

An Introduction to a
Realistic
Quantum
Physics

Giuliano Preparata



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Published by

World Scientific Publishing Co. Pte. Ltd.

P O Box 128, Farrer Road, Singapore 912805

USA office: Suite 1B, 1060 Main Street, River Edge, NJ 07661

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

AN INTRODUCTION TO A REALISTIC QUANTUM PHYSICS

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ISBN 981-238-176-7

Printed in Singapore.

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Preface

It is almost thirty years that I have been teaching university courses in the field that has (almost) totally absorbed my research activity: Quantum Field Theory (QFT) and particle interactions, today known as the Standard Model (SM). I have thus had innumerable occasions to observe the uneasiness, indeed the embarrassment of students when making the jump from Quantum Mechanics (QM) to QFT, the only sensible quantum description of the relativistic world, where the number of particles — quanta cannot be kept fixed. Sensible, that is a good word, but can it be really applied to QM itself? When pressed on this point the students, emerging from their institutional courses on non-relativistic QM, without exception showed how uncertain and uneasy their feeling was about a physical theory which is more than seventy years old, and permeates large sections of modern technology. As to their intellectual attitude toward QM, that is also without exception “conventionalistic” totally centered on rules and procedures, largely based on the Copenhagen interpretation and its subjectivistic probability approach.

I have always regarded (and obviously I have not been alone in this) this state of affairs as very unsatisfactory, including the fact that a critical debate on such fundamental issues has remained confined to a small community of “fundamentalists”, at the frontiers of physics, metaphysics and philosophy. I have thus tried to devote a (necessarily small) part of my lectures to present my point of view, which tries to reappropriate Quantum Physics (QP) to a strongly realistic view of the world, in the great tradition from Galilei to Einstein that has shaped the deep structure of modern science. But without a systematic exposition I felt that my efforts were doomed to have little or no effect at all. Thus I decided to subtract a part of my vacation time (summer 1998) to more or less futile beach talks, and

devote the following Essay to my students (and to whoever cares about the problems addressed in it) who, I hope, will benefit from being presented with ideas and analyses that are not usually found in the literature that is available to them.

This Essay is written in English for two main reasons, first this language is the common language of science, and physics students should know all too well how useful it is to read (and speak) it fluently. The second reason is that I nurture the hope that, some day it will be felt desirable to have access to its ideas in the wide world.

Milano, October 1998.

Giuliano Preparata was born in Padova, Italy on March 10, 1942. Theoretical physics was the focus of his insatiable intellectual curiosity. He succumbed to cancer in Frascati, Italy on April 24, 2000.

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Chapter 1

The Fads and Fallacies of Quantum Mechanics

Quantum Physics is about one hundred years old, it represents a new image of the physical world, that sprang from the irresolvable difficulties in which classical physics (CP) sank at the end of the XIX century. And yet, and this is the peculiarity of this (unachieved) scientific revolution, after one hundred years the basic ideas and achievements of this new and profound approach to physical reality do not belong at all to the background of our culture or shape our collective understanding of and expectations about the world.

The reason for this new and strange situation, that did not occur in other scientific revolutions, like the Copernican Heliocentrism or the Einsteinian Relativity, is to my mind due to the peculiar interpretation of its basic laws and mathematical results, that since the 1930's imposed itself, and is mainly associated with the name of Niels Bohr: the Copenhagen interpretation. Such point of view suffers from a number of strange and, in the end, untenable “dogmas” about the structure of the physical world. Let's try and identify them.

First of all, according to the Copenhagen interpretation, quantum physics, or better, Quantum Mechanics (QM) addresses the microscopic world only, i.e. the world of atoms, molecules and the plethora of particles that have been the subject of intensive studies in the second part of this Century. The macroscopic world, the world of our immediate experience, is instead fully and consistently described by the venerable ideas and laws of CP. To such world there belong all physical observers, whose measuring devices have thus the sharpness and the determinism of classical physics. In this way, according to the Copenhagen interpretation, the physical world becomes intrinsically dualistic: on one side the microscopic physical systems with their chancy motions, no more describable in terms of well defined

trajectories, on the other the classical observers with their classical devices, obtaining information about the microscopic world that can only be statistical in character and, more oddly, can in no way represent the *reality* of the microscopic system, for the *random*, unpredictable interaction with the observing apparatus is an essential aspect of the physical situation, in which the observed and the observer are inextricably entangled. And the statistical distributions — the square of the wave-functions — which obey the quantum laws of evolution, do not tell the tale of the observed, but rather of the knowledge of that tale that the observer may acquire through his devices. J. A. Wheeler once put this peculiar status of affairs quite vividly when he stated that the Schrödinger wave-function bears to (the unknowable) physical reality the same relationship that a weather forecast bears to the weather. In such way the Copenhagen physicist has given up his ambition to describe the physical world *as is*, the fundamental aim of any *realist* (like Galileo Galilei and all the great classical physicists, Albert Einstein included), contenting himself to account for what *he may say* about the world, whose reality remains fundamentally inaccessible. Thus he completely embraces the position of Cardinal Bellarmino, that cost Galilei the ordeal of the process by the Inquisition and of its abject condemnation. It is interesting, but far from amusing, that with the Copenhagen QM modern science, born from the intellectual courage and achievements of a group of “realists” like Galilei, comes full circle to subscribe to the epistemological theses of “conventionalists” like Bellarmino himself.

The reason for such drastic epistemological choice, that has caused so much turmoil in the physics of this Century and is responsible for the “marginalization” of quantum physics from the main cultural trends of our time, is the realisation that particles like the electron may show, in the experiments of the Davisson–Germer type, characteristic wave-like behaviours such as interference, which intermingle two aspects of reality that appear completely irreducible, that of a particle and its discontinuous behaviour with that of a wave with its fundamentally continuous character. And it is in the typical notion of “wave–particle complementarity” of the Copenhagen “vulgata” that any hope of a realistic, objective interpretation of QM fades away, leaving in its place a well defined set of rules to “compute” the statistical distributions of the outcomes of given observations (or observables) on a statistical ensemble of identical physical systems.

As the aim of this Essay is to show the existence and describe the structure of a realistic approach to quantum physics (which does without the deeply engrained fallacies of the Copenhagen School, by denying an

independent, self consistent status of “bona-fide” physical theory to Quantum Mechanics, which only belongs to Quantum Field Theory (QFT)), it seems appropriate to give a brief historical account of the early developments of quantum physics, that in the first two decades of our Century appeared to point in a direction completely different from what came to be generally accepted through the rest of the Century.

The birth of quantum physics is usually attributed to Planck’s theory of the Black Body’s radiation. The application by J. Jeans of the theorem of energy equipartition to the wave-modes of a classical electromagnetic field inside a “Hohlraum”, i.e. an oven, led to the well known and deprecated “ultraviolet catastrophe”, according to which the energy density of the electromagnetic field inside the oven comes out to be infinite, due to the contributions of the high frequency (ν) modes, whose energy content is instead experimentally found to be highly suppressed. Planck’s solution, in spectacular agreement with experiments, was really revolutionary in that it assumed that, contrary to Maxwell theory, the energy exchanges between a given mode of frequency ν and the “matter oscillators” of the oven’s walls could not be continuous, whence the equipartition theorem, but could only occur in quantities, or packets or quanta of energy $\epsilon = h\nu$, where h is the famous Planck’s constant ($h = 6.626 \cdot 10^{-27}$ erg. sec.).

Such “quantization” of the energy negotiations between the electromagnetic (e.m.) field and matter was completely at variance with the continuous character of the Maxwell field and of its energy density, and dramatically called for a completely new theory of both its kinematics and dynamics. In the meantime, a few years later (1905) Albert Einstein proposed that in such energy negotiations the main actor is a new strange particle-like physical object, the “quantum” of the e.m. field, which he baptized “photon”. According to Einstein’s view, when energy (and momentum) get exchanged between the e.m. field and an atomic system, a given e.m. mode of frequency ν and wave vector $\vec{k}$ can only exchange energy in quantities which are integer multiples of $\epsilon = h\nu$, while the momentum must be the *same* integer multiple of $\vec{p} = \hbar\vec{k}$ ($\hbar = \frac{h}{2\pi}$). Other exchanges are strictly forbidden. In this way he could explain the oddity of the photoelectric effect, in which the ability of an electromagnetic radiation to extract electrons from a given metal surface depended not on the energy deposited on the surface but on the frequency of the radiation. The particle-like attributes of the photon were later (1921) confirmed by experiments on the diffusion of electromagnetic radiation by a charged particle, known as the Compton effect.

To a “realist”, such as Einstein has been throughout his life, the “photons”, which invariably appear when the e.m. field interacts with matter, must *exist* in the field, and the field must *be made of* them. Yes, but how? How can the particle properties of the photon(s) be reconciled with the wave character of the transverse Maxwell field? This was the dilemma that could, perhaps, be resolved in a fully realistic theory of the quantum world had Einstein’s realism been a bit less “naive”, and Planck’s ideas received a bit more attention. It is not very well known, in fact, that while the great advancements of the Black Body’s theory were followed by Einstein’s theories of the photoelectric effect (1905) and of the specific heat of a solid (1908), a sharp debate went on between Planck and Einstein upon the physical meaning and properties of the quanta and their relationship to their quantum fields.*

According to Planck, Einstein’s attitude to attribute the “photons”, with their particle-like properties, a well defined physical reality beyond the acts of interaction in which they manifest themselves — discontinuous “avatars” of a wave-field — was too *naive* in the sense that in this way one could only account correctly for *one* side of reality, the interaction field–matter (observer), but totally ignored the *other* side of reality, namely the dynamical evolution of the field when nobody observes it, and no energy–momentum negotiation takes place with other (matter) fields. And the wave-like aspects of the latter, such as diffraction and interference, bear witness to the fact that the photons *cannot* be the whole story, for one side of reality cannot contradict another: the real world can’t be but one! Planck’s realism was thus more sophisticated than Einstein’s in that it suggested the idea that the quantum field was not a well defined collection of “photons”, a picture that suffices to account for the thermodynamics of the Black Body, but a *coherent* physical system defined in all space for all times (much as classical physics describes it), whose kinematics and dynamics, however, must be redefined so as to incorporate, under appropriate conditions, the appearance of photons. Of course at the time (the first decade of this Century) Max Planck did not know how to realize his ideas, but the real remarkable aspect of his realism is that it suggested in an unerring manner the way to avoid the type of nonsense that tragically convinced most of the physicists of this Century to give up the glorious tradition of realism, which led to modern science.

*For in the theory of the specific heat of a solid Einstein describes the atoms of a solid by a continuous acoustic field, whose “quantization” *à la Planck* produces a new type of quanta, the “phonons”.

We may now, perhaps, begin to understand how the Copenhagen interpretation came to be perceived, at the end of the 1920's, as the only way "to make sense of the nonsensical". Soon after World War I (1923) Louis de Broglie proposed to describe in a wave-like way any (microscopic) piece of matter, thus turning upside-down Planck's (and Einstein's) approach. Now the classical physical object, the particle, gets somehow endowed with a wave-like behaviour much as the quantum object, the photon, derives such properties from the classical physical system it belongs to, the e.m. field. Whereas, however, in the quantum field approach of Planck and Einstein the field aspect is essential (and remains so after "quantization") in de Broglie's idea the field aspect is totally extrinsic, it is just an abstract mental construction grafted upon a very concrete physical object, Newton's material point. Whereas for the quantum field it was the reality of the notion of photon that had to be assessed and understood in the light of the reality of the field, in de Broglie's quantum mechanics it is the reality of the matter point that ostensibly clashes with that of its "associated wave", leading inevitably to the Copenhagen's brand of conventionalism.

But the spectacular successes in the realm of atomic physics of the newborn QM of Schrödinger and Heisenberg, that soon followed (1925) de Broglie's proposal, were judged as the best demonstration of the *usefulness* and *adequacy* of QM to account for the innumerable observations, that since a few decades challenged any understanding based on classical physics. Even though, it was clear, de Broglie waves had nothing to do with real space-time physical processes, but could only be used *to calculate* the statistical distributions of the outcomes of any observation on the particular microscopic system.

One may now see the reasons which steered physics into a new, unsavoury course that severed all ties with the great intellectual tradition of realism that marks the development of modern science. Famous is the debate between Albert Einstein and Niels Bohr[†] at the Solvay Conference of 1927, in which the irreducible realist (Einstein) tried to oppose with all his intellectual might the new conventionalistic (Bohr's), and basically sceptic, approach that the "stars" of QM (Bohr, Heisenberg, Schrödinger, Born, Pauli and Jordan) were then boldly shaping. To Einstein's objections, that were all based on his philosophical choices, Bohr could oppose a remarkably effective logical system that, once its odd postulates were accepted, would

[†]For an account by the protagonists of what happened during the Solvay Conference see Schilpp,[Schilpp (1957)].

show no gap nor weakness. And to a scientific community, whose interests in the atomistic aspects of the physical world were dramatically rising, the smooth working of Copenhagen's QM was more than enough to attribute the victory to Bohr, and push Einstein out of the quantum physics' stage, and to stop to listen to his objections, that became particularly sharp in the paper (1935) written in collaboration with Rosen and Podolsky (which exposes the so called EPR paradox).

In this way the truly successful revolution of our Century, the atomistic revolution, appears to have prevented the full development of quantum physics. Einstein, of course, was totally justified in his deep unhappiness about Bohr's extreme epistemological position, but there existed no way to challenge it in purely *logical* terms, no more than Bellarmino's arguments against Copernicus could be logically disproved by Galilei. However Galilei's realism proved then a better guide for the pursuit of scientific truth than the logically unattackable conventionalistic subtleties of the Cardinal. The question now is whether Einstein's realism could not be as successful a guide in his struggle against Bohr's triumphant conventionalism. The answer is, unfortunately, no.[‡] Surprisingly, in Einstein's quest for a realistic approach to quantum physics, he seems to have forgotten the themes of his youth and, in particular, his debate with Max Planck, all focussed on the *field* aspects of the quantum world. And instead of going back to the main field theoretical aspects of early quantum physics, and to subject to a deep analysis the relationships between fields and quanta, in search of new (non-classical) principles and laws governing physical reality, he believed that the odd statistical structure of QM was but a manifestation of the fact that QM is an *incomplete* theory of the quantum phenomena, arising from a yet to be discovered averaging over *hidden* variables, whose nature had to be researched and understood. We now know that Einstein's research programme (which, however, did not arouse much interest) was doomed to failure for, as J. Bell (1964) showed, any completion of QM through hidden variables can be experimentally tested, yielding results at variance with the predictions of QM. And the experimental evidence (Aspect, 1980) is definitely in favour of QM, in spite of the impossible difficulty of understanding the non-vanishing *particle* correlations at space-like distances, implied by the quantum mechanical description of such experiments.

It thus appears quite plausible that the keen interest that has surrounded particle physics during this Century has greatly contributed to

[‡]And this, I contend, is the reason of the utter failure of Einstein's struggle.

place the particle at the centre of theoretical investigation, endowed with a basically autonomous kinematics and dynamics, in contrast to the complete dependence of the dynamics of the quantum of early quantum physics from that of its field. And in fact the theory of the quantization of a classical field, accomplished at the end of the 1920's, came to be known as "second quantization", to distinguish it from the quantization of a system with a finite number of degrees of freedom, i.e. QM. It is again the centrality of the notion of *isolated* particle in the physical thought of our times that, to my mind, has prevented an in-depth critical analysis of the relationships between QM and the "second quantization", or Quantum Field Theory (QFT). For to the mind that embraces a wider physical realm the Copenhagen epistemology is not only hard to swallow but it is also at odds with physical observations.

Let's begin with the idea that quantum behaviour has to do with the *microscopic* world only. The well-known collective phenomena of Ferromagnetism, Superconductivity and Superfluidity, whose classical impossibility is easy to demonstrate,[§] bear witness to the fact that there exist macroscopic pieces of matter whose behaviour *cannot be described by classical physics*. If not classical, what is then the relevant physics?

Most contemporary physicists have no doubt that QFT must be involved in the still mysterious[¶] workings of these fascinating phenomena, but, beyond a few phenomenological attempts, such as the Landau-Ginsburg approach, no real headway has ever been made into this kind of physics. And, I contend, the fallacious philosophy of QM is largely responsible for this unfortunate state of affairs. Conversely, couldn't the situation improve, indeed change drastically if we were to realize the centrality of QFT and find that QM is but some kind of approximation of QFT in a well defined, limiting physical situation? This is precisely what this Essay proposes to show. But let's go on.

We have just seen that it is thus not true that, as the Copenhagen physicists claim, the quantum world is the microscopic world: there is a peculiar macroscopic system, whose behaviour can only be accounted for by quantum physics. Let's now address the other basic assumption of QM,

[§]The classical impossibility of Ferromagnetism is nicely explained in Feynman's Lectures, [Feynman *et. al* (1965)].

[¶]Naturally, this refers to the generally accepted theory of condensed matter physics, based on electrostatic interactions. For the success of a new approach to condensed matter, based on Quantum Electro Dynamics see Giuliano Preparata, QED Coherence in Matter (World Scientific, Singapore, 1995).

namely the dichotomy of the world in microscopic quantum systems and macroscopic classical observers. I wish to show the fallacy of this Copenhagen's "tenet" by simply recalling that classical physics is in fact logically inconsistent, and can thus in no way provide the theoretical description of even a part of reality, that of the observer.

The inconsistency I am referring to is "the entropy crisis", a notable example of which is the "ultraviolet catastrophe", whose resolution led to Planck's discovery of quantum physics. The fundamental works in the second half of the XIX century of J. C. Maxwell and L. Boltzmann on the statistical theory of the perfect gas exposed the fundamental connection between the statistics of the configurations in classical phase space of a large ensemble of (almost) non-interacting matter points and their thermodynamical behaviour. In particular Clausius' entropy was shown by Boltzmann to be proportional (by the proportionality constant that rightly bears his name) to the logarithm of the number of different configurations that correspond to a thermodynamical (equilibrium) state; defined by the thermodynamical variables: temperature, volume, and other possible macroscopic labels.

The wonderful achievement of directly relating the great laws of Thermodynamics to the structure and the combinatorics of the classical phase-space points — the system's configurations — hid, however, a *cadeau empoisonné* that emerged when the limit of zero (absolute) temperature came to be studied in detail. The systematic analysis that Walter Nernst [Nernst ()] conducted across the XIX and XX Centuries on the low temperature behaviour of a large number of thermodynamic systems, that finally led to his celebrated "Heat theorem" (known today as the third principle of Thermodynamics), could exclude that nature exhibits the entropy singularity that for $T \rightarrow 0$ classical statistical mechanics inevitably predicts. The reason of this singularity is quite simple: at zero (absolute) temperature there exists only one possible configuration, where all particles are at rest in their equilibrium positions, hence the entropy vanishes; but if we change the temperature by a small but finite amount, the number of classical configurations corresponding to such thermodynamical states increase by an infinite amount, thus clearly exposing an unregularizable singularity. The lack of "sufficient reason" for such zero-temperature entropy singularity excludes classical statistical mechanics, and with it classical physics altogether, from the realm of possible descriptions of the physical world. And this is evidently very bad news for the Copenhagen's view, which sees its classical world of observers lose any meaning when the temperature

becomes sufficiently low; a paradox that unfortunately is little considered and understood by the quantum mechanicians of our times.

It is amusing that at the same time (mid 1920's), when the formalism of QM was being laid out and its conventionalistic interpretation tuned up, Einstein together with the young Indian physicist S. N. Bose [Einstein (1924)] succeeded in finally showing how the quantum "perfect" gas could avoid the "entropy crisis" of the classical system, going through a phase transition, the Bose–Einstein condensation, which for $T \rightarrow 0$ brought with continuity all atoms to the unique, discrete ground state, and their entropy to vanish. And in order to accomplish this they had to revisit the early quantum theory of Planck and Einstein, where the field concept is primary and the quanta, the particles, just stem from the peculiar interactions between different fields, having thus no independent, autonomous reality, which is totally engendered in the new dynamics of the quantum field.

Had more attention been paid by the physicists' community to such developments and their deep meaning, one may legitimately dream that the story would have been quite different, and this Essay could have been written a long time ago.

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Chapter 2

Kinematics: The Descriptive Framework of Physical Reality

Κίνημα, κινήματος in the Greek language means motion. Kinematics in modern physics denotes the science of motion, i.e. the mathematical description of the correlations between the space domains spanned by the generic physical system and time. Thus central for its development is a suitable mathematical theory of space and time, which Bernhard Riemann (1854) has taught us to be deeply connected to and influenced by the physical reality one wishes to describe.

In order to keep our discussion as general as possible by space we mean a three-dimensional manifold whose points can be put in a one-to-one correspondence with the points (coordinates) $\vec{x} \in R^3$, the three-dimensional continuum of real numbers. Any such correspondence, as we know well, defines a particular observer and the principle(s) of relativity can be formulated in general by specifying the allowed class of observers and their relationships, i.e. the coordinate transformations among different observers. As for time, it is described by a one-dimensional continuum of real numbers, which depends in general on the observer, so that in the coordinate transformations from one observer to another the time coordinates can in general change: only in the Galileo–Newtonian Physics time is totally independent of the observer, i.e. there exists an “absolute” time.

A physical system can then be defined by first identifying a space-region (with respect to any allowed observer) which differs from what is perceived as empty space — the Vacuum — and where some observable properties can be identified and given numerical values. In classical physics the simplest of physical systems is the matter-point, whose space-domain reduces to a single point $\vec{x}$ and its defining physical property is the mass, a positive number depending on the chosen units. A complete set of physical observables for the matter-point is the quadruple $(\vec{x}, m)$ that *at the given time*

exhaustively describes the configuration of this physical object. However such quadruple is insufficient to describe the state of motion of the matter-point, for, in order to do this, we need to specify the correlations between the matter-point's configurations at different times t , and in particular between two infinitesimally close times. It would appear that to "label" the state of motion of the matter-point one needs to assign (at a given time) $\vec{x}$, $\vec{p} = m\dot{\vec{x}}$ (the momentum) and a number of higher time-derivatives of $\vec{x}$, but dynamics, i.e. the equations of motion, shows that all time-derivatives of order higher than one are well defined functions of $\vec{x}$ and $\vec{p}$: thus any state of motion of the matter-point can be uniquely represented by a point of the six-dimensional classical phase-space $(\vec{x}, \vec{p})$, which with the flowing of time describes a well defined trajectory $(\vec{x}(t), \vec{p}(t) = m\dot{\vec{x}}(t))$.

By "glueing" together with appropriate "internal forces" a number n of such points we may construct physical objects of increasing complexity whose phase-space dimensionality is $6n$, and the basic physical observables are $\vec{x}_i, \vec{p}_i$ ($i = 1, 2, \dots, n$). But the discrete systems of Newton's *Principia* do not exhaust the domain of physical phenomena, in classical physics a great deal of attention has been paid to continuous systems, the fields, whose space-domain is continuous and the number of degrees of freedom as well as of the dimensions of phase-space (PS) is infinite. Up to the great Maxwellian synthesis of electric and magnetic phenomena into electromagnetism, the field concept could be looked at as a convenient approximation of a discrete system (a collection of atoms and molecules) with a very large number (of the order of the Avogadro number, $\mathcal{N} = 6.02 \cdot 10^{23}$) of matter-points, and this was precisely the point of view of Maxwell-Boltzmann statistical mechanics. But with the theory of electromagnetism and the utter failure of a mechanical description based on a hypothetical Aether there emerges in physics a new object, irreducible to any "mechanistic"* description, defined in *all* space for *all* times, a truly all-encompassing physical entity, which affects electrically charged matter where its intensity is perceptibly different from zero. With Einstein's General Relativity (1916) classical physics gets enriched with another genuine field, the gravitational field, which *mutatis mutandis* bears to the masses of the universe the same relation that the e.m. field bears to the electric charges. Thus, just when quantum physics (QP) was moving its first uncertain steps toward a new image of the world, classical physics (CP) had reached its zenith,

*Here, as in common parlance, "mechanistic" denotes any description that tries to reduce a given physical system to the juxtaposition of a (large) number of Newton's matter points.

delivering us a fully dichotomic world where matter is described by the relativistic generalization of the *discrete* (and discontinuous) Newton's mechanics and the fields represent that kind of continuous "alterations" of the physical Vacuum that account for the dynamical evolution of electrically charged and massive matter. This *kinematical* separation between matter (the world of "little balls") and fields (the "stressed state" of the Vacuum) and, therefore, the irreducibility of the motion of particles belonging to the former, and of the propagation of waves characterizing the latter, is perhaps the most significant feature of the picture of the world painted by classical physics, one that is deeply rooted in our immediate sensory experience.

Quantum physics has totally subverted all this, and it is thus quite remarkable that the classical distinction between matter (physical systems with a finite number of degrees of freedom) and fields has survived in the distinction between QM and the "second quantized" systems, i.e. QFT. As already anticipated, in the following I shall argue that it is just this act of hybris, which has been haunting quantum physics for almost a century, that must be finally repaired, dropping once and for all the distinction between matter and field, and recognizing that in quantum physics there exists only one consistent type of physical object: the quantum field.

2.1 States and observables in Classical Physics (CP)

Any physical system, that we think of at a given time t , *is*, i.e. it exists in a particular *state*. Our preliminary discussion has already indicated what a state of a classical system consists of: it is just a point of the classical phase-space (PS) whose dimension is $2f$, if f is the number of (Lagrangian) degrees of freedom that are necessary to describe its configuration. Thus the classical PS is the space of vectors of components q_i, p_i ($i = 1, 2, \dots, f$). For instance, for the isolated point the PS is six-dimensional, comprising the vectors $(\vec{x}, \vec{p})$, while for a rigid body it is 12-dimensional, comprising $(x_{CM}, \phi, \theta, \psi, p_{CM}, \vec{L})$, when x_{CM} and p_{CM} are the center of mass coordinates and momentum respectively, ϕ, θ, ψ the Euler angles and $\vec{L}$ the components of angular momentum. For a field we can also define a classical PS, which is now ∞ -dimensional, comprising the values of the field and of its conjugate momentum (see later) at any space point.

As for the physical observables, they are represented by all sufficiently well behaved functions $O(q_i, p_i)$, which at a given time t assume a well defined real numerical value, once the totality of $q_i(t)$ and $p_i(t)$ have been

determined. Thus in classical physics there is no basic distinction between the state of a system at the time t and its class of physical observables at the same time: for the state is *uniquely* determined by the values of the q_i 's and p_i 's, which thus constitute a complete set of observables, in the sense that any other observable can be unambiguously obtained from those values. The possibility of uniquely associating to a state of a classical system a point of the classical PS clearly stems from the fundamental hypothesis that the process of measuring the q_i 's and p_i 's has no perturbing effect whatsoever on the system, and the experimental indeterminacy can be made, with due care, arbitrarily small. Thus we may conclude that in CP between states and observables there is basically no distinction, for a state, a point of classical phase-space (PS), is uniquely determined by the values that the observables q_i 's and p_i 's attain in the state.

2.2 States and observables in Quantum Physics (QP)

The main point of departure between CP and QP is that in the quantum world there is no *unlimited observability*. As a result, states and observables are no more in a one-to-one correspondence: the process of measurement of the basic kinematical variables, the q_i 's and p_i 's of classical PS, loses its classical *neutrality* to become a fundamental element in the determination of the phenomenic properties of a given physical object.

Without going through the chain of logical arguments and the set of experimental facts that have led to the discovery of the mathematical structure of QP,[†] it suffices to recall that this latter postulates that the states of a quantum system belong to a complex vector space (Hilbert space) while the observables are just Hermitian operators in such space. Thus in QP a measurement process is represented by the acting on the state vector of the system of the Hermitian operator corresponding to the physical observable being measured. Only if the state vector happens to be an eigenvector of the observable $\mathbf{O}$, i.e. if[‡]

$$\mathbf{O}|o\rangle = o|o\rangle, \quad (2.2.1)$$

with o a real number, the measurement of $\mathbf{O}$ yields the well defined value o , belonging to its *spectrum*, i.e the set of all possible values that $\mathbf{O}$ can

[†]For this a very good book to consult still is P.A.M. Dirac, The Principles of Quantum Mechanics [Dirac (1958)].

[‡]Throughout this Essay we shall adopt Dirac's notation, which has become standard.

assume. Formally this is obtained if

- the state vectors are normalized. i.e.

$$\langle \psi | \psi \rangle = 1$$

- the value of $\mathbf{O}$, technically the “expectation value” $\langle \mathbf{O} \rangle_\psi$, in the state $|\psi\rangle$ is given by the “matrix-element”

$$\langle \mathbf{O} \rangle_\psi = \langle \psi | \mathbf{O} | \psi \rangle. \quad (2.2.2)$$

However if, in general, the state vector $|\psi\rangle$ is not an eigenvector of $\mathbf{O}$, the measurement of $\mathbf{O}$ will not give a sharply predictable outcome, for the application of the operator $\mathbf{O}$ to $|\psi\rangle$ discontinuously changes the state vector into an eigenstate $|o_n\rangle$ of $\mathbf{O}$, with eigenvalue o_n . It is here that our understanding (intuition) of the quantum world is put to a severe test: while we can easily understand (2.2.1), that attributes $\mathbf{O}$ a well defined value o , what does (2.2.2) really mean? We know from the general mathematical theory of linear, Hermitian operators in Hilbert spaces that $|\psi\rangle$ can be uniquely decomposed as the linear superposition:

$$|\psi\rangle = \sum_n c_n |o_n\rangle, \quad (2.2.3)$$

where $\{|o_n\rangle\}$ is a complete orthonormal set of eigenvectors of $\mathbf{O}$, and c_n are complex numbers. Then from (2.2.2) we obtain:

$$\langle \mathbf{O} \rangle_\psi = \sum_n |c_n|^2 o_n \left(\sum_n |c_n|^2 = 1, \text{ from the state normalization} \right), \quad (2.2.4)$$

for which we may advance the following interpretation: $|c_n|^2$ is the probability that the measurement of $\mathbf{O}$ *reduces* the state-vector $|\psi\rangle$ to $|o_n\rangle$, yielding the outcome o_n . As a result the “expectation value” $\langle \mathbf{O} \rangle_\psi$ is just the statistical average of the outcomes of the measurements of the observable $\mathbf{O}$ upon an appropriate ensemble of identical copies of the quantum system, all in the state $|\psi\rangle$.

We may now clearly see that allowing the measuring process to perturb the state of the system has produced a profound metamorphosis in our picture of the world: the complete determinacy of the observables, the sharpness of the values they assume in a given state of CP, gives way now to quantum observations whose outcomes can only be predicted *statistically*, the state vector $|\psi\rangle$, through its coefficients c_n , being only able to tell us the probability $|c_n|^2$ of the outcome o_n . Very odd, isn't it? But the evidence