Quantum gravitational proton decay at high temperature

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One of the most important challenges of contemporary physics is to find experimental signatures of quantum gravity. It is expected that quantum gravitational effects lead to proton decay but on time scales way beyond what is of any relevance to experiments. At non-zero temperatures there are reasons to believe that the situation is much more favourable. We will argue that at the temperatures and densities reached at present and future fusion facilities there is a realistic possibility that proton decay could be detectable.

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I. INTRODUCTION

One way to violate the conservation of baryon number is to form a black hole and let it evaporate through the emission of Hawking radiation [1]. The formation and subsequent evaporation of a black hole does conserve charges that are protected by local symmetries such as the electric charge. Baryon number, on the other hand, is not conserved. Whereas the creation of a real black hole is not possible in the laboratory, it has been argued that virtual Planck size black holes are produced by quantum effects. This is the space-time foam proposed by Wheeler [2] and Hawking [3]. An intriguing suggestion is that such virtual black holes can contribute to baryon number violation and consequently to proton decay. In [4, 5, 6] the magnitude of such an effect was estimated, and the lifetime of a proton was found to be given by roughly

$$\tau \sim m_p^{-1} \left( \frac{m_{pl}}{m_p} \right)^4 \sim 10^{45} \text{ years}, \quad (1)$$

where $m_p$ is the proton mass, and $m_{pl}$ is the Planck mass. This result is many orders of magnitude above the estimates of theories of grand unification and even further away from the experimental limits.

In this paper we will consider the possibility that the the life time of a proton is substantially reduced at finite temperature. Our conclusion is that the life time is of the order

$$\tau \sim \frac{m_{pl}^2}{T^3}, \quad (2)$$

In section 2 we give two independent arguments for this result, one of which is based on black hole complementarity. If the temperature is high enough, our formula predicts that the life time of a proton will be dominated by quantum gravity. In section 3 we will argue that the conditions at present and planned experimental fusion facilities are such that proton decay could be experimentally detectable.

II. BARYON NUMBER VIOLATION AT FINITE TEMPERATURE

We will now argue for the existence of temperature dependent baryon number violating processes due to quantum gravity and possibly related to the production of virtual black holes. Even though the details of such processes will have to wait for a fully developed theory of quantum gravity, it is nevertheless simple to estimate their importance. We will present two quite different arguments both yielding results in line with what is to be expected on the grounds of simple dimensional analysis.

The key ingredient in our argument will be the assumed existence of an effective smallest length of the order of the Planck length. We expect that any distance shorter than this can not be given a meaning, and as a consequence it is reasonable to expect that one can at most assign of the order of one bit of information to the corresponding Planck volume. The state of matter is encoded in the state of these bits, and in particular the state of a proton will be described in this way. In a suitable basis it should be possible to encode the baryon number of the configuration in one such bit in particular. The way this is done might include non-local and holographic aspects, details of which will not concern us. The value of this bit, and hence the baryon number, would be expected to change in response to interactions with an external agent such as a heat bath. By dimensional analysis the characteristic interaction cross section can be expected to be of order $\sigma \sim T^2_{pl}$. In the presence of a heat bath there will be a flux of, e.g., photons proportional to $T^3$, and as a consequence, we estimate the interaction rate to be given by $\Gamma \sim T^2_{pl} T^3$ and the life time is given by $\frac{1}{\Gamma}$. A similar argument has been made in [7] in the context of de Sitter space.

The argument is very simple but quite generic and it is reasonable to assume that it holds true regardless of the details of quantum gravity. The only thing we need is the presence of baryon number violation and that the rate is naturally given in terms of the temperature and the strength of gravity. Clearly, there will be other mechanisms contributing to baryon number violation which sometimes will dominate. If the temperature is too small, for instance, the decay rate will be governed by GUT ברחבי.
theory mechanisms. What we argue is simply that \( T \) sets a universal upper limit on the life time independent of the details of particle physics. As we will see below this limit is on the one hand not in conflict with any experimental results, and on the other hand within reach of realistic new experiments.

A different argument, providing further insights into the relevant physics, can be obtained by investigating space times with horizons in more detail. To this end we consider a probe in free fall towards the horizon of a black hole. As is well known, a distant observer will not actually see the probe cross the horizon but rather observe how the probe asymptotically approaches the horizon, and how it becomes ever more redshifted and effectively invisible after some time. If quantum effects are taken into account, the situation will be slightly different since there in addition will be Hawking radiation emitted by the horizon. While Hawking’s original suggestion was that this radiation did not carry any information about what ever had crossed the horizon, \( Q \), the present generally accepted point of view is different. It is believed that the radiation does carry all information with it, albeit in a way difficult to decode. In fact, what a careful observer would see when the probe approaches the horizon is how the probe is slowly fried by the Hawking radiation. In this way the probe itself is dissolved into radiation that carries all information about the probe. Note that we, in principle, can follow what happens to the probe all along – it will never disappear from sight. For us it will be important to note that this dramatic process does not conserve baryon number.

Confusingly, a second observer moving along with the probe will have a very different version of what happened. The region interpreted as a horizon by the first observer is nothing special to the second observer, who will just continue the journey along with the probe. The resolution of the puzzle is by now well known in the form of the black hole complementarity principle \( R \). The point is that the two observers will never be able to meet and disagree about what happened precisely due to the existence of the horizon.

Now, how long does the process take? The horizon of a black hole has a temperature of the order \( 1/R \). The region between two objects in free fall increases according to \( e^{HT} \), where \( H \) is a time independent Hubble constant. It is easy to show that any object further away from a given observer than \( 1/H \) will forever remain invisible. This distance will therefore represent a horizon analogous to the horizon of a black hole. Again we can consider a probe in free fall towards the horizon and again there will be radiation due to quantum effects \( D \). The argument proceeds in the same way as before, \( Q \), and again one finds a time scale given by equation (2).

We have reached our estimate for the life time of a proton (or any other particle with a conserved global quantum number) in two different ways. Furthermore – if there actually is a violation of baryon number due to quantum gravity at finite temperature – the expression we have arrived at is more or less the simplest possible. In the next section we will investigate the experimental consequences.

### III. EXPERIMENTAL PREDICTIONS

Given the independent arguments in the previous section, we are confident that our estimate for the proton life time is correct. Though the result is theoretically interesting, it would be even more important if the effects could be experimentally detectable. In other words, can finite temperature effects be important in present Earth based experiments looking for proton decay? Using our formula and using a temperature of 300K one finds an estimated proton life time on the order of \( 10^{30} \) years. This is shorter than what is expected from effects already present at zero temperature, but still several orders of magnitudes beyond the experimental limits.

What about reducing the proton life time by considering situations in which the temperature is higher? An interesting example of high temperatures sustained at a comparably long time is in the case of fusion reactors. In present fusion research using, e.g., tokamaks, the criterion used to judge the efficiency of the experiment is the
Lawson criterion. The Lawson criterion states that useful fusion will occur if \( n\tau_e T \geq 10^{21} \text{skeV/m}^3 \), where \( n \) is the number density of nuclei, \( \tau_e \) is the containment time of the plasma (i.e. the characteristic time it takes for the energy in the plasma to dissipate), and \( T \) is the necessary temperature, typically a few times \( 10^8 K \sim 10 \text{keV} \). At the present fusion experiment JET, one has almost achieved this goal.\(^{12}\) Hence, with a volume for the plasma of around \( 100 m^3 \), we can estimate that \( N\tau_e \sim 10^{22} s \sim 10^{15} \text{years} \), where \( N \) is the total number of nuclei in the plasma. At the future fusion reactor ITER,\(^{13}\) one will satisfy the Lawson criterion, and with a volume for the plasma of around \( 1000 m^3 \), one gets \( N\tau_e \sim 10^{23} s \sim 10^{16} \text{years} \). These experimental parameters should be compared with the predicted proton life time, which, using our argument from quantum gravity, is given by \( 10^{20} \text{years} \) at the temperatures relevant for fusion reactors. We conclude that in case of JET one can expect on the order of one event for every accumulated \( 10^5 \tau_e \) of running time, whereas for ITER the expected rate is one event for every accumulated \( 10^4 \tau_e \) of running time. A typical value for \( \tau_e \) is one second.

The signature of proton decay is likely to be in the form of high energy particles like pions, leptons, etc, with a characteristic total energy given by the proton mass of \( 1 GeV \) and a total unit positive charge. Our prediction is that such events will take place at JET and ITER at the above calculated rates.

It should be noted that our estimate of the proton life time is very approximate. For instance, we have used the Planck mass given by \( m_{pl} \sim 10^{19} \text{GeV} \), if instead we had used the reduced Planck mass, \( m_{pl}/\sqrt{8\pi} \sim 10^{18} \text{GeV} \), which is often used to estimate the importance of quantum gravitational effects, we would have arrived at \( 10^{18} \) years. The corresponding estimates for the necessary running times would have been two orders of magnitude shorter.

While the detailed mechanism leading to the proton decay remains to be explored, the argument presented in this letter is rather general. We therefore propose that the necessary steps are taken to look for the effect at present and future fusion facilities. A positive result would be of great importance.

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