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LPM Effect on Muon Content of Air Showers

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Abstract

The Landau-Pomeranchuk-Migdal (LPM) effect has been studied for muon pair production by extremely high energy (EHE) photons. It is found that the ratio of muon pair production to that of electron pair production shows an abrupt enhancement above a characteristic threshold energy for each medium. It is suggested that this enhancement may resolve the anomalous muon production puzzle in extensive air showers (EAS) and underground experiments. The study suggests that more showers will be observed from the direction of a EHE gamma ray source when the source is near the horizon.

Introduction: Based on the Bethe-Heitler (BH) cross sections, it was well known that the muon content of photon showers is an order of magnitude less than those of cosmic-ray showers. Thus when Samorsky & Stamm (1983) reported that showers initiated by radiation from Cyg X-3 had about the same muon content as those initiated by cosmic rays, we were faced by a puzzle. The discovery of time-modulated muons by NUSEX (Battistoni et al 1985) and Soudan-1 (Marshak et al, 1985) compounded the puzzle. More recently, Yamashita et al (1996) using a cosmic-ray telescope tracing Cyg X-3 observed time-modulated muons when Cyg X-3 was at large zenith angles. To account for the anomalous muons from Cyg X-3, "cygnet" was invented. Ruddick (1986) suggested that cygnets interact in the earth producing massive secondary particles decaying to muons. In his model, detectors on the surface of the earth should observe muons only near the horizon and now Ruddick's model is cited to fit the recent observations of time-modulated muons from Cyg X-3 (Yamashita et al 1996). The aim of this paper is to investigate the LPM effect on muon pair production and to see how the muon content of the air EHE photon showers is enriched through this effect.

LPM Effect on Muon Pair Production: In the computations of the muon content of the electromagnetic showers, the muon pair production channel and hence the LPM effect on this is generally neglected. Based on our study of LPM effect on muon production, we raise the possibility that the enhancement in the ratio of muon to electron pair production could explain the above puzzle. In Migdal's formulation (1956) natural system of units is used and electron mass does not appear explicitly. We rewrite his results showing mass (m) dependence explicitly so that they could be used for muons as well as electrons. We find the probability of pair production per unit length by a photon of energy E in a medium of density ρ, atomic number Z, and atomic mass A is

$$(W_p)_{LPM}dv = (4\alpha Ne^4/3m_e^2c^4)(m_e/m)^2[(\rho Z^2/A)ln(190/Z^{1/3})]$$

$$\times\zeta(s)[G(s) + 2v^2 + (1-v)^2]\phi(s)]dv \qquad (1)$$

Here, N is the Avogadro number, e the electron charge, v is the fraction of energy which is carried by one of the pair particles, and the functions ζ, G, ϕ and their dimensionless argument s are as introduced by Migdal. The parameter s with its mass dependence shown explicitly is,

$$s = (\alpha m_e^4 c^8/128\pi N e^6)^{1/2}(m/m_e)^2[(\rho Z^2/A)ln(190/Z^{1/3})]^{-1/2}$$

$$\times[v(1-v)E]^{-1/2}[\zeta(s)]^{-1/2} \tag{2}$$

The functions $\varphi(s)$ and $G(s)$ approach zero as $s \to 0$ and approach unity as $s \to \infty$. Since s is proportional to $E^{-1/2}$, these functions cause the suppression at high energies but at low energies $(W_p)_{LPM}$ will become identical to the BH cross section. The limiting behavior of the two suppressive functions in $(W_p)_{LPM}$ and the explicit mass dependences of $(W_p)_{LPM}$ and s show that the suppression of the pair production for muons starts at higher energies compared to electrons. Furthermore, the ratio $(W_\mu/W_e)_{LPM}$approaches unity as $E \to \infty$. That is, for gamma rays of extremely high energies in dense media, the probability of producing pair of electrons, muons, or even taus, will be nearly the same.

Integrating $(W_p)_{LPM}$ over v gives the total pair production probability which is shown in Fig. 1 for electron and muon pairs. The ratio of muon to electron total pair production probabilities for six various media, including those used in the SLAC experiments, are shown in Fig. 2. For each medium, below a certain energy the ratio of muon to electron pair production is just $(m_e/m_\mu)^2$ and above this it increases rather steeply. At high enough energies the ratio of muon to electron pair production probability approaches unity.

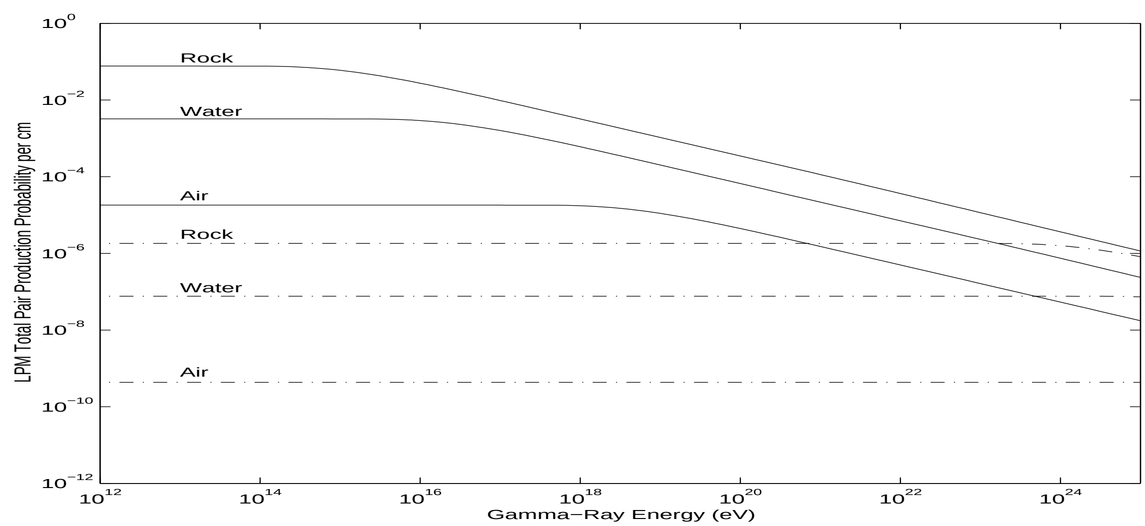

Figure 1: LPM pair production probability per centimeter for electrons (solid) and muons (dashed).

Effect on Muon Content of Air Showers: If the ratio of muon photoproduction to electron pair production cross section is defined as R, simple arguments (Gaisser 1990) show that

$$N_\mu^{(\gamma)} \sim R \times ln(E/1GeV) \times N_\mu^{(p)} \tag{3}$$

where $N_\mu^{(\gamma)}$and $N_\mu^{(p)}$are the number of GeV muons produced in showers initiated by photons and by protons, respectively, and E is the primary energy. At 10^{16} eV, with R =1.4/500, the ratio $N_\mu^{(\gamma)}/N_\mu^{(\gamma)}$ would be about 0.1 and the photon shower is called a muon-poor shower. However, at higher energies

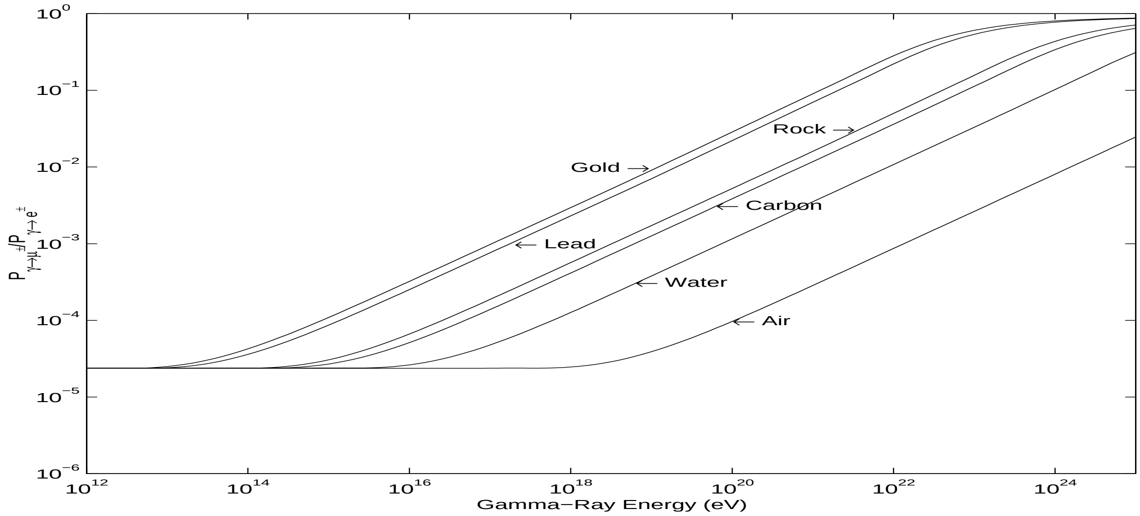

Figure 2: LPM ratio of muon to electron pair production probability for six different media.

the LPM suppression of the electron pair production will cause an increase in R. Furthermore, the muon photoproduction grows logarithmically with energy above 10 GeV. Thus, at a certain energy we will have about equal number of muons produced in showers initiated by photons and by protons. For sea level air, and for standard rock, these energies are about 10^{19} eV $2{\times}10^{17}$ eV, respectively. Thus, if a source sporadically emits gamma rays of energies higher than $5{\times}10^{19}$eV, and, if a fair number of gamma rays of energies higher than $5{\times}10^{17}$ eV reach the ground surface, LPM effect could produce the muon-rich showers observed in EAS experiments and also the anomalous muon fluxes observed in the underground experiments.

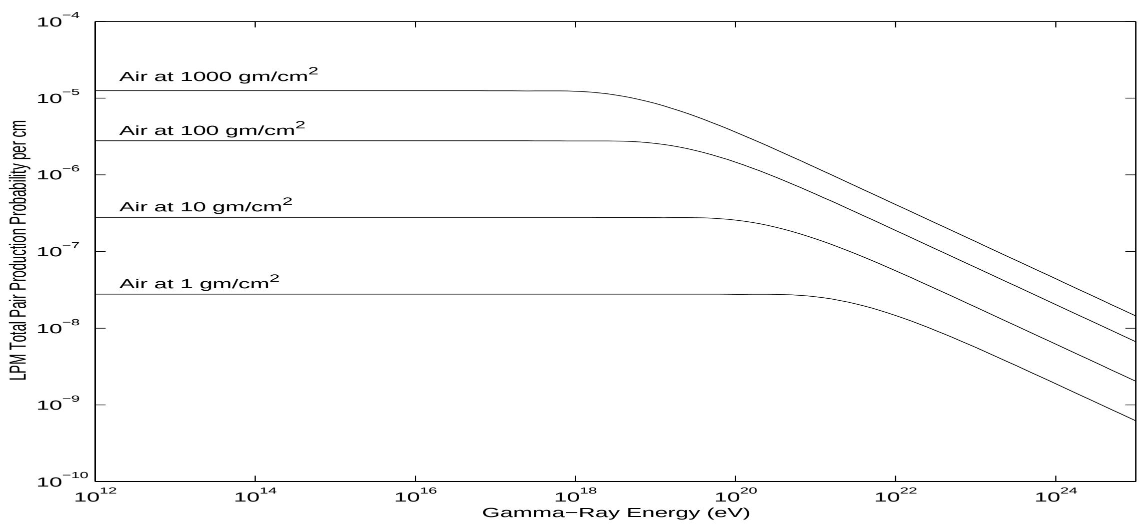

Figure 3: LPM electron pair production probability per centimeter in air at different depths.

Since the LPM effect is very sensitive to density, one has to account for the variation of LPM suppression at different atmospheric depths. Fig. 3 shows the LPM total pair production probability in air at different depths. We use this depth dependent probability to calculate the total probability of producing an electron pair up to any depth. Fig. 4 shows the result as a function of atmospheric depth for photons vertically entering the top of the atmosphere. At low energies results are identical to that for 10^{16} eV and identical to that using BH theory. It is seen that 10^{21} eV photons will have about 65% probability of vertically penetrating to the sea level without making their first interaction. EHE gamma rays coming at large zenith angles near horizon traversing through $\sim$8 times more air mass than those coming vertically, will have a much higher probability of interaction for developing an EAS. And, as discussed above, such showers initiated by EHE photons will be muon rich. Thus the zenith-angle dependent result of the recent observations (Yamashita et al. 1996) could simply be explained by the LPM effect without recourse to Ruddick's model of cygnets.

Our study suggests that a selection criterion based on the muon content of the air showers is not an appropriate one at EHEs. Due to the LPM suppression, detection of air showers initiated by EHE gamma rays is more probable at large zenith angles compared to the vertical direction. Thus, comparing observations when the source is near zenith to that when it is near horizon may turn out to be more rewarding for a positive source detection.

References:

Battistoni, G. et al. 1985, Phys. Lett., **155B**, 465.
Gaisser, T. K. 1990, Cosmic Rays & Particle Physics, Cambridge Press.
Marshak, M. L. et al. 1985, Phys. Rev. Lett., **54**, 2079.
Migdal, A. B. 1956, Phys. Rev., **103**, 1811.
Ruddick, K. 1986, Phys. Rev. Lett. , **57**, 531.
Samorsky, M. and Stamm, W. 1983, 18th ICRC, Bangalore, **11** , 244.
Yamashita, Y. et al. 1996, Nucl. Instr. & Methods, **A374**, 245.

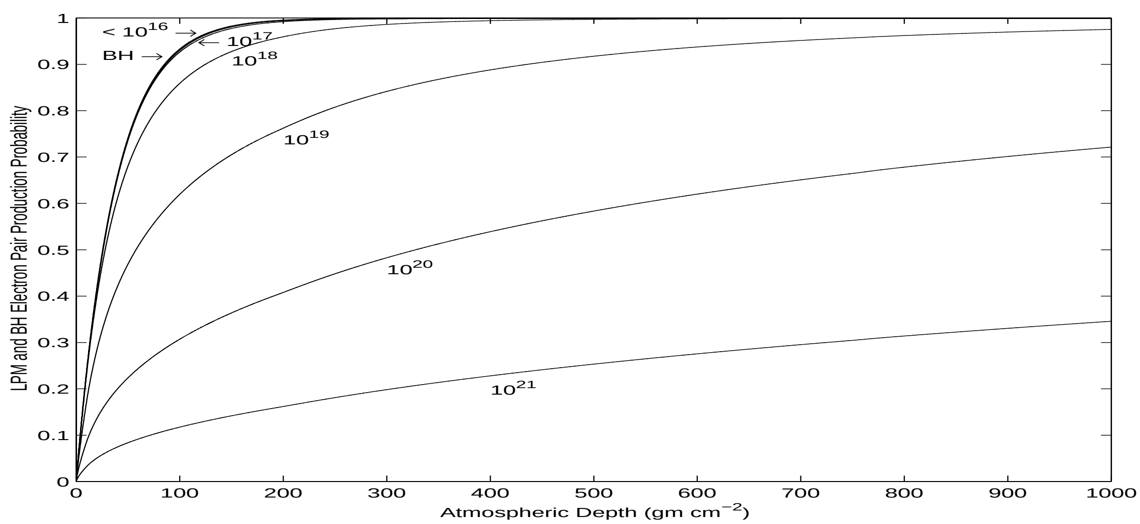

Figure 4: Total LPM electron pair production probability for photons vertically entering the atmosphere.