Supplement to Acta Philosophica
FORUM
Volume 4 (2018) 139–147

The case of quantum mechanics: The EPR experiment

Gennaro Auletta

Pontificia Università Gregoriana
auletta@unigre.it

DOI: 10.17421/2498-9746-04-09

Abstract

The EPR paper is likely the most influential paper in the history of science. This is due to a complex of characters that make of this work a *unicum*. After having presented these issues, the classical replies of Bohr and Schrödinger are reported, and a final evaluation follows.

Keywords: efficient causality, formal constraints, separability, locality, ontological ascriptions

CONTENTS

1 INTRODUCTION

The Einstein-Podolsky-Rosen (EPR) thought-experiment represents a *unicum* in the history of science (Einstein *et al.* 1935). What is extraordinary is that in a single paper very different components are connected:

- A philosophical-metaphysical one (notions of causality and reality),
- A logical one (the argument has the structure of an inference based on a XOR),
- A physical-theoretical one (the aim is to prove that quantum mechanics is incomplete)
- A physical-experimental one (this is done on the basis of a proposed experiment).

A paper of such a complexity was never published before (and up to date nothing can be compared with it) and in fact is likely to be the most influential scientific paper never published. I shall analyze the 4 aspects above and show the reasons of this impact on the scientific community.

2 PHILOSOPHICAL-METAPHYSICAL NOTIONS

Let us first consider the philosophical-metaphysical notions and start with the notion of *causality* (for what follows see Auletta et al. 2009: chap. 16; Auletta and Wang 2014: chap. 10). EPR assume a principle of *separability*. Separability is not the same as locality.

- *Locality*, and in particular (after relativity theory) Einstein's locality, tells us that no signal can be superluminal. In general, a principle of locality exerts constraints on the speed in which causal effects are propagated (the light represents the quickest form to exchange signals in our universe and therefore also the maximal speed for causal connections).
- *Separability* tells us that if there is no interaction between two systems (and *a fortiori* no causal effect or disturbance), the reality of certain properties of one of e.g. two systems cannot depend on whatever operation we perform on the other system. This principle tells us that the only way to connect physical systems is through efficient causes represented by signal exchanging.

The second philosophical-metaphysical notion is that of *reality*. EPR assume that there must exist a reality "which is independent of any theory" and of the possible operations that we can perform on it. They formulate the following criterion of reality: if we are able to predict with certainty a property of an observable (like position, momentum, energy) pertaining to a system without disturbing it, then this property must be real independently of any operation that we could perform on the system, and it is called an *element of reality*.

Note that this criterion is independent of a specific theory or also of a specific scientific discipline, and therefore it must be taken as a general philosophical assumption. Neo-positivists told us that metaphysical assumptions are meaningless since they can never be tested. However, I shall show that reality together with separability and obviously the laws of quantum mechanics has empirical consequences that can be tested and in fact have been (Tarozzi 1988).

3 THE LOGICAL ARGUMENT

The *logical argument* has an important epistemological basis. A theory is "intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves. In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) 'Is the theory correct?' and (2) 'Is the description given by the theory complete?' " (Einstein, Podolski, Rosen 1935, 777). The *correctness* of the theory is judged by the degree of agreement between the conclusions of the theory and human experience, while its *completeness* is its ability to cover the field of investigation without leaving facts or processes unexplained.

The *aim* of the EPR paper is to show that quantum mechanics is incomplete. This is done by means of a *logical* argument connected with a *thought-experiment*. The argument takes the general form:

- The Sufficient condition of reality (R) and
- The Principle of separability (S) imply
- The non-completeness (C') of quantum mechanics.

In other words,

$$RS \rightarrow C' \tag{9.1}$$

where RS denotes that R and S are connected by the logical AND, $\rightarrow$ is the symbol for logical implication, and the prime denotes negation.

4 THE PHYSICAL-THEORETICAL ARGUMENT

The *physical-theoretical* argument takes this form. In fact, as mentioned, the quantum-mechanical laws need to play a role here. They enter in two ways. First, by assuming the validity of the uncertainty relations, then by depicting a particular state of quantum particles. Let us consider the first aspect. From (i) Completeness, (ii) Principle of physical reality, and (iii) the fact that, according to the uncertainty relations (that we denote by U), two non-commuting observables cannot simultaneously have definite values, it follows that the following two statements are incompatible:

- The statement C' that the quantum mechanical description of reality given by the wave function is not complete.
- The statement R' that when the operators describing two physical quantities do not commute, the two quantities cannot have simultaneous reality.

In formal terms, we have the statement

$$C' \nleftrightarrow R' \tag{9.2}$$

where the symbol $\nleftrightarrow$ denotes an exclusive disjunction (XOR).

- The meaning of the statement (9.2) is the following: if it is possible to show (through some kind of experiment) that two non-commuting observables have in fact simultaneous reality, then we can logically conclude that quantum mechanics cannot be a complete description of reality. In other words, assuming the Sufficient Condition of Reality and by hypothetically adding the uncertainly principle (which EPR in fact did not acknowledge), from which it derives the negation of R, we can derive also statement (9.2).
- Now, if we perform an experiment and, by further assuming the Separability Principle, find in fact that R is true (i.e., we succeed in showing that the uncertainty relations are not able to formulate the correct description), then we have in this way deduced C', that is, the incompleteness of quantum mechanics, which is the consequent of the implication (9.1).
- Therefore, having derived this result from the two premises S and R, we had proved also the truth of implication (9.1).

5 PROPOSED EXPERIMENT

The *proposed experiment* originally considers two particles that have a common origin and are now separated (they have no causal connection). Nevertheless, the laws of quantum mechanics allow a state such that, if I measure the position of one of them I can predict the position of the other with certainty. However, the same state can be also expanded in the eigenbasis of another observable, say momentum (speed times mass), and thus allows us to measure the momentum of one of them and again be able to predict the momentum of the other. Since, we have performed such predictions without disturbing, in either case, the other particle, then the values of momentum and position on the second particle must be elements of reality before we measure them on the first particle. However, according to U, we could not have such two values simultaneously. Then, the conclusion is that quantum mechanics only provides a statistical description that works in the mean but is is unable to catch certain aspects of reality.

Later on David Bohm presented a simplified version of the proposed experiment (Bohm 1951). The so-called Bohm's version of the experiment is displayed in Fig. 1. Bohm considered a discrete observable like the spin that is much easier to measure than position and momentum, which, in absence of interaction, are continuous. This model permitted in fact to think about a real experiment and all the performed test (from the mid of 1970s on) followed such general scheme (see fig. 9.1).

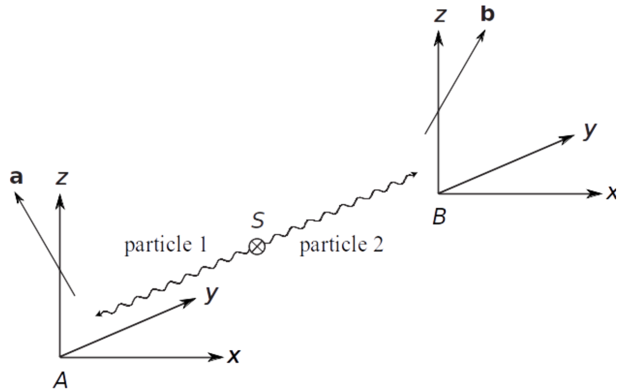

Figure 9.1: Schematic overview of the EPR-Bohm experiment.

Two spin $\frac{1}{2}$ particles are produced in a so-called spin singlet state from a common source S (e.g., by decay of a spin 0 particle). After the time the two particles no longer interact, the spin of particle 1 in an arbitrary direction **a** and the spin of particle 2 in another arbitrary direction **b** are measured with two apparatus A and B, respectively. The Euclidean vectors **a** and **b** are taken to be unit vectors as they represent here spatial directions.

In fact, from this general framework, in the 1960s J. Bell was able to derive precise numerical predictions for such an experiment (Bell 1964; Bell 1966). In particular, he assigned a maximal value that physical systems need to observe when separability and reality are assumed. Such an inequality (the first one of a whole family) is called Bell inequality. The subsequent experiments have shown that quantum mechanics is right in its prediction (and therefore that bound is in fact violated) while no classical deterministic theory based on separability and reality can do the same.

6 REPLIES

Already in 1935, both Bohr and Schrödinger rejected the EPR argument by putting one of the two main assumptions into discussion.

Bohr rejected the criterion of *reality* (Bohr 1935a-b). According to Bohr, quantum theory cannot perform predictions and ascriptions of reality without considering the experimental context. Now, the experimental contexts for measuring position and momentum are different. Note that Bohr is speaking not only of the ontological context (the factual experiment) since the no-disturbance condition makes this objection invalid, but also of the epistemic context (and therefore also about experiments that *could* be performed). However, it is not clear whether Bohr rejects property ascription or also the reality of observables. Considering the EPR argument, the focus is on *observables*. However, the experimental context in which an observable can be measured is a reality ascription. The fact that we deal with dispositions (with contexts that could be arranged) is not relevant here, so that, if Bohr's objection is against the reality of observables is not cogent. At the opposite, *properties* cannot be ascribed without actually occurring detection events.

The worry about property ascription without occurring events is the following. Properties were taken to be classically as elements of reality *intrinsic* to a given system, so as ontological facts. Nevertheless, properties are not elements of reality as such but equivalence classes, *universals* in the traditional language of philosophy. Although they have an ontological substrate they are concepts and not objects, nor elements of objects. The ontological substrate of properties is precisely represented by detection events, and in fact properties are defined as *equivalence classes of events*. In other words, properties are the result of inferences about interactions that quantum objects have with other quantum objects. Then, at a second-level of abstraction, properties can, in some cases, become intrinsic. Whitehead called this kind of error "mistaking the abstract for the concrete" (Whitehead 1925).

Schrödinger rejected *separability* (Schrödinger 1935). He correctly pointed out that the state envisaged by EPR is an *entangled state*, in which the two particles cannot be said to be independent *even in absence of signal exchanging* (and therefore also of causal connections, understood in the efficient sense, of course).

How should we interpret this situation? I have said that this has to do with causality. One of the fathers of quantum mechanics, Max Born, told us that there are two kinds of causal relations (Born 1949: Chaps. 2-4): one temporal (and spatially localized) the other atemporal. Both express *dependence* (what justifies in his view the term causality for both cases), but not of mathematical type (characterized by the notion of function). The former is efficient causation, but according to Born, the timeless meaning of causality is the fundamental one. Now, what is this form of causality? A pure dependence without action is a *constraint*. I shall show now that this is what Aristotle meant with *formal causes*.

Let us first consider an experiment. If we entangle three systems and measure the spin observable, we can have two very different situations (Greenberger et al. 1990; Krenn and Zeilinger 1996; Aravind 1997): if we measure along e.g. the z direction, the particles are no longer entangled (Borromean rings), while if we perform the measurement along another direction, they are entangled (Hopf rings; see Fig. 9.2):

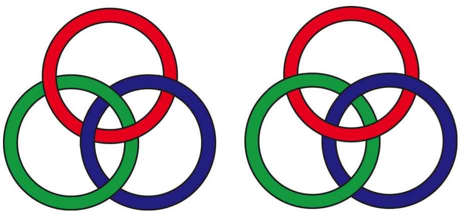

Figure 9.2: Borromean rings on the left and Hopf rings on the right. Note that the latter are entangled pair by pair while in the former case only one of the rings (e.g. the red one) entangles the other two.

This means that quantum interdependencies (entanglement) are kind of structures, of *formal* entities. First, let us remark that they exert constrains. If two or more particles are entangled certain coincidence events cannot occur (e.g. down-down and up-up for two-particle spin). In other words, quantum interdependencies *reduce the space of the possible events.* All occurring events is a situation of maximal disorder. By filtering some of them out we build more order. This is how these structures are causal relevant. However, modern Aristotelians (but not Aristotle!) mixed formal causes with efficient ones by believing that formal causes act in some way (Pasnau 2004; Auletta 2011). Formal causes are inert and do nothing by themselves. They need to be *activated* in order to display effects, for instance through detection. Thus, they are only potential like the strings of a guitar. Since the term *formal cause* has been discredited due to that confusion, I suggest to update it calling it formal *constraint.*

7 CONCLUSIONS

In conclusion, we can solve the problem raised by EPR by assuming

- A non-classical form of realism. Observables (and states) have as counterparts elements of reality as far as the possible experimental contexts determine sufficiently both. However, property ascription demands occurring physical events. Moreover, properties are classes and not elements of reality.
- The existence of causal relations of formal kind that explain non-separability. Therefore, we need to enlarge the traditional scientific view that only efficient causes do count to include formal constraints.

Jammer has shown that Einstein, with his classical realism and determinism, was deeply influenced by his Jewish background and certainly by Spinoza's metaphysics in particular (Jammer 1999). At the opposite, the main philosophical conclusion seems the following: the world is more relational and interactional than it was originally assumed in modern science and modern philosophy. This seems to be very well in agreement with the Middle-Age view of the objective intelligibility of the world. However, this issue largely overcomes the limits of the present contribution.

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