Carl Friedrich von Weizsäcker's *Ortsbestimmung eines Elektrons* and its influence on Grete Hermann

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Abstract

Grete Hermann's 1935 article *Die naturphilosophischen Grundlagen der Quantentheorie* remains not only an important historical contribution to the philosophy of physics, but until today her viewpoint concerning the issue of causality in quantum theory raises questions. Her argumentation is strongly influenced by an article by Carl Friedrich von Weizsäcker from 1931, in which he analyses the "Heisenberg microscope". My aim is to briefly review the main ideas of this article and the way how it may have shaped the thinking of Grete Hermann.

1 Introduction

Most likely Grete Hermann's contribution to the historical development of quantum theory would be almost forgotten today, if Werner Heisenberg had not dedicated a whole chapter to her in his book *Der Teil und das Ganze* [Heisenberg 1969] (the following citations are taken from the English translation *Physics and Beyond* [Heisenberg 1971]). Referring to the years 1934/35 when he was in Leipzig, he writes in the opening sentences of this chapter:

> *We were offered a special occasion for philosophical discussions [...] when the young philosopher Grete Hermann came to Leibzig. [...] Grete Hermann believed she could prove that the causal law – in the form Kant had given it – was unshakable. Now the new quantum mechanics seemed to be challenging the Kantian conception, and she had accordingly decided to fight the matter out with us.*

The mere fact that Heisenberg devotes a chapter of his book to the philosophical discussions with Grete Hermann can be taken as evidence for a positive and lasting impression, however, referring to her twice as "junge Philosophin" (in the German original) does not really pay credit to the fact that Grete Hermann was about nine months older than Heisenberg and had a PhD in mathematics. The chapter ends with the remarks:

> *"[...] Science progresses not only because it helps to explain newly discovered facts, but also because it teaches us over and over again what the word 'understanding' may mean." This reply, based partly on Bohr's teachings, seemed to satisfy Grete Hermann to some extend,*[a] *and we had the feeling that we had all learned a good deal about the relationship between Kant's philosophy and modern science.*
>
> [a]The expression Heisenberg uses in the original German edition – "[sie war], wie uns schien, einigermaßen zufrieden" – seems to express even more uncertainty about this.

Towards the end of her time in Leipzig, Grete Hermann wrote an article entitled *Die naturphilosophischen Grundlagen der Quantenmechanik.* A short version of this article, leaving out all the interesting technical details, appeared in "Die Naturwissenschaften"[Hermann 1935b], the full version was published in "Abhandlungen der Fries'schen Schule" [Hermann 1935a], which was "hardly the place where the devotees of von Neumann's defective proof were likely to ever discover it"[Gilder 2008]. In this citation, Louise Gilder refers to a proof of John von Neumann [von Neumann 1932], according to which the non-determinism of quantum theory cannot be explained by an extension of quantum theory by additional, hitherto unobserved variables.

In her article Grete Hermann points out that von Neumann's proof is based on an assumption which is physically not justified and which, according to her assessment, is circular by putting what von Neumann wants to prove already into the assumptions. (For more details see the contribution of M. Seevinck in this volume [Seevinck 2013].)

Whether Grete Hermann was really convinced of the "Copenhagen Credo" which served as a philosophical interpretation of the quantum formalism remains open. The first eight chapters of Grete Hermann's article leave the reader with the impression that she is arguing in favor of additional variables (not included in the formalism of quantum theory) which could save the principle of causality. After a very detailed and rigorous analysis (of which the refutation of von Neumann's assumptions is a part) she comes to the conclusion that additional variables are not ruled out according to the current knowledge or status of quantum theory. Such additional variables would indeed have been an explanation of the observed indeterminism in full agreement with Kantian ideas of causality. Yet, at the end of chapter eight, one senses an abrupt change in style and argumentation which gives the article a twist into a different direction. She argues that quantum mechanics does not need a completion by such variables "because all causes are already known", and essentially the same statement is repeated several times, often emphasized by italic fonts. However, her argumentation in favor of a causally complete quantum formalism is by far not as convincing as her previous refutation of all arguments against hidden variables. Heisenberg's very cautious expression that Grete Hermann was "wie uns schien, einigermaßen" satisfied adds to the impression, that this "Bohrian" style of argumentation may not really have been her full conviction. Maybe the historians of science will find the reasons for her surprising change of mind.

In this present article my main subjective is concerned with the influence of an article of Carl Friedrich von Weizsäcker onto Grete Hermann's argumentation. Already in 1931, at the age of 19 and being in the group of Werner Heisenberg for only about a year, Carl Friedrich von Weizsäcker published the results of a theoretical investigation of the Heisenberg microscope: *Ortsbestimmung eines Elektrons durch ein Mikroskop* (Determination of the position of an electron by a microscope) [Weizsäcker 1931]. Heisenberg had suggested to him to mathematically analyze the measurement of the location of an electron by the scattering of a single photon which then passes through an optical lens and is finally registered on a screen in the image plane of that lens. The question was whether a quantum mechanical (even quantum field theoretical) analysis of this situation leads to the same results as the classical treatment in the context of wave optics or even geometrical optics. In Section 2, I will review the main arguments of this article.

Grete Hermann devotes a whole section of her article to the analysis of von Weizsäcker and uses his results for her argumentation according to which quantum theory in its present form is already causally complete. In Section 3, I will analyze her arguments and the way she interprets von Weizsäcker's article. For me, her reasoning does not sound convincing – maybe except for one argument, which is not even explicitly mentioned in her text – and I doubt whether Grete Hermann was herself convinced by it. The last Section 4 addresses the question to which extend the ideas of Einstein, Podolsky and Rosen were already contained in the articles of C.F.v. Weizsäcker and Grete Hermann. With a few concluding and summarizing remarks I will finish this article.

2 von Weizsäcker's analysis of the Heisenberg microscope

Carl Friedrich von Weizsäcker had met Werner Heisenberg in Copenhagen (where his father was a diplomat) when he was fourteen and this meeting greatly influenced his decision to study physics. Around 1930, at the age of eighteen, he joined the group of Werner Heisenberg, and in April 1931 he submitted the results of an investigation of the Heisenberg microscope to the *Zeitschrift für Physik* entitled *Ortsbestimmung eines Elektrons durch ein Mikroskop* [Weizsäcker 1931]. He opens the article by writing: "In the following I will discuss a particular thought experiment for the determination of the location of an electron, namely the imaging of an electron, which is illuminated with light of a sufficiently short wavelength, by a microscope."

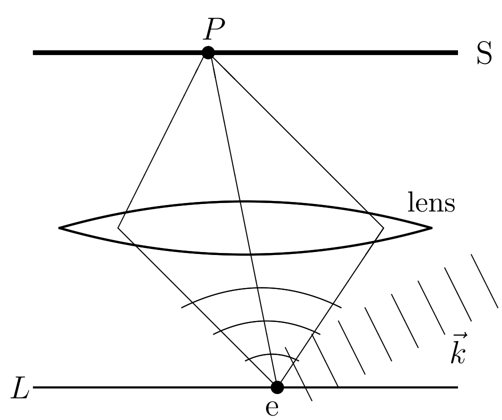

Fig. 1. An electron e is located in a plane L and allowed to move freely within this plane. A single incoming photon, described by a planar wave-vector $\vec{k}$, is scattered by the electron in form of a spherical wave. The wave is guided through an optical lens according to the classical laws of optics, and the photon hits the screen S, which is located in the image plane of the electron, in point P.

Figure 1 shows the basic set-up of the Heisenberg microscope. An electron is allowed to move freely within a plane L. The electron is hit by a single photon of which the wave vector $\vec{k}$ is known. We now assume that the photon is scattered by the electron and its quantum state is described by a spherical wave emanating from the location of the electron at the moment of scattering. The elaborate calculations of von Weizsäcker, based on a quantum field theoretic formalism developed by Heisenberg and Pauli, show that one can now essentially use classical wave optics to deduce that the wave function of the single photon propagates through the optical lens in just the same way as a classical spherical electromagnetic wave. He discusses the limitations of such an approach, but the essential results remain the same. In particular, this wave becomes focused in a small region in the image plane behind the lens and if we put a photographic plate into this plane it will register the photon in point P.

The location of P, even if it is produced by just a single photon, allows us to deduce the location of the center of the spherical wave function and, thereby, the location of the electron at the moment of scattering.

On the other hand, we can also put the photographic plate into the focal plane of the optical lens (Fig. 2). From the location of point P' where the photon hits this plate we now obtain the information about the direction from which the photon entered the lens.

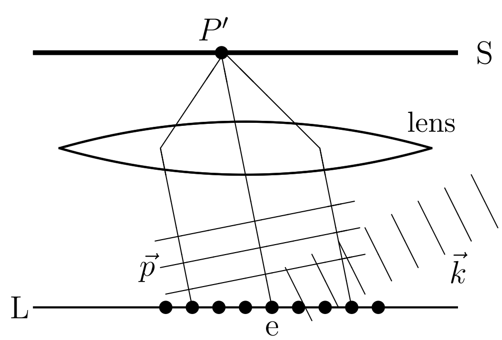

Fig. 2. If the photographic plate is put into the focal plane of the lens, point P' contains the information about the direction from which the photon entered the lens, i.e. about the wave vector $\vec{p}$ (or momentum) of the photon. For this situation, the electron has to be described by a momentum eigenstate which is delocalized (indicated by the many "virtual" electrons).

The process can now be described as follows: The photon is scattered by the electron as a planar wave with wave vector $\vec{p}$. This implies that there is no particular scattering center but the state of the electron has to be thought of as distributed over the "whole plane" and the electron is described by a momentum eigenstate. The information about the scattering center of the photon and electron is now lost, instead the difference between the initial wave vector $\vec{k}$ and the wave vector $\vec{p}$ of the scattered wave is equal to the momentum transfer from the photon to the electron. If we know the initial momentum of the electron, we can infer from P' the momentum of the electron after the scattering process.

Expressed in todays language, after the scattering the electron and the photon are to be described by an entangled state. We can expand this entangled state in two different bases: (1) a momentum base for the electron as well as for the photon (which, after the scattering, is described by a planar wave with a fixed wave vector), and (2) a position base where the electron at the moment of scattering is located at a point x and the scattered photon propagates away from this center x in form of a spherical wave. Very formally this means for the state of the total system after the scattering took place (and before the photon is absorbed by the photographic plate):

$$|\Psi_f\rangle \simeq \int \mathrm{d}p \; a(p) \; |p\rangle_{\mathrm{e}} |k-p\rangle_\gamma \simeq \int \mathrm{d}x \; b(x) |x\rangle_{\mathrm{e}} |\mathrm{s.w.}(x)\rangle_\gamma \qquad (1)$$

where $|\mathrm{s.w.}(x)\rangle$ refers to the state of a spherical wave with center x. $a(p)$ and $b(x)$ are certain expansion coefficients. The integration over x and p extends over the possible values these quantities can assume under the restriction that the electron is bounded to the plane L.[1] It is important to notice that both expansions describe the same total state of both particles, however, with respect to different bases.

Depending on whether the photon is measured in the image plane or the focal plane one either measures the center x of the spherical wave of the photon or the momentum $\vec{p}$ of the planar wave of the photon. Due to the entanglement this implies indirectly a measurement of the location x of the electron or a measurement of its momentum $\vec{k}-\vec{p}$ (actually, the momentum transfer from the photon to the electron). The situation is very similar to the one which is used by Einstein, Podolsky and Rosen four years later in their famous EPR-paper [Einstein et al. 1935], and I will come back to this point in Sec. 4.

3 Von Weizsäcker's impact onto Grete Hermann's argumentation

The tenth chapter in Grete Hermann's article is devoted to an analysis of the article of C.F.v. Weizsäcker. [2]

[1]The entanglement may not be perfect due to the size of the microscope and other influences, however, this does not change the basic structure of the argument.

[2]Interestingly enough, now it is she who simply writes about "a student of Heisenberg", mentioning his name only in the footnote with reference of the publication. The mutual

Grete Hermann first describes the set-up of the Heisenberg microscope and the two cases described above: (1) putting the photographic plate into the image plane yields information about the location of the electron, and (2) putting the plate into the focal plane yields information about the momentum transfer from photon to electron. She also mentions a third case:

> *However, if no photographic plate is put into place at all, but the light quantum can go its way without being caught, then there is a third albeit less intuitive description of this state after the collision. The wave function ascribed to the system consisting of the light quantum and the electron is now a linear combination: each of its summands is the product of [two] wave functions which describe the electron and the light quantum, respectively. Therefore, this linear combination does not describe the light quantum and the electron each by itself but only in their relationships to one another. To each state of one of the particles is associated a state of the other.*

This is an absolutely clear and precise description of what later became known as "entanglement" (this term was coined by Erwin Schrödinger in an article from 1935 [Schrödinger 1935]). Grete Hermann continues by arguing that

> *... depending on the way how one obtains knowledge about the observed system, or, equivalently, the observational context, we obtain different wave functions for the same system and the same instant – namely for the electron immediately after the collision with the light quantum. Thus, the quantum mechanical characterization cannot be ascribed to the system "by itself", like in the classical case, which means: independent of the type of observation by which one obtains knowledge about it.*

In my view it is not really clear to which instant exactly Grete Hermann refers: the entangled state of photon and electron immediately after the collision, or the state of the electron immediately after the registration of the photon in one of the planes – the focal plane or the image plane. At least from the modern perspective, the total (entangled) state of the electron and the photon immediately after the collision is independent of the observational context, however, it can be expanded in terms of different bases as in eq. 1. The electron alone does not have a definite state immediately after the

high scientific respect between Carl Friedrich von Weizsäcker and Grete Hermann is well known; however, taking into account the political situation in 1934 Germany, it remains an open question to which degree this esteem also extended to the private domain between the conservative aristocrat from a diplomat family and the member of the "social battle league".

collision, but only "relative states" with respect to the basis one chooses for the description of the photon. This state is conveniently chosen with respect to the type of measurement one intents to make (the "observational context"), therefore, also the "relative states" of the electron depend on this context.

Grete Hermann now proceeds by arguing that, in retrospective, after the observer knows the outcome of the measurement of the photon, one can with "sufficient reason" reconstruct the events which let to this outcome. If, e.g., the photon has been measured in the focal plane one can reconstruct the momentum of the electron. Here, she gives up predictability as a necessary condition for causality – which she defends in the opening sections of her article as "indispensable" – and replaces it essentially by the "principle of sufficient reason" of Leibniz [Leibniz 1714]. This principle of sufficient reason only requires that *after* something has happened it should be possible to figure out the sufficient reasons why it was so and not otherwise and thus replaces the requirement of predictability as a characterization of causality. In § 9 (before she discusses von Weizäcker's example) she explains:

> *… if one performs such a measurement … one obtains not only a quantum mechanical description for the new state [of this system] which attributes a sharp value to this quantity, but in connection with this description one can in addition find the reasons why it was exactly this, not anticipated value which was obtained.*

And after she described von Weizsäckers example, she emphasizes:

> *This example shows that the quantum mechanical formalism itself … gives sufficient reasons for these results but does not provide any clues which allow a prediction of all outcomes. In the present case it is in principle impossible to predetermine the location at which the light quantum will darken the photographic plate positioned in, say, the focal plane of the system. Nevertheless, from the observation of this location one can infer the momentum transferred to the electron during the scattering event and recognize in just this momentum transfer the reason why the light quantum hit the plate in exactly this location."*

Max Jammer writes in this context [Jammer 1974]:

It seems, however, that Hermann's claim of retrodictive causality is unwarranted. In the author's opinion she did not prove, as she claimed, that a retroactive conceptual reconstruction of the measuring process provides a full *explanation of the particular result obtained. Although such a reconstruction may prove the* possibility *of the result obtained, it does not prove its* necessity. *Thus in the Weizsäcker-Heisenberg experiment her reconstruction, starting from the observation, accounts for the fact that the photon* can *impinge on the photographic plate where it impinges, but not that it* must *impinge there.*

In my opinion this assessment is absolutely correct, but for me it is hard to believe that Grete Hermann, who proved to be such a sharp analyst in her rejection of the arguments against hidden variables, had overlooked this obvious objection. So, why does she insist that quantum mechanics already gives a complete description of the causal chain of events leading to a particular outcome? Her arguments, even though repeated several times, are not really convincing and often even circular. The following is just a attempt to figure out what she might have had in mind and to express this in a more contemporary language.

Grete Hermann uses the expression of an "observational context" ("Beobachtungszusammenhang"), which, in a very general way, refers to the experimental set-up which in turn determines the physical quantity one wants to measure. Given a state of a quantum system $|\psi\rangle$ and a measuring device which has a pointer basis $\{|\varphi_i\rangle\}$ with an initial state $|\varphi_0\rangle$, we may express the initial state of the total system before the interaction takes place as

$$|\Psi_{\text{init}}\rangle = |\psi\rangle \otimes |\varphi_0\rangle \,, \tag{2}$$

and after the interaction between both systems (but before a reading of the measuring device) by

$$|\Psi_1\rangle = \sum_i a_i |s_i\rangle |\varphi_i\rangle \,, \tag{3}$$

where the state $|\psi\rangle$ has been expanded according to the eigenstates of the observable which is represented by the measuring device.

Grete Hermann now acknowledges that a different measuring device (representing a different observable) leads to a different expansion:

$$|\Psi_2\rangle = \sum_j b_j |s'_j\rangle |\varphi'_i\rangle \,. \tag{4}$$

Note that $|\Psi_1\rangle$ and $|\Psi_2\rangle$ need not be the same states because the measuring devices are different. However, if one considers the photon as the "measuring device" for the electron (and Grete Hermann explicitly emphasizes that almost any system can act as a measuring device in certain situations) there is no "pointer base" distinguished and the two states are the same.

After the interaction between the quantum system and the measuring device has taken place, there is no "state of the quantum system" by itself, but its states can only be defined *relative* to a state of the measuring device, and different measuring devices lead to different "relative states" for the system. This is the "observational context". If the outcome of the measurement is known, we can deduce the state of the quantum system which is correlated to this outcome:

- for measuring device (1) and result k we deduce the state of the quantum system to be $|s_k\rangle$,
- for measuring device (2) and result l we deduce the state of the quantum system to be $|s'_l\rangle$.

Unfortunately, about the next point Grete Hermann is not very explicit. Some passages, like the ones cited above, can be interpreted in the sense that in her opinion the characteristic features described by $|s_k\rangle$ or $|s'_l\rangle$ were already present *before* the interaction between the measuring device and the system took place, but that due to the restrictions of the quantum formalism this state can never be known to the observer in advance. Under this assumption, everything which happened during the measuring process followed a deterministic causal chain. On the other hand, she is well aware that the uncertainty relations do not express a lack of knowledge on the side of the physicist (she explicitly mentions interference experiments which cannot be explained by assuming that we simply don't *know* through which slit a particle passes). What she does not seem to consider is that these states (depending on the measuring device) might have been *created* during the measuring process, and that this "creation" (what is today known as the collapse process) is not causal.

On the other hand, she must have been aware of such ideas: She criticizes Erwin Schrödinger for his opinion (expressed in a 1934 article [Schrödinger 1934]), that a classical form of causality may be maintained if one gives up outdated classical concepts like "location" or "spatial geometry". In this article Schrödinger satirically attacks the notion of "quantum measurement" and proposes to replace it by "Prokrustie", referring to the giant in Greek mythologie, who forces his guests into his beds by stretching or compressing them. In this context Schrödinger remarks "... I know that the experimenter cannot choose the value [of the result of a measurement]; but nevertheless he forces his victim into *one* of his beds while it fits into none".[3]

A possible reason for Grete Hermann's opinion that quantum theory is already causally complete could have been related to an aspect of the Heisenberg microscope (and, more generally, the type of entanglement involved in this situation), which, however, is never explicitly emphasized, neither in the article of C.F.v. Weizsäcker nor in Grete Hermann's article: During the interaction between the electron and the photon the complete information about the state of the electron is transferred to the state of the photon. It carries the full information about both, the location of the electron as well as the momentum of the electron. The decision of the experimentalist to put the photographic plate into the image or the focal plane allows him to extract either one of these two complementary informations about the electron from the photon. (As, in principle, the experimentalist can make this decision after the interaction between electron and photon has taken place and the electron is gone, this is a particular form of "delayed choice experiment" [Wheeler 1978].)

This complete information transfer from electron to photon might have contributed to Grete Hermann's opinion that the quantum formalism does not need the extension by hidden variables because it is already causally complete.

4 EPR anticipations?

In a letter from 1967, Max Jammer pointed out to C.F.v. Weizsäcker that the situation of the Heisenberg microscope is analogous to the one described by Einstein, Podolsky and Rosen in their famous article in 1935. In his answer, C.F.v. Weizsäcker writes [Jammer 1974]:

> *The problem which lead to this paper was certainly closely related to that raised by Einstein, Rosen and Podolsky. Except that Heisenberg, who suggested it to me, and I as well regarded this state of affairs not as a paradox, as conceived by the three authors...*

Max Jammer writes in return [Jammer 1974]:

[3] As a side-remark, in the same article Schrödinger mentions already the possibility of a "measurement without interaction" by remarking that the non-detection of a particle by a detector which surrounds a decaying atom completely except for a small hole gives a very precise information about the trajectory of this particle. The same situation was later emphasized in a famous article by Renninger [Renninger 1960].

It may well be that Heisenberg and von Weizscker were fully aware of the situation without regarding it as a problem. But as happens so often in the history of science, a slight critical turn may open a new vista with far-reaching consequences. As the biochemist Alber Szent-Györgi once said: "Research is to see what everybody has seen and to think what nobody has thought."

As I will argue in the following, indeed there was a "slight critical turn" which distinguishes the argumentation of EPR in their 1935 article from similar situations which had been discussed before. (This new type of strategy on the side of Einstein is also emphasized in [Jammer 1974].) Already many times before, Einstein's criticisms of quantum theory employed examples that implicitly relied on entanglement. A famous example is the light box thought experiment from 1930 [Bohr 1985, Jammer 1974]. However, unit about 1930 his strategy was to prove that quantum mechanics is wrong. In all these cases, Einstein tried to construct thought experiments which seem to violate the uncertainty relations, and in all cases Bohr's reply was that this violation of the uncertainty relations cannot be experimentally verified.

Applied to the case of the Heisenberg microscope, Einstein's old type of argumentation might have been, that one can use the photon to measure the *location* of the electron and simultaneously one can measure the *momentum* of the electron directly. This would mean that both, the position as well as the momentum of the electron are known which would violate the uncertainty relations. Bohr's answer to this hypothetical situation may have been, that Einstein cannot test whether his knowledge about the position of the electron is indeed correct. Measuring the position of the electron *after* the momentum measurement will, in general, yield a different result compared to the one obtained from the measurement of the first photon. Measuring this position *before* the momentum measurement (in which case it will agree with the photon measurement) may destroy any information about the momentum such that an additional momentum measurement is of no relevance.

The new type of attack against quantum mechanics, which EPR use in their 1935 article, does not refer to simultaneous measurements of complementary variables or untestable statements. Applied to the microscope, the new type of argument is: We can freely choose to measure the photon in the image plane or in the focal plane. Now we can predict ("with probability one" and without "disturbing the electron in any way" – these expressions appear in the EPR article [Einstein et al. 1935]) the result of the corresponding measurement (location or momentum) performed at the electron. Their conclusion is that both values must be an "element of reality", which they are not in the formalism of quantum theory. This is the "slight turn" of view.

I should remark that already from 1931 on, Einstein used this new type of argumentation in several articles in order to point out an incompleteness of quantum theory (see, e.g., [Jammer 1974]). However, the 1935 EPR-paper seems to be the one which provoked the strongest reactions. In a letter to Heisenberg [Pauli 1935], Pauli most clearly contrasts the old and the new type of Einstein's strategy:

> *He now has understood that much that two quantities which correspond to non-commuting operators cannot be measured at the same time and that one cannot assign numerical values to them simultaneously.*

(This refers to the old type of attack of Einstein against quantum theory.)

> *Now comes the "deep feeling" and he proceeds: "Because measurements of system 2 cannot disturb particle 1, there must be something called "the physical reality", which is the state of particle 1 in itself, independent of which measurements have been performed at system 2".*

(This sharply characterizes the new strategy.)

The old type of argument – seeking for possibilities to violate the uncertainty relations – is indeed addressed in the article of C.F.v. Weizsäcker. He writes that in order to control the position measurement performed with the photon one has to use the scattering of a second photon, and then he proceeds:

> *Now it is obvious that in this case a later measurement of the momentum [of the electron] does not allow any conclusion about the direction into which the two light quanta have been scattered, because the momentum of the electron between the first and the second scattering process has it's own undetermined value; the same holds obviously for any other control of the position measurement. If, however, one performs a momentum measurement of the electron* before *one has checked the position measurement, the question, whether the microscope has determined the position of the electron correctly, looses its meaning due to the loss of knowledge about the position induced by the momentum measurement.*

This is exactly the Bohr-type rejection of Einstein's old strategy mentioned above.

Referring to the resemblance between his 1931 article and the EPR article, Carl Friedrich von Weizsäcker writes [Weizsäcker 2002]: "I do no longer know whether I became aware of it in 1935 on the occasion of the work of Einstein, Podolsky and Rosen ...", but it seems very likely that he did not realize the relation to EPR, neither in 1935 nor later, until it was pointed out by Max Jammer. The philosopher Walter Schindler, for a long time the assistant (and, in questions of Kantian philosophy, often a kind of personal consultant) of C.F.v. Weizsäcker, remarks that "during the 1960s we often discussed the EPR article, but he [C.F.v.W.] never mentioned his work from 1931. In fact, I didn't know about this article until recently"[Schindler 2012]. Interestingly enough, C.F.v. Weizsäcker gave Walter Schindler a copy of Grete Hermann's article (the long version) during the 1960s.

So, how close is Grete Hermann to an EPR-type argument? Despite her precise characterization of entangled states, she does not seem to realize the point which later EPR make, even though she comes quite close. She explains that from the location where the photon hits the photographic plate (put into the focal plane) one can in retrospective use the causal relationships to determine the momentum transfer from the photon to the electron. She writes: "*Now we can use the mentioned causal relationship for a prediction of an observational result which we can control by actually making this observation. It* [the causal relationship] *can be used to infer the momentum change of the electron, which we now can test.*" Here she correctly argues that the measurement of the momentum of the photon leads to a prediction for the momentum of the electron, and she seems to assume (like EPR) that this momentum of the electron already has a definite value ever since the interaction (and the momentum transfer) between electron and photon took place.

It is most likely that she also is aware of the same situation for the position. We can measure the location of the photon on the photographic plate, now placed into the image plane, and from this deduce the location of the electron (at the moment of scattering). However, she does not conclude from this situation that both location and momentum of the electron must be "elements of reality". It seems that for her only the observational context (where we put the photographic plate) renders, in retrospective, one of these properties a fact.

5 Conclusions

Some of the arguments which Grete Hermann invokes in order to show that the existing quantum formalism does not need an extension by hidden variables because it is already causally complete, still remain mysterious or unclear. Her style of argumentation in this context is in complete contrast to the almost mathematical and accurate refutation of all objections against the possibility of hidden variables. It is difficult to believe that the sudden change in style and argumentation at the end of chapter 8 of her article has no external reason. Whether this reason may be found in a certain social "pressure" from her discussion partners in physics, who presumably tried to avoid even the mere thinking about hidden variables, will, presumably, never be completely uncovered. In fact, many of them had their own no-hidden-variable arguments (see, e.g., [Bacciagaluppi and Crull 2009]) and, therefore, the refutation of von Neumann's assumptions may not have left such a deep impression on them.

Concerning her arguments in favor of a causal completeness of the existing quantum formalism, the main point which remains unclear from her text is whether she considers the electron and the photon immediately after their interaction as entangled or not. If yes, and her clear characterization of "entanglement" in case the photon is not registered supports this possibility, the total state of both particles (eq. 1) does not depend on the observational context; only its expansion with respect to a particular basis does. In this case the instant which cannot be causally explained is the reduction of this total entangled quantum state to a separable state when the photon hits the photographic plate (wherever it is placed behind the lens). Today, this reduction of the quantum state – or wave collapse – is considered to be the most critical "postulate" in the formalism of quantum theory, but in 1935, the collapse problem did not seem to be the main issue. Only after the photon has been registered it is possible to assign a definite value to the momentum or the location – depending on the location of the plate – of the electron.

The other alternative, that already from the moment of interaction between electron and photon the state of the two particles factorizes, leads to a problem: The factorized state does indeed depend on the observational context, i.e., which property of the photon is (later) measured. It is very likely that Grete Hermann did not think of a "delayed choice" scenario, because the actual time scales involved in such an experiment make a delayed choice factually impossible, in particular if one takes into account the experimental capacities of that time. This means, the observational context is already defined when the scattering between electron and photon takes place. This could also be the reason why Grete Hermann misses the EPR argument: As the observational context is given at the moment of scattering, only one of the quantities – position or momentum – is relevant for causal completeness and becomes an element of reality.

On the other hand, in § 9 of her article, she explicitly remarks that any process in physics may become part of a measurement process and that the momentum measurement of a particle may, e.g. after a scattering process, also be considered as a measurement of the momentum of the scattered particle. Taking into account her discussion of von Weizsäckers article and the Heisenberg microscope, the same should hold also for position measurements. In this case, however, I cannot see how she is able to avoid the conclusion of EPR that both, momentum and position, are "elements of reality". Yet, this is in contrast to earlier arguments of Grete Hermann according to which the classical variables – momentum and location – cannot be "hidden variables", as this would contradict the interference experiments.

It is difficult to believe that Grete Hermann did not see these question marks behind her arguments, which brings us back to the question whether she was really convinced or only "wie uns schien, einigermaßen".

Acknowledgement

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References

[Bacciagaluppi and Crull 2009] Bacciagaluppi, G., Crull, E., *Eisenberg (and Schrödinger, and Pauli) on Hidden Variables*, Stud. Hist. Phil. Mod. Phys. 40 (2009) 374.

[Bohr 1935] Bohr, N., *Can quantum-mechanical description of physical reality be considered complete?*, Phys. Rev. 48 (1935) 696–702.

[Bohr 1985] Bohr, N., *Diskussion mit Einstein über erkenntnistheoretische Probleme in der Atomphysik*, in *Atomphysik und menschliche Erkenntnis*, Friedr. Vieweg & Sohn, Braunschweig, Wiesbaden, 1985.

[Einstein et al. 1935] Einstein, A., Podolsky, B., Rosen, N., *Can quantum-mechanical description of physical reality be considered complete?*, Phys. Rev. 47 (1935) 777.

[Gilder 2008] Gilder, L., *The Age of Entanglement*, Vintage Books, New York, 2008.

[Heisenberg 1969] Heisenberg, W., *Der Teil und das Ganze*, Piper Verlag GmbH, München, 1969.

[Heisenberg 1971] Heisenberg, W., *Physics and Beyond*. Harper and Row, Publishers, New York, Evanston, and London, 1971.

[Hermann 1935a] Hermann, G., *Die naturphilosophischen Grundlagen der Quantenmechanik*, Abhandlungen der Fries'schen Schule, Bd. VI (1935) 75–152.

[Hermann 1935b] Hermann, G., *Die naturphilosophischen Grundlagen der Quantenmechanik*, Die Naturwissenschaften 42 (1935) 718–721.

[Jammer 1974] Jammer, M., *The Philosophy of Quantum Mechanics: The Interpretations of Quantum Mechanics in Historical Perspective*, John Wiley & Sons Inc (1974).

[von Laue 1934] von Laue, M., *Über Heisenbergs Ungenauigkeitsbeziehungen und ihre erkenntnistheoretische Bedeutung*, Die Naturwissenschaften 22 (26) (1934) 439–441.

[Leibniz 1714] Leibniz, G.W.v., *The Principles of Nature and of Grace* (1714), from *The philosophical works of Leibnitz*, translated from the original Latin and French by George Martin Duncan; Tuttle, Morehouse & Taylor, New Haven, 1890.

[von Neumann 1932] von Neumann, J., *Mathematische Grundlagen der Quantenmechanik*, Springer Verlag, 1932.

[Pauli 1935] Pauli, W., Letter to Heisenberg, June 15th, 1935, in *Wolfgang Pauli - Scientific Correspondence with Bohr, Einstein, Heisenberg a.o.*, Karl von Meyenn (Ed.), Volume II 1930–1939, Springer-Verlag, 1985.

[Renninger 1960] Renninger, M., *Messung ohne Störung des Meßobjekts*, Z. Physik 158 (1960) 417.

[Schindler 2012] Schindler, W.; private communication in 2012.

[Schrödinger 1934] Schrödinger, E., *Über die Unanwendbarkeit der Geometrie im Kleinen*, Die Naturwissenschaften 22 (31) (1934) 518–521.

[Schrödinger 1935] Schrödinger, E., *Die gegenwärtige Situation in der Quantenmechanik* Die Naturwissenschaften 23 (1935), Part I – III.

[Seevinck 2013] Seevinck, M., *Challenging the Gospel: Grete Hermann on von Neumann's no-hidden variable proof*, in this volume.

[Weizsäcker 1931] von Weizsäcker, C.F., *Ortsbestimmung eines Elektrons durch ein Mikroskop*, Zeitschrift für Physik 70 (1931) 114–130.

[Weizsäcker 2002] von Weizsäcker, C.F., *Der Aufbau der Physik*, dtv, 2002 (4th ed.).

[Wheeler 1978] Wheeler, J. A., *The 'Past' and the 'Delayed-Choice' Double-Slit Experiment*, in *Mathematical Foundations of Quantum Theory*, Marlow, R. A. (ed.), Academic Press, 1978.