The Nature of Quantum Paradoxes

Italian Studies in the Foundations and Philosophy of Modern Physics

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KLUWER ACADEMIC PUBLISHERS
DORDRECHT / BOSTON / LONDON

Library of Congress Cataloging in Publication Data

CIP

The nature of quantum paradoxes: Italian studies in the
foundations and philosophy of modern physics.
edited by Gino Tarozzi and Alwyn van der Merwe.
p. cm. -- (Fundamental theories of physics)
Includes index.
ISBN 9027727031
1. Quantum theory--Congresses. 2. Physics--Philosophy--Congresses. I. Tarozzi, G. II. Van der Merwe, Alwyn.
III. Series.
QC173.96.Q815 1988
530.1'2--dc19

88-3068
CIP

ISBN 90-277-2703-1

Published by Kluwer Academic Publishers,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Kluwer Academic Publishers incorporates
the publishing programmes of
D. Reidel, Martinus Nijhoff, Dr W. Junk and MTP Press.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group,
P.O. Box 322, 3300 AH Dordrecht, The Netherlands.

Printed in The Netherlands

PREFACE

For three days in April of 1985, Cesena (Italy) was the scene of a national conference which was convened, by the Assessorato alla Cultura of this town under the auspices of the Societá Italiana di Logica e Filosofia delle Scienze (SILFS), in order to celebrate two historical milestones: the centenary of the birth of Niels Bohr, who was to become the leader of the orthodox, or Copenhagen, interpretation of quantum theory, and the fiftieth anniversary of the publication of the most influential challenge to this interpretation which was contained in the well-known paper coauthored by Einstein, Podolsky, and Rosen.

The proceedings of the Cesena meeting, which are collected in the present volume, are intended to provide an exhaustive and panoramic view of the most recent investigations carried out by Italian scientists and philosophers engaged in research on the foundations of quantum physics. What emerges is a critical review of, and alternative approaches to, the orthodox interpretation of the Copenhagen school.

Enrico Fermi, the acknowledged founder of modern Italian physics, early on expressed doubts about the final validity of the Copenhagen interpretation, criticizing its "tendency to refrain from understanding things." But sustained interest in the study of conceptual problems in microphysics arose in Italy only around the mid-sixties, after creative thinkers overcame the mental barriers created by the neo-idealist philosophy of Benedetto Croce and Giovanni Gentile, which viewed the Copenhagen thesis regarding the insuperability of quantum paradoxes and contradictions as the surest grounds for renouncing a scientific world view. The last twenty years since then have seen remarkably perceptive Italian works of research on the quantum-mechanical theory of measurement, the axiomatization of the quantum formalism, Bell-type theorems, and realistic local theories, all of which have greatly contributed to the renewed international debate that surrounds the foundations of physics and is aimed at understanding the nature and clarifying the origin of quantum paradoxes.

The editors owe a debt of gratitude to the institutions and individuals whose labor and cooperation made the Cesena conference possible. In particular, we should like to express our warmest thanks to Professor Alberto Pasquinelli, President of the SILFS, to Dr. Giordano Conti, assessore alla Cultura del Comune di Cesena, and to Dr. Franco Pollini and Professor Franco Selleri, members of the organizing committee of the conference.

Gino Tarozzi
Alwyn van der Merwe

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INTRODUCTION. THE ITALIAN DEBATE ON QUANTUM PARADOXES

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1. THE REACTION AGAINST THE NEO-IDEALIST PHILOSOPHY OF PHYSICS

The debate in Italy on the foundations of quantum mechanics and the discussion of the conceptual problems raised by this theory began, in relatively recent times. It was only in the late sixties that Italian physicists and epistemologists started to discuss, at a considerably high level of theoretical awareness and formal elaboration, the issues connected with the analysis of physical theories, the critical understanding of their basic concepts and principles, the philosophical implications of these concepts and principles, and the clarification of the logical functions of theories, of the open questions that they are expected to be able to solve, of the new conceptual problems they create, of the relationship between different theories and the question of their compatibility.

The main reason for this late start can be attributed to the ideological climate created by the neo-idealist philosophy that dominated Italian culture for the entire first half of this century and even later.

The strongly negative influence of idealism on the research into the methodology and philosophy of science has been widely discussed and universally acknowledged in the case of formal logic and the foundations of mathematics. It is well known that Benedetto Croce, leading exponent, along with Giovanni Gentile, of Italian neo-idealism, disparagingly dismissed mathematical logic as "something to be laughed at .... when regarded as a *science of thought* .... truly worthy of the minds that created it," in his *Logica come scienza del concetto puro* (1).

As to the foundations of physics, the situation was more complex. The neo-idealist philosophers, though they had a very restrictive attitude to the cognitive value of science, did not deny its practical value and stressed its essentially pragmatic nature. And it was physics that, more than any other empirical science (especially in the light of the fundamental early 20th century discoveries on the structure of atomic phenomena), seemed capable of satisfying the previous requirements of practical utility and pragmatic value.

G. Tarozzi and A. van der Merwe (eds.), The Nature of Quantum Paradoxes, 1–50.

From this perspective, experimental studies into the applications and technological impact of physical theories were promoted in Italy, whereas the research into their conceptual foundations, regarded by Croce as "pseudoconcepts" absolutely devoid of universality and by Gentile as too abstract and dogmatic, did not receive the slightest attention.

This was the principal cause that led to the open questions of quantum physics being almost completely neglected for a long time in Italy, while it was being heatedly debated in other European countries and in the United States.

The most critically discerning neo-idealist philosophers did not restrict themselves to denying the cognitive value of physical sciences; they also focussed their attention on the paradoxes and conceptual problems of microphysics. In these contradictions and unsolved questions, they saw the most evident demonstration of the limits of scientific knowledge and of its inadequacy to grasp a more complex and deeper reality than that of the natural world and, moreover, the proof of the need to appeal to this spiritual reality for a proper understanding of the same natural phenomena. The basic thesis of the Copenhagen interpretation, assuming the centrality of the role of the human observer, which made it possible to legitimate the insuperability of the wave-particle dualism and to avoid the investigation of a consistent physico-mathematical solution to the measurement problem, appeared thus as a confirmation of one of the fundamental assumptions of idealism according to which the properties of the physical world do not exist independently of the knowledge that we, as beings endowed with a mind and consciousness, have of them.

In de Ruggiero's treatise of history of philosophy, published in Italy by Laterza in the thirties, the "new atomism" is viewed as decisive proof of the active role of the human mind within the physical world and of the definitive overcoming of the mechanistic conception of classical physics in favour of an explicitly idealistic and finalist perspective:

> "It is not really the indeterminacy of the atom as such but rather its capacity to assume diverse determinations according to the nature of the energy field that gives cause for reflection of an idealistic nature. We perceive the presence of levels of action influencing from the top down the structure of the physical world, of teleological anticipations, ordinating and distributing the material components. While in the old atomistic conception, the mind was completely outside the description of nature and could not be introduced into it except through the double miracle of divine creation and human knowledge, in the new conception the mind appears to be more intrinsic to the picture and better distributed in its effect on the various orders and levels of cosmic life. Ancient mechanism did not know history; the mind could be regarded only as *mens momentanea*, i.e. as a negation of those characters which the mind assumes as its most distinctive

> and which are connected with the names of process and development. The new atomism attributes a wider role to these *ideal* values."(2)

Another very explicit claim as to the idealistic nature of quantum theory can be found in the introduction written in 1934 by Giovanni Gentile, Jr. to the Italian translation of a book by the English astrophysicist James Jeans. In this introduction, Gentile, Jr., son of the more famous neo-idealist philosopher and politician and together with Enrico Fermi and Ettore Majorana, one of the first university professors of theoretical physics in Italy, expresses his full agreement with the Copenhagen interpretation of quantum mechanics and a critical attitude towards the point of view of the main founders of the theory, such as Planck and Einstein, whom he accused of naive realism:

> "The person who goes in for the study of contemporary scientific thought will be able to distinguish, as is well known, two trends of opinion: one of the physicists searching for the *ultimate reality* (and this group includes men like Planck and Einstein); the other of physicists who have a more critical consciousness of the methods of scientific work and have decidedly abandoned the *traditional approach of classical physics*. The latter physicists do not, to tell the truth, like *theorizing*. They are rightly content to have *faith in their ideas* and to work with their methods."(3)

Gentile shares the thesis, implied in the Copenhagen interpretation, restricting the concepts of physical theories to the only directly observable quantities. Nevertheless, unlike Heisenberg or other exponents of the Copenhagen school, who always maintained a strictly operationistic and phenomenistic point of view requiring a direct dependence of the theoretical description on empirical procedures, the Italian physicist considers the identification of the observables with the only legitimate scientific concepts as a confirmation of the subjectivistic conception of immanentistic idealism:

> "In relation to the scientific point of view on the problem of reality, Jeans, following the ideas of Heisenberg, summarizes the situation in this way: There is *thought*, there are *then, sense data*, from which after the necessary corrections have been made, we go back to the *observables*, i.e. the knowledge *of* the quantities which are directly observable. These can then have behind them -- as is natural to suppose -- other unobservable quantities: the world beyond our experiences. What really exists, however, what creates reality, is only the observable and, according to Heisenberg, only this. The other reality, that unobservable, can be object of faith

> and hypothesis, according to taste, but not of science. Science must be concerned only with observables, all the rest is chimera or a mathematical framework. ... For my part, I wish only to emphasize that the observables account for the necessity *immanent* in thought that subject is always present to object. Otherwise, how could there be science? ... In the conclusion, Jeans raises the question whether *science supports idealism* and finds many reasons for answering in the affirmative."(4)

The inhibiting effect of neo-idealistic philosophy on the research into the foundations of physics was thus exerted in two main directions: Firstly it discouraged theoretical research in favor of the study of experimental applications, in the name of the merely practical value of scientific activity; secondly, it appealed to some philosophical consequences of the Copenhagen interpretation to support subjectivism. The epistemological status of the orthodox interpretation could be used, by legitimating the paradoxes of microphysics, to confirm the idealist conceptions, since even the most advanced scientific theory seemed forced to recognize the impossibility of eliminating the observer viewed as a subject endowed with consciousness, from the context of its theoretical and empirical laws.

After the second World War, the development of epistemological and methodological studies according to the perspective of logical empiricism's scientific philosophy due mainly to Ludovico Geymonat and his school, led to a gradual abandonment of anti-scientific, idealistic metaphysics. The work of Geymonat, however, did not have as its result the conclusive overcoming of idealism, since it was prevalently concerned with opposing Croce's and Gentile's philosophy but, in its effort to reconcile logical empiricism with dialectic materialism, completely endorsed Hegel's conception of dialectics. And it is by appealing to this very conception, as we shall see in the next section, that Geymonat and his school have proposed to solve the main conceptual problems of quantum theory.

A deeper, more penetrating criticism of idealistic philosophy was made in the sixties by Alberto Pasquinelli, who pointed out that the same logical possibility of a theory of scientific knowledge was absolutely incompatible with Hegel's idealistic metaphysics. His book, *Nuovi principi di epistemologia* published in 1964, marked the real superseding of neo-idealistic philosophy in Italy and the first systematic exposition of a scientific philosophy consistent with the logical empiricist conceptions of Rudolph Carnap, whom he had studied under at Chicago university. As its title suggests, this publication was about general epistemology, but it was more than this, and although it did not deal specifically with questions in the philosophy of physics, it nevertheless represented a methodological reference point in the development of the research into the foundations of quantum theory for at least two reasons.

The first is the priority attributed to the empirical over the formal sciences, contrasting the standard view of the Geymonat school, which saw in mathematics the paradigmatic model of scientific knowledge. Maintaining the instrumental or "auxiliary" nature of mathematics -- starting from the thesis of the analyticity of the laws of logic and appealing to the reducibility to these latter of mathematical laws, implied by logicism -- Pasquinelli thus completely identifies epistemology with the critical analysis of empirical knowledge provided by physical or "real" sciences. The second reason is the in-depth discussion of the epistemological contribution of Albert Einstein, often accused, by the supporters of the orthodox interpretation, of deterministic mechanism, naive realism, and generally of scanty philosophical awareness. Pasquinelli dwells on more than one occasion not only on the philosophical implications of the scientific work but also on the specifically critical and methodological contributions of Einstein, whom he considers "the man of science who elaborated these issues in perhaps the *most open-minded and deep manner*, arriving at a formulation of an explicit 'epistemological creed' totally in accordance with his own determinant scientific work."(5)

The assertion of scientific over metaphysical philosophy created the basis for a critical discussion of the epistemological foundations of quantum mechanics. The need for a revision of its conceptual foundations turned into a criticism of the justificationistic philosophy of the orthodox interpretation.

The reaction of Italian physicists against this interpretation took three main directions corresponding to the principal theoretical presuppositions of the Copenhagen school, namely:

- the contradictory solution given through the complementary principle to the wave-particle dualism, conceived on the basis of this principle as an insuperable dilemma;
- the inadmissible interference of the mind or consciousness of the human observer with the laws of physics, implied by the von Neumann theory of measurement;
- the myth of the completeness of quantum theory based on the unconditional acceptance of the von Neumann theorem (generalized in those very sixties by Jauch and Piron) against the same mathematical possibility of any causal generalization of the existing theory through the introduction of additional parameters (or hidden variables).

In this process of critical revision of the orthodox interpretation, which began in Italy in the sixties three fundamental dates can be singled out.

In 1962, Daneri, Loinger, and Prosperi proposed a first version, which was to be subsequently improved of their realistic theory of measurement (6) as an alternative to the subjectivistic theory of von Neumann. Unlike the latter, which appealed to the consciousness of the observer, conceived of as an entity not describable by the laws of physics but capable at the same time of interfering with their course, the theory of measurement of the Italian physicists sought to provide, as we shall see in section 6., a consistent physical explanation of the measuring process in terms of a physical interaction between the measured micro-object and the measuring macro-instrument.

In 1969, Franco Selleri advanced his realistic interpretation of the wave function founded on the assumption of the existence of physical objects devoid of the basic properties possessed by any other physical systems, such as energy and momentum, and characterizable only through relational properties.(7)

In 1970, Capasso, Fortunato and Selleri discussed the epistemological significance of superseding the theorem of von Neumann and the new prospects opened in those very years by the discovery of the Bell theorem and the consequent possibility of discriminating experimentally between local hidden-variable theories and quantum mechanics.(8)

At the same time, one is faced in the philosophical context, with Evandro Agazzi's critical re-examination of the rigidly operationistic and phenomenistic conception of physical theory, which leads to some of the basic assumptions of this conception being overcome. In his book *Filosofia della Fisica*, Agazzi proves the artificious nature of the distinction between observative and theoretical terms and shows the need to abandon the strictly operationistic interpretation of scientific concepts, reducing them to their mere measuring procedures, stressing how this interpretation, as we shall see in section 2, lies at the origin of the most serious contradictions of the orthodox interpretation of quantum mechanics. The basic idea on which the overcoming of the operationistic point of view is based can be summarized in Agazzi's statement that "a physical concept does not denote a *single* operation (or a *single set of operations, arising from an operation but which is not identifiable with it*)."(9) This idea, later formalized by the author in a proposal of intensional semantics(10), was to be developed by M.L. Dalla Chiara and G. Toraldo di Francia in their formal approach to physical theories.(11)

2. THE EPISTEMOLOGICAL OBJECTIONS TO COMPLEMENTARITY

One of the most penetrating critical analyses of the epistemological status of the complementarity principle, which constitutes, as is well known, the official interpretation of the wave-particle dualism put forward by the Copenhagen school, is contained in the book by Agazzi, just mentioned. This author highlighted the presence of two interpretations of this principle which are profoundly different from a conceptual point of view but nevertheless often are confused by the supporters of the Copenhagen interpretation.

The first, due mainly to Pauli but then *de facto* followed by many others, views complementarity simply as a synonym for the indeterminacy relations, i.e., as a prohibition of the simultaneous use of two classical concepts like position and momentum or time and energy. According to this latter meaning, the principle of complementarity is prior to Heisenberg's indeterminacy relations and corresponds essentially to the original formulation of this principle as a renunciation of the possibility of a description of microphysical phenomena which was at once a causal one -- where causal to Bohr always means "in accordance with the fundamental physical conservation laws of energy and momentum" -- and a space-time one. In both cases -- whether the use of two classical concepts is prohibited or whether the incompatibility of two classical descriptions is maintained -- one is faced with a *restrictive* interpretation which does not make any attempt to clarify the dualistic nature of quantum phenomena, restricting itself to pointing out the inadequacy of the concept of classical particles as objects for which the two properties of position and momentum can be defined simultaneously or to which a certain precise value of the energy at a well-defined time can be attributed.

The second interpretation, more closely, according to Agazzi, connected to Bohr's idea, views complementarity as the necessity to appeal, in order to explain microphenomena, to two different *classically incompatible* "images" or descriptions, the undulatory, on which Maxwell's electromagnetism was based, and the corpuscular which Newtonian mechanics was founded on. According to this perspective, complementarity is therefore synonymous with the wave-particle dualism or, rather, *dilemma* because, on the one hand, the recourse to both images seems indispensable to explain the behavior of micro-objects and, on the other, these images are experimentally incompatible.

Now, while the first interpretation of complementarity as indeterminacy seems to be quite obvious and not to produce particular problems, the second, related to the wave-particle dualism, gives rise to considerable epistemological difficulties. In the latter case, not only is the necessity to have recourse to both images or descriptions maintained, but so is the contradictoriness deriving from the application of both descriptions to the same physical situation.

At the root of the problem, there is for Agazzi the insufficient emancipation of the Copenhagen interpretation from the classical concepts, due to the physicists of this school following too strict a version of operationism which led them to identify completely the scientific concepts with their measuring procedures. The necessity to apply classical concepts to microphenomena was thus made inevitable by the fact that, in order to investigate the properties of micro-objects, one makes use, in one's observations or measurements, of macroscopic instruments describable by means of classical laws and concepts.

Agazzi, however, shows how the use of the instruments does not determine in the strict sense the investigated physical concepts, pointing out, for example, that electromagnetic phenomena can be and are *de facto* often investigated through mechanical instruments without this fact preventing the acknowledgement of the peculiarity of these phenomena and the introduction of new concepts such as that of charge, current, and induction, which are all clearly nonmechanical even if revealed on the basis of their mechanical effects registered by mechanical instruments.

To remove these difficulties, he proposes his thesis of the *contextualistic nature of the meaning* of physical concepts. According to this thesis, which is discussed in detail in Agazzi's contribution to this book, one single physical concept, such as that of "material particle," is the object of different characterizations depending on the different levels or contexts in which it appears: Thus, in the classical context it is viewed as an object endowed with *both* well-determined position *and* momentum, while in the quantum context, it loses the contemporaneous possession of these properties but assumes new properties such as spin. The difficulties of the Copenhagen interpretation regarding the wave-particle dualism might find a solution if one assumes that the classical concepts, considered at a formal level, appear as the element of a new semantic combination in which the contradiction disappears since it is not formally connected to the concepts themselves but to their classical denotation.

Agazzi believes, however, that his thesis does not provide a conclusive solution to the problem of the nature of the microphysical object and stresses the need for the introduction of concepts that are *new* not only because they are the result of a new combination of classical concepts but also because they are able to replace in whole or in part those classical components with *something really new*.

In the very year in which he was making these epistemological reflections on the nature of the wave-particle dualism, an interpretation of the wave function based on the introduction of a new concept and destined perhaps, as we shall see in Section 5, to solve the Copenhagen dilemma of the dual nature of quantum phenomena was advanced in Italy by Franco Selleri.[*]

Another detailed philosophical analysis of the complementarity principle may be found in Ludovico Geymonat's *Storia del pensiero filosofico e scientifico*, in a chapter written by Silvano Tagliagambe[(12)], and in the introduction, also by the latter author, to the book *L'interpretazione materialistica della meccanica quantistica* discussing the relationship between physics and philosophy in the USSR.[(13)]

Tagliagambe discusses complementarity from a mainly historical point of view, proposing to reconstruct its origin in Bohr's thought and the subsequent debate in the USSR that led to the attempt at a materialistic reformulation of this principle. The author's analysis of the influence on Bohr's early philosophy of Hoffding's conceptions, though it did not contain any basic novelty with respect to the theses expressed in Jammer's book *The Conceptual Development of Quantum Mechanics*, shows in greater detail the very close connection between the qualitative dialectics of existentialism and Bohr's view of the wave-particle dualism as an insuperable dilemma due to the limitations of our macroscopic categories being incapable of enabling us to fully understand the properties of the world of micro-objects.

Of special interest is also Tagliagambe's discussion of the relationship between Bohr and the Soviet physicist Fock, who attempted to disassociate complementarity from the negative connotations of existentialistic dialectics and to overcome the wave-particle dilemma by reinterpreting it as a consequence not of limitations in principle which our mental categories are subjected to but of the contingent limitations due to the unavoidable use of macroscopic instruments. Fock started from Bohr's observation that the process of interaction between the measuring apparatus and the measured object cannot be eliminated or arbitrarily reduced, because every interaction always implies the exchange of at least one quantum *h*, and concluded from this that the experimental physicist observes only a global process involving both the instrument and the micro-object and never the *intrinsic* properties of the latter. It is therefore possible that some instruments make the micro-object appear as a wave, whereas others make it appear as a particle: The undulatory and corpuscular properties of the microscopic world would thus be ways, mediated by the measuring apparata, by which microscopic systems *reveal themselves* at the macroscopic level.

This is the concept of *relativity to the observational means*, already partially anticipated by the logical empiricist physicist P. Franck in his attempt to reinterpret complementarity in terms of our instrumental limitations. Fock and the Soviet philosophers of science, followed in this operation by Tagliagambe and Geymonat, intend to provide a clarification in the positive sense of the nature of dualism by replacing the existentialistic contraposition of waves and particles with a *synthetic* view whereby the thesis and the antithesis, i.e., in this case, wave and particle, would be overcome by means of a new, but not well-defined concept. According to Tagliagambe, it is precisely this approach to the problem that enables us to solve "one of the *presumed paradoxes* of quantum mechanics, that is, that of the corpuscular-undulatory dualism of microphenomena."(14)

The concept of the relativity to the observational means is also applied by Tagliagambe to what he believes is the solution to the Einstein-Podolsky-Rosen (EPR) paradox, which can be briefly summarized by the statement that properties of micro-objects do not exist but only relational properties between micro-objects and the instruments used for observing them. The relational conception of the properties of the quantum state typical of the orthodox interpretation is in this way extended from the explanation of the ordinary measuring processes, whereby it can be in some way justified as a consequence of the *practical* inseparability between measuring instrument and measured object, to the explanation of the EPR cases by assuming the existence of a not very plausible inseparability *in principle* of the instrument from an an unmeasured object located at an arbitrarily large distance from it.

The proposing in Italy in the mid-seventies of the Soviet philosophy of physics seems to us a doubtful cultural operation, and one that was, at best, behind the times, as we have stressed elsewhere(15).

The defence by the Soviet physicists and epistemologists of some of the materialistic and also realistic conceptions, even though of a typically metaphysical realism, had already been endorsed by Valerio Tonini who, immediately after the second World War, published and discussed papers by these Soviet authors in his review *La Nuova Critica*. In this period, when the Copenhagen "paradigm" prevailed almost everywhere without meeting any opposition, the rejection of the most dogmatic and subjectivistic implications of the orthodox interpretation played instead an essential role in keeping the debate on the foundations of quantum mechanics open.

This substantially positive opinion of the Soviet philosophy of physics has recently been asserted once again by Tonini according to whom

> "in spite of some ideological and polemic excesses, it must be admitted that the views of the Soviet scientists, as a whole, provides us with a precise and legitimate epistemological approach, valid not only in a strictly materialistic context but also from a general epistemological point of view, being *classically realist* ..."(16)

A similar attempt to conciliate quantum mechanical description and a realist conception was also made in those earlier years by Antonio Pignedoli, who was one of the first Italian physicists to oppose the subjectivistic connotations of the Copenhagen philosophy, stressing how they are in contrast with the very nature of scientific research, since they would lead to an unacceptable *form of solipsism*:

> "... the particle's being cannot coincide with its being perceived because then, no probabilistic law would have general validity either, but *every observer would create his own probabilistic physics*."(17)

This realistic view lies at the basis of Pignedoli's interpretation of the indeterminacy principle according to which the prohibition expressed by this principle that a micro-object cannot simultaneously possess well-defined position and momentum has purely gnoseological significance and is inapplicable at the ontological level since it refers only to a limitation of our knowledge and not to the existence of physical situations:

> "It nevertheless appears rather arduous to admit, for example, that a photon, between the elementary act of emission and the one of absorption, has not followed a given sequence of states ...: these states, even if they are not determinate and not physically determinable, they must be thought of as philosophically existent."(18)

Some philosophical objections to the metaphysical nature of the Soviet (and Geymonat-Tagliagambe) "materialistic" interpretation of quantum mechanics have already been discussed by the present author(19). There is, however, a more serious criticism regarding the problem of the physical foundation of the principle of relativity to the observational means. This principle, since it establishes in rather precise terms the impossibility of constructing an experimental device capable of revealing both the undulatory and the corpuscular properties of micro-objects at the same time, constitutes the only non-metaphysical assumption of such an interpretation, and, precisely because of its empirical nature it can be refuted by the following *gedanken* experiment.

Let us consider the physical situation of the double-slit experiment where a very weak source, instead of quanta of light as in the standard case, emits *massive particles* such as electrons which, after passing through a first screen provided with two slits are detected by a second screen behind the slits. This experiment represents one of the starting points of several formulations of the wave-particle dualism, as we shall see in detail later: As is known, on the second screen is observed the classical interference pattern typical of the undulatory phenomena which, however, vanishes as soon as one tries to attribute to the micro-object its corpuscular individuality, by putting a detector at each slit to establish which one the particle passes through.

The interpretation of the experiment, in the light of the concept of the relativity to the observational means, is that the micro-object reveals *either* corpuscular or undulatory properties, depending on the measuring device used, i.e. *double slit* either *with* or *without* detector at the slits, but *never both* properties at the same time. Yet this is precisely what our experiment does show.

Let us suppose that we replace the ordinary detector at each slit with a "semi-transparent" particle revealing apparatus which has the characteristic of detecting the particle with a probability K, disturbing it or not detecting and allowing it to pass through without perturbation with a probability $1-K$. Let us suppose also that on the second detecting screen there is a battery of counters each of which is connected to both semi-transparent apparata in such a way as to perform coincidence measurements that make it possible to detect the passage of the particle through one of the two slits and then the arrival of the particle on the second screen.

In this way, there are two series of events: the first with probability $1-K$, where no coincidence occurs and the micro-object is revealed only on the second screen and contributes in this case to the creation of the interference pattern characteristic of the undulatory image; the second, with probability K, where coincidences do occur and the micro-object arrives on the second screen after its passage through a well-defined slit has been established but without, in this latter case, producing interference as happens for any particle. One is thus faced with a single experimental situation in which the undulatory and corpuscular properties of micro-objects reveal themselves at the same time and are, moreover, perfectly distinguishable.

In our view, this experiment does not necessarily contradict Bohr's complementarity principle, since it is not able to isolate purely undulatory properties of micro-objects, as the experiments on quantum waves, which we shall discuss in Section 5, attempt to do, but constitutes a conclusive objection to all the proposals to relativize to our means of observation the undulatory and corpuscular properties of micro-objects which, as we have just seen, can instead, at least in