Cosmic rays from heavy particle decays

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Introduction

• Ultra-high-energy cosmic rays (UHECR) are a cosmic rays with an energy greater than 10^{18} eV.

• Extreme-energy cosmic rays (EECR) are an UHECR with energy exceeding 10^{20} eV.

• The Greisen–Zatsepin–Kuzmin limit (GZK limit or GZK cutoff) is a theoretical upper limit on the energy of cosmic ray protons traveling from other galaxies through the intergalactic medium to our galaxy. The limit is 5×10^{19} eV.

Decays through virtual Black Holes

- Usually dark matter particles are supposed to be absolutely stable.
- Zeldovich mechanism (1976): decay of any presumably stable particles through creation and evaporation of virtual black holes.
- The rate of the proton decay calculated in the canonical gravity, with the energy scale equal to M_{Pl}, is extremely tiny and the corresponding life-time is by far longer than the universe age.
- However, the smaller scale of gravity and huge mass of DM particles both lead to a strong amplification of the Zeldovich effect.

Superheavy DM particles with $M_X \sim 10^{12}$ GeV may decay through the virtual BH formation with life-time a few orders of magnitude longer than the universe age.

Decays through virtual black holes

We consider the process of transformation of two quarks inside proton into antiquark and antilepton through a virtual black hole $q+q \to (BH) \to \bar{q} + \bar{l}$. Y. B. Zeldovich, "A New Type of Radioactive Decay: Gravitational Annihilation of Baryons," Phys. Lett. A 59 (1976), 254.

$$\dot{n}/n = n\sigma_{BH} = \sigma_{BH}|\psi(0)|^2,$$

$$\sigma_{BH} \sim m_p^2/M_{Pl}^4. \tag{1}$$

$$\tau_p = \frac{n}{\dot{n}} = \frac{M_{Pl}^4}{m_p^5}. \tag{2}$$

With the Planck mass, $M_{Pl} = 1.22 \times 10^{19}$ GeV, $n \sim m_p^3$, we restore the result of $\tau_p \sim 10^{45}$ years. For X-particles with mass $M_X = 10^6$ GeV their life-time is $\tau_X^{(6)} \sim 10^{14}$ years. For heavy X-particles with mass $M_X \sim 10^{12}$ GeV $\tau_X^{(12)} \sim 1.5 \times 10^{-8}$ sec.

Diagram describing gravitationally induced proton decay

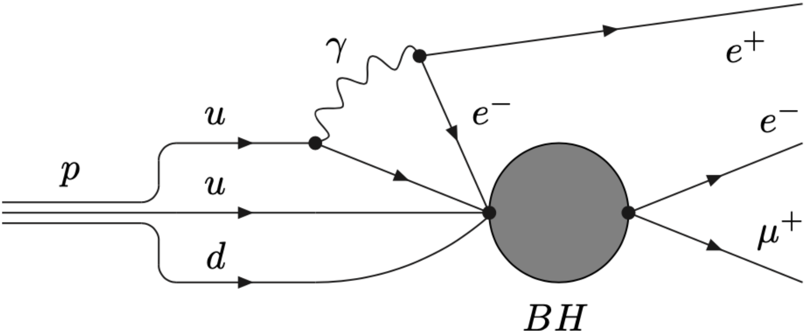

Figure 1: The diagram describing the decay of a proton into a quark-antiquark and a muon is similar to the diagram of the decay into an electron-positron pair, which is shown in the figure. Figure borrowed from article C.Bambi, A.D.Dolgov and K.Freese: https://arxiv.org/abs/hep-ph/0606321

Heavy proton type dark matter

We assume that heavy DM particles with mass $M_X \sim 10^{12}$ GeV consists of three heavy quarks, q_*, with comparable mass. The life-time of X-particles:

$$\tau_X \approx 10^{-24}\mathrm{s} \cdot \frac{2^{11}\pi^{13}}{3\alpha_*^2}\left(\frac{\mathrm{GeV}}{\mathrm{M_X}}\right)\left(\frac{\mathrm{M_*}}{\Lambda_*}\right)^6\left(\frac{\mathrm{M_*}}{\mathrm{M_X}}\right)^{4+10/(d+1)}\left(\ln\frac{\mathrm{M_*}}{\mathrm{m_{q_*}}}\right)^{-2}\mathrm{I(d)}^{-1},$$

where we took $1/\mathrm{GeV} = (2/3) \times 10^{-24}$ s and

$$I(d) = \int_0^{1/2} dx x^2 (1-2x)^{1+\frac{5}{d+1}}, \quad I(7) \approx 0.0057.$$

Now all the parameters, except for Λ_*, are fixed:

- $M_* = 3 \times 10^{17}$ GeV, $M_X = 10^{12}$ GeV, $m_{q_*} \sim M_X$, and $\alpha_* = 1/50$

The life-time of X-particles can be estimated as:

$$\tau_X \approx 7 \times 10^{12}\ \mathrm{years}\left(10^{15}\,\mathrm{GeV}/\Lambda_*\right)^6.$$

A slight variation of Λ_* near 10^{15} GeV allows to fix the life-time of DM particles in the interesting range. They would be stable enough to behave as the cosmological DM and their decay could make considerable contribution into cosmic rays at ultra high energies.

Conclusion

• It is argued that in the model of high dimensional gravity modification there may exist superheavy dark matter particles stable with respect to the conventional particle interactions. However, such DM particles should decay though the virtual black hole formation.

• With a proper choice of the parameters the life-time of such quasi-stable particles may be larger than the universe age by 3-4 orders of magnitude.

• This permits them to make an essential contribution to the flux of UHECR and, in particular, beyond the energies of GZK cutoff.

• The considered mechanism may lead to efficient creation of cosmic ray neutrinos of very high energies observed at IceCube and Baikal detectors.