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NEUTRAL PARTICLES OF EXTREMELY HIGH ENERGIES: A CLUE TO THE ENIGMA OF CYG X-3?

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НЕЙТРАЛЬНЫЕ ЧАСТИЦЫ ПРЕДЕЛЬНО ВЫСОКИХ ЭНЕРГИЙ - КЛЮЧ К ЗАГАДКЕ Cyg X-3

Предлагается гипотеза, согласно которой предполагается, что аномальные ТэВ-ные мюонные и адронные события, наблюдаемые в направлении Cyg X-3, инициированы первичными частицами (гамма-квантами и/или нейтронами) предельно высоких энергий. Реализация этой гипотезы оказывается возможной лишь в предположении существования массивных частиц с $M_x \sim I$ ТэВ и временем жизни $\tau_x \sim I0^{-6}$ с, которые должны рождаться при взаимодействиях первичных частиц в атмосфере, и далее должны эффективно рождаться в ходе развития ливня в атмосфере, приводя при распаде к образованию ТэВ-ных мюонов и адронов под большими углами.

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1. Introduction

The galactic X-ray binary Cyg X-3 continues to surprise physicists and astrophysicists by its outstanding features. Many of the reports on this object are so unusual and contradictory that the reliability of the results is put under suspect [1]. At the same time, further attempts to look for a reasonable interpretation of existing data are required.

Most disturbing are the data which rise hard questions concerning the nature of the primaries and their interaction mechanisms. The problems put forward by these data may be subdivided into two groups. The first group relates to the so-called Kiel effect consisting in an unexpectedly high content of muons in showers detected from the direction of Cyg X-3 [2]. A similar effect has been reported later by the CYGNUS collaboration for showers from the direction of Her X-1 [3]. To interpret these data, Halzen and coworkers [4,5] supposed that the meson photoproduction cross section strongly increases starting from the photon energies E_γ>10TeV. However, this assumption only is insufficient, since even in case of the photomeson production cross section increasing up to as much as the geometrical cross section of the air nuclei (~270mb), it would still remain ~~twice~~ as smaller as the e^+e^- pair production cross section [6,7]. Therefore, the e^+e^- pairs produced already at the first collision of photons with the atmosphere, will lead to degradation of the cascade gamma-rays below energies $E_\gamma \sim 1TeV$, where the speculations on the high photomeson production cross section are limited by accelerator data. The detailed Monte Carlo calculations show that even radical assumptions on the pion photoproduction cross section at $E_\gamma > 10TeV$ cannot provide the high content of muons in the photon-induced showers (see, e.g. [6,7]). The nature of the Kiel effect (which, of course, needs a more reliable confirmation by the particle arrays with large muon detectors) still remains an open question.

More questions arise for the data of deep underground muon detectors. For the first time the observations of the excess of muon events from the direction of Cyg X-3 modulated with the orbital period $P_0 = 4.8h$ have been independently reported by two groups, SOUDAN-1 [8,9] and NUSEX [10]. The reports on detection of muon events correlated with the radio bursts from Cyg X-3 have been made by the IMB [11] and SOUDAN-1 [12] groups. At the same time, several detectors, in particular KAMIOKA, BAKSAN, and FREJUS, operating under approximately the same conditions as SOUDAN-1 and NUSEX, did not see any positive signal from Cyg X-3 (see, e.g., [1]). Nevertheless, recently both the SOUDAN-1 and the NUSEX groups have confirmed the detection of the time-modulated signals from Cyg X-3 using long-term observations [13,14]. Recently multihadron events from Cyg X-3 detected by the PION installation were also reported [15,16].

These data require radical assumptions on the nature of primaries (called cygnets) emitted by Cyg X-3. These particles should be light, neutral, and long-lived. They should have

large production cross section, and a relatively large cross section of interaction with matter (see, e.g., [17.,18]). The properties of cygnets that follow readily from the experimental data (the observed fluxes and the temporal structure of the signal, the distance to Cyg X-3, etc.) rise a question: Why these particles have not yet been revealed on accelerators, in particular, in the beam dump experiments [17]? Thus, the situation seems to be close to the "no go theorem" [1].

In this paper we propose a principally new approach to the problem, assuming that the deep underground muon events from Cyg X-3 are induced by primary particles of extremely high energies, $E_0 \geq 1EeV$ (hereafter, EHE), that efficiently interact with the atmosphere, whereas in all previous models the primary particles of much lower energies ($E_0 < 1PeV$) are supposed. At the first glance, the suggestion of the primary particles with $E_0 \geq 1EeV$ seems obviously contradicting to the shower fluxes measured in this energy range. However, this contradiction can be overcome in principle, if one takes into account the wide angular spread of the observed anomalous events around the direction of Cyg X-3.

This approach makes the problem under consideration free of many difficulties that exist in the previous models. First of all, now there is no need to assume any new, exotic primary from Cyg X-3. At energies $E_0 \geq 1EeV$ the primary particles from Cyg X-3 may be the gamma-rays as well as the neutrons. In this paper we qualitatively explore this possibility.

2. The Model-Independent Restrictions to the Properties of the Primaries from Cyg X-3

Using a relatively small set of observational data, one may obtain model-independent hard constraints to the properties of the primaries from Cyg X-3. These restrictions are quite familiar and were discussed in many papers (see, e.g. Ref.[1]).

a) The primaries should be neutral, otherwise the particles would be deflected from the Cyg X-3 direction when propagating in the interstellar magnetic fields. Moreover, in order to hold the orbital phase of the binary with the accuracy $\Delta t<0.1P_0\sim2\cdot10^3$s during the flight time $t_f\sim10^{12}$s, the deflection of the primaries should not exceed $\Delta\theta\sim(2\Delta t/t_f)^{1/2}\sim10^{-4}$rad

b) Since it seems impossible that the spectrum of the primaries is monoenergetic, the requirement of holding the orbital phase results in the restriction to the typical value of the Lorentz factors of the primaries:

$$\gamma_0 \equiv E_0/M_0c^2 \geq \gamma_{min} = (R/2c\Delta t)^{1\backslash 2} \sim 10^4 , \qquad (1)$$

where M_0 is the mass of primary particle, and R~10kpc is the distance to Cyg X-3.

c) Assuming some reasonable energy for the primaries, the upper limit to the mass M_0 is obtained:

$$M_0 \leq 10\left(\frac{E_0}{100\ \mathrm{TeV}}\right)\ \mathrm{GeV}/c^2 \qquad (2)$$

d) The primaries should be almost stable, namely, their lifetime should be:

$$\tau_0 \geq (t_f/\gamma_0)\sim10^8(\gamma_0/10^4)^{-1}\ \mathrm{s}\ . \qquad (3)$$

The assumption that the anomalous deep underground muon events are due to the showers initiated by the primaries in the atmosphere, brings to significant constraint to the energy E_0. According to the data of atmosperic Cherenkov telescopes and extensive air shower (EAS) arrays, the integral spectrum of the shower-initiating particles from the direction of Cyg X-3 is approximated as $I(\geq E)=4\cdot10^{-11}(E/\mathrm{TeV})^{-1}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ [18]. Then, comparing this with the fluxes of underground muon events, one obtains:

$$E_0 \leq 20\left[\frac{I_\mu(\geq E_\mu)}{2\cdot10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}}\right]^{-1}\kappa(E_0,\geq E_\mu)\ \mathrm{TeV}\ , \qquad (4)$$

where $\kappa\equiv\kappa(E_0,\geq E_\mu)$ is the number of muons with energies $\geq E_\mu$ produced by the primary particle with energy E_0. Then for the muon flux observed by the NUSEX from the direction of Cyg X-3, $I_\mu\simeq10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [14], even for efficiency $\kappa\sim1$ one obtains $E_0<20$TeV. The assumption that the flux of underground muons detected is associated with the air showers means, that the minimal muon energy in the NUSEX experiment is $E_\mu\geq3$TeV. Then the supposed value of $\kappa(E_0=20\mathrm{TeV},E_\mu\geq3\mathrm{TeV})\sim1$ seems unreasonable. Notice for comparison, that the mean number of muons with $E_\mu\geq3$TeV produced in the atmosphere by the primary photon with $E_0=100$TeV is only $\kappa\sim10^{-3}$ [7]. Even most radical assumptions on the photoproduction cross section may increase this value to no more than an order of magnitude. Moreover, even for the primary proton we would have $\kappa(E_p=100\mathrm{TeV},E_\mu\geq3\mathrm{TeV})\simeq0.1$ [7]. It means that even for a nucleon-like nature of the cygnets, their flux above $E_0\geq100$TeV would be $I_0(>100\mathrm{TeV})\simeq2\cdot10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is in an apparent contradiction with the EAS data. This disagreement is so significant that the situation cannot be saved by any extreme assumption on the nature of the cygnets. So, it is not surprising that all the attempts to explain the deep underground muon data by exotic primaries (e.g., strange quark nuggets, di-lambdas, glueballinos, etc.) interacting with the atmosphere fail.

The situation seems somewhat better with the models suggesting muon production due to interaction of the cygnets in the rock. In this case there are no apparent problems connected with the observed EAS flux. Besides, it becomes possible to suppose that the cygnets have lower energies, which anables in principle to interpret the large angular spread of the muons around the direction of Cyg X-3 [12]. The relatively low energies of the primaries are also preferable due to the rigid requirements on the luminosity of Cyg X-3. These arguments being taken into account, the energy of the cygnets that initiate underground muon events in the rock is supposed to be in the range $E_0 \sim (1 \div 10)$TeV. Then, from Eq.(2) one finds the upper limit for the mass of the cygnets: $M_c \leq (0.1 \div 1)\,\mathrm{GeV}/c^2$.

The assumption that the muons are produced in the rock, allows to estimate the cygnet interaction cross section, $10\mu b < \sigma(cN) \leq 1mb$ [18]. The cygnet production cross section in the source should be also high enough, at least it should be comparable with the pion production cross section, otherwise the problems related to the luminosity of Cyg X-3 become too hard. The combination of these properties leads to a natural question: Why these long-lived, neutral particles with large production and interaction cross sections are were not revealed by accelerators?

So the skepticism of many physicists concerning the reliability of the deep underground muon data is quite understandable (see, e.g. Ref.[1]). Nevertheless, here we undertake one more attempt to overcome the "no go theorem".

3. The Anomalous Muon and Hadron vents Produced by Neutral Particles of Extremely High Energies

All the hard constraints on the properties of primary particles are first of all due to the assumption of relatively low energies of the primaries, $E_0 \leq 100$TeV, which is generally made so as not to contradict the air shower data. It should be emphasized that the constraint of Eq.(4) on the primary energy E_0 in fact corresponds to the assumption that the effective collection area of the ptimaries, S_{eff}, coinsides with the area of the muon detector, S_d, which is correct if the deflection of the secondaries (muons) from the primary direction can be neglected. However, more generally the effective area S_{eff} is determined not by the area S_d of the secondary particle detectors, but possibly by a much larger one covered by the secondaries due to their large deflection from the primary direction. The essential difference between S_{eff} and S_d can be demonstrated on example of the atmospheric Cherenkov telescope, which can detect air showers with impact parameter ~100m (the collection area $S_{eff} \sim 3 \cdot 10^4 m^2$), whereas the total area of it's mirrors may be only $\sim 1m^2$. This is due to the fact that the opening angle of the air Cherenkov light is $\sim 1^{\circ}$, the maximum of emission being produced at heights $h \sim (6 \div 8)$km, so that the radius of the Cherenkov light disc on the detection level becomes $r \sim 100$m.

The angular spread of the muon events observed in SOUDAN-1 and NUSEX experiments from the direction of Cyg X-3 is about $\Delta\theta \sim 5^{\circ}$ [10,12,14], which is significantly larger than the angular resolution of the detectors. Moreover, in communications on the excess of multimuon (SOUDAN-1, [19]) and multihadron (PION, [15,16]) events even larger angular spread, $\Delta\theta \sim 10^{\circ}$, has been reported. Assuming now that the muons (and the hadrons) detected are produced in the atmosphere at heights $h \sim 6$km (the depth $z \sim 500 \mathrm{g/cm^2}$), we obtain that on the level of observation the secondary particles cover an area

$$S_{eff} \simeq \pi(h \cdot \mathrm{tg}\Delta\theta)^2 \simeq 10^6 (h/6\mathrm{km})^2 (\Delta\theta/0.1\mathrm{rad})^2 \ \mathrm{m}^2 . \qquad (5)$$

So, a detector with area $S_d \sim 10\mathrm{m}^2$ actually detects the events induced by primaries that hit the surface $S_{eff} \simeq 10^5 S_d$. It means, that the fluxes of the primaries may up to 5 orders of magnitude be less than the muon fluxes detected within large acceptance angles. Then, the flux of the primaries corresponding to the muon flux observed by NUSEX, is

$$I_0(\geq E_0) \simeq 2 \cdot 10^{-17} \eta^{-1} \left[\frac{I_\mu(\geq 3\ \mathrm{TeV})}{2 \cdot 10^{-12} \mathrm{cm}^{-2} \mathrm{s}^{-1}}\right] \left[\frac{S_{eff}}{10^6\ \mathrm{m}^2}\right]^{-1} \left[\frac{S_d}{10\mathrm{m}^2}\right] \mathrm{cm}^{-2} \mathrm{s}^{-1}, \qquad (6)$$

where $\eta \leq 1$ is the probability for at least one secondary muon to cross the detector. Note that as the probability for detection of a muon crossing the detector is close to ~ 1 , then η actually corresponds to the probability of detecting the primary event. If the mean number of the muons crossing the detector is $\bar{n}_\mu \leq 1$ (per primary event), then the probability of detection of the primary event by detecting the muons is about

$\eta \simeq \bar{n}_\mu = S_d \rho_\mu \leq 1$, where ρ_μ is the surface density of the muons at the detector level.

The energy E_0 of the primary particle, which can provide a given density ρ_μ (or the probability η) of the muons at the level of detection, can be estimated as:

$$E_0 \sim N_\mu E_{th}/\delta_\mu \sim 3 \cdot 10^{18} \eta \left(\frac{S_{eff}}{10^6 \mathrm{m}^2}\right) \left(\frac{S_d}{10\mathrm{m}^2}\right)^{-1} \left(\frac{\delta_\mu}{0.1}\right)^{-1} \left(\frac{E_{th}}{3\mathrm{TeV}}\right) \mathrm{eV} . \qquad (7)$$

Here N_μ is the number of muons above the threshold $E_\mu > E_{th} \sim 3$TeV, and δ_μ is the fraction of the primary energy E_0 transmitted to the high energy muons.

It follows from Eq.(7) that when η varies within wide range $10^{-5} < \eta < 1$, the energy of the primary particle varies from $E_0 \sim 30$TeV up to $E_0 \sim 3$EeV, the relevant fluxes at these energies being $\sim 2 \cdot 10^{-12}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $\sim 2 \cdot 10^{-17} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, respectively. In principle, these fluxes do not contradict the EAS data. It should be noted, however, that very small values of η (corresponding to $E_0 < 1$PeV) lead to the problems already discussed in Section 2. From this point of view the values of $\eta > 10^{-2}$, corresponding to the energy range $E_0 > 30$PeV, are acceptable. However, it seems that the more probable energy range for the primaries is $E_0 \geq 1$EeV.

The first argument in favour of this energy range comes from the reports on the multimuon [19] and multihadron [15,16] events from direction of Cyg X-3. Thus, according to the PION data the statistical significance of the signal increases with increasing multiplicity of the hadrons in an event, n_h. At the same time, the number of excess events decreases only slowly with increasing hadron multiplicity. Obviously, it means that

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the mean number of the detector-crossing hadrons $\bar{n}_h \geq 1$, therefore $\eta_h \sim 1$. In this case the estimation of the primary energy, analogous to Eq.(7), yields $E_0 \sim 1EeV$.

The next argument for the EeV energy range of the primaries is, that at these energies the radical changes of the photonuclear cross section (up to ~100mb) seems quite possible. However this effect only is insufficient for a significant increase of the high energy muon and hadron content in the photon-induced showers as far as $\sigma(\gamma \to h) \ll \sigma(\gamma \to e^+e^-)$. Therefore an additional assumption on a decrease of the e^+e^- pair production cross section is needed. At small energies such an assumption seems impossible, whereas at extremely high energies the e^+e^- pair production cross section essentially decreases due to the Landau-Pomeranchuk-Migdal effect.

It should be pointed out that at energies $E_0 \geq 1EeV$ the neutral primary from Cyg X-3 may be not only the photon, but also the neutron, since at these energies its lifetime becomes sufficient to reach the Earth without significant losses due to decay. The efficiency of the neutron production at pp interactions in the source is as high as the gamma-ray production efficiency. Hence, at present it is difficult to make a choice between the photons or the neutrons as the primary particles from Cyg X-3.

4. The Analysis of the Large Angular Spread of the Anomalous Events from Cyg X-3

If assuming extremely high energies for the primaries, then there is no need in supposing some exotic (neutral, light the mean number of the detector-crossing hadrons $\bar{n}_h \geq 1$, therefore $\eta_h \sim 1$. In this case the estimation of the primary energy, analogous to Eq.(7), yields $E_0 \sim 1$EeV.

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4. The Analysis of the Large Angular Spread of the Anomalous Events from Cyg X-3

If assuming extremely high energies for the primaries, then there is no need in supposing some exotic (neutral, light and long-lived) particles from Cyg X-3. At the same time, the key point of the hypothesis proposed, i.e. the assumption of a large angular distribution of the high-energy secondaries, is extraordinary by itself (though the experimental data also testify to this peculiarity). However, due to this very assumption it becomes possible to reduce essentially the estimates of the fluxes of the primaries, and hence, to avoid the contradiction with the EAS data. Below we show that the wide angular distribution of TeV secondaries, $\Delta\theta \sim 0.1$rad, may in principle be possible under the assumption that massive particles with $M_X \sim 1\text{TeV}/c^2$ and lifetime $\tau_X \sim 10^{-6}$s (hereafter, X-particles) are copiously produced during the cascade development in the atmosphere.

It is obvious that the wide angular distribution of the high-energy (E>1TeV) muons and hadrons is impossible to explain while remaining within the standard perceptions on the shower development. Indeed, for deflection of a secondary high-energy particle with E>1TeV to an angle $\Delta\theta \sim 0.1$rad, the transverse momentum should be as much as $P_t \geq 100$GeV/c. The experimental results on p-p interactions in accelerators up to $\sqrt{s}=1.8$TeV (E~1PeV) indicate that the typical transverse momenta of the secondaries $\langle p_t \rangle \simeq 0.5$GeV/c [20], which is far insufficient to explain the angular spread observed.

The only possibility to explain the large angular distribution of TeV muons (and hadrons) in the shower seems to be their production via the decays of some massive particles (hereafter, X-particles) produced at the cascade development in the atmosphere. The typical deflection angle of the decay products from the direction of the parent particle is defined by the Lorentz factor of the latter:

$$\Delta\theta \sim 1/\gamma \text{ rad} . \tag{8}$$

Therefore, to provide an angular spread of ~0.1rad, the Lorentz factor of the supposed X-particles at the instant of their decay should be γ_D~10. Since at the decay of an X-particle at least two particles with energies of the same order should be produced, then even in the case of direct production of muons with the mass of the X-particle should be:

$$M_X \gg 2E_\mu/c^2\gamma \geq 0.5 \text{ TeV}/c^2 . \tag{9}$$

Note, that when the muons are not produced directly at X-particle decays (e.g.,if they are produced via the decays of intermediate hadrons), the estimate of the mass M_X in Eq.(9) should be somewhat increased.

In accordance with the scenario of the shower development considered below, the X-particles produced in the first interaction of the primary (photon or neutron) with the atmosphere, should further cascade, copiously producing X-particles of new generations. This cascading may continue down to the threshold energies E_X~E_{th}, where the energy E_{th} may be estimated from the following simple relations. At the collision of the incident X-particle with energy E_X with a nucleus of mass M_A=Am_p (A≃14 for the air) the Lorentz factor of the center-of-mass system (cms) is

$$\gamma_{cms} \simeq (E_X/2M_Ac^2)^{1/2} \tag{10}$$

(Here we suppose that the X-particle interacts with the air nucleus as with the entity object). Assuming that at the

threshold the incident X-particle produces one more X-particle, the mass M_X should be not greater than the energy of the target nucleus in the cms, i.e. $M_X \leq \gamma_{cms} \cdot M_A$. Then using Eq.(1), one obtains $E_{th}=2M_X^2c^2/M_A$. Taking into account that this energy after interaction should be distributed between the two resulting X-particles, the characteristic Lorentz factor of the X-particles of the last generation is about

$$\gamma_* = E_{th}/2M_Xc^2 \simeq 80(M_Xc^2/1\text{TeV}) . \tag{11}$$

The X-particles with Lorentz factors γ_* cannot further produce new X-particles. Since γ_* still remains by an order of magnitude larger than the value of the X-particles at the decay, γ_D~10 (needed to provide the observed angular spread of the decay products), then an energy degradation (probably, due to nuclear interactions of X-particles with the air) should take place. Obviously, in this case the total energy of the primary particle, which can be transmitted to the energy of the decay products, ΣE_s, emitted at large angles, is:

$$\delta_s = \frac{\Sigma E_s}{E_0} \leq \frac{\gamma_D}{\gamma_*} \simeq 0.13(M_Xc^2/1\text{TeV})^{-1}(\gamma_D/10) . \tag{12}$$

The assumption of a direct muon production provides the maximal efficiency δ_μ~δ_s. If the muons are produced via the decay of intermediate hadrons, the efficiency of the TeV muon production may be noticeably lower.

Since the efficiency of the TeV muon production should be at least about δ_μ~0.1 (otherwise serious problems connected with the energy E_0 of the primary arise), the mass of the X-particle should not exceed the value

$$M_X \lesssim 1.3(\gamma_D/10)\,\mathrm{TeV}/c^2 \ . \qquad (13)$$

So, the mass of the X-particle is strongly limited from both sides by Eqs.(9) and (13), and the preferable value is $M_X \sim 1\mathrm{TeV}/c^2$.

5. The Scenario of Shower Development with Copious Production and Decay of X-Particles

Prior to describing the scenario of a copious X-particle production during shower development, let us estimate the relevant cross section and the lifetime of the X-particles.

The cross section of the X-particle interaction with the air nucleus may be estimated from the following simple arguments. The X-particle(s) produced at the first interaction of the primary should further give rise to an avalanche of X-particles copiously producing each other down to heights $h \sim h_* \simeq (8-10)$km (the depth in the atmosphere $z_* \sim (300-400)$ g/cm^2), resulting in $N_X \sim 10^4-10^5$ X-particles in the maximum (see Fig.1). This number of X-particles in the shower is necessary to provide high surface density of muons, $\rho_\mu = N_\mu/S_{eff} \sim (0.01-0.1)\mathrm{m}^{-2}$ (assuming $N_\mu \sim N_X$), which corresponds to the primary event detection probability $\eta \sim 0.1-1$. According to Eqs.(6) and (7), this range of η corresponds to the fluxes of EHE primaries not contradicting to EAS data. Assuming that at each interaction about $m \sim 2 \div 3$ X-particles are produced (including the parent X-particle), the mean path of the X-particle in the air should be:

$$\lambda_X \sim \frac{z_*}{\ln N_X/\ln(m)} \simeq (20-50)\ \mathrm{g/cm}^2 \ . \qquad (14)$$

The relevant X-particle to air interaction cross section is:

$$\sigma_X \sim (450-1100)\ \mathrm{mb} \ . \qquad (15)$$

This cross section is close to the proton-to-air interaction cross section measured in cosmic-ray experiments at energies $E_0 > 10^{15}$eV (see, e.g., [20]). It should be noted, that the X-particle production cross section at the interaction of the primary (photon or neutron) with the air nucleus should be also of the same order of magnitude, since the X-particle branch of the cascade should carry out an essential fraction of the total shower energy.

Another important characteristic for realization of the scenario proposed, is the lifetime of the X-particle. The lifetime τ_X should be short enough to provide the decay of the X-particles at heights $h \sim (5-6)$km. On the other hand, τ_X should be large enough to allow effective cascading of the X-particles, and what is more important, to provide their subsequent dumping from energies $E_X \sim 100$TeV (below which the production of new X-particles is impossible) down to $E_X \sim 10$TeV. This requirement is necessary to provide the large angular spread of the secondary TeV muons. Assuming that the X-particles below $E_* = \gamma_* \cdot M_X c^2$ continue to interact with the air, in particular, through the inelastic nuclear channels ($\lambda_E \sim 100\mathrm{g/cm}^2$), from comparison of the decay and interaction lengths at heights $h \sim (5-6)$km (air density $\rho \sim 7\cdot10^{-4}\mathrm{g/cm}^3$) we obtain:

$$\tau_X \simeq 5\cdot10^{-7}\left[\frac{\lambda_E}{100\ \mathrm{g/cm}^2}\right]\left[\frac{\gamma_D}{10}\right]^{-1}\ \mathrm{s} \ . \qquad (16)$$

Thus, to explain the production of TeV muons (and hadrons) with large angular distribution, $\Delta\theta \sim 0.1$rad, we suppose the following scenario (see Fig.1). The primary particle from Cyg X-3 (neutron or photon) of energy $E_0 > 1$EeV, already in the first interaction with the atmosphere at heights (20-25)km produces a massive ($M_X \sim 1$TeV/c^2) X-particle(s) that carry away an essential (~50%) fraction of the initial energy E_0. The remaining fraction of the initial energy transmitted to the hadrons by the usual way, may be also pumped into the X-particles in the subsequent 2-3 interactions of the hadrons with the air, provided that the X-particle production cross section does not fall off drastically at lower energies. Further on, due to interactions on the X-particles with the air, the X-particle production in the avalanche occurs so that during $n \sim 10$ interactions $N_X \sim m^n \sim 10^4 - 10^5$ ($m \sim 2+3$) X-particles are produced in the shower at a height $h_* \sim (8+10)$km. Below this height the production of new X-particles does not occur, so further on the X-particles lose their energy due to nuclear interactions with the air. For the deduced lifetime $\tau_X \sim 10^{-6}$s, the energy degradation continues down to the heights h~(5-6)km, where the X-particles with typical energy $E_X \sim 10$TeV effectively decay, producing TeV secondaries (muons and/or hadrons). Since the secondary muons are produced at angles $\Delta\theta \sim 5^\circ$ high above the muon detector, at the detector level they will cover an area of $S_{eff} \simeq \pi(h \cdot tg\Delta\theta)^2 \simeq 10^6 m^2$. The muon density at this area is about $\rho_\mu = N_\mu / S_{eff} \sim (0.01-0.1)m^{-2}$, if we assume that at least one muon is produced at the decay. Therefore, for a detector with $S_d \sim 10m^2$ the mean number of muons is $\bar{n}_\mu \sim (0.1-1)$, so the NUSEX installation should detect with probability $\eta \sim 0.1+1$ a single

muon event from the showers initiated by the primaries of energies $E_0 \sim (1+10)$EeV and flux $I_0 > 10^{-17}$ cm^{-2}s^{-1}.

Due to the uncertainties connected with the nature of the X-particle as well as the dynamics of the shower development, the accuracy of estimations is obviously within an order of magnitude. These estimates may be presumably improved by including the SOUDAN-1 and the PION data into the analysis, which is, however, out of the scope of this paper. Only notice, that here we use the NUSEX data which relate to the highest energy range of muons, $E_\mu \geq 3$TeV, providing most severe restrictions to the mass of the X-particle.

6. Discussion

To explain the anomalous TeV muon and hadron events from the direction of Cyg X-3, in this paper we propose a hypothesis which may in principle overcome the "no go theorem". The main point of the hypothesis consists in the assumption of an extremely high energy domain for the primaries, $E_0 \geq 1$EeV. The problem connected with the EAS data is significantly weakened by the assumption of a large angular distribution ($\Delta\theta > 5^\circ$) of TeV hadrons and muons produced at the shower development. In the frames of conventional theories, this assumption seems very hard, since the primaries should be ultrarelativistic with the Lorentz facto $\gamma > 10^4$. Meanwhile, the large angular spread of the anomalous events around the direction of Cyg X-3 is the experimental fact emphasized in all the reports. This very circumstance allows to conclude that the effective collection area for the primaries is huge (up to 4-5 orders of magnitude greater than the detector surface). Thereby the fluxes of the primaries may be down to the same factor lower than the flux of anomalous muon events observed within a large acceptance angle. At the same time, the energy range of the primaries shifts to much higher values, $E_0 \geq 1$ EeV.

The power-law extrapolation of the fluxes from Cyg X-3 obtained at TeV and PeV ranges, $I_0(>E) \simeq 4 \cdot 10^{-11} (E/1\mathrm{TeV})^{-1} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ [18], gives the flux $\sim 4 \cdot 10^{-17} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ above $E_0 \sim 1$EeV, which is in a qualitative agreement with the flux of the primaries needed for explanation of the NUSEX data.

Recently the Fly's Eye group has reported about the positive signal from Cyg X-3 above $E \sim 0.5$EeV [21]. Later similar reports were made by Akeno [22] and Yakutsk [23] groups (see, however, Ref.[24]). In all the reports the angular spread of the signal was $\sim 5^{\circ}$. (It is interesting to notice that in case of a broad signal its maximum may be slightly shifted from the real direction of the source, depending on the zenith angle of the shower detected; this effect probably takes place in the Fly's Eye and Akeno data).

In accordance with the Fly's Eye data the flux of the primaries above 0.5EeV is estimated as $\sim 2 \cdot 10^{-17} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ [21]. This flux is somewhat lower than the fluxes needed to explain the TeV muon data. However, our estimations are only qualitative and do not pretend to a high accuracy. Besides, if the EHE showers are developed in accordance with the scenario proposed here, then it is obvious that the estimations of both the energy and the flux of the primaries reported, should be reconsidered. (Note that the influence of this effect may be quite different for different shower installations, in particular, for the Fly's Eye and the Haverah Park).

Assuming the EHE domain for the primaries, there is no need to suppose a new exotic (light, long-lived and neutral) particles from Cyg X-3. Apart from the photons, in this case the primaries may be also the neutrons. The latters are produced in the nuclear reactions in the source as efficiently as the gamma-rays, and at $E_0 > 1$EeV they reach the Earth without essential losses due to the decay.

If the proposed scenario of the shower development is valid, this may have essential consequences for the EHE cosmic ray spectrum measured by shower arrays. So, the experimental confirmation of this hypothesis seems principle. Some valuable information may be obtained by installations detecting different EAS components. However, a more direct information may be obtained by large high-energy muon and hadron detectors. In particular, the DUMAND installation with effective area of $\sim 2 \cdot 10^4 \mathrm{m}^2$ seems ideal for the test. In case of realization of the scenario proposed, it will be possible to detect by this detector the showers initiated by EHE cosmic rays. These showers may be distinguished from the background events induced by the low-energy cosmic rays, as in the former case a large number ($N_\mu > 10^3$) of the high-energy muons covering the whole surface of the detector is expected. This criterion seems very effective for the selection of the EHE cosmic rays, since at lower energies the production of the X-particles leading to copious creation of TeV muons at large angles is suppressed. Therefore, in case of background events, only a small part of the detector will be "filled" with muons.

In summary, the hypothesis proposed to explain the anomalous TeV events from Cyg X-3 require the existence of a massive (M_X~1TeV/c^2) particles effectively produced at cascade development in the atmosphere. The experimental search for these X-particles may become possible in the forthcoming experiments with cosmic rays,as well as on the future colliders with energy $\sqrt{s} \simeq (1 \div 10)$ TeV.

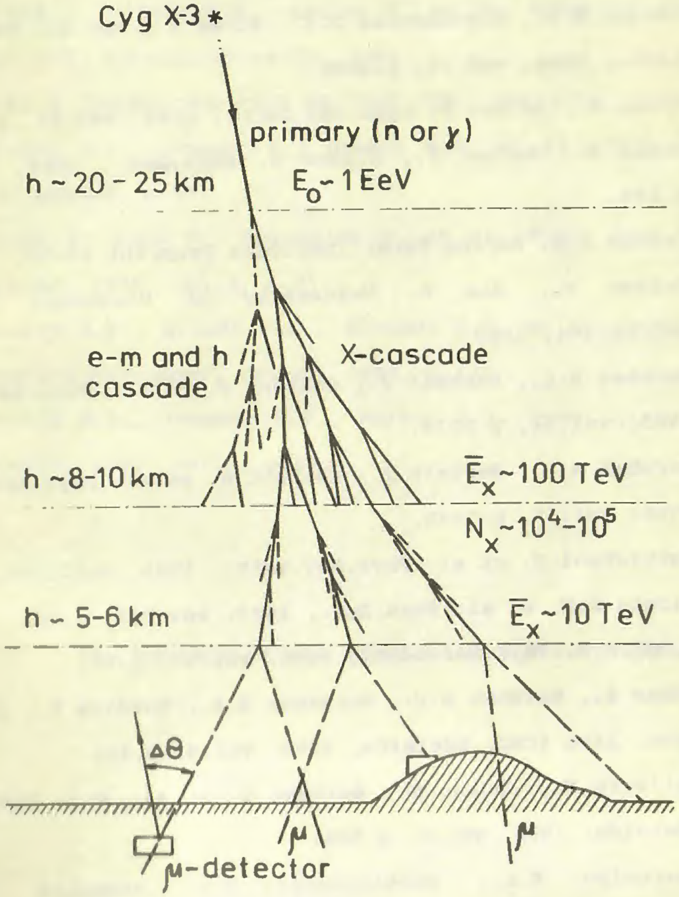

Fig.1. The schematic plot of the proposed scenario of EHE shower development with production and decay of X-particles.

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НЕЙТРАЛЬНЫЕ ЧАСТИЦЫ ПРЕДЕЛЬНО ВЫСОКИХ ЭНЕРГИЙ - КЛЮЧ
К ЗАГАДКЕ Cyg X-3

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