Measurement of the Depth of Maximum of Extensive Air Showers above \(10^{18}\) eV

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(Pierre Auger Collaboration)

1National Technological University, Faculty Mendoza (CONICET/CNEA), Mendoza, Argentina
2LIP and Instituto Superior Técnico, Lisboa, Portugal
3Istituto di Fisica dello Spazio Interplanetario (INAF), Università di Torino and Sezione INFN, Torino, Italy
4Fermilab, Batavia, Illinois, USA
5Centro Atómico Bariloche and Instituto Balseiro (CNEA-UNCuyo-CONICET), San Carlos de Bariloche, Argentina
6New York University, New York, New York, USA
7University of Santiago de Compostela, Spain
8Università di Napoli “Federico II” and Sezione INFN, Napoli, Italy
9University of Wisconsin-Madison, Wisconsin, USA
10Rudjer Bošković Institute, 10000 Zagreb, Croatia
11Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (INAF), Palermo, Italy
12University Complutense de Madrid, Madrid, Spain
13University of California Los Angeles, California, USA
14Laboratoire de Physique Nucléaire et de Haute Energies (LPNHE), Université Paris 6 et Paris 7, CNRS-IN2P3, Paris, France
15Karlsruhe Institute of Technology—Campus North—Institut für Kernphysik, Karlsruhe, Germany
16Karlsruhe Institute of Technology—Campus South—Institut für Experimentelle Kernphysik (IEKP), Karlsruhe, Germany
17University of Chicago, Enrico Fermi Institute, Chicago, Illinois, USA
18School of Physics and Astronomy, University of Leeds, United Kingdom
19Universidad de Granada & C.A.F.P.E., Granada, Spain
20$L^{1}$
We describe the measurement of the depth of maximum, $X_{\text{max}}$, of the longitudinal development of air showers induced by cosmic rays. Almost 4000 events above $10^{18}$ eV observed by the fluorescence detector of the Pierre Auger Observatory in coincidence with at least one surface detector station are
selected for the analysis. The average shower maximum was found to evolve with energy at a rate of \((106^{+31}_{-23})\ g/cm^2/\text{decade}\) below \(10^{18.24\pm0.05}\ eV\), and \((24\pm3)\ g/cm^2/\text{decade}\) above this energy. The measured shower-to-shower fluctuations decrease from about 55 to 26 \(g/cm^2\). The interpretation of these results in terms of the cosmic ray mass composition is briefly discussed.

\[
D_{10} = \frac{d\langle X_{\text{max}} \rangle}{d\ln E} = \alpha \left( 1 - \frac{d\langle \ln A \rangle}{d\ln E} \right) \ln(10),
\]

and it is sensitive to changes in composition with energy. A complementary composition-dependent observable is the magnitude of the shower-to-shower fluctuations of the depth of maximum, \(\text{rms}(X_{\text{max}})\), which is expected to decrease with the number of primary nucleons \(A\) (though not as fast as \(1/\sqrt{A}\) [8]) and to increase with the interaction length of the primary particle.

At ultrahigh energies, the shower maximum can be observed directly with fluorescence detectors. Previously published \(X_{\text{max}}\) measurements [9,10] focused mainly on \(\langle X_{\text{max}} \rangle\) as a function of energy and had only limited statistics above \(10^{19}\ eV\).

Here we present a measurement of both \(\langle X_{\text{max}} \rangle\) and \(\text{rms}(X_{\text{max}})\) using high quality and high statistics data collected with the southern site of the Pierre Auger Observatory [11]. The observatory is located in the province of Mendoza, Argentina and consists of two detectors. The surface detector (SD) array comprises 1600 water-Cherenkov detectors arranged on a triangular grid with 1500 m spacing that cover an area of over 3000 km². The water-Cherenkov detectors are sensitive to the air shower components at ground level. The fluorescence detector (FD) consists of 24 optical telescopes overlooking the array, which can observe the longitudinal shower development by detecting the fluorescence and Cherenkov light produced by charged particles along the shower trajectory in the atmosphere.

\[
\langle X_{\text{max}} \rangle = \alpha (\ln E - \langle \ln A \rangle) + \beta,
\]

where \(\langle \ln A \rangle\) is the average of the logarithm of the primary masses. The coefficients \(\alpha\) and \(\beta\) depend on the nature of hadronic interactions, most notably on the multiplicity, elasticity and cross section in ultrahigh energy collisions of hadrons with air, see, e.g., [5]. Although Eq. (1) is based on a simplified description of air showers, it gives a good description of air shower simulations with energy-independent parameters \(\alpha\) and \(\beta\) in the energy range considered here, see [6]. Only physics processes not accounted for in currently available interaction models could lead to a significant energy dependence of these parameters.

The change of \(\langle X_{\text{max}} \rangle\) per decade of energy is called elongation rate [7].
An unbiased set of high quality events is selected with the statistical uncertainty of the reconstructed $X_{\text{max}}$ being comparable to the size of the fluctuations expected for nuclei as heavy as iron ($\approx 20 \text{ g/cm}^2$) and small systematic uncertainties as explained in the following.

The impact of varying atmospheric conditions on the $X_{\text{max}}$ measurement is minimized by rejecting time periods with cloud coverage and by requiring reliable measurements of the vertical optical depth of aerosols. Profiles that are distorted by residual cloud contamination are rejected by a loose cut on the quality of the profile fit ($\chi^2/\text{Ndf} < 2.5$). We take into account events only with energies above $10^{18}$ eV where the probability for at least one triggered SD station is 100%, irrespective of the mass of the primary particle [18]. The geometrical reconstruction of showers with a large apparent angular speed of the image in the telescope is susceptible to uncertainties in the time synchronization between FD and SD. Therefore, events with a light emission angle towards the FD that is smaller than $20^\circ$ are rejected. This cut also removes events with a large fraction of Cherenkov light. The energy and shower maximum can be reliably measured only if $X_{\text{max}}$ is in the field of view (FOV) of the telescopes (covering 1.5$^\circ$ to 30$^\circ$ in elevation). Events for which only the rising or falling edge of the profile is detected are not used. Moreover, we calculate the expected statistical uncertainty of the reconstruction of $X_{\text{max}}$ for each event, based on the shower geometry and atmospheric conditions, and require it to be better than 40 g/cm$^2$.

The latter two selection criteria may cause a selection bias due to a systematic undersampling of the tails of the true $X_{\text{max}}$ distribution, since showers developing very deep or shallow in the atmosphere might be rejected from the data sample. To avoid such a bias in the measured $\langle X_{\text{max}} \rangle$ and $\text{rms}(X_{\text{max}})$ we apply fiducial volume cuts based on the shower geometry that ensure that the viewable $X_{\text{max}}$ range for each shower is large enough to accommodate the full $X_{\text{max}}$ distribution [19].

After all cuts, 3754 events are selected for the $X_{\text{max}}$ analysis. The $X_{\text{max}}$ resolution as a function of energy for these events is estimated using a detailed simulation of the FD and the atmosphere. As shown in the inset of Fig. 1, the resolution is at the 20 g/cm$^2$ level above a few EeV. The difference between the reconstructed $X_{\text{max}}$ values in events that had a sufficiently high energy to be detected independently by two or more FD stations is used to cross-check these findings. As can be seen in Fig. 1, the simulations reproduce the data well.

Results and discussion.—The measured $\langle X_{\text{max}} \rangle$ and $\text{rms}(X_{\text{max}})$ values are shown in Figs. 2 and 3. We use bins of $\Delta \log E = 0.1$ below 10 EeV and $\Delta \log E = 0.2$ above that energy. The last bin starts at $10^{18.4}$ eV, integrating up to the highest energy event ($E = (59 \pm 8)$ EeV). The systematic uncertainty of the FD energy scale is 22% [18]. Uncertainties of the calibration, atmospheric conditions, reconstruction and event selection give rise to a systematic uncertainty of $\approx 13$ g/cm$^2$ for $\langle X_{\text{max}} \rangle$ and $\approx 6$ g/cm$^2$ for the rms. The results were found to be independent of zenith angle, time periods and FD stations within the experimental uncertainties.

A fit of the measured $\langle X_{\text{max}} \rangle$ values with a constant elongation rate does not describe our data ($\chi^2/\text{Ndf} = 34.9/11$), but as can be seen in Fig. 2, using two slopes yields a satisfactory fit ($\chi^2/\text{Ndf} = 9.7/9$) with an elongation rate of $(106^{+33}_{-21})$ g/cm$^2$/decade below $10^{18.24^{+0.05}}$ eV and $(24 \pm 3)$ g/cm$^2$/decade above this energy. If the properties of hadronic interactions do not change significantly over less than 2 orders of magnitude in primary energy (< factor 10 in center of mass energy), this change of $\Delta D_{10} = (82^{+35}_{-21})$ g/cm$^2$/decade would imply a change in the energy dependence of the composition around the

FIG. 1. Difference between $X_{\text{max}}$ measured in showers simultaneously at two FD stations ($\langle \log(E/\text{eV}) \rangle = 19.1$). The $X_{\text{max}}$ resolution is displayed as a function of energy in the inset.

FIG. 2. $\langle X_{\text{max}} \rangle$ as a function of energy. Lines denote a fit with a broken line in $\log E$. The systematic uncertainties of $\langle X_{\text{max}} \rangle$ are indicated by a dashed line. The number of events in each energy bin is displayed below the data points. HiRes data [10] are shown for comparison.
ankle, supporting the hypothesis of a transition from galactic to extragalactic cosmic rays in this region.

The \( \langle X_{\text{max}} \rangle \) result of this analysis is compared to the HiRes data \[10\] in Fig. 2. Both data sets agree well within the quoted systematic uncertainties. The \( \chi^2/\text{Ndf} \) of the HiRes data with respect to the broken-line fit described above is 20.5/14. This value reduces to 16.8/14 if a relative energy shift of 15% is applied, such as suggested by a comparison of the Auger and HiRes energy spectra \[2\].

The shower-to-shower fluctuations, \( \text{rms}(X_{\text{max}}) \), are obtained by subtracting the detector resolution in quadrature from the width of the observed \( X_{\text{max}} \) distributions resulting in a correction of \( \pm 6 \text{ g/cm}^2 \). As can be seen in the right panel of Fig. 3, we observe a decrease in the fluctuations with energy from about 55 to 26 g/cm\(^2\) as the energy increases. Assuming again that the hadronic interaction properties do not change much within the observed energy range, these decreasing fluctuations are an independent signature of an increasing average mass of the primary particles.

For the interpretation of the absolute values of \( \langle X_{\text{max}} \rangle \) and \( \text{rms}(X_{\text{max}}) \) a comparison to air shower simulations \[20\] using different hadronic interaction models \[21\].

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