INTRODUCTION

Historical Premise

The great theoretical and experimental development of Quantum Mechanics (= QM) in the last twenty years has largely changed the face of this discipline, and above all has permitted for the first time the testing of a number of postulates and assumptions which from the beginning were made but never proved.

The early days Characteristic of the early days of QM was a rather rhapsodical development of the theory: the fathers of QM, on the one hand, offered a lot of genial solutions to particular problems, which were partly disconnected from each other; and, on the other, they elaborated great generalizations which disturbed the community of physicists for their abstractness and for the gap and sometimes the open conflict with traditional, classical physics or the experience of the ordinary macroscopic world. Hence one spoke and speaks [*FINKELSTEIN* 1996, 183] of a gap between quantum physics practice and its philosophical formulation. This is a historical fact and not a judgement upon physicists like Bohr, Heisenberg, Born, von Neumann, Dirac, and many others.

Further developments Already in the thirties, but particularly after the second world war, the community of physicists, mathematicians and philosophers strived to give a better foundation to the theory and interpret it. Often the results were not resolutive, but without this enormous work we would never have reached the understanding we have today.

Theoretically the turning point was between the end of the fifties and the beginning of the sixties: the theorem of Gleason [1] and later Bell's theorem were able — due to conceptual clarity and the quantification of problems — to determine some questions until the theoretical possibility to test for the first time basic assumptions and hypothesis of QM. In the second half of the seventies the development of refined conceptual and technical instruments, particularly in the domain of measurement problem, permitted the translation of that possibility into factuality.

So then, in the eighties a 'big bang' of the theory began: the experience has confirmed an incredible number of statements of the theory, and QM has revealed to us a wealth of new discoveries and possibilities; but the development was also followed by some fragmentation of the theory. A lot of areas began to develop partially independent from each other, and each approach generally reconstructs a theory in which some parts of QM are lost. This situation is a little uncomfortable because many areas overlap with each other, a lot of identical questions are given different names and 'destructive interference' is often produced.

[1] As pointed out by Busch and co-workers [*BUSCH et al.* 1995a, 1].

Aims and Character of the Book

Aims Perhaps the moment has come to attempt a more systematic and global work at the *theoretical* level. This is not an easy job, and surely the book does not want to be the final answer to this problem. Moreover, it is difficult to foresee what point of unification can be attained, and the problem is posed whether or not QM is able to undergo such a systematic formulation like classical mechanics. The aim of the book is rather a preparation of the task. An effort is necessary in order to find some points of convergence between different areas and approaches, without sacrificing the richness of theoretical and experimental results to the unity of a point of view. The ultimate justification for this approach is to be found in an operational point of view which will be developed later. In line with an operational point of view, the logical structure of the work is not an axiomatic one. In fact we do not stipulate at the beginning postulates or principles, from which we may derive some conclusions, but we formulate principles and postulates during the examination, with the aim of answering specific problems arising from the context of QM itself. Such a procedure is typical of a logic[2] and an epistemology[3] intended as *open* systems and not as closed ones. Shimony names such an 'open' methodology 'dialectical'.

And here a word of warning is necessary: The book has no pretension of globalism. It cannot reproduce all the results of QM nor all formalisms and results which are to be found in handbooks. The literature quoted is surely very partial too: Already in 1978 there were one million of articles and books available on the problem of Einstein/Podolsky/Rosen Paradox alone [CANTRELL/SCULLY 1978]. Surely more than that was published after that date. Hence the task of completeness is ruled out.

Structure In order to accomplish this partial task we need some combination of historical and theoretical approaches. The *structure* of the book partly reflects these different perspectives. The different parts of the book correspond to *thematic* areas, while the succession of chapters in each part reflects to a certain extent the *chronological* order in which the problems arise. But in such a work the historical analysis as such must already be a critical one; therefore the historical organization is dominated by the *theoretical* aim. In the critical connection between theory and history of QM one should also see a pedagogical purpose: the errors and *faux pas* of a science are an integral part of its teaching — we shall come back to this point in the final conclusions of the book. Without such a critical history a science breaks down into technique.

We can understand this point better if we see what the problems constituting the preliminary task to which this book is devoted are. The two points which we need as preliminary ones to the accomplishment of the task of a global understanding of the theory are a better development of QM's *foundations* and a first global *interpretation*. The book aims at both goals.

Some more on history Before we discuss these two aspects, some words on the historical aspect are useful. The *historical* perspective is here needed to understand how some problems were posed and partly resolved so as to condition the later developments. In fact, as we shall see in the following, almost all areas and problems of QM have originated from discussions in the twenties and thirties.

Obviously the history of QM also has an interest in itself. For the first period of the theory — from Planck to the thirties — a lot of work was already done. More is to be accomplished for

[2] For an exposition of this subject see [CELLUCCI 1993] and also [CELLUCCI 1990] [CELLUCCI 1992].

[3] See [SHIMONY 1981, 5].

the later developments of QM. Due to the tumultuous development of the latter years, it is still impossible to write an accomplished history of QM: one needs more historical distance, while we are still in the middle of the tempest. But we also need instruments *now.*

Some Preliminary Epistemological Considerations

Interpretation When one speaks of QM's *interpretation*, one refers to a *philosophical* interpretation. One may think here of the title of the famous Jammer's book *The Philosophy of Quantum Mechanics* or of some of Born's locutions[4]. But one thing is the philosophical interpretation, another is the physical one: a theory cannot only present or represent phenomena[5]. Here we are concerned with both types of interpretation. As a preliminary, to clarify the question — we shall return to the problem by discussing it from the 'inside' of the theory itself [see sections 6.2 and 6.3] —, let us say that a physical theory consists in the first instance of a *Formalism* (= F) and of a set of *Correspondence Rules* (= CR) or bridges between the theory and the experience such that it is possible to assign an empirical meaning to the terms of F.[6] As such F is a mathematical calculus devoid of empirical meaning, and its terms, charged with evocatives like 'particle', 'wave' and so on, have no meaning apart from that resulting from the place they occupy in F itself. Hence CRs are necessary for each physical theory and are an intrinsic part of it. But in F, a lot of terms occur for which we cannot find a satisfactory correspondence in the empirical reality. Such terms are named *theoretical terms.* It is a vexing question if it is possible to eliminate completely all theoretical terms so that the physical theory contains only empirically meaningful terms — which was the original program of neopositivism[7]. Sometimes one tries to do it by using a *model* of the theory and specific logical rules[8]. Generally this transformation happens at the expense of the fertility of the theory: the constraint of a logical coherence results in a loss of explanatory and predictive power. Hence the fertility of a model for QM is an open question, and we shall return to it later [see part III]. However, it is clear that no isolated propositions of a physical theory can be tested or interpreted and that only the theory itself can give the context for such an examination[9].

Hence we can say that the doubts that QM raised from the beginning, and to a certain extent still raises, are due to the absence of a global physical interpretation of it. As we shall see, the Copenhagen interpretation was partly unsound, too much epistemologically characterized and incomplete to be satisfactory. And one may wonder with Mittelstaedt [*MITTELSTAEDT* 1998, 1] that a physical theory after 70 years is almost still in this situation.

Foundations But what about the *philosophical* interpretation? It enters to the extent that such an analysis — and generally a physical theory, but often implicitly — requires a lot of metatheoretical assumptions and principles, so that without a philosophical work we could not arrive at a satisfactory *physical interpretation*, i.e. some conceptual framework built upon CRs[10]. And here we are faced with the other problem, namely the *foundations* of the theory: upon which

[4]For example in [BORN 1961, 456].

[5]On this point see also [*VAN FRAASSEN* 1991, 9–10].

[6]Examination of this problem can be found in [PRUGOVEČKI 1967] [*VON WEIZSÄCKER* 1971a, 231] [*JAMMER* 1974, 9–16] [BUNGE 1965] [DIEKS 1989, 1401] [CUSHING 1991].

[7]See examination in [*P. SMITH* 1981] [BERGSTRÖM 1984] [DILWORTH 1984].

[8]On this point see [CRAIG 1953].

[9]See [QUINE 1951] [*KUHN* 1957] [*KUHN* 1962].

[10]A point stressed by Ferrero and Santos [FERRERO/SANTOS 1997, 766–69].

principles, assumptions, postulates is the theory founded? And are those which are factually acknowledged the best ones or perhaps the only ones? In this sense we see in this book an essay of *applied philosophy*[11].

The first three parts of the book discuss these three fundamental aspects which will be further developed in the other parts and chapters of the book: the formalism, the interpretation (the first and more basic interpretations from which all others generally stem) and the foundations (a first examination of the most important problems). In the next section we give a more detailed presentation of the book's contents.

Presentation of the Content

After a short *introductory chapter* [*chapter 1*] which reports some basic concepts of classical mechanics, the *first part* begins with the first steps of the theory of the black-body problem [*chapter 2*]. Its central aim is to develop the formalism F, which represents the basis of all subsequent examinations. Chapter *3* is dedicated to the basic formalism of the theory.

The *second part* is devoted to the first interpretation of the theory, the Copenhagen interpretation. We shall see the first attempts to solve the interpretative difficulties and how the Copenhagen interpretation was born as an attempt to escape all unsound consequences of the first interpretations of Schrödinger, Heisenberg, and Einstein.

The *third part* is devoted to the first attempts at a foundation. Different problems are examined: the possibility of an axiomatization of QM, the problem of the Hilbert spaces and of the representation of arbitrary observables by operators, and the features of quantum probability. Finally *chapter 12* discusses the theory of the geometric phase.

The other parts of the book are devoted to specific areas and problems of the theory. The two problems which in the last years were mainly discussed are the measurement and the non-locality problems; therefore they also cover a large part of the book [part IV and IX, respectively]. From the fourth part to the sixth part the examination is centred on the relationship between the quantum superposition and the apparent absence of the latter by macroscopical apparatus or generally by macroscopic bodies.

The *fourth part* handles, as said, what is probably the most important thematic area of the theory: the *measurement* problem. After a first examination of some basic concepts in an introductory chapter, this part can be divided in two major blocks: in the first one [*chapters 14–17*], we examine different general proposals which are given for the problem; in the second one, [*chapters 18–20*], we synthesize specific contributions which are given for the measurement theory.

The *fifth part* is centered on the relationship between microworld and macroworld. Two problems are of interest here: is the passage from a superposition (given an observable) to an eigenstate due only to a measurement? In more general terms, what is the relationship between microworld and macroworld? Is there perhaps a sharp boundary line? The traditional starting point of the problem is the Schrödinger cat [see the Introduction to the V part], which by Schrödinger himself was understood as a paradox showing the unsoundness of the theory. And with a 'generation' of a Schrödinger cat we shall end the part [*chapter 24*]. As we shall see actual models

[11] As wished, for example, by Auroux [*AUROUX* 1990].

of decoherence are investigated and an estimate of the decoherence time is also given [*chapter 21*].

The *sixth part* is a discussion of a specific aspect of the relationship between microphysics and macrophysics: the possibility of coherent histories. After a short analysis of some proposals in this regard [*chapter 25*], the 'delayed choice' and its very important consequences for the interpretation are analysed theoretically and experimentally [*chapter 26*]. This part is practically an ideal development of the problematic of time operator treated in chapter 10: in fact *chapter 27* is devoted to the problem of reversibility/irreversibility. The irreversibility which quantum systems seem to show by a measurement-like interaction will be examined here.

The following three parts are devoted to the problem of the ontological interpretation of microrealities and its consequences.

The *seventh part* is centered on the wave/particle dualism, the problem and the mystery of QM. Different proposals are analysed: that both are always real — de Broglie's proposal [see *chapter 28*, where also recent proposals and experiments are reported] — and that none can be before a measurement — three-valued logic and later Heisenberg interpretation [*chapter 29*]. Finally a new interpretation is proposed, based on recent experiments, particularly in quantum optics and using techniques such as the Positive Operator Valued Measure [*chapter 30*].

While the seventh part is more centered on the problematic of the wave (in the binome Wave/Particle), the *eighth part*, and particularly the last chapter, treats the problem of Localization and hence of the particle, but on the other hand also of the position operator, and in this sense it is also the complement to the sixth part. It is specifically dedicated to the Hidden-Variable theories, an attempt to interpret QM in a deterministic way. The starting point is represented by the Einstein/Podoslky/Rosen thought-experiment, aiming at showing the incompleteness of the theory [*chapter 31*]. Then Bohm's proposals in order to complete the theory and some confutation at logical level are analysed [*chapter 32*]. A more concrete refutation, the Bell theorem, will be the subject of the next part, because it goes behind the problem of Hidden Variables, opening an interesting new field: that of the non-locality of QM. The last chapter of this part concerns the development of stochastic ideas treated in chapter 18.

The *ninth part* is devoted to the other main problem of the theory: the *non-locality* problem, which originally was developed from the Hidden-variables problematic, but in the last years has gone much further than the original discussion. As we shall see the Bell inequalities are a turning point in the development of QM in the seventies and eighties. Other non-local effects, like the tunnelling or Aharonov/Bohm effect, are analysed in the last chapter of this part.

The *tenth part* is devoted to the most recent QM domain — and surely one of the most promising ones: Quantum information. As we shall see, by using the means of information theory it is possible not only to open new theoretical areas and to find new technological applications, but also to reformulate, in a rich and more synthetic form, almost all the fundamental results of QM.

The *eleventh part* consists of the concluding discussion of the book. *Chapter 45* is dedicated to the problem of foundations. *Chapter 46* is dedicated to an attempt of a physical interpretation of QM.

Methodological Principles Followed in this Book

Throughout the Book, the following methodological principles have been used:

M1 Do not seek solutions to physical problems which are not in the physics' frame.

M2 Introduce new hypothesis and explanations only if they produce or stimulate new conceptual or experimental results.

M3 Do not reject acknowledged theories if a great conceptual gain determined by the proposed new theories is not evident[12].

M4 Do not formulate *ad hoc* hypothesis.

M5 Do not infer ontological conclusions from formal premisses without specific and extraformal motivations.

M6 Do not solve paradoxes with other paradoxes.

M7 Respect Ockham's principle of economy.

M8 Do not try to solve everything at all costs but accept that there can be open questions.

M9 Face the problems systematically (in all experimental and conceptual aspects and by examining the relevant literature -- to the best of our knowledge -- of it).

Technical Instructions

Finally some technical instructions about the reading of the book can be useful.

The *starred* chapters, sections or subsections can be postponed during a first reading. This signifies in no way that their content is less important, but only that they require more mathematical and conceptual instruments than the rest or that they presuppose some formalism which is treated extensively in the following. Anyway, references to these places are always given.

Definitions, corollaries, postulates, principles, and theorems which are *between horizontal lines* become constituent parts of the theory itself (sometimes the justification of their relevance is not given by their presentation but in an another place, due to the necessity of discussing them in a more general context). This does not signify that definitions, and so on, which are not between horizontal lines, are necessarily rejected by the author: it can be that we use some theoretical element which is not a constituent part of the theory (for example it has only a mathematical

[12] As a specific aspect one can also say that common sense judgments should not be discounted without clear and positive reasons [SHIMONY 1981, I, 6].

meaning or is part of classical mechanics), or which is later integrated in a more general definition, and so on. Anyway it is always explicitly said which is the case.

Squared equations are the main mathematical results of the theory.

Citations with names in *italic* mean 'book' (in plain text mean articles). As we have already said, the bibliography does not intend to be complete. However, it covers the period until the beginning of 1999.

The progressive numeration of experiments (for example One-Hole Exp. 1, One-Hole Exp. 2, and so on), refers to ideal experiments that may have or have not been performed, or also differently performed. Each time it will be specified if they are only proposed or performed experiments. Theoretical studies and models are generally not considered as experiments.

In the footnotes further expositions, developments and commentaries are reported.

Proofs and examples are reported in smaller characters. We could not prove extensively all results: we made a selection following the importance of the subject and of the proof itself and following its pedagogical value. We always, however, provide references to the articles or books in which the proofs can be found.

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