РОССИЙСКАЯ АКАДЕМИЯ НАУК

ПИСЬМА
В ЖУРНАЛ ЭКСПЕРИМЕНТАЛЬНОЙ
И ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

ОСНОВАН В 1965 ГОДУ
ВЫХОДИТ 24 РАЗА В ГОД

ТОМ 72, ВЫПУСК 3
10 АВГУСТА, 2000

Pis'ma v ZhETF, vol.72, iss.3, pp.145 - 149

POSSIBLE SIGNATURE OF LOW SCALE GRAVITY IN ULTRA HIGH ENERGY COSMIC RAYS

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Submitted 6 June 2000

Resubmitted 29 June 2000

We show that the existence of low scale gravity at TeV scale could lead to a direct production of photons with energy above 10^{22} eV due to annihilation of ultra high energy neutrinos on relic massive neutrinos of the galactic halo. Air showers initialized in the terrestrial atmosphere by these ultra energetic photons could be collected in near future by the new generation of cosmic rays experiments.

PACS: 04.80.Cc, 98.70.-f

Recently it was proposed [1] that the space is $4+n$ dimensional, with the Standard Model particles living on a brane. While the weakly, electromagnetically, and strongly interacting particles are confined to the brane in 4 dimensions, gravity can propagate also in extra n dimensions. This approach allows to avoid the gauge hierarchy problem by introducing a single fundamental mass scale (string scale) M_s of the order of TeV. The usual Planck scale $M_{Pl} = 1/\sqrt{G_N} \simeq 1.22 \cdot 10^{19}$ GeV is related to the new mass scale M_s by Gauss's law:

$$M_{Pl}^2 \sim R^n M_s^{n+2} \tag{1}$$

where G_N is the Newton constant, R is the size of extra dimensions. It follows from (1) that

$$R \sim 2 \cdot 10^{-17} \left(\frac{\text{TeV}}{M_s}\right) \left(\frac{M_{Pl}}{M_s}\right)^{2/n} \text{cm}, \tag{2}$$

gives at $n = 1$ too large value, which is clearly excluded by present gravitation experiments. On the other hand $n \geq 2$ gives the value $R \lesssim 0.25$ cm, which is below the

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present experimental limit $\sim 1\,\text{cm}$ but can be tested for the case $n = 2$ in gravitational experiments in near future.

It can be shown that the graviton including its excitations in the extra dimensions, so-called Kaluza - Klein (KK) graviton emission, interacts with the Standard Model particles on the brane with an effective amplitude $\sim M_s^{-1}$ instead of M_{Pl}^{-1}. Indeed, the graviton coupling to the Standard Model particle $\sim M_{Pl}^{-1}$, the rate [2] of the graviton interaction $r \sim (M_{Pl}^{-1})^2 N$, where N is a multiplicity of KK states. Since this factor is $\sim (\sqrt{S}R)^n$, where $\sqrt{S}$ is the c.m. energy, then substituting R from (2) we get $r \sim M_s^{-2}$. Thus the graviton interaction becomes comparable in strength with weak interaction at TeV scale.

This leads to the varieties of new signatures in particle physics, astrophysics and cosmology (see e.g. [2 - 6]) which have already been tested in experiments or can be tested in near future.

In this article we consider the possible signature of the low scale gravity in ultra high energy cosmic rays.

The detection [7, 8] of cosmic rays with energy above Greisen - Zatsepin - Kuzmin (GZK) cut-off of $\sim 5 \cdot 10^{19}\,\text{eV}$ presents a serious problem for interpretation. The origin of GZK cut-off [9] is due to resonant photoproduction of pions by protons on cosmic microwave background radiation which leads to a significant degradation of proton energy (about 20% for 6 Mpc) during its propagation in the Universe. Of course, proton energy does not change by many orders of magnitude if high energy protons come from the distances $< 50 - 100\,\text{Mpc}$. However, no nearby sources like active galactic nuclei have been found up to now in the arrival direction.

It is difficult also to relate the observed ultra high energy events with the other particles. For example in the case of ultra high energy photons due to interaction with cosmic background radiation ($\gamma + \gamma^* \longrightarrow e^+ + e^-$) the photon free mean path should be significantly less than 100 Mpc. A scenario based on direct cosmic neutrinos able to reach the Earth from cosmological distances can not reproduce the observed signatures of ultra high energy air showers occurred high in the atmosphere.

Different possibilities were considered (see e.g. [10] and references therein) in order to solve this puzzle. In particular it was proposed [11 - 13] that ultra high energy neutrinos reaching the Earth from cosmological distances interact with a halo of relic light neutrinos in the Galaxy, producing due to Z, $W^{\pm}$ boson exchange secondaries inside the galactic halo. Photons from π^0 decays and nucleons can easily propagate to the Earth and be the source of the observed ultra high energy air showers. Crucial elements of models [11 - 13] are: the existence of neutrino mass in the range $0.1 - 10\,\text{eV}$ and significant clustering of relic neutrinos in the halo up to $10^5 n_\nu$, where n_ν is the cosmological neutrino number density ($n_\nu \sim 100\,\text{cm}^{-3}$). Also the existence of ultra high energy ($> 10^{21} - 10^{23}\,\text{eV}$) neutrino flux is necessary in order to produce multiple secondaries with energies above GZK cut-off.

However if the graviton interaction comparable in strength with weak interaction at TeV scale exists then photons can be produced directly in a reaction

$$\nu + \bar{\nu} \longrightarrow g \longrightarrow \gamma + \gamma \tag{3}$$

due to virtual graviton exchange (Fig.1). In Standard Model process (3) occurs via loop diagram and therefore is severely suppressed.

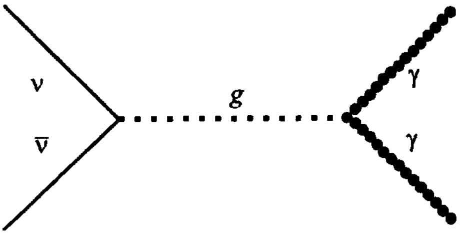

Fig.1. Neutrino annihilation into two photons

At high energies the cross section for the process (3) can be obtained immediately from that for the process $e^+e^- \longrightarrow \gamma\gamma$ including graviton exchange (see for example [3]) by substituting $e = 0$. Then

$$\frac{d\sigma}{dz} = \frac{\pi}{16}\frac{S^3}{M_s^8}F^2(1 - z^4) \tag{4}$$

where $\sqrt{S}$ is c.m.s. energy, $z = |\cos\theta|$ is the polar angle of the outgoing photon. The factor F depends on the number of extra dimensions:

$$F = \begin{cases} \log(M_s^2/S), & n = 2 \\ 2/(n-2), & n > 2 \end{cases},$$

at $\sqrt{S} << M_s$. In Eq.(4) it is also taken into account that primary beam of neutrinos is polarized.

Integrating (4) over the polar angle and including a symmetry factor for two γ we get

$$\sigma = \frac{\pi}{20}\frac{S^3}{M_s^8}F^2 \approx 7\cdot 10^{-35}F^2\left(\frac{\sqrt{S}}{\mathrm{TeV}}\right)^6\left(\frac{\mathrm{TeV}}{M_s}\right)^8 \mathrm{cm}^2. \tag{5}$$

One can see from (4) that at TeV energies the rate of the reaction (3) is comparable with the rate of weak processes [11].

Assuming $M_s \sim \sqrt{S} \sim$ TeV we find for example for $n = 3$ the following probability for the interaction of ultra high energy neutrinos inside the galactic halo: $P \approx \sigma n_G L_G \sim$ $\sim 10^{-3}$, where $L_G \sim 100$ Kpc is the size of the galactic neutrino halo, $n_G \sim 10^5 n_\nu$ is the neutrino number density in the galactic halo. This probability is significantly greater than the probability of ultra high energy neutrino interaction in terrestrial atmosphere [14].

Let us note that nearby galaxies also can be sources of additional ultra high energy photons due to neutrino interaction with relic neutrinos of galactic halos [12, 13].

TeV range in c.m.s. corresponds to the energy of extragalactic neutrino flux $E \approx$ $\approx 10^{22} - 10^{23}$ eV since:

$$E \approx \frac{S}{2m} \approx 5\cdot 10^{22}\left(\frac{\sqrt{S}}{\mathrm{TeV}}\right)^2\left(\frac{10\,\mathrm{eV}}{m}\right)\mathrm{eV} \tag{6}$$

where m is neutrino mass.

Photon distribution in reaction (3) in laboratory system is given by

$$\frac{d\sigma}{d(\omega/E)} = 8\pi F^2\frac{m^3E^3}{M_s^8}\frac{\omega}{E}\left(1 - \frac{\omega}{E}\right)\left[\left(1 - \frac{\omega}{E}\right)^2 + \left(\frac{\omega}{E}\right)^2\right] \tag{7}$$

where $\omega >> m$ is photon energy. This distribution is shown in Fig.2. It follows from (7) that photons are produced in the reaction (3) mainly within the energy range $0.2E \lesssim \omega \lesssim 0.8E$ with an average energy $\approx E/2$.

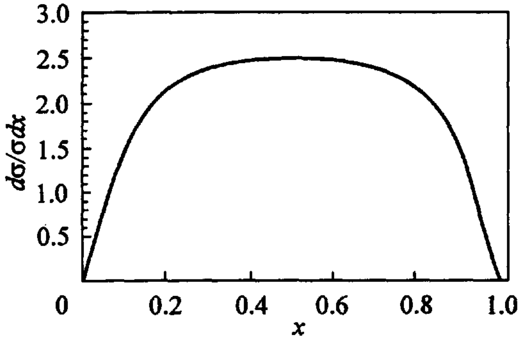

Fig.2. Energy distribution of photons ($x = \omega/E$)

Therefore existence of low scale gravity at TeV scale or above could lead to the direct production of photons with energy $\omega > 10^{22}$ eV (at these energies the mean interaction length for pair production for photons in the radio background is $\approx 1 - 10$ Mpc [15]). Such photons can be hardly produced in standard weak interaction processes because in last ones photons appear as a result of cascade processes significantly reducing photon energy in comparison with the initial neutrino energy. For example, as it was shown in [11] final energy of photons produced due to cascade processes can be by 10-100 times less than the energy of the initial neutrino flux.

Of course photons with the energy $\sim 10^{23}$ eV could be produced in cascade processes induced by neutrinos of the energy $> 10^{24} - 10^{25}$ eV but from the observations of cosmic rays we know that cosmic ray fluxes decrease with the energy as E^{-3}, and therefore the probability of such events is significantly suppressed.

Fluxes of ultra high energy cosmic rays at the Earth are very small $\Phi \sim \sim 0.03\,\mathrm{km}^{-2}\cdot\mathrm{sr}^{-1}\cdot\mathrm{yr}^{-1}$. Until now only about 60 events were collected with energies above GZK cut-off. However in near future improved Fly's Eye ($7000\,\mathrm{km}^2\cdot\mathrm{sr}$) [8] will allow to detect about 20 events/yr. It seems possible that such detector could collect rare ultra energetic photons ($\omega > 10^{22}$ eV). The detection of such events could be an indication that these ultra high energy photons were produced in $\nu\,\bar{\nu}$ annihilation in the galactic halo due to effects of low scale gravity at TeV scale. Neutrino-gamma interaction in low scale gravity also was considered in [16].

Authors thank D.Fargion for interesting discussions on ultra high energy cosmic rays. One of us (RVK) is grateful to Physics Department of New York University for warm hospitality. The work of SGR was partially performed in the framework of Section "Cosmoparticle physics" of Russian State Scientific Technological Program "Astronomy. Fundamental Space Research", with the support of Cosmion-ETHZ and Epcos-AMS collaborations.

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