

Quantum Optics as a Relativistic Theory of Light

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Abstract

In analogy with Bohm's elucidation of special relativity, in this paper we criticize the Copenhagen interpretation and try to reinterpret quantum theory in the light of new evidence of quantum optics. In doing this, we are led to regard the real photon as only expressing an elemental relationship established between a quantized light field and a detector in the actual detection processes. With this kind of relational approach to quantum physics, new concepts are then needed to describe physical phenomena, and the mathematical structure of quantum theory of radiation is viewed as a conceptual map, in the same way as the Minkowski diagram in Einstein's special relativity, which already has the perspective of the observer implicit in it.

Key words: relational approach to physics; basic physical laws as invariant relationships; inherent ambiguity in the meanings of physical objects, according to the Copenhagen interpretation; mathematical structure of quantum optics as a conceptual map; intrinsic unfalsifiability of Einstein-Podolsky-Rosen paradox

We dedicate this essay to the memory of Professor David Joseph Bohm (1917-1992), whose brilliant exposition of the meaning of relativity we here convey.

1. INTRODUCTION

Modern physics owes much to Galileo, who was the first to advocate experimentation and mathematical description of natural processes. In his opinion, any reasonable theory in physics should be based on measured facts of observation, for it might extricate, to some extent, description and deduction from ambiguity and groundless speculation. Along this line, Newton discovered classical mechanics, which explains the motion of man-sized objects; at the same time, he also provided more precise definitions to those absolute concepts of space, time, and physical objects.

A great transition in modern physics, however, was rendered by Einstein, who realized that *those observable properties (immediate facts) were only relational properties*. In other words, *by measurement we establish physical relationships between an "object" and the measuring apparatus*. This is in sharp contrast to Newtonian physics, in which an observation or measurement is that of the absolute property of the "object" itself. In this way, the objectivity of nature then will manifest itself as the possibility of finding what is invariant underlying those relational properties that are observable, and we shall consider those "objects," like space, time, and physical objects, not as absolute, but as relative invariants, which are abstracted from those relationships within certain observation domains. As the domain under investigation is broadened, we may expect to come to new invariant relationships containing the older ones as approximations and limiting cases.⁽¹⁾ Thus this bilateral trait of

physical observation has permanently cast the basic pattern of cognition by which man learns of the world. It is just as the principle of relativity goes: "The general laws of nature are to be expressed by relationships which are generally invariant, and which are in principle observable."

Early this century Einstein proposed that space and time coordinates are only relative properties consisting of relationships of objects and events to the measuring instruments and usually fail to be independent beings in broader domains. Instead, they fuse into one, as a four-dimensional continuum in which the existent exists. Thus Einstein radically reformed two concepts out of the three absolute notions provided by Newton.

Among these three basic notions the concept of physical objects is at the heart of our metaphysics and physics thinking. Objects with figure and size and motion under the law of causality are indeed more concrete and more direct than space and time. Newton wrote the following:

It seems probable to me, that God in the beginning form'd matter in solid, massy, hard, impenetrable, moveable particles, of such sizes and figures, and with such other properties, and in such proportion in space, as most conduced to the end for which he form'd them; and that these primitive particles being solids, are incomparably harder than any porous bodies compounded of them; even so hard, as never to wear or break in pieces; no ordinary power being able to divide what God himself made one in the first Creation.⁽²⁾

With this particle model of matter, not only did Newton succeed in describing the behavior of man-sized objects, but also

man could in later centuries overstep the bounds to exploit the atomistic structure that qualitatively accounted for a variety of natural phenomena ranging from electricity and magnetism to chemistry. Thus when this model came out at the end of the nineteenth century, it already seemed to be an “inevitable” truth, and many people then believed that the foundation of physics had been soundly established based on the mechanistic concept of nature.

As atom-sized phenomena were further investigated in the early days of this century, classical physics incurred several grave problems such as the “orbital collapse” of the Rutherford model. To save this planetary structure of the atom, Bohr had no choice but to introduce quantum rules. Those phenomenological rules, indeed, could explain the spectral data of simple atoms like hydrogen, yet they seemingly could not go on to quantitatively predict more complex systems, since formulas of this old quantum theory contained physical quantities (electronic orbits of definite dimensions and periods) lacking definition of measurement.⁽³⁾ However, what concerned the physicists of this time more was how to construct a theory. In the eyes of positivism the theory based on quantities without measuring meaning was a kind of metaphysics.

Influenced by the idea of employing only observable quantities in Einstein’s relativity theory, Heisenberg made a great step forward in 1925.⁽⁴⁾ He successfully bypassed those unobservables by using other existing quantitative relationships of empirical facts to found quantum formalism effectively. For over seventy years since its establishment, this formalism has been crowned with amazing success in nearly all branches of physics, and few people now defy its reigning position over the formal foundation of modern science.

The theory of special relativity exerted a great impact on Heisenberg’s ideas for the development of a quantum formalism, as has been discussed in many books on the history of quantum mechanics.^(5,6) Indeed, in both theories the physicists emphasized that only measurable quantities, that is, observables, belong in a theory. In quantum mechanics this has been referred to as “a guiding philosophical principle,” and in Einstein’s theory it is also regarded as “one of the keys to special relativity.”⁽⁵⁾ However, it seems that Heisenberg did not fully realize the implications of Einstein’s relational approach to physics, which was only many years later amplified exhaustively by Bohm in his book on this subject.⁽¹⁾ When in 1927 Heisenberg tried to interpret the new formal structure that he had established,⁽⁷⁾ rather than question the older ideas of physical objects in Newtonian physics, he was still, in a way, trying to retain them in the new mechanics. Indeed, such a habitual tendency to regard older modes of thought as inevitable might be quite natural, as was analyzed in detail by Bohm in the same book from a perception background, but it ultimately would also lead to ambiguity and confusion.

Thus in this paper, in analogy with Bohm’s elucidation of special relativity, we intend to interpret quantum physics as another relativistic theory. To this end the outline will be as follows. We begin in Sec. 2 with a preliminary analysis of some of the main facts underlying our use of particle and wave

pictures in quantum physics (parallel to that in Chaps. XI and XIII of Ref. 1), which are to be revealed as only consisting of relationships established in the processes of interaction. This analysis will help us not only appreciate Heisenberg’s success in formulating a quantum formalism, but also realize the inevitability of the older notions in interpreting the formalism.

There then follows a detailed discussion of Heisenberg’s interpretation which proceeds again in contrast with the discussion of Lorentz’s theory by Bohm (Chaps. IV to X of Ref. 1). Considerable emphasis is placed on its efforts to try and retain Newtonian concepts, the consequence of which is not that the interpretation disagrees with experiment, but that those concepts entering into the Heisenberg interpretation are inherently ambiguous.

After bringing out the difficulty as a result of the retention in the Heisenberg interpretation, we go on, in Sec. 3, to the adoption of a relational approach to quantum optics (similar to that of Einstein as in Chaps. XIII and XIV of Ref. 1), in which the photon is regarded as expressing a *relationship* established between a quantized light field and a photodetector in the detection. On the basis of the observed fact of the wavy modulation in the probability amplitude of the actually detected counting signals along the propagation direction, one sees that the observer cannot assign a particle trajectory for light. Thus it is clear that in the new domain of quantum investigation we need new notions for describing physical phenomena that admit the older ones, such as the particle concept, as limiting cases.

In the discussions following, we stress the roles of *field* and *interaction* as basic in the relativistic theory of light, instead of that of the *object* and its *motion*, which are basic in Newtonian theory (whereas the *event* and *process* are basic in Einstein’s special relativity, in Chaps. XXVI to XXX of Ref. 1). This leads us to an “interactive” pattern provided by the framework of quantum optics with its invariant structure that unites particle and wave pictures as two sets of relative invariant features of the same field in different frames of detection. On the basis of this unification it is made clear that the quantum failure of observers with different detection frames to acquire the same physical picture in no way falls into “subjectivism,” since the framework of quantum optics already has the perspective of the observer implicit in it.

Finally, we end this section by borrowing Bohm’s discussion of the relationship between a conceptual map and reality itself (Chap. XXXI of Ref. 1) to further remove the confusion in wave–particle duality.

The main text is then concluded in Sec. 4 and followed by an appendix on quantum paradoxes. Again, with Bohm’s discussion on the falsification of theories (Chap. XXV of Ref. 1), we show that the Einstein–Podolsky–Rosen (EPR) paradox becomes unfalsifiable within the Copenhagen interpretation, since, according to the Wigner–Araki–Yanase theorem, in the theory a great many of the physical quantities are in fact unmeasurable. In the same appendix we also summarize our resolution of the Schrödinger cat paradox.

In the whole paper, if we seem to belabor an analogy of Bohm’s exposition in his book, this is deliberate. However, if

the reader could be persuaded to believe that quantum optics is also a relativistic theory of light, then we will have achieved our aim.

2. OBSERVATION FOUNDATION IN QUANTUM PHYSICS

In physics the concept of a noninteracting object does not exist because its presence cannot be established. For the same reason, only by means of interaction can one discover the objective world. Consequently, *relationships established as a result of interaction exhaust all the physical facts*. To shed light on what this means to quantum theory, we begin with an analysis of some of the main facts behind our use of particle and wave models.

Two experiments that led to notions of particle and wave in atomic physics were Wilson photographs and Davisson and Germer's diffraction of matter waves. When high-energy rays pass through a cloud chamber, they cut line tracks across the vapor. From this experiment, as Heisenberg described in his book⁽⁸⁾ *Die Physikalischen Prinzipien der Quantentheorie*, we are likely to regard the rays as consisting of minute "particles" at high speeds, with the tracks of condensed droplets indicating their trajectories. However, as Heisenberg also noticed, the formation of tracks is due to ionization when flying "particles" collide with the vapor atoms in their way, that is, as a result of interaction, by which the emerging ions then turn into original kernels causing the condensation of supersaturated vapor around them, whereupon droplets arrange themselves along the flight paths to shape tracks that are directly observed by us. Then one sees that Wilson's chamber registered only the occurrence of interactions.

From the description above one may now see that, similar to the way all the facts underlying space and time notions were analyzed by Bohm in his book,⁽¹⁾ the physical facts here also consist only of sets of *relationships* as a result of interaction involved in the registration (exchange of energy and momentum), in which no absolute particle is ever to be seen.

If the particle concept is only as a *relative* invariant extracted from those physical facts with certain experimental arrangement (the particle frame of detection), what then is the origin of the Newtonian idea of an absolute particle, a supposedly solid, massy, hard, and impenetrable substance, essentially independent of all relationships? "Evidently it does not come primarily from experiment and observation," as Bohm suggested,⁽¹⁾ but rather from the continuation in modified form of our "common sense" view of physical objects. In this view, matter is formed from discrete particles, each of which has a certain place, size, and form. Thus the particle is in effect "substantialized" and taken as an absolute.

Similarly, Davisson and Germer's detectors also recorded only the exchange processes of energy and momentum happening in the detection; wave as a notion merely represents a relative, rather than absolute, invariance of the relationships of observed facts in the corresponding circumstances (the wave frame of detection).

Through this parallel analysis to Bohm's, once the nature of

physical facts and our concepts as relative invariant features are clarified, the implications are far-reaching. First, if we recall the success of Heisenberg in 1925, we should have come to realize that it hinged essentially on considerations involving the relational properties associated with two Bohr states (spectral lines that characterize the relative energy changes), rather than any absolute property of an electron itself, tied to single Bohr orbit: *two* instead of *one*, as Dirac briefly commented.⁽⁹⁾

Second, if we look into Heisenberg's interpretative attempt in 1927, we will find that his validating classical concepts to interpret the quantum formalism was, fatally, an effort to retain our ordinary notions beyond their proper domain, where the theoretical frame excludes the possibility of a complete description of the particle concept (simultaneous momentum and position).⁽⁶⁾ At this point, in order to exhibit more clearly the nature of the problems to which the older concepts gave rise in quantum mechanics, we still need to delve into the Heisenberg interpretation in some detail.

In 1900 Planck's study of the properties of radiation undoubtedly began a new page for twentieth-century physics, for it constituted the first evidence that sharply denied the basic assumption of continuity, which is essential to classical physics. It ultimately would trigger a whole revolution in our concept of physical objects. Yet it must not be expected that this should be completed in one move. Indeed, as was only natural, radical changes only occur after a long series of alternative interpretations are tried and fail, with the objective of saving our "common sense" notion of particle that is behind Newton's laws of motion. In this respect, even Heisenberg's interpretation was without exception, no matter how radical he was when he established the quantum formalism.

Heisenberg began by accepting the assumption that classical notions remain valid in quantum mechanics: "All concepts which can be used in classical theory for the description of a mechanical system can also be defined exactly for atomic processes in analogy to the classical concepts."⁽⁷⁾ However, his basic new step was to study the dependence of the measurement of position and momentum on the relationship between the physicality of apparatus and its irreducible participation in the measurement. To do so, he constructed the famous gedanken microscope experiment to measure very accurately the position of an electron.⁽⁸⁾ Heisenberg showed that when the indivisible quanta of action must be taken into account in the measurement process, the uncontrollable disturbance to the electron eventually made it impossible to assign simultaneously precise values of position and momentum, as regulated by an uncertainty relation. Thus in the way of considering that the apparatus was part of this physical world and must undertake the same irreducible interaction to observe, which in effect disturbed what is to be measured, Heisenberg's interpretation preserved the particle notion within the new quantum framework, that is, led to a reconciliation. (At this point let us compare this with Lorentz's way of trying to reconcile the ether hypothesis with the result of the Michelson-Morley experiment, as discussed in Bohm's book.⁽¹⁾ When considering that the arms of the interferometer were composed of atoms and should undergo the same shift now

called the Lorentz contraction, Lorentz actually did prove that no fringe shift could ever be detected by the apparatus of Michelson and Morley.) Nor is this all: he could even develop a whole set of uncertainty relations to imply that in quantum mechanics, because of the irreducible disturbance *all the complete descriptions of classical notions will be impossible*.

Nevertheless, the Heisenberg interpretation of the microscope experiment is formulated in terms of position and momentum of an electron, measured by an apparatus that is supposed to have an irreducible disturbance to the electron. Therefore, the measured values *ought* to be corrected to take into account the effect of the participation before we can know what they really mean. But if the Heisenberg interpretation is right, there can thus be no way to give exactly the simultaneous values of position and momentum. The *simultaneous* position and momentum that define a particle in classical dynamics are therefore inherently ambiguous, because they drop out of all observable relationships that can be found in actual measurement and experiments.

Therefore, the Heisenberg interpretation has also brought about “a novel kind”⁽¹⁾ of problem, which “goes to the root of basic notions that are at the foundation of physics.” Just as in the Lorentz theory on space and time,⁽¹⁾ the difficulty of this mainstream of the Copenhagen interpretation⁽¹⁰⁾ is not its disagreement with experiment. On the contrary, it is in accord with all that has been observed since then. Rather, the problem essentially is that the *fundamental concepts* entering into the interpretation, for example, the notion of particle, are in fact *completely ambiguous*. For, as we have seen, it was deduced on the basis of Heisenberg’s uncertainty relation itself that no means at all could ever be found to give precisely to a particle simultaneous values of position and momentum. Indeed, since the complete description of classical notions of a particle cancel out of all observable results, it makes no difference whether or not we need such a classical concept of particle in quantum mechanics.

From the above discussion we have seen the remarkable similarity rooted in both the Heisenberg interpretation and Lorentz theory as detailed by Bohm.⁽¹⁾ Both theories were developed during a time of crisis in physics when new evidence showed certain straightforward contradiction to some basic hypotheses of classical physics (Sir Kelvin’s two clouds). To retain the older notions in the new formalism frames established by the new evidence, both theories need to refer to a mechanism of the action of apparatus in the measurement, which in effect distorts or cancels our exact knowledge of these notions. However, as a direct result, those basic notions have become intrinsically ambiguous.

According to Einstein’s relational approach to physics,⁽¹⁾ however, the resolution of this fundamental ambiguity involves a radical change in thinking by basing ourselves as far as possible on the facts and on hypotheses that are in principle testable. What are these facts? At the beginning of this section we analyzed one aspect of the relevant facts, viz., that all our actual knowledge of physical objects is based on observable *relationships* established by interaction. To avoid ambiguity in

our fundamental notions of physical objects, it is therefore necessary to express the whole content of physical law in terms of such relationships and not in terms of a particle with intrinsically untestable properties (e.g., simultaneous values of position and momentum) that are inherently ambiguous.

In the next section we shall show that the quantum theory of radiation, or its development since 1960s into quantum optics, provides a clear notion for the description of detection processes, which is decisive for the study of physical content in terms of those relationships.

3. RELATIONAL APPROACH TO THE QUANTUM THEORY OF RADIATION

Since the time of Faraday and Maxwell, physics has been developing a field theoretical description of nature. Thus our knowledge nowadays of fundamental processes is viewed through various fields and their interactions. To develop a relational approach to quantum physics, however, it is not necessary to go too far in this direction, but to concentrate our discussion on the quantum theory of light, for the reason that “in quantum optics it is often possible to address such questions from essentially first principles and to carry out accurate tests of the theory in the laboratory.”⁽¹¹⁾

According to Maxwell’s electromagnetic theory, light is a transverse field. In a vacuum it is described by

$$\begin{aligned}\nabla \times \mathbf{E} &= -\partial \mathbf{B} / \partial t, & \nabla \times \mathbf{B} &= (1/c^2)(\partial \mathbf{E} / \partial t), \\ \nabla \cdot \mathbf{E} &= 0, & \nabla \cdot \mathbf{B} &= 0,\end{aligned}\quad (1)$$

where its total energy and momentum are

$$\begin{aligned}H &= \frac{1}{2} \varepsilon_0 \int d^3r (\mathbf{E}^2 + c^2 \mathbf{B}^2), \\ P &= \varepsilon_0 \int d^3r \mathbf{E} \times \mathbf{B}.\end{aligned}\quad (2)$$

It is appropriate to say that the rise of two of the most important principles of physics in this century, relativity and quantum mechanics, was connected to the studies of field theories. Indeed, Einstein’s special relativity was created out of the investigation of the electrodynamics of moving bodies. In contrast, quantum mechanics brought about new interpretations of the “meaning” of field theories. This began with Schrödinger, who introduced a wave equation. Based on a particle notion, Born interpreted the wave function as a probability amplitude, the square of which is the probability of finding the particle at a particular point in space. When this is applied to light, the particle is called a “photon.” This interpretation indeed is fascinating, for it can account for all phenomena that have been observed. But such a “success” is also at the cost of the key notions in the interpretation being inherently ambiguous, as discussed in the previous section.

According to this statistical interpretation, quantum mechanically, one cannot think of a classical particle as being

