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On the possibility of macroscopic violations of the laws of thermodynamics

by

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SUMMARY. — It is shown that macroscopic violations of some laws of thermodynamics such as the second law, the postulates of additivity and thermodynamic equilibrium, are not forbidden by Gibbs' statistical mechanics. Macroscopic violations are forbidden only by the addition postulate—the thermodynamic concept; according to this concept the existence of microscopic-dynamic systems, the statistical theory of which allows macroscopic violations of thermo-dynamics, is forbidden. Such violations, however, are allowed by the opposite postulate—the dynamic concept. For example, according to the dynamic concept, the existence of particles with negative energy and mass is possible.

The possibility of the existence of the « thermodynamic machine of the second kind » somewhere in the universe, with heat sources of negative energy and negative temperature, is examined.

The possibility of violations of the causality principle and existence of systems having a negative time direction is also considered.

SOMMAIRE. — On montre que la mécanique statistique de Gibbs n'interdit pas la violation macroscopique de certaines lois de la thermodynamique comme le second principe, le principe d'additivité ou le postulat d'existence d'un équilibre thermodynamique. Les violations macroscopiques ne sont interdites que par le postulat d'addition et la « conception thermodynamique » qui interdit l'existence de microsystèmes dont la théorie statistique

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permettrait des violations macroscopiques des lois de la thermodynamique. De telles violations sont permises au contraire par la « conception dynamique » qui permet, par exemple, l'existence de particules de masse négative.

On étudie également la possibilité de l'existence, quelque part dans l'Univers, d'une machine thermodynamique de seconde espèce avec des sources de chaleur à énergie et température négatives. On considère enfin la possibilité de violations du principe de causalité et l'existence de systèmes pour lesquels la direction du temps serait négative.

I. INTRODUCTION

Are macroscopic violations of the laws of thermodynamics possible ? The usual answer is: « Of course not ! the laws of thermodynamics may be violated only in the micro domain. This was shown by Boltzman and Gibbs, and was clearly demonstrated by Einstein and Smoluchowski with Brownian motion. »

This negative answer seems as justified as the one stating that no perpetual machine is possible.

An opposite, positive answer to the above question may, for example, mean that we accept the following possibilities:

1) Somewhere in the universe a « thermodynamic machine of the second kind » is possible; this machine produces perpetual work at the expense of some heat reservoir which undergoes unlimited cooling in the process.

2) The existence of systems which can never be in a state of thermodynamic equilibrium.

3) Somewhere in the universe there exist macroscopic regions where the entropy is decreasing, i. e., where the macroscopic history goes back in time.

There may be other physical processes which are considered impossible by the rational mind, if we accept the positive answer.

We shall try, however, to show that the above negative answer—even though it seems obvious—is only an expression of some *a priori* point of view, or concept, which does not follow from Gibbs' statistical mechanics. We shall also try to show that there exists an opposite concept which allows a positive answer to the question about the possibility of macroscopic violations of thermodynamics. Let us formulate these two concepts.

I. Thermodynamic concept. — The laws of thermodynamics apply to all macroscopic systems. They cannot be violated on a macroscopic scale. Only such microscopic physical systems and laws governing their motion are allowed, which do not violate the laws of macroscopic thermodynamics.

II. Dynamic concept. — The thermodynamic laws are only consequences of the statistical theory of the dynamic-microscopic systems. The microscopic laws are not limited by any consequences of the laws of thermodynamics. Microscopic-dynamic systems are possible, the statistical theory of which may give a new thermodynamics different from the usual classical thermodynamics.

It seems that there are no contradictions between these two concepts in the statistical physics of today. In all textbooks, starting with Gibbs', it is shown that thermodynamics is a natural consequence of the statistical mechanics of any dynamic system. It is therefore assumed that macroscopic violations of thermodynamics which take the dynamic concept into account, do not occur in nature. Consequently, it seems that the thermodynamic concept follows from statistical physics which is based on the dynamic concept. However, such a conclusion can arise only if some assumptions on which the derivation of statistical mechanics is based, are neglected.

It was already known to Gibbs that for some classes of dynamic systems the statistical integral does not converge. For example this is the case with systems of molecules which interact according to Newton's law ⁽²⁾. This system can never exist in a state of equilibrium and it is not possible to formulate a classical thermodynamic theory in this case.

Similarly before Gibbs, Boltzmann analyzed the contradiction between the irreversibility of macroscopic thermodynamics and the reversibility of microscopic-dynamic systems. He came to the conclusion that from a kinetic point of view, regions of cosmic dimensions may exist in the universe in which the entropy decreases systematically, that is the thermodynamic law of increasing entropy can be violated on a macroscopic scale.

Gibbs, in his book, « Elementary Principles in Statistical Mechanics », has treated only those micro systems from which classical thermodynamics could be derived. He confined himself to only one remark which indicated that non-thermodynamic microscopic systems can exist. Subsequent authors usually have ignored this remark and treated statistical physics and its thermodynamic consequences as a theory for all dynamic systems.

⁽²⁾ See, for example, reference [1, 2].

If one takes into account that for some systems which are allowed according to general dynamic principles (for example the principle of Hamilton), statistical theory cannot yield classical thermodynamics, it is necessary to choose between concepts I and II. Such non-thermodynamic systems can be considered physically possible only from a dynamic point of view. If the thermodynamic concept is taken to be correct, any dynamic models which lead to non-thermodynamic systems must be considered forbidden by classical thermodynamics.

In order to arrive at a choice of one or the other concept, we shall now examine the fundamental consequences associated with each.

2. SOME CONSEQUENCES OF THE THERMODYNAMIC CONCEPT

We shall first examine the most important consequences of the thermodynamic concept.

I-1. Let us consider *the law of increasing entropy*, that is

$$\frac{ds}{dt} \geq 0. \quad (1)$$

According to the thermodynamic concept there is an absolute macroscopic law which is never violated in any macroscopic process. This law of increasing entropy is the physical basis for the concept of irreversibility and the unidirectional property of time in all of the universe, that is if it is considered as an absolute law.

All known microscopic laws of motion are absolutely reversible in time. Therefore the statistical theory of reversible microscopic systems leads to the law of monotonically increasing entropy, as well as to its decrease with time. To put it in a different way from a point of view of statistical physics, not only irreversible macroscopic processes which occur with increasing time are possible, but also those irreversible processes are possible which go back in time.

Only if the principle of increasing entropy is taken as an absolute macroscopic law, can the macroscopic process which go back in time and are allowed by the mathematics of statistical physics be rejected. Consequently the thermodynamic concept is inseparably connected to the concept of irreversibility and unidirectional property of time. The irreversibility of time is a consequence of the thermodynamic concept. Conversely, the

obvious notion of irreversibility of time can serve as an argument for the thermodynamic concept.

I-2. The universality and absoluteness of the *causality principle* also follows from the thermodynamic concept. This principle states that of two related events, the earlier one must be the cause of the later one; this time sequence of cause and effect cannot be changed by any choice of frame of reference. Indeed, reversing the time sequence of an arbalest shot, followed by the arrow hitting the target, would mean reversal of an irreversible process, that is a macroscopic violation of the law of increasing entropy.

The principle of causality does not follow from the reversible dynamic laws of micromotion. The principle of increasing entropy is the only physical law to which causality can be related. Therefore the principle of causality can be regarded either as a consequence of the law of increasing entropy [3], or as an independent postulate from which the concepts of absoluteness of the law of increasing entropy is a consequence. Since the thermodynamic concept is more general than the principle of causality, it may be considered a consequence of the former.

I-3. According to the theory of relativity no body can attain a velocity greater than that of light—this deduction is directly based on the principle of causality. Since the principle of causality is a consequence of the thermodynamic concept, the above limitation of velocity, can itself be considered as a consequence of the thermodynamic concept.

Thus, the fact that the maximum attainable velocity is that of light, follows only from the thermodynamic concept used in the four dimensional space-time theory described by the Lorentz group.

I-4. The thermodynamic concept does not allow the existence of any macroscopic energy source which continuously produces work at the expense of unlimited cooling of any sort of matter. Such an energy source would be a « thermodynamic machine of the second kind ».

I-5. It also follows from the thermodynamic concept that no system can possess a negative energy or mass.

The microscopic dynamic theory allows the existence of particles with a negative mass, as shown by Dirac. However, systems of such minus-particles can exist in thermodynamic equilibrium only in conjunction with a negative absolute temperature [4]. From thermodynamics it is known that ordinary bodies in contact with heat sources of negative temperature, can obtain energy only at the expense of a continuous and unlimited decrease in temperature of the heat source. Thus a « thermodynamic machine of

the second kind » would be possible if a heat source consisting of minus-particles were available. However, this would contradict the thermodynamic concept.

I-6. From a point of view of the thermodynamic concept, macroscopic systems where the intermolecular interaction decreases slowly with increasing distance are not possible. For such systems the additivity of energy would not be satisfied, not only on a microscopic scale but also on a macroscopic scale. Consequently, the thermodynamic concept demands a correction of the laws of interaction at large distances, such as, for example, Newton's law of gravitation.

3. SOME CONSEQUENCES OF THE DYNAMIC CONCEPT

These questions can be solved differently from a point of view of the *dynamic* concept.

II-1. From the point of view of the dynamic concept an increase in entropy in all the universe is not necessary. Macroscopic regions are allowed where the entropy decreases. Consequently the direction of time is not absolute, but can change upon a transition to different cosmic regions, or to different epochs. In our ordinary macroscopic experience, we do not observe any macroscopic processes which occur in the opposite sense of time; however, this we cannot explain with the aid of the dynamic concept by stating that such observations would be in violation of thermodynamics. The absence of such processes in our experience may mean that they may occur under historical conditions which do not exist on earth.

It is to be noted that the observation of astronomical systems which are developing in the opposite sense of time cannot be made in the usual manner. Apparently, such galaxies cannot shine, because their stars absorb rather than emit light. Therefore the discovery of such systems can be made only with apparatus capable of registering absorption rather than emission of light. Up to now, however, astronomers have observed only emission.

II-2. In the dynamic concept, the principle of causality cannot be regarded as absolute and unviolable. Indeed, if we recognize the existence of macroscopic systems where the entropy is decreasing, we can also allow the reverse process of the arbalest shot and target.

Consequently, the principle of causality and the unidirectional property

of time must be regarded only as macroscopic rules which hold for those macroscopic systems with which we are familiar in our macroscopic surroundings. Thus, the dynamic concept allows even macroscopic violations of causality.

II-3. Since the dynamic concept does not exclude violations of the causality principle, it permits the existence of bodies which have velocities greater than that of light [3, 4]. Such super-light velocity particles must possess an imaginary rest mass M , since according to the well known formulae (2) $M^2 < 0$ at $v > c$.

$$\vec{P}^2 - \frac{E^2}{c^2} = -c^2 M^2, \quad \vec{v} = c^2 \frac{\vec{P}}{E}. \quad (2)$$

Such particles cannot be, however, created or observed at any single point in space, as is the case with the usual particles of real and positive mass. This is because, in principle, absorption or emission processes of super-light velocity particles cannot be distinguished. In one frame of reference a super-light velocity particle can be imagined as being absorbed by any body and in another frame of reference as being emitted.

The creation or absorption of a super-light velocity particle must be related to two points in space: the points of emission-absorption and absorption-emission. It follows that special type of instruments are required for the detection of super-light velocity particles.

The principle of causality and the second law of thermodynamics does not permit any super-light velocity signals in our finite world. In other words, processes which transmit information or negentropy with velocities greater than that of light are not allowed. Consequently super-light velocity particles cannot transmit negentropy. However, they can transmit energy or momentum between real particles.

Thus, the dynamic concept does not contain any absolute forbiddenness of super-light velocity particles. If they do not exist in nature, this must be due to more fundamental reasons than those of the causality principle or second law of thermodynamics.

Within the framework of the Lorentz group in the theory of relativity such particles are allowed.

II-4. The dynamic concept does not exclude the existence of energetic sources which operate like the « thermodynamic machine of the second kind ». Such sources cannot, of course, be realized with ordinary macroscopic bodies to which classical thermodynamics apply.

In modern physics, however, systems are known which allow there realization of models of a « thermodynamic machine of the second kind ». An

example are systems of spins in a magnetic field which may exist in a state of negative temperature. Such systems can in practice yield work; for example, they can accelerate electrons or amplify a light beam only at the expense of an increase of negative temperature.

Naturally such models cannot serve as practical energetic sources, since spin systems cannot be cooled indefinitely and yield an unlimited amount of energy. However, they illustrate the possibility of realizing such sources with a different kind of heat source; an example would be a heat source possessing a negative energy and mass.

II-5. Negative mass and energy are not prohibited by the dynamic concept. The possibility of a « thermodynamic machine of the second kind » with a heat source of particles of negative mass is no more a contradiction, since such a machine is allowed according to the dynamic concept.

Particles of negative mass, or minus-particles must possess many strange properties. For example, if such a particle is moving under usual friction in an ordinary medium, it must undergo continuous acceleration.

Minus-particles cannot be in thermodynamic equilibrium at a positive temperature. Indeed, the statistical sum

$$Z = \sum_k e^{-\frac{E_k}{\Theta}} \quad (3)$$

diverges for a system of minus-particles. This is because the energy levels are not limited by any minimal energy, but are limited by a maximal energy:

$$-\infty < E < E_{\max}. \quad (4)$$

However, the statistical sum of such a system converges when $\Theta < 0$, i. e., at negative temperatures. Consequently a system of minus-particles can exist in thermodynamic equilibrium only at a negative absolute temperature. This is in contrast to systems of real plus-particles, which may exist in equilibrium only at positive temperatures.

It is well known that such minus-particles have never been observed. However, no one has tried to observe them, since for their detection special types of instruments are required. Indeed, all instruments used for the detection of usual particles (Wilson cloud chamber, Geiger counter, Čerenkov counter, photo-emulsions, etc.), are activated by the energy carried by the particles which are absorbed. This energy initiates the irreversible detecting process. However, minus-particles carry negative energy and cannot give up any energy to the instrument when they are absorbed. During the absorption process they can only remove energy rather than give

it up to the instrument. Ordinary instruments could detect emission of minus-particles; however, experiments are set up for the detection of already existing particles, but not for the detection of any possible emission from the instrument itself.

Thus, according to the dynamic concept, the existence in the universe of energy sources which yield work at the expense of unlimited cooling of a heat source consisting of minus-particles is possible.

In accordance with this concept, the creation of plus- and minus-particles pairs are possible. If such processes occur somewhere in the universe, they could be observed with the usual instruments as creation of matters since only the plus-particles would be registered and the minus-particles would fail to register.

If such processes would occur with great intensity, they would be observed as a creation of energy which would be unexplainable by the usual nuclear reactions.

For the time being we will not examine the questions about the possible mass, spin, charge and other properties of minus-particles. We shall only note that it is not likely that such particles have an electric charge. In our environment which consists of plus-particles, the electrically charged minus-particles would be strongly accelerated and would rapidly increase the energy of plus-particles.

We do not have, however, any objections against weak or strong interactions between minus- and plus-particles. Apparently the minus-particles must interact gravitationally with each other and with plus-particles.

II-6. In contrast to the thermodynamic concept, the dynamic concept allows the existence of systems of nonclassical thermodynamics, for example of nonadditive thermodynamics. We can arrive at such thermodynamics if besides the usual molecular interaction forces we take Newtonian gravitational forces into account. Indeed, according to Newton's law of gravitation the energy of gravitational interaction is proportional to

$$U_g \sim -k \frac{(\rho V)^2}{V^{1/3}} = k\rho^2 V^{5/3} \quad (5)$$

where k gravitational constant, ρ density of matter, V volume occupied by the system. The internal energy of such a system is proportional to ρV . Thus, with increasing volume at constant density the total energy increases in a manner which is not proportional to the volume, i. e., the law of additivity of energy is not realized. Accordingly, large fluctuations in volume and entropy (1, 2), i. e., macroscopic deviations from the law of monotonic increase in entropy are possible.

Of course, these conclusions must be regarded as being qualitative in nature, since a more exact gravitational field must be examined with the aid of Einstein's equations and not those of Newton.

4. CONCLUSION

Thus, the thermodynamic concept discussed in I-1 to I-5 leads to conclusions which do not demand a radical revision of the well known and familiar physical ideas. However, it forces us to arrive at the following question : « Why can thermodynamic laws which are only a consequence of the statistical theory of dynamic microsystems, limit the microscopic systems and their laws of motion ? » We doubt that anybody, who accepts the thermodynamic concept can answer this question; however, if someone would answer as follows : « This follows from our daily macroscopic experience », he would not be correct, since only macroscopic experience on earth was used to construct classical thermodynamics and experiments on a cosmic scale were not employed.

As far as I-6 is concerned, the thermodynamic concept must yield to generalization of nonadditive thermodynamics. However, if one accepts any generalized thermodynamics, why should not the law of increasing entropy be considered relative ?

The dynamic concept is more logical. However, points II-1 to II-5 allow conclusions to be made which are difficult to reconcile with our everyday experience of the irreversibility of time and the possibility of influencing only future events.

Besides being logical, the dynamics concept has another merit—it gives rise to many new possible physical experiments. Even if these experiments will yield negative answers and will prove the correctness of the thermodynamic concept, experimental technique will have improved. In the case that negative answers are obtained, a new problem will also arise for theoretical physics—the problem of explaining the reverse influence of macroscopic consequences of statistical theory on the structure of the micro-domain.

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