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NIELS BOHR'S INTERNATIONALIZATION OF SCIENCE AND THE COPENHAGEN INTERPRETATION

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Niels Bohr's Internationalization of Science and the Copenhagen Interpretation

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It is a great pleasure to address this international gathering of scientists and humanists that is celebrating the centennial of the birth of Niels Bohr, one of whose great inventions was the internationalization of science.

Never before had there been a place of research and scholarship like Bohr's Institute for Theoretical Physics in Copenhagen. The Institute was established in 1921 with funds from Denmark and abroad. Through the power of his personality and the acumen of his physics, Bohr brought together at his Institute an international group of young physicists. There he served as both mentor and benevolent father figure to this extraordinary assemblage. The cast reads like a virtual who's who in physics, among them were: Werner Heisenberg, Pascual Jordan, and C.F. von Weizsäcker from Germany; Lev Landau and George Gamow from Russia; Wolfgang Pauli and Victor Weisskopf from Austria; Léon Rosenfeld from Belgium; Enrico Fermi from Italy; Hendrik Casimir and Hendrik Kramers from Holland; John C. Slater and John A. Wheeler from the USA; Christian Moller from Denmark; and P.A.M. Dirac from England. These physicists returned to their own countries and established their own departments or institutes in the Copenhagen spirit of open inquiry.

Bohr's continuing interest in the internationalization of science is demonstrated in the instrumental role he played in the establishment of NORDITA and CERN.

And in addition to pushing back the frontiers of science, at the proper moments Bohr stepped forward to assume the role of principal spokesman for responsible science -- that is, the control of nuclear weapons. In his approaches to Roosevelt and Churchill in 1944, and in his Open Letter to the U.N. in 1950, Bohr made another prediction which, this time unfortunately, was correct -- namely, that if there is no international control over nuclear weaponry, then there will be a nuclear arms race.

To elucidate Bohr's interactions with the younger scientists who flocked to his Institute, today I will discuss a case study, namely, the interaction with Werner Heisenberg, with whom Bohr worked most closely in Copenhagen during the heroic era that is defined by the genesis of modern atomic theory, 1913 through 1927.

What is impressed indelibly into the memories of all physicists who interacted with Niels Bohr is, as Léon Rosenfeld recollected, Bohr's "unrelenting effort to attain clarity [of foundations] -- true as ever to his Schiller aphorism, 'Only fullness leads to clarity/ And truth lies in the abyss'." In a similar vein Victor Weisskopf distinguished between research at the three major centers of atomic physics: "In Munich and Göttingen you learned to calculate...In Copenhagen you learned to think."

By 1927 atomic physics had fallen into an abyss of ambiguities. And this occurred for reasons that had little to do with considerations of empirical data. In fact, never before in the history of science had there been a case in which conceptual problems were paramount. The principal reason was the failure of physicists to extend into the atomic domain intuitive concepts and their visualizations of phenomena that had been assumed essential to understanding nature. Today I will discuss how this realization came slowly and with great reluctance. By 1925 not only had visualization been lost in the atomic domain, but electrons and atoms were found to have properties unlike anything that could be imagined from experience in the world of sense perceptions -- for example, an electron could be a wave and particle at the same time. During the critical period of 1925 through 1927 when Bohr realized the fullness of the concepts required to raise atomic physics from the abyss, more than anyone else he interacted with Werner Heisenberg who had, as Weisskopf put it so well, "learned to think" in Copenhagen. Bohr and Heisenberg grappled with questions that cut to the very core of how we construct knowledge in the world in which we live, questions such as: How thoroughly connected are intuition and visualization? How is the intuition that leads to one sort of visualization replaced by another? Their replies to questions such as these altered our view of physical reality in ways that are still not completely understood.

I will proceed as follows:

(1) To set the stage I will review the state of Bohr's atomic theory in 1922.

(2) I shall then use the principal problem of atomic physics during 1923 through 1925 -- namely, the interaction of light with atoms as an Ariadne's thread to trace the demise of Bohr's theory and then

the invention of the new atomic physics by Heisenberg in June of 1925, which became known as quantum mechanics.

(3) I shall then turn to the problems of interpreting the new atomic physics during Fall 1926 into Autumn 1927 which led to Heisenberg's invention of the uncertainty principles and then Bohr's formulation of complementarity.

(4) Then I shall discuss certain non-scientific per se avenues to complementarity, in particular psychology and cubist art.

First with levity and then with ever-increasing concern, Bohr, Heisenberg and Wolfgang Pauli referred to the mixture of half-classical and half-quantum concepts in the Bohr theory as a "swindle." By allowing physicists to play both ends against the middle, this swindle served as a useful guide into the atomic domain. The reason is that the perception-laden meaning of mathematical symbols from the violated classical mechanics permitted a visualization of the atom in its stationary states as a miniscule solar system. Bohr's concern with extrapolating language carrying meanings from the world of sense perceptions into the atomic domain is a central theme in what turned out to be a series of papers that he wrote from 1913 through 1927.

By 1922 Bohr's theory had achieved a magnificent superstructure replete with solar-system atomic models that held great appeal for many physicists. For example, Max Born waxed poetic in 1923: "A remarkable and alluring result of Bohr's atomic theory is the demonstration that the atom is a small planetary system...the thought that the laws of the macrocosmos in the small reflect the terrestrial world obviously exercises a great magic on mankind's mind."

In the summer of 1922 Bohr lectured on his atomic theory at the so-called Bohr Festspiele in Göttingen. There he met the 20 year old Wunderkind Heisenberg. As a result of Heisenberg's incisive questions on the problem of the interaction between light and atoms, Bohr invited him for private conversations.

In a letter of 27 November 1933, Heisenberg reminisced to Bohr of their conversations at the Festspiele: "[Until that meeting] I could do physics only in the Sommerfeld style [i.e., emphasis on mathematical techniques]. Yet without understanding every detail from your lectures suddenly I had almost the impression of understanding the real context of atomic physics." Similarly had Bohr been impressed with Heisenberg. "He understands everything," Bohr was reported to have said after their conversations.

One fundamental difficulty that Bohr discussed with Heisenberg was that an adequate description of elementary processes in space and time is not possible. But according to classical physics such a description is assumed possible. To Bohr ferreting out a paradox was essential to clarification.

By 1923, however, the solar system image of the atom withered away principally because recent empirical data indicated that atoms did not respond to light as a solar system atom should. A possible resolution was in Einstein's light quantum, another invention from his annus mirabilis of 1905. Most physicists were critical over light quanta, and their criticisms had little to do with empirical data. Rather, they were opposed to the light quantum's counterintuitiveness. In the German-language scientific literature the term "intuition" has a particularly loaded connotation that is rooted in Kantian philosophy. By "intuition" physicists like Bohr, Born, Heisenberg, Pauli and Erwin Schrödinger, meant the mental imagery that is abstracted from phenomena that we have witnessed in the world of sense perceptions. For example, the mental imagery or customary intuition of light as a wave phenomenon is abstracted from the behavior of water waves. But light quanta were counterintuitive because no visualizable model could be constructed for how they produced interference. Then there was the mind-boggling wave-particle duality of light which led one physicist to wonder how something could behave "as though it possessed at the same time the opposite properties of extension and localization." Light quanta were to be avoided right from the start. Bohr agreed.

In order to continue to exclude light quanta from atomic physics, in 1924 Bohr with Kramers and John C. Slater included into his theory a mathematical formalism in which an atom's constituent electron reacted to an incident light wave as if the electron were represented by as many harmonic oscillators as there are atomic transitions. Although we may visualize an atomic oscillator to be a billiard ball like electron attached to a spring, there are so many possible transitions that a constituent electron is neither localized nor visualizable. Loss of visualization of atomic processes was the high price that Bohr was willing to pay, as he wrote in 1924, to satisfy the demand of our "customary intuition" that light be a continuous phenomenon.

Among the startling predictions of the physics of desperation cooked up by Bohr, Kramers, and Slater was violation of the conservation laws of energy and momentum in individual atomic processes. By early 1925, to most everyone's relief, the Bohr, Kramers, and Slater theory was empirically disproven. Little further progress was made. A lull fell over the landscape of atomic physics. Bohr lamented over the "essential failure of pictures in space and time." But in June 1925 Heisenberg realized the far-reaching importance of the mathematical framework of the fallen Bohr, Kramers, and Slater theory. Heisenberg was the sort of physicist who thrived in periods of flux.

So, in June 1925 when visualization of the atom itself had been lost, mathematics was the guide. This situation suited Heisenberg and he followed a promising line of research to its fruition. He based the new atomic physics, called quantum mechanics, on properties of the atom that are measureable experimentally, for example, spectral lines instead of the unobservable orbits. Yet we read in subsequent key papers by Heisenberg and Born, among others, the desire for some sort of visualization of atomic processes.

With the publication in early 1926 of Erwin Schrödinger's version of atomic physics with wave imagery and assumed continuity, the search for some kind of visualization of atomic processes intensified and took a subjective turn in the published scientific literature. In a March 1926 publication Schrödinger stressed how important visual imagery is to physicists. Schrödinger wrote that he formulated the wave mechanics because he "felt...repelled by the lack of visualizability" of Heisenberg's quantum mechanics. He went on to write that we should not approach atomic physics with a "theory of knowledge" in which we "suppress intuition." For, he continued, although there may exist "things" that cannot be comprehended by one's "forms of thought," the atom is not one of them. Needless to say, wave mechanics appealed to classical realists such as Einstein who had nothing but praise for it.

Heisenberg thought otherwise. In correspondence he referred to Schrödinger's pictures as "trash," and the wave mechanics as useful only for calculational purposes. As for Schrödinger's imagery, Heisenberg recalled that he found the "actual psychological situation of that time very upsetting because Schrödinger tried to push us back into a language in which we had to describe nature by intuitive methods."

During the brief period mid-1925 through fall of 1927 problem after problem that had resisted treatment in the old Bohr theory was solved, and several exciting and unexpected new results emerged. In further virtuoso performances Heisenberg, himself, was responsible for the solution of several key problems. Some of the new results were puzzling and misunderstood because until the Autumn of 1927 the new atomic physics lacked unambiguous interpretation of its syntax. For example, although results of calculations agreed with empirical data, neither the meaning of intermediate manipulations nor the newly emerging mysterious properties of subatomic particles were understood. This situation was rooted in the total failure of physicists to extend the mental imagery of classical physics, i.e., customary intuition with its perception-laden language, into the domain of the atom.

Physicists were adrift with no anchor to the world of sense perceptions. Continued reliance on customary intuition was the stumbling block in Bohr's and Heisenberg's heroic struggles at Bohr's Institute in Copenhagen during fall of 1926 into Spring of 1927 to interpret the syntax of the new atomic physics. As Heisenberg wrote in his November 1926 article "Quantum Mechanics," "the electron and the atom possess not any degree of direct physical reality as the objects of daily experience...The new program of quantum mechanics has above all to free itself...from intuitive pictures."

On 23 November 1926 Heisenberg wrote to Wolfgang Pauli, "What the words 'wave' and 'corpuscle' mean we know not any more." Heisenberg recalled that these struggles left Bohr and himself in a state of "despair." The naive realism of classical physics had utterly failed in the atomic domain. The probing of foundations in this extraordinary paper of Heisenberg reflects what Pauli wrote of him around this time -- "Heisenberg has learned a little philosophy from Bohr in Copenhagen." The despair of Bohr and Heisenberg at this time squares with what the psychologist Rudolf Arnheim, describes in his book Visual Thinking, of the "apprehension" that develops in a scientist when the change is made to a "model of higher complexity [when] the timeless stability of concepts, cherished by the thinker, no longer has its counterpart in the world these concepts describe."

By late 1926 Bohr accepted the wave-particle duality of light and matter and, recalled Heisenberg, "wanted to take this dualism [as the] central point." Consequently, Bohr could deal effectively in Gedanken experiments with pictures. Heisenberg persisted in focusing on his own quantum mechanics with its essential discontinuities and unvisualizable particles.

Requiring a respite from their intense interactions, in early February of 1927 Bohr went on a skiing trip to Norway. It was during this break that Heisenberg realized a means for interpreting the mathematics of the quantum mechanics, which he formulated in his paper submitted for publication in March 1927, "On the Intuitive Content of the Quantum-Theoretical Kinematics and Mechanics." The importance of the concept of intuition to Heisenberg is made forcefully clear here, because it is in the title to this important paper in the history of ideas. There Heisenberg demarcated boldly between "to be understood intuitively" and the visualization of atomic processes. Focusing exclusively on the quantum mechanics with its unvisualizable particles, and taking support from the redefinitions of physical reality in the large required by the special and general theories of relativity, Heisenberg proposed tHat in the atomic domain a revision of our usual physical concepts "appears to follow directly from the fundamental equations of the quantum mechanics." That is, Heisenberg permitted the mathematics of the quantum mechanics to determine the restrictions on such perception-laden symbols as position and momentum. These restrictions are the uncertainty relations. Consequently, Heisenberg redefined the concept of intuition through the theory's mathematics, and separated intuition from visualization.

In later years Heisenberg recalled Pauli's response to the uncertainty principle paper as: "Es wird Tag in der Quantentheorie."

Bohr thought otherwise. Later in February Bohr returned to Copenhagen and disagreed vociferously with Heisenberg's approach. In the interim Bohr had realized that the wave-particle duality of light and matter, and not the essential discontinuities, was the root of the need to redefine physical concepts. Bohr pressed his own view relentlessly and a tense atmosphere developed.

Although by May of 1927 relations improved between Bohr and Heisenberg, all differences of opinion were not yet settled. For example, in a letter to Pauli dated 16 May 1927, Heisenberg wrote that there are "presently between Bohr and myself differences of opinion on the word 'intuitive'." This is reasonable because to Bohr a mathematical formalism that stressed discontinuities and unvisualizable particles could not decide what was intuitive.

On 16 September 1927 at the International Congress of Physics, Lake Como, Italy, Bohr read a version of what would be the final published installment in the series of papers that reached back to 1913. It is a Bohr tour-de-force, dense with a labyrinthine web of arguments that lead essentially to two principal conclusions which comprise the principle of complementarity.

(1) In the atomic domain an essential difference lies between pictures and the actual development of atomic systems. For in this domain physical laws require a "departure from visualization in the

usual sense."

(2) Bohr's masterstroke in 1927 was to realize that the wave-particle duality of light and matter was only paradoxical because of limitations in the atomic domain on our language. Rather, in the atomic domain both horns of the dilemma are connected. That is, Planck's constant links quantities that characterize a localized entity like a particle (energy and momentum) with quantities that characterize an extended entity like a wave (frequency and wavelength). Bohr reasoned that just as the large value of the velocity of light had prevented our realizing the relativity of time, the minuteness of Planck's constant rendered paradoxical the wave-particle duality of matter and light. For, Planck's constant places restrictions on the use of our language in the atomic domain and so too on our customary intuition or mental imagery, which enables us to describe only things that are either continuous or discontinuous but not both. Yet subatomic particles are simultaneously localized and extended. So, stressed Bohr, the wave and particle modes of light and matter are neither contradictory nor paradoxical but complementary. Both modes or sides are required for a complete description of the atomic entity. The observed, that is, measured, mode or side depends on the experimental arrangement.

As had been the case in Einstein's invention of special relativity, the roots of complementarity run deeper and are more far-ranging than considerations of physics or even philosophy per se. For example, in 1913 there was Bohr's concern over the problem of assigning semantics or meaning to the mathematical symbols in his first atomic theory paper. Well known is Bohr's life-long interest in how meaning is assigned to words; how meaning is affected by context or interaction; and how context depends on the mental imagery constructed from the world in which we live. As Bohr put it in the published 13 April 1928 Die Naturwissenschaften version of his Como lecture, "every word in the language refers to our mode of intuition."

The linguistic root of complementarity has a psychological part which could have been triggered by or at least gained support from Bohr's awareness of William James's book Principles of Psychology, Soren Kierkegaard's writings and/or their interpretation by the Danish philosopher Harald Hoffding, who had been a university teacher of Bohr's and then life-long friend. Bohr broached the psychological dimension in the April 1928 printed version of the Como lecture, and it echoes James and Kierkegaard. For example, wrote Bohr, the failure of our "customary intuition" in the atomic domain can be traced to "the general difficulty in the formation of human ideas, inherent in the distinction between subject and object." Suffice it to say here that the origins of Bohr's psychological component of complementarity is still a puzzle for the historian of ideas, owing mainly to contradictory historical data. This complex issue has been explored in some depth by Gerald Holton and Max Jammer.

What I should like to add to the mosaic that is the background of complementarity is Bohr's interest in art, especially cubism. We might expect, therefore, to see in his study a painting by one of the acknowledged masters of this genre -- for example, a Braques, a Gris, a Duchamp, or maybe a Picasso. Instead Bohr exhibited Jean Metzinger's 1924 painting L'Ecuyere. This choice indicates a quite special interest in cubism, and perhaps a clue to yet another path to complementarity -- that is, assuming that Bohr had known about Metzinger prior to 1927. It may be the case that after 1927 Bohr found in Metzinger's writings another example of complementarity. Let's make the first assumption and attempt to find what it was in Metzinger that interested Bohr. Most art historians consider Metzinger to have been a minor cubist painter, but everyone agrees that he was a major theorist of the cubist school. In 1912, Metzinger and Albert Gleizes published a systematic exposition of cubist methods in their widely-read book Du Cubisme. A cubist painting, they wrote, represented a scene as if the observer were "moving around an object [in order to] seize it from several successive appearances...". Cubists achieved this motif through the interpenetration of figure and space in order to free the artist from a single perspective in favor of multiple viewpoints. And this was what impressed Bohr about cubism. Mogens Anderson, a Danish artist and friend of Bohr, recollected Bohr's pleasure in giving "form to thoughts to an audience at first unable to see anything in [Metzinger's] painting -- They came with a preconceived idea of what art should be." Such had been the case in 1913, when atomic physicists had a preconceived visual image of the atom. By 1925 atomic physicists had come to realize the inadequacy of visual perception, as had the cubists. In 1927 Bohr offered a motif for the world of the atom with striking parallels to the motif of multiple perspectives offered by cubism for glimpsing beyond and behind visual perceptions: According to complementarity the atomic entity has two sides -- wave and particle -- and depending on how you look at it, that is, what experimental arrangement is used, that is what it is.

Today I have discussed how Niels Bohr was led into ever-deeper levels of analyses of atomic phenomena that moved from examining physics per se into an analysis of perceptions and then into an analysis of thinking itself. In this way, one that squares with Schiller's aphorism, Bohr recognized the fullness contained in the wave-particle duality of matter and light, thereby raising atomic physics out of the abyss.

I will conclude with a quote from Bohr's letter of 24 August 1927 to Heisenberg that captures so well the emotional intensity of their research in atomic physics, research that defined a heroic age: "The kind words you wrote about your stay in Copenhagen were a great pleasure to read. Also for me this has been an unforgettable time."