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## THE “COPENHAGEN INTERPRETATION” OF QUANTUM MECHANICS AND PHENOMENOLOGY

### INTRODUCTION: THE “SCIENCE WARS”

The conflict that has come to be known as the “Science Wars” started when the biologist, Paul R. Gross, and the mathematician, Norman Levitt, published the book, *Higher Superstition: The Academic Left and Its Quarrels with Science*. The book was a fierce attack on certain quarters within the history of science, philosophy of science and sociology of science – such as existentialism, phenomenology, postmodernism, feminism, multiculturalism and so on. The next year, 1995, the book was followed up with a conference in New York given by the New York Academy of Sciences titled *The Flight from Science and Reason*. The conflict gained momentum when the physicist Alan Sokal published the article “Transgressing the Boundaries: Towards a Transformative Hermeneutics of Quantum Gravity” in the journal for cultural studies, *Social Text*. Soon after the article was published, Sokal revealed that the entire thing had been a hoax. He had intentionally written an article that contained a lot of nonsense, however it was written using fashionably correct terminology with references to a range of “postmodern” thinkers. The hoax gained worldwide publicity, and many of the participants in the debate have claimed that this debate shows that C.P. Snow’s “two cultures” still exist.<sup>1</sup>

Yet the fronts in this debate do not coincide with Snow’s “two cultures” right off. The two camps are not divided between the humanities/social sciences on the one side and the natural sciences/technology on the other. The majority of the contributors to *The Flight from Science and Reason* were humanists and social scientists. Among these were a well-known philosopher of science (Mario Bunge) and a well-known historian of science (Gerard Holton). At the outset, therefore, the issues raised apply to different academic disciplines. Alleged irrational tendencies in the natural sciences were also attacked. That Ilya Prigogine would be criticized could be expected. But it has not been generally recognized that Niels Bohr and Werner Heisenberg were attacked from the very beginning. Indeed, *Higher Superstition* has an article attacking Bohr and Heisenberg, accusing them of advocating irrationalism and subjectivism.<sup>2</sup>

The stumbling block is what is known as the “Copenhagen interpretation of quantum mechanics.” The name alludes to the central role played by Bohr and his institute in Copenhagen in the development of the interpretation. However, it was early accepted by the majority of physicists, and in ordinary discourse the “Copenhagen interpretation of quantum mechanics” is synonymous with “quantum mechanics.”

One example is the article by Mara Beller, professor of history and philosophy of science at the Hebrew University of Jerusalem: “At Whom are We Laughing?” Its main thesis is that Sokal’s hoax applies to the founders of quantum mechanics as much as it applies to the “postmodern” milieu that Sokal wanted to ridicule.<sup>3</sup> The irony is that the attacks on Bohr and Heisenberg indirectly constitute an assault on what may be regarded as the very foundation of modern physics.

In this article I shall try to show that the attack on (the Copenhagen interpretation of) quantum mechanics in the Science Wars is no accident, and that quantum mechanics and phenomenology have more in common than being attacked in the Science Wars.

### A SHORT HISTORY OF QUANTUM MECHANICS

It is now one hundred years since Max Planck hesitatingly introduced the notion of the quantum, as an attempt to solve a specific problem in physics concerning so-called black-body radiation. The next step was taken by Albert Einstein in 1905. He was able to explain a hitherto unexplained phenomenon related to the photoelectric effect by assuming that light can only transfer energy in specific quantities, so-called light quanta or photons. In 1913, Bohr proposed his model of the hydrogen atom, which implies that electrons in an atom can only circle the nucleus in certain orbits, and that a light quantum is absorbed or emitted when the electron jumps from one orbit to another. This was in accord with Einstein’s photon hypothesis. In 1924, Louis de Broglie assumed that matter, for example electrons, may be regarded as waves. But this assumption implied a paradox. Light, which was previously regarded as waves, revealed properties which could only be explained by assuming that it consisted of particles. Matter, which was regarded as being made up of particles, revealed properties that could only be explained by assuming that the alleged particles behaved as waves. But can something be both a wave and a particle at the same time?

Bohr early recognized that quantum mechanics was incompatible with some of the basic assumptions in classical physics, assumptions that had been taken for granted since Galileo and Descartes. One assumption was that a complete description of the world in the final outcome had to be deterministic. Another was that objectivity means describing reality as it is independently of man. According to Bohr and his pupil Heisenberg<sup>4</sup> it is impossible to maintain this notion of objectivity. The observer has to be taken into consideration, and they emphasized that in quantum mechanics it is impossible to maintain an absolute separation between the knowing subject and the object of knowledge. In Heisenberg’s words:

...the traditional requirement of science ...permits a division of the world into subject and object (observer and observed)...This assumption is not permissible in atomic physics; the interaction between observer and object causes uncontrollable large changes in the system being observed, because of the discontinuous changes characteristic of the atomic processes.<sup>5</sup>

Therefore, in observing a property, for example, the position of an electron, a disturbance of the object is unavoidable. In 1927 Heisenberg formulated his famous

uncertainty relations, according to which the product of the uncertainties in two (non-commuting) entities must necessarily exceed a given constant. This can be written

$$\Delta x \cdot \Delta p \geq h/4\pi$$

For example,  $x$  can denote the position of a particle, and  $p$  its linear momentum.  $\Delta x$  is then the uncertainty in the determination of the position, and  $\Delta p$  is the uncertainty in the determination of the momentum of the same particle.  $h$  is Planck's constant. The implications are radical. For example, if we know the position of a particle exactly, its momentum is totally unknown, and if we know the momentum exactly, its position is totally unknown.

However, this relation may be interpreted in different ways. One might argue that the particle has a well-defined position and momentum, but our knowledge of these magnitudes is limited. This is the *hidden variable interpretation* of quantum mechanics. We shall later see that among others Albert Einstein maintained this view. However, according to the Copenhagen interpretation, we cannot ascribe physical reality to magnitudes that are not measured. Heisenberg put it this way:

When one wants to clarify the meaning of the words "the position of an object," for example an electron (relative to a given frame of reference), one has to specify certain experiments with which one can measure the "position of the electron": if this is not the case, the words have no meaning.<sup>6</sup>

### EINSTEIN: QUANTUM MECHANICS IS INCOMPLETE

Although the Copenhagen interpretation was quickly accepted by the majority of physicists, there were some famous dissidents. They count Einstein, Schrödinger, and Bohm, to name a few. In a paper from 1935, "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?" Einstein and his co-authors Podolsky and Rosen challenged the Copenhagen interpretation. Because this article set the stage for all subsequent debates on the interpretation of quantum mechanics, I outline the main arguments of the article.

Einstein, Podolsky, and Rosen start with two criteria which any acceptable theory must satisfy: 1) It must be correct and 2) it must be complete. The first criterion was not a problem, because quantum mechanics was in agreement with known observations at the time. Therefore, the paper discusses the second criterion exclusively, the question if quantum mechanics may be regarded as a complete theory. Completeness is defined as the requirement that "every element of the physical reality must have a counterpart in the physical theory (condition of completeness)." But the term "physical reality" which appears in the definition cannot be taken for granted. The authors do not attempt to give a complete definition of reality, but give the following criterion, which is crucial in the later discussion:

If, without in any way disturbing a system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity [criterion of physical reality].<sup>7</sup>

The first deals with the observation of a single particle. According to Heisenberg's uncertainty principle, in the case that the position is exactly known, the momentum is completely unknown. According to the criterion of physical reality the momentum has no physical reality because it cannot be predicted at all. In this case one may argue that this is due to the inevitable disturbance of the system in carrying out measurements. So far it looks plausible. However, when Einstein, Podolsky and Rosen extend the example to two particles, an apparent paradox arises. I shall give a simplified version

of the example, leaving out all technicalities, but retaining the essential features. In the thought experiment two particles have interacted so that we know that they have correlated properties. The properties used by Einstein, Podolsky and Rosen are position and momentum of each particle. After the interaction the two particles fly off in different directions. They do not interact any more, and may therefore be regarded as two separate systems.

Let us call the two particles I and II respectively, and we carry out measurements on particle I. Because the two particles are correlated, we can infer from particle I to particle II. We have then two possibilities: 1) We can either measure the position of particle I, and infer the position of particle II, or 2) we can measure the momentum of particle I, and infer the momentum of particle II. According to Einstein, Podolsky, and Rosen, the paradox arises in the following way: On particle I we either measure the position or the momentum. When one of them is measured, the other is excluded. This follows directly from Heisenberg's uncertainty relations and can be explained by the inevitable disturbance involved in the measuring process. We should keep in mind that according to the Copenhagen interpretation the unknown property has no physical reality, and this applies to particle II as well as to particle I. Therefore, in case 1) the position of particle II has no physical reality, and in case 2) the momentum of particle II has no physical reality. But according to Einstein, Podolsky, and Rosen, particle II is a different system, separated from particle I. In observing particle I, particle II has not been affected. They therefore ask the question: How is it possible that what we observe on particle I, may determine which property of particle II has physical reality?

Einstein, Podolsky, and Rosen propose two possible alternatives: The first alternative is that the magnitudes do not have physical reality when they are not observed<sup>8</sup>. According to their view this implies that the event that particle I is observed is transmitted to particle II with a velocity that exceeds the velocity of light. According to the special theory of relativity signals cannot be transmitted faster than the velocity of light ("Einstein locality"). Therefore, this alternative violates Einstein locality, and Einstein, Podolsky, and Rosen exclude this possibility. (Einstein later called this alternative "spooky action at a distance"). According to the second alternative there are elements of physical reality (in case 1 the momentum of particle II and in case 2 the position of particle II) which are not represented in the theory. They conclude that the theory is incomplete.

In an article with the same title as Einstein, Podolsky, and Rosen's article, Bohr answered the criticism, and argued that quantum mechanics is indeed complete. He makes two main points. The first is that the expression "without in any way disturbing the system," in the criterion of physical reality is inadequate. Any description of physical reality must include the *measuring instruments* required to observe this reality. Bohr gives a detailed analysis of measurements of the position and momentum of a particle. The conclusion of these considerations reflects "even at this stage"

there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system*. Since these conditions constitute an inherent element of the description of any phenomenon to which the term "physical reality" can be properly attached, we see that the argumentation of the mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete.<sup>9</sup>

Bohr's second point is that the two particles in the thought experiment cannot be separated into two systems. Even if the two particles are travelling in opposite directions with the speed of light, they are from a quantum mechanical point of view

one unseparable system. Bohr therefore chooses the second of Einstein, Podolsky, and Rosen's alternatives: violation of Einstein locality (non-locality or quantum entanglement).

Bohr rejected Einstein, Podolsky, and Rosen's definition of physical reality. His own alternative goes like this: "In objective description, it is indeed more appropriate to use the word phenomenon only to refer to observations obtained under specified circumstances, including an account of the whole experimental arrangement."<sup>10</sup>

It is worth noticing that whereas Einstein, Podolsky, and Rosen's definition of physical reality is basically the same as Galileo's and Descartes', Bohr's definition is more in accordance with the notion of objectivity held by a working scientist. The basic requirement in experimental science is the reproducibility of an experiment by fellow scientists. However, this is only feasible when an adequate description of the experimental setting is provided.

The controversy between Bohr and Einstein concerned the philosophical interpretation of quantum mechanics, and not its empirical validity. On the contrary, it looked as if the two interpretations would always yield the same predictions. However, in 1964, John Bell formulated the relations that have later been known as the "Bell inequalities." If Einstein, Podolsky and Rosen's interpretation of quantum mechanics was correct, the inequalities would not be violated, but if the Copenhagen interpretation was correct, they would in some situations be violated. Therefore, it looked as if the controversy could be settled through experiments. The first experiments were carried out in 1972, and later a series of experiments have been carried out, the most famous being the "Aspect experiments." With a few exceptions they have all violated the Bell inequalities and supported the Copenhagen interpretation. However, needless to say, the experimental results have not ended the controversy.<sup>11</sup>

### IS THE COPENHAGEN INTERPRETATION POSITIVIST?

Bohr's and Heisenberg's position is sometimes regarded as positivist or instrumentalist. Like Ernst Mach they allegedly regarded physical magnitudes as nothing but theoretical constructions. There are reasons for maintaining that at least Heisenberg was influenced by Mach, and if we look at the quotation from Heisenberg cited above, this allegation has some plausibility. There are also quotations from Bohr that have a positivist flavour. One example is the following: "There is no quantum world. There is only an abstract quantum description. It is a mistake to think that it is the task of physics to find how nature is. Physics is about what we can say about nature."<sup>12</sup>

But nevertheless it is a misunderstanding to regard the Copenhagen interpretation of quantum mechanics as positivism. The root of this misunderstanding is the simple dichotomy used in much of the literature addressing this question. It is inferred that Bohr was a positivist by using the following argument: Einstein was a realist and there was a fundamental disagreement between Bohr and Einstein. Therefore, Bohr was a positivist. In this context, "realism" means Einstein's realism. But Einstein's realism is not the only realist alternative. We remember that according to realism, scientific objectivity describes physical reality independently of man. This is essentially the realism of Galileo and Descartes. Bohr doubtless did not accept such a naive realism. But this does not make him a positivist.<sup>13</sup> To avoid this fallacy requires distinctions other than the realist/ instrumentalist dichotomy. I shall not discuss realism. But I shall

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