Antimatter and the second law of thermodynamics

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Abstract

In this short paper we make a proposal that the second law of thermodynamics holds true for a closed physical system consisting of pure antimatter in the thermodynamical limit, but in a reversed form. We give two plausible arguments in favour to this proposal: one refers to the *CPT* theorem of relativistic quantum field theories while the other one is based on general thermodynamical arguments. However in our understanding the ultimate validity or invalidity of this idea can be decided only by future physical experiments.

As a consequence of the proposal we argue that the dynamical evolution of pure macroscopic antimatter systems can be very different from that of ordinary matter systems in the sense that sufficiently massive antimatter systems could have stronger tendency to form black holes during time evolution than their ordinary counterparts. Taking into account the various uniqueness theorems in black hole physics as well, as a result, antimatter could tracelessly disappear behind black hole event horizons faster in time than ordinary matter. The observed asymmetry of matter and antimatter could then be explained even if their presence in the Universe was symmetric in the beginning.

1   Introduction

Our basic experience and intuition about reality teaches us that space and time possess spatial or temporal extension, respectively, in a manner such that this extension arises as the collection or union of disjoint "places" or "moments", respectively, which themselves are however extensionless. The former concept is abstracted or idealized in a straightforward way from our everyday experience of a floating mote of dust in the air (visible e.g. in a dark room exposed by a sharp horizontal sidelight through the window) hence has an objective origin; on the contrary the latter concept emanates from our purely subjective feeling of the "now" which is much more problematic from the aspect of an objective description of reality. Nevertheless we have the strong conviction that both space and time with their spatial and temporal extensions are somehow built up from their extensionless constituents.

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The contradictory tension between the spatio-temporal extension—or equivalently the *continuum*—and its disjoint constituents lacking any extension—or equivalently the *discretum*—forms the core of *Zeno*'s perhaps never-solvable paradoxes. It is also reflected in the structure of the contemporary mathematical model of the continuum, namely the *arithmetical continuum* or equivalently, the *set of real numbers* $\mathbb{R}$. In fact the division of the arithmetical continuum into the collection of disjoint points causes difficulties not only in pure mathematics (cf. e.g. [13]) but even spills over into the description of the physical world by contemporary theoretical physics formulated in the language of this mathematics (cf. e.g. [1, 4]), too; in this way completing a *circulus vitiosus*.

Although this contradictory tension, possessing no immediate observational relevance, could have been suppressed or abandoned for centuries, the innocent period of human thinking has gone once and for all by our encounter with contemporary striking experimental facts. Experiences with quantum phenomena (in the form of *Heisenberg*'s uncertainty relations or various *EPR* phenomena, for instance) dictate that the physical space cannot be the simple union of extensionless, disjoint empty "places"; likewise and probably even more embarassingly psycho-physiological evidences (cf. e.g. [8]) indicate that time cannot be the simple union of our "nows". Indeed, nothing in the outer physical world seems to correspond to a (conscious) observer's inner "now experience". As *Carnap* recalls a personal conversation ([9, pp. 37-38]):

> Once Einstein said that the problem of the Now worried him seriously. He explained that the experience of the Now means something special for man, something essentially different from the past and the future, but that this important difference does not and cannot occur within physics. That this experience cannot be grasped by science seemed to him a matter of painful but inevitable resignation. I remarked that all that occurs objectively can be described in science; on the one hand the temporal sequence of events is described in physics; and, on the other hand, the peculiarities of man's experiences with respect to time, including his different attitude towards past, present, and future, can be described and (in principle) explained in psychology. But Einstein thought that these scientific descriptions cannot possibly satisfy our human needs; that there is something essential about the Now which is just outside of the realm of science.

In this context it is therefore remarkable that within the conceptual framework of our contemporary natural sciences (especially theoretical physics) subject to permanent critical revision and apparently built exclusively on massive objective concepts only, the idea of the "now" or—as called more neutrally—the "moment of time" yet plays a central role. Quite interestingly and paradoxically, this seemingly subjective, human origin concept converts the time of theoretical physics into a structure which is so alien to us, the same humans. Namely, if a "moment of time" indeed exists then at least in the classical (more precisely celestial) mechanical description of a physical system time reversal symmetry is expected to hold which means that given an existing physical system, an instantaneous reflection of its dynamics about this "moment" gives rise to another existing (in reversed time) physical system. Thereby in classical (or at least in celestial) mechanics the past and future are completely interchangable rendering time a *homogeneous continuum built up from individual constituents* akin to space (and as a consequence both time and space can be mathematically modeled by the arithmetical continuum). But even more, the existence of a "moment of time" makes the homogeneous time itself redundant since the whole past and future evolution of a classical (or at least celestial) mechanical system can be compressed in the form of initial data into a single "moment" only.

The idea of a homogeneous time is unfamiliar to us because our experience with time says that the past is very different from the future; e.g. one can remember the past but cannot remember the future [12]. But the idea of a homogeneous time is in deep contradiction with other branches of theoretical physics, too: most notably with thermodynamics in the form of the already more-than-a-century-old

problem of how to derive the second law from the principles of classical mechanics and one perhaps should mention here the measurment problem in quantum mechanics as well. These and other difficulties had led several philosophers and physicists to refute the objective existence of a temporal moment hence a homogeneous time; for instance one can declare temporal duration to be an irreducible element of reality (cf. *Bergson*'s concept of the *durée* [3]) or consider the fundamental difference between past and future as an irreducible aspect of time (cf. *Weizsäcker*'s idea of the *chronologicality of time* [12]). A common feature of these approaches is that the second law of thermodynamics gains a substantial role in the sense that it is considered as a *fundamental* law of Nature (and not one to be derived from apparently simpler ones).

Hopefully motivated with these introductory remarks in some extent, in this note, in Section 2 below, in the realm of the structure of time we shall revisit the problem of the absence of antimatter from the Universe on macroscopic scales. What we are going to do is simple: instead of trying to derive the second law of thermodynamics from other abstract laws of theoretical physics we shall regard it as an underivable, irreducible, fundamental law expressing a basic *observational fact* about the temporal behaviour of macroscopic matter. The consequent application of considering the second law as an observational fact imposes at least one non-trivial constraint on its appearance in the physical world namely in its known form it is immediately applicable only to *ordinary* matter for this is the only form of matter which we have direct phenomenological contact with. Then we exhibit two plausible arguments, based on various principles of theoretical physics but commonly refer to the aforementioned observational validity of the second law, that the second law continues to hold for large antimatter systems but in a *reversed* form. Their converse thermodynamic behaviour could then lead to their swift confinement behind black hole event horizons hence to the absence of antimatter on marcroscopic scales from the Universe. This conclusion sounds appealing for it does not require the existence of any new asymmetric mechanism around Big Bang times to explain the macroscopic matter-antimatter asymmetry, as usually assumed in string theoretic and other speculations.

2 A proposal and its consequence

The idea of an elementary antiparticle had quite unexpectedly dropped out from the theoretical efforts to reconcile the basic principles of special relativity and quantum mechanics; shortly thereafter their individual existence was verified using cosmic ray detectors, nuclear reactors and high energy particle colliders. However *no* physical experiment or even any kind of human experience in the broadest sense exists so far which could provide some phenomenological insight into the *macroscopic* i.e., *thermodynamical* properties of pure antimatter built up from the bound states of these antiparticles. Even assuming that the basic principles of (classical or quantum) statistical mechanics continue to hold for physical systems consisting of pure antimatter—*and confessing that the derivation of the second law of thermodynamics from these principles is yet problematic*—the thermodynamical behaviour of such alien macroscopic physical systems is, honestly speaking, unknown to us in this moment. Therefore apparently we are not in contradiction with any element of our contemporary description of physical reality if we make the following counterintuitive

Proposal. *Let $\mathscr{S}_{\text{antimatter}}$ be a closed physical system consisting of pure antimatter (in the thermodynamical limit). Then the entropy S of this system never increases in time i.e., $\Delta S(\mathscr{S}_{\text{antimatter}}) \leqq 0$.*

Because challenging the **Proposal** experimentally or theoretically is not straightforward, we would like to rather offer here two heuristic arguments for its validity. However of course we acknowledge that

none of them can be considered as a physical (or even not to mention, a rigorous mathematical) proof of the **Proposal**. Its ultimate validity or invalidity can be decided only with future physical experiments designed to unfold the dynamics of large antimatter systems (in this context it is worth revisiting the already observed asymmetry between the decay processes $K^0 \rightarrow \overline{K}^0$ and $\overline{K}^0 \rightarrow K^0$ as well, cf. [7]).

An argument based on the CPT theorem of relativistic quantum field theories. In light of our accurate experimental evidences, we have no reason to doubt the validity of the basic rules of relativistic quantum field theory when applied to both matter and antimatter. One of the most fundamental results of the relativistic quantum field theoretic description of physical reality is the *CPT* theorem which asserts that the triple action of charge conjugation *C*, spatial reflection *P* and time direction reversal *T*, when applied to a relativistic particle system, represents a symmetry of it (cf. e.g. [11, Chapter I.5.8]). Since macroscopic matter is built up from the bound states of these relativistic particles it is reasonable to expect that the *CPT* theorem continues to hold for macroscopic physical systems in an appropriate *effective* form. We will assume two things: (i) the parity transformation *P* alone is already a symmetry of a physical system in the *thermodynamical limit* (this is not true at the elementary particle level) and (ii) both at elementary and macroscopic levels the dynamics of a physical system can be described by a common abstract "time parameter" hence the time direction reversal operation *T* is applicable in the *thermodynamical limit*, too.

Consider now an ordinary closed physical system $\mathscr{S}_{\text{matter}}$ consisting of pure (normal) matter in the thermodynamical limit, evolving forward in time. Therefore, as a *theoretical consequence*, the *CPT* theorem about $\mathscr{S}_{\text{matter}}$ tells us that

$$CPT(\mathscr{S}_{\text{matter}}) = \mathscr{S}_{\text{matter}} \ .$$

Another *observational fact* about $\mathscr{S}_{\text{matter}}$ is the validity of the second law of thermodynamics which states that

$$\Delta S(\mathscr{S}_{\text{matter}}) \geqq 0$$

i.e., the entropy of a closed physical system consisting of pure ordinary matter never decreases. Putting together these we get

$$\Delta S(CPT(\mathscr{S}_{\text{matter}})) \geqq 0 \ .$$

However, accepting the validity of the *CPT* theorem in the thermodynamical limit in an effective form discussed above, the *CPT* transformation converts a closed physical system of matter evolving forward in time into a closed physical system containing antimatter evolving backward in time i.e.,

$$CPT(\mathscr{S}_{\text{matter}}) = \mathscr{S}_{\text{antimatter in reversed time}} \ .$$

Therefore the last inequality gives

$$\Delta S(\mathscr{S}_{\text{antimatter in reversed time}}) \geqq 0$$

i.e., the entropy of an antimatter system never decreases in reversed time hence switching back to ordinary time we come up with

$$\Delta S(\mathscr{S}_{\text{antimatter}}) \leqq 0$$

leading to the **Proposal**.

Another argument based on general thermodynamical considerations. Consider a closed physical system $\mathscr{S}$ consisting of a physical entity in the broadest sense surrounded with electromagnetic radiation. We can suppose that this physical object and the electromagnetic field is in thermal equilibrium

at a certain temperature i.e. a balance exists between three processes: spontaneous and induced emission and induced absorption of electromagnetic radiation by the object. However allowing shorter and shorter observational times we can in principle assume without destroying the entity that this equilibrium temperature is arbitrary high hence beyond a threshold temperature the three processes above are supplemented with two further ones namely spontaneous particle pair creation and recombination (annihilation) effects as well. Consequently, if we do not want to be short-sighted in our considerations, we have to admit that our very general physical system, beyond electromagnetic radiation, generally consists of both matter and antimatter i.e. $\mathscr{S} = \mathscr{S}_{\text{matter+radiation+antimatter}}$.

Let us then take a general physical system of the above kind which is furthermore macroscopic i.e. exists in the *thermodynamical limit*. Being in equilibrium, as a *theoretical consequence* its entropy is constant i.e.

$$\Delta S(\mathscr{S}_{\text{matter + radiation + antimatter}}) = 0 \ .$$

Consider the situation when the distribution within this physical system is not homogeneous at least during the relevant observational time in the sense that it contains well-separated spatial regions mainly dominated by at least temporally existing macroscopic bound states of ordinary matter and antimatter giving rise to approximately closed subsystems $\mathscr{S}_{\text{matter}}$ and $\mathscr{S}_{\text{antimatter}}$, respectively (which themselves are however not necessarily in equilibrium). These together with the subsystem $\mathscr{S}_{\text{radiation}}$ provided by pure radiation allow us to write $\mathscr{S}_{\text{matter+radiation+antimatter}} = \mathscr{S}_{\text{matter}} + \mathscr{S}_{\text{radiation}} + \mathscr{S}_{\text{antimatter}}$. Exploiting the (sub)additivity of entropy then we can write the entropy conservation above as

$$\Delta S(\mathscr{S}_{\text{matter}}) + \Delta S(\mathscr{S}_{\text{radiation}}) + \Delta S(\mathscr{S}_{\text{antimatter}}) = 0 \ .$$

The additional *observational fact* about this system is again the validity of the second law which strictly speaking again means only that

$$\Delta S(\mathscr{S}_{\text{matter}}) \geqq 0 \ .$$

As explained we have inserted an appropriately defined radiation term as well in order to take into account the spontaneous pair creation and recombination effects of very short characteristic time which certainly take place in a closed physical system with mixed matter-antimatter content. Then within the closed system the subsystem $\mathscr{S}_{\text{radiation}}$ consists of pure thermal radiation in equilibrium at fixed temperature $T(\mathscr{S}_{\text{radiation}})$ occupying a fixed volume $V(\mathscr{S}_{\text{radiation}}) \leqq V(\mathscr{S}_{\text{matter+radiation+antimatter}})$. Thus by the Stefan–Boltzmann law $S(\mathscr{S}_{\text{radiation}}) = \frac{4}{3} a T^3(\mathscr{S}_{\text{radiation}}) V(\mathscr{S}_{\text{radiation}})$ implying

$$\Delta S(\mathscr{S}_{\text{radiation}}) = 0 \ .$$

Comparing the last three expressions we conclude that

$$\Delta S(\mathscr{S}_{\text{antimatter}}) \leqq 0$$

ending up with the **Proposal** again.

Let us emphasize once more that in both (certainly bit naive) arguments for the **Proposal** the validity of the second law as an observational fact about *macroscopic* ordinary matter systems played a crucial role. This also explains the absence of any kind of supporting microscopic calculations from the above considerations: from the circle of our arguments it follows that the converse thermodynamical properties of antimatter is recognizable only macroscopically i.e. compared to that of ordinary particles, we have not modified the microscopic dynamics of antiparticles at all! (Actually any modification would be a difficult task in light of accurate particle collider experiments, but cf. again [7].) Putting differently, we can say that the converse second law for antimatter is non-derivable from time-symmetric microscopic dynamics in exactly the same way as the ordinary second law is not derivable from it (yet).

To close we mention one consequence of the **Proposal**. Consider a closed macroscopic physical system $\mathscr{S}_{\text{antimatter}}$ built up from pure antimatter only hence not disturbed by recombination effects; therefore the time evolution of $\mathscr{S}_{\text{antimatter}}$ is governed only by its own gravitational, electromagnetic and thermodynamical phenomena. Accepting the **Proposal**, it says that $\mathscr{S}_{\text{antimatter}}$ tends to evolve into more-and-more ordered states in time. Assuming that a macroscopic antimatter system obeys the same equation of state (expressing a phenomenological relation between its energy, temperature, pressure, volume, etc.) as the corresponding macroscopic ordinary matter system, this evolution into more-and-more ordered states could imply its *stronger* tendency for spatial contraction. Therefore, in sharp contrast to an ordinary matter system, the structural tendency of $\mathscr{S}_{\text{antimatter}}$ for spatial contraction in its own gravitational field could be *enhanced* by the functional tendency of $\mathscr{S}_{\text{antimatter}}$ for spatial contraction thanks to its reversed thermodynamics.[*] For example take a massive and in the beginning cold antimatterial ideal gas satisfying the usual equation of state $pV = nRT$ hence having entropy change

$$nR \log \frac{V_{\text{final}}}{V_{\text{initial}}} + C_V \log \frac{T_{\text{final}}}{T_{\text{initial}}} = S(V_{\text{final}}, T_{\text{final}}) - S(V_{\text{initial}}, T_{\text{initial}})$$

in any process. Then in any, in the beginning, isothermal process by the reversed inequality

$$\log \frac{V_{\text{final}}}{V_{\text{initial}}} = \frac{1}{nR} \left(S(V_{\text{final}}, T) - S(V_{\text{initial}}, T) \right) \leqq 0$$

we find that $V_{\text{final}} \leqq V_{\text{initial}}$ hence the gravity-driven self-contraction of the gas is amplified in this way, too. As a result, one would expect that sufficiently massive macroscopic antimatter systems are more capable to form black holes during the course of their dynamical evolution than ordinary macroscopic matter systems. Consequently, in light of the various uniqueness ("no-hair") theorems of black hole physics (cf. e.g. [6]) pure macroscopic antimatter systems could tracelessly disappear behind black hole event horizons faster in time than their ordinary counterparts. For clarity we remark that this process is not in contradiction with Hawking's area theorem (cf. e.g. [2, 5]) because the fall of antimatter into a black hole, whatever weird its dynamical behaviour is, continues to transport further mass, (squared!) electric charge and angular momentum into the black hole hence continues to increase the area of the instantaneous event horizon of e.g. the Kerr–Newman black hole. Of course all of these rough qualitative considerations might be invalidated by analyzing the highly complex details of time evolution of realistic physical systems; however this analysis is beyond the limits of this short note.

Nevertheless our speculations might shed a light onto the origin of the observed matter-antimatter asymmetry in the current Universe, even if matter and antimatter was produced in symmetric amounts in the Big Bang. Indeed, if we assume that the initial matter-antimatter distribution in the Universe contained small spatial inhomogeneities (caused e.g. by thermal fluctuations visible in current high-resolution CMB data) then the undisturbed pure antimatterial spatial regions could form black holes faster than the pure matterial ones. This asymmetric mechanism together with the symmetric recombination effects could be responsible for the deficit of antimatter as well as for the rapid early galaxy formation around supermassive black hole cores in the observed Universe.

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[*]It is illustrive to regard the structural and functional characters as sort of spatial and temporal projections, respectively, of a common abstract "character" of a physical system. In this language we can say that physical systems possess an abstract "contraction tendency" whose structural and functional manifestations are the gravity and the thermodynamical phenomena, respectively (cf. Verlinde's idea of entropic gravity [10]) and they attenuate each other in the case of ordinary matter systems while enhance each other in the case of antimatter systems.

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