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IF LHC IS A MINI-TIME-MACHINES FACTORY, CAN WE NOTICE?

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Abstract. *Assuming the hypothesis of TeV-scale multi-dimensional gravity, one can imagine that at LHC not only mini-black-holes (MBH) will be intensively created, but also other exotic gravitational configurations, including hypothetical mini-time-machines (MTM). Like MBH, they should quickly evaporate, but one can wonder if their temporal existence at the moment of high-energy collision can leave any traces in the observable data. We briefly discuss five thinkable effects: (i) change of the energy spectrum due to the frequency-filtration property of MTM, (ii) possible production of anomalously energetic particles, accelerated by passing many times through gravitational field inside the MTM, (iii) acceleration of particle decays, since the proper time of a particle moving inside MTM can strongly exceed the laboratory time, (iv) CPT and naive unitarity violation (thermalization) due to effective non-local interactions caused by MTM and to possible ambiguity in the population of closed world-lines inside MTM, (v) collective effects due to conversion of a single particle into a bunch of its co-existing copies within the MTM. Despite possible particle-antiparticle conversion inside MTM, they do not seem to produce any specific CP-violation effects.*

Key words: *LHC, mini-time-machines*

1. Introduction

The string-theory-inspired TeV-Gravity models [1], where matter lives on a 3-brane embedded into a D-dimensional space-time with the extra

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$D-4$ dimensions compactified on a manifold of the inverse size $\sim 1 \div 10$TeV, opened a potential possibility to observe non-trivial gravitational effects in accelerator [2], cosmic ray [3] and neutrino [4] experiments. So far, attention in this field was restricted to effects, associated with the possible production of mini-black-holes (MBH), which can be *massively* produced already at LHC if TeV-Gravity models are true. These MBH are supposed to evaporate instantaneously (see, however, [5]), but – since Hawking radiation does not distinguish between the sorts of particles and space directions – can cause energy and momentum redistribution between the products of reaction, which is potentially observable (though not too pronounced – as usual for the TeV-energy experiments).[2]

It is natural to assume that the story should not be restricted to MBH: once Pandora box of gravitational effects on particle physics is open, all of its content can show up. This implies that other types of multi-dimensional gravitational configurations could also be born, along with the MBH. Since much less is known about such configurations, except that they appear on equal footing with black holes in general relativity, we can just *assume* that the same is true in particle theory: namely, that, like MBH, they are created in particle collisions *classically*, with the cross-sections, defined by their geometrical sizes, with only a modest damping caused by radiation of gravitational waves, and decay almost instantly, either classically or due to some analogue of Hawking radiation. If one agrees to accept this assumption, the question arises whether any such configurations can leave traces in the properties of particle collisions, essentially different from those of mini-black-holes.

The most interesting from this perspective are the (mini-)black-rings [9] and, especially, (mini-)time-machines (MTM): geometries with existing closed time-like worldlines. There is a long story of discussions around time-machines in general relativity [10], we agree with the recent conclusion of

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[2] We need to mention here that while discussing experimental evidence of the black hole evaporation one has to look after various conservation laws like baryon number conservation. In particular, we believe that the probability of black hole formation by quarks within a proton with a subsequent evaporation, i.e. a proton decay into mesons and, possibly, leptons is vanishing. Basing on some arbitrary assumptions about what quantum gravity is, [6], one may estimate [7] the proton lifetime to be M_{Pl}^{d+4}/m_p^{d+5} ($4+d$ is the number of dimensions where quarks propagate) which is unacceptable large for Tev-Gravity models. Note, however, that this is completely *quantum* gravity (whatever it means) effect, while forming black holes in accelerators is completely *classical* and, therefore, say, arguments in [8] are absolutely misleading.

[11, 12, 13], that no reasons were found to forbid their existence.[3] Thus we suggest to switch the direction of the discussion: from whether time-machines are allowed to exist and be observable (not separated from us by any sort of impenetrable horizon like in the case of non-traversable wormhole, say, the Einstein-Rosen bridge, [16]), to whether we can notice them. As explained above, the TeV-gravity models allow one to shift this discussion to the solid ground of particle physics and perhaps even to forthcoming accelerator experiments. In this context the basic question is: can massively produced and quickly "evaporating" mini-time-machines leave traces, somehow different from those of pure-particle-physics processes (with no gravity effects) and from those caused by mini-black-holes? We do not say that discussion of mini-time-machines production rates are not important – quite the opposite, we shall see that these rates can essentially affect the answer and need be evaluated, – just, given all the experience of discussion of "chronology protection principle" [17], we believe that one can try to overstep this controversial subject and see what happens: if something interesting occurs, then we can come back with more enthusiasm and devotion.

One more word of caution is needed, this time not from the general-relativity, but from the particle-theory side. The best one can technically do at the moment is to consider MBH and MTM, once they are created, as classical backgrounds and see what happens to particles embedded into

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[3] Touching the subject of time machines, one, probably, should not avoid comment on the celebrated grandfather, known also as butterfly or, in scientific literature, as Polchinski [14], paradox: what if, while traveling to the past, one affects or even destroys the preconditions for its own creation. Here one should be careful in distinguishing between "affects" and "destroys". In the *former* case, there is no trouble: one should just modify the relation between initial and final conditions (causes and corollaries), remembering also that solutions to differential equations on spaces with non-trivial topology are uniquely defined by initial conditions for non-compact directions *and* by "zero-modes" for compact ones (in other words, the "residents" of the time-machine should be included into formulation of the Cauchy problem). In the *latter* case, the "problem" is actually a one of a Gödel- or Echer-style "impossible things": describing in a Human-created language a non-existing entity. In quantum theory, one should sum over all possible *globally defined* histories (world lines), and the paradox normally describes in words a (self-contradictory) history, which actually does not exist: if *somebody* killed your grandfather, then his world line terminated and could not lead to your birth-day, thus, that *somebody* was not you. Hence, there is no continuous world line, satisfying the conditions of the paradox, and the *non-realizable* history of *you* killing *your* grandfather does not contribute to the functional integral. It is kinematically, not dynamically, forbidden. Thus, the scientific problem related to grandfather paradox is that of classical determinism and of accurate formulation of Cauchy-like problems, existence and uniqueness of its solution, in the presence of time machines. It is sometime a difficult, but in no way a paradoxical problem. See [15] for more considerations.

them. In MBH case it was sufficient to accept the existence of Hawking radiation, in the MTM case we discuss below a some more delicate aspects of particle propagation. Strictly speaking, such consideration is safe when the scale of the background exceeds the particle's Compton wavelength – what is hardly true for MBH and MTM, created in high-energy collisions (though one of the two parameters of the MTM – duration T – can actually be large). We *assume* that qualitative effects can still be evaluated in above "approximation", like it is assumed about the Hawking radiation of MBH, but more justification is needed here.

Surprisingly small is known about the testable properties of time machines: most discussions seem to concentrate on philosophical issues and not much is done in estimation (and even definition) of concrete quantities. In the rest of this paper, we try to list possible qualitative effects in particle physics that could be of interest for further quantitative investigation.

2. Basic assumptions

2.1 On MTM-induced corrections to scattering probabilities

In quantum theory of fields $\phi(t,\vec{x})$ the mini-time-machines modify probabilities of scattering processes in the following way:

$$\textstyle\sum_{\text{over geometries}} \rho_{\text{geometry}} \left| \langle \phi(t_1,\vec{x}_1)\dots\phi(t_n,\vec{x}_n)\rangle_{\text{geometry}} \right|^2 \tag{1}$$

This formula reflects the fact that the story is about *classical* gravity: only matter fields are quantum, and no interference is considered between different geometries, say, between mini-time-machines with different duration of time loops.

2.2 On probability of MTM creation in particle collisions

The probability ρ_{geometry} of given geometry to contribute characterizes the probability to the corresponding object (mini-black-hole, mini-black--ring, mini-time-machine etc) to be created at accelerator (or in cosmic ray event) at energy $\mathcal{E}$. Like in the mini-black-hole case we assume that this probability is basically defined by the geometrical size $\mathcal{R}$ of the object (Schwarzschild radius or a size of the time-machine mouth) and the threshold energy $\mathcal{E}_{threshold}$:

$$\rho_{\text{geometry}} \sim \mathcal{R}^2\theta\left(\mathcal{E}-\mathcal{E}_{threshold}(\mathcal{R})\right), \tag{2}$$

where $\theta(x)$ is the Heaviside step-function. Of course this is a disputable formula ("chronology protection principle", if true, would simply put ρ for time-machines equal zero, and even the analogue of this formula for mini-black-holes caused long discussion [18]), but we just state that at the moment nothing forbids one to *assume* that (2) *can* be adequate. It just reflects the assumption that mini-time-machines can be created *classically* in particle collisions, with no quantum damping (which would characterize *quantum* creation of a *coherent* classical, i.e. consisting of *many* particles, object from *a few* colliding particles) and the obvious existence of some minimal energy needed for strong deformations of flat space-time to occur. As known from considerations of MBH, the cross-section (2) with $\mathcal{R}$ and $\mathcal{E}_{threshold}(\mathcal{R}) \sim \mathcal{R}m_{Pl}^2$, allowed by TeV-gravity models (i.e. with $m_{Pl} \sim 1 \div 10$ TeV), is enough to make LHC a *factory*, producing an MBH every second, and we can imagine that the rate of MTM production can be comparably high. This feeling that time machines are often associated with the black holes, so that the probabilities of their existence can be indeed comparable, both in the Universe and in accelerator processes, starts to get some support in the general-relativity literature of the last years [19]. Of course, there is a more delicate dependence on the parameters of MTM in the proportionality coefficient, implied in (2), and it is important for any kind of numerical and even qualitative estimates, but it is hard to evaluate without addressing concrete models of MTM.

2.3 On MTM geometries

A typical example of time-machine geometry is obtained by cutting two $4d$ balls out of Minkowski space and identifying (gluing) the boundaries of emerged holes ("mouths"). If one of the balls is inside the light-cone of another, we obtain a time-machine Wheeler's wormhole, see Fig.1 (otherwise it would be a Wheeler's wormhole with no closed time-like curves). This particular construction of the space with closed time-like curves was originally proposed in [20, 21]. As seen from Fig.1 the MTM has two essentially different parameters: the size of the mouth (length of the cut) $\mathcal{R}$ and duration (distance between the cuts) T. Note that in (2) we assume that in the first approximation the probability of MTM creation does not depend on T, in particular large T may not be damped as strongly as large $\mathcal{R}$, and T can essentially exceed $\mathcal{R} \sim \mathcal{E}/m_{Pl}^2$. This is a disputable assumption, but it is supported by some studies of time machines in general relativity, implying that T is indeed a soft (nearly zero-) mode (even negative in same cases) of the time machine solutions [22, 19].

Another popular construction of the time-machine is a traversable wormhole suggested in [23], see also [24]. Important addition to Fig.1 is a tube, connecting the balls boundaries (instead of gluing them directly, as in Fig.1), and appearance of a new parameter: time-loop duration T can generically exceed the time-machine time-life $\mathcal{T}$. On a general class of wormhole geometries, see [25]; on the stability of wormholes, see [26]; on the gravitating matter creating wormholes, see [27]; on rotating wormholes solutions which are presumably more stable, see [28]. Other constructions of time machines can be found in [10]. One can think about other ways to construct time-machine geometries. We do not discuss classification of time-machine geometries and their differences, example of Fig.1, sometime with addition of additional parameter $T \geq \mathcal{T}$ will be sufficient for our purpose of listing some interesting phenomena in particle physics, induced by the presence of time-machines.

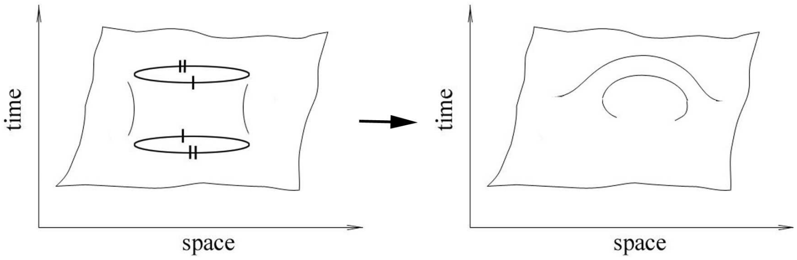

Figure 1: A time-machine wormhole, represented by flat space with cuts (with their sides appropriately identified). The second picture shows topology of emerged space (geometrically it can still be flat almost everywhere). The tube in the second picture can easily change its width far from its ends, and this allows to distinguish between the characteristic time loop duration T and the time-machine life-time (in laboratory frame) $\mathcal{T}$. Both T and $\mathcal{T}$ can be soft modes and do not need to be restricted by collision energy as strongly as the cut length (ball size) $\mathcal{R}$.

2.4 On MTM evaporation (decay)

If MTM contains strong gravitational fields and gravitational horizons, they can lose energy by a direct analogue of the Hawking radiation [29]. Remarkably, the same can be true if gravitational fields are small and no event horizons[4] are formed, like in our flat-space-time wormhole in Fig.1. Then time-machine's energy is fully carried by its "residents" – particles, which move along closed world lines (or zero-modes of fields in another formulation). Virtual-pair creation can produce an antiparticle to annihilate any given resident, then the other element of the pair can escape out of the time machine, thus forcing it to loose its residents and thus the energy. This process is possible because the finite size of the time machine makes – through quantum zero fluctuations – the particles inside, even in their

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[4] Of course, a Cauchy horizon, separating the domain where initial conditions at remote past are not enough to fix the solutions of evolution equations uniquely, is obligatory present in any time machine.

classically stable ground states, slightly more energetic than outside, what favors their escape, whenever possible. Properties of such evaporation should be, indeed, similar to the Hawking radiation, in particular, it should also be thermal because of uncertainty in the non-controllable state of the residents.

2.5 On second quantization formalism:

the key one for particle-theory causality and unitarity

Individual correlators in (1) can be represented in two essentially different ways: in second and first quantization formalisms. In the former case the correlator is given by a functional integral over fields,

$$\int D\phi\ e^{iS\{\phi\}}\phi(t_1,\vec{x}_1)\ldots\phi(t_n,\vec{x}_n), \tag{3}$$

and Feynman diagrams are made out of propagators, which are obtained by solving Klein-Gordon and Dirac equations in the space with non-trivial topology, like in Fig.1. It is a non-trivial problem to find explicit expressions for such functions, as everybody knows from the study of oversimplified examples in electrostatics or in the theory of Riemann surfaces. Even for Fig.1, and even for the case when spheres are deformed into straight cuts and even in $2d$ instead of $4d$ it is quite a problem to write an adequate Green function explicitly.[5] If known, such expressions could be used to somehow extract the commutators[6] $\Big\langle[\phi(x,t),\phi(x',t')]\Big\rangle$ and check if they vanish outside the light-cone – and thus study the naive particle-physics causality in the time-machine geometry. Unfortunately, because of problems with explicit expressions, not much can be done with the causality-related problems in the second quantization formalism.

2.6 On first-quantization formalism

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[5] In $2d$ one readily writes down a *Euclidean* Green function

$$\log\left(\vartheta(\Big|z-z'\Big|\tau)|^2\exp\pi\frac{\mathrm{Im}(z-z')^2}{\mathrm{Im}\ \tau}\right)+\text{contribution of the zero}-\text{mode}$$

with τ in the argument of Jacobi theta-function defined through the ratio $T/\mathcal{R}$ and

$$z\equiv\int^x\frac{dx}{\sqrt{\left(x^2-\frac{R^2+T^2}{4}\right)^2+T^2x^2}}$$

is obtained by the Jacobi map. However, this formula actually describes a Green function after compactification of a plane to CP^1 and can not be directly used for analytical continuation into non-compact Minkowski space with appropriate boundary conditions.

[6] For example, the equal-time commutator for $t'=t$ can be found with the help of the BJL theorem [30]: picking up the coefficient in front of ω^{-1} after Fourier transformation in time direction. However, even in this case there can be problems with making Fourier transformation in time-machine geometry, where the time t is not globally defined.

The first-quantization formalism is much better suited to study (counter-)intuitive problems. It represents propagators as sums over all *possible* world-lines of a particle in the space-time, leading from initial to the final point. Interactions are taken into account by forming usual Feynman diagrams out of these propagators. A non-trivial problem, however, arises with what are "possible" world-lines in Minkowski space-time. In non-relativistic quantum mechanics [31] the sum is over all world lines of the type $\vec{x}(t)$ with $-\infty < x_j(t) < +\infty$ and $t_i < t < t_f$ and $\vec{x}(t_i) = \vec{x}_i$, $\vec{x}(t_f) = \vec{x}_f$, i.e. one allows classical equations of motion to be broken, but time-ordering is preserved. In relativistic situation where the typical particle action is $S\{\vec{x}(t)\} = m\int\sqrt{1-\dot{\vec{x}}^2}dt$, one can impose additional constraint $\left|\dot{\vec{x}}\right| \leq 1$ – particles can not travel faster than light. The sum over world-lines with this restriction would provide the "causal particle propagator"

$$g(\vec{x}_f, t_f|\vec{x}_i, t_i) = \int \left\{D\vec{x}(t)\prod_{t=t_i}^{t_f}\theta\left(1-\dot{\vec{x}}^2\right)\right\}\exp\left(im\int_{t_i}^{t_f}\sqrt{1-\dot{\vec{x}}^2}dt\right) \quad (4)$$

– an obviously causal quantity in Minkowski space. However, for geometrical intuition this object does not look very natural if space and time are to be treated on equal footing. From that point of view, instead of summing over all functions $\vec{x}(t)$ in (4) one would rather sum over all curves $\vec{x}(s), t(s)$ in the space time. The difference is two-fold, see Fig.2: first, not all curves are inverse images of projections onto the time segments (t_i, t_f); second, not all curves satisfy the restriction that velocities never exceed unity (the speed of light). The latter subject is in fact a delicate one, related to analytical continuations and other peculiarities of Polyakov's method to handle non-

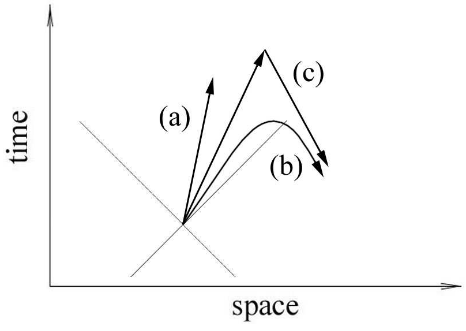

Figure 2: Difference between a particle world line (a), generic path (b) and a singular path (c), implied in the definition of Feynman propagator. The last one consists of pieces, which look like particle/antiparticle world lines, i.e. belong everywhere to the light cones, are invertibly projected on the time axis and projection preserves/inverts the direction.

polynomial actions [32], while the former difference is taken into account by composition of any space-time curve from a sequence of well-projectable fragments, going along and backwards in time. The full integral over all curves – the Feynman's propagator $G(\vec{x}_f, t_f|\vec{x}_i, t_i)$ – is a multi-linear combination of g and $\bar{g}$, interpreted as propagators of particles and anti-particles [33], depending on the sign of dt/ds:

$$\begin{gathered} G(\vec{x}_f, t_f|\vec{x}_i, t_i) = g(\vec{x}_f, t_f|\vec{x}_i, t_i) \\ + \int_{|\vec{x}_f - \vec{x}| \le t_f - t,\ |\vec{x}_i - \vec{x}| \le t - t_i} \bar{g}(\vec{x}_f, t_f|\vec{x}, t) g(\vec{x}, t|\vec{x}_i, t_i) + \ldots \end{gathered} \tag{5}$$

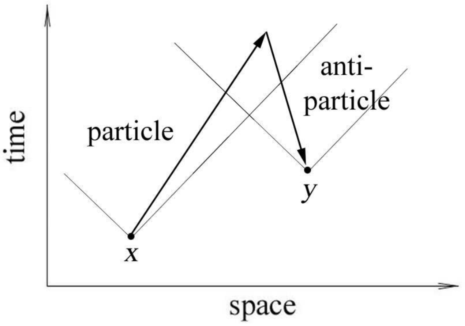

Figure 3: A typical contribution to the Feynman "propagator" outside the light-cone. Both particle and antiparticle travel inside their light cones and no causality violation takes place. However, this *correlator* does not describe *propagation* of any physical entity: it is instead an amplitude to create and annihilate a pair. This obvious fact makes interpretation of amplitudes (especially, the loop diagrams), evaluated with the help of Feynman propagators somewhat tricky.

As clear from Fig.3, the Feynman "propagator" does not vanish outside the light-cone (still, and somewhat ironical, it is often called "causal"), and does not need to vanish, see, e.g., [34]. Better understanding of these problems seem important for clarification of physics of time machines, and they seem to remain under-investigated.

3. PARTICLES IN TIME-MACHINE

The typical world-line of a particle, traveling through time machine of Fig.1 is shown in Fig.4.

It passes n times through the time-machine and finally escapes. In laboratory frame all n walks do not take any time, but in the particle's own frame the situation is different: nT units of its proper time pass before it escapes. If the particle could decay or radiate (in Fig.4 the radiation case is shown), it was doing so during all its life in time-machine and comes out

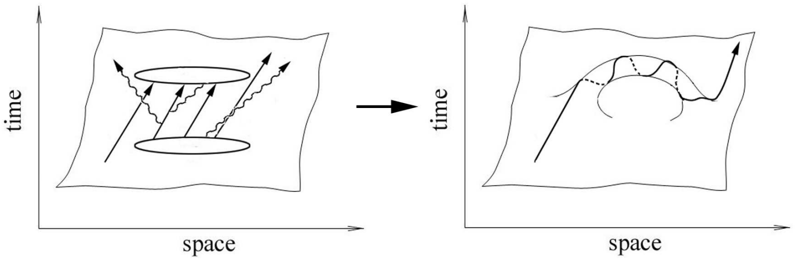

Figure 4: A particle, traveling $n = 3$ times through a time machine with the time loop of length T. In the left-side picture also two photons are shown, radiated by the particle. The one which escapes immediately after being emitted looks for a distant observer as coming from the place where no particle was present and can cause non-locality of effective theory.

much older – by nT – than its twin particle, which never was in the time machine (note, that in special relativity, the traveling twin returns younger than the one who stayed at home, but in the case of time machine, as well as of a travel in strong gravitational field, things are different: the traveler gets older). We now list some effects obvious from Fig.4, together with their possible implications for observations. In every case it is important to figure out, whether an effect can occur

– without any gravitational effects,

– also in the presence of MBH,

– in presence of any kind of wormholes (i.e. effect does not distinguish between space- and time-like wormholes),

– only for time-machine geometries.

3.1 Frequency filtration

The field, describing a particle with frequency ω, acquires a phase factor $e^{i\omega T}$ every time it makes a cycle along the time loop of duration T in time machine. After n cycles the wave function will be proportional to

$$\sum_{k=0}^{n} e^{ik\omega T} \longrightarrow \sum_{m} \delta\left(\omega - \frac{2\pi m}{T}\right)$$

for large enough n. Of course, one should take into account the space-dependence of the wave function, but the phenomenon is already clear from above oversimplified formula: original frequency spectrum at the entrance into the time-machine is re-shaped, mostly frequencies which are integer multiples of $\frac{2\pi}{T}$ will penetrate through the time machine. This frequency filtration implies that gravitational effects can modify the original spectra of particles, calculated in neglect of them. Actually, such modifications are caused both by MTMs and MBHs. Though effect of particular MTM is quite specific: frequency filtration (and nothing equally specific would be caused by particular MBH), it is obscured by averaging over various time-loop durations T in formula (1).

3.2 Unexpectedly energetic particles

It was noted in [17] that the gravitational field in a time machine could provide a particle[7] with additional energy each time it passes through the time machine, so that it can acquire a lot during a period of time which is nearly zero in laboratory frame. This would cause another peculiar type of modification of spectrum, providing some particles with a large excess of energy at expense of the other particles: the latter are produced in evaporation of the MTM, which lost part of its gravitational energy to acceleration of the former. This effect is again specific for time machines (as compared to the MBH and space-like wormholes), but again, since spectrum modification involves a lot of averaging, it can be not too pronounced in actual experiments.

As usual, one should add a word of caution. Already in [17] it was argued, that the time machines with accelerating ability can be not observable for one or another reason (they can decouple from our universe or instead quickly renormalize the accelerating gravitational field down to zero). Furthermore, in [17] it was noted that the geometry in a tube region around the closed curved acts as "a diverging lens" [11], which disperses *energy*, even if it concentrates the *energy density.* Thus, if a point particle is substituted by a wave packet, its total energy can actually decrease instead of increasing. According to [17] this is indeed the case for the wormholes of [23]. A more careful analysis for (quantum) point-like particles is still needed.

3.3 Accelerated aging, intensification of decay and oscillation processes

If a particle travels n times along a time loop of duration T, its proper-time (age) exceeds the laboratory time by nT. This means that from the point of view of laboratory observer such particle ages much faster than it would in the absence of time machine. In particular, if the particle decays and probability of its existence decreases as $e^{-\Gamma t}$, the presence of time-machine seemingly accelerates the decay for the outside observer: $e^{-\Gamma t} \longrightarrow e^{-\Gamma(t+nT)}$. Note that nT can considerably exceed the characteristic time $\mathcal{T}$

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[7] In [17] it was a photon traveling along the first closed null-curve to come into existence as the time-machine is formed. This photon is blue-shifted every time it makes a closed loop inside the time machine. See also [35].

of evaporation of mini-time-machine (which can be smaller than 10^{-28} s for MTM possibly created at LHC and is negligible as compared to life-time of all ordinary particles), both because T can be much greater than $\mathcal{T}$ and because n can be large.

Similar phenomenon will take place with the loss of energy due to radiation. As shown in Fig.4, the radiated photons can have different fates – they can escape from the time machine immediately or can continue to make time loops in it,– this does not affect the radiation rate of original particle. Other effects, related to the age of particles, like kaon or neutrino oscillations will also be seemingly accelerated in the presence of MTM.

3.4 Effective non-locality, possible CPT and unitarity violation

As shown in Fig.4, a photon, emitted by a particle when it was traveling inside the time machine, can escape, but its emission point will have nothing to do with that of the escaping particle itself (if escaping photon was emitted not at the last, but at some intermediate travel of the particle along the time loop, and if we notice that trajectories of these travels in space can differ from time to time – as shown in Fig.4). This means that from the point of view of external observer a kind of non-local emission of photon took place: a potentially non-local effective interaction is generated by time machine. This opens a room for CPT-violation, though more detailed analysis is needed to decide whether it can indeed be caused by MTM (see also [36] for a toy two-dimensional model discussion of the issue)[8].

Naive unitarity violation in time-machine geometries is considered very probable [38], because of existence of the Jinnee-type world histories [39], shown in Fig.5, which are not fully controlled by initial conditions at remote past and should be somehow averaged over. Of course, after evaporation of MTM the *formal* unitarity should be recovered, like it happens in the case of evaporating black holes [40] (or molecular theory). However, physically relevant thermalization-style effects remain and can probably be observed.

3.5 Collective effects

Fig.4 shows that a time-machine converts, at some stages of evolution, a single particle into an ensemble of co-existing particles. Moreover, the particles in the ensemble are copies and thus are strongly correlated. This opens a room for various collective effects to occur, if interaction is taken into account, up to bose-condensation, superfluidity and superconductivity of copies inside the time-machine. Since phase transitions may affect the behavior of particles, including, say, their decay rates and radiation distri-

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[8] For possible CPT violation effects due to non-trivial topology see, e.g., a recent paper [37] and references therein.

butions, they may affect the outcome of particle collisions. This kind of collective effects, caused by cloning of a single particle, seems to be absolutely peculiar for time machines.

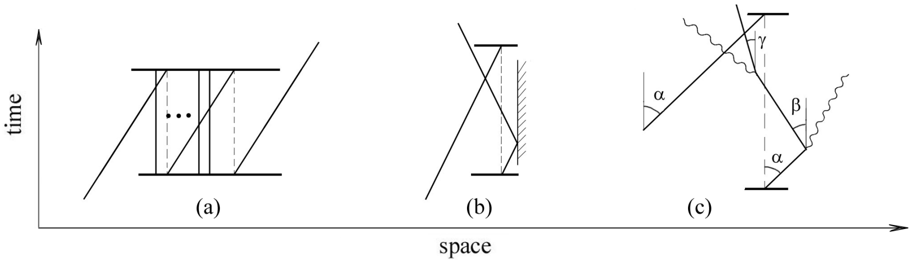

Figure 5: Encounters of external particle with the “residents” of the time machine, nicknamed ”Jinn” in ref.[39]. They can interfere with the incoming and outgoing particles and are well observable, but they are not controlled by specification of *in* or *out* states, what requires a more accurate formulation of unitarity when particle theory is considered in the time-machine geometries. **(a)** Vertical lines (classically unobservable Jinn-at-rest) can be added in any number at any place of the cuts. This represents the ambiguity in the world-history of a particle traveling through the time machine. In the picture it is assumed that particles interact as in central collisions of tiny balls: they exchange momentum and energy in every act of interaction. **(b)** A non-trivial meeting with Jinnee. Encounter with the Jinnee is not controlled by the initial condition at remote past. One and the same pattern (which contributes exactly once to the functional integral) allows different *interpretations*: one can say that a particle gets through the time-machine without interaction with the Jinnee living inside or that a particle itself passes along a time-loop inside time machine and escapes, with changes in its motion, caused by self-interaction. **(c)** Here the aging (dissipating) Jinnee is shown: as time goes, our particle can radiate (or decay or dissipate energy in other ways). The remaining kinetic energy and thus the age of the particle is characterized by the angle between the world line and time-axis. It is clear from the picture that as result of encounter with the Jinnee the particle becomes older – in accordance with the second interpretation in (b): that it have spent extra proper time inside the time machine. The typical (proper-time) history of a ”wild” Jinnee is as follows (see [39] for discussion of artificially created Jinn). Radiation can cause incoming particle to be trapped inside the time machine and become a Jinnee. After that the aging Jinnee looses energy and becomes sterile Jinnee-at-rest, which has no more energy to loose and can no longer radiate. Still, since the energy of resting Jinnee can exceed its mass due to zero-fluctuation effects in the time-machine of a finite size, the quantum interaction with virtual pairs can allow the Jinnee to escape: this effect contributes to quantum evaporation of time-machines (gravitational fields, if any, can also be considered as a sort of Jinn).

3.6 Extra production of antiparticles at intermediate stage

As clear from the presentation of wormhole geometry in the right-hand-parts of Figs.1 and 4, while traveling through the time-machine, a probe particle will sometime move backwards in time from the point of view of the laboratory frame. Probably, at this part of its history it can be considered as antiparticle. In other words, the MTM seem to temporarily convert particles into antiparticles, however, as clear from Fig.6, for external observer the decay products of *these* antiparticles are indistinguishable from those of original particles, at least in the theory without CP-violation. Thus, experimental consequences of temporal presence of antiparticles are obscure.

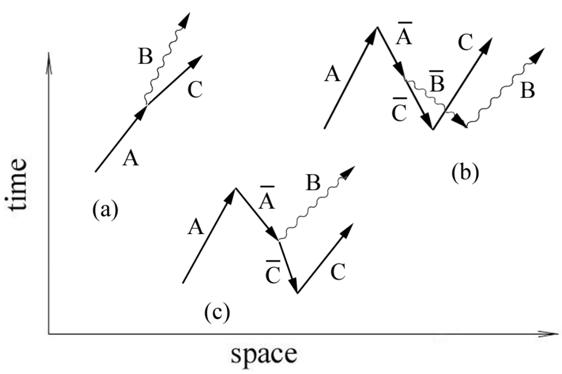

Figure 6: Irrespective of time-directions in which the particle A can move inside a time-machine (and its possible conversion into anti-particle $\bar{A}$), the observer at remote future will see only B and C (and not $\bar{B}$ or $\bar{C}$) in the products of A decay. **(a)** A particle A can emit B and turn into C. **(b)** When moving backwards in time, C looks like a normally moving anti-particle $\bar{C}$, which turns into $\bar{A}$ after collision with $\bar{B}$. **(c)** Alternatively, $\bar{C}$ can convert into $\bar{A}$ by emission of B.

If CP is violated, a more interesting question arises: antiparticles should have coupling constants, which are complex conjugate of their particle's counterparts (CP-violating mass terms, e.g. $i\mu(K_0^2 - \bar{K}_0^2)$ as opposed to the ordinary $m^2 K_0 \bar{K}_0$, are usually considered as additional valence-two vertices in Feynman diagrams). In the first quantization formalism this means that when moving backwards in time the particle should have different parameters. Such abrupt change is not a problem in the formalism, involving singular paths of Fig.3c, where world lines of particles and antiparticles lie inside light cones and are well separated. However, adequate description in terms of smoothly U-turning paths of Fig.3b is less obvious. In Fig.4, associated with the time-machine geometry, the light-cone is *smoothly* turning upside down along the world line, what resembles the "geometric" Fig.3b, rather than "physical" Fig.3c. All this means that the story of geometrical first-quantized formulation of theories with CP-violation and, in particular, the problem of particle-antiparticle conversion in MTM is somewhat obscure and deserves further investigation.

4. CONCLUSION

No question, the statements in the previous sections and even their mutual compatibility are disputable or at least require a lot of comments and justification. However, attempts to make above naive arguments more rigorous would take us back to controversial discussion of time-machine physics, which we suggested to avoid in the Introduction. Instead, as we suggested, one can try to make equally naive estimates of the values of above effects, assuming that – for one or another reason – they can avoid the existing or the future counter-arguments and still show up in physical experiments. Of principal importance for reliable estimates is deeper understanding of the issues, mentioned in s..

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G.T.Horowitz and H.S.Reall, Class.Quant.Grav. **22** (2005) 1289, hep-th/0411268
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  M.Alcubierre, Class.Quuant.Grav. **11** (1994) L73
  ref.[16, 23, 12, 20] below.

- Attempts to forbid the types of matter needed to generate time-machines (resembles a war between weapons and defense: for every concrete "protection principle" a counter-example is being found and a new protection principle is needed to forbid the new kind of matter):

  S.Deser, R.Jackiw and G.t'Hooft, *Phys.Rev.Lett.* **68** (1992) 267
  S.Deser and R.Jackiw, preprint BRX TH 334, CTP #2101, 1992
  ref.[17] below: This paper proposes "a chronology protection principle" that "prevents the appearence of closed time-like curves and so makes the universe safe for historians".

- Especially extensive is the literature confronting the time machines and the Weak Energy Condition (WEC) which forbids a negative energy density of the gravitating matter,

  S.W.Hawking and G.F.R.Ellis, *Large scale structure of space-time*, Cambridge University Press, 1975

  Say, the wormhole solutions violate the WEC (see, however, [27] below). One can construct the time machine which does not violate the WEC [12]. Moreover, systems that obey the WEC at the classical level, may do not obey it after being quantized (e.g., due to the Casimir efect,

  H.B.G.Kasimir, Konink.Nederl.Akad.Weten., Proc.Ser.Sci. **51** (1948) 793
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  The point is that the quantum expectation value of the stress energy tensor can be negative, see

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see also [27] below.

- Considerations of "pathological properties" of time machines:
  L.Susskind, gr-qc/0503097
- Grandfather paradox: refs.[14] and [15] below;
- Energy production: refs.[17], [11] and [35] below;
- Unitarity violation: refs.[38] and [41] below
- For reviews of time-machine properties and paradoxes see [11] and the recent paper
  A.Everett, gr-qc/0410035
- For consideration of time-machine effects, caused by a possible superluminal propagation of light in gravitational field caused by quantum corrections, see
  I.T.Drummond and S.J.Hathrell, Phys.Rev. **D22** (1980) 343
  A.Dolgov and I.Novikov, Phys.Lett. **B442** (1998) 82, hep-th/9807067
  and the capture to Fig.3.
- Papers, accepting the time-machine existence:
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  refs.[39], [15], [11] and [12] below.
- Claims that time-machines are natural products of black hole evolution (in presence of reasonable, but still exotic matter):
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