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Acceptance of the Pierre Auger Southern Observatory fluorescence detector to neutrino-like air showers

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Abstract. We compute the acceptance of the Southern Pierre Auger Fluorescence Detectors to neutrino-like showers with zenith angles greater than 80° and, based on modern neutrino flux models, estimate that the rate for detection of showers arising from $(\nu_e + \bar{\nu}_e)N$ via charged-current interactions will be $\sim 2/y$ at best above 10 EeV.

1 Introduction

The Pierre Auger Observatory (PAO) will be able to detect EAS originated by 10 EeV and higher energy primaries with zenith angles ranging from 0° to 60°. For more inclined primaries the electromagnetic component becomes dramatically reduced due to the increase in slant atmospheric depth. The column depth encountered by a vertical primary is $\sim\ 1030\ g/cm^2$ while a primary reaching Earth tangentially will encounter an equivalent column depth of $\sim\ 36,000\ g/cm^2$. This means that strongly interacting primaries entering Earth's atmosphere with large zenithal angles will have their shower development phase at higher altitudes than vertical or near vertical ones where the lower density encountered will translate into larger hadron mean free path, allowing the mesons from the hadronic cascade to decay at higher energies, resulting in a narrow muon beam reaching ground. On the other hand, EAS initiated by weakly interacting particles or neutrinos (ν-like showers) will occur, if at all, at lower altitudes where the atmospheric density is higher resulting in both direct electromagnetic and muonic components reaching Earth. Despite the fact that neutrino interaction lengths above 10 EeV are still a few orders of magnitude larger than the path length encountered by primaries reaching Earth tangentially it is possible that cosmic ray observatories with $km^3 \cdot sr$ water equivalent acceptances may detect some of these ν-like showers.

For the case of the PAO particle-detector, surface array acceptances have been estimated to be (in units of $km^3 \cdot sr$) 2.3 at 0.1 EeV, 17.2 at 1 EeV, and 43.2 at 10 EeV (see Billoir (1997)) where ν-like showers have been approximated by highly inclined proton showers injected at low altitudes with a fraction of the neutrino energy (for neutral and charged currents giving a non-decaying heavy lepton), or a mixture of proton and photon showers with the full energy of the neutrino (charged currents supplying an electron). Gandhi et al. (1998) have calculated event rates using a variety of models for neutrino fluxes from AGNs, gamma-ray bursters, topological defects, and cosmic-ray interactions in the atmosphere (see figure 1) and have found that for the PAO surface array the highest rates arise from $(\nu_e,\bar{\nu}_e)N$ charged-current interactions in the AGN-M95 model of Mannheim (1995) and AGN-P96 model of Protheroe (1996). These estimates are listed in table 1. (Note that the ν_e+$\bar{\nu}_e$ flux from the $\pi \rightarrow \mu \rightarrow$ e decay chain is $\sim$ half of the ν_μ+$\bar{\nu}_\mu$ flux).

Surface detectors face, however, the great difficulty of discriminating the few ν-like showers from abundant muonic-tale background originating from very inclined hadronic showers (see Ave et al. (2000)).

Model	$E_{sh} \geq 10^8\ GeV$	$E_{sh} \geq 10^9\ GeV$
AGN-M95	6.1	3.3
AGN-P96	8.9	2.6

Table 1. Predicted PAO surface array annual event rates for nearly horizontal air showers induced by $(\nu_e,\bar{\nu}_e)N$ charged-current interactions taken from Gandhi et al. (1998). (The CTEQ4-DIS in this reference has been used).

In this paper we present a study of the PAO Fluorescence Detector (FD) acceptance to deep penetrating exotic primaries. This paper is divided as follows: Firstly we present a review of the Fluorescence technique followed by a brief discussion of hadron initiated HAS, and conclude presenting acceptance and event rates of the Southern Auger FD to ν-like EAS.

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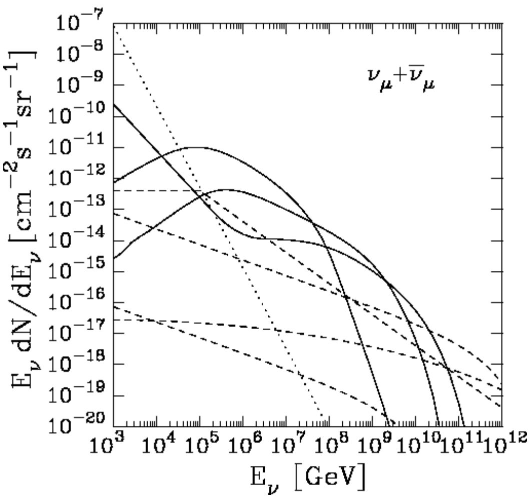

Fig. 1. ν_μ+$\bar{\nu}_\mu$ fluxes on Earth's surface. AGN model predictions are in solid lines. At 1 TeV neutrino energy and decreasing in magnitude these are: the pγ model of Mannheim (1995) (AGN-M95), of Stecker et al. (1991) (escaled by 0.3), and of Protheroe (1996) (AGN-P96). Following the same convention, the dash lines correspond to the models of: Waxman and Bachall (1997), Wichoski et al. (1998)(denoted TD-WMB12 and TD-WMB16), and of Sigl et al. (1997). The angle-averaged atmospheric neutrino flux is represented by the dotted line.

2 Fluorescence Technique Review

Fluorescence telescopes detect the optical fluorescence from the ionization of air N_2 molecules when cosmic rays shoot through the atmosphere.

The fluorescence yield has proven to be proportional to charged-particle energy deposit (see Kakimoto et al. (1996)) and can vary from 3 to 5.6 photons/m/charged-particle depending on altitude and temperature, isotropically emmitted, with a spectrum ranging from ~ 280 to $450\ nm$.

The amount of fluorescence light generated per shower electron is small. However, EHE cosmic rays showering through the atmosphere produce enough electrons that the isotropically emitted fluorescence light can be detected by photomultiplier tubes (PMTs) many km away from its point of emission. As an illustrative example, a 10 EeV primary will produce an EAS with $\sim 6 \cdot 10^9\ e^-$ near shower maximun and will dissipate more than 0.1 J in $\sim 30\mu s$.

After subtracting for atmospheric transmision, camera obscuration, mirror reflectivity, filter transmittance, and PMT quantum efficiency, only a small fraction of fluorescence photons that were within the PMT's FOV at emission, $(3-5)\%$ in average, will be converted into photoelectrons (pes).

The main source of background light comes from the night sky. The HiRes experiment has measured this number to be (filters included) 40 photons$/m^2/deg^2/\mu s$ (27.1 $pe/\mu s$) in the frequency range of interest for fluorescence detection (see Bird et al. (1993)). These numbers can be better understood by saying that fluorescence light can be detected, in average, as far as 30 km or 50 km when produced by 10 EeV or 100 EeV primaries, respectively, with zenith angles up to 60 degrees.

3 HAS induced from strongly interacting particles

Monte Carlo simulations of EAS have shown that for $10^{19}\ eV$ primaries and depths exceeding $3,000\ g/cm^2$ (equivalent to $70°$ slant depths) the electromagnetic component is highly attenuated (see Ave et al. (2000)). Thus, depending upon the geometry of a particular shower with respect to the viewing Fluorescence Eyes, we can subdivide very inclined hadronic showers into two categories: showers viewed way past shower maximum, and showers viewed near shower maximum. A complete characterization of both will require a Monte Carlo which is in progress at the moment. However, in what follows, we make some observations.

3.1 Near-horizontal hadronic EAS past shower maximum

Simulations of a 10 EeV proton primary by Ave et al. (2000) have shown that at depths exceeding $70°$ the N_e is $\sim 7 \cdot 10^6\ e^-$, which is almost three orders of magnitude smaller than the number at shower maximum, and arises mainly from μ-decay. We can make a simple calculation and find out up to what distances will the fluorescence due to the previous electron size trigger a FD PMT. In the case of the PAO-FD a single PMT triggers when the sum of any 10 consecutive ADC (10 MHz) readings gives a total photoelectron (pe) count greater or equal to $48\ pe$ (equivalent to 4σ, with $\sigma = \sqrt{2}7.1$ since the PMT anode is AC-coupled). A simple calculation shows that if the camera-shower distance is greater than $\sim 1\ km$ there will be no PMT trigger. This will result in short pmt pulses, making such showers difficult to reconstruct. Given that the PAO-FD will look only up to $\sim 32°$ above horizon, these showers will have to pass at a height above gound smaller than $\sim 500\ m$ in order to trigger enough PMTs so as to produce a mirror trigger. Aerosol scattering's intrincic difficulty to model shall, in addition, contribute to the difficulty in analysis of any such data.

For higher energy primaries with zenith angles greater than $70°$ we assume that N_e arises from μ-decay, and that it scales with muon number. Ave et al. (2000) have calculated the number of muons (N_μ) produced by 10 EeV proton and Iron primaries, and have found that N_μ has a power law dependance on primary energy with exponent close to 0.9 (depending on primary composition). If we take an intermediate case (mixture of proton and Iron) then we find that very inclined 100 EeV primaries will produce ~ 8.2 times more N_e than a 10 EeV primary. In this case fluorescence light reaching the FD from distances smaller than $\sim 3.5\ km$ will trigger pixels (at the 4σ level). The same difficulty to analyze such data applies as in the previous case.

We conclude saying that detecting fluorescence light from highly inclined hadronic primaries (viewed way past maximum) having energies below $\sim$ 100 EeV would be a cumbersome task.

3.2 Near horizontal hadronic EAS near shower maximum

In principle, and depending upon primary energy, combinations of zenith angles and heights above ground -amounting to a $\sim 1,000\ g/cm^2$ equivalent column depth of traversed atmosphere- may produce mirror triggers. Two examples are: 1) horizontal hadrons whose projected trajectory overpasses ground at 30 km height, and 2) hadrons entering earth's atmosphere with a zenith angle of 80 degrees whose projected trajectory would overpass ground at $\sim 14\ km$ height. In both cases it is possible that hadrons carrying an energy barely greater than 10 EeV may trigger a mirror. These showers will be very interesting since their observed profiles could be very different from the non highly-inclined ones.

4 Neutrino-like Showers: Acceptance and Rates

We have performed a Monte Carlo calculation of the Southern Auger FD acceptance to HAS. We have approximated neutrino EAS by proton showers interacting deep in the atmosphere using the Gaisser-Hillas function. In this simulation Cerenkov emission was not taken into account.

We have thrown neutrinos with zenith angles equal or greater than 80 degrees, and have allowed the primary to have its first interaction anywhere within a cylindrical volumen centered directly above the Central Eye. We have varied this volumen and have found that the acceptance (product of target volume and detection efficiency) reaches a maximum (which depends on primary energy) and then falls down (see figure 2).

The fluorescence technique has the great advantage that fluorescence light can be detected very far away from its point of emission, unlike the surface array which is constrained to lateral distances (vertical in the case of HAS) of a few km maximum, (3-5) km, from ground level. Two effects contribute to this: 1. that the atmosphere becomes thinner with altitude making the EAS longitudinal development extend over a larger distance enhancing the probability of detection by an -otherwise- distant eye; and 2) that the horizontal Rayleigh photon mean free path increases greatly with height (from $\sim (10-20)$ at ground level km to $\sim (100-200)$ km at 15 km a.s.l.). Therefore, the acceptance will largely increase with increasing shower energy. In figure 3 we plot the ground-projected trayectories of all 10 and 100 EeV EAS detected by the PAO central eye.

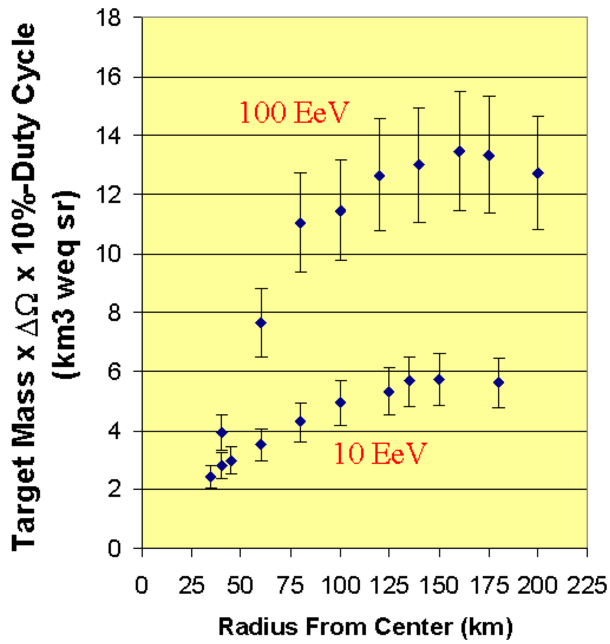

Fig. 2. Acceptance at 10 and 100 EeV shower energy to neutrinos incident in the Earth's atmosphere with zenith angles above 80 degrees.

In figure 4 we plot the fluorescence exposure (Acceptance times duty cycle, taken to be 0.1) calculated in this work, as well as that calculated for the Telescope Array (see The Telescope Array Design Report (2000)). Calculated values are, in units of $km^3\ weq \cdot sr$: 6 and 13 at 10 EeV and 100 EeV, respectively. Despite the increase in acceptance with increasing primary energy, actual detection rates are, however, limited by the FD duty cycle which is $\sim 10\%$. At 100 EeV the calculated FD acceptance still falls below that of the surface array acceptance. For comparison, also shown in figure 2 are the acceptances calculated by Billoir (1997) for the Surface Array. We may note that at 10 EeV the Telescope Array exposure reaches a value of $\sim 30\ km^3\ w.eq. \cdot sr$, which is a factor of 5 times larger than that of Auger-South at the same energy. This is in principle, and making a very rough comparison, in accordance with the fact that Telescope Array will employ ~ 5 times as many telescopes as Auger.

We have followed Gandhi et al. (1998) in order to make predictions for the PAO-FD ν-like events. We take their cross sections for $(\nu_e,\bar{\nu}_e)N$ charged-current interactions according to the CTEQ4-DIS parton distribution functions. We find that at 10 EeV the FD will be most sensitive to neutrinos and antineutrinos arising in the AGN-M95 model of Mannheim (1995). At 100 EeV, however, the FD will be more sensitive to neutrinos arising from decays of topological defects in the TD-WM16 model of Wichoski et al. (1998). In either case, the estimated differential event rate is $(1-2)/y$ at best. Predicted are rates summarized on table 2.

Finally, let us mention that random fluctuations of the dark

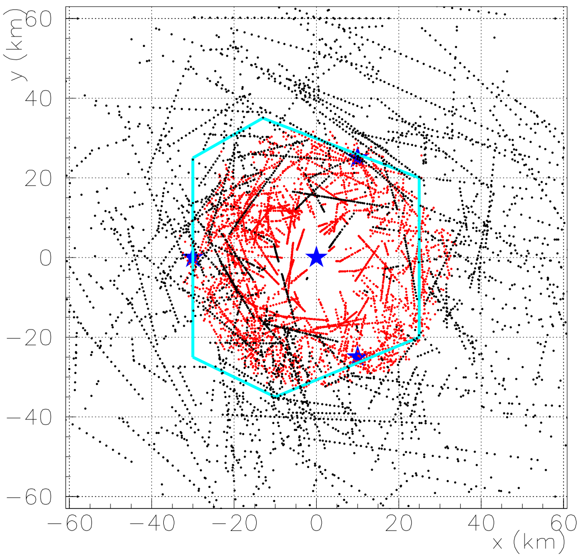

Fig. 3. Central eye sensitivity to ν-like EAS. Ground-projected trayectories of showers triggering the PAO central Fluorescence detector. Black and red dots refer to 100 EeV and 10 EeV primaries, respectively. The position of the 4 Fluorescence detectors are marked with a star. The polygon marks the boundary of the $3,000 km^2$ surface array.

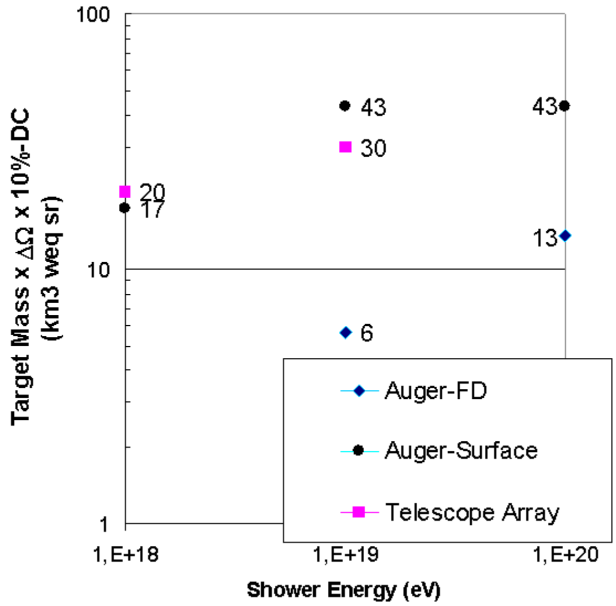

Fig. 4. Acceptance of ground surface array and exposure of Fluorescence detectors to ν-like showers. In the case of the fluorescence detectors, the predicted Telescope Array exposure at 1 EeV and 10 EeV is also shown.

Model	$E_{sh} = 10^{19}\ eV$	$E_{sh} = 10^{20}\ eV$
AGN-M95	≤ 1	
TD-WMB12		≤ 2

Table 2. Estimated PAO-FD annual event rates for horizontal air showers induced by $(\nu_e,\bar{\nu}_e)N$ charged-current interactions. The CTEQ4-DIS was taken form Gandhi et al. (1998)

night background giving rise to fake near-horizontal showers can be discriminated easily: For a pixel trigger threshold set at 4σ (100 Hz pixel trigger rate) and a 4-pixel-fold-coincidence time window of $50\ \mu s$ the rate of randoms is of the order of 10^{-4} Hz (or one every 3 hours) which is very high. However, if we demand a pixel count of 24 pe above background ($4.6\ \sigma$) this will lower the rate of random single pixel triggers to 10 Hz, and the rate of 4-fold random coincidences to 10^{-8} Hz (or less than 1 per every 3 years!).

References

M. Ave, R.A. Vázquez, E.Zas, J.A. Hinton and A.A. Watson, In press.

Pierre Billoir "Estimation of the acceptance of the Auger ground detector to quasi horizontal showers induced deeply in the atmosphere", Pierre Auger project note GAP-97-049, available at http://www.auger.org/admin.

K.S. Capelle, J.W. Cronin, G. Parente, and E. Zas, "On the detection of ultrahigh-energy neutrinos with the Auger observatory", Astropart. Phys. 8, 321 (1998) (also as astro-ph/9801313).

R. Gandhi, C. Quigg, M.H. Reno and I. Sarcevic. hep-ph/9807264 6Jul 1998.

D.J. Bird et al., 23rd ICRC (Calgary) 2 (1993) 450.

F. Kakimoto, E.C. Loh, M. Nagano, H. Okuno, M. Teshima and S. Ueno. Nucl. Instr. Meth A 372 (1996) 527-533.

K. Mannheim, Astropart. Phys. 3, 295 (1995).

R. J. Protheroe, astro-ph/9607165.

G. Sigl, S. Lee, D. N. Schramm and P. Coppi, Phys. Lett. B392, 129 (1997).

F. W. Stecker, C. Done, M. H. Salamon, and P. Sommers, Phys. Rev. Lett. 66, 2697 (1991); ibid. 69, 2738E (1992).

The Telescope Array Collaboration Design Report, 19 July 2000.

E. Waxman and J. Bachall, Phys. Rev. Lett. 78, 2292(1997).

U.F. Wichoski, J.H. MacGibbon, and R.H. Brandenberger, "High Energy Neutrinos, Photons and Cosmic Rays from Non-Scaling Cosmic Strings", BROWN-HET-1115 (also as hep-ph/9805419).