Experimental search of bursts of very high energy gamma rays from primordial black holes

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Abstract. **The technical procedure of a search of bursts of very high energy gamma rays from evaporation of primordial black holes on air-shower array "Andyrchy" of Baksan Neutrino Observatory of Institute for Nuclear Research is described. The theoretical model used in the present work assumes that the chromosphere around the evaporating black hole does not form. For minimization of the cosmic ray background the method of multidimensional analysis of modelled as well as experimentally detected events is applied. The new upper limit on the concentration of evaporating primordial black holes in the local region of Galaxy is obtained. The comparison of the results of different experiments is given.**

Keywords: **primordial black holes, gamma rays, extensive air showers**

I. INTRODUCTION

Primordial black holes (PBHs) can be formed in the early Universe through the gravitational collapse of primeval cosmological density fluctuations. Therefore, the formation probability of PBHs and their observational manifestations depend significantly on how the primeval density fluctuations emerged and developed. Theoretical predictions of the PBH formation probability depend strongly on the adopted theory of gravitation and on the model of gravitational collapse. The evaporation of black holes [1], on which their experimental search is based, has not been completely studied either. Thus, PBH detection will provide valuable information about the early Universe and can be a unique test of the general theory of relativity, cosmology, and quantum gravity [2]. Direct searches for the bursts of gamma rays from the evaporations of PBHs have been carried out in several works during the last 15 years [3], [4], [5], [6], [7], [8].

The search for high energy gamma ray bursts on a shower array reduces to the search of space and time correlations (clusters) of registered extensive air showers (EAS). If time intervals used for the search are rather small, this search is performed in a horizontal reference frame. For each shower i having absolute registration time t_i and arrival angles $(\theta, \phi)_i$ the cluster of events $i, i + 1, i + 2, ..., i + n - 1$ is sought for, using a condition that arrival directions should differ less than α_r from the weighted mean direction. Thus, each cluster is characterized by multiplicity n, duration Δt, absolute time T, and arrival direction (θ, ϕ).

During such a search, experimentally obtained dependencies (e.g., cluster registration frequencies for each n) are compared to the ones expected from the background of accidental coincidences. If measured frequencies of cluster registration can be explained with distributions expected for accidental coincidences, one can obtain the constraints on a gamma ray burst frequency producing clusters with a given multiplicity (and thus having particular energy flux).

Evaporating PBHs which have almost reached their final evaporation state are a possible source of high energy gamma ray bursts. Since the calculated temporal and energy characteristics of such bursts depend on the theoretical evaporation model [9], the technique of an experimental search and the constraints imposed on the PBH number density in the local Universe are model dependent. PBHs can be sought for in experiments on arrays designed to detect EASs from cosmic rays with effective primary gamma-ray energies of 10 TeV or higher only within the assumption that the evaporation model without a chromosphere [10] is correct (in such a model, evaporated particles do not interact with each other). The duration of the high-energy GRBs predicted by chromospheric evaporation models is too short, much shorter than the dead time of EAS arrays, and other methods have to be applied for the PBHs search in this case [11].

It should be noted that the duration of the high energy GRBs is fairly short in the evaporation model without a chromosphere as well. Therefore, the effect of the array dead time on the burst detection probability should be taken into account when interpreting the experimental data from EAS arrays with a high threshold energy of the primary photons. Such analysis have been performed in our previous work [8].

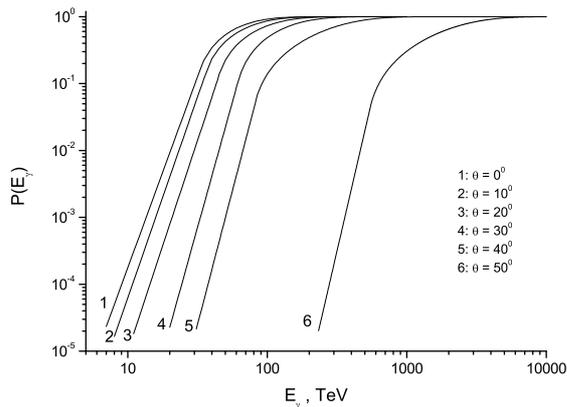In the experiments searching for gamma ray bursts

Fig. 1: Probabilities of EAS detection by the Andyrchy array versus primary gamma-ray photon energy for various zenith angles.
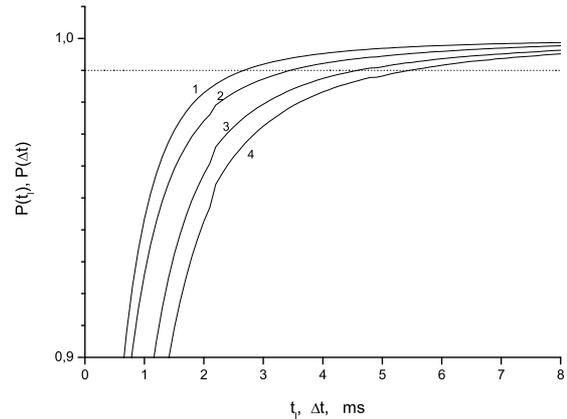

Fig. 2: Curves 2,3,4: probabilities $P(\Delta t)$ for the clusters with $n = 2, 3, 4$ to have the duration in the time interval between 0 and Δt, for zenith angle $\theta = 30°$. Curve 1 shows, for comparison, the probability $P(t_l)$ for photons to be evaporated during time interval between 0 and t_l.

produced by PBHs, the constraints on the PBH number density are usually obtained from a condition of absence of clusters with a given multiplicity and duration. Thus, an one-dimensional task is solved - each cluster (not depending on multiplicity) corresponds to the point with coordinate Δt on a time axis, and cluster duration distribution is analyzed then. However, for the cluster with n showers, the number of independent parameters (time intervals) is $n - 1$ and such a cluster can be represented as a point in space with $n - 1$ dimensions. One can expect that in those cases when time characteristics of PBH produced clusters are different from ones arising due to accidental coincidences, the increase the number of parameters can help to separate PBH events from background ones. In this case, due to background reduction, the constraint on the PBH number density obtained on a given array can be improved.

This paper is devoted to exploring this idea and improving the constraint on PBH number density obtained previously on Andyrchy array [8]. The detailed description of this experimental facility can be found in [12].

II. THE EXPERIMENT

The detection probabilities $P(E_\gamma, \theta)$ of the EASs generated by primary gamma-rays with energy E_γ falling on Andyrchy array at zenith angle θ were determined by simulating of electromagnetic cascades in the atmosphere and the detector (see Fig. 1) [13]. Total number of gamma rays which can be detected by the array (integral burst profile) is given by

$$N_\gamma(\theta, t_l) = \int\limits_0^\infty dE_\gamma P(E_\gamma, \theta) dN_\gamma/dE_\gamma. \qquad (1)$$

It depends on the time t_l left until the end of PBH evaporation.

In our previous work [8] we have defined the burst duration t_b for the given array as time until the end of PBH evaporation during which 99% of photons which can be detected by this array are evaporated. This interval was used as the interval for search of clusters from PBHs, i.e., $T_s = t_b$ (and shower clusters with $\Delta t \leq t_b$ were sought for).

Because the exact moment of PBH evaporation is unknown, the obtained experimental distributions for cluster lengths should be compared not with the burst profile, but with the calculated distribution of clusters with given multiplicity. Fig. 2 shows, for $\theta = 30°$, the calculated integral Δt distributions for clusters with $n = 2, 3, 4$ (curves 2,3 and 4). In the calculation, the dead time of the array had been taken into account. In
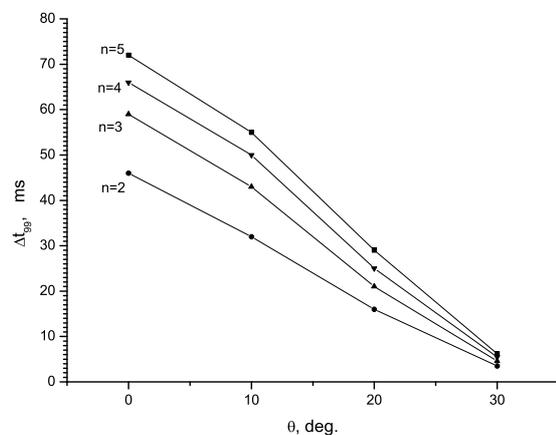

Fig. 3: The dependencies of $\Delta t_{99}(n)$ on zenith angle for cluster multiplicity $n = 2, 3, 4, 5$.
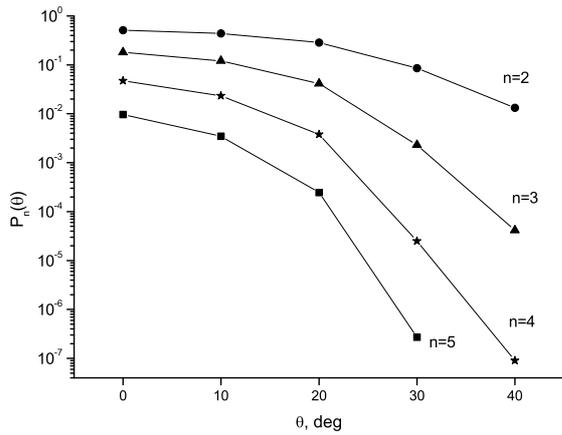
Fig. 4: Probabilities of registering the gamma ray clusters from the evaporating PBH, for the Andyrchy array, as a function of zenith angle.
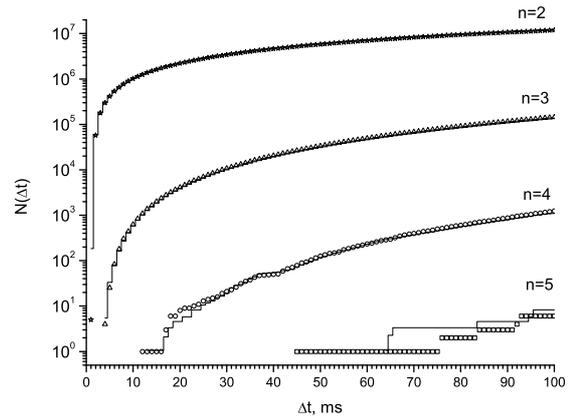

Fig. 5: Integral duration distributions for clusters with multiplicity $n = 2, 3, 4, 5$, detected by the array for the whole region of zenith angles. Points represent the experimental results; lines show the calculated distributions expected from the cosmic ray background.

the same Fig. 2 the burst profile (i.e., the probability to detect a gamma particle from evaporating PBH in the interval of time between $t = t_l$ and full evaporation) is also shown (curve 1). It is seen from this figure that 99%-level for clusters is achieved at durations much larger than t_b.

Correspondingly, the time interval for search T_s should be taken now as $T_s = \Delta t_{99}(n)$ which we define as the time interval in which 99% of clusters with multiplicity n fall. Fig. 3 shows the dependence of $\Delta t_{99}(n)$ on zenith angle for different n. One can note that time intervals $\Delta t_{99}(n)$ shown in this figure are larger than t_b (e.g., for $\theta = 0°$, $t_b = 40$ ms - see [8]). Because of this, maximum multiplicities for registered clusters also increase: for the case $T_s = t_b$, maximum multiplicities were 4,4,3,2 for zenith angles $\theta = 0°, 10°, 20°, 30°$; for the case $T_s = \Delta t_{99}(n)$ these values are 4,4,4,3 for the same corresponding values of zenith angles.

The probability to detect all showers hitting the array in a cluster with multiplicity n was calculated using Monte-Carlo method taking into account the dead time of the array (only those clusters were taken for which time interval between consecutive events was larger than a dead time of the array $t_d \sim 1$ ms), see Fig. 4.

The result of the search for shower clusters from evaporating PBHs is the set of duration distributions of clusters for different n and θ. Fig. 5 shows the experimentally measured distributions for a full observational time ≈ 1100 days, summarized over all zenith angles. For the search of clusters, we took $\alpha_r = 7.0°$ - such a region contains 90% of events from a point source. In the same figure, we show modeled distributions for clusters produced by accidental coincidences of regular EASs.

It is seen from Fig. 5 that, generally, experimentally registered cluster distributions can be explained as acci-
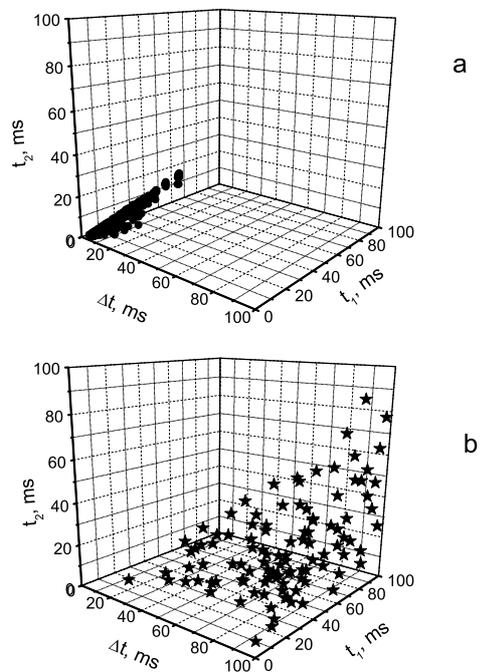
dental coincidences of EASs produced by cosmic rays.

Fig. 6: 3-dimensional distributions for clusters with $n = 4$, zenith angle is $\theta = 30°$. a) Events, expected from the evaporating PBH; b) events registered by the Andyrchy array.

III. MULTIDIMENSIONAL ANALYSIS

For clusters with n showers, as we have seen, number of independent parameters (time intervals) is $n - 1$, and such a cluster can be represented as a point in space with corresponding number of dimensions. As an example, Fig. 6 shows 3-dimensional distributions of clusters expected from PBHs (Fig. 6-a) and experimentally registered clusters (Fig. 6-b) for the case of $n = 4$ and $\theta = 30°$. It is seen that the measured clusters and the ones expected from PBHs occupy different regions in 3-dimensional space of time intervals.

In the subsequent analysis, the probabilities for the modeled PBH event to get into a $(n - 1)$-dimensional cell with size 1 ms in each dimension were calculated for each range of zenith angles θ and cluster multiplicities n. These probabilities were summarized for each cell which contained experimentally registered events. If this sum did not exceed 10^{-3}, we assumed, for PBH number density constraint calculation, that number of registered PBH events is zero (for particular values of n and range of zenith angles). We have obtained $3, 3, 3$, and 2 for maximum cluster multiplicities of registered events, for $\theta = 0°, 10°, 20°, 30°$, correspondingly.

IV. RESULTS AND CONCLUSIONS

The constraints on the number density of evaporating PBHs in the local region of Galaxy were obtained using technique described in work [7]. Let a PBH be located at distance r from the array and be seen from it at zenith angle θ. The mean number of gamma-ray photons detected by the array over the burst duration is then

$$\bar{n}(\theta) = \frac{\epsilon N(t_b(\theta)) S(\theta)}{4\pi r^2} \ , \qquad (2)$$

where $S(\theta)$ is the array area and $\epsilon = 0.9$ is the fraction of the events from a point source that fell into an angular cell with a size of α_r. The number of bursts detected over the total observation time T can be represented as

$$N = \rho_{\text{pbh}} T V_{\text{eff}} \ , \qquad (3)$$

with effective volume of the space surveyed by the array

$$V_{\text{eff}} = \int d\Omega \int_0^\infty dr r^2 F(n(\theta), \bar{n}(\theta)). \qquad (4)$$

Here, $F(n, \bar{n})$ is the detection probability of a cluster of n or more EASs with the mean value of $\bar{n}$. It can be expressed through the Poisson probabilities for having i showers (and $i = n, n + 1, ...$) with average value of $\bar{n}$ and probabilities $P(i(\theta), t_d)$ [see Fig. 4] to detect all i showers having a dead time for one event t_d:

$$F(n, \bar{n}) = \sum_{i=n}^\infty P(i(\theta), t_d) \cdot \frac{e^{-\bar{n}} \bar{n}^i}{i!}. \qquad (5)$$

For the calculation of the effective volume, we take $n(\theta) = n'(\theta) + 1$ (this means that the distributions of the detected clusters in multiplicity can be explained by the background of accidental coincidences; $n'(\theta)$ is

the maximal multiplicity of the detected cluster obtained using multidimensional analysis).

Numerically, we obtain $V_{\text{eff}} = 2.8 \times 10^{-9} \text{ pc}^3$. If the evaporating PBHs are distributed uniformly in the local region of the Galaxy, then the upper limit ρ_{lim} on the number density of evaporating PBHs at the 99% confidence level can be calculated from the formula

$$\rho_{\text{lim}} = \frac{4.6}{V_{\text{eff}} \cdot T}. \qquad (6)$$

As a final result, we obtain $\rho_{\text{lim}} = 5.4 \times 10^8 \text{ pc}^{-3}\text{yr}^{-1}$. This is slightly better than the result obtained in our previous work [8] with the same set of data but without using multidimensional analysis ($\rho_{\text{lim}} = 8.2 \times 10^8 \text{ pc}^{-3}\text{yr}^{-1}$).

The detailed comparison of the results of different experiments searching for evaporating PBHs can be found in [8]. This work slightly improves the PBH number density constraint of [8], but it is still significantly weaker than the best (to date) limit obtained in the experiment on the Whipple Cherenkov telescope [7] ($\rho_{\text{lim}} = 1.08 \times 10^6 \text{ pc}^{-3}\text{yr}^{-1}$). However, it should be noted that the effective gamma-ray energy in our experiment is two orders of magnitude higher than that of the Whipple telescope. Thus, our upper limit pertains not to black holes in general, but to black holes with certain properties (those emitting 100-TeV gamma-rays at the end of their evaporation during bursts lasting ~ 10 ms).

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