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Influences, Histories, and Reality[1]

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It is stressed that any theory of which it is claimed that it is compatible both with standard realism and with the experimental data is subject to severe constraints. One is that it must either incorporate superluminal influences or negate the free will of the experimentalist. The other one is that, in it, it is only at the price of accepting "backward causality" that a measurement can be interpreted as revealing the value the measured quantity had, just before, rather than just after, the measurement took place.

1. INTRODUCTION

As far as I remember, Professor Jammer and I only met twice: recently, in the 1991 Cesena meeting in memory of John Bell, and a very long time ago, when I seized the opportunity of a trip to Jerusalem to pay a short visit to him. But of course, as all theorists, I consider his contribution to the history and philosophy of quantum physics as a milestone in the field. For me it is therefore both an honor and a pleasure to dedicate this work to him.

Roughly speaking, there seems to be two ways of understanding physics (there may be more than two, of course, but for the sake of brevity let us focus on the extremes). One consists in interpreting it—along the lines of standard, or conventional, realism—as directed toward lifting the veil of the appearances and describing reality "as it really is." The other one is to see it merely as synthetizing human experience in the field. Within the first approach the word "reality" is, of course, understood as meaning mind-independent reality. Within the second one it means the set of

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the phenomena, in the philosophical sense of the word, that is, what has been called "empirical reality." Both points of view are tenable. But they are mutually incompatible, so that we should be careful not to inadvertently switch from one to the other in the course of our reasoning.

As long as what is aimed at is a conception of quantum mechanics that should make it instrumental and as free as possible from interpretational riddles, the second approach is, of course, the most economical. But the first one is more in line with a tradition in the physical sciences that goes back at least to Galileo and that may be called "standard realism." Standard realism is not aimed at "ontological" knowledge (Galileo strongly criticized the view of many philosophers that basic notions such as those of substance, cause, etc. should be totally cleared up before we could efficiently start up with quantitative physics), but it definitely considers physical objects and their attributes (their dynamical properties, we would say) as being elements of a mind-independent reality. In view of what follows, let us note one of its distinctive feature, which is that, in it, counterfactual statements are considered as possessing a truth value. In a case, for instance, in which there is a table in the next room, the statement "if I raised my hand there would be a table in the next room" is, in standard realism, considered as meaningful; and, at least when the assumption is made that no influence can travel from this room to the next one, it is, even, considered true.

Be it in virtue of tradition or because of a widespread view that alternative standpoints are absurd, the fact is that standard realism has met within the last decades with renewed favor, even among theoretical physicists, so that theories have been, and still are, developed, aimed at rendering quantum mechanics compatible with it. As is well known, this is no easy endeavor and it is interesting to inquire how and to what extent some notions that naturally fit into it, such as the one of possessed values and the related ones of causality and influences, can be accommodated within the quantum mechanical rules.

Only very partial aspects of this program are taken up here. Section 2 concerns problems related to the notion of influence and Section 3 deals with the question of possessed values and causality.

2. ON SUPERLUMINAL INFLUENCES

2.1. A Criterion for Superluminal Influences

As is well known, the problem of formally defining in a strict and general way the twin notions of "cause" and "influences" is fraught with considerable difficulties when it is requested—as it must be—that the definitions should capture our intuitive idea of what a cause and an influence is and is not. However, when the question is just to specify, within standard realism, a sufficient condition for the statement "in such and such instances superluminal influences take place" to hold good, the objective is more reachable: It suffices to identify this condition with a violation of *local causality* as initially defined by John Bell.[1] Let R_1 and R_2 be any two spatially separated space-time regions. Local causality stipulates that when *all* the elements of physical reality in the overlap R' of the backward lightcones of R_i and R_j are specified the probabilities of events taking place in R_i remain unaltered by specification of what takes place in R_j ($i, j = 1$ or 2, $i \neq j$).

In their broad outlines the reasons why this condition is appropriate are known,[1] but a more precise account of them may be worthwhile. Firstly, let $(B \mid A, X)$ be the conditional probability of an event B occurring *if* some other events A, X occur (here X stands for some set of events other than A). Even without having a precise definition of the word "influence," we all consider such a definition should somehow imply that whenever the function $(B \mid A, X)$ effectively depends on A this reveals that some influence is exerted, *either* directly between A and B, *or* from some set of prior events C separately on A and B. In the second case we moreover consider that *the (only) reason why the function* $(B \mid A, X)$ *depends on* A—*if it does—is that it depends on these* C's *and these* C's *influence* A. The latter view implies that no effective functional dependence of $(B \mid A, X)$ on A is possible when this probability is defined subject to the condition that the variables specifying the C's are all kept at fixed, given values—otherwise said, when the set of events X incorporates all events C. Secondly—and, again, whatever the precise definition of influences may be—the notion that influences travel with a velocity not exceeding that of light implies that, if A is in R_1 and B in R_2, (i) A and B cannot directly influence each other and (ii) for influencing both A and B the events C should lie within the overlap R' of the backward lightcones of A and B. Let now $(B \mid A, C, Y)$ be the probability of B given A and *all* the elements of physical reality in R' (plus, possibly, other data, represented by symbol Y). $(B \mid A, C, Y)$, considered as a function of A, is one particular instance of the functions $(B \mid A, X)$ of A considered above. But it is a function of A in which, by definition, the parameters specifying the C's all have given values. From what we just noted we must therefore infer that it does not effectively depend on A, that is, that local causality (as stated above) holds good. It follows, of course, that any directly or indirectly established specific dependence of $(B \mid A, C, Y)$ on A implies the existence of superluminal influences. Q.E.D.

2.2. Consequences

The criterion in question has important bearings concerning all the theories consistent with the philosophy of standard realism. Any "realist" theory in this sense must have an answer to the question "what is real?," concerning the systems it considers. The answer may be: "the wave function" or "the density matrix" or "the events in the theory" or "the set of the hidden variables" or whatever. The requisite is just that the answer be definite, the thus designated entities being then considered as elements of mind-independent reality (not just as "human representations" of it). Moreover, in the theory measurements and measurement outcomes must be real, in the sense just explained.

Such theories are those to which Bell's theorem applies.[3] And this theorem amounts to stating that if local causality holds and the experimentalists are free to choose at whim the orientation of their instruments, the Bell inequalities are satisfied. Since these inequalities are violated by the experimental data, it follows that in *any* theory of which it is claimed that it matches standard realism and in which experimenters are not denied free will, local causality is violated and therefore, according to the foregoing argument, superluminal influences are present.

2.3. What About "Consistent Histories" Theories?

Initially, the consistent histories theories were conceived of by their authors as being "realist" ones, and as being preferable to the Copenhagen interpretation just because they matched standard realism much better. In the face of argumented criticism (see, e.g., Refs. 2–4) some of these authors watered down this claim. Some now concede (privately at least!) that their theory is merely a human (or "IGUSian") representation of reality, that is, something akin to a theory of empirical reality. This removes any specific difficulty since it has been shown[(2)] that in a theory of such type local causality (and also, therefore, the foregoing criterion) cannot even be stated. But other such authors, particularly in popular books and articles, maintain that their theory does away with the necessity of basically referring quantum physics to human operations such as measurements. Indeed some claim that it is essentially as realistically interpretable as classical physics. And at the same time, they claim it involves no superluminal influences. To quote a specific example, in his book *The Quark and the Jaguar*,[(5)] Murray Gell-Mann considered, within his theory, the case of

[3] It is therefore a serious error (one, unfortunately, often made; see, e.g., Ref. 5, Chapter 12) to hold that Bell's theorem applies exclusively to the restricted class of (mostly deterministic) theories known by the name "hidden variables theories."

a standard EPR–Bohm experiment performed on a photon pair, noted that in a history in which the polarization of one photon is measured the polarization of the other one is specified, and claimed both that this case is similar to the one of classical correlation effects (he referred to Bell's "Bertlmann socks" example[6]) and that in it no superluminal influence takes place.

In fact, both claims are flawed. While the meaning of the word "similar" is, of course, vague and subject to appreciation, still it is inappropriate to apply it in this example since any similarity with classical physics vanishes as soon as a—totally legitimate!—question is asked, namely: what would take place if, instead of the actually measured polarization another one were measured. This is because, in the considered theory, the "history" being different, the direction along which the second photon has a sharp value would be different as well, whereas, in a classical, local theory of a similar experiment (performed on a correlated pair of objects such as, say, oppositely oriented darts) the real, factual situation of the second object would, of course, be totally independent of whatever happens to the first one, and in particular of whether or not a measurement is performed on it. Since the possibility of considering counterfactual situations (such as the one envisioned here) is an essential element of standard realism as we saw, Gell-Mann's first claim is misleading. As for his second claim it is misleading as well since it is obviously incompatible with the foregoing criterion and the violation of the Bell inequalities. Indeed it could be substantiated only by attributing to the word "influence" a meaning differing from the one explained above and that would basically refer to the well-known fact that the superluminal influences that have to do with the Bell theorem do not carry information. Within a purely operational approach to physics it could consistently be claimed that therefore, by definition, such superluminal influences do not exist; and it may benevolently be surmised that this is the definition Gell-Mann actually had in mind. But even this does not, when all is said and done, make his position consistent since it amounts to switching to a purely operationalistic standpoint incompatible, as we noted, with his own claim to the effect that his theory is no more anthropomorphic than classical physics.

3. POSSESSED VALUES, TIME REVERSAL, AND CAUSALITY[4]

By definition, an ideal measurement is a measurement of such a type that, if it is performed twice on the same system within an infinitely short

[4] This section complements and partly modifies Appendix 3 of Ref. 2.

time interval, the two outcomes coincide. When an ideal measurement —call it M—has been performed on some observable A, with outcome a say, it is known that if another ideal measurement, M', of A were made immediately after M its outcomes would be a, and from this counterfactual remark ("counterfactual" since the "other" measurement is conceived of as not being actually performed) it is commonly and quite naturally inferred that immediately *after* an ideal measurement the measured observable *has* the value the measurement indicates (see, e.g., Ref. 2, Chapter 3). While such an inference sounds natural, its parallel but "time-reversed" one, based on imagining the "other" (counterfactual) measurement, M', to be performed just *before* M, is so artificial that it is normally viewed as not being valid: Instinctively (and correctly) we argue that measurement M is performed with the help of an instrument of some kind, that, even if M is ideal, the interaction between the measured system and this instrument may well have rendered "sharp with respect to a" a state that was unsharp before (more precisely: it may have changed the initial state, whatever it was, into an eigenket of A corresponding to eigenvalue a), and that there is therefore no ground for considering that, before M, A had value a. The question addressed to here is whether or not some alternative standpoint may be consistently adopted concerning this. In fact, in some of the consistent histories theories[7,8] it is stated that a measurement reveal what the value of the measured quantity was, just before the measurement took place, or, equivalently, the state in which the system then was. In classical physics this idea implies no conflict with causality and is indeed a feature of any good measurement, so that the prospect of recovering it within a quantum formalism may sound attractive and natural. Let us therefore inquire on what it implies within standard quantum mechanics.

Something makes this question a little bit subtle and intricate. It is the fact, clearly shown by Aharonov, Bergman, and Lebowitz,[9] that a completely "time-symmetrical" quantum mechanics—a theory in which part and future have symmetrical roles—can be constructed, but does not apply to the problems we normally have to deal with. Here, we are not interested in such a theory since what we want to investigate is the set of the various possibilities of interpreting the *actual* theoretical formalism: the one that works. Our purpose is therefore to preserve the validity of the standard rules of quantum mechanics.

With this goal in mind let us consider the simple situation in which two noncommuting observables A and B both commuting with the system Hamiltonian and with nondegenerate spectra

$$A\,|\phi_n\rangle = a_n\,|\phi_n\rangle \tag{1}$$

$$B\,|\chi_k\rangle = b_k\,|\chi_k\rangle \tag{2}$$

are successively measured, at times t_1 and t_2 respectively and by means of ideal measurements, on an ensemble E_i of systems S. Let us provisionally assume E_i may be considered initially as a pure case, described by the ket $|\psi_i\rangle$, and let Q be an observable such that

$$Q\,|\psi_i\rangle = q_i\,|\psi_i\rangle \tag{3}$$

The tentative interpretation of the quantum mechanical predictive rules that we consider in this section is based on the following two assumptions.

Assumption a. Just before the A measurement every S had a well-defined A value, namely one of the a_n, and was therefore in the corresponding state $|\phi_n\rangle$ (hence we may consider that the measurement reveals to us in what state the system was).

Assumption b. The probability that, at time t_1, a system having $A = a_n$ goes over into state $|\chi_k\rangle$ is

$$p_{n,k} = |\langle \chi_k | \phi_n \rangle|^2 \tag{4}$$

Contrary to expectation, these assumptions are tenable ones provided that suitable conventions are made.

Convention 1. *In this alternative interpretation, counterfactuality in the usual sense must be given up.* As stressed by Zeh[10] giving it up is obviously necessary for the probability rule (4) to make sense. This is because the $|\chi_k\rangle$ that appear in (4) are the eigenkets of B and the set $\{|\chi_k\rangle\}$ therefore depends on the choice of the observable B: However, B is measured at time t_2, while $p_{n,k}$ is relative to what takes place at time t_1. The proposed interpretation therefore makes sense only if "the future is (partly) given." In it, it is therefore inconsistent even to *imagine* that, after t_1 we could decide to, at t_2, measure something else than B (or nothing!). As we see, Convention 1 refers, in a sense, to a kind of—counterintuitive—backward causality.

Convention 2 (Time-Reversed Collapse). *The initial ensemble* E_i *is a mixture in proportions* $p_{n,i} = |\langle \phi_n | \psi_i \rangle|^2$ *of states* $|\phi_n\rangle$. With Convention 1 made, Convention 2 is consistent. The objection one uses to address such a description of E is that, observationally, a mixture in the strict sense is not equivalent to a pure case since if, at time t_1, *instead* of measuring A, we measured Q we should, according to the description under scrutiny, get outcome q_i with a probability $\sum_n |\langle \phi_n | \psi_i \rangle|^2\, |\langle \psi_i | \phi_n \rangle|^2$ whereas, obviously, the correct value of the said probability is 1. But as soon as Convention 1 has been made, such an argument cannot be formulated consistently, for the reason that, in contradiction with Convention 1, it assumes we are at liberty, when discussing the status of the ensemble before t_1, to imagine that the measurement of A at t_1 could be replaced by something else. For this reason, the set of Conventions 1 and 2 is consistent.

Moreover, it can also be shown that these interpretative conventions are compatible with the standard formula expressing the probability $W_{n,k}$ of getting outcomes a_n and b_k upon successive measurements of A and B performed on E_i. This well-known formula is

$$W_{n,k} = \mathrm{Tr}[P^{B_k} P^{A_n} \rho_i P^{A_n} P^{B_k}] \tag{5}$$

$$= \mathrm{Tr}[\,|\chi_k\rangle\langle\chi_k|\phi_n\rangle\langle\phi_n|\;|\psi_i\rangle\langle\psi_i|\phi_n\rangle\langle\phi_n|\;|\chi_k\rangle\langle\chi_k|\,]$$

$$= |\langle\chi_k|\phi_n\rangle|^2\;|\langle\phi_n|\psi_i\rangle|^2 \tag{6}$$

and the compatibility just mentioned consists in the fact that Eq. (6) may be derived from the conventions in question. Explicitly, the argument goes as follows:

"Account being taken of the existence, at time t_1, of the measuring instrument that will serve for measuring A, ensemble E_i, according to Convention 2, may, conventionally, at the initial time t_0, be identified with a mixture in proportions $p_{n,i}$ of systems S in states $|\phi_n\rangle$: so that by yielding outcome a_n, the measurement of A performed at t_1 on one particular system S reveals, in fact, the state in which S was. Similarly, after t_1 each one of the subensembles described by a given $|\phi_n\rangle$ must, because of the existence, at time t_2, of the measuring instrument that will serve for measuring B, be considered as being a mixture in proportions $|\langle\chi_k|\phi_n\rangle|^2$ of systems in states $|\chi_k\rangle$. On all of these, the measurement of B yields b_k, thus revealing the state in question. Formula (6) follows."

To sum up, within standard quantum mechanics (no "hidden variables") the assumption that quantum mechanical measurements reveal the initial rather than the final value of the measured quantity may be rendered consistent, but, it seems, only at the price of giving up two most intuitive ideas. One is that we have some free choice concerning the future, and giving it up implies a kind of—most counterintuitive—backward causality. The other one is that the thus revealed values were preexisting and *independently* possessed by the system. Indeed, the existence at time t_2 of a B measuring instrument is here not just merely a circumstance making it possible to know what the value of B was, on a given S, just before. It *determines the set* of the possible B values (and the same, of course, with

A and the set of the a_n's), so that the aforementioned analogy with the classical case is much more apparent than real.

Remark 1. The model is not just a time-reversed copy of the standard quantum mechanical rules, in which predictive rules would be replaced by retrodictive ones. Here there are no probabilistic formulas for retrodiction and there is one for prediction.

Remark 2. For "pedagogical" reasons, and in order to keep as close as possible to the standard quantum formalism, a quantum mechanical description, by means of $|\psi_i\rangle$, of the initial ensemble E_i was provisionally postulated. However, it should be observed that contrary to the said standard formulation, this one does not allow for any operational definition of such a $|\psi_i\rangle$, which therefore is but a redundant algorithm. In the final description of the scheme only the $p_{n,i}$'s should therefore appear. It is easily seen that this preserves consistency.

4. OUTLOOK

An often heard criticism of the Copenhagen interpretation is that it fails to account for the structure of the universe, since it crucially relies on the notion of outside observers. The objection is not as powerful as it seems to be at first sight since it rests on the idea that the universe as a whole is just a physical system as any other one and this idea itself is in fact, as most philosophers know, not obvious but conjectural. Nevertheless the criticism in question was put forward by authors of several theories as a strong argument in favor of their own approach. What is more, the notion of "events" was taken as central in those theories, which indicates that their authors essentially aimed at building up "realist" theories. Some of them went as far as requesting that, in their theory, a measurement should reveal the value the measured quantity had just before the measurement took place, as is normally the case in classical physics. *A priori* these are perfectly respectable goals. What has been shown here is, however, that the first one can be reached only if some sort of strongly objective superluminal influences exist and the second one only if (assuming no hidden variables) some sort of backward causality is accepted. These results may reasonably be viewed as corroborating the idea that physical theories should not be imparted the overambitious role of yielding a faithful description of the contingent features of mind-independent reality and that their domain of efficiency essentially is the detailed description of just empirical reality.

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