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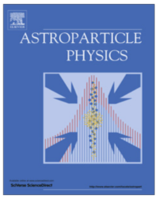

# Back-to-back black holes decay signature at neutrino observatories

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ABSTRACT

We propose a decay signature for non-thermal small black holes with masses in the TeV range which can be discovered by neutrino observatories. The black holes would result due to the impact between ultra high energy neutrinos with nuclei in water or ice and decay instantaneously. They could be produced if the Planck scale is in the few TeV region and the highly energetic fluxes are large enough. Having masses close to the Planck scale, the typical decay mode for these black holes is into two particles emitted back-to-back. For a certain range of angles between the emitted particles and the center of mass direction of motion, it is possible for the detectors to measure separate muons having specific energies and their trajectories oriented at a large enough angle to prove that they are the result of a back-to-back decay event.

## 1. Introduction

In brane world models with a large extra-dimensional volume [1–3] or in even in four dimensions if there is a large hidden sector of particles [4], quantum gravitational effects could become important anywhere between the traditional Planck scale, i.e. some $10^{16}$ TeV and a few TeV. If the Planck scale, i.e. the energy scale at which quantum gravitational effects become important, is in the lower end of this energy range, the collision of particles can result in the creation of small black holes with TeV masses when particles collide with center of mass energies larger the Planck scale.

The formation of black holes in the collision of particles has been studied since the 70's. In 1972, Thorne proposed the *Hoop conjecture* [5] which states that a black hole forms whenever the impact parameter $b$ of two colliding objects (of negligible spatial extension) is shorter than the radius of the would-be-horizon (roughly, the Schwarzschild radius, if angular momentum can be neglected) corresponding to the total energy $M$ of the system [1]

$$b \lesssim \frac{2\, l_{Pl} M}{M_{Pl}}. \tag{1}$$

While the hoop conjecture is intuitively very satisfactory, it is not enough to prove that black holes do indeed form in such collisions. However, there are now a proofs available of the formation of a closed trapped surface when two particles collider at very high energy above the Planck scale. The formation of a closed trapped surface suffices to demonstrate gravitational collapse and hence the formation of a black hole.[2] The proofs [6–9] covers both zero and non-zero impact parameters. Remarkably the proof of Eardley and Giddings is analytical in the case of a four dimensional space–time [9]. This demonstrates the formation of a classical black hole in the collisions with a non-zero impact parameter of two particles with energies much larger than the Planck mass. This work has been extended to the semi-classical regime by Hsu [10]. Semi-classical black holes are expected to have masses in the range from 5 to 20 times the Planck scale [11].

Most of the articles related to the production of small black holes via particle collisions at colliders or in cosmic rays have considered semi-classical black holes [12–20]. It is however possible that the center of mass energy available in such high energy collisions is not large enough to create semi-classical black holes. It was therefore proposed [21–23] to consider quantum black hole which are non-thermal objects with masses close to the Planck mass which should be easier to produce. As they are non-thermal objects, quantum black holes are expected to decay into a small number of particles, typically two. Experimental signatures for such decays are very different from the one of semi-classical objects which are expected to decay into several particles in a final explosion, see e.g. [24,25] for recent reviews.

Bounds on the Planck scale using Earth skimming neutrinos creating black holes in the Earth crust have been derived in [18,17,26].

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[1] We shall use units with $c = \hbar = 1$ and the Boltzmann constant $k_B = 1$, and always display the Newton constant $G = l_{Pl}/M_{Pl}$, where $l_{Pl}$ and $M_{Pl}$ are the Planck length and mass, respectively.

[2] The first calculations were performed by Penrose who never published his findings.

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The back-to-back decay signature for quantum black holes produced in cosmic ray events was first proposed in [27]. The authors study the possibility for the two particle showers produced by the particles resulting from the back-to-back decay of the black holes to be spatially separated and detected as two simultaneous shower events by cosmic ray observatories (current earth based or future space based experiments). That case study refers to quantum black holes which are generated due to the interaction of ultra high energy cosmic rays (UHECR) or neutrinos with particles in the upper atmosphere and decay instantaneously into two particles which move back-to-back in the center of mass reference frame. It is shown in [27] that even if a small percentage of this type of events can be detected, there is parameter space for which detection is possible.

Here we propose to take the idea one step further by analyzing whether it is possible to discover such a black hole decay signature in ice or water with the help of neutrino observatories. Besides being produced at colliders or in the atmosphere by high energetic collisions of cosmic rays with nuclei, quantum black holes can also be produced due to the collision between highly energetic neutrinos with nuclei in water or ice. Neutrino observatories are designed to detect muons induced by high-energy neutrinos. Because of the characteristics of the propagation of muons in water and ice, the neutrino direction can be derived with high accuracy [28,29]. As neutrinos only interact weakly and their trajectory points back to their sources, energetic neutrino events would point directly towards sources capable of producing these energetic events. We propose that these observatories can be used to search for quantum black hole events. Indeed, when neutrinos of high enough energies collide with particles in water or ice, if the center of mass energy is larger than the Planck mass, quantum black holes can be created. As stated before, black holes with masses close to the Planck mass decay preferentially into two particles which then produce secondary showers which can be seen by the neutrino experiments.

If the Planck mass is of the order of a few TeV, only black holes with masses above this energy scale can be produced. This implies that, to form a black hole, the energy of the neutrino has to be of the order of $10^7$ GeV or above. The range of interaction lengths for neutrino energies ($E_\nu$) between $10^7$–$10^9$ GeV is $6.6 \times 10^3$–$9.4 \times 10^2$ km water equivalent in rock [30]. This means that the Earth is opaque to electron and muon neutrinos with energies in this range or larger. Only Earth skimming neutrinos [31] and those coming from above the horizon are thus useful for our considerations.

## 2. Black holes production

In this section we briefly describe the production cross section for quantum black hole formation. Note that the formulas are extrapolated from the semi-classical regime. The black hole production cross section as a result of a neutrino interacting with nucleon ($\nu N \to BH$) is given by

$$\sigma(E_\nu, x_{min}, M_D) = \int_0^1 2z dz \int_{\frac{(x_{min} M_D)^2}{y(z)^2 s_{max}}}^1 dx F(n) \pi r_s^2 \left(\sqrt{\hat{s}}, M_D\right) \sum_i f_i(x, Q). \tag{2}$$

In this equation $M_D$ is the $4+n$ dimensional reduced Planck mass, $z = b/b_{max}$ with $b$ the impact parameter and $b_{max}$ the maximum value of the impact parameter for which black hole creation can occur as a result of the collision between the two particles, $x_{min} = M_{BH,min}/M_D$ and $n$ is the number of extra-dimensions. $F(n)$ and $y(z)$ are the factors introduced by Eardley and Giddings [9] and by Yoshino and Nambu [32]. The Schwarzschild radius in $4+n$ dimensions is given by

$$r_s(us, n, M_D) = k(n) M_D^{-1} \left[\sqrt{us}/M_D\right]^{1/(1+n)}, \tag{3}$$

where

$$k(n) = \left[2^n \sqrt{\pi}^{n-3} \frac{\Gamma((3+n)/2)}{2+n}\right]^{1/(1+n)}. \tag{4}$$

Furthermore, note that $\hat{s} = 2x m_N E_\nu$, with $m_N$ the nuclei mass and $E_\nu$ the neutrino energy. The functions $f_i(x, Q)$ are the parton distribution functions. Black hole production by cosmic neutrinos might be suppressed in comparison to the production rate from UHECRs [33]. However this is a model dependent question. It is worth mentioning that although the parton level black hole cross section grows with energy to some power, the cross sections at the nuclei level go quickly to zero because of the energy dependence of the parton distribution functions.

Only the flux of highly energetic neutrinos is relevant for the present case of study, flux which can be estimated by considering two sites of productions: at the source and between the source and the detection place, usually Earth. The production sites of the extragalactic UHECR, which include (AGN) and (GRBs), are also associated with the ones for neutrinos which are produced through pion decay in proton–proton or proton–photon interactions within the source [34] and the flux depends on the composition of the cosmic rays at high energies, which can be pure protons, neutrons, heavy nuclei or a mix of these [35,36].

In order to estimate the number of quantum black hole events expected at a neutrino detector like IceCube, we use two models for the energy flux of the neutrino at high energy proposed in [37]. Here they use a a smoothly-broken power law to estimate the fluxes of high energy neutrinos reaching the Earth that also include the recent observation of two PeV-energy shower events by IceCube. These two models are based on a $E^{-2}$ accelerated proton spectrum, [38], and use first a $\pi^+$ only decay channel and then $\pi^\pm$ and $\mu^\pm$ decay channels to produce neutrinos. We combine this with the geometrical acceptance of the IceCUBE detector, [39] to find the numbers of the quantum black holes produced by a flux

**Table 1**
Number of black hole events per year expected at the IceCube experiment for which the separation of the two showers is larger than 1° in the reference frame of the laboratory/experiment when using the first model for the neutrino flux, with $n$ representing the number of extra dimensions.

| $n$ | $M_{Pl}$ | $M_{Pl}$ | $M_{Pl}$ | $M_{Pl}$ | $M_{Pl}$ | $M_{Pl}$ | $M_{Pl}$ | $M_{Pl}$ |
|---|---|---|---|---|---|---|---|---|
| | 1 TeV | 2 TeV | 3 TeV | 4 TeV | 5 TeV | 6 TeV | 7 TeV | 8 TeV |
| 0 | 0.11 | 0.0055 | 0.00080 | 0.00020 | 0.00010 | 0.000016 | 0.0000052 | 0.0000016 |
| 1 | 2.9 | 0.19 | 0.033 | 0.0085 | 0.0026 | 0.00088 | 0.00030 | 0.000096 |
| 2 | 11 | 0.79 | 0.14 | 0.040 | 0.012 | 0.0041 | 0.0014 | 0.00046 |
| 3 | 25 | 1.8 | 0.33 | 0.090 | 0.029 | 0.010 | 0.0035 | 0.0011 |
| 4 | 43 | 3.2 | 0.59 | 0.16 | 0.051 | 0.018 | 0.0062 | 0.0020 |
| 5 | 64 | 4.8 | 0.89 | 0.24 | 0.078 | 0.027 | 0.0095 | 0.0031 |
| 6 | 88 | 6.5 | 1.2 | 0.33 | 0.11 | 0.038 | 0.013 | 0.0044 |
| 7 | 110 | 8.5 | 1.6 | 0.44 | 0.14 | 0.050 | 0.017 | 0.0057 |