Nonlocality and Interaction

Manfred Buth

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

Abstract

In order to understand nonlocal phenomena, the corresponding processes must be treated as scattering experiments and investigated in the frame of quantum field theory. Quantum mechanics is not sufficient for this task, because it is only concerned with the influence of a potential on a physical object. But in processes with nonlocal effects the role of interaction between physical objects must be sufficiently respected. – All this is shown first of all for the special case of the spin-1/2-experiment, and then generalized to arbitrary scattering processes.

1. What is the problem?

Nonlocal phenomena are discussed and analyzed, since Einstein, Podolsky and Rosen in their famous paper [1] have drawn attention to a difficulty of quantum mechanics. By means of their also famous gedankenexperiment the three authors have demonstrated their thesis that quantum mechanics is incomplete. So called local theories were developed in order to repair this pretended fault. The work of Bell [2] consisted in describing mathematically a general kind of such theories, and inferring the inequality bearing his name from characteristic features of such theories by mere logical deduction. In quantum mechanics a corresponding condition can be given, too. These two inequalities are not compatible with one another. Hence it seems to be quite natural to decide between them by experiment. Since all results of experimental investigations from Aspect et al. [3, 4] up to Erven et al. [5] have shown that Bell's inequality is not compatible with the empirical results, local theories nowadays are quite generally refuted. On the other hand all these experiments are supporting the results of quantum mechanics. Hence one could infer that quantum mechanics is correct. But that would be an illegal conclusion, because the agreement with experiment is a necessary, but no sufficient condition for the validity of a theory. Hence one would convert a double negation into a positive assertion.

In this paper the thesis is claimed and proved that quantum mechanics, indeed, is incomplete, not on the philosophical level, where Bohr and Einstein were quarrelling, but in an immediately physical sense.

Quantum mechanics is describing events that are concerned with elementary particles only by considering the effects of external potentials. For this purpose the applied mathematical tools are sufficient. It is mainly the linear algebra on a Hilbert space. But in order to understand nonlocal phenomena one must sufficiently respect the role of interaction. Hence one has to change from quantum mechanics to quantum field theory. That is a theory, in which interaction is playing a central role, especially in the analysis of scattering processes. If one is proceding this way, then nonlocal phenomena will appear to be quite natural. Local theories are not needed, and hence no Bell equation, in oder to refute them.

In the next section the example of the so called spin-1/2-experiment is investigated in the frame of quantum field theory. Afterwards, in section 3, the results are generalized to arbitrary scattering processes.

2. The example of the spin-1/2-experiment

In the so called spin-1/2-experiment 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 α for one particle and under β for the other one.

In quantum field theory the decay of a spin-0-particle in two spin-1/2-particles is considered as a special kind of scattering process. Hence it must be treated as a scattering process. But there are obstacles withstanding this task. In case of the spin-1/2-experiment it is not even clear, how to couple a spin-0-field to a spin-1/2-field. Hence it is impossible to analyze the interaction in detail. Not even an approximation by perturbation theory can be done. According to experimental work with photons it is not clear what exactly is happening in the calcium atoms or in the lasers. In spite of these restrictions a deduction shall be tried under the hypothesis that the process of decay is rotational invariant.

The tensor product of two representations of the rotation group with spin 1/2 is decaying into two representations with spin 1 and spin 0.

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

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 product of the decaying spin-0-particle is described by the singlet state s.

The physical meaning of the result is a correlation between the two spin-1/2-particles. If a measurement for the particle 1 under the angle α is carried out, then one surely is knowing that a measurement for the particle 2 under the same angle α will give the opposite result. Under another angle β the result is only known with the probability

$$P(\alpha, \beta) = \cos^2(\alpha - \beta)$$

Whether this almost purely deduction in spite of the unclear initial situation can be considered adequate is not sure.

But, in order to stress once more the essential point: The spin-0-particle is decaying into a couple of spin-1/2-particles. These are carrying away with them from the place of interaction some information, which at least is concerning the laws of conservation. Since the correlation does not take place between the measuring devices or the measuring processes, but between the particles and their states, there is no danger that the theory of specific relativity might be violated. Hidden parameters are not needed. In summa, nonlocal effects are quite natural phenomena, for the spin-1/2-experiment as well as for all the other scattering processes. The decisive point is the interaction between particles.

This idea can be illustrated by the following variation of a well known story.

Mr. Winter has only two relatives, his daughter Anne and his nephew Bert. Some days, after Mr. Winter had died, Anne and Bert were bidden to come to a notary's office. Here the notary told them, that they are heirs to an amount of \$300,000. He gave each of them a letter in a closed envelope with the demand to deliver it to a notary or a local authority of their respective residence. Then Anne and Bert went back to their home towns. When Anne had handed over her letter to a notary, she heard that she had inherited \$200,000. At that moment Anne knew that Bert would get \$100,000, although Bert is living far away from Anne, and no communication had taken place.

In orde to come back from this fairy tale to physics, one can consider the two spin-1/2-particles as common heirs of the spin-0-particle and the inherited money either as the total spin or as any one of its components.

3. Generalization to arbitrary scattering processes

It is claimed that entanglement is a phenomenon appearing quite generally in scattering processes and not only in special examples as for instance the spin-1/2-experiment or the emission of polarized photons. The justification of this assertion shall be restricted to processes with two ingoing particles and two outgoing particles. Further assumptions are not needed. The usual treating of scattering processes in the literature (cf. [9] to [12] and [13] for examples) will be sufficient.

In scattering processes of the mentionned kind two particles i_1 and i_2 are generated by two independent sources Q1 and Q2. They are prepared with certain values and directed to a region of time-space, where they will interact. By the interaction the two ingoing particles are melted into a new object that afterwards is passing into a system of two spatially departed particles f_1 and f_2. These are measured by two detectors D1 and D2. The two outgoing particles bear with them some common information that at least is concerning the laws of conservation. This is the cause of entanglement.

Now two different cases are to be distinguished. If the two initial particles are directed in such a way that they don't meet and hence don't interact, then no entanglement will occur. In all other cases interaction takes place with the consequence that the outgoing particles are correlated.

Mathematically scattering processes are described by the S-matrix. This has the form

$$S = E + gR(i_1, i_2; f_1, f_2)$$

with a coupling constant g and a term E that is standing for the case that the ingoing particles don't meet. In perturbation theory one has a series of approximations to S. By calculating them the correlation can be inspected explicitly. If the outgoing particles are identical, the exchange term of quantum statistics must be added. Then one has

$$S = E + gR(i_1, i_2; f_1, f_2) + \text{sign}\, gR(i_1, i_2; f_2, f_1)$$

On closer inspection nonlocality reveals to be no special feature of scattering processes in quantum field theory. It can already be observed, when two shunting railway carriages are pushed together and then moving away from each other. The annoying fact of all this is obviously the possibility that a quantum object can consist of two parts that are correlated, in spite of a great distance between them. But that is psychology and has nothing to do with theoretical physics.

References

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

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

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

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

[5] C. Erven et a.: Nature Photonics, **8** 292–296 (2014)

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

[7] F. Selleri: Die Debatte um die Quantentheorie, Braunschweig, 1990

[8] F. Selleri: Quantum Paradoxes and Physical Reality, Dordrecht, 1990

[9] M. E. Peskin/D. V. Schroeder: An Introduction to Quantum Field Theory, Reading (Mass.), 1995

[10] S. Weinberg: The Quantum Theory of Fields Bd. 1, Cambridge, 1995

[11] M. Maggiore: A Modern Introduction to Quantum Field Theory, Oxford University Press, 2005

[12] M. Srednicki: Quantum Field Theory, Cambridge, 2007

[13] J. D. Bjorken, S.D. Drell: Relativistic Quantum Mechanics, Mc Graw-Hill Book Company, New York, 1964