LIMITS ON DEEPLY PENETRATING PARTICLES IN THE $>10^{17}$ EV COSMIC RAY FLUX

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ABSTRACT

We report on a search for deeply penetrating particles in the $>10^{17}$ eV cosmic ray flux. No such events have been found in 8.2×10^6 sec of running time. We consequently set limits on the following: quark-matter in the primary cosmic ray flux; long-lived, weakly interacting particles produced in p-air collisions; the astrophysical neutrino flux. In particular, the neutrino flux limit at 10^{17} eV implies that $\bar{z}$, the red shift of maximum activity is <10 in the model of Hill and Schramm[6].

1. Introduction. We report on a search for deeply penetrating particles in the $>10^{17}$ eV cosmic ray flux. The search was performed using the University of Utah Fly's Eye detector[1], as part of its normal operation. No unusual deeply penetrating events have been found in 8.2×10^6 sec of running time.

We consider the following as candidate sources for such events (2): a. metastable quark matter as part of the primary cosmic ray flux; b. taus and other long-lived particles produced in the interaction of the primary cosmic ray flux with the atmosphere; c. weakly interacting particles of astrophysical origin such as neutrinos.

2. Search Philosophy. We search for deeply penetrating particles in two ways. EAS's observed in the Fly's Eye fiducial volume with $80<\theta_z<90$ typically must traverse >3000 g/cm^2 of atmosphere before interacting. We expect to see no such events from normal hadronic interactions in our exposure time. Upward EAS's must originate in the Earth and hence must be produced by weakly interacting particles. Figures 1 and 2 show the observed zenith angle and depth of first observed interaction (Xo) distributions in our data. Note that the Xo distribution extends beyond the expected distribution of the actual point of first

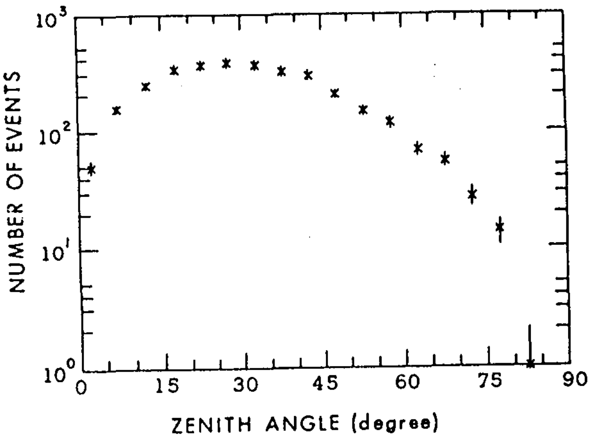

Figure 1

Zenith Angle Distribution

interaction since Xo is always an upper limit on the actual interaction length.

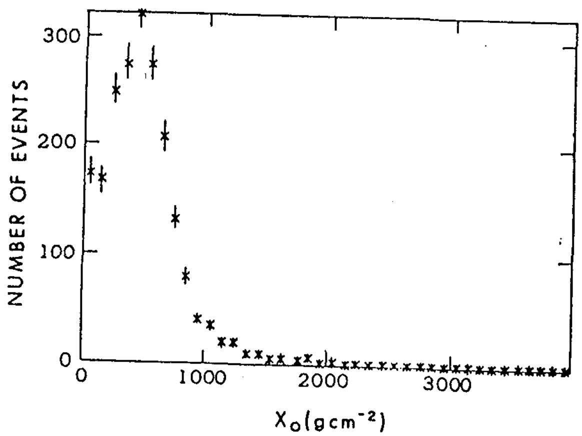

Figure 2

Depth of First Observed Interaction X_0

3. Quark Matter Limits. We search for metastable quark matter globs exploding deep in the atmosphere via the mechanism proposed by Bjorkien and McLerran[3]. In that picture, quark matter globs of a given baryon number No will explode at a given atmospheric depth, independent of initial energy (assuming they have not ranged out before exploding). We detect such events by searching for downward EAS with Xo between 3000 and 10000 g/cm^2. Table 1 gives resultant quark matter flux limits in $(cm^2 sec\ sr)^{-1}$ as a function of explosion depth and explosion energy. The 10^{15} eV data point is derived by assuming that the Mt. Chacaltaya Centauro events[4] are quark-matter explosions.

TABLE 1
Limits on quark-matter flux in the primary cosmic-ray spectrum in units of $(cm^2 sec\ sr)^{-1}$

Explosion depth g/cm^2	Explosion energy (eV)	10^{15}	10^{18}	10^{19}
500		$3x10^{-14}$		
3000			$1.0x10^{-18}$	$3.7x10^{-19}$
6000			$8.8x10^{-19}$	$1.4x10^{-19}$
9000			$1.3x10^{-18}$	$2.1x10^{-19}$

4. Limits on Long-Lived Weakly Interacting Particle Production. Hadronic decays of $>10^{17}$ eV taus and tau like particles produced in the interactions of the primary cosmic-ray flux with the atmosphere are possible sources of deeply penetrating downward EAS. Very distant cosmic ray interactions, not themselves detectable by the Fly's Eye, could produce taus which penetrate into the Eye's fiducial volume and decay into observable EAS's. We set limits on tau production cross sections by using the known cosmic ray flux intensity for $10^{17} < E < 10^{19}$ eV and the known tau lifetime and branching ratios. Our sensitivity for such decays is maximized for $1.0<X<.1$ and $10^{18}<E<10^{19}$ where $X = E\tau/Ep$ and Ep is the energy of the primary particle. In this interval, we set a limit on $(\sigma_\tau/\sigma_{tot}) \cdot n(X)$ where σ_τ/σ_{tot} is the probability of producing a tau in a cosmic ray interaction and n(X) is the normalized tau distribution function for such interactions. We find $\sigma_\tau/\sigma_{tot} \cdot n(X)$ is less than $4.0x10^{-2}$ and $1.3x10^{-1}$ for X=1.0 and

X=0.5 respectively. If the cosmic ray flux at these energies is primarily composed of protons, we find, using our measured p-air cross section of 520 mb[5], that $\sigma_\tau \cdot n(X) < 20$ mb for X=1.0 and <69 mb for X=.5.

We also set limits as a function of the decay length on production cross sections for hypothetical weakly interacting particles produced in cosmic ray interactions with decay lengths $20 < c\gamma\tau < 500$ km (see Table 2). These are assumed to decay into hadron and/or electrons with a branching ratio of 0.5.

TABLE 2

Limits on $(\sigma/\sigma_{tot})n(x)$ for weakly interacting particles in cosmic-ray-air interactions as a function of $c\gamma t$ and X.

E_p(eV)	$c\gamma\tau$(km) 50	100	200	500	1000
X=1					
1.0×10^{17}	5.9×10^{-3}	2.2×10^{-3}	1.3×10^{-3}	1.2×10^{-3}	1.3×10^{-3}
1.0×10^{18}	8.8×10^{-2}	3.6×10^{-2}	2.2×10^{-2}	1.9×10^{-2}	2.2×10^{-2}
1.0×10^{19}	6.1×10^{-1}	2.5×10^{-1}	1.5×10^{-1}	1.2×10^{-1}	1.3×10^{-1}
X=0.5					
4.10^{17}	4.4×10^{-2}	1.8×10^{-2}	1.1×10^{-2}	8.8×10^{-3}	1.0×10^{-2}
1.0×10^{18}	1.3×10^{-1}	5.4×10^{-2}	3.4×10^{-2}	2.8×10^{-2}	2.8×10^{-2}
1.0×10^{19}		4.4×10^{-1}	2.6×10^{-1}	2.2×10^{-1}	2.7×10^{-1}
X=0.1					
1.0×10^{18}		2.2×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	1.9×10^{-1}

5. Limits on the Ultra-high energy Neutrino Flux. We have recently reported limits on astrophysical electron neutrino fluxes at energies of $>10^{18}$ eV[2]. Here we update the flux limits and extend them down to 10^{17} eV.

If the neutrino interaction cross section for $E > 10^{17}$ eV is 10^{-33}cm^2 as predicted by the standard model, we maximize our sensitivity to such a neutrino flux by searching for upward EAS's. Electron neutrino interactions in the earth's crust will be detectable at depths of hundreds of meters below the surface because the LPM effect slows down the rate of shower development for the high energy electron produced in the interaction. This allows the electron shower to emerge into the atmosphere and be detected. Figure 3 shows the electron shower size at shower maximum as a function of electron energy and depth of interaction in the crust. Table 3 gives limits on the neutrino flux as a function of energy. Calculations by Hill and Schramm[6] indicate that if the neutrino flux is produced by interaction of UHE protons with the 2.7 deg black body radiation, then the flux at 10^{17} eV is sensitive to $\bar{z}$, the red-shift of maximum activity. Their calculation indicates that with our flux limit of $2.0\times10^{-12}\nu/\text{cm}^2$sec str at 10^{17} eV, $\bar{z}$ must be less than or equal to 10.

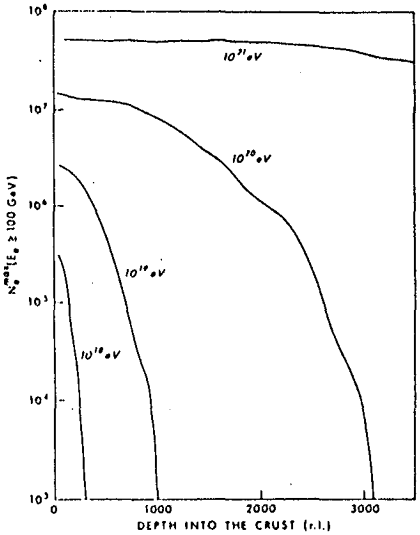

Figure 3. Electron Shower Size at Shower Maximum as a Function of Electron Energy and Depth of Interaction in the Crust.

Figure 3

TABLE 3

Limits on ν_e flux based on upward events (ν/cm^{2}sec str.) and $\sigma_\nu = 10^{-33}$cm^2.

E_ν(eV)	10^{17}	10^{18}	10^{19}	10^{20}	10^{21}
	1.3×10^{-12}	5.3×10^{-14}	6.6×10^{-15}	2.8×10^{-16}	3.6×10^{-17}

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