PHYSICS

Ya. P. TERLETSKII

1960

SovietRxiv

Abstract

Full Text

PHYSICS

Ya. P. TERLETSKII

THE PRINCIPLE OF CAUSALITY AND THE SECOND LAW OF THERMODYNAMICS

(Presented by Academician Louis de Broglie, 30 III 1960)

1. In modern theoretical physics, alongside general physical laws, the "principle of causality" is often used as a postulate concerning the conditioning of all subsequent events by certain preceding ones and concerning the impossibility of changing the temporal sequence of causally connected events by means of any transition to another frame of reference*. From this postulate, understood as a universal absolute law of nature, a number of concrete physical consequences are derived. It is used, for example, in the theory of relativity to prove the impossibility of the existence of signals (or other energy-carrying localized disturbances) propagating with a speed greater than the speed of light in vacuum. This conclusion is often used in the theory of elementary particles.

Although the "principle of causality" is tacitly regarded by most authors as a certain absolute and universal law of nature, there nevertheless exists no clear physical and rigorous mathematical formulation of it**. And this is no accident, since the "principle of causality" is inseparably connected with the idea of the **directionality** of physical processes in time. If, however, it is regarded as a universal absolute physical law, then it is necessary to postulate the absolute directionality of all physical processes in time. But in modern physics the fact of the absolute reversibility of all elementary physical processes has been firmly established, i.e., the fact that there is no distinguished direction of the flow of time for phenomena of the microworld.

The latter contradiction, however, is easily removed if the "principle of causality" is regarded only as a macroscopic law (i.e., a statistical one), capable of being violated in the microworld. In this case it seems possible in general to regard the "principle of causality" as a consequence of the second law of thermodynamics or as a certain special expression of it. Indeed, the second law, in the form of the law of increase of entropy, contains the idea of the directionality of processes in time. The contradiction between macroscopic irreversibility and microscopic reversibility is removed, as is well known, by statistical physics, where the second law is regarded only as a statistical law, valid almost as an absolute one for macroprocesses and appearing merely as a purely probabilistic tendency for microprocesses.

* Physicists are also familiar with other conceptions of causality, which is due to the presence in philosophy of a more general understanding of causality as a particular case of the universal interconnection and mutual conditioning of the phenomena of nature (see, for example, (1, 2)). In the present article, by the "principle of causality" we shall understand only the proposition formulated above, as is customary in modern physical literature.

** All existing formulations of the principle of causality have rather an a priori-intuitive character.

Let us explain this connection between the "principle of causality"and the second law in somewhat greater detail. Let us imagine a certain cause-and-effect chain of events, i.e., a collection of physical systems in which certain physical processes take place in such a way that the process in system n causes (at the next instant of time) a process in system $n+1$. In turn, the process in system n is conditioned by the process in system $n-1$ (at the preceding instant of time). If this chain of events is causal, then it must be irreversible, since otherwise the process could be reversed in time, and in that case causes and effects would exchange places. But every irreversible process proceeds with an increase of entropy. Consequently, in each subsequent system a spontaneous increase of entropy is produced after the action (signal) received from the preceding system.

From the thermodynamic point of view this means that each of the systems is initially in a metastable equilibrium state, from which it is brought out by the addition of negative entropy, $-\Delta S_n$, received from the preceding system, and then spontaneously passes into a more stable equilibrium state, while sending into the next system a certain new portion of negative entropy, $-\Delta S_{n+1}$ (the next signal).*

Thus, it appears possible to carry out a physical analysis of interactions by proceeding not from the "principle of causality," which has no noncontradictory physical formulation, but directly from the second law of thermodynamics as a rigorously formulated physical law.

In this article we shall analyze the question of the possibility of signals propagating with a velocity greater than the velocity of light in vacuum and, correspondingly, the reality of particles with imaginary rest mass, proceeding not from the principle of causality, as is usually done, but directly from the second law of thermodynamics as a statistical law.

2. First of all it is necessary to clarify the concept of a "signal." In relativistic theory, a "signal" is usually understood to mean any spatially localized disturbance that carries energy and, consequently, can produce physical effects in the system receiving the signal. However, from the thermodynamic point of view a signal must carry entropy, since otherwise it will not produce an irreversible change and thus will not be able to establish a cause-and-effect relation between the emitter and the receiver.** Thus, by a signal we shall mean such a localized disturbance which, moving from the emitter to the receiver, carries negative entropy.

Let, when a localized disturbance is emitted by an emitter, the entropy of the latter increase by the amount ΔS_1, and when this disturbance is absorbed the change in the entropy of the receiver be equal to ΔS_2. We call this disturbance a signal if $\Delta S_2 < 0$. But by virtue of the law of entropy increase:

$$\Delta S_1 + \Delta S_2 \geq 0. \tag{1}$$

Consequently, $\Delta S_1 > 0$, i.e., a signal can be emitted only with an increase in the entropy of the emitter.

For theoretical analysis it is useful to introduce the concept of an ideal, or reversible, signal, for which $\Delta S_1 + \Delta S_2 = 0$. Obviously, then

---

* The quantity $-\Delta S$ must be sufficient to transfer the system from one entropy maximum to another, higher one, across the pit of the entropy curve separating these maxima, i.e., it must be $|\Delta S| > S_{\max} - S_{\min}$, where $S_{\max}$ is the entropy of the metastable state.

** From the point of view of information theory (3), a "signal" must also carry entropy, since in the receiver system it must increase information, i.e., decrease entropy. The latter is possible only if the signal carries negative entropy.

all signals for which $\Delta S_1 + \Delta S_2 > 0$ must be called **irreversible**. An example of a reversible signal may be a photon emitted by a previously excited atom and absorbed completely by exactly the same kind of, but unexcited, atom. An example of an irreversible signal may be a bullet fired by a gun (the emitter) and striking a target (the receiver).

One can also imagine an "antisignal," i.e., such a localized disturbance which, upon emission, decreases the entropy of the emitter (i.e., $\Delta S_1 < 0$) and increases the entropy of the receiver upon its absorption (i.e., $\Delta S_2 > 0$).

From the point of view of macroscopic thermodynamics, any antisignals are forbidden by the second law, since spontaneous emission of radiation with an increase in the entropy of the emitter could be used to create a perpetual motion machine of the second kind. However, from the point of view of statistical physics, reversible antisignals are allowed as fluctuations of a special kind. In the macroworld such processes are extremely improbable (for example, the spontaneous ejection of a bullet by a target, its reverse motion along the trajectory, and, finally, the reverse loading of the gun). However, they are admissible, and in the microworld they may even turn out not to be too improbable.

One can also imagine localized disturbances that produce physical effects but carry no entropy (i.e., $\Delta S_1 = 0$ and $\Delta S_2 = 0$). Such disturbances are forbidden neither by macroscopic thermodynamics nor, all the more, by statistical physics. Conventionally, they may be called zero signals.

3. Let us consider a signal propagating with a speed greater than the speed of light in vacuum. For simplicity we shall regard it as reversible. It is known from the theory of relativity that for this process one can always find such a Lorentz frame of reference in which the moment of absorption will precede the moment of emission, since these events are connected by a spacelike interval. Consequently, in this frame of reference the receiver and the emitter change places. First there occurs a decrease of entropy in the system previously regarded as the receiver, and then an increase of entropy in the system previously regarded as the emitter. In other words, the signal is transformed into an antisignal. Since this transformation depends only on the choice of the frame of reference, i.e., on the manner of representing the physical phenomenon, this process is in general forbidden by the second law, considered purely thermodynamically, because the second law is violated in at least one frame of reference. However, this process is not absolutely forbidden, just as antisignals in general are not. It may occur as a purely fluctuation process with a violation of the second law permitted by statistical physics.

As for zero signals, i.e., localized disturbances carrying no entropy at all, such disturbances propagating with a speed greater than the speed of light are forbidden neither by formal thermodynamics nor by statistical physics.

Thus, "signals" propagating with a speed greater than the speed of light are forbidden by macroscopic thermodynamics, just as they are forbidden by the "principle of causality." However, localized disturbances carrying physical effects are not forbidden if they proceed as processes of a fluctuation character and, in this way, are not signals in the thermodynamic sense. Zero signals, which, strictly speaking, are not "signals," are also not forbidden.

4. Consequently, particles moving with a speed greater than the speed of light or, in other words, particles with imaginary rest mass* are not categorically forbidden as supposedly physically unreal. Only

* Since the momentum p, the energy ε, and the rest mass m are related by the relations $m^2c^2 = \varepsilon^2/c^2 - p^2$, $p = (\varepsilon/c^2)v$, it is obvious that, for real p and ε, $m^2 < 0$ when $v > c$.

the process of emission of such particles as systematically repeatable and associated with an increase in the entropy of the emitter. The emission or absorption of such particles may be either a process of a purely fluctuation character, or may proceed reversibly and, in general, without any change in the entropy of the emitter or receiver.

Obviously, processes of the type of photon emission by an excited atom, or the process of radioactive decay of one elementary particle into several others (processes associated with a change in the proper mass of the initial system), are processes of an irreversible character, proceeding with an increase of entropy (the reverse processes, as spontaneous ones, are improbable). Consequently, in processes of this type, the emission of particles with imaginary mass can only be a process of the fluctuation type, proceeding with the same probability as the reverse process.

However, processes of emission of particles of imaginary mass without a change in the rest mass of the initial particle are possible. Indeed, let a particle of mass M decay into particles of masses M_1 and M_2. Obviously:

$$M^2 = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 = M_1^2 + M_2^2 - 2(E_1 E_2 - \mathbf{p}_1 \mathbf{p}_2) \tag{2}$$

(here and below we put $c = 1$). For $M_1^2 > 0$ and $M_2^2 > 0$, $E_1 > p_1$, $E_2 > p_2$, and the equality $M_1 = M$ cannot be combined with (2). But for $M_1^2 > 0$, $M_2^2 < 0$, obviously, $E_1 > p_1$, $E_2 < p_2$, and therefore relation (2) is satisfied for $M_1 = M$, if one assumes that in the reference frame where $\mathbf{p}_1' = 0$,

$$E_2' = -M_2^2 / 2M. \tag{3}$$

Consequently, a particle of real mass can emit and absorb particles of imaginary mass, changing only its kinetic energy of translational motion and not changing its proper mass. However, the processes of emission and absorption must occur with equal probability, since the entropy must not change in either case.

Obviously, when a system consisting of ordinary particles of real mass interacts with a gas of particles of imaginary mass, the entropy of the first system must not change. Thus, a particle of real mass moving in a gas of particles of imaginary mass may change the direction of its motion, but it will retain its mean energy, since dissipative friction in interaction with imaginary particles is impossible.

Thus, particles with imaginary proper mass, moving with a velocity greater than the speed of light, may be regarded in reversible microprocesses as physically real. This conclusion does not contradict the theory of relativity, understood as a four-dimensional theory of space-time, if one rejects the a priori notion of the supposedly absolute character of the "principle of causality" and regards it only as a consequence of the second law of thermodynamics.

What has been said above, of course, should not be interpreted as a rejection of causality (determinism) in the broad general-philosophical sense. This question was considered by us in special detail earlier in (^{1}).

In conclusion, I take the opportunity to express my sincere thanks to Louis de Broglie for his attention to the work, and also to J.-P. Vigier and G. Lochak for fruitful friendly discussions.

Henri Poincaré Institute
Paris, France

Received
23 III 1960

REFERENCES CITED

1. Ya. P. Terletskii, *Dynamic and Statistical Laws of Physics*, Moscow, 1949.
2. D. Bohm, *Causality and Chance in Modern Physics*, IL, 1959.
3. N. Wiener, *Cybernetics*, Moscow, 1958.

Note: Figure translations are in progress. See original paper for figures.

Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.