DOI: http://doi.org/10.5007/2175-7941.2026.e111400

The genesis of the Uncertainty Principle: a historical-epistemological analysis of the Heisenberg-Pauli correspondence (1927)[+*]

Marcos Antonio Barros[1]
State University of Paraíba
Campina Grande – PB
Jenner Barreto Bastos Filho[1]
Federal University of Alagoas
Maceió – AL
Pablo Francisco Honorato Sampaio[1]
Federal Institute of Education, Science and Technology of Paraíba
Patos – PB

Abstract

This article investigates the historical–epistemological genesis of the Uncertainty Principle through an analysis of the scientific correspondence between Werner Heisenberg and Wolfgang Pauli, with particular emphasis on the long letter dated 23 February 1927, written immediately prior to the publication of the paper in which the principle was formally introduced. In contrast to retrospective narratives that treat uncertainty as a direct consequence of the mathematical formalism of Quantum Mechanics, the study demonstrates that the principle emerged from a gradual process of conceptual elaboration grounded in operational reflections on measurement, the redefinition of the physical meaning of classical quantities, and the role of observation. A close, commented reading of the letter reveals an intermediate stage in which relations of indeterminacy appear as heuristics tied to conditions of measurability, before being discursively stabilized as a general principle in the published article of 1927. The comparison between private correspondence and public exposition makes it possible to identify conceptual continuities,

[+] A gênese do Princípio daIncerteza: um análise histórico-epistemológica da correspondência Heisenberg-Pauli (1927)

[*] *Received: March 5, 2026.*
Accepted: May 8, 2026.
Published: August 31, 2026.

[1] E-mails: marcos_fis@hotmail.com; jenner@fis.ufal.br; pablo.sampaio@ifpb.edu.br

epistemological shifts, and rhetorical strategies associated with the consolidation of the principle. It is argued that the construction of the Uncertainty Principle is best understood as the outcome of a collective and argumentative process, shaped by epistolary exchange, institutional debate, and public controversy, including the discussions at the 1927 Solvay Conference. By foregrounding primary sources, the article contributes to a historically informed understanding of Quantum Mechanics and to a critical reassessment of excessively formalist interpretations of its foundations.

Keywords: *Uncertainty Principle; Quantum Mechanics; History and Philosophy of Science; Scientific Correspondence; Measurement and Observation.*

I. Introduce

The formulation of the so-called Uncertainty Principle[2] [3] occupies a central place in the conceptual history of Quantum Mechanics and stands among the most extensively discussed milestones of twentieth-century physics. Since its publication in 1927, the principle has been widely presented, both in textbooks and in part of technical and philosophical literature, as a direct consequence of the mathematical formalism of the theory, particularly of the commutation relations between canonical operators. Within this retrospective reconstruction, the inequality expressed by the product of the standard deviations of position and momentum is frequently interpreted as an intrinsic physical or ontological limit of microscopic systems. Although mathematically consistent, such a narrative tends to obscure the actual historical process through which the concept was elaborated. A gradual, argumentative, and contextually situated construction thus comes to be presented as if it were an atemporal deduction.

---

[2] A first point concerns the conceptual category of *uncertainty*, insofar as it may be understood as an attribute of the subject rather than of the physical objects to which the theory refers. The designation that uses the word *indeterminacy* would likewise suffer from this same difficulty. From the standpoint of realist interpreters, the expression *Dispersion Principle* would therefore constitute a more appropriate terminology than the designations *Uncertainty Principle* or *Indeterminacy Principle*, respectively.

[3] A further point, closely related to the argument advanced in the preceding footnote, is that the issue cannot be reduced merely to a nominalist choice or, in other words, to purely denotative preferences. There are, in fact, radical differences in the epistemological conceptions underlying each of these designations. If Quantum Mechanics is taken to be an objective physical theory like any other, then anthropomorphic projections, such as *uncertainty,* ascribed to quantum objects (electrons, photons, mesons, pions, etc.) would be regarded as illegitimate within certain realist interpretations. No property of Quantum Mechanics depends on the peculiarities of the subjects who study it.

* Translated by Pablo Francisco Honorato Sampaio.

Since the classical studies in History and Philosophy of Science (HPS), it has been recognized that this type of retrospective reconstruction oversimplifies the real dynamics underlying the development of Quantum Mechanics. The theory did not emerge as a closed conceptual system in a sudden manner; rather, it took shape within a period marked by semantic ambiguities, debates concerning the status of physical quantities, and tensions between competing theoretical programs. In this context, classical categories such as position, momentum, and orbit were progressively problematized, redefined, or even abandoned, as it became necessary to ascribe physical meaning to newly introduced mathematical structures.

Over the past decades, the historiography of physics has emphasized the role of discursive practices, scientific dialogue, and internal controversies in the construction of Quantum Mechanics. This perspective shifts the focus away from isolated mathematical formalization toward collective processes of conceptual negotiation, in which letters, seminars, and informal discussions play a decisive role. From this standpoint, the Uncertainty Principle may be understood not merely as a technical result, but as a response to concrete problems involving the operational definition of physical quantities, the conditions of observation, and the scope of classical categories within the quantum domain. On the eve of the centenary of the 1927 paper in which Werner Heisenberg formally introduced the principle, it becomes particularly timely to revisit critically its historical process of elaboration. Commemorative dates of this kind have increasingly encouraged, within contemporary historiography of science, not only celebratory accounts but also conceptually grounded reassessments based on primary sources and refined historical–epistemological approaches.

In this context, the scientific correspondence immediately preceding the publication of the 1927 paper acquires relevance. Among the available primary sources, special attention must be given to the long letter sent by Heisenberg to Wolfgang Pauli on 23 February 1927[4], written only a few weeks before the article *Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik (“On the Intuitive Content of Quantum-Theoretical Kinematics and Mechanics”)*. In this document, Heisenberg articulates still-unsystematized reflections on the operational definition of position and velocity, a critique of the classical notion of electronic orbit, the disturbing role of measurement, and the emergence of relations of indeterminacy between conjugate quantities. In contrast to the published text, these ideas appear in a heuristic and exploratory language, revealing a prior stage of conceptual consolidation.

The motivation for the present investigation is also connected to research and training practices in History and Philosophy of Science developed within the Graduate Program in Science and Mathematics Education at State University of Paraíba, where the reading and

[4] The handwritten letter from Werner Heisenberg to Wolfgang Pauli, dated 23 February 1927, was originally written in German. The Portuguese version used in this article is based on a translation by Luan Florêncio dos Santos Félix, to whom we express our gratitude. The document forms part of the corpus of correspondence preserved in the historical archives of CERN (records 84566, 84567, and 84541).

analysis of primary sources have been employed as a strategy to deepen the epistemological understanding of fundamental concepts and their historical processes of construction. It was within this context that the proposal emerged to carry out a systematic analysis of the February 1927 letter, initially conceived as a complement to a chapter of an ongoing doctoral thesis and later expanded into an autonomous historiographical investigation.

From a historiographical standpoint, both classical and contemporary studies have drawn attention to the need to understand the Uncertainty Principle in terms of its effective process of elaboration rather than solely through its finals, stabilized formulation. Early analyses highlighted the role of measurability relations and the redefinition of the physical meaning of quantities in the genesis of the principle (Jammer, 1974; Pais, 1982), whereas more recent approaches emphasize the dialogical, argumentative, and collective character of conceptual construction in Quantum Mechanics, with particular attention to scientific correspondence and internal controversies during the period 1925-1927 (Beller, 1999; Camilleri, 2009; Cassidy, 2020).

Within the Brazilian literature, studies in History and Philosophy of Science and in Physics teaching have likewise emphasized the importance of historical-epistemological approaches grounded in primary sources, both to avoid oversimplified retrospective reconstructions and to promote a critical understanding of the foundations of Modern Physics (Martins, 2006; Peduzzi, 2011; Videira, 2013; Monteiro; Nardi, 2017). In addition, investigations on the foundations and interpretations of Quantum Mechanics (Freire Jr.; Pessoa Jr., 2011; Ostermann; Ricci, 2004; Pessoa Jr., 2006) have stressed the importance of analyzing the conditions under which quantum concepts acquire physical meaning, reinforcing the need to avoid anachronistic readings and situating the present study in dialogue with national scholarship in the field.

The aim of this article is to reconstruct the historical–epistemological genesis of the Uncertainty Principle through the correspondence between Heisenberg and Pauli, highlighting its initially operational, argumentative, and provisional character, as well as the process of conceptual consolidation that culminates in the 1927 published paper. To this end, the text develops four interconnected analytical movements: (i) it situates the February 1927 letter within the intellectual context of Quantum Mechanics between 1925 and 1927; (ii) it examines its main conceptual cores, with emphasis on operational definitions of physical quantities, the critique of classical categories, and the role of measurement; (iii) it analyzes the reformulation and normalization of these arguments in the published article; and (iv) it discusses the historical-epistemological implications of this genesis for understanding the principle, particularly in light of its centenary. By adopting this approach, the article seeks to contribute to a historically informed understanding of Quantum Mechanics, emphasizing the processual, argumentative, and collective character of the construction of one of its fundamentals principles, as well as the role of primary sources in critically reassessing consolidated retrospective narratives. It should be noted that this analysis does not aim to provide an exhaustive reconstruction of the interpretative debates surrounding Quantum Mechanics in the period 1925-1927 but rather focuses on the conceptual dynamics visible in the transition from private correspondence to published text.

II. The Historical–Intellectual Context of Quantum Mechanics between 1925 and 1927

Historiography typically treats the period 1925‑1927 as a decisive interval in the consolidation of Quantum Mechanics. During this time, the theory evolved from partial formulations into a relatively stable mathematical formalism, albeit one that remained conceptually problematic. The introduction of matrix mechanics by Werner Heisenberg in 1925, followed by reformulations by Born, Jordan, and Dirac, established an algebraic structure grounded in the non-commutativity of canonical quantities (Mehra; Rechenberg, 2000; Pais, 1982). The physical meaning of these structures, however, remained largely indeterminate.

In parallel, Erwin Schrödinger's wave mechanics (1926) revived expectations of recovering classical notions such as trajectory and electronic orbit. As documented by Pais (1982) and Mehra and Rechenberg (2000), the coexistence of mathematically equivalent yet conceptually distinct formalisms intensified interpretative debates regarding the status of observables and the role of measurement. In other words, formal equivalence did not resolve conceptual problems; rather, it rendered them more urgent by demanding clarification of the shared "physical content" underlying both formulations.

Within this context, the Institute for Theoretical Physics in Copenhagen, directed by Niels Bohr, became a particularly significant locus for discussions on the foundations of the theory. More than a center of technical production, the institute functioned as an environment of systematic conceptual critique, in which epistemological issues were treated as an integral part of theoretical practice (Cassidy, 1992; Beller, 1999). Young physicists were encouraged to confront the limits of classical categories and to explore the conceptual consequences of quantum formalism.

Scientific correspondence, in practice, functioned as an intermediate space for conceptual elaboration. As shown by Mehra and Rechenberg (2000) and Cassidy (2020), letters exchanged between Heisenberg, Wolfgang Pauli, Bohr, and other interlocutors constituted privileged instances of provisional formulation, in which arguments were proposed, criticized, and reformulated prior to public exposition. In this respect, Pauli occupied a singular position, exercising rigorous technical and conceptual criticism that compelled his correspondents to clarify the physical meaning of their propositions.

Between 1926 and early 1927, a particularly debated issue concerned the possibility of assigning simultaneous and well-defined values to conjugate quantities such as position and momentum. Although formalism already incorporated non-commutation relations, their physical scope remained contested. According to Mehra and Rechenberg (2000), the central concern was not merely mathematical consistency, but the interpretation of available experimental procedures and the disturbances introduced by the act of measurement. It is within this context that the letter sent by Heisenberg to Pauli on 23 February 1927 must be placed. The document should be understood as part of a broader process of conceptual clarification, in which Heisenberg sought to articulate, in operational terms, the physical implications associated with commutation relations. As Pais (1982) observes, ideas that would later be presented as the “Uncertainty Principle” initially appeared as qualitative arguments grounded in experimental resolution, disturbance, and statistical distributions of results, prior to their stabilization in a more systematic formulation.

From a historiographical perspective, this set of interactions, private correspondence, seminars in Copenhagen, and debates at Solvay, reinforces the interpretation that the Uncertainty Principle did not emerge as an isolated result, but rather as the product of a collective process of conceptual construction. As argued by Beller (1999), Quantum Mechanics developed through a “quantum dialogue,” in which physical arguments, linguistic choices, and epistemological commitments were progressively negotiated. Situating the February 1927 letter within this context is therefore a necessary condition for the historical-epistemological analysis developed in the following section.

Although the present analysis takes the letter of 23 February 1927 as its central axis, this source is understood here as part of a broader circuit of production and circulation of ideas, encompassing other correspondences, seminars in Copenhagen, and subsequent public debates. In this sense, the letter is not treated as isolated evidence, but rather as a privileged entry point for reconstructing a collective process of conceptual elaboration, extensively documented in the historiography (Mehra; Rechenberg, 2000, v. 6; Cassidy, 2020).

This process of conceptual elaboration finds a particularly significant moment of public articulation in the Fifth Solvay Conference, held in October 1927. Although the February letter precedes this meeting, many of the issues addressed therein, such as the impossibility of simultaneously assigning well-defined values to conjugate quantities, the constitutive role of measurement, and the status of physical description, reappear centrally in the debates between Niels Bohr and Albert Einstein. As emphasized by Kragh (1999, p. 206-215), these discussions not only consolidate tensions already present in the period 1925-1927 but also reveal that the interpretation of Quantum Mechanics emerged as the result of a collective process of conceptual negotiation. In the same vein, the detailed analysis of the proceedings of the 1927 Solvay Conference by Bacciagaluppi and Valentini (2009) shows that the debates were far from reaching immediate consensus, marked by explicit disagreements regarding the role of measurement, the status of physical quantities, and the very completeness of the theory.

In this direction, Bohr would later assert “The impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments,” that is, “A impossibilidade de qualquer separação nítida entre o comportamento dos objetos atômicos e a interação com os instrumentos de medida” (Bohr, 1983, p. 210). Likewise, he maintained that “evidence obtained under different experimental conditions cannot be comprehended within a single picture, but must be regarded as complementary,” meaning that “evidências obtidas sob diferentes condições experimentais não podem ser compreendidas em um único quadro, devendo antes ser consideradas complementares” (Bohr, 1983, p. 213). The correspondence between Heisenberg and Pauli may thus be understood as part of the intellectual background that informed these discussions.

III. A Commented Historical-Epistemological Analysis of the Letter from Werner Heisenberg to Wolfgang Pauli (23 February 1927)

From a methodological standpoint, the letter analyzed here is not treated as providing transparent or immediate access to Heisenberg’s thought, but rather as a situated historical artifact, produced within a specific context of scientific interlocution. Like any correspondence, the document is shaped by rhetorical strategies, expectations of reception, and the critical role played by its recipient, in this case, Pauli. In this sense, the analysis of the letter requires attention not only to its conceptual content, but also to its function within a broader communicative process, in which arguments are tested, adjusted, and reformulated prior to their public presentation.

The letter sent by Heisenberg to Pauli on 23 February 1927 constitutes a privileged document for reconstructing the genesis of the Uncertainty Principle. Unlike the article published a few weeks later, the epistolary text does not present the principle as a finished formulation, but rather as a sequence of reflections centered on concrete conceptual problems, such as the definition of physical quantities, the role of measurement, the critique of classical categories, and the statistical interpretation of Quantum Mechanics. In this section, the letter is analyzed according to its principal argumentative cores, to highlight the historical–epistemological character of the emergence of the principle.

III.1 Operational Definition of Position and the Role of Measurement

At the very beginning of the letter, Werner Heisenberg reformulates the question “what is the position of the electron?”[5] into “how is the position of the electron defined?”, thereby shifting the problem from an ontological to an operational plane. Position becomes inseparable from a concrete experimental procedure, exemplified using a microscope with a given resolution. The precision of the measurement is related to the wavelength of the radiation employed, while the disturbance introduced into the system is associated with the Compton effect. This shift appears to be decisive for the initial formulation of what would later be called the Uncertainty Principle. Uncertainty does not emerge here as an abstract limit “of nature”, but rather because of the physical conditions of observation and of the unavoidable interaction

[5] “Die Position des Elektrons ist nur durch das Experiment definiert, das sie bestimmt”- (“the position of the electron is defined solely by the experiment that determines it.”).

between the system and the measuring apparatus[6]. The commutation relation between position and momentum appears in the letter as a formal expression of this operational limitation, rather than as the starting point of the argument.

III.2 Critique of the Classical Notion of Electronic Orbit

A striking feature of the letter is the explicit rejection of the notion of a well-defined electronic orbit, even in stationary states such as the ground state of hydrogen. Werner Heisenberg argues that referring to the "1S orbit" is not only empirically problematic, but conceptually meaningless, since any attempt to determine the electron's position with sufficient precision would lead to the destruction of the atomic state itself[7].

This passage indicates a semantic rupture with Classical Physics. It is not merely a matter of recognizing experimental limitations, but of denying the conceptual legitimacy of certain categories when transposed into the quantum domain[8]. In this way, the orbit ceases to function as a constitutive element of description and is replaced by probability functions, whose interpretation is explicitly statistical.

III.3 Statistics, Phases, and the Role of Experiment

In discussing stationary states, Heisenberg introduces a crucial distinction between two ways of understanding the statistical character of Quantum Mechanics. On the one hand, in line with Jordan, he acknowledges that natural laws take on a statistical form; on the other hand, in agreement with Paul Dirac, he maintains that statistical behavior is primarily introduced by experimental procedures, due to the impossibility of controlling or knowing the phases involved.

In this respect, the epistemological implication is clear: statistics are not presented as a fundamental ontological feature, but rather because of the conditions of preparation and observation[9]. The ignorance of phases, linked to the impossibility of measuring them without destroying the state, grounds the probabilistic character of theoretical predictions.

---

[6] Jammer emphasizes that, in Werner Heisenberg's initial formulations, uncertainty emerges from an analysis of the conditions of measurability rather than from a strong ontological thesis about microscopic reality. It constitutes a form of methodological operationalism aimed at clarifying the physical meaning of the mathematical symbols of the theory (Jammer, *The Philosophy of Quantum Mechanics*, ch. 4).

[7] "Hat keinen klaren physikalischen Sinn". ("has no clear physical meaning.").

[8] Beller interprets this type of statement as part of a process in which classical language is progressively destabilized. The rejection of the "meaning" of the orbit stems from a shift in the criteria of physical significance, negotiated in the dialogue between Werner Heisenberg, Wolfgang Pauli, and Niels Bohr (Beller, *Quantum Dialogue,* ch. 6).

[9] Jammer notes that this conception distinguishes Werner Heisenberg's initial position from stronger ontological readings of quantum indeterminism that would only consolidate later. In the letter, the emphasis falls on epistemic limits tied to experimental practice (Jammer, *op. cit.*).

III.4 Generalization of Indeterminacy Relations and the Emergence of the Principle

In the central part of the letter, Werner Heisenberg generalizes his considerations to arbitrary pairs of canonical quantities, formulating a qualitative relation between the mean errors associated with conjugate variables. Although expressions anticipating $\Delta p \cdot \Delta q \approx h$ appear, the argument remains grounded in physical and experimental considerations. It is important to note that, at this stage, what would later be termed the "Uncertainty Principle" has not yet taken the form of a rigorous inequality, nor that of an explicitly formulated general principle. Rather, it appears as an empirical-conceptual regularity, derived from the analysis of measurement conditions and expressed in terms of orders of magnitude[10].

III.5 Observation, Wave Packets, and the Construction of the "Orbit"

In the transition from the micro to the macro domain, Werner Heisenberg criticizes Erwin Schrödinger's attempt to recover classical orbits through stable wave packets. In contrast, he proposes that the notion of orbit emerges as the result of a sequence of observations, each of which redefines the state of the system within certain limits of indeterminacy. This conception anticipates central elements of what would later be known as the Copenhagen interpretation, particularly the idea that observation plays a constitute role in the definition of physical phenomena. However, in the letter, this idea is still presented in a pragmatic and operational manner, without the more elaborated philosophical framework that would characterize later formulations.

It is important to emphasize, however, that the notion of observation mobilized by Heisenberg at this stage does not fully coincide with the concept of complementarity later formulated by Niels Bohr. In the February 1927 letter, observation appears predominantly associated with the physical disturbance of the system caused by the act of measurement, as evidenced by the role of the Compton effect and the discussion of the gamma-ray microscope. It is, therefore, an essentially operational approach, centered on the limitations imposed by experimental procedures. By contrast, Bohr's complementarity shifts the focus from disturbance to the conditions of describing phenomena, emphasizing the need to employ mutually exclusive experimental arrangements to account for the totality of observable aspects. As highlighted in the historiographical literature, these positions are neither equivalent nor do they justify the view of a homogeneous and already fully consolidated "Copenhagen interpretation" at that time (Beller, 1999; Camilleri, 2009; Howard, 2004). In this sense, the

---

[10] Camilleri (2009) emphasizes that the subsequent formalization entails a shift in status: from an operational heuristic to a structural principle. The February 1927 letter documents this intermediate stage, in which the principle is still under construction (Camilleri, "Heisenberg and the Interpretation of Quantum Mechanics," *Studies in History and Philosophy of Modern Physics*).

letter analyzed here makes it possible to identify a moment prior to the consolidation of this conceptual articulation[11].

III.6 States, Successive Measurements, and the Linearity of the Theory

In the final sections, Werner Heisenberg discusses successive measurements and the redefinition of the quantum state after each observation. By asserting that, after a measurement, the description of the system must be replaced by a new solution of the wave equation compatible with the observed result, he anticipates, albeit without formal axiomatization, the idea of state projection. The justification, grounded in the linearity of the quantum equations, reveals a concern with preserving the formal coherence of the theory, while simultaneously acknowledging the active role of experiments in selecting physically relevant solutions[12].

III.7 Concluding Remarks of the Letter and Its Provisional Character[13]

The letter concludes with a revealing remark, in which Heisenberg acknowledges that his reflections may appear outdated, vague, or insufficiently grounded[14]. This self-critical stance reinforces the exploratory character of the text, in contrast to the more systematic tone of the article published a few weeks later. From a historical–epistemological perspective, this contrast highlights the transition from a working discourse, open to criticism and revision, to a public exposition that is already stabilized[15].

---

[11] Beller (1999), Howard (2004), and Camilleri (2009) emphasize that, during this period, Werner Heisenberg develops a conception of observation centered on the physical disturbance associated with the act of measurement, which does not fully coincide with the notion of complementarity later formulated by Niels Bohr. Although both approaches share a rejection of complete classical descriptions of the quantum system, they differ with respect to the epistemological status attributed to observation: Heisenberg's approach is more directly linked to experimental procedures, whereas Bohr's emphasizes the conditions of possibility of describing phenomena.

[12] Jammer notes that this line of reasoning constitutes a precursor to the "wave packet reduction postulate," explicitly articulated in later works (Jammer, *op. cit.*).

[13] After extensive discussions and controversies, certain realist readings—such as that of Mario Bunge (1987)—argue that conceiving Heisenberg's Principle as a general feature of the mathematical formalism of Quantum Mechanics is far more acceptable than interpreting it in terms of an operational heuristic, which, although valid within the historical development of the discussion, is not sustainable as a basis for attributing it the status of a general principle. In this regard, it is worth citing Bunge:

"The adherents of the Copenhagen school propose not just one but several interpretations of Heisenberg's inequalities, which indicates the imprecision with which they formulate their principles. The most popular are: (a) the dispersions are measurement errors and (b) the dispersions are uncertainties (in the minds of certain subjects) concerning the position and momentum of the quantum object. Such interpretations, however, are illegitimate, since the premises from which Heisenberg's theorem is derived do not refer to the observer or to the means of observation. The theorem is completely general: it applies to any material micro-object, whether free or subject to measurement. Moreover, the theorem cannot refer to any mental state of the observer, since Quantum Mechanics does not deal with physicists, but with what physicists' study" (Bunge, 1987, p. 97).

[14] "vielleicht alt oder nicht genügend begründet" - ("perhaps outdated or not sufficiently well-founded").

[15] There is strong evidence that Wolfgang Pauli replied to this letter prior to the publication of the article. In a postcard dated 2 March 1927, Werner Heisenberg notes that he is "responding to some of Pauli's questions." A

In this context, the role of Wolfgang Pauli cannot be reduced to that of a passive interlocutor but must be understood as an active component in the process of conceptual elaboration. His critical engagement, widely recognized in historiography, contributed to challenging, refining, and testing Heisenberg's formulations, thereby reinforcing the dialogical character of the genesis of the principle.

IV. Letter and the 1927 Paper: Continuities, Reformulations, and the Consolidation of the Uncertainty Principle

The publication, in March 1927, of the paper *Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik*[16] marks the discursive stabilization of the Uncertainty Principle within the corpus of Quantum Mechanics. In comparison with the letter sent to Wolfgang Pauli a few weeks earlier, the article presents a more systematic argumentative structure, a carefully selected vocabulary, and a rhetorical strategy oriented towards public exposition and conceptual defense of the principle. A comparative analysis allows us to identify both continuities and shifts in the epistemological status attributed to uncertainty.

IV.1 Conceptual Continuity: Measurement, Disturbance, and Observability

There is a clear continuity in the core of the argument. In both texts, the point of departure is the redefinition of the physical meaning of classical quantities through concrete measurement procedures. Position and momentum cease to be properties that can be simultaneously attributed to the system and instead become operationally defined in terms of observational conditions.

The thought experiment of the microscope, already outlined in the letter through the discussion of optical resolution and the Compton effect, reappears in the article in a more structured form and assumes a central role. The disturbance introduced by the act of measurement remains a fundamental element for understanding the limitations on the simultaneous attribution of precise values to conjugate quantities. Thus, the article does not introduce a decisive new idea but rather reorganizes and refines arguments already present in the correspondence. From a historical perspective, this continuity reinforces the view that the principle does not emerge abruptly in the published text, but results from prior elaboration in which the letter plays a decisive role.

few days later, on 9 March 1927, he sent Pauli the manuscript of the paper, observing that the text was, in essence, identical to the content of the previous letter. This sequence suggests that issues raised by Pauli were incorporated into the final elaboration of the principle, although his reply has not been preserved or made accessible in published form. Cf. *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u. a.*; Mehra & Rechenberg (2000).

[16] "On the Intuitive Content of Quantum-Theoretical Kinematics and Mechanics". **Zeitschrift für Physik**, v. 43, p. 172-198, 1927.

IV.2 From Operational Heuristics to the Formulation of a General Principle

Despite this continuity, the comparison between the two texts suggests a significant shift in the epistemological status attributed to uncertainty. In the letter, relations of indeterminacy appear as heuristic results, expressed in terms of mean errors, orders of magnitude, and varied examples; the text retains an exploratory character. In the article, these considerations are reorganized to support the formulation of a general principle, in which the relation between uncertainties in position and momentum is presented as a necessary expression of the conditions of observability in quantum description.

Although a rigorous mathematical derivation of inequality is not the central focus, the argument confers upon uncertainty a structural character, rather than a merely operational one. This transition, from experimental heuristics to the formulation of a general principle, constitutes an important step in conceptual consolidation. From this point onward, a limitation associated with measurement practices comes to be presented as a constitutive feature of quantum description, independently of specific experimental details.

IV.3 Rhetorical Reorganization and the Selection of Examples

Another important aspect of this transformation concerns rhetorical reorganization. The letter mobilizes multiple examples and lines of reasoning: microscopy, the Compton effect, stationary states, wave packets, resonance fluorescence, Stern-Gerlach-type experiments, among others, reflecting its exploratory character. In the article, by contrast, this plurality is reduced. Werner Heisenberg selects a limited number of paradigmatic examples, especially the gamma-ray microscope, and develops them with greater coherence. The suppression of secondary examples and the concentration on a privileged scenario strengthen the persuasive force of the text and facilitate its reception. From a historiographical standpoint, this selection forms part of a process of discursive alignment in which certain arguments are elevated to exemplary status, while others are relegated to the background.

IV.4 The Status of Statistics: From Epistemic Limitation to Structural Feature

An important difference concerns the treatment of statistics. In the letter, Heisenberg emphasizes that the statistical character arises from the practical and conceptual impossibility of knowing certain quantities (such as phases), given experimental limitations. Statistics thus appear because of epistemic constraints associated with experimental practice.

In the article, although the operational dimension remains, the statistical character is presented in more general terms, as an expression of the conditions of observability in the quantum domain. This shift is subtle but significant: statistics cease to be merely a by-product of practice and come to be presented as a structural component of the description. This movement later contributed to interpretations emphasizing ontological indeterminism, even though such reading is not explicitly formulated by Heisenberg at this stage.

IV.5 From Private Dialogue to Public Exposition

The difference in tone between the two texts is equally revealing. The letter is marked by hesitations, self-criticism, and invitations to Pauli's "ruthless criticism," assuming an ongoing dialogue. In the article, this dialogical character is replaced by a more assertive exposition; ambiguities are suppressed in favor of a stable and authoritative presentation. Recognizing this transition is crucial to avoid anachronistic readings that project onto the letter the conceptual status that the principle only fully acquires after its publication and reception.

IV.6 Comparative Synthesis

The table 1 summarizes the main differences and continuities identified.

Table 1 – Letter to Pauli (Feb. 1927) and the 1927 paper: conceptual comparison.

Aspect	***Letter***	***Published Paper***
Status of the argument	Heuristic and exploratory	Systematic and stabilized
Role of measurement	Central, with multiple examples	Central, with selected examples
Formulation of uncertainty	Qualitative error relations	General principle
Statistics	Epistemic consequence	Structural feature
Discursive tone	Dialogical and provisional	Assertive and public

Source: Authors' elaboration based on primary sources.

IV.7 Historical-Epistemological Implications

The comparative analysis indicates that the Uncertainty Principle should not be understood as the immediate consequence of an abstract mathematical structure, but rather as the product of a progressive process of conceptual construction. The February 1927 letter documents a crucial stage in which operational arguments, epistemological reflections, and thought experiments are mobilized to confer physical meaning upon formalism. The article, in turn, stabilizes this process, transforming an operational heuristic into a general principle. Recognizing this transition contributes to a more historically informed understanding of Quantum Mechanics and sheds light on epistemological debates concerning the genesis and consolidation of scientific principles.

V. Epistemological Discussion: The Genesis of the Uncertainty Principle as a Historical Process

The interpretation developed here, which emphasizes the operational and epistemic character of the genesis of the Uncertainty Principle, is not the only one present in the historiography. Part of the literature has interpreted the principle in terms closer to an ontological indeterminism, associated with a more radical rupture with Classical Physics. On the other hand, authors such as Beller (1999) and Camilleri (2009) emphasize the discursive and argumentative character of the process, while philosophically oriented analyses problematize the scope of the so-called Heisenbergian "operationalism". The present approach aligns with this second perspective by privileging the historical reconstruction of arguments within their context of production, without presupposing a strong ontological reading of the principle in its initial formulation.

The analysis of the letter from Werner Heisenberg to Wolfgang Pauli, considered alongside the 1927 paper, makes it possible to advance toward a more historically refined understanding of the Uncertainty Principle. In contrast to retrospective narratives that present it as a direct consequence of formalism, the examination of primary sources reveals a process of conceptual elaboration grounded in operational reflections on measurement and in questioning the physical meaning of classical categories.

From an epistemological standpoint, the letter records a stage in which uncertainty does not yet possess the status of a general principle but emerges as a regularity linked to concrete conditions of observation. The limitations in assigning simultaneous precise values to conjugate variables are understood as consequences of these conditions, rather than as ontological properties immediately attributable to microscopic systems. In this sense, uncertainty initially appears as an epistemic–operational limit, tied to experimental practice and to the unavoidable interaction between system and apparatus.

The centrality of the issues discussed in the February 1927 letter and the article published in March becomes even more evident when considered considering the epistemological debates before[17] and during the Fifth Solvay Conference. As shown in contemporary analyses of the Solvay proceedings (Bacciagaluppi & Valentini, 2009), the debates between Niels Bohr and Albert Einstein not only illustrate deep epistemological divergences but also reveal that the interpretation of Quantum Mechanics remained open and contested, contrary to later narratives that suggest a rapid and consensual stabilization.

These debates demonstrate that issues such as the definition of physical quantities, the role of measurement, and the limits of classical description were not merely technical questions,

[17] In the volume dedicated to Wolfgang Pauli (*Theoretical Physics in the Twentieth Century: A Memorial Volume to Wolfgang Pauli*), edited by Markus Fierz and Victor Frederick Weisskopf (1960, first edition), p. 40 contains an account reported by Werner Heisenberg of a meeting held in June 1927 (Pauli, Heisenberg, and Niels Bohr), whose aim was to reconcile their divergent views, particularly Niels Bohr's dissatisfaction with the inconsistency between complementarity and the Uncertainty Principle as presented in the published article.

but fundamental epistemological challenges. As argued by Bohr (1983), the impossibility of a complete simultaneous description in classical terms requires a reformulation of the conditions of intelligibility of the theory. In this sense, the letter analyzed in this article may be interpreted as a moment prior to the full articulation of these issues, in which such problems still appear formulated predominantly in operational terms, while already pointing toward the epistemological tensions that would later be thematized more systematically in the Solvay debates.

The transition from the letter to the article reveals an epistemological shift: in the published text, operational arguments are reorganized and elevated to the status of a general principle, applicable independently of specific experimental details. This discursive adjustment facilitates the interpretation of uncertainty as a structural feature of the theory and opens the way for later ontologically oriented readings. Historical analysis suggests caution, however, since such interpretations are neither necessary nor fully supported by Heisenberg's original formulations.

The episode analyzed here makes it possible to identify a recurring dynamic in the History of Science, in which principles often originate as local heuristics, linked to concrete problems, and acquire a more abstract status through processes of conceptual reformulation, rhetorical selection, and communal validation. Private correspondence, seminars in Copenhagen, and public debates culminating in Solvay (1927) together constitute this process of stabilization.

From a historiographical perspective, the analysis reinforces approaches that conceive science as an argumentative and collective practice, in which concepts are negotiated, tested, and reformulated within specific institutional contexts. In this way, the February 1927 letter demonstrates that the construction of the Uncertainty Principle cannot be adequately understood without considering the role of critical dialogue, such as the interaction between Heisenberg and Pauli, and the centrality of epistemological concerns in the development of Quantum Mechanics. Moreover, the study recommends caution regarding anachronistic readings that project onto early texts meanings that were only consolidated later. Recognizing the provisional and situated character of these formulations contributes to a more precise understanding of both history of Quantum Mechanics and the nature of scientific principles.

From the standpoint of Physics Education, the results of this analysis suggest the relevance of approaches that integrate History and Philosophy of Science into the discussion of fundamental concepts of Quantum Mechanics. Reconstructing the genesis of the Uncertainty Principle based on primary sources allows for the problematization of simplified interpretations and promotes a more critical understanding of the limits of classical descriptions. Didactic sequences that incorporate historical documents, such as the letter analyzed here, may foster the development of scientific argumentation, reflection on the Nature of Science, and a deeper understanding of the role of experimentation and language in the construction of physical knowledge.

VI. Final Considerations

Considering the centenary of the 1927 paper, this study has proposed a historical-epistemological reconstruction of the genesis of the Uncertainty Principle based on a commented analysis of the correspondence between Werner Heisenberg and Wolfgang Pauli. By taking as its central source the letter of February 1927 and comparing it with the article published a few weeks later, the study sought to demonstrate that the principle did not emerge as an immediate deduction from mathematical formalism, but rather as the result of a progressive process of conceptual elaboration, grounded in operational reflections on measurement, observability, and the scope of classical categories.

The analysis situated the letter within the intellectual context of Quantum Mechanics between 1925 and 1927, a period marked by tensions among competing theoretical programs and debates concerning the physical meaning of fundamental quantities. Within this scenario, it was shown that Heisenberg's reflections initially take on a heuristic character, in which relations of indeterminacy appear associated with conditions of observation and with the limitations of experimental practice. The examination of the conceptual cores highlighted the centrality of operational definitions, the critique of the notion of electronic orbit, and the constitute role of measurement in quantum description. These elements, still formulated in an exploratory manner in the letter, are reorganized in the 1927 article, in which uncertainty acquires the status of a general principle. This transformation does not correspond to a conceptual rupture, but rather to a process of selection, refinement, and discursive formalization.

The identification of an effective epistolary exchange between Heisenberg and Pauli in the days immediately preceding the publication of the 1927 paper reinforces the dialogical and collective character of this genesis. Although Pauli's reply has not been preserved, the available documentary evidence suggests that his questions and objections formed part of the final process of conceptual elaboration of the Uncertainty Principle, confirming the role of scientific correspondence as an intermediate space for the construction of knowledge. This private dialogue is articulated, a few months later, with the public discussions of the Fifth Solvay Conference, in which the newly formulated principle was subjected to intense conceptual scrutiny. The rigorous debates between Albert Einstein and Niels Bohr, concerning the status of uncertainty, the completeness of the theory, and the role of observation, demonstrate that the consolidation of the Uncertainty Principle did not result from immediate consensus, but from a prolonged process of argumentation, critique, and conceptual negotiation. Taken together, the epistolary exchange, the seminars in Copenhagen, and the Solvay debates exemplify the historical dynamics through which fundamental concepts of Modern Physics emerge, are publicly tested, and become stabilized within the scientific community.

From a historical-epistemological perspective, this study contributes to a more precise understanding of the Uncertainty Principle by replacing overly formalist retrospective readings with an approach that emphasizes its processual, argumentative, and situated character.

Quantum Mechanics is, certainly and justifiably, a theory constructed collectively and one that has proven extraordinarily successful in describing physical reality at the microscopic level. However, even this remarkable success has not prevented discomfort among realist scientists and philosophers regarding the strongly instrumental character through which its results have often been, and continue to be, interpreted in various scholarly contexts. As an emblematic example of this situation, John Bell wrote a vigorous and provocative article, published in 1990 for a conference held in Erice, Italy (August 4-12, 1989), entitled *Against Measurement*, in which he presents a wide-ranging list of terms and concepts commonly employed in excellent textbooks on Quantum Mechanics, identifying *measurement* as the most problematic[18] among them. This situation of conceptual ambiguity, highlighted by Bell in relation to a theory that at the time had already been formulated for more than sixty years, appears to persist even as it approaches its centenary.

In this sense, the analysis proposed here not only contributes to the historiography of Quantum Mechanics but also offers support for a more epistemologically rigorous approach to the teaching of its foundations. To reinforce this recommendation, that complex and enduring issues should be embraced as challenges for a scientific education open to new perspectives, Bell concludes his article by invoking Max Weber, as an exercise in what may be understood as a necessary utopia[19], one of the most important functions of education, and especially of science education.

References

BACCIAGALUPPI, G.; VALENTINI, A. **Quantum Theory at the Crossroads**: reconsidering the 1927 Solvay Conference. Cambridge: Cambridge University Press, 2009.

BELL, J. S. Against Measurement. **Physics World**, p. 33-40, 1992.

BELLER, M. **Quantum dialogue:** the making of a revolution. Chicago: University of Chicago Press, 1999.

BOHR, N. Discussion with Einstein on epistemological problems in atomic physics. *In*: WHEELER, J. A.; ZUREK, W. H. (Org.). **Quantum Theory and Measurement**. Princeton: Princeton University Press, 1983. p. 200-241.3

[18] "Here are some words which, however legitimate and necessary in application, have no place in a *formulation* with any pretension to physical precision: *system*, *apparatus*, *environment*, *microscope*, *macroscopic*, *reversible*, *irreversible*, *observable*, *information*, *measurement*. […] On this list of bad words from good books, the worst of all is 'measurement'". (BelL, 1990, p. 34).

[19] "...All historic experience confirms that men might not achieve the possible if they had not, time and time again, reached out for the impossible" (Max Weber apud BelL, 1990, p. 40).

BUNGE, M. **Epistemologia**: curso de atualização. 2. ed. Tradução: Claudio Navarra. São Paulo: T. A Queiroz Editor, 1987.

CAMILLERI, K. Heisenberg and the interpretation of quantum mechanics: the physicist as philosopher. **Studies in History and Philosophy of Modern Physics**, Oxford, v. 40, n. 3, p. 290-302, 2009.

CASSIDY, D. C. Beyond uncertainty: Werner Heisenberg and the dynamics of scientific change. **Physics in Perspective**, Basel, v. 22, n. 1, p. 1-29, 2020.

CASSIDY, D. C. **Uncertainty:** the life and science of Werner Heisenberg. New York: W. H. Freeman, 1992.

FREIRE JR., O.; PESSOA JR., O. (Orgs.). **Teoria quântica:** estudos históricos e implicações culturais. Campina Grande: EDUEPB, 2011.

HOWARD, D. Who invented the "Copenhagen interpretation"? A study in mythology. **Philosophy of Science**, v. 71, n. 5, p. 669-682, 2004.

JAMMER, M. **The philosophy of quantum mechanics:** the interpretations of quantum mechanics in historical perspective. New York: John Wiley & Sons, 1974.

KRAGH, H. **Quantum Generations:** A History of Physics in the Twentieth Century. Princeton: Princeton University Press, 1999.

MARTINS, R. A. **Introdução à história e filosofia da ciência**. São Paulo: Livraria da Física, 2006.

MEHRA, J.; RECHENBERG, H. **The historical development of quantum theory**. The completion of quantum mechanics 1926-1941. New York: Springer, 2000. v. 6

MONTEIRO, M. A.; NARDI, R. História e filosofia da ciência no ensino de física moderna. **Revista Brasileira de Ensino de Física,** São Paulo, v. 39, n. 1, e1403, 2017.

OSTERMANN, F.; RICCI, T. Interpretações da Mecânica Quântica no ensino de física. **Revista Brasileira de Ensino de Física**, São Paulo, v. 26, n. 1, p. 15-24, 2004.

PAIS, A. **Inward bound:** of matter and forces in the physical world. Oxford: Oxford University Press, 1982.

PEDUZZI, L. O. Q. Sobre a utilização didática da História da Ciência. **Caderno Brasileiro de Ensino de Física**, Florianópolis, v. 28, n. 3, p. 426-443, 2011.

PESSOA JR., O. **Conceitos de física quântica**. 2. ed. São Paulo: Livraria da Física, 2006.

VIDEIRA, A. A. P. História e filosofia da ciência: campos interdisciplinares. **Scientiae Studia**, São Paulo, v. 11, n. 2, p. 351-368, 2013.