# Nonlocality and Interaction

Manfred Buth

Bataverweg 35, D22455 Hamburg
e-mail: manfred-buth@t-online.de

**Abstract**

Three statements are asserted: (a) There is no contradiction between quantum mechanics and special relativity, if the rôle of interaction in the analysed experiments is sufficiently respected. (b) There is no paradoxical situation in the gedankenexperiment of Einstein, Podolsky and Rosen. (c) The principles of quantum statistics describe nonlocal effects. From (b) one can infer that the whole discussion about EPR and all that was and is dispensable. It could have been avoided, if in time the analysis of possible experiments would have been carried out a bit more carefully.

## 1. Some problems and the way to solve them

For a long time people are worried about the possibility that quantum mechanics might be incompatible with special relativity. The reason for such doubts are certain phenomena being described within the frame of quantum mechanics. Here they altogether shall be denoted as nonlocal. The amazing feature of such appearances is the fact that two systems are correlated, although they are separated in space, and even, if a formerly present interaction meanwhile is switched off. Thus one can have the impression that there is a contradiction to special relativity. A variation of this topic is the famous publication of Einstein, Podolsky and Rosen [1]. In this paper the authors describe and analyze a gedankenexperiment, whose investigation is leading to a paradoxical situation and thus raises doubts concerning the correctness of quantum mechanics. A survey on the different contributions to this topic in the literature will reveal an almost total lack of adequate respect for the rôle of interaction in the analysed processes. For this reason the present investigation shall be concentrated on the connection between nonlocality and interaction. It is not performed in full generality, but for the well known spin-1/2-experiment as an example. The results, at least for the analyzed example, will be:

(a) There is no reason to fear that nonlocal phenomena could be in contradiction to special relativity.

(b) The paradox of Einstein and coauthors is vanishing into thin air with the consequence that the whole discussion following [1] is dispensible.

(c) The exclusion principle for fermions and its counterpart, the 'inclusion principle' for bosons, are special cases of nonlocal phenomena.

In the following section a short survey on the debate concerning nonlocal effects is given. The experiments being discussed in the various contributions of this debate are analyzed in section 3 under the aspect, to what extent interaction is occurring in them. The spin-1/2-experiment is described qualitatively in section 4 and on this footing analyzed quantitatively in section 5. Section 6 is dedicated to an attempt to explain the non ending discusion about nonlocal phenomena, about EPR, and all that as the expression of a certain kind of desease. In section 7 the idea is sketched that the exclusion principle, too, might be a kind of nonlocality. Section 8 summarizes the results of the investigation.

## 2. A short historical review of the debate about nonlocal phenomena

The discussion about nonlocal phenomena in quantum theory was initiated by the famous gedanken-experiment of Einstein, Podolsky and Rosen [1]. A precise formulation of the process described in the original paper [1] was given by Bohm and Aharanov [2]. They proposed to separate a molecule of spin zero into its two atoms, each of them with spin one-half, and then to measure the spin component of one of the atoms into a given direction. Quantum theory in this case predicts that the same spin component, but for the other atom, will be opposite to that of the first one. Since it is difficult to carry out a test of this prediction, Aspect et al. ([4], [5]) have performed an equivalent experiment with photons. Their measurements confirmed the predictions of quantum mechanics.

Beside this experimental work on a theoretical level attempts were made to repair the pretended deficiencies of quantum mechanics, as given in [1], by the so called theories of local realism. But these were refuted by the inequalities of Bell [3]. Nevertheless the discussion about nonlocal phenomena continued until these days, as well as experimental work, too. Some contributions to the debate are a bit mysterious, as for instance this one: "Entanglement, like many quantum effects, violates some of our deepest intuitions about the world. It may also undermine Einstein's special theory of relativity." (Scientific American, March 2009, p. 26). For further detail see Selleri [6].

## 3. The role of interaction in the quoted experiments

While in the paper of Einstein and coauthors interaction is only mentionned, but without any concrete statement, the dissociation of a molecule in the experiment of Aharonov and Bohm clearly can be recognized as a decay process and thus, as usually, considered as scattering process. It could be analyzed in detail. But for the present purpose this is not necessary. One can leave away all special features, only considering the spin dependence. In this form the experiment will be descibed and analysed in the next two sections. In the experiment of Aspect and others "the polarisation correlations of visible photons emitted in a $(J = 0) \rightarrow (J = 1) \rightarrow (J = 0)$ atomic radiative cascade" are measured. This again can be considered as a kind of decay and thus, at least in quantum field theory, as a special kind of scattering process.

## 4. The spin-1/2-experiment: Desciption and mathematical representation

In the experiment of Bohm and Aharanov all special features might be left away. Then one can assume that a resting spin-0-particle is decaying into two spin-1/2-particles that are moving away from the place of their creation on linear trajectories into opposite directions. In each of the two orbits an instrument is implemented in order to measure the spin component in a plane orthogonal to the orbit and under an angle $\alpha$ for one particle and under $\beta$ for the other one. On a theoretical level rotational invariance is assumed for the whole process of decay. Then the experiment can be described by decomposing the tensor product of two representations of the rotation group with spin 1/2 into two representations with spin 1 and spin 0.

$$\mathbf{\frac{1}{2}} \otimes \mathbf{\frac{1}{2}} = \mathbf{1} \oplus \mathbf{0}$$

If $\uparrow$ and $\downarrow$ denote two basis vectors in the space for $j = 1/2$, then

$$t_1 = (\uparrow_1\uparrow_2) \qquad t_2 = \frac{1}{\sqrt{2}}(\uparrow_1\downarrow_2 + \downarrow_1\uparrow_2) \qquad t_3 = (\downarrow_1\downarrow_2)$$

are three basis vectors for the representation with $j = 1$, while

$$s = \frac{1}{\sqrt{2}}(\uparrow_1\downarrow_2 - \downarrow_1\uparrow_2)$$

up to a phase factor is the only element of the representation space for $j = 0$. Because of the conservation of spin the products of the decaying spin-0-particle is described by the singlet state $s$.

## 5. The spin-1/2-experiment: Discussion of some different versions

### 5.1 The first version

A measurement of the spin component of particle 1 according to the angle $\alpha$ reduces the state function. If the result of the measurement is +1, then one obtains the new state function

$$r = \uparrow_1\downarrow_2$$

and hence is safe to predict that a measurement for the same angle $\alpha$, but now for the particle 2, will produce the value -1. This is quite natural and not at all pardoxical.

Already this fact is a reason for the question, whether the result is compatible with special relativity or demands a signal faster than light. But yet in the description of the measuring procedure given above a decisive mistake is hidden, which also can be found in the literature. It is alleged that there are two systems, which are the particle 1 and the particle 2. But they came into existence by a decay, which in quantum field theory is considered as a special kind of scattering process. Thus they form a unique object, even when the phase of interaction has finished. This object is carrying common information for the whole system, and thus for the different parts, too. Hence a measurement at particle 1 and at particle 2 is redundant. A measurement at particle 1 is sufficient to get information about the whole system and especially for particle 2. There is no need for transfer by a signal.

A situation of daily life, though somewhat constructed, may illustrate this.

During an opening of a last will two persons are told that they are heirs of an estate to equal shares. Each of them receives an assignment in a closed envelope and is instructed to present it at the office of his or her residence. There he or she will hear about the height of the heritage and will receive the money. If now one of the persons actually has got its heritage, she or he is knowing without any transfer of a signal what the other person will receive in its residence. Only after the lucky heirs begin to spend their money in different ways the hereditary community has ceased to exist.

Even a classical experiment can serve as an example in order to illustrate nonlocality.

Two little waggons with known masses are resting on a rail. By a suited mechanism they are repelled and move into opposite directions. If the velocity of one of them is measured, one can - by means of momentum conservation - predict the velocity of the other one. Despite of all differences between this experiment and the one for spin-1/2-particles, between classical mechanics and quantum mechanics, two common features are decisive in the context of nonlocality: Interaction is at work and some quantity is conserved.

### 5.2 The gedankenexperiment of Einstein and coauthors

Why are the objections that Einstein and coauthors raised in [1] against the validity of quantum mechanics not acceptable?

(a) It was not taken into account that the two systems mentioned on page 779 only are subsystems of a unique object and that hence any measurement at one of the subsystems is to be considered as a measurement for the whole system. Related to the spin-1/2-experiment this is to say that a measurement of the spin component of particle 1 attaches a wave function to the whole object and not only to particle 2. Therefore the choice of the angle $\alpha$ doesn't matter. Different choises of $\alpha$ may lead to different wave functions for the whole object. But this fact again is not at all paradoxical.

(b) For the above statement (a) it is irrelevant that the interaction meanwhile is 'switched off'.

(c) The fact that the measurement for an angle $\alpha$ and another one for the angle $\alpha'$ in general are not compatible, is only of interest in the case that both measurements are carried out. But then the existent object is destroyed by an uncontrollable interaction with the measuring device.

A new object consisting of particle 1 and the measuring device will be created. In this case no inference from particle 1 to particle 2 can be made.

Taken all together no paradoxical situation can be found.

5.3 Another version

In a series of measurements with a lot of decays both spin components can be observed, one of them by a device for the angle $\alpha$ and the other one by a device for the angle $\beta$. Coincidence measurements assure that the registered values come out pairwise from the same decay. For the expectation value $P(\alpha, \beta)$ the theoretical analysis delivers

$$P(\alpha, \beta) = -\cos(\alpha - \beta)$$

(cf. [5]). This result is confirmed by experiment.

## 6. Remark concerning the discussion about nonlocality, EPR and all that

If one is willing to accept that the spin-1/2-particles, being created by the decay of a spin-0-particle, must be regarded as a single object, then it is not too hard to understand, why from the result of one measurement inferences can be drawn for other measurements far away from the first one. Thus for the sake itself there is no reason for the misgiving that the nonlocal appearances could contradict special relativity. But, what is the reason that the discussion about nonlocality and related topics as for instance EPR does not find an end? Perhaps it is a desease about the fact that an object of the microworld containing only two elementary particles may have an extension that usually is only found in the macroworld. But such a feeling is a topic of psychology and has nothing to do with theoretical physics.

## 7. The exclusion principle as a special kind of nonlocality

There is a great amount of common features between the spin-1/2-experiment and the electron-electron-scattering: Both cases are bound to the existence of interaction, and in both cases the outgoing particles are described by antisymmetrical state functions. Hence the idea emerges that the exclusion principle for fermions and, of cause, the 'inclusion principle' for bosons might be a special case of nonlocality, too.

## 8. Summary

Nonlocal phenomena appear in processes, in which interaction occurs. They don't contradict special relativity. The gedankenexperiment of Einstein, Podolsky and Rosen does not lead to a hidden paradox. Hence the whole discussion concerning EPR is dispensable. The principles of quantum statistics can be considered as special cases of nonlocality.

All this was demonstrated by the spin-1/2-experiment as an example. But it seems to be of general validity.

## References


[1] A. Einstein et al.: Phys. Rev. **47** 777 (1935)

[2] D. Bohm, Y. Aharonov: Phys. Rev. Letters, **108** 1070 (1957)

[3] J.S. Bell: Physics, Vol. **1**, No. 3, 195 (1964)

[4] A. Aspect et a.: Phys. Rev. Letters, **47** 460 (1981)

[5] A. Aspect et a.: Phys. Rev. Letters, **49** 91 (1982)

[6] F. Selleri: Quantum Paradoxes and Physical Reality, Dordrecht, 1983