THE NUCLEAR MASS COMPOSITION OF UHECR WITH THE PIERRE AUGER OBSERVATORY

Rencontres de Moriond:
Very High Energy Phenomena in the Universe
La Thuile, 9th – 16th March 2013

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69° W, 35° S
1400m a.s.l. - X = 870g/cm²

1600 SD stations, 1.5km spacing
3000km²

Surface Detector (SD)

3000 km²

Fluorescence Detector (FD)

4 FD buildings
6 telescopes each

Taking data since 2004
Installation completed in 2008

+ Auger Enhancements: HEAT, AMIGA, Radio Array, ...
Surface Detector (SD)

Samples lateral density of charged particles at ground

Čerenkov water detector

- 10 m² water surface area
- 1.2m water depth (12 tons)
- 3 PMTs
- solar panel
- communications system
- 100% duty cycle

- Sensitive to muons, electrons and very high energy photons
- Signal proportional to geometric muon track length in water
- 85% of EM component is absorbed
Fluorescence Detector (FD)

Measures EM longitudinal shower profile

**Fluorescence Telescope**

- Schmidt optics
- $11\, \text{m}^2$ spherical mirror
- 440 PMTs at focal surface
- $30^\circ \times 30^\circ$ FoV ($180^\circ$ azimuth for 6 telescopes)
- Measure UV light (250 - 450 nm)
- ~13% duty cycle
- Full efficiency for $E > 10^{19}\,\text{eV}$
Event Reconstruction

SD

- Lateral Distribution Function (LDF)
- Energy estimation at 1000m from the shower core - $S(1000)$
- High statistics

FD

- Longitudinal Shower Profile
- Energy estimation by integral of longitudinal profile
- Direct $X_{\text{max}}$ measurement
- High precision energy measurement

Hybrid Events

- Measured by SD and FD
- FD provides energy calibration to SD
- Higher accuracy in shower parameters
Composition Sensitive Variables
Longitudinal EM Shower Profile

- $X_{\text{max}}$ correlates with first interaction point
- Proton showers reach the shower maximum later in the atmosphere
- Shower-to-shower fluctuations larger for proton primaries
- $X_{\text{max}}$ evolves with the energy of the primary by:

$$<X_{\text{max}}>=X_0+D_{10}(E/E_0A) \text{ (Elongation Rate)}$$

- $<X_{\text{max}}>$ is sensitive to changes in average cosmic ray composition with energy
- $\text{RMS}(X_{\text{max}})$ is sensitive to the shower-to-shower fluctuations
Selection Cuts

P. Facal, ICRC 2011

Data from December 2004 to September 2010

6744 events selected

Quality cuts

- Low aerosol content and cloud coverage
- $E > 10^{18} \text{eV}$ with at least one triggered SD station
- Angle towards the telescope above 20°
- $X_{max}$ inside the telescope FoV
- Event statistical uncertainty below 40g/cm²

Anti-bias cuts

- Viewable $X_{max}$ range large enough to accommodate the full $X_{max}$ distribution
- Zenith angle and distance to SD station must provide a trigger independent of the primary composition
$X_{\text{max}}$ Resolution

P. Facal, ICRC 2011

**Resolution**

- $< X_{\text{max}} >$: 22 g/cm$^2$ over all range
- $RMS(X_{\text{max}})$: 27 to 17 g/cm$^2$ as energy increases

**Systematics**

- $< X_{\text{max}} >$: 10 to 13 g/cm$^2$, increasing with energy
- $RMS(X_{\text{max}})$: 5 g/cm$^2$ over all range

Systematics cover:
- uncertainties in the calibration,
- atmospheric data and
- event reconstruction and selection
Full $X_{\text{max}}$ Distributions

As the energy increases:
- distributions become narrower, and
- deep $X_{\text{max}}$ tail becomes less evident

Interpretation, especially at high energy, is difficult since we have to rely on the extrapolation provided by the different models.
Results

Data best described by two slopes changing at

\[ \log_{10}(E/\text{eV}) < 18.38^{+0.07}_{-0.17} \]

\[ D_{10} = 82^{+48}_{-8} \text{g/cm}^2/\text{decade} \text{ (Low energy)} \]

\[ D_{10} = 27^{+3}_{-8} \text{g/cm}^2/\text{decade} \text{ (High energy)} \]

Slope change is nearly the energy of the ankle

Data is described by a mixed composition changing from a very light to a heavier composition

(CNO or higher) as energy increases, provided that the hadronic models are basically correct
Signal components of the SD FADC Traces

Hard to disentangle EM from muon signals

**EM signal**
- More affected by Multiple Scattering
  - Signal is spread out in time
  - Time distributions reflect the shower age
  - Dominate close to the shower core and low zenith angles

**Muon signal**
- Few interactions during propagation
  - Arrives first to the ground
  - Muon arrival time is related with the production distance
  - Dominate far from the shower core and at high zenith angles

Rise time ($t_{1/2}$): time required to go from 10% to 50% of the total integrated SD signal.

Rise time is related to the shower development, thus it is sensitive to the primary composition.
Asymmetry of the Signal Risetime

Vertical symmetry in the signals

Inclined asymmetry!!

Very inclined no asymmetry

\[ \langle t_{1/2}/r \rangle = a + b \cos \zeta \]
(by grouping events in E and sec\(\theta\) bins)

Early-late asymmetry \(b/a\).
\(\Theta\) is the \(b/a\) maximum,
is sensitive to the primary mass
D. Garcia-Pinto, ICRC 2011

Data from January 2004 to December 2010
18581 events selected

Quality cuts

- Events with $E > 3 \times 10^{18}$ eV
- $30^\circ < \theta < 60^\circ$
- Event must pass the fiducial trigger (T5 trigger)
- SD stations with $S > 10$ VEM at $500\,m < r_{core} < 2000\,m$
- Hottest station cannot be saturated

Systematics: $\Theta \leq 10 g/cm^2$

- Core reconstruction
- Event selection
- Value of $t_{1/2}$ vs $r$

Activities

- Value of $t_{1/2}$ vs $r$
- Systematics: $\Theta \leq 10 g/cm^2$
- Event selection
- Core reconstruction
Muon Production Depth – MPD

Muons produced close to the shower axis and travel in nearly straight lines.

Muons arrive with a time delay wrt shower core due to

\[ t = t_g + t_\epsilon + t_B + t_{MS} + \ldots \]

\[ \frac{dN}{dt_g} = \frac{dN}{dX} \frac{dX}{dt_g} \quad \frac{dN}{dt_\epsilon} = \frac{dN}{dE} \frac{dE}{dt_\epsilon} \]

MPD reconstruction requires stations at \( r_{core} > 1000\) m

Muon Energy Spectrum

Reconstructed Muon Longitudinal Profile (event by event basis for \( E > 10^{19.2}\) eV)

\[ l = \sqrt{r^2 + (z - \Delta)^2} \]

L. Cazón et al., Astroparticle Physics 23 (2005) 393-409

10/03/2013
MPD Results

D. García-Gámez, ICRC 2011

High zenith angles to avoid EM contamination

Data from January 2004 to December 2010
244 events selected

Quality cuts

- Events with $E > 2 \times 10^{19}$ eV
- $55^\circ < \theta < 65^\circ$
- Event must pass the fiducial trigger (T5 trigger)
- SD stations with $S > 3 \text{VEM}$ at $r_{core} > 1800 m$
- Gaisser-Hillas fit must be good
- Shower radius of curvature with $R < 29000 m$

Systematics: $X_{\mu_{\text{max}}} = 11 \text{g/cm}^2$

- Reconstruction bias
- Core position
- EM contamination
- $\chi^2$ cut
- Selection efficiency
Summary and Conclusions

FD and SD

- $X_{\text{max}}$ Results compatible with previous publications
- $X_{\text{max}}$ distributions become narrower with increasing energy
- Direct FD composition measurements extended to higher energy by the SD measurements
- Direct and indirect independent composition variables yield compatible results with different systematics

Interpretation

- At low energy data is compatible with a significant fraction of protons
- Break on the elongation rate slope seems to indicate a change in composition towards a predominance of heavier nuclei at higher energies
- $\langle X_{\text{max}} \rangle$ and RMS($X_{\text{max}}$) show similar trends towards heavy-like showers at high energies, but exact values of several variables are difficult to explain with existing hadronic interaction models, for simple mass composition scenarios
- Results are model dependent. Any changes on the model predictions will affect our interpretation of primary mass composition
Back-Up Slides
Old/New Hadronic Models Predictions

Tevatron $E = 10^{15}\text{eV}$

LHC $E = 10^{17}\text{eV}$