New Hadrons as Ultra-High Energy Cosmic Rays

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Abstract

New hadrons with mass 1.5–3 GeV can be responsible for ultra-high energy cosmic rays (UHECR) at the highest energies $E > 10^{20}$ eV. For the first time we constructed a self-consistent model which includes the production of such hadrons in proton collisions with infrared/optical photons in astrophysical sources. This production mechanism, in contrast to proton-proton collisions, requires the acceleration of protons only to energies $E \leq 10^{21}$ eV. The diffuse gamma-ray and neutrino fluxes in this model obey all existing experimental limits. We predict large UHE neutrino fluxes well above the sensitivity of the next generation of high-energy neutrino experiments. As an example we study hadrons containing a light bottom squark. Such models can be tested by accelerator experiments, UHECR observatories and neutrino telescopes.

1. Introduction

All relevant experiments have detected UHECR with energies $E > 10^{20}$ eV. Because there are no nearby sources behind such events they can not be protons, which quickly lose all energy within 50 Mpc due to pion production on cosmic microwave background photons (the so called Greisen-Zatsepin-Kuzmin (GZK) cutoff [3]). Moreover, if the small scale clusters found by the AGASA experiment are due to point like sources, then the total number of sources of all UHECR with $E > 4 \times 10^{19}$ eV is so small that the distance to the nearest of them is about 100 Mpc [4]. In that case the GZK cutoff will exponentially sharp at $E < 10^{20}$ eV and even the HiRes data are inconsistent with the model of protons coming from uniformly distributed sources.

Here we consider the possibility that UHECR with energies above the GZK cutoff are due to new hadrons S. The main idea of this kind of models is that for $M_S > 1.5$ GeV hadrons with $E \sim 10^{20}$ eV will able to propagate from much

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larger distances than protons, $D \gg 50$ Mpc, both due to a shift of the cutoff to higher energies and due to a reduction of the hadron-photon cross section (see, e.g. Fig. 3 in [4]). From the other side, the observed air showers are consistent with light hadrons with $M_S < 3$ GeV [1].

From these requirements, we derive general conditions on the interactions of new UHE primaries. We study in detail the production of new hadrons and show that it is accompanied by an unavoidably high neutrino flux. We show that high energy neutrino experiments will be able to test such models in the near future. As specific examples, we investigate the case of a bottom squark containing hadron which we call "shadrons" from now on. Such light bottom squark was introduced to explain the anomaly in the bottom quark production cross section at Tevatron [2].

2. Production of new hadrons in astrophysical objects

New hadrons can be produced in astrophysical objects in proton collisions with background protons or photons. Simultaneously a significant amount of pions is produced in these reactions. Pions decay in the source, producing secondary gamma-rays and neutrinos. Neutrinos freely escape from the source, while gamma-rays cascade down to the MeV-GeV energies, at which astrophysical sources are transparent to them. As result, the diffuse gamma-ray flux at MeV-GeV energies measured by EGRET experiment together with bounds on high energy neutrino flux from AGASA, the Fly's Eye, the RICE, and the Goldstone experiment (GLUE) put strong restrictions on new particle production mechanism by new protons, see Fig. 1..

The two essential quantities which play the key role in this production mechanism are the ratio of the shadron production cross section to total one, $\sigma_S/\sigma_{\rm tot}$, and the energy fraction transfered to new hadrons, E_S/E_p. In proton-proton collisions the typical center of mass energy is extremely high, $E_{\rm cm} = \sqrt{2E_pM_p} \sim 300$ TeV. This means that the multiplicity is also high $M \sim 1000$ and the energy transfered to new particles will be as low as $E_S/E_p \sim 10^{-3}$. Then one needs to accelerate protons up to 10^{23} eV to produce 10^{20} eV shadrons. Although the production cross section can be relatively large, the total energy transfered to secondary photons and neutrino is so high that it will violate existing constraints. We conclude that proton-proton collisions in astrophysical accelerator cannot produce high enough fluxes of new primaries without contradicting existing measurements of photon and neutrino fluxes.

By contrast, we find for a light shadron with mass ≤ 3 GeV and the astrophysically more realistic case of UHE proton collisions on optical/infrared background photons no contradiction with existing limits. The main reason is that center-of-mass energy is now small $E_{\rm cm} = \sqrt{2E_pE_\gamma} \sim 10$ GeV, and new hadrons can be produced near threshold. The transfered energy fraction can be as high

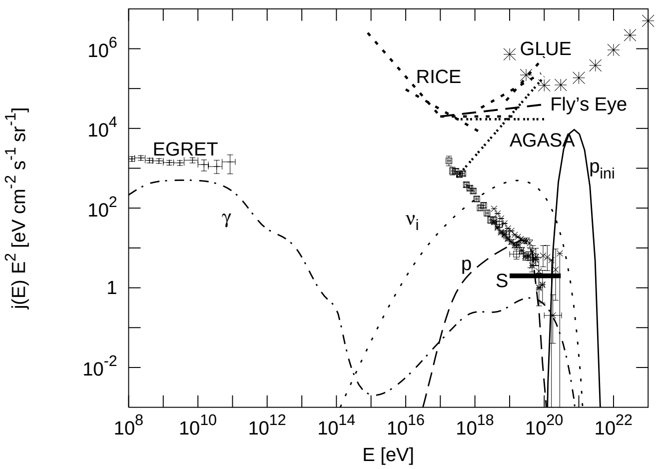

Fig. 1. Flux of new hadrons S (thick solid line) and protons (dashed line) together with cosmic ray data from AGASA and HiRes. Protons accelerated to the energy $E = 10^{21}$ eV (line $p_{\rm ini}$) produce secondary photons (dashed-dotted line) and neutrinos (dotted line). Photon flux constraint from EGRET and upper limits on the diffuse neutrino fluxes from AGASA, the Fly's Eye, the RICE, and the Goldstone experiment (GLUE) as indicated. See all related references in [4]

as 10-50%. Also, the required initial proton energy is not too extreme, $E \leq 10^{21}$ eV (see Fig. 1.), which is compatible with existing acceleration mechanisms. The only essential condition for the sources is that they should be optically thick for protons in order to produce these new hadrons. (This condition is similar for all models with new particles produced by protons). The numerical calculations were done with the code [5]. In Fig. 1. we show both initial proton and secondary fluxes of neutrinos, photons, protons and shadrons. Shadrons explain UHECR events with $E > 10^{20}$ eV, the other fluxes obey all existing constraints.

3. Secondary neutrino flux

One of the important features of the proposed model, and any model in which the production cross section $\sigma_{p\gamma\to S}$ of a new particle S is much smaller than the total proton-photon cross section $\sigma_{p\gamma}$, is the high flux of secondary high-energy neutrinos. This neutrino flux is connected via the relation $F_{\rm CR}\sigma_{p\gamma}/\sigma_{p\gamma\to S}$ to the maximal contribution of S particles to the cosmic ray flux, $F_{\rm CR} \approx 1/E_{20}^2$ eV/(cm^2 s sr). As shown in Fig.2. it can be detected by future UHECR experiments like the Pierre Auger Observatory, the Telescope Array, EUSO and OWL. Alternatively, neutrino fluxes can be detected by triggering onto the radio pulses from neutrino-induced air showers or by the acoustic detection. There are plans to construct telescopes to detect fluorescence/Čerenkov light from near-horizontal showers pro-

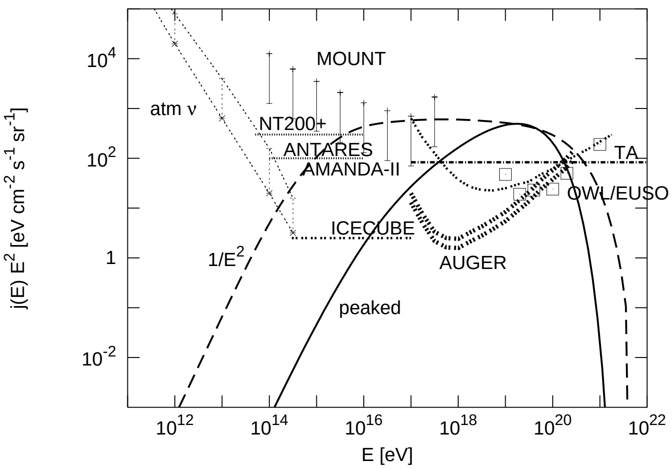

Fig. 2. The neutrino flux for one flavor in the model used in Fig. 1. and sensitivities of the currently being constructed Auger project to electron/muon and tau-neutrinos, and the planned projects telescope array (TA) (dashed-dotted line), MOUNT, and, OWL/EUSO, NT200+ (Baikal), ANTARES, AMANDA-II and ICECUBE, as indicated. Also shown (dashed line) is an extreme scenario with initial proton spectrum $1/E^2$, leading to a neutrino flux extending to relatively low energies where Baikal, ANTARES and AMANDA-II will be sensitive, and the atmospheric neutrino flux for comparison. See all related references in [4]

duced in mountain targets by neutrinos at intermediate energies. Moreover, if the sources are optically thick for protons, the neutrino flux can be significant both at high energies and down to energies 10^{16-17} eV, depending on the pion-production threshold on optical/infrared photons, see Fig.2. and [6]. Therefore, one may observe neutrinos from the same sources both by future UHECR experiments and by neutrino telescopes like AMANDA, ICECUBE, GVD, ANTARES, NESTOR or NEMO.

4. References

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