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Locality and indeterminism preserve the second law

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It is argued that anything that outraces c contradicts not only relativity theory but also the second law of thermodynamics. The case of quantum-mechanical correlations is considered, where quantum indeterminism guarantees that no superluminal signal can be sent by such correlations. Discussing theories that seek to reestablish some form of quantum determinism, a distinction is introduced between "source determinism' and "collapse determinism". Theories based on the former hypothesis seem to render the second law a mere secondary consequence of initial conditions. Theories of the latter type seem to allow superluminal communication as well as violations of the second law. Locality and quantum indeterminism are therefore deeply related to the second law. These conclusions impose fundamental constraints on any realistic model of wave-packet collapse or tachyons.

1. Introduction

Eddington [1] has made a famous statement concerning the second law of thermodynamics:

"The law that entropy always increases – the second law of thermodynamics – holds, I think, the supreme position among the laws of nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations – then so much the worse for Maxwell's equations. If it is found to be contradicted by experiments – well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation."

During the years, the imperative to preserve this unique law has proved fruitful in a wide range of issues, from black-hole physics [2] to CPT-invariance [3]. Recently, Valentini [4] has raised the interesting question concerning a possible relation between the three fundamental "impossibility principles", namely, (i) the absence of instantaneous signals, (ii) the uncertainty principle and (iii) the statistical law of entropy increase. He sought to derive the two former ones from a subquantum H-theorem, suggesting that the universe has undergone a "heat death" in the subquantum level, which gave rise to the uncertainty principle and the resulting inability to send superluminal signals via quantum-mechanical correlations.

In this Letter I would like to take a somewhat different approach. Instead of the uncertainty principle, I will take indeterminism as the quantum-me chanical "impossibility principle". This principle has actually been dismissed by Valentini, as his model preserves determinism in the microscopic level. Once, however, indeterminism is taken to be a fundamental principle, then the resulting triad of principles imposed by relativity, quantum mechanics and thermodynamics will reveal further new affinities between these three domains of physics.

2. Why is superluminal velocity impossible?

There seems to be something unclear about the rationale for the relativistic prohibition against velocities larger than c. This rationale usually runs as follows: "For any pair of causally-related events, all observers must be able to agree on the question of which event is the earlier and which is the later (or, to put it differently, which event is the cause and which is the effect), because otherwise nature would allow effects preceding their causes." The problem with this reasoning is that virtually all fundamental interactions are T-symmetric, the exceptions being certain weak effects involving K mesons. Hence the designations "cause" and "effect" are conventional rather than absolute. Consider a case where a superluminal interaction connects two events. It is true that two observers travelling in opposite directions would give each event opposite designations of "cause" and "effect", yet neither of them would observe any violation of the basic physical laws. The fundamental relativistic requirement that *all observers should observe the same natural laws*, is fully met in this case.

An apparently stronger objection to superluminal velocities has been raised by Tolman (quoted in ref. [5]) and recently by Penrose [6] in a popular account. Consider a system A sending to another system B a superluminal signal which causes B to send another, faster superluminal signal back to A. If we assume special relativity, then the signal from B must reach A before A sent its signal to B (fig. 1). Now what if A is constructed in such a way that any signal from B will turn off the machinery that produces the superluminal signal to B?

Several authors (e.g., refs. [5,7–10]) have shown that such paradoxes can be avoided in the framework of a Lorentz-invariant theory of tachyons. The simple quantum-theoretical procedure of reinterpretation reverses all charges and velocities so that any particle appears as an anti-particle, any emission appears as absorption and vice versa. This way, the supposed advanced signal from B to A is reinterpreted as an ordinary signal from A to B, hence no strange loop occurs. Similarly, more ingenious paradoxes involving tachyon exchanges in more than one dimension (e.g., ref. [11]) have not survived careful applications of the reinterpretation procedure [9] [#1].

For these reasons it has often been argued [7–10] that superluminal velocity does not contradict physical intuition. I submit that thermodynamics provides a stronger reason why no signal should outrace light.

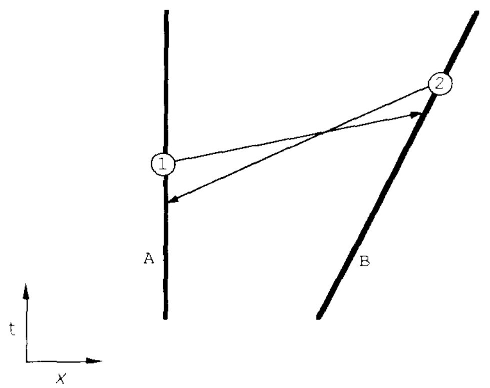

Fig. 1. An apparent paradox involved with superluminal signalling.

3. The bearing of the second law

Suppose that a single object exerts superluminal influence on a set of distant objects. For example, a jolt in the single object produces jolts in the set of distant objects (fig. 2). By energy and momentum conservation laws, each of the latter jolts should be weaker than the former one. An observer moving from the set of objects to the single one would see nothing unusual: The influence of the first jolt would appear to spread as it proceeds from its origin, producing weaker jolts in the affected objects. However, to an observer moving in the reverse direction the process would clearly look bizarre: A number of objects would exhibit weak jolts, their effects converging with perfect timing and precision on one distant object so as to produce one strong jolt.

While no mechanical law is violated in this observation, one would expect the probability for the occurrence of such accidental precorrelations to decrease strongly with the number of particles involved

[#1] Another objection against superluminal velocity, pointed out, e.g., by Penrose [6], is that it conflicts with the freedom of choice, since one's free choice can be counteracted by advanced actions from the future. However, Arntzenius [5] has shown that the conflict between advanced and retarded actions should be treated like the conflict between two ordinary retarded forces. Interestingly, Cufaro-Petroni and Vigier [12] argued that superluminal velocity is impossible because *there is no free choice*: "If, as claimed by our model, absolutely everything (bodies man, 'free will', etc.) are completely determined, all events are fixed somewhere in space–time, so that we cannot properly speak of "signals'." Like Penrose's argument, this argument should equally apply to the classical domain and be met on similar grounds.

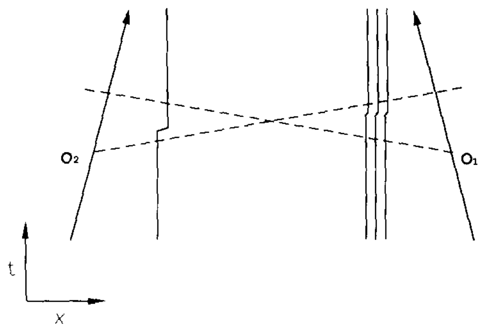

Fig. 2. A superluminal interaction viewed by two observers. The dashed lines indicate the observers' "presents."

in them. Yet this example shows that superluminal velocities give rise to precorrelations as a *constant* occurrence in some reference frames. This violation of the second law provides a strong reason why superluminal signalling cannot exist.

4. Quantum-mechanical non-locality and indeterminism

The above example involved dispersal of the effect. But perhaps there are superluminal signals that obey the second law by simply avoiding dispersal? Tachyons come to mind as a possible example. The following discussion will show, however, that even such a restriction on the signal's spreading would not avoid the conflict with the second law.

First, let us study a process in which some sort of superluminal influence has already been established, namely, the EPR correlations. Experimental violations of Bell's inequality [13] prove that the values of two correlated quantum objects cannot have existed prior to the measurement. Hence, the measurements must somehow affect the results of one another, even if they are spacelike separated. This holds also for a single particle. According to quantum theory, a single particle's position is described by a wave packet spreading in space. Only when the particle has been measured it assumes a definite position. This alleged transition from the linear evolution of a wave packet, required by the formalism, to the non-linear evolution, yielded by actual observation, indicates non-local influences between distant parts of the wave packet: If the particle "decides" at the moment of measurement to reside at a certain point, the wave packet must vanish at all the other points. This correlation is created instantaneously [14]. What bearing has the second law on this non-local influence?

At first sight, no violation of the second law is involved here because the correlations are amenable to reinterpretation: They are Lorentz-invariant in that each measurement can equally be viewed as either the "cause" or the "effect" of the other [15] [#2]. Also, no attenuation of the non-local influence with the increasing distance is observed [18], thus avoiding the paradox pointed out above in fig. 1.

However, this peaceful coexistence between quantum non-locality and the second law can hold only as long as quantum mechanics is inherently indeterministic. Any attempts to give a concrete physical mechanism of non-locality is likely to conflict with thermodynamics. It is therefore instructive to study the theories that seek to introduce some degree of determinism into the quantum-mechanical formalism.

4.1. Source determinism

Let "source determinism" denote all the theories that ascribe the measurement's outcome to some preexisting, hidden causes. Before examining these theories, let us recall the orthodox, indeterministic quantum-mechanical account of a particle exchange. How should the T-reversed interaction proceed? Would the particle be reabsorbed by the source? As Penrose [6] has shown, this is not certain at all: The normal wave function assigns equal probability for the detection of the particle at several points on its surface, hence the time-reversed wave function must assign equal probability for the particle's absorption by several objects other than the source. Consequently, in a macroscopic process, entropy will increase even under the complete reversal of all molecular motions since the initial state is extremely unlikely to be restored. Quantum indeterminism, in contrast to Newtonian physics, thus renders the sec-

[#2] Notice that in the case of a single particle even a negative result ("interaction-free measurement" [16]) is a real process, in which the detector's non-clicking can produce striking observable effects [17].

ond law a *fundamental* principle, independent of initial conditions.

An alternative to the standard formalism is proposed by the causal interpretation [19,20]. It introduces source determinism into quantum mechanics by postulating hidden variables that determine the system's evolution. A particle, according to the causal interpretation, consists of both a particle and a wave, the latter guiding the former's motion. It therefore has definite values prior to the measurement, but these undergo abrupt changes once a measurement has taken place.

This interpretation implies that a reversal of a quantum interaction requires reversing not only the particle's motion but also its accompanying guide wave. Hence, in order to reverse a particle exchange, all other surrounding objects that have absorbed the empty wave must simultaneously reemit it. This way, the causal interpretation allows entropy to decrease locally once all the interactions have been correctly reversed.

It should be noticed, however, that due to the extremely evasive nature of the guide wave as portrayed by the causal interpretation [#3], such a reversal of the guide wave is actually impossible. This considerably reduces the causal interpretation's determinism, as it turns out that the absorption of the empty wave does not give rise to any observable effect that can serve as an initial condition for the time-reversed process. Moreover, in order to be consistent with the observed Bell-inequality violations, the causal interpretation emphasizes that there is an inherently stochastic element in the hidden variables [19,20]. Otherwise, of course, non-local correlations would have never been observed. Bohm [19] has long ago stressed this stochasticity in order to rule out information transfer through the EPR correlations. This renders the determinism of the causal interpretation only a partial one.

The bearing of the causal interpretation on the second law can therefore be summarized as follows. *If* it is possible to time-reverse the absorption of the empty wave together with the absorption of the particle, then the second law is not a fundamental law but merely a result of initial conditions. Conversely, if the time reversal of the guide wave is impossible, then the causal interpretation is deterministic only in the weak sense of the word.

[#3] In this context it should be borne in mind that, despite enormous theoretical and experimental efforts, no empirical evidence for the guide wave has been found so far.

4.2. Collapse determinism

As the Bell-inequality violations severely restricted any model of source determinism, they inspired an alternative approach. "Collapse determinism" assumes that the other end of the interaction – absorption, "measurement" or "observation" – constitutes the cause for the value obtained. These theories regard the "collapse of the wave packet" as a real physical process.

Wigner's hypothesis concerning the role of human consciousness [21] is a notable example. It suggest that the physical values of a system are superposed until it interacts with a conscious observer. There is something in consciousness, so goes this argument, that evades physical explanation and is responsible for the strange occurrence of the collapse. Notice, however, that this hypothesis still preserves quantum-mechanical indeterminism: While the system's transition to a definite state is caused by the observer, its specific value is completely unpredictable. One cannot tell in advance, for example, whether a particle's spin would be $\frac{1}{2}$ or $-\frac{1}{2}$. As long as indeterminism is thus preserved, no conflict with the second law occurs.

Another type of collapse determinism is proposed by Penrose's hypothesis [6,22,23] that ascribes the wave packet collapse to the gravitational field. The boldness of this hypothesis lies in its realistic aspiration: Unlike Wigner's model, Penrose's hypothesis seeks to provide an *observer independent* explanation for the strange transition that the wave packet apparently undergoes. Now the crucial question is this: How deterministic can such a model be? If we take, for instance, the case of spin measurement, does the model explain only the mere occurrence of a definite outcome due to the gravitational effect, or can it also predict when this outcome would be $|\frac{1}{2}\rangle$ or $|-\frac{1}{2}\rangle$?

Penrose (ref. [22], p. 60, ref. [23], p. 34) does not regard the latter possibility as outrageous as many other physicists would: "Perhaps the choice of alternative is just made by change, or perhaps there is something deeper underlying this choice" (ref. [6],

p. 476). It turns out, however, that in the latter case the model would conflict with relativity. Once we know the factor that caused the superposed value $(1/\sqrt{2})(|\frac{1}{2}\rangle+|-\frac{1}{2}\rangle)$ to collapse into a definite outcome $|\frac{1}{2}\rangle$ or $|-\frac{1}{2}\rangle$, it would be possible to manipulate that factor to produce the desired result. Consequently, in an EPR experiment, one experimenter would be able to send superluminal messages to the other experimenter who measures the correlated particle. It suffices if only, by inspecting the measuring apparatus, the experimenter can predict when the collapse of the wave packet would yield the outcome $\frac{1}{2}$. This would enable him to remove the instrument every time this result is predicted. This would slightly but significantly affect the distribution of outcomes obtained by the other experimenter, thereby allowing communication.

Here, the reinterpretation procedure might bypass the relativistic prohibition but not the second law. Consider such an EPR experiment in which an experimenter determines by the above technique the results of one measurement, thus affecting the result obtained at the other measurement (fig. 3). An observer travelling in the direction of this superluminal message would first observe the measurement of the affected particle, M_2, which he would regard as the "cause" of the other measurement, M_1. The next event he would observe is not M_1, but the alleged cause that has lead to the specific outcome of M_1. Hence, in the reference frame we consider, M_2 and the operation preceding M_1 would always appear as two correlated "causes" converging into the same "effect."

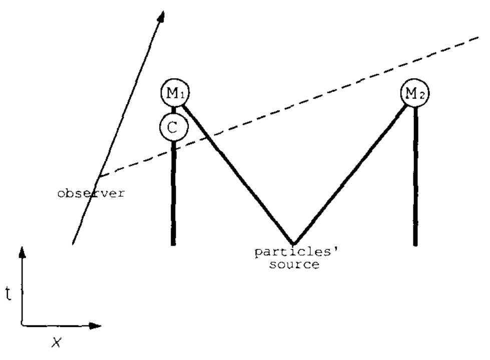

Fig. 3. Superluminal EPR signalling. C denotes an event that can be identified as the cause of the measurement's outcome. The observer's "present" gives rise to the anomalous causal sequence M_2–C–M_1.

This conclusion seems to apply to all proposals made so far (e.g., refs. [24,25]) to harness quantum-mechanical correlations to superluminal communication. It similarly holds for all variants of Wigner's interpretation in which mind is capable of deciding the measurement's outcome at will, thereby giving rise to paranormal phenomena (e.g., refs. [26,27]).

In fact, strong collapse determinism allows even clearer entropy decreases that would appear in all reference frames. For example, a manipulation of the collapse of a photon's wave packet, whereby its final position can be decided at will, would enable one to cause several photons emitted from various sources to spontaneously converge on one object, reversing entropy's direction. Conflicts with the second law await collapse determinism even if it does not allow deliberate manipulations of the collapse but only points out a cause for the result of the quantum-mechanical measurement. By simply observing, from an appropriate reference frame, the alleged cause of the collapse, and observing its consequences in some distant location on the wave packet, one would witness the above precorrelations.

Such objections equally apply to tachyons. If tachyons interact in a causal, deterministic manner with ordinary matter, such that there can be a mechanism of tachyon emission, then in a reference frame moving in the direction of the tachyon's flight a clear anomaly would appear: The first observed event would be the tachyon's arrival, next the (strictly correlated) event of the tachyon-source's triggering, and finally the tachyon's actual emission. Reconsidering the tachyonic scenarios discussed at the beginning of this article, we can now point out a more straightforward objection against their reality. Landsberg [28] has shown that an experimenter using tachyonic communication must be uncertain whether his instrument emits a tachyon or absorbs one. When this uncertainty is translated into probabilities, a thermodynamic anomaly follows: One might observe perfect convergences of tachyons "emitted" from independent "sources". Thus, although the paradoxes pointed out so far have been resolved by reinterpretation, the thermodynamic anomaly provides a more compelling reason to outlaw tachyonic signalling.

5. Summary

The second law lies at the heart of one of the most difficult problems of present-day physics, namely, the time-asymmetries. Entropy, the universe's expansion, CP-symmetry violations and a few other T-asymmetric processes pose the question as to which is the master asymmetry of the universe from which the others can be derived (see, e.g., ref. [29]). Our discussion shows that if quantum indeterminism is an inherent feature of the physical world, then the origin of the asymmetries lies at nature's most fundamental level.

Aharonov [30] has argued that quantum-mechanical indeterminism is obliged by the theory of relativity, because it rules out superluminal communication via quantum-mechanical correlations. The second law seems to yield an additional reason. Perhaps God plays dice in order to preserve both relativity theory and thermodynamics. Be that as it may, it is probably not a coincidence that the relativistic upper limit on velocity, the inherent indeterminism of quantum mechanics, and the second law of thermodynamics preserve one another in such subtle ways [#4]. The fundamental relationship between these three domains of physics is still unknown, but it is obviously there and is worth looking for.

Acknowledgement

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[#4] Elsewhere [18,31] the second law has been shown to have interesting bearings also on some other aspects of quantum nonlocality.

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