Detection of Neutrino-Induced Air Showers

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Overview

• Where might \( \sim 10^{18} \text{ eV} \) neutrinos come from?
• Principles of detection
• Auger observatory and it potential as a high energy neutrino detector
• Other shower detectors
  • EUSO
  • ASHRA
The Neutrino - Cosmic Ray connection

• **UHECR mechanisms produce \( \nu \)**
  - By interaction (matter/radiation) [Fermi]
  - By fragmentation [“Top Down”]

• **UHECR Transport**
  - Interaction with CMB
  - [GZK cutoff \( \Leftrightarrow \nu\)-spectrum:
    \[ \gamma_{2.7K} + p \rightarrow n + \pi^+ \]

• **Detection** [CR and \( \nu \) produce Air Showers]
  - Auger
  - EUSO, ASHRA ...
ν / p flux ratio

Step towards UHECR source origin

• Acceleration

\[
\begin{array}{c}
p + \gamma \\
p + p
\end{array}
\]

\[
p : \nu \\
1 : 6
\]

• Fragmentation

\[
\begin{array}{c}
\nu, \mu, \tau \\
\gamma \\
p, \pi^+, \pi^-, \eta, \ldots
\end{array}
\]

\[
\begin{array}{c}
\gamma : \nu, \mu, \tau \\
2 : 4 : 2
\end{array}
\]

\[
p : \gamma : \nu \\
0.09 : 2 : 6
\]

BUT, keep in mind, UHECR might be heavy, nuclei:

He\(^4\) ..... Fe\(^{56}\)
Figure 2: The neutrino spectrum produced in the propagation of the UHE heavy nuclei — $^4$He (green dashed), $^{16}$O (red dot-dashed) and $^{56}$Fe (blue dots) — compared to the result for protons (black solid). Note that the spectra for oxygen and iron have been multiplied by a factor of 3.
νs can induce air showers

- NC & CC $\mu$ or $\tau$ flavour
  - Hadronic showers (fewer particles)
  - [Double showers ($\tau$ flavor)]

- CC (e-flavour)
  - “Mixed showers”
    - $\langle y \rangle = 0.2 \Rightarrow 20\%$ Energy to hadronic shower
    - 80\% Energy to electromagnetic shower
Neutrino shower characterization

- Large fluctuations
- $X_{\text{max}}$ fluctuations
- Radius of Curvature
- Risetime
- Lateral distribution (steeper)
- Inclined showers (identify)
- $\mu / (\gamma e)$ ratio (cc/nc, flv)

at any depth
Concept of neutrino detection via horizontal showers:
Berezinsky and Smirnov 1975; Capelle et al 1998

20% em halo from decay and interaction
The Pierre Auger Observatory marries two well-established techniques

AIM: Study of UHECR – Neutrino search comes free!

Fluorescence

Array of water Cherenkov detectors
Auger Southern Observatory: Malargüe, Mendoza (Argentina)

- 1600 tanks
- 4 Eyes
# Status of the Auger Observatory

**Auger Office Complex**

<table>
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<tr>
<th>15 Countries</th>
<th>60+ Institutions</th>
<th>350+ Scientists</th>
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**Ground breaking Ceremony: 17 March 1999**
Communications antenna

GPS antenna

Electronics enclosure

Solar panels

Battery box

Plastic tank with 12 tons of water

3 - nine inch photomultiplier tubes
Continuous calibration with background muons

Muon decay spectrum

Electron charge (about 15% of the muon charge)

Muon charge spectrum

Compare

ICARUS T600

Liquid Argon TPC detector

Muons decay spectrum from ICARUS

Data
SM
Best fit

ICARUS T600

Fully operating for a year

Los Leones

fully operating since July

Coihueco

Los Morados – under construction
The Fluorescence Detectors

4 “Eyes” (6 telescope units)
Each unit:
3.4 meter mirror
Camera: 440 PMTs
341 SD tanks running (June 10th)

On-line monitoring: “Big Brother”

As at 17 August there are 407 tanks operating
Energy > $10^{19}$ eV

Good Progress in Analysis
Detailed studies under way
Inclined events are common.

5 May 2004      33 tanks $\theta=72^0$      R=37 km
FD reconstruction

Signal and timing
Direction & energy

Pixel geometry
shower-detector plane
$N_e$ maximum $\sim 7 \times 10^{10}$ for energy $= 10^{20}$ eV

Fluorescence energy $\sim 2 \times 10^{19}$ eV

Surface detector energy $\sim 2.1 \times 10^{19}$ eV

preliminary!
Effective target volume for neutrinos


• HAS with em component (conservative)
  – $\theta > 70^0$
  – 3 tanks in a row (trigger)
  – 1 VEM/m$^2$ in each tank (em only)

• Two cases:
  – Only impact inside the array
  – Include showers “over” the array
Auger $\nu$-acceptance

Acceptance ($\text{km}^{3} \text{w.e. eq. sr}$)

$\text{Shower Energy (GeV)}$

$10^{-1}$ $10^0$ $10^1$ $10^2$

$10^8$ $10^9$ $10^{10}$ $10^{11}$ $10^{12}$

em hadronic

$70^0$-$90^0$
# 207116: zenith angle = 13°

Eastings = 458740 ± 35 m
Northing = 6083187 ± 11 m
dt = 32.4 ns

Theta = 13.3 ± 0.7 deg
Phi = 50.1 ± 2.2 deg

R = 4.0 ± 0.2 km.

S(1000) = 67.27 ± 5.96 VEM
E = 16.05 EeV ± 9%
FADC traces for #207116

Distance ratio = 3.7  Density ratio = 134  R = 4 km
# 193485: zenith angle = 76°

Eastings: 458900 ± 183m
Northing: 6084974 ± 78m

\[ \text{dt} = 10.0\text{ns} \]

\[ \text{Theta} = 75.8 \pm 0.5 \text{deg} \]

\[ \text{Phi} = 11.6 \pm 0.4 \text{deg} \]

\[ R = 27.1 \pm 11.6 \text{ km} \]

\[ S(1000) = 2.64 \pm 0.57 \text{ VEM} \]

\[ E = 5.40 \text{ EeV} \pm 21\% \]
Distance ratio = 3.5  Density ratio = 7.5  R = 27 km
Tau neutrino detection

- Principle:
  - Interaction length in the earth ~ 300 km at $10^{18}$ eV
  - Tau time of flight ~ 50 km at $10^{18}$ eV
  - 1° below horizon $\Rightarrow$ 200 km of rock
  - Shower maximum ~10 km after decay
  In practice $85^\circ < \theta_z < 95^\circ$
  AUGER window: $10^{17}$ to $10^{20}$ eV

Paul Mantsch May 2002
\[ \nu_\tau \text{ acceptance} \]

Improve bounds at lower energies?


- **CC \( \nu_\tau \) interactions**
  - \( 180^\circ > \theta > 60^\circ \) (dominated by \([90^\circ - 91^\circ]\))
  - 4 tanks (trigger)
  - 0.3 VEM/m\(^2\) in each tank

- **Two cases:**
  - QuasiHorizontal \( \tau \) decays
  - Mountain interactions (<10%)

  (in progress: Santiago, Leeds, Naples, Paris)
Sensitivity (1/yr/decade of energy)
EUSO

Extreme Universe Space Observatory

an Explorative Mission
probing the Extreme of the Universe
using the Highest Energy Cosmic Rays and Neutrinos

doing Astronomy looking downward the Earth Atmosphere
Focal surface $\approx 2 \times 10^5$ pixels

Double side Fresnel lens

- Cerenkov
- Cosmic ray
- Fluorescence

$\approx 8 \text{ km}$
Figure 2.2-1 Schematic view of the EUSO main detector, the EECR/$\nu$ telescope.
Figure 6.3.1-1 Schematic view of a track along the two projection view (as registered by the read-out electronics). EAS simulated at energy $\sim 5 \times 10^{20}$ eV and arrival direction zenith angle $\sim 60^\circ$. 
EUSO ~ 300 x AGASA ~ 10 x Auger
EUSO (Instantaneous) ~ 3000 x AGASA ~ 100 x Auger
ESA recently decided NOT to proceed to Phase B.

Figure 6.2.3-3 Slant depth of the shower maximum ($X_{\text{max}}$) for protons (red) and neutrino (green) induced events. Same event sample as for fig 6.2.3-1.
New Eye for Particle Universe

Key Technology:

- **4M**-pixel CMOS sensor covering 50deg FOV

Leading Features:

- All-sky Survey
  => **Discovery Potential**

- 1arcmin directional accuracy
  => **Source ID**

- Simultaneous Detection for Cerenkov & Fluorescence
  => **Physics ID**

Pioneer Experiment for VHE Particle Astronomy:

Ashra-1 station
12 telescopes with 50deg FOV

whole hemisphere 48M-pixels
Ashra Project Plan

- **2002**: Phase 0 R&D
- **2003**: Sub-telescope prototype in labo.
- **2004**: Phase 1 Pioneering
  - 1 + 1/3 stations
- **2005**: 2 Mt.s on the Hawaii ls.
- **2006**: Complete 3 stations
- **2007**: Phase 2 High Statistics
  - 3 Mt.s on the Hawaii ls.
Fly’s Eye
Hi-Res
Auger Fluor.

Usual PMT array camera
=> resolution ~1°

PMT array: 1 deg resolution

Virgo cluster

ASHRA: 1 arc minute resolution
$	au$ neutrino detection: Earth and Mountain

**Tau Appearance**

**Vacuum Oscillation with Super-long Baseline**

- $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$
- Search $\Delta m^2 > 10^{-17} eV^2$
- pseudo-Dirac-$\nu$
  
  (Beacom et al., astro-ph/0307151)
Neutrino Sensitivity

- 1 event/year/decade of energy (curve)
- 90% upper limit assuming $E^{-2}$ flux (horizontal line)

$E_{\nu} > 10$ PeV

great chance for the first detection of UHE Neutrinos
Conclusions

Auger Observatory has POTENTIAL for \( \nu \)-detection
– at no extra cost

ASHRA has potential of significant improvement in angular resolution for UHECR and neutrinos
– but less sensitive than Auger

EUSO may fly on ISS via Japanese module and has great potential for neutrino detection
– if UHE neutrinos are sufficiently abundant

Thanks for inviting me to this marvellous meeting!