Production and Detection of Black Holes at Neutrino Array

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Abstract

We consider the production of black holes caused by the collision between high-energy cosmic neutrinos and nuclei contained in detectors. If the fundamental scale $M_*$ is $O$(TeV), as some higher-dimensional theories suggest, ICECUBE detector may observe about $10^4 \sim 10^2$ black holes per year.
Collision of particles can produce black holes if their energy is higher than the Planck scale, $M_{pl}$. It was generally thought that the Planck scale is so large, $M_{pl} = G^{-1/2} = 1.2 \times 10^{19}$GeV, that our experiments could not create black holes.

However, if our world is higher-dimensional and the fundamental scale is TeV scale $\left[1, 2, 3\right]$, we can access black holes by real experiments. The production of black holes at the Large Hadron Collider (LHC) is considered $\left[4, 5, 6, 7, 8\right]$. Black holes also can be created by high-energy cosmic rays $\left[9, 10, 11\right]$. The detection of black holes enables us to investigate the physics of quantum gravity directly, and its detailed study must be done.

In this paper, we consider the detection of black holes at neutrino array like ICECUBE. Black holes are produced by the collision between high-energy neutrino cosmic rays and nuclei contained in the ice of ICECUBE detector. The huge amount of ice in ICECUBE enables us to observe many black holes if the fundamental scale is $O$(TeV). Once the black hole is produced, its evaporation leads to a very clean signal and it cannot escape the detection.

The Schwarzshild radius $R_S$ of a $(4 + n)$-dimensional black hole is $\left[12\right]$: 

$$R_S = \frac{1}{\sqrt{\pi} M_*} \left[ \frac{M_{BH}}{M_*} \left( \frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right)^{\frac{1}{n+1}} \right]. \quad (1)$$

Here $M_*$ is the fundamental scale of higher-dimensional world, and $M_{BH}$ is the mass of black holes. We only consider semiclassical black holes. This means we do not use the quantum gravity, but use the general relativity only. Then, the production cross section of black holes is estimated as

$$\sigma(M_{BH}) \sim \pi R_S^2 = \frac{1}{M_*} \left[ \frac{M_{BH}}{M_*} \left( \frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right) \right]^{\frac{2}{n+1}}. \quad (2)$$

This is valid if the mass of black hole $M_{BH}$ is much larger than the fundamental scale $M_*$. $\dagger$

We consider the collision of high-energy neutrinos off nuclei. Typically high-energy neutrinos are produced by the decay of charged pions produced by cosmic ray interactions with interstellar gas, primarily proton-proton interactions $\left[13\right]$. 

\begin{footnote}[1]{Although, there are some arguments which do not support this naive cross section $\left[13, 14\right]$.}
Figure 1: The expected high-energy neutrino cosmic ray flux.

Some models to reproduce the observed ultra high-energy cosmic rays also predicts ultra high-energy neutrinos as decay products of superheavy dark matters [16, 17]. Their flux is studied in [18].

The expected flux of high-energy neutrino was estimated in [15], and it is drawn in figure [1]. The black hole production cross section by neutrino-nucleus scattering is [11]

\[
\sigma(\nu N \rightarrow BH) = \sum_i \int_{(M_{BH}^{min})^2/s}^1 dx \sigma_i(xs)f_i(x, Q).
\]  

(3)

Here, we have used MRST2001 parton distribution function [19].

Let \( j(E) \) denotes the flux of high-energy neutrino cosmic ray and \( N \) denotes the number of nucleon in the detector. For \( n = 2 \) and \( M_\ast = 1 \text{TeV} \), the expected rate of black hole production \( R \) becomes:

\[
R = 4\pi n \int_{M_{BH}^{min}}^{E_{max}} \frac{d\sigma}{dE} j(E) dE \\
= 1.1N \times 10^{-42} \text{ (events/sec)} = 3.5N \times 10^{-35} \text{ (events/yr)}. 
\]  

(4a)

(4b)

Huge neutrino array like ICECUBE is the most suitable detector for black hole. ICECUBE uses the ice of South Pole and its volume is \( 1 \text{km}^3 \). It means \( N = 6 \times 10^{38} \).
Thus ICECUBE can produce about 21000 black holes per year if $M_* = 1$TeV and $n = 2$. The dependence of the number of produced black holes on the fundamental scale $M_*$ is shown in figure 2.

The main target of ICECUBE detector is high-energy neutrinos whose energy is about $O$(TeV). High energy neutrinos coming up through the earth will occasionally interact with ice or rock and create a muon; such a muon emits Cherenkov light when passing through the array, and it can be tracked by measuring the arrival times of these Cherenkov photons at the PMTs.

Once produced, black holes immediately decays into the SM particles. I do not enter its theory in detail. (see [6]). The important point is that the decay of black holes does not discriminate any particles: It decays into all particles with roughly equal probability. The Standard Model contains about 60 particles, with 6 charged leptons. Black holes with mass $O$(TeV) are mainly produced in ICECUBE detector, As we can infer from the high-energy neutrino flux (figure 1). Therefore we can observe the events of black holes from its decay into hard leptons with energy $O$(TeV).

To summarize, in this paper we consider the possible production of black holes
caused by the collision between high-energy neutrino cosmic rays and nuclei in a large experimental detector. We observe that ICECUBE detector should observe about $10^4 \sim 10^2$ black holes per year if the fundamental scale is $O(\text{TeV})$ and the number of extra dimension is $n = 2$. 

**Note added**

After we finished this paper, we learned from B.Harms that they studied the evaporation of black holes in the presence of extra dimension [24, 25, 26]. Their conclusion was that black holes in the presence of extra dimensions would likely not evaporate.

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\(^2\)Although there are severe cosmological constraints on the fundamental scale and the number of extra dimension [21, 22, 23]
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