Cygnus X-3 events and very-high-energy photonuclear cross sections

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We examine the possibility that a large increase in the photon-hadron cross section at the Fermi scale (few hundred GeV in the c.m.) could account for the anomalous muon rate which seems to be associated with the radiation from Cygnus X-3. Such an explanation appears to be marginal but not perhaps entirely excluded. We point out that if this is indeed the case, then tests are possible with present colliding-ring machines.

I. INTRODUCTION

Cosmic-ray observations[1–3] show the existence of very-high-energy radiation from Cygnus X-3 and perhaps other astronomical sources. The most plausible explanation of the nature of this radiation is that it consists of photons, as we shall see. At the same time there have been reports,[4,5] not entirely confirmed,[6] of a high-energy muon signal associated with Cygnus X-3 in deep-underground detectors. Should the muon signal be confirmed, this would appear to pose a severe problem since the conventional theory of the development of photon-induced cascades in the atmosphere cannot give the necessary high rate of energetic muons. Conventional cascades arise mainly from e^+e^- production and bremsstrahlung and do not contain a substantial hadronic component with pions or other particles that can decay to muons.

Since the energies involved are approaching the Fermi scale, a possibility which comes to mind is that there is a new threshold in the few-hundred-GeV (c.m.) region in which the photonuclear cross section has a sharp rise. This is conceivable if the photon partakes in some new strong interaction, and then the associated pions and other particles produced will be a new source of muons. In this paper we would like to examine this hypothesis. Although results from the MUTRON detector[7] indicate that there is no unusual behavior of the photonuclear cross section up to about 3 TeV (lab), or 80 GeV (c.m.), we believe there is no direct evidence against such an assumption for higher energies.

It is worth noting that in hadron-hadron reactions at these energies, as investigated at the CERN collider, a very great effect on the cross section cannot be expected due to such a threshold. Because of the "old strong interaction" the partial-wave amplitudes up to about the geometric size of the nuclear or nucleon targets are nearly saturated, and a new interaction cannot have a strong effect on the total cross section. The photon, however, is different. Although the vector-dominance mechanism causes it to behave, up to now, as "hadronlike" in most ways, its partial-wave amplitudes are only of order e. Nuclear matter is essentially transparent to the photon and were it, at some energy, to become strongly interacting with nuclear matter the cross section has plenty of room to grow. The situation is somewhat analogous to the onset of the production of a new flavor where, for example, in π-nucleon scattering nothing dramatic occurs at the strangeness threshold at 1 GeV. In e^+e^- annihilation, on the other hand, there is a jump in R after a flavor threshold because we are dealing with an unsaturated amplitude. In the following, we will only consider the phenomenological implication of such a jump in the photonuclear cross section, without speculating on its precise dynamical origin.

II. NATURE OF THE PRIMARY

We begin by briefly reviewing those aspects of the Cygnus phenomenon relevant to determining the nature of the radiation and why the most plausible explanation is that it is photons. We would like to stress the following points.[8]

(1) The primary particles must be neutral, have a long lifetime, and be light. Neutral in order to travel the galactic distances [>12 kpc (Ref. 9)] straight to the Earth despite the galactic magnetic fields of[10] $>1\mu$G, which produce a Larmor radius of 10 pc at 10^{16} eV. The long lifetime is required for a particle to survive the flight. This restriction excludes the neutron, for example, which would have to have more than 10^6 TeV to reach Earth before decay. The particle has to be light in order that the dispersion in velocity which a massive particle would have not smear out the relatively well-defined arrival time of the events in the Cygnus X-3 period. If we ask that the arrival time be well defined within a narrow phase interval of the 4.8-hr period presumably associated with the orbit of the binary system, we arrive at a mass bound on the order of a GeV. On the other hand, if we take the recent report that the pulsar rotation period (12.6 ms) was seen in very high-energy cosmic-ray bursts[11] a mass bound of about 1 keV results. In these estimates it is assumed that the energy spread is of the order of the energy itself. This point is important in excluding many speculations involving new particles supposedly not yet detected in the laboratory because of their great mass.

(2) The primary causing the air showers must have a relatively large cross section in air >10 mb per nucleon or electron. Otherwise the showers would start much closer

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to the ground and would not be as wide in reaching the detectors as actually observed.[1] This point is important in excluding particles interacting with the air via some new interaction involving the exchange of some heavy quantum, which would give a small cross section.

(3) If the underground events and the air showers are caused by the same primary, then practically every incoming primary must produce a fast (say $x > 0.2$) penetrating particle (muon). This follows from a comparison of the rates of the underground detectors and the rates reported from atmospheric Cherenkov-light detectors,[12] which are nearby in energy and give about the same rate (see Fig. 1).

If the underground events are induced by a different primary than the air showers, this primary's cross section could be smaller than the 10 mb found above, but it still must be bigger than about 0.05 mb. This follows from the absence of a "zenith angle effect" where particles arriving at a flat angle and having been produced by a particle with a small cross section (such as a neutrino) should have been produced with the same rate or even more frequently than at vertical incidence since the primary traversed more material. Instead, it is found that the Cygnus-associated underground events have roughly the same zenith angle dependence as other (atmospheric) muons. The figure of 0.05 mb follows from a spectral index $\alpha=1$ and depth $d=1800$ hg/cm^2 as for the Soudan detector, and the assumption that the primary interaction does not occur more often underground than in the air [mean free interaction path $\lambda > d/2(\alpha+1)$].

Surveying these points, we see that of the known particles, only the neutrino and the photon are allowed by

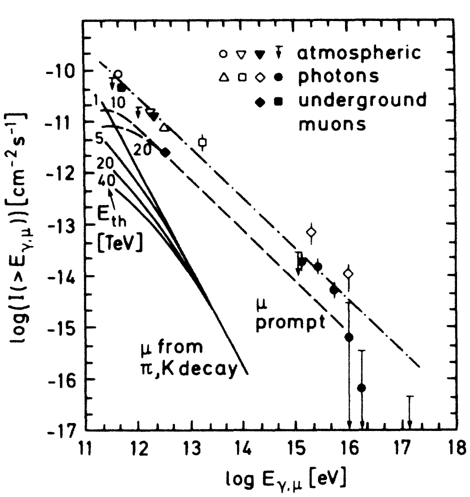

FIG. 1. Compilation (Ref. 2) of the integral γ-ray flux data from Cygnus X-3 from atmospheric experiments (Refs. 1, 2, and 12) together with a power-law fit [$\alpha=0.97$ (Ref. 2), dashed dotted line] and the integral muon flux from two underground detectors (Refs. 4 and 5). The curves represent our calculations for underground muons based on the hypothesis of an increased photonuclear cross section above an energy threshold E_{th}, for various choices of E_{th}, and for the two cases of (a) prompt μ production in the primary γ-air collision and (b) from π or K decays. For the choice of relevant parameters see text.

points (1) and (2), and that the neutrino is eliminated by point (3). A new particle would have to be relatively stable, light, and without too small a cross section, and so would most probably have already been seen in the laboratory. Thus we are lead to consider the photon as the most plausible candidate for the incoming radiation, and to assume that both the air showers and the underground events are induced by photon primaries.

A final point concerning the underground data which seems very difficult to understand is an apparent spread of a few degrees greater than experimental resolution in the arrival angle around the direction of Cygnus X-3. We can offer no explanation in the present context and must assume an observational problem of some kind is involved.

We are then left with the problem of the penetrating particles produced in these events. Presuming them to be muons, there are then two observations that cannot be understood on the basis of conventional understanding: The excess muon content reported in the Kiel air-shower work[1] for showers which otherwise have the appearance of conventional electromagnetic showers, and the need for a very high rate of production of energetic muons as mentioned under point (3).

III. INCREASE OF THE PHOTONUCLEAR CROSS SECTION

We would now like to examine how the hypothesis of a substantial increase of the photonuclear cross section at very high energy might explain these two problems. Qualitatively, it is obvious that if high-energy photons develop a nuclear cross section approaching the order of the e^+e^- production cross section which is responsible for the absorption of the photon in the atmosphere, then there will be many pions and therefore muons in the cascade. In addition there is the likely production of new sources of prompt muons in the new process.

The e^+e^- production cross section on nitrogen at high energy is 470 mb. For a working hypothesis for the γp cross section we remove the $\alpha=\frac{1}{137}$ from the usual photon-nucleon cross section of 130 μb to give about 20 mb on the proton and so about 200 mb on nitrogen. Thus we would have that about one photon in three undergoes a nuclear interaction when it is above the threshold energy, and very-high-energy cascades would show a mixed electromagnetic and hadronic character, tending to explain the Kiel muon excess. Note that once the energy of the photon in the cascade drops below the new threshold, the shower proceeds as normal. As far as the precise position of the threshold of the new cross section in energy is concerned, we shall see below that it has an important effect on the interpretation of the data.

Having made the radical assumption of a photonuclear cross section like that of a hadron, we must, in order to proceed, have an estimate of the photon flux in the atmosphere, as induced by the primaries of Cygnus. We shall take this as in the standard electromagnetic shower[13] and assume, in the spirit of a perturbation calculation, that it is unchanged by the new interaction. This is perhaps acceptable as a rough approximation, with the small parameter being L_R/λ_γ, where L_R is the radiation length, characterizing the shower development (37 g/cm^2 in air) and λ_γ is the absorption length for the new interaction (120 g/cm^2 in air). Then for a primary photon spectrum $I(>E)=AE^{-\alpha}$ one obtains at depth z in the atmosphere[13]

$$I^\gamma(>E,z)=AE^{-\alpha}(e^{-z/\lambda_1}+e^{-z/\lambda_2})/2 \tag{1}$$

with characteristic exponents λ_1,λ_2 depending on α.

An important feature of the energy spectrum from Cygnus is that it appears to be quite flat (Fig. 1), with α in the vicinity of one. In the case $\alpha=1$ the exponents are $\lambda_1^{-1}=0$, $\lambda_2=0.56L_R$. This has the interesting consequence that the photon flux has a component that does not die out with depth in the atmosphere; that is, if the incoming photon spectrum is $I(>E)=AE^{-1}$, then the photons in the cascade have a component $\frac{1}{2}AE^{-1}$ independent of depth z. This may be viewed as coming from down scattering from photons at very high energies and obviously cannot be true to arbitrary depth if there is an upper energy cutoff where the E^{-1} spectrum stops. In the case of Cygnus there seems to be such a cutoff at about 10^{17} eV. Under the assumption[13] that the particles in the cascade lose $\frac{1}{2}$ their energy in every radiation length, this cutoff leads to a maximal depth $z_{\max}$. For us, however, $z_{\max}$ is determined by the condition that the energy of the photons in the cascade fall below the threshold of the new effect. This yields $z_{\max}=13L_R$ for a 10-TeV threshold. We shall thus assume a constant spectrum of photons in the atmosphere of $\frac{1}{2}AE^{-1}$, down to a depth of 13 radiation lengths.

We first examine the possibility that a new threshold would be associated with new particles which decay immediately (promptly) into muons, and thus do not have to compete with absorbtion in the atmosphere. This prompt muon possibility can be described in terms of a parameter $X_{\mu\gamma}$ which gives the ratio of the produced muon flux to the incoming primary photon flux. If the incoming flux is power-law behaved $I\sim E^{-\alpha}$, then the outgoing muon flux from prompt decays has the same power behavior and the production (integral flux) at depth z is given by

$$\frac{dI^\mu}{dz}=\frac{1}{\lambda_\gamma}X_{\mu\gamma}I^\gamma\,,$$
$$X_{\mu\gamma}=\int x^{\alpha-1}F_{\mu\gamma}(x)dx\,, \tag{2}$$

where F is the inclusive production spectrum $F_{\mu\gamma}\equiv\sigma^{-1}x\,d\sigma/dx$ of the muons from prompt decay in the photon-air-nucleus reaction. Note that with $\alpha=1$, $X_{\mu\gamma}$ is the momentum fraction carried by the muons. Using the constant photon component in the cascade, as just described, gives us for the final ratio of the integral muon flux to the primary integral photon flux, at high energy

$$\frac{I^\mu}{I^\gamma}=\frac{1}{2}X_{\mu\gamma}\frac{z_{\max}}{\lambda_\gamma}\,. \tag{3}$$

Because of the large factor $z_{\max}/\lambda_\gamma\sim4.3$ it does seem possible with say $x_{\mu\gamma}\sim\frac{1}{10}$ to have a muon flux not much below the primary flux, as seems to be required if we take the results of Soudan and NUSEX (nucleon-stability experiment).

This is encouraging, but a difficulty with this prompt muon explanation arises when we consider the fact that the threshold of the underground detectors are rather low [0.6 TeV (Soudan) or 3 TeV (NUSEX)] compared to what we might anticipate as the threshold appropriate to the Fermi scale. A c.m. energy of $(G_F\sqrt{2})^{-1/2}\approx250$ GeV in a photon-nucleon collision corresponds to a photon energy ("lab") of 30 TeV. The fact that our detectors are substantially below this energy means that the energies between the detector thresholds and the new effect threshold are "lost", leading to a reduction in the ratio factor (3). In Fig. 1 the dashed lines show some model calculations of the threshold effect. In these calculations we take $F_{\mu\gamma}(x)=aX_{\mu\gamma}\exp(-ax)$ with $a=5$ and $X_{\mu\gamma}=0.1$. With this choice expression (3) gets multiplied below the threshold $E_{\rm th}$ by $1-\exp(-y)+yE_1(y)$, where $y=aE/E_{\rm th}$ and $E_1(y)$ is the exponential integral. We see that the threshold would tend to give a flattening of the spectrum at low energy, which does not seem to be the case if we take Soudan and NUSEX. This conclusion might be avoided if the muon production process leads to muons at very low x (i.e., a large a) but in such numbers that the momentum fraction $X_{\mu\gamma}$ remains substantial.

We now turn to conventional sources of muons, assuming that the new photo-nuclear cross section leads to muons through pion production, with the characteristics we know at lower energies.

The pion propagation equation has the photon source term Eq. (1) on the right-hand side:

$$\frac{dI^\pi}{dE\,dz}=-\left[\frac{1}{\lambda_\pi}-\frac{X_{\pi\pi}}{\lambda_\pi}\right]\frac{dI^\pi}{dE}+\frac{X_{\pi\gamma}}{\lambda_\gamma}\frac{dI^\gamma}{dE}\,. \tag{4}$$

Here the mean free interaction length for pions is taken as $\lambda_\pi=\lambda_\gamma=3L_R$. The momentum fractions X_{ab} defined as in (2) are estimated from inclusive pion production data[14] as $X_{\pi\pi}=0.62$, $X_{\gamma\pi}=0.18$, $X_{K\pi}=0.08$; for photoproduction we take the same basic numbers but replace the leading pion by a leading photon resulting in $X_{\pi\gamma}=0.40$, $X_{\gamma\gamma}=0.40$, $X_{K\gamma}=0.08$. This leads to a pion spectrum at depth z

$$\frac{dI^\pi}{dE}=AE^{-2}\sum_{i=1}^{2}\pi_i(e^{-z/\lambda_i}-e^{-z/\lambda})/2\,, \tag{5}$$

with $\lambda=\lambda_\pi/(1-X_{\pi\pi})$ and $\pi_i=X_{\pi\gamma}/(1-X_{\pi\pi}-\lambda_\pi/\lambda_i)$ (here $\lambda=7.9L_R$, $\pi_1=1.05$, $\pi_2=-0.08$), which in turn gives muons by[15]

$$\frac{dI^\mu}{dE\,dz}\cong\frac{b_\pi}{E}\frac{m_\pi}{m_\mu}\frac{1}{z}\frac{dI^\pi}{dE}(z,m_\pi E/m_\mu)\,. \tag{6}$$

Here b_π is the important parameter, the momentum at which the pion decay and interaction mean free path are comparable, $b_\pi=115$ GeV. An estimate of the K contribution has been made along the same lines. We get, finally, after integration of (6) up to $z_{\max}$ for the ratio of the muon flux to the primary flux $0.05(E/1\text{ TeV})^{-1}$ for $E>E_{\rm th}$, whereas for $E<E_{\rm th}$ this result gets multiplied by $1-(1-y)\exp(-y)+y^2E_1(y)$ with $y=aE/E_{\rm th}$ ($a=3.5$ here). These results are shown in Fig. 1. The trend of the

results, as seen as the solid lines in Fig. 1, is similar to the data but the absolute magnitude is low. This can be understood, in contrast with the prompt model, from the fact that the pion-decay muons are mainly from small-x pions which have a better chance-to decay before absorption, and thus the results are less sensitive to the threshold effect. Again, as the results depend on the combination aE/E_{th}, the threshold energy could be moved up without losing intensity if a were increased, i.e., with a softer pion distribution $\exp(-ax)$.

Thus on the question of underground muons, it seems that with optimistic assumptions it is possible to come with an order of magnitude of the observations, assuming a rise in the photonucleon cross section to the 20-mb level in the vicinity of the Fermi scale. Given the uncertain state of many of the observational points[16] and also the possibility of fluctuations in the activity of the source, this might be regarded as encouraging for the hypothesis. On the other hand, the difficulty of obtaining a thoroughly convincing agreement with all aspects of the observations, if they are all taken at face value, may be seen as a measure of how difficult it is to understand the Cygnus effect in something like a conventional framework.

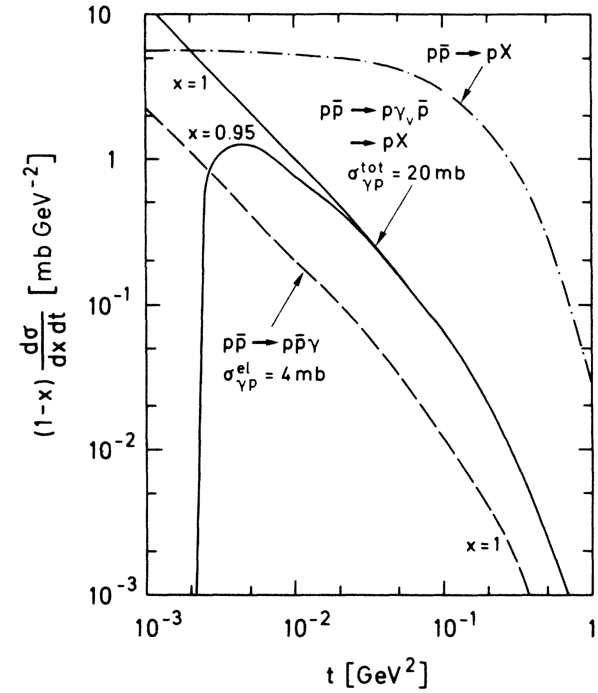

FIG. 2. Inclusive spectra for the p in $p\bar{p} \to pX$ from almost real photon scattering on the $\bar{p}$ according to Eq. (7), using the hypothesized large photonucleon total cross section, for two choices of x, corresponding to different $t_{\min}$ effects (solid curves) and background from single diffractive scattering as observed at CERN ISR and Fermilab (dashed-dotted curve). The dashed curve shows the similar expectation for the elastic channel $\gamma_v p \to \gamma p$. This process is to be studied through identification of the final state $p\bar{p}\gamma$ in distinct kinematic configurations strongly reducing the background (bremsstrahlung and π^0).

IV. COLLIDER TESTS

Regardless of what one may think of the degree of agreement on muons, however, there is the interesting possibility that the hypothetical jump in the photonuclear cross section could be observed in existing $p\bar{p}$ storage rings. A proton or antiproton in the storage ring has a cloud of virtual photons which can interact with a substantial fraction of the total energy. For example, a photon with only $x_\gamma = 0.1$ from the proton can collide with the antiproton in the Fermilab collider ($\sqrt{s} = 2000$ GeV) to yield a $\gamma\bar{p}$ c.m. energy of $\sqrt{s_1} = 630$ GeV, above the threshold in question. The formula for the photon-induced cross section in such collisions for a given momentum transfer t and Feynman x of the proton which emits the almost real photon ($x = 1 - x_\gamma = 1 - s_1/s$) is[17]

$$\frac{d\sigma}{dx\,dt} = \frac{\alpha}{4\pi}\,\frac{1}{1-x}\,\frac{-t+t_{\min}}{t^2}\,\sigma^{\text{tot}}_{\gamma\bar{p}}(s_1)F_p{}^2(t)\ , \qquad (7)$$

where the total $\gamma\bar{p}$ cross section $\sigma^{\text{tot}}_{\gamma\bar{p}}$ enters. In a system where this very forward proton can be detected, $\sigma^{\text{tot}}_{\gamma\bar{p}}$ can be measured by looking at the Coulomb peak at very small transverse momentum given by Eq. (7), if it exceeds the background from inelastic diffraction scattering. In Fig. 2 we compare the spectrum of the thus scattered proton when $\sigma^{\text{tot}}_{\gamma\bar{p}}$ is 20 mb with the background from inelastic hadronic processes at Fermilab and CERN ISR energies.[18] For the proton form factor we choose $F_p(t) = (1 - t/0.7\ \text{GeV}^2)^{-2}$. Only at very small $t < 10^{-3}$ GeV^2 and large x, i.e., very high energies $\sqrt{s}$ for a given subenergy $\sqrt{s_1}$, when the minimal momentum transfer $t_{\min} = -m_p{}^2(1-x)^2$ is sufficiently small, can this signal be observed. This situation could be improved, if in the new process prompt muons were produced. In this case one would expect a substantial muon enrichment in the Coulomb region, suggesting a search for a muon excess in such events.

Another promising possibility here would be to observe $\gamma\bar{p}$ elastic scattering and to detect the distinctive final state $\gamma\bar{p}p$ where a very forward proton plus photon (with substantial x_γ) add up to the beam energy and the other particle has exactly the beam energy. All three final particles are coplanar and there is a reasonable momentum transfer (300 MeV) to the $\bar{p}$. With $\gamma\bar{p}$ total cross sections like that of πN at lower energies, we would expect an elastic scattering of say 4 mb. This leads to the distribution shown in Fig. 2 by the dashed line and to the total cross section for the $\gamma p\bar{p}$ final state through elastic scattering of $\sim 10\ \mu$b. The main background here is bremsstrahlung in elastic $p\bar{p}$ scattering and the reaction $p\bar{p} \to p\bar{p}\pi^0$ where one decay photon is lost. Though both background processes have comparable integrated cross sections to our sought for process, they could be effectively suppressed with increasing γ and $\bar{p}$ scattering angles and angular resolution because of the special kinematic constraints.

V. SUMMARY

To summarize, if, as seems plausible, the incoming primaries from Cygnus X-3 are photons and are indeed associated with a deep-underground muon signal, then an explanation is not possible, in conventional terms. We then investigate the consequences of the hypotheses that there is a sharp increase (as allowed by unitarity) of photonuclear cross sections around the Fermi scale and find it might thus be possible to explain the main effects (although not the angular anomaly) to within an order of magnitude. The threshold for the new effect must be relatively low, however. An important aspect of this hypothesis is that the large γp cross section could be studied at existing $\bar{p}p$ colliders.

ACKNOWLEDGMENTS

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