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Estudios

THOUGHT EXPERIMENTS: THE EPISTEMOLOGICAL PROBLEM

EXPERIMENTOS IMAGINARIOS: EL PROBLEMA EPISTEMOLÓGICO

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Abstract

Thought experiments in physics involve epistemological questions such as: How can we learn about the world through merely thinking about imagined scenarios? Realist and empiricist philosophers face that question disregarding that such experiments are about idealized systems. We try to sustain that thought experiments, because of their very nature, neither provide new knowledge —confirmed true statements— nor new empirical data about the physical world. Instead, as Kuhn maintains, their import could improve our conceptual apparatus, allowing a new understanding of the physical world. As a study case, we analyze Einstein, Podolsky, and Rosen´s paradox to give support for these claims. The proposed novel topic in this paper is the study of such paradox in the light of Kuhn´s epistemological account of thought experiments.

Keywords: world view; idealized systems; conceptual change; Einstein Podolsky Rosen paradox; quantum entanglement.

Resumen

Los experimentos imaginarios en física involucran cuestiones filosóficas tales como: ¿cómo podemos aprender del mundo por medio de pensar acerca de escenarios imaginarios? Filósofos realistas y empiristas confrontan esa cuestión desatendiendo que tales experimentos son sobre sistemas idealizados. Intentamos sostener que los experimentos imaginarios, debido a su propia naturaleza, no pueden proporcionar nuevo conocimiento —enunciados verdaderos confirmados— ni nuevos datos empíricos del mundo físico. Más bien, como Kuhn mantiene, su significación reside en mejorar nuestro aparato conceptual, permitiendo una nueva comprensión del mundo físico. Como caso de estudio, analizamos la paradoja Einstein, Podolsky y Rosen para dar soporte a esas aserciones. El tema nuevo propuesto en este artículo consiste en el estudio de esa paradoja a la luz de la concepción epistemológica de Kuhn de los experimentos imaginarios.

Palabras clave: concepción del mundo; sistemas idealizados; cambio conceptual; paradoja Einstein Podolsky Rosen; entrelazamiento cuántico.

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1. INTRODUCTION

Thought experiments in the field of physics, involving different aims and imports, are worthy of scientific research. An issue that arises concerning thought experiments is whether their import could be an increase in our knowledge of the physical world. If thought experiments are performed in the laboratory of our minds, drawing Brown's metaphor, and granting no new empirical data are incorporated, how could it be possible to obtain new knowledge from them? Brown and Fehige (2019) pose that issue as an epistemological challenge: "How can we learn about the real world through merely thinking about imagined scenarios?" (p. 11). Moreover: "Are there really thought experiments that enable us to acquire new knowledge about nature without new empirical data? If so, where does the new information come from?" (p. 1).

Kuhn (1964) responds to the epistemological issue involved in thought experiments. We adopt Kuhn´s view of such experiments and try to give additional support via an analysis of Einstein, Podolsky, and Rosen´s thought experiment, showing that it fits well with Kuhn´s stance on such thought experiments. Thus, we take the EPR thought experiment as a *case study* to support Kuhn´s thesis about the *import* of thought experiments. We think that a way of arguing in favor of certain sorts of epistemological theses, beyond logical arguments, consists of offering study cases that accord with such theses.

Many questions are involved in that legitimate epistemological issue, such as the features of thought experiments and the concept of knowledge itself. Scientific realistic and antirealistic stances lie behind the discussion about thought experiments. For a scientific realist, there is an epistemological challenge about thought experiments and maybe a paradox. In contrast, for an antirealist about science, as Kuhn, the epistemological issue can be stated without entailing empirical import, and no paradox is related.

However, our issue here is *not* the debate on realism/antirealism in science but the former epistemological question. Again, we intend to show that what one could obtain from thought experiments is not new knowledge of the physical world but rather a conceptual change in our theoretical framework, which eventually gives place to a reconceptualization or a novel understanding of the physical world and that there is not a paradox in Kuhn's view of thought experiments.

In general, theories and models of physics involve abstractions and idealizations. Some physical experiments involve abstractions or idealizations also. Thought experiments are abstract in character and are not exempt from idealizations; moreover, since such kind of experiments includes imaginary scenarios, it becomes plausible that they rest on some idealizational suppositions, either contra-actual or counterfactual, perhaps of the sort pointed out by McMullin (1985) as "experimental idealization." This speaks for a conceptualist approach to thought experiments and against a realist view because such idealizations are unrealistic in character.

Some authors point out a paradox in Kuhn's view of thought experiments. This paradox consists of the "puzzling fact that thought experiments often have novel empirical import even though they are conducted entirely inside one´s head" (Horowitz and Massey 1991, p. 1). Apart from the former central purpose, we intend to display that there is not such a presumed paradox. It is worth noting that the detractors of Kuhn´s account of thought experiments did not show a paradox in Kuhn (1964); they just suggest that there is such a paradox. For example, Brown and Fehige point out that there is a puzzle in such Kuhn´s view, without using the term ‘paradox’, concerning the rationality of a scientific revolution as a paradigm

change related to a specific thought experiment. (2019, section Conceptual Constructivism). Nevertheless, that presumed puzzle comes from the criticism of the rationality of scientific revolutions in Kuhn´s philosophy of science, not from a specific trait of thought experiments in Kuhn´s view.

First, we expose some of the main features of thought experiments from a conceptualist approach. After, we analyze Kuhn's view on thought experiments, discussing the presumed paradox. Next, we briefly examine Einstein, Podolsky, and Rosen´s thought experiment in quantum mechanics, including Bell´s theorem and the EPR-type physical experiment realized by Aspect, Dalibard, and Roger. Then, we return to the epistemological problem to show that, adopting the conceptualist vein of Kuhn's philosophy of science, the import of thought experiments is a new understanding of some aspect of the physical world. However, there is neither new knowledge in the traditional realist sense nor new empirical knowledge of the world; instead, thought experiments permit us to reconceptualize the phenomena that are their subject matter and, thus, to some extent, change our world view. We ended with a few conclusions.

There is a vast literature about thought experiments, including the EPR thought experiment; however, as far as I know, no work on such thought experiment related to the epistemological problem from Kuhn's view exists, which is my main concern here. That is the *novel* topic of this paper. Kuhn's paper analyzed Galileo's thought experiment, and most authors of studies on this kind of experiment chose the cases due to Galileo also. There are important exceptions. For example, about the epistemological problem, Semra Uçar studied the Einstein elevator thought experiment, concluding, "They [thought experiments] help to prepare real world experiments. In my opinion, thought experiments are the stage that precedes the hypothesis (assumption) [...] Whether or not thought experiments can be performed, they are prerequisites for physical experiments." (2019, pp. 461-462). Besides, Maarten Van Dyck analyzed Heisenberg's gamma-ray microscope thought experiment and maintained, in Kuhnian vein, that thought experiments help conceptual transformation, such as removing conceptual ambiguities; moreover, he concluded that: "Kuhn's analysis not only teaches something about Heisenberg's thought experiment, there is also a reciprocal relation: we can see that not only straight inconsistencies showing up in a thought experiment pave the way for conceptual transformation, but that ambiguities can play the same role in the right kind of context." (2003, p. 101).

2. FEATURES OF THOUGHT EXPERIMENTS

We consider that there is no general concept of thought experiment that embraces all thought experiments in the history of science, even physics, from Galileo's free fall bodies to Newton's bucket, the Schrödinger cat, the Einstein elevator, the Einstein train, the Einstein box and the Einstein, Podolsky and Rosen imaginary experiments. However, from the sources of several works on thought experiments, we can extract certain features that, to some extent, share thought experiments in physics.[1] All these features are interrelated and conform to one whole; our brief exposition is for analysis.

[1] Kuhn 1964, Brown 1991, Sorensen 1992, Norton 1991 and 1996, Gendler 2000, Stuart, Fehige and Brown 2018, Reiss 2018, Brown and Fehige 2019.

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First, thought experiments are conceived from the conceptual framework of a physical theory assumed or constructed; thus, they are, to some extent, constrained by the concepts and laws of that theory.

Second, at their very core, thought experiments involve imaginary situations or scenarios that give them the status of mental, unreal experiments. The imagined situations are substitutes for our thoughts on the physical situations of laboratory experiments; the experiment is performed, so to speak, in the context of those imagined scenarios given some conceptual framework. A thought experiment contains a description of such an imagined scenario and depicts some experimental operations on a conceptual level.

Third, thought experiments contain some suppositions, either realist or idealizational. A realist assumption concerns the entities postulated by a theory and the quantities that that theory attributed to them, which are relevant to a thought experiment. The set of such assumptions is the physical background of the thought experiment, and to the extent that the theory has been confirmed, one may deem them realists. Idealizational assumptions concern the abstract and ideal situations or systems that physicists envisage and, in contrast, are not provided by the theory involved. In general, they refer to idealized systems that have been conceived through abstraction, selecting some intervening magnitudes and subtracting others, as well as via deliberate idealizations that simplify and distort the systems under study. The key idea is that such abstract and idealized systems do not exist in the physical world. We can distinguish two kinds of idealizational assumptions. Some suppositions only omit or miss a physical factor, such as air resistance, as an outcome of abstraction, but that is, at least, physically possible to integrate such a factor in the system; thus, that kind of supposition is only counter-actual. In contrast, certain idealizational assumptions become counterfactual as a result of idealizations because they lack a physical correlate and cannot be removed without reconceptualizing the whole system under study, such as the electron circular trajectory around a proton in the original Bohr´s model of the hydrogen atom.[2] Both realist and idealizational suppositions have the role of premises, explicit or tacit, of the argument, which is part of a thought experiment.

Fourth, any thought experiment includes an argument, explicit or not, persuasive or dissuasive, never demonstrative, which intends to arrive at a conclusion about the subject matter of the associated thought experiment. The argument generally has an imagined scenario or situation that rests on some idealizational assumptions as a background.

Fifth, thought experiments have outcomes or results related to their conclusions, with an import about their subject matter as a function of their aim.

In sum, thought experiments are conceived from the conceptual system of a theoretical framework and include 1) suppositions, either realist or idealizational; 2) imaginary scenarios concerning abstract and idealized systems containing some counter-actual or counterfactual situations tacitly; 3) imaginary experimental operations on such idealized systems; 4) arguments, persuasive or dissuasive; 5) some outcome, result or conclusion; and 6) some aim and import.

3. KUHN ON THOUGHT EXPERIMENTS

First, Kuhn claims that sometimes thought experiments are powerful tools for increasing our understanding of nature. To this thesis, he relates three issues: 1) What are the conditions

[2] See McMullin 1985, Weisberg 1989, Nowak 1992, Rolleri 2013.

of verisimilitude of the imagined situation in a thought experiment, given that it cannot be arbitrary? 2) How, without new data, can a thought experiment lead to new knowledge or understanding of nature? and 3) What sort of new knowledge or understanding of nature can a thought experiment produce? (See Kuhn 1964, pp. 240-241).

In the first instance, to that second problem, which is central from an epistemological point of view, Kuhn responded that thought experiments generate a new understanding of the scientist´s conceptual apparatus but no new knowledge of nature (see 1964, p. 242). The way that scientists obtain that new understanding consists of correcting some confusion, mistakes, or even paradoxes involved in a conceptual apparatus. An inconsistent conceptual apparatus can be faced with paradoxes, as in the case of Aristotelian concepts of motion, which Galileo resolved using his thought experiment: "Galileo's thought experiment brought the difficulty to the fore by confronting readers with the paradox implicit in their mode of thought. As a result, it helped them to modify their conceptual apparatus." (Kuhn 1964, p. 251).

Nevertheless, the alluded inconsistencies are not internal or intrinsic to a conceptual apparatus but rather extrinsic concerning specific applications of it to some physical phenomena: "Nature rather than logic alone was responsible for the apparent confusion." (Kuhn 1964, p. 261). The corrections of confusions or mistakes in conceptual frameworks are not, however, the unique role of thought experiments. Indeed, Kuhn maintains that: "Because it embodies no new information about the world, a thought experiment [...] can teach nothing about the world. Instead, it teaches the scientist about his mental apparatus. Its function is limited to the correction of previous conceptual mistakes." (1964, p. 252). Nevertheless, if the result of a given thought experiment is the elimination of some confusing concepts, the import of that could be an improvement of the conceptual framework, which avoids some conceptual mistakes and allows us to think more clearly or even more richly and adequately.

Hereafter, Kuhn strongly responds to that key second question in the following terms: "I want now to argue that from thought experiments most people learn about their concepts and the world together. In learning about the concept of speed Galileo's readers also learn something about how bodies move." (1964, p. 253).

From a conceptualist stance, I find pretty right Kuhn's thesis that from thought experiments, we can learn about our concepts as well as about nature since we think and understand the world based on the conceptual framework, or conceptual vocabulary, of our theory, that is, we conceptualize the world, in certain mode, relatively to a physical theory assumed or constructed. If that is so, then it becomes sound to claim that a change in our concepts could bring with it a change in the mode of how we conceptualize nature. In this respect, the key point of thought experiments consists of *conceptual changes* being operated by our thinking alone, without needing a laboratory.

Moreover, Kuhn relates thought experiments to revolutionary changes in physics, pointing out that, occasionally, they have played a critical role in the development of physical science. In this respect, as one of his conclusions, Kuhn says: "The outcome of thought experiments can be the same as that of scientific revolutions: they can enable the scientist to use as an integral part of his knowledge what that knowledge had previously made inaccessible to him. That is the sense in which they change his knowledge of the world." (1964, p. 263). According to Kuhn, when a scientific revolution begins, the data required for it have existed before, and they emerge in a crisis as part of a revolutionary reconceptualization, which allows us to see them in a new way (see 1964, p. 263). This happens also due to a successful thought experiment: the data already exist, and a thought experiment permits us to see them differently, that is, reconceptualize them. It seems that the parallels that Kuhn intends to set between thought

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experiments and scientific revolutions are that both change our world view to a lesser or more extent.

Realist and empiricist philosophers, among many others, Brown (1986) and Norton (1991), respectively, have found in Kuhn's answer to the former second question a sort of puzzle or even paradox, while both share with Kuhn the thesis that from thought experiments we can learn something about our conceptual framework and the world together.[3] If one maintains, as classical realist philosophers do, the traditional concept of knowledge as justified true beliefs or confirmed true statements, Kuhn´s claim about obtaining new knowledge of nature from a thought experiment seems implausible. In addition, if one sustains that all knowledge of nature is obtained from experience, as empiricists do, the former claim of Kuhn becomes unlikely. From the previous order of philosophical ideas about knowledge and experience comes the interpretation of Kuhn´s account of thought experiments as entailing a puzzle or even a paradox.

All readers of the Kuhn *Structure* must realize that he disagrees with the traditional concept of knowledge, particularly with the very idea of truth as correspondence with the world facts (see Kuhn 1970, Postscript). Thus, the realist interpretation of that thesis of Kuhn about how thought experiments could improve our knowledge of the world as paradoxical is misleading; it becomes from a misreading. That realist philosophers disagree with Kuhn ´s philosophy of science, in general, is another question beyond our purposes here. A fair interpretation of that thesis is in terms of understanding as conceptualization, not in terms of that traditional concept of knowledge. Empiricist philosophers missed the topic that abstractions and idealizations permeate either physical theory —their concepts and laws— or even actual experiments in the laboratory. Moreover, given that thought experiments in physics invoke an imagined situation, it becomes feasible that they rest on some counter-actual or counterfactual suppositions without empirical content.

Kuhn´s view about thought experiments can be well understood if we consider his answer to the former third question. Concerning what sort of new knowledge or understanding thought experiments can produce, Kuhn's response could be that thought experiments increase our understanding or conceptualization of the physical phenomena under consideration by removing some confused concepts and improving our conceptual apparatus.

Finally, in response to his first question about the conditions of verisimilitude, Kuhn states that the imagined situation of thought experiments "must be one to which the scientist can apply his concepts in the way he has normally employed them before." (1964, p. 242). Perhaps this answer about the conditions of verisimilitude is partial, only as a necessary condition. A sufficient condition could be that the imagined situation be consistent with the law-like statements available or with a new one derived from the thought experiment itself, as in the case of Galileo's experiment. Newton's bucket and Einstein's clock thought experiments were discarded because they missed some physical factors related to law-like statements.

Thus, Kuhn's view on thought experiments does not imply that their outcomes or results have any *empirical* import, as Horowitz and Massey (1991), among others, claim. As the case of Galileo´s experiment shows, the import is *theoretical*: a new law, to some extent idealized, not an empirical regularity or something like that, together with a change in our understanding of certain phenomena. The import of a thought experiment is, sometimes, an

[3] They elaborated their conceptions of thought experiments as alternatives to Kuhn´s view: Brown's Platonic conception of thought experiments (1991) and Norton's empiricist version of thought experiments as arguments (1996).

improvement in our conceptual apparatus, not an increase in our empirical knowledge. Hence, Kuhn's view of thought experiments does not involve any paradox. A significant difference between thought and physical experiments is that the latter contribute new data and thus have empirical import, not the former. Still, the outcomes of both kinds of experiments could change our world view.

4. THE EINSTEIN, PODOLSKY, ROSEN THOUGHT EXPERIMENT

The sometimes called EPR paradox is an exemplary case of a thought experiment: it contains an explicit and sound argument, an imagined, idealized scenario, and a conceptual experiment performed on such a scenario, and it aims to show that the formalism of quantum theory is incomplete because some real magnitudes do have not their counterpart in the theory. Besides, its implicit import was that there could be some unknown magnitudes, hidden variables, that could make quantum mechanics a complete theory able to give deterministic descriptions and predictions of quantum systems and processes. EPR's thought experiment intended to demonstrate that, under the orthodox interpretation, quantum theory could not be the whole truth. EPR argument becomes no demonstrative because it assumes the classical principle of separability which was refuted by a physical experiment performed by Alain Aspect and colleagues. The quantum domain holds a non-separability principle involving the entanglement of quantum systems. It is worth noting that EPR's thought experiment, as well as Bohm's version of it, fulfill Kuhn's condition of verisimilitude since they were formulated in terms of the concepts of the physical theories available at the time, and they were highly plausible, presumably in concordance with quantum formalism but against to the Copenhagen interpretation of it.

Let us begin by exposing briefly the EPR paradox. Again, it aimed to show that quantum mechanics is not a complete theory. They develop a sound, persuasive argument based on an imagined scenario and a thought experiment, the conclusion of which is that the description of the quantum systems given by Schrödinger´s wave function is incomplete. EPR proposes as a necessary condition for the completeness of a physical theory that: "Every element of the physical reality must have a counterpart in the physical theory." (Einstein, Podolsky and Rosen 1935, p. 777). Besides, they establish as a sufficient criterion of reality the following: "If, without in any way disturbing a system, we can predict with certainly (i. e., with probability equal to the unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity." (1935, p. 777). It is worth noting that Einstein and coauthors propose this criterion as an alternative of measurement as the unique criterion of reality, accepted by the Copenhagen interpretation, which establishes that if the values of a physical quantity can be measured, then that quantity exists. Thus, two criteria for claiming physical reality or existence are involved in the EPR argument: measurement and prediction. Further, EPR appeals to a principle of locality when they argue that: "On the other hand, since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system." (1935, p. 779). According to relativity theory, this principle excludes causal effects transmitted at a velocity faster than the velocity of light.

The imaginary scenario is a quantum system of two particles that interact at a given time, after which there is no extended interaction between them. The issue consists of the possibility of assigning, by measurement or by prediction, precise values to two non-commutating quantities, the momentum P and the position Q, of the two particles, contrary to

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the Heisenberg indeterministic principle. The thought experiment consists of conceiving the possibility of measuring the values of both of these quantities on one of the systems I or II, which have interacted in a given time, and predicting the values of these quantities on the other system. Under the supposition that one knows the states of systems I and II before the time of their interaction, EPR pointed out that using Schrödinger´s equation, one can calculate the state of the combined system I + II at any posterior time. However, according to quantum mechanics, EPR argued, we can know the particular state of any of the two systems after the interaction only by measurement, not by calculation.

An outline of the EPR argument is as follows. The measure of any quantity . on the system I involve a process called reduction of the wave packet, which yields a single eigenvalue from an infinite sequence of eigenvalues α_1,α_2,α_3, ... with the corresponding eigenfunctions $u_1(x_1)$, $u_2(x1)$, $u_3(x_1)$, ..., where x_1 represents the variables that describe the system I. Then, using a Ψ function of x_1, one obtains the following equation

$$\Psi(x_1, x_2) = \sum \cup_n(x_2)u_n(x_1), \text{ with } n = 1 \rightarrow \infty ,$$

where x_2 represents the variables that describe system II and $\psi_n(x_2)$ designates the coefficients of expansion of Ψ into a series of orthogonal functions $u_n(x_1)$. From the former, EPR states: "Suppose now that the quantity A is measured and it is found that it has the value a_k. It is then concluded that after the measurement, the first system is left in the state given by the wave function $u_k(x_1)$ and that the second system is left in the state given by the wave function $\psi_K(x_2)$." (1935, p. 779). Similarly, for the other quantity B of the system I with eigenvalues b_1, b_2, b_3, ... and eigenfunctions $v_1(x_1)$, $v_2(x_1)$, $v_3(x_1)$, ..., one can obtain the expansion of the coefficients φs´s:

$$\Psi(x_1, x_2) = \sum \varphi_n(x_2)\upsilon_n(x_1), \text{ with } n = 1 \rightarrow \infty .$$

Then, EPR indicates that if the measurement of B gives the value b_r: "We conclude that after the measurement the first system is left in the state given by $v_r(x_1)$ and the second system is left in the state given by $\varphi_r(x_2)$." (1935, p. 779). The general conclusion of the previous is that: "Thus, *it is possible to assign two different wave functions* (in our example ψ_k and φ_r) *to the same reality* (the second system after the interaction with the first)." (Einstein, Podolsky and Rosen, 1935, p. 779).

All the preceding is general, abstract thinking on an imagined scenario about a quantum system, which EPR reproduce specifically ─using Schrödinger´s equation, Dirac delta-function, and Planck constant─ on a system of two particles for two non-commuting operators **P** and **Q** that stand for physical quantities momentum P and position Q, which allows them to claim that it is possible to derive ψ_K and φ_r eigenfunctions for P and Q, as well as determine their p_K and qr eigenvalues, respectively, of both particles involved (see Einstein, Podolsky and Rosen 1935, pp. 779-780).

The general outcome of EPR´s thought experiment is that by measuring both physical quantities involved on a first particle, one can predict with certainty, without disturbing the whole system, either the value p_k of the quantity P or the value q_r of the quantity Q of the second particle. The related result is that, as has been proven, it is possible to assign different wave functions ψ_k and φ_r to the same reality; one may consider that, in the first

case, the quantity *P* is an element of reality as well as, in the second case, the quantity Q is an element of reality, according with the previous criterion of reality —that is, these two physical quantities belong to the same reality in opposition to the quantum indeterministic principle. Thus, by a thought experiment, Einstein and coauthors intend to show that some unknown quantities are missed by quantum mechanical descriptions of the systems within its domain. The discovery of such unknown quantities could make it possible to provide deterministic descriptions of quantum systems.

The import of the EPR paradox is implicit in the final paragraph of their paper, where they mentioned the possibility of the subsequently called hidden variables theories: "While we have thus shown that the wave function does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe, however, that such a theory is possible." (Einstein, Podolsky and Rosen, 1935, p. 780).

We wish now remark that in case the EPR thought experiment is confirmed by a physical experiment in the laboratory, if they were right, our world view would change radically from an indeterministic conceptualization of the quantum world, where random processes occur everywhere, to a reconceptualization of it where there is no place for any objective chance, where everything happens deterministically with plenty of causes and probabilities are only the expression of our ignorance. In agreement with Kuhn's view of thought experiments, the EPR paradox neither requires additional experimental data nor yields new knowledge; its import is theoretical and involves a change in our world view.

5. HOW CAN THE EXISTENCE OF HIDDEN VARIABLES BE TESTED?

An intended significant interpretation of elementary quantum formalism supplemented with additional variables to restore causality in the quantum domain was advanced by David Bohm (1952). However, as John Bell indicated, its structure is grossly non-local; that is, the hidden variables assumed by Bohm, contrary to the principle of locality contained in EPR´s paper, would transmit causal influence instantaneously —which was the reason for rejecting it. (see Bell 1964, p, 195).

The route against hidden variable interpretations of quantum mechanics has been rather indirect. The theorem proved mathematically by Bell (1964) is a crucial advance in that direction. He proved that any theory with local hidden variables that could make predictions about an imagined quantum system, under certain conditions, becomes incompatible with the probabilistic predictions derived from quantum mechanics. Bell concluded that "Then for a least one quantum mechanical state, the "singlet" state in the combined subspaces, the statistical predictions of quantum mechanics are incompatible with separable predetermination." (1964, p. 199). The central underlying difficulty consists of the principle of separability that the EPR-type thought experiments assume, which, in Einstein's words, says: "The real factual situation of the system S_2 is independent of what is done with the system S_1, which is spatially separated from the former."[4] As we will see below, quantum theory involves a principle of no-separability.

Bell used an EPR-type thought experiment proposed by Bohm and Aharonov (1957).[5] The imaginary scenario consists of "Consider a pair of spin one-half particles formed somehow in the singlet spin state and moving freely in opposite directions." (Bell, 1964, p. 195), where

[4] Quoted by Bell 1964, p. 220, from *Albert Einstein, Philosopher-Scientist*. P. A. Schilpp (ed.), *Library of Living Philosophers*, Evanston, Illinois, 1949, p. 85. Bell calls this principle, locality and separability indifferently.

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the directions of two particles p_1 and p_2 are arbitrary. The key of the associated thought experiment is the supposition that spin measurements can be made on selected components in any direction —which is feasible by Stern-Gerlach magnets— in such a way that if the measurements are made at places distant from one another, the orientation of one magnet does not influence the result obtained with the other.

Now, Bell points out that according to quantum theory, if a measurement of a given component, assuming some unit vector, yields the eigenvalue $+1$ for particle p_1, the measurement of the other particle p_2 must produce the eigenvalue -1, and vice versa. Observe that the possibility of making such predictions of the states of one or another particle rests on the principle of superposition of states, as just a formal device, which is a mathematical consequence of the Schrödinger equation; in this special case, establish that the composed system is either in the superposed state $|+>p_1 \otimes |->p_2$ or in the superposed state $|->p_1 \otimes |+>p_2$.

The crucial step is, as Bell asserts, that since we can predict in advance the result of measuring any chosen component on one particle by previously measuring the same component of the other particle, it follows that the result of any such measurement must be predetermined (see 1964, p. 195). This predetermination suggests the possibility of a fuller specification of the state, let's say by the parameters λ, because the initial quantum mechanical wave function does not determine the result of an individual measurement. Bell further remarks that: "In a complete physical theory of the type envisaged by Einstein, the hidden variables would have dynamical significance and laws of motion; our λ can then be thought of as initial values of these variables at some suitable instant." (1964, p. 196). This last observation about the hidden variables agrees pretty well with the realism and causal determinism sustained by Einstein.

From the former, the EPR paradox, in Bohm´s version, emerges because it seems that we can predict with certainty the spin state of one particle based on previous measurements of the spin state of the other particle, without altering the entire system. By the criterion of reality, the quantity spins of both particles exist independently of whether we measure them or not. According to the separability principle, they exist in determinate states with specific values independent of each other. By the criterion of completeness, we conclude that QM does not entirely describe the reality.

In contrast to the former, Bell proved that any theory that includes hidden variables that causally determine the results of measurements in EPR-type thought experiments predicts probability distributions incompatible with the probabilistic prediction of quantum mechanics. Such theories assume that causal influence is transmitted at a velocity faster than the velocity of light; that is, they assume non-local hidden variables. In brief: "In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measurement device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously so that such a theory could not be Lorentz invariant." (Bell 1964, p. 199). Thus, the acceptance of hidden variable deterministic theories is contrary to the principle of locality.

The alternative to the anterior consists of realizing quantum entanglement, which the quantum theory formalism implies. With the recognition of the existence of entangled quantum systems, hidden variable theories have become pointless. Quantum entanglement is

[5] The proof of Bell´s theorem is mathematically too technical to reproduce here, so we give only a brief survey of the relevant theoretical elements involved.

consistent with the principle of locality; however, it demands the principle of no separability. This principle establishes that a pair of subsystems that somehow develop from certain interactions remain linked in such a way that the state of one subsystem, at any future time and spatially separated by any distance, is correlated with the state of the other subsystem. We may say that there is only one system whose elements have states entangled, no matter how remote they are. It is relevant to note that Bell´s theorem embraces an EPR-type thought experiment whose import, the exclusion of local hidden variables, profoundly impacts our view of the quantum world.

In 1982, Aspect, Dalibard, and Roger (ADR) performed a series of EPR-type experiments in the laboratory with polarized photons to determine the correlations predicted by quantum theory and those derived from a local hidden variables theory such as that envisaged by Bell. A key feature of the experimental device that they used is that causal signals between the polarizers avoided changing their orientations so quickly that there was insufficient time for the signal to reach one polarizer from the other before simultaneous measures of polarization of a pair of photons were performed; according to the hint advance by Bohm and Aharonov: "the settings are changed during the flight of the particles…" (see Bell 1964, p. 199). ADR have success in such tasks, so their experimental results agree with the principle of locality since the physical variables that intervene are local.

The correlations obtained by ADR experiments agree with those predicted by quantum mechanics and thus disagree with a local hidden variable theory such as that involved in Bell´s theorem. An interpretation of the quantum correlations is that the states of the subsystems involved are linked and entangled in such a way that they are not isolated. Quantum entanglement, which seems to be confirmed by such an experiment, excludes the classical principle of separability from the quantum domain that Einstein sustains. An alternative interpretation, consistent with the previous experiment's results, resides in supposing that the intervening variables are non-local. The evidence obtained in several further experiments performed during various years by different scientific teams agrees with the ADR experimental results, supporting thus the quantum theory of non-separate systems contrary to non-local hidden variables theories. It seems that, in contrast to the EPR thought experiment, the ADR physical experiment confirmed the completeness of the quantum theory. There are no unknown variables missed; instead, what was missed is the acknowledgment of entangled quantum systems.

6. RETURNING TO THE EPISTEMOLOGICAL PROBLEM

Let us return to our main issue: the epistemological problem. It is clear from the previous discussion that EPR´s thought experiment provides neither new empirical data nor new knowledge in the traditional sense. Instead, it suggests a reconceptualization of the quantum domain where some unknown quantities causally determine quantum processes. This suggestion was developed by Bohm´s version of the EPR paradox —in a way that facilitates its experimental test in terms of local hidden variables with no loss of import— without providing new empirical knowledge. The import of Bell´s theorem is against Bohm´s claim about a deterministic theory with local variables in the quantum domain. Still, it does not prove the inexistence of non-local hidden variables in the physical world.

All of the former, that is, EPR´s thought experiment, Bohm´s version, and Bell´s theorem, rest on some imagined, idealized scenarios and envisaged experimental operations on abstract systems at the conceptual level. The first two of them, thought experiments, assume

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the principles of locality and separability. The first principle belongs to relativity theory, whereas the second is a classical principle refuted by Bell´s theorem at the conceptual level and by ADR´s experiments at the physical level. The opposite of that principle, the non-separability principle, belongs to quantum theory. These principles are part, explicitly or implicitly, of the conceptual framework that permits those great scientists to conceive their thought experiments, which play central roles, as we have seen.

In contrast to such thought experiments, ADR-type experiments provide new experimental data of the physical world. Based on the evidence provided by those experiments, we can say that they confirm that some kinds of quantum systems are entangled under certain conditions; that is, though spatially remote, their component subsystems are linked and correlated.

Neither Einstein nor Bohm succeeded in providing new knowledge of the quantum world by employing thought experiments; nevertheless, such thought experiments propose a conceptualization, an understanding of that world, very different from the orthodox view. If they were right, and their intended interpretation of quantum mechanics was experimentally confirmed, our present view of the quantum world would be classic, embracing causal determinism and excluding random processes.

In concordance with Kuhn´s view, in the light of the results of ADR´s experiment related to Bell´s theorem, one can conclude that the final import of the development of the EPR paradox was the acknowledgment of the entanglement of quantum systems, which, according to Schrödinger, was already involved in the original quantum formalism. Since 1935, he advanced the concept of entanglement system: "When two systems, of which we know the states by their respective representatives [wave functions], enter into a temporary physical interaction…and when after a time the systems separate again, then they can no longer be described…by endowing each of them with a representative by its own. I would call that not *one* but rather *the* characteristic trait of quantum mechanics."[6] In a sense, the experiments performed by Aspect, Dalibard, and Roger confirmed quantum entanglement, which was obstructed by the classical principle of separability.

7. CONCLUSION

We intend to display that our analysis of the EPR´s thought experiment fits well with Kuhn's view, which regarding the epistemological problem of thought experiments, as we have characterized them, shows that thought experiments neither provide new knowledge nor new empirical data of the physical world. Empirical data can be obtained only through scientific experience. However, via thought experiments, it is possible to get a new conceptualization or understanding of the physical world —*this is the import of such experiments*. As the case of EPR's thought experiment shows, sometimes (but not always), the outcome or result of thought experiments can be tested by physical experiments, providing the possibility of obtaining new knowledge. Classical Galileo´s thought experiment on the free fall of bodies is a clear example of this when the impediment of air resistance was removed, and Galileo's law was confirmed. In contrast, Schrödinger´s cat thought experiment has not been tested; however, its aim was not to obtain new knowledge or empirical data but rather to show

[6] Quoted by Peacock, 2018, p. 225, from Erwin Schrödinger, "Discussion of probability relations between separate systems", *Proceedings of the Cambridge Philosophical Society* 31, 1935, p. 555.

how odd quantum mechanics is at the physical macrolevel, which comes from a realist interpretation of the principle of superposition of states.

In general, the import of thought experiments is not new knowledge or new empirical data. For that reason, both realist and empiricist approaches to the epistemological issue involved in thought experiments are misleading. Indeed, Einstein and Bohm aim to provide a *truthful* conception of the quantum domain; nevertheless, thought experiments cannot do that because of their very nature as conceptual, theoretical devices.

In the vein of Kuhn´s philosophy of science, a conceptualist approach to thought experiments seems more appropriate for confronting epistemological questions about them, which do not demand strong goals such as obtaining new knowledge or empirical data. What thought experiments could attain is a new conceptualization or an improved reconceptualization of their subject matter, which, in turn, could eventually increase our knowledge of the physical world.

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