thus change the "objective" reality.

An issue closely related to the previous one, and currently of great interest, is that of "separability" and "entanglement", about which a lot is being written. For example, if we have a system composed of two "interacting" subsystems 1 and 2, the wave function of the system is some combination of the wave functions for the states of the two subsystems. If I make a measurement on one subsystem, say 1, I may alter is state, and depending on the symmetry of the whole wave function and the strenght of the interation, the state of system 2 must also change. That is the states of the two interacting systems are entangled, even if they appear separated. As expressed in 1935 by Schrödinger, this "is the characteristic trait of QM". The problem begins when the two systems separate a great distance, so that their interaction decreases to a very small value. I say that in that case the entanglement also tends to disappear, but others I am sure have a different opinion and introduce a series of notions such as "hidden variables" and "teleportation", about which I do not want to argue. There is a very rich literature on the subject that those interested can consult.

An interesting point, worth speculating, is whether QM can contribute to understand life phenomena, that depend very critically on many physical factors, chemical elements and processes that occurr in carbon based living systems. Living systems are very special open adaptive complex systems that, as Jacques Monod has indicated, have three characteristics, not found in inert matter: teleonomy, autonomous morphogenesis and reproductive invariance. Nevertheless the functioning of living systems obeys the laws of inert matter, though it depends on the activity of a few chemical elements. The most important elements are carbon, hydrogen, oxygen and nitrogen, that appear in several compounds. But equally important is that the energy available to those elements and their compounds must be closely related to their quantum stationary states, otherwise they would not be stable or react. The Anthropic Principle (of which there are several versions) speculated on this point by analyzing how the values of some physical quantities, related to the fundamental components of the world, make life possible, or were designed to make carbon-based life possible, at some time during the evolution of the universe. Living beings are highly complex and unstable but predictable systems that depend for their organization and functioning on many elaborate molecular interactions to which QM formalism applies. The brain in particular is a most complex system that functions by moving electrons around potential barriers according to QM, and is regulated by ions carried by several molecular compounds across electric potential differences. What physical processes at the molecular level account, for example, for the memory and, in general, for cognition is not known. So it seems reasonable to expect that physicists in the next century, working with biologists, will find new insights about life by applying QM to biological processes and place quantum biology on a sound basis.

On the more practical side, an area in which QP may have an important impact during the next century is "quantum computation". The basic idea is very simple. A system with only two states, such as an electron having spin up or down in a magnetic field, may be used for manipulating quantum bits or "qubits". One state would designate 0 and the other 1 in the binary language of the computer. However the implementation of this interesting idea is still in its early infancy and it is very risky to try to predict its future, although a lot of theoretical work is going on this subject and in its related area, cryptography.

Finally, now "miniaturization" is the marching order for the design of micro-electronic devices and the question is "How far can we go in the miniaturization efforts without violating the basic principles of QM and conflicting with the Uncertainty Principle? Time will tell.

EPILOGUE

In concluding I would like say that during the 20th century QP has given us a coherent, reliable and simple picture of the microscopic world, that escapes our direct sensorial experience, and has required to depart from many conceptions that are a result of such sensorial experiences of were inherited from past centuries, but that we still apply to the macroscopic world. The QM picture of the world is still unfinished and nobody can predict what new ideas will emerge or even if a new world model will be designed. Science is by its own nature a very dynamic and envolving endeavor in which the creativity and skills of human beings play a fundamental but unpredictable role. Next century physicists will have an important role regarding our view of the world, by refining and playing with the formalism of QP they have developed this century and applying it to a variety of old and new issues.