Doi.
Artículo académico

Fundamental Concepts of Quantum Mechanics from the meeting between Heisenberg and Kant

Conceitos Fundamentais da Mecânica Quântica do encontro entre Heisenberg e Kant

Conceptos fundamentales de la mecánica cuántica: del encuentro entre Heisenberg y Kant

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Abstract

Abstract: In this article, we analyze the German physicist Werner Heisenberg's understanding and use of Kantian philosophy. Heisenberg was the winner of the 1932 Nobel Prize in Physics and the formulator of the uncertainty principle. In addition to being a remarkable physicist, he was one of the most prolific physicist-philosophers of the generation that founded quantum mechanics. Heisenberg appears to adopt a Neo-Kantian understanding of the nature of science, according to which science does not deal with reality in itself, but only with the way it presents itself—which inevitably depends on the interaction between the subject and the object of knowledge. Ultimately, there is no break with realism, for reality in itself is there, existing in and of itself, even though scientific theories are merely—and always—approximations. In this article, we will examine how Heisenberg addresses the principle of causality in modern physics, scientific determinism, and the impossibility of knowing "nature in itself." Heisenberg draws on Kant not to follow him, but to develop his own philosophical thought and apply it to the foundational problems of physics characteristic of his time.

Keywords: Physical theory, modern epistemology, quantum mechanics, unity of nature, experimental physics.

Resumo

No presente artigo, analisamos a compreensão e o uso da filosofia kantiana pelo físico alemão Werner Heisenberg, ganhador do Prêmio Nobel de Física de 1932 e formulador do princípio da incerteza. Além de físico notável, foi um dos mais prolíficos físicos filósofos da geração dos fundadores da Mecânica Quântica. Heisenberg parece adotar uma compreensão neokantiana da natureza da ciência, segundo a qual a ciência não lidaria com o real em si, mas apenas com a forma como ele se apresenta, o que depende inevitavelmente da interação entre o sujeito e o objeto do conhecimento. Não há ruptura com o realismo, em última instância, pois o real em si está lá, existente em si mesmo, embora as teorias científicas sejam apenas, e sempre, aproximações. No presente artigo veremos como Heisenberg trata do princípio de causalidade na física moderna, do determinismo científico e da impossibilidade de conhecermos a "natureza em si". Heisenberg recorre a Kant não para seguí-lo, mas para desenvolver seu próprio pensamento filosófico e aplicá-lo aos problemas de fundamentos de física, próprios do seu tempo.

Palavras-chave: Teoria física, epistemologia moderna, mecânica quântica, unidade da natureza, física experimental.

Resumen

En el presente artículo analizamos la interpretación y el uso de la filosofía kantiana por parte del físico alemán Werner Heisenberg, ganador del Premio Nobel de Física en 1932 y formulador del principio de incertidumbre. Además de ser un físico destacado, fue uno de los físicos-filósofos más prolíficos de la generación de los fundadores de la mecánica cuántica. Heisenberg parece adoptar una concepción neokantiana de la naturaleza de la ciencia, según la cual la ciencia no se ocuparía de lo real en sí mismo, sino únicamente de la forma en que este se presenta, lo cual depende inevitablemente de la interacción entre el sujeto y el objeto del conocimiento. En última instancia, no hay ruptura con el realismo, pues lo real en sí está ahí, existiendo por sí mismo, aunque las teorías científicas no sean más que aproximaciones, y siempre lo serán. En el presente artículo veremos cómo aborda Heisenberg el principio de causalidad en la física moderna, el determinismo científico y la imposibilidad de conocer la «naturaleza en sí». Heisenberg recurre a Kant no para seguirlo, sino para desarrollar su propio pensamiento filosófico y aplicarlo a los problemas fundamentales de la física propios de su época.

Palabras clave: Teoría física, epistemología moderna, mecánica cuántica, unidad de la naturaleza, física experimental.

1. Introduction

This paper analyzes how the Kantian philosophy influenced Heisenberg's philosophy of physics, highlighting two points: (1) how Heisenberg's concept of physical reality is marked by the Kantian distinction between “phenomenon” and “thing in itself” and (2) the way that the philosopher physicist understands and rejects the Kantian definition of causality as a category of understanding[1]. Therefore, we analyze the incompatibility between Heisenberg's uncertainty principle and a classic causal description of physical events, as pointed by Heisenberg and Weizsäcker. We illustrate the principle of uncertainty and the breakdown of classical causality through Mach-Zehnder interferometer experiments and Scully's delayed choice.

In this sense, we are not dealing with Kant's theory of knowledge, but with how it was understood and applied by Heisenberg in his epistemology of modern physics. It is not our intention, therefore, to discuss how much Heisenberg would have understood Kant, but what is the epistemological use that he made of Kant's philosophy in the elaboration of an epistemology that aimed to encompass not only quantum mechanics but natural science in a broader, although the QM is, in fact, the great reference of such an epistemological program.

2. Discussion

2.1. Nomological or “unsubstantialized” realism and the “thing in itself”

Kant's importance to Heisenberg is due to the fact that, for the philosopher physicist, natural science itself is, above all, a discourse about our understanding of the real, and not of the real in itself. This interpretation takes him away from naive realism, from the idea of direct access to

[1] The relation between Heisenberg's thought and Kantian philosophy was taken, from different perspectives than ours, by CAMILLERI , 2006 e LEITE, 2012.

reality, but makes his realism more sophisticated, conceiving that there is an objective reality, independent of the mind, although we do not have access to it. There is the real, but we cannot fully conquer it, just get closer, indefinitely. The Kantian idea that the "thing in itself" is unknowable extends, in Heisenberg, to all-natural science: science does not deal with the nature independent of the subject of knowledge, but with the way it appears to us and is the object of understanding:

> Therefore, the atomic physicist had to resign himself to considering his science only as a link in the infinite chain of contact between man and nature and accepting that his science cannot simply speak of nature "in itself". (HEISENBERG. 1981: 14).

We can consider him a "nomological realist", or "mathematical-nomological realist", for arguing that the real is unified and ordered by mathematical principles of symmetry, which would constitute the fundamental ontological level (Plotnitsky, 2026)[2]. At the most profound and fundamental level of the world, we would not find the elementary particle, the matter, but the order expressed by mathematical relations. Videira speaks of an unsubstantialized realism in when dealing with Heisenberg's metaphysical thought[3], which would have removed the idea of substance, of matter, from its central position in the ontology of physics:

> For Heisenberg, today, mathematical symmetries are better suited to explain phenomena than elementary bodies. The elementary particles of atomic physics

[2] For Heisenberg "the ultimate nature of reality considered is represented purely mathematically, in the absence of physical concepts. It was then and has remained an uncommon position, although it has some affinities with, and may even be seen as a form of (ontic) structural realism, developed later" (Plotnitsky, 2026, p. 3).

[3] See (Silva, 2024).

> are best expressed by symmetry and cannot be considered 'beings' - they are not eternal and immutable. (VIDEIRA. 2017:103).

This conception brings him closer to what he understands as "Platonic idealism" present in *Timeu*[4]. But the level of reality, which emerges from a "central order", cannot be apprehended directly. We can represent it through the mathematical formalism of physics that does not have a direct connection with experience:

> The "thing in itself" is, after all, for the physicist, if he really makes use of this concept, a mathematical structure; this structure, however, is - contrary to what Kant thought - indirectly deduced from experience. (HEISENBERG. 1995: 71).

The experience would thus reach the phenomenon, that which "appears", which we can observe directly. Experimental physics, when dealing with observations, measurements, experiments, would approach the phenomenological level of the real. In this sense, there would be two places for mathematics. Either it would be a step away from the real, from the thing in itself, or a step closer.

In the first case, mathematical formalism would be a language developed to represent the experience data symbolically. In the second, mathematical formalism would express regularities, symmetries, ontological relations, in short, the ordering of the real. Our current understanding is that Heisenberg does not understand these dimensions of mathematics as antagonistic. In this understanding, mathematics is found before and after the experience (Plotnitsky, 2026). Every experience presupposes a theoretical basis, a system of statements and logical rules, a conceptual framework and a symbolic language, elements without which it cannot be realized. After the

[4] Leite and Simon approach the relation between Heisenberg physics and Platonic philosophy in another way. We also deal with the subject in Silva.

experiment has been carried out, its result must be interpreted and represented also through a logical-mathematical language.

Another relevant point in Heisenberg's[5] philosophy of nature is that in the Copenhagen Interpretation of quantum mechanics[6], there is no way to separate the observer from the observed system - both are intertwined since the measurement process undertaken *by the* observer changes the configuration of what *is being* observed. Certainly, observers and observed systems are distinct entities. However, science cannot, for our author, be taken as a discourse about the world. Instead, it occurs as part of our relationship with the world, because every time we experience the world, we modified it.

> The problem of the existence of these particles "in themselves", in time and space, can no longer present itself in this form since we can always speak and only of the processes that take place when we want to infer the behavior of the particle by the reciprocal action between it and any other physical system, for example, the measuring device. (HEISENBERG. 1981: p. 14).

This epistemological notion of Heisenberg, that the mathematical structures that appear in quantum mechanics, "describing" the regularities of the "behaviors" of elementary particles do not represent properties of nature in itself (but features of our understanding of such particles) can lead us , again, to find Kant, because this is precisely the proposal that we have in *The Critique of Pure Reason* (A125): "Thus, order and regularity in appearances, what we call Nature, we ourselves introduce them." (KANT, 1987: 172-173).

[5] Like other philosophical physicists as Einstein and Schrödinger, for example, Heisenberg is a sophisticated thinker, who has phases, and whose thinking dialogues with many authors. We understand that over time your membership of the Copenhagen Interpretation has become less clear.

[6] The name "Copenhagen Interpretation" can be misleading if we do not pay attention to the peculiarities of the scientific and philosophical thought of its "adherents", starting with Heisenberg and Bohr. For a closer look at the philosophical originality of both, we recommend: (Heelan, 2015).

However, we must emphasize that in making such claims, Heisenberg's epistemology is still strongly linked to the Copenhagen Interpretation philosophical program. Subsequently, this “Kantian” element will give way to an increasingly “Platonic” conception (Gallus, 2025). Indeed, at maturity, Heisenberg will commit to the thesis that the ultimate foundations of reality are mathematical structures, such as symmetries. In fact, it seems to us that Heisenberg never indicated that he would have difficulties in making Kantian epistemology compatible with Platonic ontology in this specific case (Silva, 2024). The thing is itself, the real, it is the ideal mathematical entity, the pure Platonic form. Symmetry is the *eidos* of the matter since the elementary particle is like a product of fundamental symmetries. Ideal mathematical entities are objective, fundamental, although they cannot be known in their completeness. The physical theory is a continuous effort to approach and unveil the real, always partial, but increasingly refined. What we perceive, which presents itself to our senses, is not the real “in itself”. To take what it *is* for what it *seems to be* is to confuse the real ideal entity with the sensitive object that is its "shadow" (Silva, 2024).

Heisenberg considers, therefore, that the development of the idea of “thing in itself” was an essential step by Kant towards the type of philosophical realism fundamental to modern science. This investigative tradition, perhaps, could be fostered only by an intellectual environment in which predominates the type of philosophical realism with which, according to Heisenberg, Kantian philosophy remains linked:

> The uncomfortable question of whether "things really exist" or not, which gave rise to philosophical empiricism, also appears in the Kantian system. Kant, however, did not follow Berkeley and Hume's line, although such a choice would have been logically consistent. He preserved the notion of the "thing in itself" as being different from what is perceived and, in this way, maintained some connection with philosophical realism. (HEISENBERG. 1995: 69).

It seems to us, however, that, according to Heisenberg, the importance of Kant's work for the development of natural sciences, and more specifically of theoretical physics, does not go beyond these aspects – if for Heisenberg Kant's philosophy is fundamental for affirming the impossibility of knowing "nature in itself", other elements of his thought, in turn, are not compatible with modern science, as is the case with the notions of time, space and causality of Kantian philosophy[7].

2.2. A priori elements of a closed system of propositions

In addition to not admitting space and time as *a priori representations*[8], Heisenberg draws attention to the fact that, in Kantian philosophy, there are other fundamental physical concepts, considered *a priori*, that cannot be viewed this way by the new physics:

> Concerning physics, Kant took, as a priori judgment, in addition to space and time, the law of causality and the concept of substance. In a later stage of his work, he tried to include, in the same category, the law of conservation of matter, the equality of "action and reaction" and even the law of gravitation. No physicist would be inclined to follow Kant's view if the expression a priori was used in the absolute sense ascribed to it by the Königsberg philosopher. In mathematics, Kant accepted the a priori character of Euclidean geometry. (HEISENBERG. 1995: 69).

7 Regarding the modes of relationship that can be articulated between modern science and traditional ontology from Kant, we can also refer to Martin, 1963.

8 For such a formulation, see CRP B39. As for the a priori nature of the space, which Heisenberg opposes, see CRP A25 / B40. Regarding time, CRP A31.

Heisenberg considers that contemporary physics cannot accept *a priori* concepts in a strong or *absolute* sense, that is, as they are admitted, in his understanding, in the Kant system[9]. However, he admits that there is certain knowledge *a priori* in natural science, in a more moderate sense. He considers that certain concepts, such as "space", "time" and "energy" should be regarded as *a priori* foundations within a closed system of propositions (which form the structure of a given theory), although they are not pre-defined conditions for “human understanding” in general. What we call the “closed system of propositions” is the set of elements of a theory: its postulates, hypotheses, axioms, statements and conclusions, items that do not need to be shared by other theories, that have limits of applicability. To use an example, we can refer to the proposition system of classical mechanics. It is perfectly acceptable to agree that this system only makes sense if we take the concepts of "space", "time" and "force" as a priori. Therefore, although they are not preconditioning *for* understanding, these concepts are a precondition *for* understanding *this* specific system of propositions. Such concepts are *a priori* even if such a system is not true (it is not true to reality), and even if such ideas are dispensable for the logical construction of other closed systems of propositions.

Kant considered causality as a category of understanding[10]. Thus, for Heisenberg, we could not, from Kant's definition, elaborate a vision of nature, intuitive or formal, that does not presuppose the law of causality. In other terms, as we cannot think about the existence of a body without first think about the presence of space and time, we also could not do it without considering the causal relationships. Therefore, to say that *x* exists is to say that in space *E* and in time *T* there is something that we can call *x*, or that *x* occupies at least a fraction of space *E* and lasts at least an instant in time *T*. This does not mean to say that *E* and *T* are real physical entities, but that, first of all, they are *a priori* forms of intuition, since any operation to understand the physical world must first assume them - to think of any material event without the

[9] As Heisenberg removes from the Kantian a priori “certain claim to the absolute”.

[10] Causality is listed in the table of categories, which Kant presents as the “pure concepts (...) of the synthesis that the a priori understanding contains in itself”. CRP B106/A81.

presupposition of *T* and *E* would be totally meaningless, in fact, and a much stronger proposition, to believe that a body does not occupy any fraction of space and does not last any moment of time would be the same as thinking that such a body does not exist.

Likewise, Kant argues that causal relationships are preconditions for understanding. Given a series of physical events, such as (..., *c-3*, *c-2*, *c-1*, *c0*, *c1*, *c2*, *c3*, ...,) we cannot think that each element of the series came out of nowhere, being completely independent of the other elements. Thus, if we have an event *c2*, this implies two different events: a factual event c1 and a possible event *c3*, respectively "cause" and "effect" of *c2*.

Quantum mechanics introduced indeterminism to the heart of science. As stated by Paty, "Quantum physics was the occasion for the most vivid criticism against not only determinism, but also causality". According to Weizsäcker, in classical physics, "causality" does not mean anything more than a connection between physical states in different measures of time, that is, connections between events. Technically, this means that if a state is completely known at a given moment, it is possible to calculate the state's values at any other time point, before or afterward, as Laplace defended. It is not the case that causality is false within the scope of the formal structure of quantum mechanics. Weizsäcker argues that the logic of quantum mechanics must presuppose the concepts of "Applicable" (A) and "Non-applicable" (~ A). Thus, the proposition "Given the system of propositions in quantum mechanics, causality propositions are false" is false. In fact, the law of causality does not apply to the proposition system of quantum mechanics. This is because for every quantum system analyzed, Heisenberg's uncertainty relations must be considered.

Heisenberg's principle of uncertainty (or indeterminacy) describes the impossibility of knowing the position and the "moment" of a quantum particle simultaneously. If we obtain the position precisely, its moment becomes completely uncertain, if we obtain its moment, its position becomes completely uncertain. According to the ontological interpretation of such a principle, this is due neither to a limitation of reason nor to an experimental technological limitation, but it is an elementary property of nature.

According to Heisenberg's uncertainty, in quantum mechanics, we can never know the exact location of a particle. This implies that we cannot think of trajectories, in the sense of classical physics. In this way, it is not possible to establish an exact connection between temporal transition events in the same system. Technically, if we do not know a particular state exactly, we cannot calculate the situation of that state in later or previous events, which is to say that it is not feasible to consider the connections between quantum events in terms of causality. That is why Heisenberg cannot admit, with Kant, that causality is a “pure concept of understanding”, without which a representation of physical events is impossible.

The causal process is a continuous event of connection between the state of a physical system at time *t* and that state at all times before and after *t* [11]. To say that state *x* is the cause of state *y*, in this sense, is not merely to say that from *x* follows *y*, but that there is a continuous transition event whereby *x* “becomes” *y*. However, quantum processes are discontinuous, and this is the main feature of quantum nature. As stated by Einstein and Infeld:

> If we were to characterize the main idea of quantum theory in one sentence, we could say: it must be admitted that some physical quantities hitherto considered continuous are composed of elementary "quantas". (EINSTEIN; INFELD. 1980, p. 202, own translation).

Not only is the matter composed of “quantas”, that is, discontinuous, but also the quantum events are disconnected once they obey Heisenberg's uncertain relations. Therefore, we cannot say that a state *x* is the cause of a state *y*, simply because “between” *x* and *y* there is a discontinuity. However, we can probabilistically predict the result of such a discontinuity and consider that a discontinuous state *x* will follow a discontinuous state *y*, *x* times every *n* cases.Think, for

[11] This assumes that causal events are local, that is, they are ordered in space and time. For the problem of nonlocality in quantum mechanics, see (Khrennikov, 2024).

example, of a quantum experiment in which beams of γ particles are fired at a constant speed *c* against a target A. After *x* firing, we notice that even under the preservation of all firing conditions in each of the *x* cases, different target regions were reached. We say that such variation is intrinsically statistical and that we cannot determine a cause for it.

In classical physics, if we repeated such an experiment with marbles and ensured (such an analysis, being an idealization, it can only be a "thought experiment") (1) that all particles have precisely the same properties, and (2) that were projected in the same direction with the same speed, (3) that the initial conditions of the entire system were identical (like pressure, temperature, air currents, electric field values and gravitational, for example), then they should all hit the same part of the target. If the experiment's initial conditions were the same on many occasions, then the experiment's result would also be the same. We performed *X* experiments *S* and found that, in all cases, we obtain the exact value of *P* as a result. We can deduce that the "cause" of this happening is due to the initial conditions of *S*.

However, quantum "behavior" is different. In the thought experiment in question, 100% of the shots occurred at speed *c*, with the projector in the *x* position. 90% of the beams reached the "d" region, according to the classic forecast. Approximately 9% of the beams suffered a quantum statistical deviation and were detected in the "a" region. About 1% of the beams suffered statistical deviation and was detected in other regions. If we carried out an experiment in which a high number of isolated photons were fired at one or two targets, we would find that the higher the number of photons fired, the clearer the formation of a diffraction pattern in the targets. Such a pattern is typical of wave phenomena.

We can perceive quantum non-causality through the simulation of an experiment with the Mach-Zehnder interferometer. The virtual experiment was developed by the team of Prof. Fernanda Ostermann of the Institute of Physics from the Federal University of Rio Grande do Sul. With the development of computational sciences, simulations became significant scientific instruments.

Programs that perform simulations of physical events are *software* configured with empirical data designed to anticipate real physical results from the relation between the physical properties that compound the systems in question. Therefore, the simulations, can predict how certain events will occur if we take specific variables into account, with more than 90% accuracy. In a Mach-Zehnder simulator, after 3778 photons fired at a rate of 10 photons per second against two targets, A and B, 1880 hit target A and 1889 hit target B, forming a diffraction pattern typical of wave phenomena. The formation of such a pattern cannot be predicted classically, that is, it cannot be described in terms of causality. According to the laws of classical physics, if we shoot particles at targets, in addition to the highly unlikely formation of a pattern of diffraction (by this we only mean that it is not mathematically impossible, although the probability is very remote), such formation is not necessary, contrary to what happens in quantum mechanics.

Such an experiment reveals three fundamental characteristics for the understanding of quantum systems: wave-particle duality, the statistical character of quantum processes and non-causal events. This last element illustrates Heisenberg's denial of Kant's understanding of causality as a category of understanding. The wave-particle duality must be viewed ontologically, and not just hermeneutically, that is, it is not just a matter of combining these two realities in scientific discourse, but of admitting that such realities are conjugated in nature. Even when firing particles alone, we obtain a diffraction pattern. Such elements are part of the heuristic nucleus of quantum mechanics; that is, they are among the most fundamental characteristics of quantum mechanics to be understood by contemporary physics researchers. Concerning wave-particle duality, in an experiment such as the Mach-Zehnder interferometer, as long as the quantity of particles is not large enough, everything happens as if isolated corpuscles hit the target.

Other experiments[12] by which we can illustrate quantum non-causality were carried out by Marlan Scully and collaborators. In Scully's "delayed choice" experiment[13], a photon is fired by a *p* projector at an *a* target. Halfway there is a transversal target *b* forming 90˚ in relation to the projector. Given the speed of light *c* and the distance between the projector and the target, we can calculate that the photon will take one nanosecond between *p* and *a*. In some cases, Scully's team introduced a 90˚ deviation in the middle of the path between *a* and *p*, so that the photon would hit target *b* if deflected. However, such a deviation has always been introduced well after ½ nanoseconds, i.e., the photon has passed through that region, according to the classical calculation. The addition of such a deviation, in the classical sense, should not mean anything, which means that causal relations depend on both space and time, and time has an arrow, an unalterable direction. Events at time *t3* could not influence the state of systems at *t2*, given the direction of the time flow. The temporal and causal arrows advance in the same direction and are transversely interconnected, i.e., each event at one point on one of the arrows is necessarily correlated to an event at a point on the other arrow.

However, Scully's experiment demonstrates the breakdown of classic causality because it has been verified the occurrence of cases in which the photon reached target *b*, that is, events in which the increase in the deviation in *t3* generated the change in the state in *t2*. In such events, the causal arrow has been broken, which contradicts classic causality. This could only happen if (i) the information that the experiment was altered went back in time, causing the photon to be deflected by the mirror that was not there when it passed, or if (ii) the photon's state before observation was a superimposed reality of the two possibilities (reaching target A or B), and that only the experimental intervention succeeded by the observational verification could select these two possibilities, making one of the two possible. In the case where the mirror is placed, the probability that the photon will reach target B is valid, and the other is discarded and vice versa.

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[12] One of the most famous is reported in Scully.

[13] Delayed-choice experiments have been proposed since 1978 by John Weeler. Delayed-choice experiments challenge our most basic understanding of physical concepts like space, time and causality.

The superposition effects are phenomena predicted by quantum theory, widely known, and in a way already evidenced by experiments such as the "double gap" and so many others[14].

3. Conclusions

In short, what Heisenberg and Weizsäcker argue and what experiments like Scully's and Mach-Zehnder's interferometer confirm is that, at the quantum level, classical causality is broken, or, logically speaking, that the concept of classical causality does not is applicable to the quantum mechanics statement system. Thus, in Heisenberg's conception, Kant was mistaken when he maintained, keeping to the classic tradition, that causality is the category without which no understanding of the physical world is possible. Contemporary physics would have shown the opposite: classical causality is inapplicable *a priori* whenever the object of understanding is quantum. We must emphasize, however, that there is no consensus between physicists and philosophers on this point. There are many efforts to preserve the notion of causality in quantum mechanics. For example, Einstein never accepted this aspect of QM, believing that such an answer could not be the final solution. In turn, David Bohm developed an interpretation of the hidden variables of QM that seek to preserve physical determinism at a deeper level.

We saw that in Heisenberg's understanding, Kant is an indispensable author for understanding the conception of nature that arises with modern science. Heisenberg disagrees with the Kantian conception of causality, considering it inapplicable to quantum mechanics.

[14] Conducted by Thomas Young (1773-1829) around 1801.

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