The nuclear mass composition of UHECR with the Pierre Auger Observatory

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Malargüe, Mendoza
Latitude 35 S – Longitude 69 W
1400 m a.s.l. X=870 g cm$^2$
Data taking since 2004
Installation completed in 2008

Surface Detector (SD)
1600 Cherenkov stations spaced 1.5 km
Area of 3000 km$^2$
100% duty cycle
Provides Large Statistics

Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg
~10% duty cycle
Provides High Accuracy

+ Enhancements: AMIGA, HEAT, Radio, etc

See also the other Auger contributions on: Photons, neutrinos, anisotropies, hadronic interactions, Auger Enhancements, and the review talks on Cosmic Rays
Hybrid detector
FD & SD

\[ E_{\text{cal}} = \int dX \frac{dE}{dX} \]

\( X_{\text{max}} \)

FADC trace
\( r_{\text{tank}} = 2098 \text{ m} \)

FADC trace
\( r_{\text{tank}} = 2262 \text{ m} \)

FADC trace
\( r_{\text{tank}} = 2481 \text{ m} \)
**$X_{\text{max}}$ and primary composition**

- $X_{\text{max}}$ reflects properties of the first interaction through $X_1$.
- Distributions for heavy primaries, as iron, are narrower and shallower. Lighter primaries, like protons, have a characteristic tail towards deep $X_{\text{max}}$.
- Hadronic interaction models predict different $\Delta X = X_1 - X_{\text{max}}$. 

Selection cuts

**Data Sample:** FD events with signal in at least 1 SD station from December 2004 to September 2010

**Selection of high quality events:**
- Low aerosol content (vert. opt. depth > 0.1) & cloud coverage (<25%).
- $\chi^2/Ndf < 2.5$ for profile fit.
- Statistical uncertainty $X_{\text{max}} < 40 \text{ g/cm}^2$.
- Angle between shower and telescope > 20° (avoid high Cherenkov fractions).
- $X_{\text{max}}$ observed.

15,979 events pass this quality selection [$E > 10^{18} \text{ eV}$].

**Unbiased selection:**
- Select the distance to the SD station, and zenith angle so that the tank trigger probability does not depend on the mass of primary.
- Select event geometries that allow to sample the whole $X_{\text{max}}$ distribution (from measurement).

6744 events selected
$X_{\text{max}}$ resolution

Validated with events with more than 1 FD station

**Systematic Uncertainties**

$X_{\text{max}} \rightarrow$ from 10 to 13 g/cm$^2$

$\text{RMS}(X_{\text{max}}) \rightarrow$ 5 g/cm$^2$

Energy dependent: low energy events have less signal and smaller tracks. At high energy, events are farther away and aerosol content uncertainty dominates.
Data are best described with two slopes; break is near the same energy as the ankle feature of the spectrum.

When compared to the models at high energy, data suggests a gradual increase of the average mass.

If hadronic interactions do not change much over less than 2 decades, this change on $D_{10}$ would imply a change on the energy dependence of the composition around the ankle.
Resolution is subtracted from data: 27 g/cm² → low energy 18 g/cm² → high energy

There is a change in behavior around the same energy as $X_{max}$: above $2.5 \times 10^{18}$ eV there is a fast decrease of RMS($X_{max}$) towards the values expected for heavy primaries.
As the energy increases:
- narrower distributions
- deep $X_{\text{max}}$ tail
less evident

Interpretation rely on the extrapolation provided by the different models
The model predictions have similar shapes but different $<X_{\text{max}}>$
Shape comparison

Shape at low energy fits lighter composition. Shape at high energy fits heavier composition.

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Time structure of SD signals

Particle signals are merged in the Cerenkov tank. (Untangling is difficult).

**EM**: multiple scattering. Spread out in time. Their time distributions is related to the shower age. Dominate the signal in vertical showers and close to the core.

**µ**: less interacting. Travel in straight lines, they arrive first. Dominate at large distances to the core and in inclined showers. Time distribution is related to the distance of production.

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

**The time structure of SD signals has information about shower development**
Assymetry of signal risetime

The early-late assymetry \((b/a)\) as function of the zenith angle has a maximum \((\Theta_{\text{max}})\) which is correlated with \(X_{\text{max}}\).

\[
< t_{1/2} / r > = a + b \cos \zeta
\]

Event selection:
- \(30^\circ < \Theta < 60^\circ\)
- \(500 \text{ m} < r < 2000 \text{ m}\)
- \(E > 3.16 \times 10^{18} \text{ eV}\)

Systematic uncertainty \(\leq \sim 10\%\) proton-iron separation
Using Hybrids events

$\Theta_{\text{max}}$ and $X_{\text{max}}$ are correlated. This correlation is independent of the primary.

18581 SD events (Jan 2004 – Dec 2010)

$E > 3.16 \times 10^{18}$ eV, and $30^\circ < \theta < 60^\circ$
Depth Profile of Muon Production Points

Muons are produced within a narrow cylinder centered on the shower axis. They travel along straight lines, practically unaffected by multiple scattering, pair production and bremsstrahlung.

This implies a direct relation between arrival time delay and the muon production distance

\[ z \approx \frac{1}{2} \frac{r^2}{ct} + \Delta \]

Muon Production Depth: the depth, measured parallel to the shower axis, at which a given muon is produced. It can be obtained from the SD signals far from the core, for single events.

Event selection:
- \(55^\circ < \theta < 65^\circ\)
- \(r > 1800 \text{ m}\)
- \(E > 20 \text{ EeV}\)

Systematic uncertainty \(\leq 11 \text{ g/cm}^2\) (\(\leq 14\%\) proton-iron separation)
**$X_{\mu_{\text{max}}}^\mu$ results**

**$X_{\mu_{\text{max}}}^\mu$ vs $X_{\text{max}}^\mu$**

**$<X_{\mu_{\text{max}}}^\mu>$ vs $E$**

MC events

244 SD events (Jan 2004 – Dec 2010)

$E > 20$ EeV $55^\circ < \theta < 65^\circ$

EPOS 1.89

OGSJETI 0.3

SIBYLL 2.1

Syst. Unc.
Conclusions

- \( <X_{\text{max}} > \) and RMS(\( X_{\text{max}} \)) recently updated with 80% more statistics, compatible with previous publication.

- \( X_{\text{max}} \) distributions become narrower as the energy increases. The deep \( X_{\text{max}} \) tail becomes shorter.

**INTERPRETATION**

- If hadronic interactions do no change much over less than 2 decades, this change on \( D_{10} \) would imply a change on the energy evolution of composition around the ankle towards heavier.

- At low energy, the data is consistent with a significant fraction of protons.

- The shape of the distributions is heavy-like at high energy, but for most of the models data would have to be adjusted to simultaneously match \( X_{\text{max}} \) and RMS(\( X_{\text{max}} \)) to a given composition mixture.

- **Change on the predictions of the available hadronic models would modify the interpretation in terms of primary mass**
Several SD observables related with the longitudinal development of air showers have been reconstructed: SD statistics allows us to reach higher energies.

- Compatible results with different systematics.
- Assuming that the hadronic interaction models are correct, the comparison of the data and simulation leads to the conclusion that the mean mass rises as the energy increases.

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The End
Back up slides