Relativistic Quantum Non-Locality

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Abstract

The controversy between relativistic causality and quantum non-locality can be resolved by establishing the general relativistic background of quantum non-locality.

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1 Introduction

The relaxation of restrictions, imposed by the relativistic causality on links between distant physical events, seems to have no reasonable alternative in many fields of physics. In cosmology, the synchronous start of expansion is hard to explain without an instantaneous omnipresent initiation. Such a problem persists, e.g., in the model based on Sakharov’s idea of a non-singular initial state, as well as in inflationary models, which suggest the synchronous start of the phase transition at the end of inflation. On the other end of scale, the relativistic causality is challenged by the quantum non-locality.

This challenge is the subject of the discussion below aimed to merge quantum non-locality with relativistic physics.

2 Time arrow representation

The spacetime history of a quantum object is built up by two kinds of events: interactions at the intersections of histories, and free falling, with no disturbance reaching the object.

Quantum mechanics describes a free falling object by a set of constants, quantum numbers and mechanical integrals of motion, defined by quantum and relativistic conservation laws. At intersections, the conservation laws generally leave room for the redistribution of conserved variables among the products of interactions. The final distribution is predicted, at best, only stochastically.

The source of stochasticity can be formally described as the exposure of quantum objects to random fluctuations obeying the uncertainty principle. Conservation laws strictly suppress the effect of fluctuations on a free falling object: in the average, all the uncertainties must vanish (just this lets us see remote celestial objects). But at the intersections the fluctuations can randomly affect interactions. This distinguishes a free falling quantum object from an interacting one.

In principle, the randomness attributed to fluctuations could be driven by some deterministic machinery. (Recall, e.g., the infinite decimal expression for the number...
π: the sequence of figures is perfectly random, though each figure is strongly determined.) Far from being resolved, the issue of determinism is still out of reach of contemporary theory, and the real concern is reversibility rather than causality.

Because of the time-symmetry of quantum formalism, we admit that it must be applied to a direct physical process and to its reversal identically. This means that if the theory defines a physical process stochastically, the same is true for its reversal, with the reversed process being dependent only on its past in terms of the reversed time (cf. Ref. [2]). We will call a process reversible if the reversal of the time direction (time reversal for short), being employed twice, returns exactly the original process. It follows then from the quantum formalism that, contrary to the explicit reversibility of free falling histories, the intersections of the space-time histories are generally irreversible because of the stochasticity of quantum formalism. This means that some aspects of preexisting reality are theoretically unrecoverable, and the subsequent evolution is not completely predictable.

Since the information lost during interactions is not restored by time reversal, we may admit that it is the loss of information that inside intersections creates the local distinction between the past and the future, making cause and effect non-interchangeable physically. Such occurrences can be labeled as the arrow of time.

The intersections, however, do not cover the whole spacetime. What then in the remaining part of spacetime—let us call it open spacetime—creates the local distinction between past and future, i.e., between cause and effect? The striking answer is “nothing”. The constants, determining the state of a free-falling object, do not specify the arrow of time. The spacetime geometry is alien to the notion of direction, so that no geometrical means exists for delivering the time arrow from afar. The fact that free falling histories are future-directed in the global reference frame is not relevant, because the principle of relativity denies the influence of relative velocity on local physics.

Thus, in open spacetime a quantum object is free of the arrow of time. We face the alternative: either this is a kind of easily removable degeneration, which is unnoticeably eliminated in any interaction, or this is the inherent property of free falling quantum objects, and then the way in which such objects behave is radically
distinct from that of free falling macroscopic bodies.

Decoherence, prevailing in the microscopic structure of the latter, involves a lot of causally related properties, such as irreversibility and the arrow of time. Based on these properties, the propagation of a disturbance through a macroscopic body proceeds along the time arrow with the speed of sound. In the absence of the time arrow, the notion of propagation, as a continuous sequence of the cause and effect, becomes self-contradictory. Thus, physics without the arrow of time is also deprived of the cause and effect propagation. So, entering interactions, a free falling quantum object can behave only as an indivisible whole. The consideration of the distant quantum objects in the next section reveals just this type of behavior.

3 Deon, distant entangled object

A quantum object is called entangled if its wave function is not the product of the wave functions of its components. If its size is much larger than the sizes of its components, it is called a distant entangled object; we will call it deon for short.

Consider Bohm’s version of the well-known EPR-thought-experiment, which historically turned out to be the first challenge to relativistic causality.

An emitter in each of its working cycles shoots out in opposite directions along its axis a pair of spin-1/2-particles, with total spin zero, but with the spin of each particle remaining undetermined. The last condition implies that the particles share the zero spin of the pair, and this creates some kind of interdependence between them. Only a pair as a whole is an independent quantum object, which is a deon with the growing distance between its constituents.

The EPR-deon is one of the innumerable quantum entangled objects, whose constituents share some quantum numbers and display the behavior known as quantum non-locality.

Let, on each side of the emitter, be stationed an observer who measures a spin component of the approaching particle. For measurements, each observer independently chooses one of the two predetermined mutually orthogonal directions, normal to the emitter axis. Quantum formalism predicts that the stochastic distribution of
readings, found by any single observer, depends neither on the independent choice made by the other, nor on the fact that the particles belong to a deon. This means that the particles’ link with a deon does not affect local physics. In particular, EPR-deon cannot be a means of communication between observers.

The occurrence of deons can be revealed only post factum by analysis of the correlation between readings pertaining to the pairs of particles. The cases, when the measurements, related to the same pair, have been made in distinct directions, reveal no correlation, but the same choice of direction always yields the opposite results, and this discloses the presence of the deon, i.e, a quantum number shared by both particles.

In terms of quantum formalism, this pattern can be explained only if the measurement of the spin of one particle somehow changes the wave function of the twin particle, which also acquires the definite spin component. The latter is opposite in direction to that found for the first particle. Then and only then the required pattern appears, and angular momentum is conserved.

The mechanism of this process is, however, obscure. To keep the angular momentum unchanged, the interaction between the deon constituents either should be instant, and then the process cannot be described in terms of relativistic causality, or quantum formalism is incomplete, and then it can be expanded to include a carrier, which transports action from one deon constituents to another (cf. Ref. [4]).

The seven-decade attempts to incorporate the last idea into quantum mechanics, however, failed. Thus, quantum non-locality—quantum instant (or, in other words, spacelike) propagation—is, most likely, in the nature of things. Though this is seemingly in variance with relativistic causality, the discrepancy is conceptual rather than physical, because, just as for the EPR deon, the local physics is never affected, and by means of that no actual violation of relativistic causality takes place.

The simplest suggestion for resolving the problem is that the place, where relativistic causality is in force, is separated from that where the quantum non-locality can be observed. The suitable places are open spacetime and intersections of histories.

The expected deon behavior supports this idea. At the intersections of histories with massive redistribution of conserved variables, multiple deons can appear; each
of them being a cluster of free falling particles, which share some quantum numbers. When a multiple deon runs into an intersection, the particles, which are actually involved in interactions, instantly acquire definite quantum numbers, and so do their twins. Thus, due to these instant adjustments, the deon as a whole escapes interactions. Only former constituents that have broken off with the deon are actually involved in the interaction. Constituents, keeping their non-local quantum ties intact, remain in open spacetime where they form the altered deon. Deons therefore exist merely in open spacetime as free falling objects, and therefore escape from the incompatibility with the relativistic causality acting merely inside intersections of histories. It is worth emphasizing that this separation of powers is essentially based on the quantum non-locality.

4 Relativistic quantum non-locality

A causal interaction is continuously decomposable into local cause-and-effect relations along paths confined to a light cone. Since quantum non-locality does not affect local physics, it cannot be displayed in this way. This, in classical terms, looks like the action at a distance. The Lorentz invariant counterpart of the latter is tachyon mechanics, the internally consistent superluminal paraphrase of special relativity [5]. This implies that quantum non-locality should obey tachyon mechanics and therefore is Lorentz invariant.

As was shown long ago [6], tachyonlike faster-than-light links between physical events can be incorporated into quantum formalism without causality breaking, but only if tachyons are virtual and never appear as free propagating particles. This essential restriction is actually inherent in tachyon mechanics itself. Indeed, let \( u \) be the velocity of a particle and \( \Delta t \) the time interval between its emission and absorption measured by an inertial observer. Lorentz transformations indicate that another inertial observer, moving in the same space-direction with the relative velocity \( v \), finds this time interval to be (\( c = 1 \)):

\[
\Delta t' = \frac{1 - uv}{\sqrt{1 - v^2}} \Delta t.
\]
If the particle is a tachyon, \(i.e.\ u > 1\), and the velocity \(v > u^{-1}\), then \(\Delta t\) and \(\Delta t'\) are of opposite signs. This means, that what one observer sees as emissions, another does as absorption, and vice versa. This is in striking contrast to relativistic causality, where it is of the prime importance that the sequence of cause and effect, or in other words the arrow of time, is Lorentz invariant. This means that an invariant time arrow cannot be introduced in tachyon mechanics, \(i.e.\) the latter does not describe the real propagation of anything. (The tachyon propagation is spacelike, so that in terms of causality it deals with the already existing relations between things.) This feature of tachyon mechanics is, however, completely in line with above-considered properties of non-locality.

Thus, we have at hand: The concept of open spacetime deprived of the arrow of time and by means of that providing the room for non-locality. The Lorentz invariant tachyon mechanics that describes the spacetime properties of non-locality. Quantum non-locality—the collection of supporting facts that fills up the still empty tachyon niche in relativistic physics. These three ingredients seem to be the foundation of the relativistic quantum non-locality. Causality survives, and non-locality comes as a part of the same relativistic physics, which is responsible for causality. This brings to a close the debate on the conflict between quantum non-locality and relativistic causality.

At present, we can only guess the possible physical role of the relativistic quantum non-locality. We cannot rule out that it is the spacelike links, introduced by the non-locality, which are responsible for the simultaneous start of the cosmological expansion, as well as for the homogeneity and basic hallmarks of the universe arising from the initial state with all conserved quantities globally shared.

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with modern inquisitiveness make it clear that no deciphering of the quantum reality allows avoiding the exploration of the spacelike paths in general relativity. As a matter of fact, this final victory of quantum thinking is coming without sacrificing Einsteinian relativity.

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