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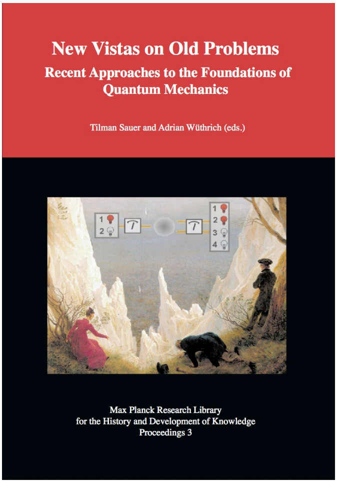

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(How) Did Einstein Understand the EPR Paradox?

Tilman Sauer

Abstract. *An unpublished formulation by Einstein of the EPR paradox in terms of spin variables raises the question as to his precise understanding of this argument. I review various formulations of the argument in this respect and argue that a core tenet of his understanding was completeness in an ambiguous sense. On the one hand, incompleteness is implied when differences in reality are not captured by the theoretical representation of that reality. But for Einstein quantum mechanical incompleteness also implies a contradiction, i.e. when the same physical state of affairs is described by two formulations that are "different in kind." The critical word here is "different" and it is argued that Einstein intends a notion of "different" that implies empirical non-equivalence. Nevertheless, Einstein elaborates on an example where no-signalling applies, a fact which renders the notion of empirical non-equivalence problematic.*

1 Introduction

A great deal of current philosophical reflections on the foundations of quantum mechanics refers back—directly or indirectly—to the incompleteness argument put forward in 1935 by Albert Einstein, Boris Podolsky, and Nathan Rosen (Einstein et al., 1935). As is often the case with such landmark writings, the assessment of their significance, in our case the assessment of the significance of the EPR argument, changed over time. Niels Bohr (1935) felt challenged to respond to the EPR paper right away with a paper that appeared in the same journal under the same title. In later years, the criticism of the foundations of quantum mechanics associated with Einstein's name was often given short shrift. Einstein had turned, in the eyes of many working physicists, from revolutionary to reactionary, and his later views were considered curious at best. In his 'Subtle is the Lord...,'—still the best and only scientific biography of Einstein that we have—Abraham Pais only devoted a single page to the EPR paper. According to him

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> it simply concludes that objective reality is incompatible with the assumption that quantum mechanics is complete. This conclusion has not affected subsequent developments in physics, and it is doubtful that it ever will. (Pais, 1982, 456)

In fact, Pais goes on to side with Bohr:

> 'It is only the mutual exclusion of any two experimental procedures, permitting the unambiguous definition of complementary physical quantities which provides room for new physical laws,' Bohr wrote in his rebuttal. He did not believe that the Einstein-Podolsky-Rosen paper called for any change in the interpretation of quantum mechanics. Most physicists (myself included) agree with this opinion. (ibid.)

This was written in 1982, i.e., at around the time when experiments by Aspect et al. (1982) vindicated Bell's suspicion that the EPR argument actually captured something deeper about the conceptual foundation of quantum mechanics (Bell, 1964, 1987). With Bell's famous theorem and with similar other theorems advanced since then it became clear that the notions of causality, reality, and locality that play a central role in the EPR argument do indeed lend themselves to the formulation of precise and testable experimental predictions.[1]

In recent years, many physicists have taken the incompatibility between certain notions of causality, reality, and locality and the empirical data (correctly described by quantum mechanics) less and less as a philosophical stumbling block, that would best be avoided if one does not want to get snarled up in unproductive interpretational subtleties. Instead, more and more physicists came to regard this tension as a productive resource for new ideas about quantum entanglement, quantum computation, quantum cryptography, quantum information, and similar topics. And, at least in their own way of identifying historical tradition and indebtedness, they began to cite, routinely, the original EPR paper. Einstein, the old, stubborn critic of the new quantum mechanics, became a prescient visionary of new revolutionary ideas again.[2]

The question whether Einstein and his attitude toward quantum theory is justly regarded as either stubborn or prescient is not without some interest for us today. When we project back our modern understanding of the EPR argument to any of its original formulations we may find that Einstein's words do not quite fit with

[1] For one such experiment, see the contribution by Philip Walther in this volume.

[2] See (Home and Whitaker, 2007) for a recent reappraisal of Einstein as a critic of quantum theory.

what we would expect he should have said. Depending on our attitude towards Einstein's understanding of physics, we may then either feel challenged to try to make sense of Einstein's way of thinking. We might either hope that we will get some good insights from this historical endeavor that will help us advance our understanding of current philosophical issues. Or else we may find that his words are just incompatible with what we now take as our best understanding of the issue at hand. In the latter case, we might hope to learn something about the conceptual progress that physics has made since the days of Einstein.

2 The EPR Paper

The EPR paper (Einstein et al., 1935) was received by the *Physical Review* on 25 March 1935 and published in its issue of 15 May of that year.[3] It is, of course, a famous paper, indeed one of the most frequently cited works by Einstein, and its text is well-known. Nevertheless, it is difficult to understand, its logic is convoluted, and its technical argument can be regarded as flawed.[4] It has often been observed that it is not the best place to study the EPR argument.

Let me nevertheless remind you of its more well-known features. The abstract summarizes the argument:

> In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1)

[3] For a discussion of the prehistory of that paper, see (Howard, 1990).

[4] For instance, Cooper (1950) pointed out that the original EPR argument depended on the representation theorem for the momentum operator but violated a necessary premise for the applicability of that theorem. This is because the joint wave function was assumed to vanish at some place, which renders the momentum operator Hermitian but no longer self-adjoint, since its domain is restricted to the positive or negative half-line. Einstein rebutted Cooper's argument with a limiting argument. See (Jammer, 1974, 236–238) for a discussion of further contentions of the EPR argument.

> is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete. (Einstein et al., 1935, 777)

It was pointed out many years ago by Arthur Fine (1996) that Einstein was not responsible for the actual composition of the published EPR paper. About that publication, he wrote in a letter to Erwin Schrödinger:

> Dear Schrödinger:
> I was very happy with your long letter, which dealt with my little paper. This one was written, for linguistic reasons, by Podolsky, after many discussions. It did not come out in the end so well quite what I wanted; rather the main point was, so to speak, buried by erudition.[5]

One thing we learn about Einstein's understanding of the EPR argument from this letter is that he regarded the technical details with which the argument was spelled out as irrelevant for the core of the argument. In fact, he thought that the mathematical details actually obscured the main argument in this case.

In Einstein's letter, we learn what the essential point in his understanding was. He talks about a "difficulty," and in response to Schrödinger who had used the term "contradiction," he also used the terms "incompatible" ("unvereinbar") and "contradict" ("widerspricht").

In the following, I want to argue that the contradiction arises with an ambiguity in the concept of completeness as it seemed to be understood by Einstein. According to a *prima facie* reading of the EPR paper, completeness is used in a straightforward sense. There are demonstrable differences, matters of fact, in reality that are not captured in the theory. But on this interpretation it is not easy to see why Einstein considered the argument to be paradoxical. It seems to me that on a second reading the incompatibility or contradiction may rather be located between the fact that there is one and only one real state of affairs but at least two different, i.e. non-equivalent descriptions of this state of affairs. And this is a contradiction under the claim that quantum theory provides a complete description of reality, in the sense that in a complete description, every element of reality corresponds uniquely to one and only one element of the theory.

The problem seen in this way is really not so much one of completeness. It is rather one that is very similar to the problem of overdetermination. If there is a

[5]Translation taken from Don Howard (1985), see also (Howard, 1990); for the original text, see (Meyenn, 2011, Doc. 206).

unique given state of affairs, a complete theory has to provide a unique description of that state of affairs, and if the theory provides different descriptions, then the differences have to be shown to be, at least, empirically equivalent. Ideally, the descriptions should also be logically equivalent but this is, clearly, a stronger requirement. The burden of the EPR argument therefore is to show that there are two different descriptions of the same state of affairs that make empirically different predictions.

Let me provide some textual evidence for this ambiguity in Einstein's use of the concept of completeness.

In his letter to Schrödinger, Einstein repeated the mathematical argument of the EPR paper of expanding the wave function at point B in two different sets of eigenfunctions as Ψ_B and $\underline{\Psi_B}$. He then wrote:

> The essential point now is only the fact, that Ψ_B and $\underline{\Psi_B}$ differ from one another at all. I claim that this being different is incompatible with the hypothesis that the Ψ description is coordinated in a one-to-one way with the physical reality (the real physical state of affairs).[6]

The other premises of the EPR setup are only auxiliary to this conclusion:

> After the interaction the real state of affairs of (AB) consists of the real state of affairs of A and the real state of affairs of B, which two states have nothing whatsoever to do with each other. *The real state of affairs of B now cannot depend on what kind of measurement I perform at A.* ("Separation hypothesis" [...]).[7]

And he concludes the argument by stating again what the contradiction is:

> But then there are two (and in general arbitrarily many) equally valid Ψ_B associated with the same state of affairs of B in contradiction to

[6] "Wesentlich ist nun ausschliesslich, dass Ψ_B und $\underline{\Psi_B}$ überhaupt voneinander verschieden sind. Ich behaupte, dass diese Verschiedenheit mit der Hypothese, dass die Ψ-Beschreibung ein-eindeutig der physikalischen Wirklichkeit (dem wirklichen Zustande) zugeordnet sei, unvereinbar ist." (AEA 22-047; Meyenn, 2011, Doc. 206)

[7] "Nach dem Zusammenstoss besteht der wirkliche Zustand von (AB) nämlich aus dem wirklichen Zustand von A und dem wirklichen Zustand von B, welche beiden Zustände nichts miteinander zu schaffen haben. *Der wirkliche Zustand von B kann nun nicht davon abhängen, was für eine Messung ich an A vornehme.* ("Trennungshypothese" [...])." (AEA 22-047; Meyenn, 2011, Doc. 206), (Einstein's emphasis).

> the hypothesis of a one-to-one or complete description of the real state of affairs.[8]

3 Other Formulations

Einstein makes the same point on his first occasion for discussing the EPR argument in print. This is in his 1936 lecture on "physics and reality." There, he calls the EPR argument "the paradox recently demonstrated by myself and two collaborators."[9] The conclusion is very similar to his explanation in the letter to Schrödinger quoted above. He wrote:

> Since there can be only *one* physical condition of B after the interaction and which can reasonably not be considered as dependent on the particular measurement we perform on the system A separated from B it may be concluded that the Ψ function is *not* unambiguously coördinated with the physical condition. This coördination of several Ψ functions with the same physical condition of system B shows again that the Ψ function cannot be interpreted as a (complete) description of a physical condition of a unit system. (Einstein, 1936a, 376)[10]

In 1948, twelve years later, Einstein gave another formulation of his objection in print. In his contribution to a special issue, edited by Wolfgang Pauli, of the Swiss journal *Dialectica*, he reiterated the EPR-argument with special emphasis on what he saw as the basic assumption of objective reality in physics. He emphasized that the experimenter is perfectly free to choose which observable he wants to measure at the first system S_1, and then he wrote:

[8] "Dann aber gibt es zu demselben Zustande von B zwei (überhaupt bel. viele) gleichberechtigte Ψ_B, was der Hypothese einer ein-eindeutigen bezw. vollständigen Beschreibung der wirklichen Zustände widerspricht." (AEA 22-047; Meyenn, 2011, Doc. 206).

[9] ("[...] eine von mir zusammen mit zwei Mitarbeitern jüngst dargestellte Paradoxie." Jammer (1974, 186) claimed that Einstein never referred to the EPR argument as "paradoxical," a statement that was refuted already by Fine (1996, 47, n. 11).

[10] "Da es nur *einen* physikalischen Zustand von B nach der Wechselwirkung geben kann, welcher vernünftigerweise nicht davon abhängig gemacht werden kann, was für Messungen ich an dem von B getrennten System A vornehme, zeigt dies, dass die Ψ-Funktion dem physikalischen Zustande *nicht* eindeutig zugeordnet ist. Diese Zuordnung mehrerer Ψ-Funktionen zu demselben physikalischen Zustande des Systems B zeigt wieder, dass die Ψ-Funktion nicht als (vollständige) Beschreibung eines physikalischen Zustandes (eines Einzelsystems) gedeutet werden kann." (Einstein, 1936b, 341)

> Depending on this choice we obtain representations of ψ_2 of a different kind, specifically such that depending on the choice of measurement at S_1 different (statistical) predictions result for measurements to be taken at S_2 after the fact.[11]

In his setup of the argument he had earlier distinguished two alternative interpretations. According to one, a particle "really" has a definite location and a definite momentum, and the quantum mechanical description is considered incomplete (Ia). According to the other alternative, a particle has no definite location and no definite momentum before any measurement takes place, and the quantum mechanical description is considered complete (Ib). Einstein then argues:

> From the point of view of the interpretation Ib this means that depending on the choice of the complete measurement at S_1 different real situations are generated, which are described by different ψ_2, $\underline{\psi_2}$, $\underline{\underline{\psi_2}}$ etc.[12]

But, of course, the locality argument is crafted exactly to invalidate the assumption that physically different (as opposed to representationally different) situations can be "generated" by the choice of measurement at the distant wing. Hence we are left again with the situation that different descriptions of different empirical content are coördinated with the same physical state of affairs. The statistical interpretation (in Einstein's understanding) is not a solution for the description of any individual measurement, since it only picks out a subensemble depending on the choice of parameter at one wing, which can make a difference for measurements at the other wing.

Lastly, in his *Autobiographical Notes*, we find the same formulation again. The problem is to have a "different," or "very different" wave function, i.e. one "of a different kind" ("andersartig" or "verschiedenartig") for the same state of affairs:

[11] "Je nach dieser Wahl erhalten wir für ψ_2 eine anders-artige Darstellung, und zwar derart, dass je nach der Wahl der Messung an S_1 verschiedenartige (statistische) Voraussagen über an S_2 nachträglich vorzunehmende Messungen resultieren." (Einstein, 1948, 322)

[12] "Vom Standpunkte der Interpretation Ib bedeutet dies, dass je nach der Wahl der vollständigen Messung an S_1 eine verschiedene reale Situation hinsichtlich S_2 erzeugt wird, die durch verschiedenartige ψ_2, $\underline{\psi_2}$, $\underline{\underline{\psi_2}}$ etc. beschrieben werden." (Einstein, 1948, 322)

> According to the type of measurement which I make of S_1, I get, however, a very different ψ_2 for the second partial system (ψ_2, ${\psi_2}^1$, ...).[13]

And similarly:

> For the same real situation of S_2 it is possible therefore to find, according to one's choice, different types of ψ-function.[14]

Clearly, it is the fact that in quantum theory one obtains several *different* descriptions of the *same* state of affairs was at the core of Einstein's unease about it.

The difference between the different descriptions has to be essential and cannot merely be formal or even notational. The objection cannot be that we may denote the wave function by $\psi(x)$ or $\Psi(x)$ or $\varphi(x)$. Different notations are logically equivalent, and such differences can readily be captured by a distinction between symbolic types and tokens. But the objection also cannot be that we may add a phase factor $e^{i\alpha}$ to the time-independent Schrödinger wave function. The equivalence here is less obvious but it is still a mathematical equivalence, in the sense that the fundamental equation, the Schrödinger equation is invariant under such gauge transformations. But what is the qualitative difference between benign differences in notation or mathematical gauge fixing and fatal differences that render the theory "incomplete?"

As we have seen, in none of the known formulations of the EPR paradox does Einstein give an explicit discussion of what the crucial difference in non-equivalent descriptions might be. Obviously, one would suspect that it would be a difference that render the two descriptions empirically non-equivalent. Einstein seems to suggest that the choice of parameter at one wing entails different predictions about measurement outcomes at the other wing. But it is not clear whether this empirical non-equivalence pertains to the individual measurement or to a statistical ensemble.

Let us review one more formulation of the EPR paradox in this respect. It is another concise, non-technical formulation and it is, in all probability, Einstein's latest formulation of the argument. It is found on the bottom half of a sheet that is

[13] "Je nach der Art der Messung, welche ich an S_1 vornehme, bekomme ich aber ein andersartiges ψ_2 für das zweite Teilsystem (ψ_2, ${\psi_2}^1$, ...)," (Einstein, 1982, 84/85).

[14] "Für denselben Realzustand von S_2 können also (je nach Wahl der Messung an S_1 verschiedenartige ψ-Funktionen gefunden werden." (Einstein, 1982, 84/85)

part of a larger batch of manuscript pages with calculations on general relativity and unified field theory (Sauer, 2007). There is a good chance that it was written down by Einstein after reading David Bohm's (1951) textbook on *Quantum Theory*, in which we find the EPR argument for the first time formulated in terms of spin variables.

Let me quote the formulation in full. In a slightly smoothed English translation it reads (Sauer, 2007, 882):[15]

> Composite system of total spin 0.
>
> 1) The description is assumed to be complete.
> 2) A coupling of distant things is excluded.
>
> If the spin of the subsystem I is measured along the x-axis, it is found to be either 1 or -1 in that direction. It then follows that the spin of the subsystem II equals 0 along the y-direction. But if instead the spin of subsystem I is measured along the y-direction, it follows that the spin of the subsystem II is equal to 1 or -1.
>
> If there is no coupling, then the result of a measurement of the spin of subsystem II may in no way depend on whether a measurement was taken of subsystem I (or on what kind of measurement).
>
> The two assumptions therefore cannot be combined.
>
> If the description is *not* assumed to be complete for the individual system, then that what is being described is not a single system but an ensemble of systems. Then a measurement of subsystem I amounts to the selection of a subensemble of the ensemble of the total system. Then the prediction for a measurement of subsystem II can depend on the choice of the measurement of subsystem I.
>
> The conclusion is valid under the assumption that the assertion of quantum theory is correct, which we can hardly put into doubt.

The following lines were written at the right margin of the page:

> a) the description by the quantum theory is an incomplete one with respect to the individual system, or
> b) there is an immediate coupling of states of spatially separated things.

[15] For a faithful transcription of the original German manuscript, see (Sauer, 2007, 886).

In view of our preceding discussion, we first observe that Einstein clearly thought the different descriptions of the partial subsystems were *empirically* inequivalent. He argues that the "result of a measurement" would come out differently depending on the choice of parameter in the distant wing. But the explication that Einstein gives before arriving at this conclusion is disturbing. Although less clear from the text, he seems to have in mind a situation of an *individual* measurement. He considers a (now standard) setup for the EPR argument, in which the spin of two quantum particles, each of spin $1/2$ but adding up to a vanishing total spin, are measured along two mutually orthogonal directions at distant wings. But what Einstein asserts does not square with quantum theory, whose assertions he explicitly claims to be "correct:" If Alice measures the x-component of the particle at her wing and finds it to be a definite value (+1 or -1), and if Bob *then* measures the y-component of his particle, he would also find it to be either +1 or -1, and quantum theory does not give a prediction as to which value would be obtained. That is so because a measurement by Alice of the x-component collapses the joint entangled wave function and hence puts the particle at Bob's end into an eigenstate to the x-component. Therefore, measuring the y-component at Bob's end would result in either +1 or -1 with a 50% probability each. Similarly, we read that Einstein is considering the case that Alice is measuring the y-component of her particle's spin, but, apparently, without taking note of the outcome. In that case, Bob's particle will collapse into an eigenstate of the y-component, and, again, he would measure the y-component of his particle to be either +1 or -1. Again, quantum theory cannot predict, which value Bob will actually see, and only predicts that he will see the outcome to be distributed with equal probability 50% between the two possible value. Note that this result does not depend in any way on Alice's taking note of the outcome of her measurement, since, by construction, she could not inform Bob about her measurement result *before* he would actually measure his particle's spin.

The situation is an illustration of a more general no-signalling theorem, which says that the EPR setup is not suited to send information from Alice to Bob faster than with the speed of light, or, in other words, even though the wave collapse occurs instantaneously along the entire space, it does not provide a means to convey significant bits of information.

Let us now read Einstein's argument under the assumption that he was having in mind a statistical reading. Statistically, there is, of course, a significant difference between the two cases. In the first situation, we have no correlation between Alice's and Bob's measurements, in the second situation we have complete anticorrelation. So far so good. But again, this is not what Einstein seems to have had in mind. Another reading seems to fit more natural with the text. According to this reading, Einstein would be thinking about statistical means. But this is problematic, too. We would have, of course, the situation that conditional on Alice's measuring an x-component of +1, Bob's y-component would average to a value of 0. The same holds for conditioning Bob's probability on Alice's measuring an x-component of -1. In contrast, Bob's y-component would average to $+1$ (or -1) if conditioned on Alice's measuring the y-component of her particle to be -1 (or $+1$).

But this interpretation does not go well with Einstein's insistence that the outcome of Bob's measurements should "in no way depend on whether a measurement was taken of subsystem I (or on what kind of measurement)." This latter formulation clearly suggests that he was taking the choice of parameter, not the measurement outcome, as the critical experimental intervention that must not have an effect on the measurement outcome at Bob's end. But, as we have seen, no-signalling in the situation at hand tells us that the outcome of Bob's measurement does not depend on the choice of parameter at Alice's experiment, neither for the individual measurement nor for a statistical ensemble.

4 A No-Signalling Theorem by David Bohm

It is even more puzzling that a no-signalling theorem of the kind that we just sketched was discussed and proven explicitly in David Bohm's book, which quite possibly was a source of inspiration for Einstein's new formulation of the EPR paradox (Sauer, 2007). Let me briefly indicate what Bohm had to say on this question. In the penultimate chapter of his textbook on quantum theory (which was still defending Bohr's views of quantum mechanics[16]) Bohm discussed the "quantum theory of the measurement process." The chapter sets out by a general discussion of how to include the measuring apparatus in a quantum mechanical description (very much in the spirit of von Neumann's axiomatic analysis),

[16] In a 1989 interview, Bohm recalled: "First I studied quantum mechanics and relativity, and in doing this I began by more or less accepting the ideas of Niels Bohr. Later I wrote a book called *Quantum Theory*, in which I was really quite strongly in favor of his ideas as I understood them. Well, I became somewhat dissatisfied towards the end of this period, around 1950 when I finished the book. I sent copies of the book to various physicists, including Pauli, Bohr, Einstein. Pauli liked the book. Einstein liked the book, but when I discussed it with him he said he was still not satisfied. Both of us felt that the key question was: 'What is the nature of reality?'." (Bohm, 2004)

then illustrates the general account by a detailed description and analysis of the Stern-Gerlach experiment, and finally comments on the EPR paper. This layout of the chapter allowed Bohm to discuss (apparently for the first time) the EPR argument with spin variables and with a hypothetical experimental setup using Stern-Gerlach apparatus and their analysis. In this context, Bohm very clearly formulated a no-signalling theorem. He wrote about the hypothetical EPR experiment:

> One more significant point arises in connection with this experiment; namely, that the existence of correlations does not imply that the behavior of either atom is affected in any way at all by what happens to the other after the two have ceased to interact. (Bohm, 1951, 618–619)

He also gave a proof of this statement. Define basic wave functions ψ_c and ψ_d as $\psi_c = u_+(1)u_-(2)$ and $\psi_d = u_-(1)u_+(2)$, where u_+ and u_- denote "the one-particle spin wave functions representing, respectively, a spin $\hbar/2$ and $-\hbar/2$, and the argument (1) or (2) refers, respectively, to the particle which has this spin." Bohm had earlier in the chapter argued that a measurement of the z-component of the spin at one wing would generate uncontrollable phase factors $e^{-\alpha_c}$ or $e^{-\alpha_d}$ to the spin wave functions, such that the total spin of the joint system is no longer defined. He could therefore now proceed to give a brief proof of his no-signalling theorem which states more precisely that the expectation value of any function g of the spin $\sigma = (\sigma_x, \sigma_y, \sigma_z)$ of particle 2 does not depend on whether or not a measurement of some spin component of particle 1 was done. Here is how Bohm phrased his proof:

> To prove this statement, we first evaluate the mean of any function $g(\sigma_2)$ of the spin variables of particle No. 2 alone. With the wave function before a measurement took place, we obtain
>
> $$\overline{g}_0(\sigma_2) = \frac{1}{2}(\psi_c^* - \psi_d^*)g(\sigma_2)(\psi_c - \psi_d) = \frac{1}{2}\left[\psi_c^* g(\sigma_2)\psi_c + \psi_d^* g(\sigma_2)\psi_d\right]$$

> (By virtue of the orthogonality of ψ_c and $g(\sigma_2)\psi_d$.) After the spin of the first particle is measured, the average of $g(\sigma_2)$ becomes
>
> $$\overline{g}_f(\sigma_2) = \frac{1}{2}(\psi_c^* e^{-i\alpha_c} - \psi_d^* e^{-i\alpha_d})g(\sigma_2)(\psi_c e^{i\alpha_c} - \psi_d e^{i\alpha_d})$$
> $$= \frac{1}{2}\left[\psi_c^* g(\sigma_2)\psi_c + \psi_d^* g(\sigma_2)\psi_d\right]$$
>
> This is the same as what was obtained without a measurement of the spin variables of particle No. 1. The behavior of the two spins is, however, correlated despite the fact that each behaves in a way that does not depend on what actually happens to the other after interaction has ceased. (Bohm, 1951, 619)

Einstein, I believe, must have read and known this passage, which is part of a longer chapter that also discusses his EPR paper. Yet, he does not seem to acknowledge in his manuscript notes the fact that the EPR setup for spins as discussed by Bohm obeys a no-signalling theorem. Such a theorem, it seems, would undermine his argument that the EPR paradox is a contradiction in the sense that quantum theory here gives rise to two empirically different descriptions of the same physical state of affairs.

5 Concluding Remarks

What do we make of this? It appears that Einstein either did not understand what quantum theory actually predicts in the EPR situation that he was considering, or, at least, that he did not bother to spell out the theory's prediction carefully in so many details. But this conclusion is at odds with the fact that Einstein, for all we know otherwise, had an excellent understanding of quantum theory as well as of statistical physics and its underlying concepts. On the other hand, history has shown that Einstein's intuition behind the EPR setup was well borne out by the subsequent development of quantum physics. Should the conclusion then be that Einstein's general realist philosophical perspective let him anticipate difficulties of quantum theory[17] even though he would not spell them out in his later years as clearly as he would have done when he was still young?

[17] For Einstein's (and Paul Ehrenfest's) prescient anticipation, as it were, of the quantum measurement problem in their discussion of the difficulties in interpreting the result of the Stern-Gerlach experiment, see (Unna and Sauer, forthcoming).

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