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What Bohr wanted Carnap to learn from quantum mechanics

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ABSTRACT

Niels Bohr's interpretation of quantum mechanics is often cast as positivist and sometimes explicitly claimed to be influenced by logical positivists due to some similarities in their thinking. While it is certainly the case that some logical positivists attempted to recruit Bohr, this paper argues that Bohr had interests of his own in the logical positivists.

Bohr's interpretation of quantum mechanics focuses on observation, the use of classical concepts in quantum mechanics, and indeterminacy of quantum processes as opposed to uncertainty of measurement. His view thereby shares some common ground with the logical positivists' views on verification, the observation language, and anti-metaphysics. But Bohr also emphasized complementarity: that certain pairs of concepts – such as position and momentum – are mutually exclusive in quantum mechanics since they, according to Bohr, are only meaningful relative to *different* experimental arrangements.

Bohr believed that complementary brought a general epistemological lesson for all of science that an objective description of nature is not separable from the observational and experimental conditions under which we explore nature. Motivated by the common ground between himself and logical positivism, Bohr tried to persuade the logical positivists and Carnap in particular to adopt and champion complementarity as well as part of their unity of science program. Though his efforts ultimately proved in vain, Bohr's attempts to influence logical positivism disprove the claim that his engagement with them was reluctant and purposefully limited.

1. Introduction

Niels Bohr's interpretation of quantum mechanics took place during the heydays of logical positivism. It seems therefore natural to believe that logical positivism may have provided a considerable influence on Bohr's understanding of the nature of quantum phenomena. Some philosophers have aired this kind of thinking by calling Bohr's view positivistic or subjective in its presentation of the quantum world. Indeed, there are certain similarities between Bohr and Carnap's approaches to language and observation, but these developed independently of each other.

As this paper finds, when Bohr in the thirties was finally in touch with some of the leading logical positivists – instead of being influenced by them, except perhaps with respect to avoiding metaphysically loaded formulations – Bohr himself had strong hopes of convincing the logical positivists about his interpretation of quantum mechanics in terms of complementary descriptions. Furthermore, Bohr believed that understanding quantum phenomena as complementary brought us an epistemological lesson that could be extended to our knowledge in other areas of science and humanities. His endeavor to apply this lesson on subjects other than the atom was congenial with the positivists' efforts to establish an epistemological theory for the unity of science.

One of the most important tenets of the unity of science movement within logical positivism was the claim that all scientific statements, in order to be meaningful, should be related to objectively describable, directly observable states of affairs. Likewise, the movement insisted on the existence of some unitary observational and methodological principles from which all scientific knowledge could be established. So when Bohr got a chance to engage with the unity of science movement, as we shall see, he nurtured a desire to persuade them to see complementarity as the general epistemological lesson for all of science that an objective description of nature is not separable from the observational and experimental conditions under which we explore nature.

Importantly, this suggestion that it was Bohr who sought to recruit the logical positivists – at least as much as they sought to recruit him – goes against the presentation sometimes seen that Bohr's engagement with the logical positivist was reluctant and purposefully kept to a minimum (e.g. Favrholdt, 2015). We shall argue to the contrary that Bohr took active

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part in getting the positivists over to his side in relation to Einstein's objection by pointing to agreements between himself and them. Our thesis is that Bohr did not only seek the recognition of the positivists but wished to convert them to complementarity.

2. The epistemological lesson

On September 19, 1938, Leon Rosenfeld sent an intriguing letter to Martin Strauss; a German physicist and philosopher who had spent a year between 1935 and 1936 at Bohr's Institute in Copenhagen, where Rosenfeld stayed much of the time between his duties at the University of Liege. In the letter, Rosenfeld remarks that he and Bohr hope that Strauss can teach Carnap "about the seriousness and real significance of the epistemological problem of quantum theory."[1] This remark is intriguing for two reasons: First, it suggests that Rudolf Carnap – one of the leading figures of logical positivism – was on Bohr's mind in the late 1930s. This goes against an account of Bohr's engagement with logical positivism as brief, reluctant, and purposefully kept to a minimum. Second, and more importantly, the remark indicates that Bohr wanted Carnap to learn something important from quantum theory. In other words, around that time Bohr seems to have had an interest of his own in the logical positivists. The logical positivists should recognize the "real significance" of quantum theory. For Bohr, this went beyond the recognition of quantum theory as a profound new insight in physics. Rather, we argue that throughout the 1930s Bohr attempted to convince Carnap and other logical positivists to take up a general epistemological lesson that Bohr believed the interpretation of quantum mechanics in terms of complementarity taught us.

Sometimes philosophers have accused Bohr's interpretation of quantum mechanics for being positivistic. But except for his attempt to express himself less metaphysically after criticism by some of the logical positivists, little supports such an allegation. Bohr had arrived at his interpretation years before his personal encounter with Carnap and Otto Neurath and before his correspondence with the latter (Faye & Jaksland, 2021). Bohr based for the most part his interpretation on physical considerations and not on philosophical principles. It is true that Bohr very early on was in touch with the Danish philosopher, Harald Høffding, who considered himself an empiricist and classical positivist. Through him Bohr had received a general introduction into philosophy, which indeed was part of the philosophical presuppositions behind his approach into understanding quantum theory (Faye, 1991). But apart from Høffding's early inspiration, Bohr was not influenced by contemporary philosophy.

In fact, Bohr believed that much influence between physics and philosophy went in the other direction such that philosophy learned from physics. In an interview for *Izvestia*, when Bohr visited Soviet Union in 1934, he expressed this line of thought:

> When one raises the question of which philosophical consequences arise from modern physics, one may not thereby understand the question to mean which old philosophical schools comply with modern physics. Every new generation of philosophers learns from the new discoveries of other sciences of its time. Although some consequences of modern physics have something in common with the viewpoints of many great philosophers, yet it seems to me, that if men such as Spinoza or Marx were alive today they would probably, together with the rest of us, enjoy learning new things from modern physics of relevance for general philosophy (Bohr, 1934/2005, p. 200).

Thus, Bohr believed that the discovery of quantum mechanics could and should inform philosophy about new ways of understanding human knowledge.

It is already well documented in the literature how Bohr thought that quantum theory brought us a general epistemological lesson (e.g. Folse, 1985). Based on his interpretation of quantum theory, Bohr argued that the unified causal-space-time description of classical physics had to be replaced by complementary descriptions in quantum mechanics in order to preserve objectivity. In quantum theory, we must use the same concepts as in classical mechanics, but the meaningful application of these concepts to atomic objects is tied to the experimental and observational situation, which excludes that those concepts, which normally apply simultaneously in classical physics, also did so in quantum mechanics. It was Bohr's firm belief that this lesson could be extended to other areas of human knowledge as well.

> The epistemological lesson we have received from the new development in physical science, where the problems enable a comparatively concise formulation of principles, may also suggest lines of approach in other domains of knowledge where the situation is of essentially less accessible character (Bohr, 1948/1998, p. 147).

Likewise, in another essay he wrote:

> The importance of the epistemological lesson which the exploration of the world of atoms has given us must be seen on the background of the impact of the mechanical conception of nature on general thinking through the centuries. Above all, the recognition of an inherent limitation in the scope of the deterministic description within a field of experience concerned with fundamental properties of matter, stimulates the search in other domains of knowledge for similar situations in which the mutually exclusive application of concepts, each indispensable in a full account of experience, calls for a complementary mode of description (Bohr, 1956/1998, p. 175).

In some of his many essays from the 1930s and onwards, Bohr attempted to identify descriptive situations, in particular in biology and psychology, where the application of concepts was subject to the same mutual restrictions as was the case with the classical concepts in quantum mechanics.

While these published works have been extensively studied, Bohr's attempts at spreading these ideas behind the scene have largely been overlooked. Bohr did not only promote this general epistemology of complementary in print, he also actively sought to convey its message to the logical positivists through his personal contacts with them and their associates. Anja Jacobsen (2012) does hint at this when she in relation to the above mentioned letter from Rosenfeld to Strauss – which she was the first to bring attention to – remarks that "Bohr deemed in worthwhile to support Strauss, because he thought Strauss could teach the philosophers the physical background proper of their philosophy" (Jacobsen, 2012, p. 130). Taking a lead from Jacobsen, section 6 gives further details about Strauss's associations with both Bohr and Carnap, which on our view show just how keen Bohr was to recruit Carnap. As we shall argue in the preceding sections, Bohr saw similarities between that lesson from quantum theory and central elements of logical positivism, which apparently encouraged him to attempt to recruit logical positivists for his cause in the first place. Since Carnap, whom Bohr met in person, was a major figure among them, it seems quite natural that Bohr found it especially important to convince him about the revolutionary impact the discovery of the quantum of action had for the possibility of objective knowledge in general.

3. Bohr and Carnap

The first, and only time, Bohr met with Carnap was on November 14, 1932, when Carnap visited Copenhagen. Jørgen Jørgensen was a professor of philosophy at the University of Copenhagen and he had invited Carnap to give a talk. At that time, Jørgensen had become a central member of the positivist circle. The title of Carnap's talk was "About the character of the philosophical problems." In his diary, Carnap summarized his discussion with Bohr after the talk, where Carnap also had a

[1] Rosenfeld's letter to Strauss, September 19, 1938, Niels Bohr Archive. Quoted and translated in Jacobsen (2012, p. 130).

long private conversation with Bohr. About the discussion, Carnap tells us that Bohr had aired his objections to Einstein: "He complains that one cannot understand how Einstein is now so conservative; he always comes up with counterexamples, but they are simply not correct" (Carnap, 2021, entry on November 14, 1932). Then Bohr had pointed out that we cannot understand quantum mechanics if we do not take into consideration the experimental situation. In Carnap's words, Bohr had emphasized how "[i]t is simply a matter of stating that the observer cannot be separated. This is an insight that can no longer disappear from science. It is an epistemological question" (ibid.). Bohr may probably have used the word 'the observer' himself, but by using this term he did not think of the observer as a subject who influences the outcome of the experiment, but by selecting a particular experiment the observer influences what kind of prediction would be possible. Carnap finally reports that Bohr "always stresses that he basically agrees with us" (ibid.).

In our opinion, something speaks in favor of Carnap's impression that Bohr basically agreed with the positivists with respect to epistemology and the importance of observational language. Nonetheless, Bohr might have felt that they did not understand the importance of the physical conditions of using complementary descriptions. Bohr might therefore have expected that since he and the positivists mutually shared some basic ideas about observation, then the positivists might eventually become advocates of complementarity if they worked more closely with the observational problems connected to it. After several visits to Copenhagen in 1934, also Neurath saw similarities between Bohr's views and those of the logical positivists. About his encounters with Bohr, Neurath writes to Carnap that he "obviously tries to come into agreement with us."[2] This is seen from the Neurath's perspective, but from Bohr's perspective, as we argue here, such an agreement would also consist in the positivists' acceptance of complementarity.

An interesting part of Carnap's diary note on the meeting with Bohr is his reflection about Bohr's motives for his remarks. Apparently, Bohr had mentioned that the logical positivists had made excellent analyses of relativity theory:

> The Wiener Kreis had said good things about the *R Th* [relativity theory], which Einstein himself had not seen so clearly. (Perhaps he thinks we would now like to express ourselves more clearly about quantum mechanics? Or he does not entirely agree with Schlick's or Frank's statements about it? It is not quite clear to understand because he expresses himself very carefully …) (Carnap, 2021, entry on November 14, 1932).

These statements seem to indicate that Carnap saw Bohr's remarks as an indirect request to work on the epistemological problem of quantum mechanics like Carnap himself and other positivists had done before with relativity theory. But Carnap is in doubt and continues to speculate whether Bohr was dissatisfied with what Moritz Schlick and Philipp Frank had said about quantum mechanics, something Carnap cannot understand since Bohr had stressed his basic agreement.

However, Bohr might not have been completely satisfied with what the positivists had to say about quantum mechanics up to then, and had therefore wanted them to look into it again from the perspective of complementarity. A few years later, after Strauss had attended the Second International Congress for the Unity of Science in Copenhagen in 1936, he wrote to Hans Reichenbach about the result of the conference, saying "Also *Frank* who in Konigsberg still misunderstood quantum mechanics in a completely positivistic manner converted to complementarity."[3] Strauss is here referring to the Second Conference on the Epistemology of the Exact Sciences held in Königsberg September 5–7, 1930. This conference was dedicated to two topics: the foundations of mathematics and the philosophical questions arising from quantum mechanics. The contributions were published in *Erkenntnis* a year later. Carnap himself had been present at this conference together with Frank, Reichenbach, John von Neumann, Werner Heisenberg, and many others. Although Bohr may not have read any of papers published in *Erkenntnis*, Heisenberg might have informed him about some of the positivists' discussions about quantum mechanics. Heisenberg's report will in turn most likely have been a negative one since Strauss in the same letter to Reichenbach says of Heisenberg that "[h]e swears a lot at the positivists."

We shall here speculate, however, that Bohr's dissatisfaction may also reflect the disappointment that the positivists' discussions of quantum theory known to Bohr were limited to the epistemology of microphysics. On August 15, 1932, Bohr gave a presentation in Copenhagen on – among other things – the role of the observer (as sketched above) and complementarity in biology. He subsequently published these ideas in March the following year under the title "Light and Life" (Bohr, 1933). What Bohr saw as a general epistemological lesson of quantum theory was, in other words, very much on his mind when he met Carnap in November 1932. Bohr seems to have brought up this general lesson when he talked about the role of the observer in *science*, as Carnap writes, not merely in *physics*. Indeed, Bohr must have emphasized this point to a degree that made it the only concrete philosophical thesis on Bohr's part that Carnap recorded in his diary after their hour-long conversation. Some of it may have been lost on Carnap though, as suggested by his puzzlement over Bohr's remarks about quantum mechanics and logical positivism, since Bohr might, out of politeness, not have expressed his direct disappointment at what the positivists had achieved regarding quantum theory so far.

The role of the observer and the question of complementarity in science in general were on this account what Bohr found missing in the logical positivists' treatment of quantum theory. Bohr therefore tried to convey this general epistemological lesson from quantum theory to Carnap at their meeting in 1932, though with mixed results. This interpretation of events is supported by a letter sent from Frank to Bohr on November 26, 1932. Frank was at the time professor of physics and a colleague of Carnap's at the University of Prague. Frank's letter to Bohr – the first letter in the longer correspondence between the two – was sent only days after Carnap's return to Prague from Copenhagen and was accompanied by one of Frank's books; most likely *Das Kausalgesetz Und Seine Grenzen* (1932). As Frank writes in the letter, the book discusses – though in Frank's own words "only very superficially" – Bohr's "views on the application of quantum theory to life processes."[4] On the reason for sending the book, Frank writes: "Mr. Carnap told me that you were interested in such questions." Carnap, it seems, must have told Frank about the meeting with Bohr in Copenhagen and more specifically reported his impression that Bohr was interested in the implications of quantum theory beyond microphysics. So perhaps Carnap did not misunderstand Bohr's intention after all. Carnap's mention in his diary of Frank's statement about quantum theory could concern the very book Frank sent to Bohr and not Frank's more physics specific remarks from the Königsberg conference. If so, then this is evidence that Bohr already in 1932 tried to recruit the logical positivists to his cause. Notably, this is several years before the logical positivists allegedly began their attempts to recruit Bohr to their ranks.

Unfortunately, Bohr and Carnap never met again, since Carnap was not able to participate in the Second International Congress for the Unity of Science in Copenhagen in 1936. Already in September 1935, when Neurath told Carnap that the conference would take place the next year in Copenhagen, Carnap remarked in his diary that he was not able to attend the conference (Carnap, 2021, entry on September 18, 1935). The reason presumably was that Carnap was about to leave Prague, where he

[2] Neurath's letter to Carnap, November 14, 1934, RC-029-10-10. University of Pittsburgh. Quoted and translated in Faye (2010, p. 34).

[3] Strauss's letter to Reichenbach, July 1936, HR-013-35-07. Quoted in Röseberg (1995, p. 114).

[4] Frank's letter to Bohr, November 26, 1932. Niels Bohr Archive. BSC-95-1. Our translation from German to English.

had stayed since 1931, for the US.[5] So Carnap's visit to Copenhagen in 1932 was the only time that he and Bohr discussed in person. Nor is it known that they corresponded except once.[6] Nevertheless, as we shall discuss below, Carnap and Bohr still interacted through two intermediaries: Neurath and Strauss. These interactions, along with the events at the Second Congress for the Unity of Science further bolster our case that Bohr actively attempted convince the logical positivists that complementarity entailed a general epistemological lesson.

4. Bohr and the unity of science movement

The unity of science movement adopted the old idea that all sciences have something in common. That we apply the word 'science' to many areas of knowledge is because of the existence of some unifying features that hold these areas of knowledge together, but also because of the existence of some common values which those areas are able to meet. What was new was that the unity did not arise from metaphysical presumptions. The unity originated from how the empirical sciences allowed themselves to be subject to the same logical analysis of language by which they describe observations.

The manifesto of logical positivism in 1929, written by Hans Hahn, Neurath and Carnap, confessed to "the unity of science without metaphysics". At this time Carnap had delivered the most meticulous analysis of the logical foundation of knowledge with his book *Der logische Aufbau der Welt* (1928) within the Vienna Circle. It took a phenomenalist and constitutive-relationalist approach to the unity of science in the sense that a rational reconstruction of scientific statements about the empirical world should be reducible to sentences about elementary experiences. This holistic view on the unity of science regarded scientific knowledge as a system of statements that could be related to an observational basis that were directly verified by observation.

Neurath, however, criticized Carnap's proposal, arguing that science was an intersubjective enterprise and that the phenomenalist basis of observational sentences would make science subjective. In 1931 he introduced another proposal, the thesis of physicalism, according to which observational sentences were protocol sentences consisting of objective statements that expressed observable things, events and processes in space and time.[7] Even statements about behavior and physiological events were to be expressed in a physicalistic language. Moreover, Neurath favored what he called an "encyclopedia model" for the unity of science in contrast to Carnap's "system model". His attitude was that many sciences used a language that contained imprecise and ineliminable terms that they had borrowed from our ordinary language.

Carnap had accepted Neurath's criticism of an epistemic foundation based on sentences about elementary experiences when he published *The Logical Syntax of Language* (1934/1937) but he made up his own form of physicalism. However, Carnap still believed that the right model for expressing scientific knowledge was the axiomatic system, and that different systems could be ordered in hierarchies, which could be formally analyzed. Neurath, on the other hand, did not see how this would be possible. Our knowledge of economy cannot be reduced to our understanding of electrons. Rather the unity is a local affair where "it must be possible to connect each law with every other law under certain circumstances, in order to obtain new formulations" (Neurath, 1931/1983, p. 59). Such an encyclopedic view was dynamical in nature by seeing our knowledge changing as science progressed.

It was in the midst of this debate about protocol sentences that Bohr discussed with Carnap in 1932 and with Neurath in 1934. Neurath visited Copenhagen twice this year, and when he gave a series of six lectures in October that year, Bohr attended a couple. Afterwards Neurath wrote Carnap about his meeting with Bohr where he complains that Bohr in print expresses himself very metaphysically. However, he also says that Bohr

> possesses certain basic attitudes which agree with mine, e.g., that in science one cannot clear up everything at once, but that the individual scientific-logical actions have to pay a price, as it were. An idea of compensation, which with him naturally tends to be connected with the uncertainty relation. Obviously tries to come into agreement with us. But since his circle confirms him in his habit to express himself somewhat unclearly, one would have to be able to work on him for a long time, which he would be prepared to do.[8]

Apparently, Neurath believed that the positivists could recruit Bohr for the unified science movement. In his effort to bring attention and support to the attitude behind the unity of science, Neurath set up an institute, congresses, and founded a book series *the International Encyclopedia of Unified Science* in 1935. A long exchange of letters between Neurath and Jørgensen reveals that Neurath was eager to get Bohr's backing for his various projects. Bohr's name does in fact figure on the list of supporters in the announcement for *the International Encyclopedia of Unified Science*. It should not be forgotten that Neurath was able to convince Bohr to write a short paper, called "Analysis and Synthesis in Science" (1938/1999) for the very first issue of the Encyclopedia.

We also see that Bohr was in basic agreement with Neurath about the holistic nature of scientific knowledge. After his discussion first with Carnap and then Neurath, Bohr seemed to have believed that the epistemological lesson, which the new physics had taught the scientific community, could contribute to the development of the foundation of the unified science. Bohr emphasized that the objectivity in science was a question of providing an unambiguous description of the phenomena, and that such a description had to use ordinary language supplemented with a technical terminology.

> From a logical standpoint, we can by an objective description only understand a communication of experience to others by means of a language which does not admit ambiguity as regards the perception of such communications. In classical physics, this goal was secured by the circumstance that, apart from unessential conventions of terminology, the description is based on pictures and ideas embodied in common language, adapted to our orientation in daily-life events. The exploration of new fields of physical experience has, however, revealed unsuspected limitations of such approach and has demanded a radical revision of the foundation for the unambiguous application of our most elementary concepts, like space and time, and cause and effect (Bohr, 1953/1998, p. 157).[9]

The limitation that Bohr here talks about is of course that the application of what he also calls "the classical concepts" with respect to observation in quantum mechanics is restricted to a certain experimental context. These restrictions in the use of classical concepts are what make descriptions relying on them complementary to one another.

In some ways, Bohr's view on the description of observation was closer to Neurath's thesis of physicalism. Bohr believed that it was the

[5] In the spring of 1936, Carnap was teaching in Chicago and gave lectures at Harvard, Columbia, and Princeton, so he also seems to have been too busy to go back to Europe for the congress in June. We wish to thank an anonymous reviewer of this journal for providing these details about Carnap's absence from the congress.

[6] In a letter to Strauss, Carnap does in fact mention having received a letter from Bohr asking Carnap for his assessment of Strauss's academic qualifications apparently in an attempt to secure funding for Strauss. See Carnap's letter to Strauss, February 18, 1939. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 179: 7-Carnap-18-2-1939.

[7] An excellent treatment of the debate between Carnap and Neurath is Thomas Uebel (2007).

[8] Neurath's letter to Carnap, November 14, 1934, RC-029-10-10. University of Pittsburgh. Quoted and translated in Faye (Faye, 2010, p. 34).

[9] Even though the quotation is taken from Bohr (1953/1998), it gives us a precise description of Bohr's attitude to language very early on. His printed papers from the 1930s already expressed a similar view.

practical use of the classical concepts in relation to our observation of physical things, like the record of the physical apparatus, which gave these concepts meaning. Also, Bohr's appeal to ordinary language as an inevitable component in the objective description of nature, even in physics, is something we recover at Neurath. Moreover, by claiming that similar complementary descriptions could be found in other sciences – descriptions both necessary for an exhaustive understanding of the phenomena – Bohr thereby excluded that the reduction of basic concepts between various sciences makes much sense. Since Bohr has applied complementarity to biology in his paper "Light and Life" (1933), he had reasons to believe that complementarity captured some very important aspects of the epistemological conditions for objective descriptions in all sciences.

On the day Neurath left Copenhagen, Bohr sent him the German version of *Atomic Theory and the Description of Nature* (1931), containing his physical and philosophical considerations concerning the interpretation of quantum mechanics. In a letter accompanying the book, Bohr expressed his pleasure to find out that their ideas were not so far apart, as one might have expected given their different ways of expression.[10] Overall, Bohr and Neurath had apparently found in their discussions a common understanding of the epistemological conditions for describing science. That both the logical positivists and Bohr nurtured a strong desire to move in the same direction seems to be confirmed by the fact that Bohr opened his mansion in Copenhagen for holding the Second Congress for the Unity of Science in 1936. Nonetheless, they presumably had different motives. Neurath probably thought it would be a feather in the cap of the unity of science program if a leading quantum physicist like Bohr joined the unity of science program. Bohr, on the other hand, believed that the epistemological lesson learned from quantum mechanics offered a common ground for understanding the nature of scientific knowledge in general and that the logical positivists might adopt the view of complementarity in their analysis of observations.

5. The Copenhagen congress

Facing a crowd of philosophers and scientists Bohr went straight to the matter that was so much on his mind in his opening talk at the Second Congress for the Unity of Science in 1936. Here is what he said[11]:

> On several occasions I have pointed out that the lesson taught us by recent developments in physics regarding the necessity of a constant extension of the frame of concepts appropriate for the classification of new experiences leads us to a general epistemological attitude which might help us to avoid apparent conceptual difficulties in other fields of science as well. Since, however, the opinion has been expressed from various sides that this attitude would appear to involve a mysticism incompatible with the true spirit of science, I am very glad to use the present opportunity of addressing this assembly of scientists working in quite different fields but united in their striving to find a common ground for our knowledge, to come back to this question, and above all to try to clear up the misunderstandings which have arisen (Bohr, 1937, p. 289).

Then he continued by first telling the audience how the development in physics "has contributed to the general philosophical clarification of the presuppositions underlying human knowledge" (Bohr, 1937, p. 290). According to Bohr, this clarification consisted in a "revision of the problem of observation," in which "the [unambiguous] use of our most simple concepts, such as space-time description and causal connection" (Bohr, 1937, p. 290), by which we describe our experiences, is strictly limited to the context of actual observation and is not applicable outside the experimental context. This holds in quantum mechanics as well as in the theory of relativity. Hence, the epistemological lesson we can draw from physics is that the expansion of the conceptual framework we use to describe our experiences to include new areas of observation is possible only if we restrict their application to what we directly can observe. And the reason is that this is the only way physicists can avoid descriptive inconsistencies.

Hereafter Bohr turned to what some had seen as "mysticism." "[I]n this connection it appeared to me to be of interest to point out that also in other regions of human knowledge we meet apparent contradictions which might seems to be avoidable only from the point of view of complementarity" (Bohr, 1937, pp. 294–295). What he had in mind was, on the one hand, the use of causal descriptions and, on the other hand, the use of functional and intentional descriptions in biology and psychology.

In case we describe an organism from a physical point of view, we do it in causal terms, but on the atomic or molecular level, we would refer to the laws of physics and not to laws that relate the description to life. "The only logical possibility of avoiding any contradiction between the formulation of the laws of physics and the concepts suitable for the description of the phenomena of life ought therefore to be sought in the essentially different character of the conditions of investigation concerned" (Bohr, 1937, pp. 295–296). Bohr therefore suggested, "the existence of life itself would have to be regarded in biology, both as regards the possibilities of observation and of definition, as no more subject to analysis than the existence of the quantum of action in atomic physics" (Bohr, 1937, p. 296). Life is an unexplainable fact just as the quantum of action. Thus, in biology causal and functional/intentional descriptions should be understood as complementary modes of descriptions limited to what part of phenomenon the scientists actually observe.

Bohr's presentation was followed by a presentation by Frank on the topic of the philosophy of quantum theory. Based on Carnap's logical syntax and the verificationist criticism of metaphysics, Frank warned against the conception that quantum theory introduces a principled *uncertainty* as captured by Heisenberg's relations. Such a description implicitly assumed the metaphysical notion of a thing in itself behind the measurable reality. According to Frank, Heisenberg's relations should instead be interpreted as introducing *indeterminacy*. On Frank's view, this notion was exactly what was captured by Bohr's account of, for instance, position and momentum in terms of complementarity, which Frank – in the published version of the presentation – cast as "the introduction of a new syntax for these words for the purposes of quantum mechanics" (Frank, 1936, p. 308, our translation). In the conclusion of the same paper, Frank summarized Bohr's idea in the following way:

> The atomic processes, as new physics has shown, cannot be described in [everyday] language. Bohr has now shown in an in-depth analysis of modern physics that parts of the language of everyday life can nevertheless be retained for certain experimental arrangements in the field of atomic processes, but different parts for different experimental arrangements. The language of everyday life thus contains complementary components that can be used in the description of complementary experimental arrangements (Frank, 1936, p. 316, our translation).

However, Frank interestingly generalizes this appreciation of complementarity when he continues:

> There is no doubt that this idea is also fruitful for logical syntax in general and deserves to be applied to other areas of science.[12] In psychology, too, one would have to start from the language of everyday life and see whether parts of this language can be retained in

[10] Bohr's letter to Neurath, October 24, 1934, *Archief Wiener Kreis,* inv. nr. 198. Mentioned in Röseberg (1995, pp. 112–113).

[11] See Werkmeister (1936) for first hand report of this and the other presentations at the congress.

[12] Notice that Frank uses the German term 'Wissenshaften', which includes both natural science, social science and the humanities. For brevity, we here use 'science' to denote all of these disciplines.

> the transition to more subtle problems. One could, for example, start from the physicalistic "protocol language" of Carnap and Neurath and see whether components of these are particularly suitable for describing certain situations. Perhaps the symbolic language of psychoanalysis is an indication of such a partial language. The phenomenal language, of which Carnap often spoke in his earlier works, must be dropped as a general language, but could provide a useful description for certain experimental situations as part of a general language in the sense of Bohr's view (Frank, 1936, pp. 316–317, our translation).

We cannot be certain if these remarks were included already in the presentation of the paper at the Copenhagen congress or whether they were only added afterwards. In any case, however, the remarks show that by the end of 1936 Frank – a leading figure in logical positivism and a friend[13] and former colleague of Carnap – had adopted Bohr's view of complementarity as a general epistemological lesson for all of science. Like Bohr, Frank speculates that complementary concepts (or whole complementary language fragments) will become relevant when we approach "more subtle problems" in other sciences such as psychology.

Bohr and Frank were in continuous contact since Frank had sent his book to Bohr in 1932. The early letters primarily concern Bohr's attempts to find a position in Prague for the Jewish physicist Guido Beck. However, the letters of 1935 and 1936, i.e. those leading up the Copenhagen congress, feature detailed discussions of differences between Einstein's realist and Bohr's complementarity-based views on quantum mechanics which Frank suggests to exemplify "the contrast between a metaphysical and a positivistic view of physics."[14] In a letter to Frank, dated May 27, 1936, Bohr mentions the idea to regard complementarity as a general epistemological lesson as part of an outline of the content of his upcoming presentation at the Copenhagen congress. This was far from the first time that Bohr aired this idea. As shown above, he promoted it already in the early 1930s.[15] However, its presence in a letter to Frank again indicates that Bohr was particularly hopeful that the logical positivists would find this idea compelling. A hope that might in part be due to the similarities between Bohr's views and those of logical positivism which Frank himself had emphasized in the correspondence with Bohr. Frank's subsequent endorsement of complementarity as a general epistemological lesson in his own presentation not only confirms the claim that Bohr sought to convey this lesson to the logical positivists, but also that he partly succeeded in doing so.

Bohr on his part must have been encouraged by Frank's remarks about complementarity. These remarks indicated that Frank had converted to his cause, but they also suggested that complementarity fit well with Carnap's framework of logical syntax *and* with the view of language adopted by both Carnap and Neurath. Frank's statement showed, in other words, that logical positivism resonated well with Bohr's epistemological lesson, which must have made Bohr hopeful that even Carnap and perhaps Neurath could also be persuaded to adopt complementarity as an epistemological principle of all science.

Most likely, these hopes were only further amplified by Strauss's presentation at the Copenhagen congress. Strauss presented a view very similar to Frank's, though limited to quantum physics, and gave a more precise proposal of how to implement complementarity into the framework of logical syntax. Strauss observed that for instance position and momentum cannot be simultaneously determined according to the quantum formalism. From this observation, Strauss argued that if we consider two sentences, one stating the position of a particle and the other stating the momentum of the same particle at the same time, then the quantum formalism

> does not allow the connection of such sentences that deal with the measurement result of complementary quantities […]. Since one can only decide one of two such sentences according to QM [quantum mechanics], it is clear that their connection through any of the logical sentential connectives (truth functions) would not result in a meaningful sentence; consequently the logical-syntactical determinations of the quantum-mechanical language can be grasped in such a way that such meaningless expressions cannot be formed at all (Strauss, 1936a, p. 337).

Strauss proposal is that the implementation of complementarity into logical syntax may happen as a change of the formation rules such that sentences can be connected by connectives only if they are not complementary. This makes certain that the syntax forbids the formation of meaningless sentences, which would otherwise result from connecting two complementary sentences. According to Strauss's formalization, complementarity therefore requires the abandonment of classical logic for what Strauss (1936b) denotes "complementarity logic": a two-valued logic with restricted sentential connectivity.

Strauss's ideas cannot have been new to Bohr. Strauss had been a visiting researcher at Bohr's institute in Copenhagen since September 1935 and stayed there until December 1936, when he left to work with Frank in Prague. Strauss's stay in Copenhagen gives some reason to believe that his exposition of complementarity was at least to some extent sanctioned by Bohr. In a letter of October 4, 1938, Bohr's explicitly praises Strauss's doctoral dissertation that under the title "Mathematical and Logical Contributions to Quantum Mechanical Complementary Theory"[16] had further developed the ideas already given in the presentation at the Copenhagen congress. Bohr mentions in the same letter that he has brought Strauss's work to von Neumann's attention; a remark that indicates that Bohr found Strauss's ideas worth spreading.[17] Röseberg, however, says of Strauss's work on complementarity logic that "neither Bohr nor Heisenberg shared this view" (Röseberg, 1995, p. 114).[18] As evidence, Röseberg quotes the protocol from a discussion between Bohr and von Neumann about the possibility of quantum logic where Bohr is summarized as saying: "The aim of the idea of complementarity was to allow of keeping the usual logical forms while procuring the extension necessary for including the new situation relative to the problem of observation in atomic physics" (Bohr, 1939, pp. 38–39; quoted in; Röseberg, 1995, p. 121).

It is correct that Bohr opposed the replacement of classical logic in favor of a quantum logic. Late in life he wrote:

> The question has been raised whether recourse to multivalued logics is needed for a more appropriate representation of the situation. From the preceding argumentation it will appear, however, that all departures from common language and ordinary logic are entirely avoided by reserving the word 'phenomenon' solely for reference to unambiguously communicable information, in the account of which the word 'measurement' is used in its plain meaning of standardized comparison (Bohr, 1960/1998, p. 183).

[13] In his autobiography, Carnap testifies to this close relation with Frank when he writes: "Later he [Frank] brought about my joining the University in Prague, and during my stay there (1931–35) we were in continuous close contact. I received many fruitful ideas from my talks with him, especially on the foundations of physics" (Carnap, 1963, p. 31).

[14] Frank's letter to Bohr, January 9, 1936. Niels Bohr Archive. BSC-95-11. Our translation from German to English.

[15] Actually, Bohr referred to this already in 1929 in the Planck essay in *Atomic Theory and The Description of Nature* (1929, p. 101), the next piece after Como. We are grateful to an anonymous reviewer of this journal for pointing this out.

[16] The original German title is "Mathematische und Logische Beiträge zur quantenmechanischen Komplementaritätstheorie."

[17] Bohr's letter to Strauss, October 4, 1938. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss No. 172: 1-Bohr-4-10-1938.

[18] Röseberg also claims that "Bohr recommended the publication of [Strauss's] papers, but accepted no responsibility for their logical part" (Röseberg, 1995, p. 114). Röseberg provides no reference for this claim, so it is difficult to assess whether it is based on some historical evidence or on Röseberg's own analysis.

However, in contrast to multi-valued logics, whose application to quantum phenomena that, for instance, Reichenbach (1944) had suggested, Strauss's complementary logic was a two-valued logic with certain syntactical restrictions. Perhaps one may think that Bohr did not consider Strauss's proposal as a violation of ordinary logic, since what Strauss did was exactly to formalize an extension of classical logic by restricting sentential connectivity with respect to observational contexts. However, this is not the place to go into a deeper discussion of Bohr's views on variants of quantum logic. Even though we believe that Bohr ultimately would have disagreed with Strauss's suggestion, Bohr continued to support Strauss as we shall see in the next section, which might just be regarded as further evidence for Bohr's commitment to the attempt at persuading the logical positivists to adopt complementarity as a general epistemological lesson.

6. Martin Strauss – the middleman

It appears that Strauss – like Bohr – got into contact with Carnap through Jørgen Jørgensen. During Strauss's stay in Copenhagen, he and Jørgensen must have discussed Carnap's work on logical syntax, since they sent a letter to Carnap asking for clarifications on several points.[19] On February 21, 1937, Carnap responded to these questions in a letter to Jørgensen that Carnap also mailed to Strauss. Already in his reply to Carnap on June 25, 1937, Strauss brings up a question "closer to his heart" namely that of "a general syntactic definition of complementarity."[20] Strauss then briefly outlines the view also expressed in his congress paper and inquires about some specific detail before he ends with the following remark: "It would be very important to me to hear your opinion on this question and on the logic of complementarity in general." Strauss is sharing Bohr's hope that Carnap will engage himself in this question.

Unfortunately, it seems as if Carnap replied to this and the other points raised in Strauss's letter when they both attended the 9th International Congress of Philosophy in Paris 1937. But Carnap must have shown an interest in Strauss's project, since in a letter of August 17, 1938, Strauss asks Carnap whether he will host him as a visiting researcher in Chicago in case he is able to get a scholarship from the Rockefeller Foundation. Strauss's proposal[21] is to formulate and discuss "Bohr's idea of the complementarity between the principles of physics and those of biology as a suggestion concerning the syntax of a unified scientific language."[22] Strauss, in other words, intended to pursue Bohr's general epistemological lesson within Carnap's programs of logical syntax and unity of science. Carnap's reply was brief but positive asking when and where he could write to support Strauss's application. Carnap accompanied this letter by four pages of detailed comments on Strauss's doctoral dissertation which he – like Bohr – praises writing "I read [it] with great interest", though he also adds: "Of course, I don't have the necessary technical knowledge for the chapters on quantum mechanical calculus."[23] Carnap's comments on his lack of technical knowledge also reflects the fact that he nowhere in these comments addresses complementarity or any other of the quantum mechanical themes.[24] However, Carnap must still have gained some acquaintance with Bohr's views of complementarity and Strauss's formalization of them through this and other works by Strauss, which he mentions having read in subsequent letters.

On October 4, 1938, Bohr also wrote Strauss, telling him that he was willing to support his application to the Rockefeller Foundation. More intriguing, however, is the already mentioned note from Rosenfeld to Strauss in September 1938. Strauss and Rosenfeld had apparently become close friends during Strauss's stay in Copenhagen and they kept an extensive correspondence in the second half of the 1930s (Jacobsen, 2012, pp. 129–130). In an earlier letter, Strauss had requested Rosenfeld as a friend and colleague for Bohr's possible support for the application to the Rockefeller Foundation. Rosenfeld answered:

> We all think that you could play a meritorious role with Carnap by teaching him a little about the seriousness and real significance of the epistemological problem of quantum theory! I am therefore pleased that I can officially inform you that Bohr will be pleased to support a proposal from you for the purpose mentioned in your letter.[25]

The context of Strauss's application suggests a very concrete interpretation of these remarks. Strauss was going to Chicago to work with Carnap on a project that sought to formulate Bohr's general epistemological lesson within a logical framework that the logical positivists not only accepted but promoted. Thus, Bohr must have hoped that Strauss with a shared background in physics and logical positivism could present Bohr's general epistemological lesson in a way that Carnap would find compelling. When articulated by someone like Strauss, the similarities that Bohr had emphasized all along between his interpretation of quantum theory and the views of logical positivism might finally overcome the ambiguities that the logical positivists found in Bohr's own exposition. Bohr hoped, in other words, that Strauss would succeed where he had partly failed.

Strauss's Rockefeller application, however, was unsuccessful and despite repeated efforts by both Bohr and Carnap to secure funding for Strauss, he never traveled to the USA. Instead, Strauss received an invitation from Neurath to come to The Hague. From there he escaped to Great Britain in April 1939 and worked as a schoolteacher during the war. While Strauss never got a chance to teach Carnap about the real epistemological significance of quantum mechanics in person, he continued to raise related issues in his correspondence with Carnap. On November 26, 1938, Strauss mailed some comments on Carnap's draft of *Foundations of Logic and Mathematics* (1939). Here, Strauss questioned Carnap's assumption that classical logic always applies with the objection that "no possibility of formulating quantum mechanics on the basis of classical logic is known; "[26] an objection Strauss also raises against Joseph Woodger's *The Technique of Theory Construction* (1939) in a letter to Carnap on September 11, 1939.[27] Carnap's reply to Strauss's first comment on January 1, 1939, indicates that Carnap was less sure that one is required to abandon classical logic even in quantum mechanics:

> I still have doubts whether one can say that it has already been proven that quantum mechanics cannot be formulated on the basis of usual

[19] Jørgensen had already commented on Carnap's manuscript before it was published, and he later wrote a review of the book for *Erkentniss*. See Koch (2010, p. 154).

[20] Strauss's letter to Carnap, June 26, 1937. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 179: 18-Strauss-25-6-1937-Bl-2. Our translation from German.

[21] Strauss, however, does remark that he is ready to pursue another question of Carnap's choice.

[22] Strauss's letter to Carnap, August 17, 1938. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 179: 19-Strauss-17-8-1938-Bl-1-r. Our translation from German.

[23] Carnap's letter to Strauss, October 2, 1938. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 179: 4-Carnap-2-10-1938. Our translation from German.

[24] Carnap's comments on Strauss's *Mathematische und Logische Beitrage zur quantenmechanischen Komplementaritätstheorie*, Oktober 2, 1938. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 17: Bemerkungen-Bl-1-4.

[25] Rosenfeld's letter to Strauss, September 19, 1938, Niels Bohr Archive. Quoted and translated in Jacobsen (2012, p. 130).

[26] Strauss's comments on Carnap's *Foundation of Logic and Mathematics*, November 26, 1939. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 34: Bl-3.

[27] Strauss's letter to Carnap, September 11, 1939. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 179: 23-Strauss-11-9-1939-Bl-1.

> logic. In spite of the opinion of Frank and you, I would consider it worthwhile to make at least one attempt to make the necessary change in the structure of language only in the physical part and to keep the logical basis in the usual form. Only once you have carried out such an experiment can you find out, by comparing it with your language system, which system is simpler and therefore preferable.[28]

Even though Carnap was well aware that both Frank and Strauss had promoted the idea that complementarity requires a change of classical logic, both in the context of quantum mechanics and in the general context of the unified language of science, Carnap was reluctant to endorse this proposal.

7. Carnap on quantum mechanics

Despite being merely a brief reply to an even briefer comment by Strauss, there are reasons to suppose that Carnap had given this question about complementarity and logic in quantum mechanics some consideration. After all, he had read Strauss's doctoral dissertation on the topic, but more importantly, his mentioning of Frank shows that he was well aware that he here also took a different view than that of a respected friend and former colleague. Furthermore, Carnap's reluctance still persisted more than 25 years later – despite Carnap's continued contact with Frank[29] and Strauss[30] for some of those years – when he addressed this question in print for the first time in *Philosophical Foundations of Physics* (1966).

Discussing whether the uncertainty relations requires modifications of the language of physics, Carnap noted that the "most extreme proposals for such modification" have been made by Frank, Strauss, and Moritz Schlick who all have argued that "under certain conditions, the conjunction of two meaningful statements in physics should be considered meaningless" (Carnap, 1966, p. 289). If anything, Carnap at this time seems even more dismissive of the idea when he remarks: "In my view, such a radical change is inadvisable" (Carnap, 1966, p. 289). In the same pages, Carnap also rejects Reichenbach's suggestion of using a multi-valued logic for describing quantum mechanics.

By rejecting that quantum mechanics requires a change of the formal part of the language, Carnap might seem to be in agreement with Bohr. Bohr, however, is quite clear that complementarity is nevertheless central to the interpretation of quantum theory. Bohr's (possible) disagreement with Strauss concerned whether or not complementarity was a consequence of the quantum formalism as such and therefore reflected by the syntax, as Strauss argued. Bohr's view on complementarity seems rather to be semantical because he holds that the experimental conditions under which the inevitable classical concepts precisely apply determine their truth conditions. Carnap, in contrast, never mentions complementarity; or Bohr for that matter.[31] Maybe Carnap regarded Strauss's exposition of complementarity to be representative of Bohr's view and therefore considered it more precise to discuss this idea using established logico-syntactical terminology.

Ironically, some of Carnap's hopes, expressed in his letter to Strauss in 1939, to accommodate quantum mechanics by a "change in the structure of language only in the physical part and to keep the logical basis in the usual form", i.e. classical two-valued logic, might exactly be captured by the difference in the explication of complementarity between Bohr and Strauss but without Carnap knowing it. Nonetheless, Carnap would most likely have been dismissive of Bohr's exposition as well, though he might have found it more agreeable than the one of Strauss. Bohr was, after all, not exactly changing language, but rather arguing that the use of classical language and classical logic were unavoidable so long as the need for complementarity was recognized.

Furthermore, Carnap's remarks when he returned to this issue in *Philosophical Foundation of Physics* indicate that he perhaps even hoped that the change in language could do away with such complementary consequences of quantum theory, rather than merely accommodating them. Frank and other logical positivists had insisted that measurement in quantum mechanics – to avoid speculative metaphysics – had to be analyzed in terms of indeterminacy rather than uncertainty, a view that Bohr also adopted at least partly on their initiative.[32] Carnap, in contrast, is notably vague between these two when he describes how it, for momentum and position, "is not possible in principle to measure both with a high degree of accuracy. If we know exactly where a particle is, its momentum components become hazy. And if we know exactly what its momentum is, we cannot pin down exactly where it is" (Carnap, 1966, p. 284). This vagueness may seem purposeful when he follows this up with the remark:

> Some physicists today are convinced (as was Einstein) that this feature of modern quantum mechanics is questionable and may some day be discarded. That is a possibility. But the step would be a radical one. At the moment, no one can see how the uncertainty principle can be eliminated (Carnap, 1966, p. 284).

Carnap, in other words, leaves open the possibility that the apparent indeterminacy/uncertainty of quantum mechanics – and thus the underlying motivation for the introduction of complementarity – can be avoided.[33] When Carnap remarks that Strauss's "radical change" of the logic is inadvisable, this may not merely express the view that the indeterminacy it implies should be accommodated in another way, but may indicate that Carnap saw it as an open question whether quantum mechanics required any change at all to the structure of language. This could suggest that Carnap changed his view between 1939 and 1966, but more likely he was never convinced of the need for complementarity neither in its syntactical nor its semantical form.

Ultimately, Carnap seems to favor the view that it – at the time of writing – was still too early to draw conclusions from quantum mechanics. About the language of physics in general and of quantum mechanics in particular, Carnap complains that "[t]his language is still, except for its mathematical part, largely a natural language; that is, its rules are learned implicitly in practice and seldom formulated explicitly" (Carnap, 1966, p. 291). In Carnap's view, a proper formalization will not only improve communication between physicists, but also aid the interpretation of quantum mechanics: "The application of modern logic and the axiomatic method to physics will […] make it easier to create new concepts, to formulate fresh assumptions" (Carnap, 1966, p. 291). Carnap provides no further details for this idea, but his hopefulness that new concepts will better the understanding of quantum mechanics could be viewed as a rejection of complementarity. For Bohr, complementarity

[28] Carnap's letter to Strauss, January 3, 1939. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 179: 6-Carnap-3-1-1939-Bl-2.

[29] Ádám Tuboly (2017, p. 259) reports that Carnap and Frank corresponded at least until 1943 though their relation might have gone sour towards the end of that period, possibly due to the conflict between Neurath and Carnap.

[30] The last letter between Strauss and Carnap known to us is from May 19, 1947. Strauss's letter to Carnap, May 19, 1947. Archiv der Berlin-Brandenburgischen Akademie der Wissenschaften. NL Strauss Nr. 179: 32-Strauss-19-5-1947-Bl-1.

[31] On the conspiratorial side, we might add that Carnap does mention the contributions of Planck, Einstein, Schrödinger, and Heisenberg in the development of quantum mechanics, and the omission of Bohr could therefore seem almost purposeful. However, we shall instead take the view here that Carnap most likely considered Strauss's work to represent Bohr's view.

[32] See Frank's letter to Bohr. January 9, 1936. Niels Bohr Archive. BSC-95-11. For Bohr's reply, see Bohr's letter to Frank. January 14, 1936. Niels Bohr Archive. BSC-95-13.

[33] Notice that Bell's (1964) theorem – despite being recently published – was not widely known at this time. It is therefore likely that Carnap did not know that such hidden-variables theories inevitable entailed a radical form of non-locality.

is central to the interpretation of quantum mechanics precisely because the concepts we already have – like the classical concepts of momentum and position – are a precondition for objective communication and thus intersubjective understanding. These concepts are irreplaceable, according to Bohr, whereas Carnap may be arguing that new concepts might change this circumstance.

This disagreement may illustrate a more general difference in Bohr and Carnap's views on the relation between philosophy and science, a difference that may provide another reason why Bohr could not convince Carnap to adopt complementarity as a general epistemological lesson.[34] On Bohr's view, physics should inform philosophy. Despite his apparent disagreement with some details in Strauss's work, Bohr seems to have been happy with his approach of informing the syntax of the language of science based on the insights provided by the physics. Carnap, in contrast, seems more hesitant when he insists that physics – such as quantum mechanics – must be properly axiomatized *before* any conclusions are made about the physical theories' philosophical implications. Natural language being the basis for Bohr's epistemological lesson of complementarity makes it inherently dubious by the standards of Carnap's logico-syntactical epistemology. For Carnap, this would not be changed by the insistence of Bohr and Strauss that complementarity was an empirically established fact of quantum mechanics (contentious as that claim might be). Where Bohr at places entertained the idea of an entirely empirically driven philosophy, Carnap insisted on the (prior) need for "Wissenschaftslogik" whose aim was "to articulate the logical structure of the empirical sciences" (Friedman, 2012, p. 3).

This difference is perhaps illustrated by the two very different approaches of Bohr and Carnap to their shared theme of interest: observation and measurement. Throughout his life, Bohr explored the minute details of subtle physical experiments – both actual and thought experiments – and used these to inform his views about the general conditions for observation and measurement. Carnap's approach to observation and measurement is in comparison abstract and idealized (e.g. Carnap, 1956). This may be seen as reflecting his view that a proper philosophical understanding of observation and measurement is required before it is sensible to begin the analysis of subtle cases such as those explored by Bohr. Carnap and Bohr may therefore have disagreed about the epistemic status of the results that Bohr arrived at. More precisely, where complementarity, by Bohr's standards, was a fact firmly established by empirical evidence, Carnap might have regarded it as a premature speculation of a theory that was still in need of *input* from philosophy or "Wissenschaftslogik" to better its foundations.

Furthermore, Carnap at places rejects altogether that empirical evidence can force a certain conceptualization and axiomatization upon us. As Michael Friedman observes:

> Carnap's experience in mathematics and physics taught him that the empirical evidence justifying the use of various theoretical entities in modern physics presupposes the prior choice of an abstract mathematical framework […] – including whatever portion of higher-order logic or set theory is necessary for establishing the formal inferential links between physical theoretical assertions and the results of experimental measurement procedures. To suppose that there can be empirical evidence, in this sense, for the mathematical framework itself is therefore non-sensical (Friedman, 2012, p. 8).

Indeed, if this was Carnap's view, he would have had principled methodological reasons to reject Bohr's claim that complementarity brought a general epistemological lesson about the admissible uses of language – whether imposed by syntax or semantics. If a framework must already be in place for empirical evidence to establish something like complementarity, then it would be non-sensical to inform that very framework by complementarity, as Bohr wanted. By his principle of tolerance (Carnap, 1934/1937, §17), Carnap would arguably not forbid the adoption of the framework of complementarity either. But as he later argues, the adoption of a framework is a pragmatic and not a theoretical question (Carnap, 1950), where the criterion for such a choice is fruitfulness. Irrespective of what the empirical evidence is, on Carnap's view there can be no fact of the matter whether to adopt complementary or not. Empirical evidence can nevertheless be relevant, but only as part of the evaluation of the utility of a framework given certain aims. Maybe Bohr and Strauss would have had better luck, if they had formulated their arguments in these pragmatic terms. In any case, this remains speculation because Carnap did not give his reasons when he rejected it as inadvisable to change logic in light of quantum mechanics. One might argue, though, that the considerations above are what he is getting at when he called for the application of "the axiomatic method to physics."

In the end, however, quantum mechanics was not close to Carnap's heart. While Carnap discussed relativity theory in detail, his treatment of quantum mechanics was comparably much less elaborated. It may be telling of Carnap's acquaintance with quantum mechanics that discussions of the interpretation of quantum mechanics are largely absent in his writings, apart from those issues that concern the logical formulation of quantum mechanics such as the work of Birkhoff, Frank, Schlick, Reichenbach, and von Neumann. Likewise, when Adolf Grünbaum (1963), in his contribution to *The Philosophy of Rudolf Carnap*, discussed time reversal from the perspective of both relativity theory and quantum mechanics – the latter explicitly mentioning Bohr and complementarity – Carnap, merely familiar with relativity theory, only considered this theory in his reply.

Nothing indicates that Bohr ever succeeded in converting Carnap to complementarity, not even in the context of quantum theory. So Bohr's attempts seem ultimately to have been in vain. Bohr wanted to teach Carnap the "real significance of the epistemological problem of quantum theory," but both methodological disagreements and Carnap's limited acquaintance with quantum theory seem to have come in the way. In comparison, Bohr had more success – at least for a while – with other logical positivists – such as Frank and Strauss – who notably knew more about quantum mechanics.

8. Conclusion

Throughout his life, Bohr seemed to have had little patience with philosophers. The day before he died, Bohr said in an interview: "I felt that philosophers were very odd people who really were lost, because they have not the instinct that it is important to learn something and that we must be prepared really to learn something of very great importance."[35] In a similar vein, Rosenfeld reported in a letter to Strauss in 1935 that Bohr had taken Heisenberg's discussions with Kantians as an opportunity to stress that it was "psychologically (and of course in the first instance substantively!) important that one does not enter into any compromises with philosophers."[36] Given this attitude, Bohr's own connections with the logical positivists might come across as strange or outright hypocritical. Especially, if one regards this contact as a period where Bohr tolerated the logical positivists' attempts to recruit him.

The analysis of the present paper, however, implies that Bohr may have considered his contact with "philosophers" as different in nature from that of Heisenberg. Bohr did not seek to reach a compromise with the logical positivists. Instead, his intention was primarily to make the logical positivists convert to complementarity in its general form as captured by Bohr's general epistemological lesson from quantum theory. Bohr seemed to have tried to accommodate the logical positivists'

[34] We want to express our thanks to an anonymous reviewer of this journal for suggesting this methodological difference between Bohr and Carnap's views.

[35] Interview with Professor Niels Bohr on November 17, 1962, conducted by Th. S. Kuhn, Aage Petersen and Erik Rüdinger. *Archive for the History of Quantum Physics*.

[36] Rosenfeld's letter to Strauss, November 16, 1935. Niels Bohr Archive. Quoted and translated in Jacobsen (2012, p. 134).

criticism of him and thus gone against his own advice not to enter into any compromises with philosophers. However, Bohr must have seen this as a small sacrifice for the greater good: Namely to facilitate his influence on the logical positivists and thus to fulfil his general vision – expressed in the interview in *Izvestia* – that physics should influence philosophy rather than the other way around.

Nevertheless, World War II changed everything. The connection between Bohr and the leading positivists stopped. Most logical positivists had immigrated to the US, and after the War the movement lost its steam. The driving force behind the movement, Otto Neurath, died the very year the War ended. In the years to come Carnap was more interested in probabilities, inductive logic, and formal semantics. Though Frank wrote various papers about the interpretation and misinterpretation of physics and quantum mechanics after the 1940s, he turned towards the sociology of science and cared about quantum mechanics from this point of view (Tuboly, 2017). And Strauss never visited the US. After the War he returned to East Germany, DDR, and in line with the Soviet ideology became rather hostile toward positivism and Bohr's interpretation (Jacobsen, 2012, pp. 284–285).

So, it is no wonder that Bohr was disappointed that his endeavor of making a contribution to the logical positivists' ideas of a unified science did not succeed. In 1949, he wrote about his discussions with Einstein. Herein he alluded to his talk at the Copenhagen conference in which he had argued for using complementary considerations outside physics: "Yet, I am afraid that I had in this respect only little success in convincing my listeners, for whom the dissent among the physicists themselves was naturally a cause of skepticism as to the necessity of going so far in renouncing customary demands as regards the explanation of natural phenomena" (Bohr, 1949, p. 236). Also Jørgensen's favorable attitude towards Bohr's interpretation changed during the 1950s as he distanced himself from Neopositivism and became a critical realist who assumed the existence of a hypothetical reality independent of observation. The post-War generation of scientific philosophers, like Paul Feyerabend, Imre Lakatos, Mario Bunge, and Karl Popper, took the same course as Jørgensen did. In the end Bohr found little support among philosophers, until around 1968–69 when Feyerabend, in his revaluation of complementarity and in opposition to his earlier criticism, claimed "Back to Bohr!" (Feyerabend, 1969, p. 103). But by that time Bohr was no longer among the living.

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