A new operational definition of internal time

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ABSTRACT. The present work is focused on the relationship between the internal energy of muons and the magnetic field as it appears in an Eisele's work. Eisele, with the aim of corroborating the clock hypothesis, demonstrates that muons in the storage ring can be considered relativistic clocks since their decay rate is in agreement with relativistic laws about the measure of proper time as linked to the length of the world line described in spacetime. In the light of Eisele's theoretical analysis rather we believe that a clear difference must be deduced between atomic clocks, whose internal energy, in agreement with general relativity, depends on gravitational and pseudo gravitational potential, and muon clocks, whose internal energy is linked to the magnetic field and does not depend on gravitational or pseudo gravitational potential. In the optics of the thermal time hypothesis, we propose to consider radioactive clocks as particular examples of thermal clocks. In the conclusive section a new operational definition of internal time is proposed as the rate of transformation of matter and energy.

1 Introduction

The matter can be resumed in the following points:

- remarks about relativistic proper time and the operation of real clocks that should measure it;
- considerations about radioactive clocks in the light of the theoretical analysis given by Eisele about muons in the storage ring at CERN and of the clocks hypothesis;

- hypothesis about the nonequivalence between atomic and muon clocks and about radioactive clocks as possible examples of thermal clocks;
- formulation of a new operational definition of time as a measure of the rate of transformation of matter-energy.

In the light of the concluding remarks time must be considered a measure of the rate of a transformation that occurs inside a clock and not as an abstract property of relativistic spacetime, that should be measured by clocks in relation to the world line they describe. This leads to the need of selecting whether to use a relativistic description of phenomena or a quantum-thermodynamic theoretical picture, according to which the concept of time is derived from the concepts of energy and transformation.

2 Relativistic proper time and real clocks

In 1905's paper [1] Einstein predicts the time dilation effect, without raising possible objections about the effective experimental verifiability with real devices. It is noteworthy that while time dilation consists in the dilation of the measure of a duration made by an observer that sees a clock in motion with respect to the measure provided by an observer at relative rest, the different durations measured by two clocks that describe different world lines between two fixed extreme events is a phenomenon known as clock-twin effect. In this case the effect is necessarily linked to the internal structure of clocks, then to their proper period, while in the first case the time dilation is a simple consequence of the different spatiotemporal coordinates measured with respect to two inertial reference frames in relative motion, so it is independent from the observed device. According to the conceptual framework of general relativity it is possible to deduce the following approximate relation between proper period and potential for a relativistic clock, experimentally tested on atomic, optical, quartz, based on the use of maser or at resonant cavity clocks:

$$T(\varphi) = T_0(1 - \frac{\varphi}{c^2}) \tag{1}$$

φ being the gravitational or the pseudogravitational potential, T and T_0 respectively the proper period in presence or in absence of potential. Relativistic time is measured by atomic clocks through the count of the number of reversible periodical phenomena, namely through the count of a number of beats linked to the energy difference ΔE between two fixed quantum levels, from which the proper period of the instrument depends. Since this energy difference depends on the gravitational and pseudo gravitational potential φ according to the relation [2]:

$$\Delta E = \Delta E_0 \sqrt{1 + 2\frac{\varphi}{c^2}} \tag{2}$$

where ΔE_0 is the energy difference in a null potential, and the proper period is linked to the energy difference according to the relation $T = \frac{h}{\Delta E}$, we get the approximate equation (1). In all probability in such instruments the different durations, quantified along different world lines with the same extreme events (as in the case of atomic clocks initially at relative rest and finally rejoined after one of them was brought on a plane to circumnavigate the globe), are a consequence of the variation of the proper period of the traveler as a function of the gravitational or the pseudo gravitational potential, whose intensity has significantly changed as a consequence of the circular motion at high speed and high altitude. In his works Einstein does not enter the empirical issue about the operation of real clocks, since the loss of synchronicity is a necessary consequence of the relativity of simultaneity, and therefore of the principles on which special relativity is founded, whereby it must necessarily occur, unless to falsify the whole theoretical building. It is worth mentioning that Einstein, when speaking of clocks, thinks to ideal devices (namely, all with the same proper period) at rest with respect to a given observer and synchronized by the exchanging of light signals. He consistently remarks that the synchronization procedure of clocks in separate places provides a definition both of simultaneity and of time. If we conceive the relativistic spacetime as a space filled with punctiform (ideal) clocks, at rest and synchronized with respect to a given observer, it is immediate to recognize that a second observer, in motion with respect to the first one, will use a different (at rest) set of clocks, synchronized with each other but not with those of the first observer. The fact that a clock can move with respect to a given observer, change its speed and return at rest in the starting point, showing a delay in the measurement of time with respect to the near clocks belonging to its same set, implies an unjustified logical jump in the theory, as the network of clocks is only a conceptual device that ideally allows to transform the three-dimensional spatial continuum in a four-dimensional spatiotemporal continuum. Ideals clocks, in essence, should not move with respect to the observer, as they serve as indicators of the instant in which a given phenomenon occurs at the point where they are placed. The effect of a speed variation on real clocks requires a new ad hoc postulate, the clock hypothesis, according to which the measurement of a duration corresponds to the length of a world line. Experimental tests have been carried out in large numbers and varieties during the twentieth century: we remember in particular the measurements on unstable particles, observed at rest and in flight, into linear beams [3, 4] or in curvilinear motion into the storage ring at CERN, at an extremely high ($10^{18}g$) centripetal acceleration [5]. In each of these tests the in-flight particles have decayed in a lesser number with respect to those in the laboratory. According to the shared interpretation the unstable particles, behaving as clocks, when in flight decay in a longer time: if we consider a thousand muons flying towards the Earth and a thousand muons in a terrestrial laboratory, when the in-flight sample reaches the Earth it will contain a considerable number of undecayed muons more than the one in the laboratory. The dilation by the γ factor of the average lifetime measured on particles in flight with respect to that measured on identical particles in the laboratory appears to be an undisputable as clear proof of the relativistic theory of proper time. It should however be noted that in the case of unstable particles the measure of the duration is obtained not through the motion of a hand (as in mechanical clocks) or of a light ray (as in light clocks), but through a transformation internal to the particle. It is a conceptually decisive aspect: what is the physical meaning of the measure of a time interval through a muon clock?

3 Muon decay and radioactive clocks

If we use the count of the number of decayed muons to measure time, we can consider a sample of muons a radioactive clock that allows to verify the clock effect. While in a mechanical or in a light clock the measure is achieved through a periodic motion, a similar motion is not described by muons: in this case the period is related to a phenomenon internal to the particles, in which is not important the motion but the transformation of initial corpuscles into different particles. According to the theoretical analysis of the phenomenon in spacetime, no matter if it's muons or living organisms or anything else, because a relativistic duration is the length of the corresponding world line, independently from the physical entity that describes it. Combining the law of radioactive decay with the theory of proper time, it is deduced a fewer number of muons decayed in flight than in the terrestrial laboratory. This apparently explains both time dilation and clock effect: if two samples of muons equally numerous (namely, two radioactive clocks initially synchronized) are separated so that one of them is brought to fly on a plane, they should present a different number of decayed muons at the return of the traveler sample. However, even if the explanation provided by special relativity seems incontrovertible, and the experiments with unstable particles are considered one of the most significant tests of the relativistic theory of proper time, a deeper reflection leads to the possibility of a different interpretation of the phenomenon, so to the need of a revision of the theoretical foundations from which conclusions were drawn currently considered indisputable.

4 Relationship between time and energy and alternative interpretation of the clock effect

Muon decay is described by the reaction $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. The average lifetime of a muon, then its average proper time in the hypothesis of considering the particle a clock, depends on the probability of the transition leading to the creation of a virtual W^- boson and of a muon neutrino (ν_μ), then to the decay of W^- in an electron antineutrino ($\bar{\nu}_e$) and an electron: this probability increases at the decreasing of the internal energy of the particle, then if the coupling between the interacting particles inside the muon is weaker. The problem is: do the muons rotating into the storage ring have the same internal energy of those observed at rest in the laboratory? In case of negative answer, since particles having higher internal energy are to all effects different from those of lower internal energy, it is as if we were observing different clocks: it is muons in both cases, but the different internal energy makes them, in the light of the theory of relativity, nonequivalent clocks. This is a conceptual aspect of relevant theoretical importance, since Einstein's theory predicts that clocks traveling in spacetime record the different lengths of the world lines they describe, regardless of the processes occurring inside them, in the hypothesis of considering them equivalent. The equivalence of clocks, in the case of muons in the storage ring or in linear beams produced by the cosmic rays in the upper atmosphere, occurs only if the internal energy of the particles in flight is equal to that of the particles at rest in the laboratory. Here we limit to the case of muons accelerated into the storage ring, about which the detailed energy calculation was made by Eisele [6], with the aim of gaining a quantum foundation of the clock hypothesis, namely the independence of the proper period of radioactive clocks from acceleration and, indirectly, a quantum proof of the relativistic clock effect. According to the clock hypothesis, relativistic clocks must measure the proper time

$$\Delta\tau = \int_{t_1}^{t_2} \sqrt{1 - \frac{v^2}{c^2}} dt = \int_{t_1}^{t_2} d\tau \qquad (3)$$

The explicit Eisele's goal is to compare the decay time of the particles into the storage ring, inside a magnetic field responsible for their circular motion at very high centripetal acceleration (as in Bailey's experiment), with the decay time of those at rest in the laboratory, in the light of the weak interaction theory. In the conclusive section Eisele claims that only the energy, whose value for the particles in the ring is approximately equal to

$$E = m\sqrt{1 + \frac{B}{B_{cr}}} c^2 \qquad (4)$$

(where $B_{cr} = \frac{2\pi m^2 c^3}{eh}$ is the critical magnetic field [1] for a charged particle of mass m), is responsible for the decay time of particles-clocks. This leads to deduce that radioactive clocks in the ring measure a shorter duration than those at rest in the laboratory because of their greater internal energy, due to the interaction with the magnetic field: radioactive clocks in the ring are therefore nonequivalent to those at rest [2]. It follows a serious problem associated with the operation of measure: what does a clock measure? According to the theoretical framework of relativity, if two clocks initially at relative rest separate as one of the two increases its speeds, etc., when they rejoin they must have measured different durations as they have described world lines of different length. We have evidence of this different behavior of moving clocks in the case of atomic clocks (see the GPS [7], the Hafele-Keating experiment [8], the Alley experiment [9]), whose proper period, as above remarked, depends from gravitational and pseudo gravitational potential in accordance with

[1]The critical magnetic field is the limit value for the intensity of the field within which it does not produce $e^+ e^-$ pairs.

[2]We remark that the unstable particles produced in the high atmosphere are internally more energetic with respect to those produced in a laboratory on the ground, due to the high energies of the cosmic rays from which they derive. On this matter an accurate and deep theoretical analysis should be performed.

the predictions of general relativity. At a closer look, in fact, the atomic clocks of GPS or those employed in the Hafele-Keating or Alley experiments have traveled in a gravitational and in a pseudo gravitational potential that have significantly altered their proper period with respect to those remained on Earth: the different durations measured, for example, by clocks returned from the circumnavigation of the globe in the Hafele-Keating experiment are a likely consequence of an increasing of the proper period. The effect, in the light of (2), must be considered of energetic nature, since these clocks are sensitive to changes in the gravitational and pseudo gravitational potential, which alters the energy difference of the quantum transition between two fixed levels, from which the proper period of the instrument depends. Even in this case, it is not a matter of different durations measured by equivalent clocks (a necessary condition, in the light of Einstein's theory) that record the different lengths of the corresponding world lines, but of energetically nonequivalent clocks that measure different durations as a consequence of a variation of the internal energy of traveler clocks with respect to those on the ground.

5 Nonequivalence between atomic and radioactive clocks

If we conceive (4) as the increasing ΔE in internal energy for a particle in the magnetic field with respect to the energy E_0 of the same particle outside the field, and we consider that the proper period of the unstable particle is linked to ΔE through the above remembered relationship $T = \frac{h}{\Delta E}$, we easily deduce that the proper period of a muon inside the magnetic field does not match the relativistic law (1). In fact, Eisele does not remark a relationship between the internal energy of muons and the pseudo gravitational potential linked to the centripetal acceleration, whose value in the ring was of enormous intensity with respect to an observer in the laboratory [3]. The remembered relationships clearly prove that atomic and radioactive clocks operate according to different internal phenomena, so in all probability they behave differently in equal experimental conditions. If we consider that the internal energy of atomic clocks depends on gravitational or pseudo gravitational potential while the internal energy of radioactive clocks depends on the intensity of the magnetic field, we must necessarily conclude that a ra-

[3] Analogously an observer at rest with respect to the rotating muons should measure a pseudo gravitational potential linked to the centrifugal acceleration, but Eisele does not analyze the phenomenon with respect to a noninertial reference frame

dioactive clock brought in flight does not have a greater decay rate if its initial internal energy is equal to that of a radioactive clock remained on the ground, namely if the radioactive clocks are equivalent: it is deduced that, when compared after the trip, they must measure the same internal time. Ultimately, atomic and radioactive clocks are not equivalent.

6 Reversible and irreversible transformations inside clocks

An important remark must be done about the way of taking the measure of a duration through an atomic or a muon clock. Inside an atomic clock the excitation of the electrons from a fixed level to a fixed upper one is produced through an internal energy consumption and a consequent overall increasing of the entropy, that however is not quantified by the instrument. In fact, while a muon clock, measuring a duration through the counting of the number of decayed particles, directly measures the internal increase in entropy inside the system (namely, the quantity of irreversible transformation of the initial system-particle into a different one, and therefore the increasing of internal disordered energy), that can be considered a measure of the internal time in which the particle is decayed, in an atomic clock the number of beats scanned in correspondence of a given phenomenon (whose duration is measured by the clock) is related to the emission of energy caused by the return of the electron to the fundamental level, that can be considered with good approximation a reversible process. Since the energy difference (2) between two fixed levels leads to a proper period in accordance with (1), an atomic clock can be considered a device that allows to measure relativistic durations. A muon and an atomic clock are therefore clocks of different nature: a muon clock, as a device that quantifies an irreversible transformation of energy, measures the thermodynamic internal time, whereby, in the light of the hypothesis about the nonequivalence between thermal time and relativistic time, it does not measure the relativistic proper time [10] .

7 Conclusions. Muon clocks as thermal clocks. A new operational definition of internal time

The given examples prove that internal time is directly linked to a transformation in which a particle system (a radioactive clock) transforms into a different one as a consequence of a decay phenomenon. In the case of muons a duration is measured through the decay of the particles, whose frequency increases at the decreasing of their internal energy. We remark the need of radically distinguishing from the relativistic concept of proper time the operational concept of internal time as a physical quantity linked to the internal energy, related to the theoretical framework of thermodynamics or of quantum mechanics, where are fundamental the statistical phenomena occurring inside the matter. We summarize in the following points the conclusions of the critical analysis proposed in this work:

a. the muons into the storage ring decay in a lesser number than those remained on the ground as it comes to clocks having higher internal energy: in the light of Eisele's theoretical analysis it can be deduced that time dilation tested on unstable particles is not a consequence of their different state of motion, but of the different internal energies of the observed radioactive samples, which are therefore nonequivalent radioactive clocks;

b. if an experiment like those performed by Hafele and Keating or by Alley (clocks on airplanes compared with identical clocks on the ground) is carried up with radioactive clocks, the internal energy during the flight remains unchanged (being the variation of the magnetic field for the flying clock undoubtedly negligible), whereby equivalent radioactive clocks (namely having the same initial internal energy) on an airplane and on the ground must count the same number of decayed particles when compared at the end of the trip, then they must measure the same duration;

c. insofar as Eisele does not propose a theoretical analysis of muons in flight in linear beams, it is likely that, due to the high energy of the cosmic rays interacting with the terrestrial atmosphere, the unstable particles produced by this interaction are internally more energetic than those produced in a terrestrial laboratory, as in the case of muons interacting with the magnetic field into the storage ring.

The above considerations lead to consider the likely nonequivalence between relativistic proper time, that corresponds to the measure of the length of the world line described by the clock, and quantum-thermodynamic internal time, associated to an energy or to a particle transformation, therefore to an irreversible phenomenon [10]. Since an irreversible phenomenon has statistical nature, radioactive clocks can be considered examples of thermal clocks, so we expect that they do not behave as relativistic clocks. If the experiments to which we refer in this work were verified, they should confirm the hypothesis, formulated in [11], about the nonequivalence between thermal clocks and relativistic clocks. Ultimately, in the light of Occam's razor principle, it needs to select whether to use a space-time description of phenomena (as in the relativistic theory, according to which the measurement of a duration corresponds to the length of a world line, neglecting what happens inside the material bodies), or a quantum-thermodynamic theoretical picture, where the concept of time is derived from the concepts of energy and transformation. Internal time, and implicitly thermal time [12], in this theoretical framework can be defined as a measure of the rate of transformation of matter and energy, a macroscopic reflex of the transformations that occur in Nature. In fact the probability of the transformation is due to statistical phenomena linked to the internal energy, that with high probability are independent from the properties of relativistic spacetime. Assuming that the energetic nature of time is confirmed, the relativistic theory of time clearly becomes obsolete since, even if we limit to the case of radioactive and atomic clocks, in Nature exist clocks that do not behave in the same way in equal experimental situations. The consistent evolution of theories anyhow requires to radically reopen the discussion around the physical meaning of one of the most controversial quantities about the interpretation of natural phenomena.

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