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Beyond Ideology: Epistemological Foundations of Vladimir Fock's approach to Quantum Theory*

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Summary: Vladimir Fock was a Soviet theoretical physicist who, from the 1930s, worked to prove that modern physics was compatible with the Marxist philosophy of dialectical materialism. In 1957, he went to Copenhagen, and a dispute over the interpretation of quantum mechanics began with Niels Bohr. Fock later claimed that he had found points of convergence with his Danish colleague, most of them concerning issues of wording and recognition of the reality of the world independently of our mind. It led to a specific narrative among historians of physics on Fock and his interpretation of quantum mechanics: The Soviet physicist is often described as a member of the Copenhagen school that contributed to the rapprochement of the Soviet philosophy of physics with the ideas of complementarity in stripping away the positivism in its formulation. Our contribution aims to show that this ideological dimension was only one aspect of reality. Returning to the foundations of Fock's epistemology of physics, we argue that he relied on the principles of antireductionism and scientific realism to develop an interpretation of the theory that sought to overcome Bohr's approach and that the differences between the two men cannot be reduced to mere questions of formulation.

Keywords: Vladimir Fock, quantum mechanics, interpretation of quantum mechanics, antireductionism, scientific realism, dialectical materialism, Niels Bohr.

1. Introduction

Vladimir Fock was an essential figure in Soviet theoretical physics. Elected Academician in 1939, he contributed during his career at Leningrad State University to various fields such as mathematical physics, theoretical optics, physics of continu-

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ous media, the theory of gravitation, and quantum physics.[1] For the last one, he accompanied its creation and its development with several significant contributions.[2] Notably, in 1926, he independently derived the Klein-Gordon equation, a relativistic generalization of the Schrödinger equation for spinless particles.[3] In 1930, he contributed to the Hartree-Fock method of approximation for the determination of the wave function in many-body problems.[4] He also developed in 1932 the so-called Fock space, a mathematical tool used to describe quantum states in situations in which the number of particles is not fixed.[5] It was one of the many works that contributed to his international recognition.

Less known to the community of physicists, Fock worked, from the 1930s, to prove that modern physics was compatible with the Marxist philosophy of dialectical materialism—at the time an essential component of the state ideology in the USSR—to which he had adhered with conviction.[6] As an indirect consequence, his 1957 visit to Copenhagen gave rise to a dispute with Niels Bohr on the interpretation of quantum mechanics. This episode contributed to a specific narrative among historians of physics on Fock's contribution to the interpretation debate. Max Jammer, who in 1974 published a book that would become the cornerstone of historical studies on the interpretation problem, *The Philosophy of Quantum Mechanics*, introduced Fock as a member of the "Russian branch" of the Copenhagen school who "paved the way for the rapprochement of Soviet philosophy of physics with the ideas of complementarity."[7] Indeed, after the 1957 meeting, the Soviet physicist claimed in the USSR that Bohr had approached the correct materialistic treatment of quantum mechanics. For his part, Loren Graham, the main contributor to the historiography of Fock's interpretation of quantum mechanics, once described the physicist as follows:

> In quantum mechanics, Fock may be correctly defined as a follower of Bohr's Copenhagen interpretation if one defines the Copenhagen Interpretation in terms of its minimum rather than its maximum claims. … Fock wrote that he entered into philosophical discussion of quantum mechanics because he believed it was possible to agree with Bohr's scientific approach without accepting his philosophical conclusions. He decided that he would strip away the "positivistic coating" on Bohr's formulation.[8]

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[1] Smirnov and Vreden-Kovetskoj 1956; Vladimirova 2012. These biographical works, very factual, are in Russian. English readers can consult the preface to Fock's *Selected works* in Faddeev et al. 2004. See also the secondary literature dealing mainly with the theory of gravitation and quantum physics: Graham 1982; Graham 1987, esp. 337–343, 367–378; Gorelik 1993; Freire 1994; Martinez 2019.

[2] Fock's major articles on quantum theory were republished as a single volume in English in 2004: Faddeev et al. 2004.

[3] Kragh 1984.

[4] Martinez 2017.

[5] Kojevnikov 1988.

[6] Unfortunately, there is no room in the present article to open a discussion on Fock's adhesion to dialectical materialism. It must be taken for granted, and various contributions testify to the sincerity of the Soviet physicist as to the influence of Marxist philosophy on his work: Graham 1982; Graham 1987, esp. 337–343, 367–378; Gorelik 1993; Martinez 2019.

[7] Jammer 1974, on 248–250.

[8] Graham 1987, on 337.

To sum up, the main secondary literature on Fock and quantum mechanics contributed to the diffusion of an image of the Soviet physicist as a member of the Copenhagen school who had mainly contributed to the debate on quantum mechanics by fighting the positivist wanderings of its formulation. Consequently, some people even considered the Leningrad physicist as a henchman of the Soviet regime in the interpretation problem of modern physics.[9]

We do not want to refute the judgments of Jammer and Graham. They reveal essential facets of the debate. However, we also regret that their presentations of the Soviet physicist primarily emphasize aspects related to the ideological dichotomy between positivism and materialism, the latter being regarded as a doctrinal system of ideas in the USSR. Indeed, we do consider that the dispute between Fock and Bohr contained important information about what the Leningrad physicist thought the true meaning of quantum mechanics was, and that it was physically more significant than merely rejecting the "positivist coating" of the Copenhagen school. It is true that some of these aspects have been put forward by the historians mentioned above, notably Graham, who has carefully approached the variations of Fock's thinking at different stages of his career.[10] Also, Olival Freire Jr. later pointed out—in a mainly contextual study of the 1957 dispute—that Fock's criticisms of Bohr were not only questions of terminology but also epistemological questions.[11] Unfortunately, the true nature of these questions, their origin and structure as fundamental components of Fock's understanding of modern physics, have never been thoroughly studied. As a result, his contributions to the interpretation of quantum mechanics remained in the shadows and misunderstood. The present article intends to fill this gap and to examine the essential content of Fock's epistemology, its regularities, in order to reconsider his position on quantum mechanics and his debate with Bohr.

In this direction, we will pay little attention to sociocultural aspects because they are not essential to understanding the originality of Fock's interpretation of quantum mechanics. Moreover, as regards the influence of dialectical materialism on the thought of the Soviet physicist, we will confine ourselves to a few observations in conclusion. Indeed, we want to move away from a discourse that places too much emphasis on Fock's approach as mere ideological militancy. We consider that the Soviet physicist incorporated this influence into his daily practice of science in the form of two main epistemological principles that were actually not

[9] Peter Freund notably gave one of the most caricatural descriptions of the events: "Something *was* done, and the way the Copenhagen interpretation was reconciled with Marx very much resembles the way the Iranian ayatollahs reconciled prostitution with the Koran. The ayatollahs ruled that the Koran specifically allows temporary marriages and that therefore a male visitor to a 'house of chastity' … is there to enter into a temporary marriage … Marx was taken to the Copenhagen altar in much the same spirit. The only surprise was that the ayatollah officiating at Marx's house of chastity, was none other than V. A. Fock, one of the greatest Russian theoretical physicists of the twentieth century." See: Freund 2007, on 78–79.

[10] Graham 1987, esp. 320–343; Graham 1988. More comments on Graham's approach to Fock's work in section 3.1.

[11] Freire Jr. 1994, esp. 71–72.

limited to Marxist circles: antireductionism[12] and scientific realism. For Fock, dialectical materialism was primarily a philosophy with valuable epistemological content and not an ideology. In 1998, Peter Galison and Andrew Warwick argued that understanding science as a cultural activity "means learning to identify and to interpret the complicated and particular collection of shared actions, values, signs, beliefs and practices by which groups of scientists make sense of their daily lives and work."[13] Thus, in the spirit of the present special issue, we wish to emphasize that Fock, the main theoretical authority of the Leningrad School of Theoretical Physics, developed a primarily epistemological quantum culture and identity.

The first section of this article will focus on Fock's epistemology, considering respectively antireductionism, scientific realism, and their combination under the concept of physical rigor. The second section will be devoted to the interpretation of quantum mechanics by the Soviet physicist. After exposing its characteristics, we will discuss its actual distance from Bohr's approach.

2. Fock's Epistemology

2.1. Antireductionism

Fock developed his antireductionist position most clearly in a Russian article published in 1936 by *Uspekhi fizicheskikh nauk*, "Printsipial'noye znacheniye priblizhennykh metodov v teoreticheskoy fizike" (The Fundamental Significance of Approximate Methods in Theoretical Physics).[14] This work, initially presented at a meeting of the mathematical group of the USSR Academy of Sciences on 21 May 1936, has proved to be a true article of epistemology dealing with the question of intertheoretical relations. The Soviet physicist mentioned successively quantum electrodynamics, quantum mechanics, the Hartree-Fock method, the perturbations method, the old Bohr theory, and finally classical mechanics, to discuss "the process of the formation of notions in the opposite direction to the historical development of a theory."[15] He developed an approach that can be defined as a diachronic epistemological antireductionism.[16] "Epistemological," as Fock was interested in the state of knowledge, our modes of representation of the world. He considered concepts and theories. "Diachronic," or homogeneous, as Fock was referring to the relations between theories concerning the same object of study, the motion of matter.

To explain how Fock expressed an antireductionist point of view in this article, two points need to be clarified. First, the Leningrad physicist conceived theories as applying to various sets of phenomena. He did not consider quantum mechan-

[12] The term pluralism can be considered more elegant. However, our preference for antireductionism is to indicate that, in this case, this philosophical position has been forged in Marxism, a customary philosophy of critical and opposition discourse.
[13] Galison and Warwick 1998, on 288.
[14] Fock 1936b. Also in: Faddeev et al. 2004, 389–402.
[15] Fock 1936b, on 1071.
[16] Reductionism—as well as its opposite, antireductionism—is a philosophical position which can be approached in different ways. To specify its use by Fock, we rely on clarifications made by Ayala and Andersen: Ayala 1974; Andersen 2001.

ics as a theory of the principles of quantization but as a theory of the dynamics of phenomena for which physicists cannot neglect the Planck constant. Secondly, Fock introduced a form of hierarchy among the theories that can only be understood on the basis of the following postulate: "The equations of theoretical physics can never be absolutely accurate: one always has to ignore this or that secondary factor while deriving them … any physical theory, any physical notion, is, as a matter of fact, an approximation."[17] A scale of complexity thus governed the hierarchy between theories, the particular ones being simplified from more general ones including them as special cases: "The transition to a simplified theory means, in reality, the usage of one or another approximate method based on the possibility to ignore one or another secondary factor, one or another small quantity in the problem."[18]

One of the most fundamental notions of antireductionism is emergence.[19] It expresses the possibility of appearances of properties, concepts, objects, etc., whose integral knowledge is irreducible to its fundamental parts. Fock never made explicit reference to the philosophical concept of emergence, but a parallel may be made with his approach to modern physics in 1936. If more general theories are considered the most fundamental representations of nature, one could conceive that epistemological emergence would be achieved if physical approximations gave rise to new notions that are inexplicable within the framework of these more general theories.[20] And this is precisely the direction that the Soviet physicist was taking in addressing the historical development of quantum theory. First, Fock considered that physicists used to pay attention "to the acquisition of new concepts during the generalization of a theory" and neglected the "denial of old ones."[21] He wanted to argue that, in the process of approximations of theories, "at each simplification, at each transition to a more particular theory newer and newer physical notions arise."[22] Secondly, in various cases, Fock was explicit on the idea that such notions were meaningless in more general theories, and he pointed out their specificities in the theoretical framework of their appearance.[23] Besides, he also discussed approximation processes that cause changes in physical laws. Most notably, the Soviet physicist unequivocally declared that "the laws of quantum mechanics lead to the conclusion of the impossibility of an objective description of the detailed behavior of physical processes", while in classical mechanics "the new (however, historically old) physical [notion] of objective processes" comes into play.[24] Both characteristics—inexplicable notions in more general theories and modification of the physical laws by approximation processes—argue in favor of a form of epistemological emergence within the physical sciences.

[17] Fock 1936b, on 1071, 1082.
[18] Fock 1936b, on 1071.
[19] For a discussion of the concept of emergence see, e.g.: Kim 2006; Kistler 2007.
[20] For considerations on epistemological emergence in intertheoretical relationships within the physical sciences, see: Batterman 2002.
[21] Fock 1936b, on 1070–1071.
[22] Fock 1936b, on 1071.
[23] Fock 1936b. It was the case for the notion of simultaneity in special relativity that Fock used as a preamble example (esp. 1071), for the notion of mass in nuclear physics (esp. 1072) and for the notion of the state of an electron (esp. 1080).
[24] Fock 1936b, on 1077, 1082.

The arising concepts in less general theories had for Fock a fundamental value for physics; for example, the notion of the state of individual electrons in an atom, although absent in quantum mechanics—which only provides knowledge of the state of the whole system—is essential to explain the structure of Mendeleev's periodic table.[25] Thus, the initial hierarchy introduced by the Soviet physicist in his 1936 article did not necessarily imply a qualitative judgment on the theories. A complete description of nature was permitted only by the conjunction of all the different notions within the scientist's reach. A combination of theories, related to one another by approximation relations, governed science; these theories did not wholly overlap because of the various concepts arising within them. Although Fock was not systematic in his philosophical approach, in 1936 he clearly developed an antireductionist conception of modern science.

This position had essential consequences for scientific practice. In particular, according to Fock, the formulation of a physical theory must be accompanied by a strict evaluation of its scope, as well as that of the various concepts used: "That is why to start to formulate such a theory, first of all, it is necessary to establish what are [the] neglects [of the approximation] and what are the limitations of applicability of basic physical notions operated by this theory."[26] In this direction, he attributed a major role to mathematical inequalities:

> The validity of given approximate methods … can be estimated using standard mathematical inequalities, which characterize the negligibility of the quantities omitted in the situation. However, this "error evaluation" in the common sense gives at the same time the criteria of applicability of the physical notions connected with this approximate method. Thus, a more difficult logical, or perhaps philosophical question concerning the applicability of some physical notions acquires here a concrete mathematical expression.[27]

The Heisenberg indeterminacy relations, giving the limit of applicability of classical mechanics, then constituted at the time the most egregious example of mathematical inequalities defining the scope of a theory.

2.2. Scientific Realism

In 1936, Fock was also responsible for the translation into Russian of the article by Albert Einstein, Boris Podolsky, and Nathan Rosen, known as the EPR paradox, and of Bohr's response.[28] Einstein and his colleagues refuted the completeness of quantum mechanics, that is, the view that the wave function would provide a complete description of physical reality.[29] This question of physical reality

[25] Fock 1936b, esp. 1080.
[26] Fock 1936b, on 1072. Fock was delivering general comments on "the most general theory at the present period of the development of physics," quantum electrodynamics. It should be taken as general methodological considerations, as it was the first in his process of sequential simplification of theories.
[27] Fock 1936b, on 1071.
[28] Einstein et al. 1935; Bohr 1935; Fock 1936a.
[29] We do not intend to detail physics and philosophy beyond this statement, and we invite the reader to consult, among others, the following references: Hooker 1972; Selleri 1988; Murdoch 1994; Fine 1996.

was of importance, especially since the three men claimed a scientific realist approach to science, which was spelled out in an article entitled "Einstein Attacks Quantum Theory," published in the *New York Times* on 4 May 1935:

> Physicists believe that there exist real material things independent of our minds and our theories. We construct theories and invent words (such as electron, position, etc.) in an attempt to explain to ourselves what we know about our external world and to help us to obtain further knowledge of it. Before a theory can be considered to be satisfactory it must pass two severe tests. First, the theory must enable us to calculate facts of nature, and these calculations must agree very accurately with observation and experiment. Second, we expect a satisfactory theory, as a good image of objective reality, to contain a counterpart for every element of the physical world. A theory satisfying the first requirement may be called a correct theory, while, if it satisfies the second requirement, it may be called a complete theory.[30]

Fock added an introduction to his translation of the articles from the EPR debate.[31] There, he defended Bohr's position on the completeness of quantum mechanics, although, on the theme of realism, he proved at different stages of his career that he shared convictions similar to those of Einstein.[32] Indeed, the Soviet physicist also believed in the existence of real material things independent of our minds and our theories. However, if Fock and Einstein shared the ontological thesis of scientific realism, we can observe some divergences about the epistemological thesis and about how science can provide us with a representation of the outside world. While the author of the theory of relativity was focusing on the "counterpart for every element of the physical world," the Soviet physicist thought that "quantum mechanics [was] truly engaged in the study of the objective properties of nature, in the sense that its laws [were] dictated by nature itself and not by human imagination."[33]

To better understand Fock's position, one must examine his approach to mathematical formalism. In 1932, he published the first textbook on quantum mechanics in Russian language, *Nachala kvantovoy mekhaniki* (Principles of quantum mechanics). In the introduction, the Soviet physicist explained the fundamental character he attributed to mathematics for the description of nature:

> To identify and describe new concepts and properties of physical objects, i.e., for the formulation of the new laws of nature, it was necessary to create a new language … Speaking of language, we have mainly in mind the mathematical language.[34]

Later, in 1951, in a critique of an approach that viewed the mathematical formalism of quantum mechanics as purely symbolic, Fock clearly stated a realist interpretation of the problem: "Mathematics always works with symbols, but since in physical theories these symbols admit some physical interpretation, they cease to

[30] Max Jammer reproduced this article excerpt in Jammer 1974, on 189. He attributed its preparation to Podolsky.

[31] Fock 1936a.

[32] If Fock never explicitly developed his position towards realism, an overview of his epistemological approach to this question can be found in: Graham 1987, esp. 337–343, 367–378; Gorelik 1993.

[33] Fock 1936a, on 437.

[34] Fock 1932, on 12.

be abstract symbols and reflect reality."[35] Or, by symmetry, reality has a structure that can be described by mathematical theories. This relation to mathematics underpinned Fock's epistemological position in favor of scientific realism.

Gennady Gorelik, in an analysis of Fock's approach to the theory of relativity, suggested that "one could, with some imagination, recognize something close to Platonic (true mathematical) idealism."[36] However, in Fock's work there is no such thing as a reification of immaterial things, nor a Realm of Ideas. The Soviet physicist was primarily interested in the "physical objects" described by the mathematical formalism of a theory. Thus, we want to argue that this physical dimension calls for Fock to be considered primarily as a materialist, and not a Platonist, in the sense that materialism holds that everything is composed of matter and that, fundamentally, all phenomena are the result of material interactions.[37] Such a philosophy is traditionally opposed to that of idealism which, simply speaking, asserts that reality, or reality as humans can know it, is fundamentally mentally constructed, or otherwise immaterial. Einstein's realist claim in the EPR paradox, despite the assertion of the existence of real material things independent of our thoughts, mentioned constructed theories and invented words to explain to us what we know about our external world. Consequently, it opened the door to idealism. Fock, on the other hand, rejected idealism by considering that physical laws were dictated by nature and by approaching mathematical formalism as a direct reflection of material reality.

As a result, Fock's reflections on mathematical formalism were at the basis of his approach to modern theories in physics. As early as 1927, in his first Russian publication devoted to quantum mechanics, Fock stressed that in order "to understand Schrödinger's theory, it is *essential* to become familiar with the basic rules of mathematical formalism in which its concepts [energy levels, spectral line intensities] are treated."[38] Such an assertion is trivial, but we want to underline that it was the opening of a recurrent turn of phrase throughout Fock's career, which aimed to juxtapose the mathematical apparatus of a theory to its conceptual apparatus, to determine the physical meaning of the former.

This concern in Fock's career is sharply illustrated by a talk entitled "Predel'nyye zadachi teorii kvantov" (Extremal problems in quantum mechanics) given by the physicist in 1930.[39] By "extremal problems," we must understand the mathematical approach to quantum mechanics, the theory of linear operators. Thus, the subject of Fock's presentation was: "[T]he relations between the mathematical theory of extremal problems and the physical theory of quanta."[40] In other words, the Leningrad physicist confronted a mathematical theory, that of linear operators, and a physical theory, that of quantum mechanics, to demon-

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[35] Fock 1951, on 8.
[36] Gorelik 1993, on 325.
[37] For a complete account of materialism in a historical perspective see, e.g., Charbonnat 2013.
[38] Fock 1927, on 111. Emphasis added.
[39] Fock 1935. We are aware of this talk through the *Selected Works* of Fock, edited in 2004 (Faddeev et al. 2004). It seems however that an error has slipped into the referencing of its publication, announced in volume 15 of the journal *Uspekhi fizicheskik nauk*. Our researches in the database of this journal proved unsuccessful.
[40] Fock 1935, on 381.

strate their adequacy. Following a strict analysis of the physical meaning of mathematics used in quantum theory, Fock concluded that he had shown "that a certain physical notion corresponds to each notion from the mathematical theory of linear operators."[41] To formalize such a result, he even proposed a "dictionary to translate the notions from the mathematical language to the physical one:"[42]

Table 1

Mathematics	Physics
Linear operator L	Physical quantity λ
Characteristic numbers [eigenvalues] λ'	Values taken by the physical quantity
Fundamental function for the characteristic number [eigenvalue] λ	State of a mechanical system for which λ equals λ'
Commutativity of operators	Simultaneous observability of physical quantities
Absolute value squared $\lvert\psi\rvert^2$ of the wave function	Probability density
Normalization $\int \lvert\psi\rvert^2 dV = 1$	Total sum of probabilities equals 1.
Orthogonality $\int \bar{\varphi}\psi dV = 0$	Incompatibility of states φ and ψ
Completeness of the system of fundamental functions $\psi(r, \lambda')$	Values $\lambda = \lambda', \lambda''$ are the only possible ones.
Integral $\int \bar{\psi} L \psi dV$	Expectation value of quantity λ in state ψ
Square of the decomposition coefficient of $\varphi(r)$ by $\psi(r, \lambda')$, $\lvert\int \bar{\psi}(r, \lambda')\varphi(r)dV\rvert^2$	Probability of the equality $\lambda = \lambda'$ in the state φ
Normalization for the continuous spectrum	Finite probability of the inequality $\lambda' < \lambda < \lambda' + \Delta\lambda$

This "dictionary" is exemplary to highlight Fock's desire to reveal the true physical meaning of the mathematical formalism of a theory. Mathematics being a reflection of reality, it should be able to be converted into purely physical concepts, and physicists should strive to achieve this conversion. Therefore, one would not be surprised to see the Leningrad physicist involved in the debates on the interpretation of modern physics. And in reality, they became a big part of his work starting in the mid-1930s.[43] To convince ourselves of such a link, we can take a look at the second edition of Fock's quantum mechanics textbook, published posthumously in 1976.[44] As for the first edition, it was a real plea for a systematic revelation of the physical meaning of the mathematical formalism, but the Soviet physicist also directly asserted that the interpretation of the theory depended on this approach:

> The use of this apparatus [the theory of linear operators] in quantum mechanics made it possible to give a theoretical explanation of some fundamental properties of matter … But more than that—and this is no less important to us—the physical in-

[41] Fock 1935, on 386.
[42] Fock 1935, on 386–387.
[43] It is clear that one of the main reasons for Fock's active participation in the interpretative debates was the defense of modern physics against ideological attacks in the Soviet Union. See: Vizgin 1999. However, we argue that he was epistemologically predisposed to deal with such a situation.
[44] Fock 1976.

> terpretation of the mathematical concepts used in quantum mechanics leads to a number of profound and principled conclusions.[45]

These "profound and principled" conclusions were then the basis of his discourse on the interpretation of quantum mechanics.

2.3. Physical Rigor

Before detailing Fock's interpretation of quantum mechanics, it seems necessary to summarize the implications of the Soviet physicist's epistemology in terms of scientific practice. In this direction, one can consider the fundamental boundary that he drew between mathematics and theoretical physics. This was made especially explicit in a presentation he made on 12 October 1940 at Leningrad State University, on the book *Mathematische Grundlagen der Quantenmechanik* (Mathematical Foundations of Quantum Mechanics) published in 1932 by John von Neumann.[46] The latter, a Hungarian-American mathematician, is today mainly known for his role in the axiomatization of quantum mechanics.[47] One of its most successful expressions was the work discussed here by Fock. Fock's conclusion of the presentation, a comment on his conception of the work of the physicist and the mathematician, is of particular interest to us:

> *Morality.* The difference between the physicist and the mathematician.
> The physicist is interested in the result. He needs a result to be true, and the rigor of reasoning is secondary to him.
> The mathematician is interested in reasoning. He needs rigorous reasoning; a rigorous result is necessarily obtained from premises. If the premises are true, the result is true—but for a mathematician, it does not matter.
> Neumann is a typical mathematician: everything from him is strictly rigorous, but nothing is true.[48]

Here, "true" must be understood from a realistic perspective. For Fock, the premises were true only if they reflected the reality of the outside world. The Soviet physicist, therefore, implicitly contrasted a concept of mathematical rigor with another concept of physical rigor.

We find a preliminary definition for the latter in his 1936 article dealing with the fundamental significance of approximate methods in theoretical physics: "The correct account of all really essential factors for a physical problem is called

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[45] Fock 1976, on 19.
[46] "O knige Neyman," Archive of the Russian Academy of Sciences – St. Petersburg Branch, 1034-1-156. See also: von Neumann 1932.
[47] On von Neumann's contributions to quantum mechanics, see: van Hove 1958; Lacki 2000; Redei and Stoeltzner 2001.
[48] "O knige Neyman," Archive of the Russian Academy of Sciences – St. Petersburg Branch, 1034-1-156. Fock's criticism of von Neumann was particularly virulent. Before the final comment reproduced here, the Soviet physicist had already stated: "Almost everything [of what is said] in the physical part [of von Neumann's book] is either insignificant or false. The analysis of the measurement process is totally wrong. Remain true: the introduction of the statistical operator and the study of its simplest properties, although we can do without it, limiting ourselves to the wave functions and applying the theory of probabilities. … For the rest, it is about pure mathematics: the theory of the linear operators."

physical rigor."[49] Fock then added: "Physical rigor is necessary for solving physical problems as common mathematical rigor does for solving the problems of the analysis."[50] Such "necessity" implies that the Soviet physicist applied physical rigor to his scientific practice throughout his career. Our investigations on his epistemological approach to physics then help us to propose an attempt to reconstruct the different "essential factors" for physical rigor that Fock advocated for:

– The premises and results of a problem must reflect the reality of the outside world.
– The mathematical formalism used must have a clear physical meaning.
– The field of applicability of theories and concepts must be clearly defined.

To testify to the actual application of a concept of physical rigor based on these precepts, one can briefly examine some comments of Fock on the difficulties related to the development of quantum electrodynamics in the 1930s. The solution of the equation representing the evolution over time of the interaction between matter and an electromagnetic field gave rise to different terms for which a physical interpretation was difficult. Therefore, in his 1936 article on approximations, Fock believed that "to obtain minimal physical rigor here, one must give up a mathematical one," neglecting the problematic terms.[51]

The Soviet physicist developed this issue in 1937, in an article on the functional method in electrodynamics.[52] The essential factors for physical rigor mentioned above were then present all along with its developments. In the introduction Fock was particularly cautious about the basic assumptions and the range of phenomena treated by quantum electrodynamics, mentioning the various prerequisites for "a better approximation of reality."[53] However, as he regretted, the theory encountered difficulties due to the divergence of some integrals and to various mathematical difficulties which prevented the possibility "to obtain a rigorous solution of its equations."[54] Thus, after a general presentation of the mathematics used in the theory, Fock concluded as follows:

> As was mentioned in the Introduction, the basic equation of quantum electrodynamics can be solved only approximately. This equation does not account for the structure of material particles and their properties at rather high energies; therefore its accurate solutions hardly have a physical meaning. A more exact description of matter and radiation properties should be based on radically new ideas, and this is one of the main problems of the further development in theoretical physics.[55]

In other words, because it was unable to have a clear physical meaning, quantum electrodynamics did not reach physical rigor. A more accurate—realistic, according to Fock's requirements—description of the properties of matter and radiation required a completely new theory, based on original concepts with a broader field of application, including the structure of the material particles and their properties at rather high energies.

[49] Fock 1936b, on 1070.
[50] Fock 1936b, on 1070.
[51] Fock 1936b, on 1075.
[52] Fock 1937. For the English version, see: Faddeev et al. 2004, on 403–420.
[53] Fock 1937, on 110.
[54] Fock 1937, on 110.
[55] Fock 1937, on 124.

On the other hand, Fock did not hesitate to present quantum mechanics as a rigorous theory: "From the physical point of view this theory—quantum mechanics in its proper meaning—presents a closed logical scheme operating with notions defined sufficiently rigorously."[56] Thus, under the idea of physical rigor, the concepts of realism, physical meaning, and field of applicability were tools for Fock, not only to pose physical problems and discuss their results, but also to validate theories. Their role cannot be underestimated in the perspective of an interpretation debate.

3. Quantum Mechanics

3.1. Fock's Interpretation

In *Science, Philosophy, and Human Behavior in the Soviet Union*, Graham considered the temporal evolution of Fock's views on quantum mechanics.[57] In particular, he discussed the subtle differences between the positions of the Soviet physicist before and after World War II concerning the physical significance of the wave function.[58] The historian then linked this evolution to contextual issues, as part of a discussion also aimed at highlighting various aspects of the ideological and political dimensions of Soviet science. On the contrary, our approach exclusively claims to reconstruct Fock's epistemology and to put forward the specificities of his interpretation of quantum mechanics at the stage of his dispute with Bohr. In this direction, the temporal evolution of the Soviet physicist's views appears to be irrelevant, unlike the epistemological regularities of his thought. And in fact, if so far we have mainly referred to primary sources from the 1930s, we defend that throughout his career Fock acted as an antireductionist and a scientific realist, and that this epistemology was decisive in the postwar period.[59] It was the case not only during Fock's meeting with Bohr in Copenhagen in 1957, but also for the various publications where he detailed his position on quantum mechanics.

One of the most complete versions of Fock's postwar interpretation of quantum mechanics can be found in a small booklet published by the Leningrad State University in 1965, *Kvantovaya fizika i stroyeniye materii* (Quantum physics and structure of matter).[60] The same year, it was translated for its main parts in French and appeared as an article in the journal *Dialectica* under the title "La physique quantique et les idéalisations classiques" (Quantum physics and classical idealizations).[61] As this title shows, one of the greatest interests of this publication is that Fock discussed precisely the boundary between classical and quantum physics, thus revealing the antireductionist dimension of his approach. But instead of emphasizing the special character of quantum mechanics, as is usually

[56] Fock 1936b, on 1076
[57] Graham 1987, esp. 320–343.
[58] Graham 1987, esp. 323–324.
[59] We also defend that Fock's explicit criticism of Bohr in the 1950s was already germinating in the 1930s. This point, which deserves specific attention, will be the object of a future publication.
[60] Fock 1965a.
[61] Fock 1965b.

done in the scientific literature, he began by pointing at the specificities of the classical description of phenomena. He wished to make explicit the reasons why this latter possesses "particular features … which make it inapplicable to the atomic objects," arguing that it was "characterized by certain idealizations or abstractions."[62] The Soviet physicist notably distinguished two of them that he called "absolutization" and "detailization," both linked to the conditions of observation of physical phenomena.

The "absolutization" concerned the independence of the phenomenon studied in relation to its means of observation. For Fock, in classical mechanics:

> A physical phenomenon was treated as something that takes place for itself, and not as something that requires, to be perceived, specific well-defined means of observation. In other words, a phenomenon was considered not in relation to a given structural measuring apparatus, but, at most, in relation to a measuring apparatus whose movement is given (that is, in regard to a given system of reference).[63]

In consequence of this first abstraction, the "detailization" expressed the possibility to indefinitely specify the observation, modifying its conditions and combining the data obtained in order to know all the aspects of a single phenomenon. Theoretically, in classical mechanics, it should be possible "to conduct [an] experiment so that all aspects of the phenomenon are manifested at once and with unlimited precision."[64] Fock then associated with these abstractions the deterministic nature of classical physics, that is, the assumption that the unfolding of a phenomenon is uniquely determined by the initial state of the system and the laws of motion.[65]

For the Soviet physicist, the classical description of phenomena was then absolute, detailed, and deterministic. Nevertheless, he had also illustrated with the support of examples—the wave-particle duality of electrons and the spherical symmetry of the hydrogen atom—that this description, applicable with high precision to objects of macroscopic scale, has proved inapplicable to micro-objects such as the electron.[66] Concerned by the accurate definition of this inapplicability, Fock then proceeded with physical rigor, proposing to answer the following question: "[W]hat is the limit of applicability and what is the precision of the classical method of description?"[67] For this purpose, he focused on the role played by Heisenberg's indeterminacy principle. If Fock there followed the main trends in modern physics, it is interesting to note that he emphasized that this principle does not "set limits to our knowledge of nature."[68] The Soviet physicist did not consider the mathematical quantities Δx and Δp_x as "errors" or "inaccuracies." These terms would presuppose the existence of exact values for the quantities measured, which would not allow a precise measurement for an unknown reason. Such an interpretation would then have an unsatisfying physical meaning. For

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[62] Fock 1965b, on 225.
[63] Fock 1965b, on 225.
[64] Fock 1965b, on 226.
[65] Fock rejected the conclusion that everything that happens in nature can be determined in advance, leading to fatalism. He limited his reasoning to physical systems. See: Fock 1965b, esp. 226–227.
[66] Fock 1965b, esp. 223–225.
[67] Fock 1965b, on 230.
[68] Fock 1965b, on 232.

Fock, since the teaching of mathematical formalism was of a realistic nature, the Heisenberg inequalities were essentially the expression of an inexistence rather than a mere impossibility:

> In reality, the actual cause of the impossibility of measuring with precision lies in the nature of the particle, which does not admit of simultaneous localization in common space and in that of impulses [momenta], its essence being at once corpuscular and wave-like. In other words, if certain quantities or groups of quantities are not measurable, it is because their exact values do not exist.[69]

In this, Fock clearly stated that the limit of applicability of the classical description of physical phenomena did not mean the abandonment of a realistic depiction of nature. Absolutism, detailism, and determinism were not "a necessary premise, … given once and for all, for the scientific description of natural phenomena."[70]

An epistemological frontier has been established, and as a consequence of Heisenberg's indeterminacy principle, Fock recognized that one of the main characteristics of the quantum domain was that its study could not do without an intermediary: the measuring device. This necessity led to the need to reconsider the description of phenomena:

> By accepting, as the main element of the description of the behavior of an atomic object the result of its interaction with a classical apparatus, we are far from considering the object as "less real" than the apparatus, or from reducing the properties of the object to the properties of the device. We simply introduce the concept of *relativity to the means of observation*, which generalizes the well-known concept of relativity to a reference system.[71]

Later, in 1973, Fock discussed at length the concept introduced here.[72] He elevated the relativity to the means of observation to the rank of an epistemological principle of which "the role was particularly important during the period of creation [of the theory of relativity and quantum mechanics]; the analysis of the real possibilities of observation [having] helped to find the laws of nature which determine these possibilities and which are at the base of them."[73] By renouncing the classical description and addressing the thorny question of the description of phenomena, many thinkers might consider that Fock flirted dangerously with idealism. However, the circularity introduced in this last quotation shows that, for the Soviet physicist, the relativity to the means of observation was more than an epistemological principle. It should also be treated as an intrinsic property of the systems studied, excluding any form of subjectivity from the treatment of atomic phenomena.

In his 1965 article, Fock asserted that the means of observation must always be described according to classical methods. He was then explicit that the introduction of a measuring device of a classical nature, in order "not to exceed the limits of the possible" given by the inequalities of Heisenberg, leads to considering situa-

[69] Fock 1965b, on 231.
[70] Fock 1965b, on 229.
[71] Fock 1965b, on 234.
[72] Fock 1973.
[73] Fock 1973, on 327.

tions in which different aspects and properties of an object do not manifest together.[74] There is an incompatibility between external conditions for the quantum object to reveal itself under one or another of its different aspects. Fock considered that these aspects, which do not manifest themselves together, were complementary and proved that the abstraction of detailism was no longer possible. As a result, based on his realistic approach to the mathematical formalism of quantum mechanics and his interpretation of Heisenberg's indeterminacy principle, the Soviet physicist stated that "there is no sense to consider as simultaneous complementary properties. This is why the concept of 'wave-corpuscular dualism' is well founded and contains no internal logical contradiction."[75] In this, he affirmed the complementary nature of the atomic description.

Finally, Fock argued that the description of atomic phenomena required a new mathematical formalism:

> The new position of the problem of the description of physical phenomena … requires a mathematical formalism more developed and more complicated than that of classical physics which did not raise the question of means of observation and "absolutized" phenomena.[76]

This formalism, developed in the 1920s for quantum mechanics, accounts for the interaction of the atomic object with the measuring device and led to the conclusion that in the case of a statistical study on a fixed initial state, the results would take the form of a probability distribution. The Schrödinger equation, a linear partial differential equation that describes the wave function of a quantum-mechanical system, provides us with such a distribution.

To summarize, Fock opposed to the classical description an atomic description that was complementary, relative to the means of observation, and probabilistic. This was a real recognition of the observational dimension of the quantum mechanics. However, at this stage, our analysis is incomplete, as the Soviet physicist considered that the theory had another purpose. For him, quantum mechanics was above all a theory aimed at studying the reality of the outside world, and more particularly its constituent, matter. This was announced most forcefully in an article he published in 1957, after his meeting with Bohr:

> [T]he aim and purpose of investigation are not the instrument readings, but the properties of the atomic object. Such properties of atomic objects as charge, mass, spin, form of energy operator and the law of interaction with an external field are wholly objective and can be abstracted from the means of observation (from the instruments).[77]

In agreement with our comments on Fock's conception of the atomic description of phenomena, for which the measuring device was a central element, the realization of such abstraction was a real challenge. But the Soviet physicist was looking for a way to achieve it, if not completely, at least partially. From this ambition came the essence of the originality of his interpretation of quantum mechanics.

[74] Fock 1965b, on 233.
[75] Fock 1965b, on 234.
[76] Fock 1965b, on 237–238.
[77] Fock 1957a, on 646.

Most notably, Fock defended the need to think about the subdivision of experiments. He introduced this approach in 1951, and considered three different stages of the experiment: the preparation part, corresponding to the moment when the external conditions are fixed; the active, or intermediate, part, where the atomic phenomena take place; the recording part, where the measurement is processed.[78] As a materialist, the Soviet physicist wanted to valorize the active part, explaining that it "can occur in natural conditions," regardless of the measuring device or any human intervention.[79] In 1965, Fock refined his approach and used different terminology. The preparation part has become the "initial experiment," which "relates to the future."[80] It provided predictions, which could only be verified after the interaction of the system with a measuring device, during the recording part, or "final experiment," considered by Fock as a "verification process … which relates to the past."[81] The Soviet physicist then added that, for the same initial experience, it is possible to carry out final experiments of different types, and therefore relating to various quantities. Then, one can obtain, according to a statistical approach, the distribution of probabilities for each measurable quantity in the final experiment.

Compared to 1951, in 1965, Fock was no longer speaking of the active part of the experiment. Instead, he preferred to elaborate on the notion of "state of a system," the physical concept which, for him, carried all available information on the atomic objects, and that was directly associated with the wave function of an atomic system. The Leningrad physicist then took advantage of his subdivision of experiments to explain the physical meaning of the wave function and to clarify the notion of state in quantum mechanics. Indeed, in the mathematical formalism, it is obvious that it is the wave function that is capable of giving the distribution of probabilities for the final experience, whatever it may be, resulting from a given initial experiment; the wave function is the same for all physical quantities. Fock thus explained that it described the different "potential possibilities" for each type of final experience. In other words:

> Since the wave function provides the most complete description of the state of a physical system, it can be said that in quantum mechanics the state of a system is characterized by the virtually possible reactions of the system with the measuring devices.[82]

It is, therefore, the act of measurement that transforms the virtually possible for each physical quantity, the potential possibilities, into a *fait accompli*. By introducing this concept of potential possibility, Fock then asserted that the wave function contains not only a description of the properties of the physical objects but also of their behavior with respect to the means of observation.

Many philosophers of mathematics and physics would probably associate Fock's concept of potential possibility with Karl Popper's concept of "propensity"

[78] Fock 1951, esp. 6–7.
[79] Fock 1951, on 7. Fock notably mentioned later in the article (esp. 11) the radiation of atoms in the stars.
[80] Fock 1965b, on 236.
[81] Fock 1965b, on 236.
[82] Fock 1965b, on 239.

in a more general approach to probability theory.[83] The Austrian philosopher conceived probability as a physical propensity, the tendency of a given physical situation to obtain a result of a certain type. Such a given physical situation, which determines the outcome of an experiment, was considered by Popper to be "a set of generating conditions."[84] So, a set of generating productions has the propensity *p* to give a result *E*. It can be easily seen that Fock's "initial experiment" could serve to determine Popper's "set of generating conditions" and that the concepts of "potential possibility" and "propensity" could be merged. Both approaches were developed independently, but we can notably observe from Popper's considerations on probability and quantum mechanics that the same concern for scientific realism moved both men.[85] They understood probability as a real physical property of a physical system. In the case of Fock, it was the only possible physical meaning to give to a probabilistic equation such as that of Schrödinger.

In the process that led Fock to think about the interpretation of quantum mechanics using the notion of potential possibility, physical rigor was present all along. First of all, the Soviet physicist wanted the theory to be considered as a description of real atomic phenomena and not just as an analysis of observational situations. For this purpose, however, he had to recognize the fundamental nature of the interaction between atomic objects and measuring devices to describe the phenomena of the micro-world. But it was especially important because it resulted from this situation an epistemological frontier between the quantum and classical descriptions. For Fock, the theories were not reducible to each other. While classical physics was absolute, detailist, and deterministic, quantum mechanics required a description which was complementary, relative to the means of observation, and probabilistic. Then, the Leningrad physicist fully accepted that the new theory would include a completely innovative conceptual apparatus. To reveal it, guided by his scientific realism and his special attention to the mathematical formalism, he embraced the probabilistic nature of quantum mechanics and gave to the wave function the physical meaning of "potential possibility" which symbolized the originality of his approach. Not only did antireductionism and scientific realism shape his approach to physical problems, but they also influenced his interpretation of modern physics.

3.2. Actual Distance to Bohr

In conceiving the description of atomic phenomena as complementary, relative to the means of observation, and probabilistic, Fock had joined Bohr on the most fundamental aspects of his understanding of quantum theory. Thus, Jammer legitimately considered that the Soviet physicist had given "[o]ne of the most trenchant and acclamatory formulations of [the] relational version of complemen-

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[83] Popper 1957; Popper 1959.
[84] Popper 1959, on 34.
[85] Popper 1957. See also: Freire 2004; Howard 2012. However, it must be noted that Fock and Popper did not reach the same conclusions on quantum mechanics in particular, because their opinions diverged on the question of the specificities of the description of atomic phenomena.

tarity" defended by the Danish physicist.[86] Fock even proved his loyalty at different stages of the quantum debate in the Soviet Union. As already mentioned, in 1936, he took a stand for Bohr in the EPR debate.[87] Also, in 1961, he was responsible for the publication in the USSR of Bohr's collection of articles, *Atomic Physics and Human Knowledge.*[88] This set of criteria fully justifies Fock being considered as a true member of the Copenhagen school in the philosophy of quantum mechanics. However, it has also been shown that the Copenhagen interpretation is not a homogeneous view.[89] The existence of significant disagreements must not be irreversibly excluded and one cannot neglect that Fock's thought actually presented different specificities that also marked a form of independence. In reality, the Leningrad physicist was a fierce critic of Bohr in the 1950s, as evidenced by a 1951 article entitled "Kritika vzglyadov Bora na kvantovuyu mekhaniku" (Criticism of Bohr's views on quantum mechanics),[90] as well as their dispute in Copenhagen in 1957.

This 1957 dispute with Bohr gave rise to various publications in which Fock affirmed that Bohr had recognized the reality of the outside world, refusing to approach the interpretation problem as a positivist.[91] Also, the Soviet physicist claimed to have convinced his colleague to make changes to the formulation of his interpretation of quantum mechanics. Fock was indeed delighted with an article published in 1958, in which Bohr responded to some of his comments in Copenhagen.[92] In particular, the Danish physicist newly asserted his will to describe nature from an objective point of view and specified that quantum mechanics was incompatible with a "deterministic," and not a "causal," description of atomic phenomena. He also abandoned the term "incontrollable interaction," which was used to describe the relation between the measuring device and atomic objects and to explain the origin of the indeterminacy relations. For Fock, an interaction considered as a physical process was always controllable and the concept of "incontrollability" resulted from the use of "classical concepts beyond the region of their validity."[93]

In the Soviet context, Fock considered that this convergence of opinions with Bohr, although minor, would help generalize and support complementarity, which was strongly being challenged by alternative points of view, especially statistical interpretations.[94] He thus contributed, with his publications, to the creation of a narrative of his stay in Copenhagen which highlights ideological aspects and considerations relating to the formulation of the interpretation of quantum mechanics. Other dimensions of the debate—such as the "epistemological" ones mentioned by Freire Jr.[95]—became secondary and made the object of minor at-

[86] Jammer 1974, on 202.
[87] Fock 1936a.
[88] Bohr 1958b; Bohr 1961. See: Freire 1994, esp. 75–78.
[89] Howard 2004; Henderson 2010.
[90] Fock 1951.
[91] Fock 1957a; Fock 1957b; Fock 1960.
[92] Bohr 1958a.
[93] Fock 1957a, on 646.
[94] Graham 1988; Kojevnikov 2012.
[95] Freire 1994, on 71–72.

tention and developments, even though Fock also continued to put forward various disagreements with Bohr. However, we argue that such elements, which are at the basis of Fock's originality in the interpretation problem, played a fundamental role in a debate that proved more significant than mere questions of language.

This vision is supported by the analysis of two documents prepared by Fock during his stay in Copenhagen, respectively dated 23 February and 1 March 1957.[96] Both entitled "My reply to Professor Niels Bohr," they retrace the content of discussions between the two physicists and summarize many of the elements developed by Fock in his first explicit criticism of Bohr published in 1951.[97] They have a common core, since the second document is simply a version supplemented by the most recent elements of the debate. These were the language issues developed above, as well as comments on the idea that when speaking of "complementarity," Bohr should stress that there was "no limitation in our knowledge of the nature and properties of atomic objects."[98]

However, what really interests us is the common core of these documents. Fock initiated the debate on epistemological issues, and their privileged position suggests that they were of greater importance for him. He first defended the idea that quantum mechanics was primarily intended to describe the properties of the atom, in a realistic perspective. Fock wanted to go beyond Bohr's observational approach. He then began by blaming the Danish physicist for the specific use he made of the conceptual apparatus of quantum theory:

> [O]f all the quantum-mechanical concepts *you use* in your philosophical discussions *only the negative part*, namely the restrictions imposed on classical description by the uncertainty relations. But there are other notions, like *states and probabilities* and the laws governing their variation in time, *that are not to be discarded* in discussions of the philosophical aspect of the problem.[99]

To go beyond Bohr's approach and highlight different aspects of the theory, Fock was conscious that the new notions to be used "acquire[d] a definite meaning only by their relations to classically describable experiments." Nevertheless, he was also convinced that once this point was admitted and well understood, it was "quite safe to use these notions."[100] This is precisely the approach he applied in invoking a subdivision of experiments to introduce the concept of potential possibility.

Fock was dissatisfied that Bohr could regard Heisenberg's indeterminacy relations as a limit to our knowledge and, as mentioned above, in the final version of

[96] "My reply to Professor Niels Bohr," 23 February 1957, Niels Bohr Archive, Copenhagen, Microfilm Bohr Scientific Correspondence 1930–1945, no. 28; "My reply to Professor Niels Bohr," 1 March 1957, Niels Bohr Archive, Copenhagen, Niels Bohr Scientific Correspondence, Supplement, 1910–1962, folder 96.

[97] Fock 1951.

[98] "My reply to Professor Niels Bohr," 1 March 1957, Niels Bohr Archive, Copenhagen, Niels Bohr Scientific Correspondence, Supplement, 1910–1962, folder 96.

[99] "My reply to Professor Niels Bohr," 23 February 1957, Niels Bohr Archive, Copenhagen, Microfilm Bohr Scientific Correspondence 1930–1945, no. 28.

[100] "My reply to Professor Niels Bohr," 23 February 1957, Niels Bohr Archive, Copenhagen, Microfilm Bohr Scientific Correspondence 1930–1945, no. 28.

his response, on 1 March 1957, added similar comments regarding complementarity.[101] If the mathematical result of Heisenberg and its interpretation by Bohr are obviously related, it is interesting to note that Fock considered them interchangeable.[102] Such a restrictive approach thus justifies the physical foundations on which he sometimes criticized complementarity. Indeed, as soon as 1951, the Soviet physicist wrote that Bohr was losing meaning to complementarity by considering it as a "certain universal principle … applicable not only in physics but even in biology, psychology, sociology, and in all sciences."[103] In general, Fock felt that Bohr was too much attached to the principle of complementarity, overestimating the role of the measuring device in observational situations and underestimating the properties of atomic objects. In other words: "[Bohr] disminish[ed] the role of quantum mechanics (leaving it only a symbolic meaning) and exaggerate[ed] the importance of the uncertainty relation."[104]

The term "symbolic" is of importance. In his 1987 analysis of Bohr's philosophy of physics, Dugald Murdoch argued that for the Danish physicist a purely mathematical theory was an ideal construction of reason, whose entities were abstract.[105] Therefore, its applicability to the real physical world was strictly instrumental. For Murdoch, Bohr "held a non-realist view of the cognitive status of applied mathematics—non-realist in the sense that he was highly doubtful of the view that the physical world has a structure that is uniquely describable in terms of some theory of pure mathematics."[106] Such views were incompatible with Fock's materialism and conception of the mathematical formalism that rejected any idea of the primacy of thought in mathematics. As a result, the Soviet physicist's criticism of Bohr was recurrent in this respect. The following statement of 1957 can summarize it:

> You [Bohr] often stress the difference between the *mathematical symbols* in quantum mechanics and in classical mechanics. You say that, in quantum mechanics, they are only symbols while, in classical mechanics, they are something physical. I do not see any difference in the role played by mathematics in classical and in quantum mechanics.[107]

Fock claimed that the formalism of quantum mechanics reflected a reality, had a physical meaning, which the Danish physicist dismissed as symbolic. In this, the Soviet physicist proved to have provided a coherent critique of his colleague's understanding of the theory: Bohr's treatment of the mathematical formalism was an explanation for his lack of interest in the properties of atomic objects and his focus on observational situations.

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101 My reply to Professor Niels Bohr," 1 March 1957, Niels Bohr Archive, Copenhagen, Niels Bohr Scientific Correspondence, Supplement, 1910–1962, folder 96.
102 In 1949, Fock notably wrote: "There is a general rule that emphasizes the limits of the applicability of classical models. It is Heisenberg's indeterminacy relations that Bohr calls relations (or principle) of complementarity." See: Fock 1949.
103 Fock 1951, on 13.
104 Fock 1951, on 13.
105 Murdoch 1987, esp. 216–221.
106 Murdoch 1987, on 217.
107 "My reply to Professor Niels Bohr," 23 February 1957, Niels Bohr Archive, Copenhagen, Microfilm Bohr Scientific Correspondence 1930–1945, no. 28.

On 23 February 1957, at the conclusion of his first *reply* to Niels Bohr, Fock explained: "On the basis of your ideas, one may and must introduce quantum-mechanics concepts. They are not symbolic, but quite physical. There is no reason to avoid them in the description of nature."[108] The claim was both of an antireductionist and a scientific realist. Fock can be considered as a member of the so-called Copenhagen school, but in his debates with Bohr, two epistemologies confronted each other on this common ground. The Soviet physicist believed in the complementary, relative to the means of observation, and in the probabilistic nature of quantum mechanics, but he also believed that the new epistemological frontier drawn by Heisenberg's indeterminacy relations opened up new opportunities for the knowledge of the properties of matter. This point of view cannot be reduced to mere questions of language.

4. Conclusion

In the philosophy of dialectical materialism, matter is considered as an infinitely complex concept, accessible through relative truths in an asymptotic progression of knowledge. As the leading thinkers of this philosophy with regard to the natural sciences, Engels and Lenin thus developed a profoundly antireductionist and materialist epistemology.[109] As a Soviet physicist, Fock was for his part immersed in a context conducive to the reading of their works.[110] Indeed, dialectical materialism had imposed itself as an essential component of the state ideology in the Soviet Union, and it greatly influenced scientific research, from science policy to aspects such as the rhetoric employed by scientists.[111] Strong ideological campaigns took place, and scientists suffered the politicization of their professional culture. The authorities expected them to fight against idealism as the enemy's philosophy, and Fock, as a social actor of Soviet science, was part of that dynamic. During periods of intense ideological pressure, he became more involved in modern physics debates, and he also adjusted some of his rhetorical traits.[112] Also, he significantly promoted Bohr's complementarity after his visit to Copenhagen in response to various opposition movements.

Nevertheless, we have shown that it would be wrong to reduce Fock's scientific approach to such polemical aspects. Above all, the Soviet physicist had found in the reading of Engels and Lenin epistemological principles which he considered useful for solving problems in physics. Antireductionism and materialism, as a form of scientific realism, became for him necessary conditions of physical rigor, which physics could not do without. There were no such things in his daily scientific practice as the philosophical opportunism—the possibility for the physicist to adopt different philosophical positions according to the circumstances—

[108] "My reply to Professor Niels Bohr," 23 February 1957, Niels Bohr Archive, Copenhagen, Microfilm Bohr Scientific Correspondence 1930–1945, no. 28.
[109] On dialectical materialism, see: Graham 1987, on 24–67; Truchon 2013.
[110] On Fock and Lenin, see: Gorelik 1993, esp. 311–312. There is also archival evidence of Fock's reading of Engels: "Konspekt knigi Engel'sa 'Anti-Dyuring,'" Archive of the Russian Academy of Sciences – St. Petersburg Branch, 1034–2–42.
[111] Josephson 1991; Krementsov 1997; Kojevnikov 2004.
[112] Martinez 2019.

sometimes defended by Einstein.[113] This latter had also been criticized by Fock regarding the theory of general relativity.[114] The Soviet physicist once defined the nature of his criticism in a way that echoes our comments on Bohr and quantum mechanics: "The teachings of dialectical materialism helped us to approach critically Einstein's point of view concerning the theory created by him and to think anew."[115] So, if scientific culture is to be defined in terms of values and practices, and if dialectical materialism is understood as a combination of epistemological principles, this sentence reflects much of Fock's own culture. Once it was applied to understanding the physical meaning of quantum mechanics, Fock turned out to be more than a random member of the Copenhagen school. He wanted to go beyond the main conclusions of that school, and he became the fervent defender of a subcurrent of thought that constantly reminded the scientific community that quantum mechanics could have been more than Bohr imagined.

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[113] Einstein 1949. See also: Gorelik 1993, esp. 325.
[114] Graham 1982; Graham 1987, esp. 367–378; Gorelik 1993; Martinez 2019.
[115] Fock 1964, on 8.

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