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

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We describe the measurement of the depth of maximum, $X_{\max}$, 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^{+35}_{-21}) g/cm^2/decade below $10^{18.24\pm0.05}$ eV, and (24 ± 3) g/cm^2/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.

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Introduction.—The energy dependence of the mass composition of cosmic rays is, along with the flux and arrival direction distribution, an important parameter for the understanding of the sources and propagation of cosmic rays at very high energy. There are several models that describe the observed flux of cosmic rays very well, but each of these models has different assumptions about the cosmic ray sources and correspondingly predicts a different mass composition at Earth. For example, the hardening of the cosmic ray energy spectrum at energies between 10^{18} and 10^{19} eV, known as the "ankle", is presumed to be either a signature of the transition from galactic to extragalactic cosmic rays or a distortion of a proton-dominated extragalactic spectrum due to energy losses [1]. Moreover, composition information may eventually help to decide whether the flux suppression observed above 4×10^{19} eV [2] is due mainly to the interaction of cosmic rays with the microwave background or a signature of the maximum injection energy of the sources [3].

Because of the low flux at these energies, the composition of cosmic rays cannot be measured directly, but has to be inferred from observations of extensive air showers. The atmospheric depth, $X_{\max}$, at which the longitudinal development of a shower reaches its maximum in terms of the number of secondary particles is correlated with the mass of the incident cosmic ray particle. With the generalization of Heitler's model of electron-photon cascades to hadron-induced showers and the superposition assumption for nuclear primaries of mass A, the average depth of the shower maximum, $\langle X_{\max}\rangle$, at a given energy E is expected to follow [4]

$$\langle X_{\max}\rangle = \alpha(\ln E - \langle \ln A\rangle) + \beta, \tag{1}$$

where $\langle \ln A\rangle$ is the average of the logarithm of the primary masses. The coefficients α and β 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 α and β 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 $\langle X_{\max}\rangle$ per decade of energy is called *elongation rate* [7],

$$D_{10} = \frac{d\langle X_{\max}\rangle}{d\,\lg E} \approx \alpha\left(1 - \frac{d\langle \ln A\rangle}{d\ln E}\right)\ln(10), \tag{2}$$

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, rms($X_{\max}$), 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 $X_{\max}$ measurements [9,10] focused mainly on $\langle X_{\max}\rangle$ as a function of energy and had only limited statistics above 10^{19} eV.

Here we present a measurement of both $\langle X_{\max}\rangle$ and rms($X_{\max}$) 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 km^2. 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.

Data analysis.—This work is based on air shower data recorded between December 2004 and March 2009. Only events detected in the hybrid mode [12] are considered; i.e., the shower development must have been measured by the FD, and at least one coincident SD station is required to provide a ground-level time. Using the time constraint from the SD, the shower geometry can be determined with an angular uncertainty of 0.6° [13]. The longitudinal profile of the energy deposit is reconstructed [14] from the light recorded by the FD using the fluorescence and Cherenkov yields and lateral distributions from [15]. With the help of data from atmospheric monitoring devices [16] the light collected by the telescopes is corrected for the attenuation between the shower and the detector and the longitudinal shower profile is reconstructed as a function of atmospheric depth. $X_{\max}$ is determined by fitting the reconstructed longitudinal profile with a Gaisser-Hillas function [17].

An unbiased set of high quality events is selected with the statistical uncertainty of the reconstructed $X_{\max}$ being comparable to the size of the fluctuations expected for nuclei as heavy as iron ($\approx 20\ \mathrm{g/cm^2}$) and small systematic uncertainties as explained in the following.

The impact of varying atmospheric conditions on the $X_{\max}$ 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 ($\chi^2/\mathrm{Ndf} < 2.5$). 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° 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 $X_{\max}$ is in the field of view (FOV) of the telescopes (covering 1.5° to 30° 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 $X_{\max}$ for each event, based on the shower geometry and atmospheric conditions, and require it to be better than $40\ \mathrm{g/cm^2}$.

The latter two selection criteria may cause a selection bias due to a systematic undersampling of the tails of the true $X_{\max}$ 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 $\langle X_{\max}\rangle$ and $\mathrm{rms}(X_{\max})$ we apply fiducial volume cuts based on the shower geometry that ensure that the viewable $X_{\max}$ range for each shower is large enough to accommodate the full $X_{\max}$ distribution [19].

After all cuts, 3754 events are selected for the $X_{\max}$ analysis. The $X_{\max}$ 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 $20\ \mathrm{g/cm^2}$ level above a few EeV. The difference between the reconstructed $X_{\max}$ 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 $\langle X_{\max}\rangle$ and $\mathrm{rms}(X_{\max})$ values are shown in Figs. 2 and 3. We use bins of $\Delta\,\mathrm{lg}E = 0.1$ below 10 EeV and $\Delta\,\mathrm{lg}E = 0.2$ above that energy. The last bin starts at $10^{19.4}$ 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 $\leq 13\ \mathrm{g/cm^2}$ for $\langle X_{\max}\rangle$ and $\leq 6\ \mathrm{g/cm^2}$ for the rms. The results were found to be independent of zenith angle, time periods and FD stations within the experimental uncertainties.

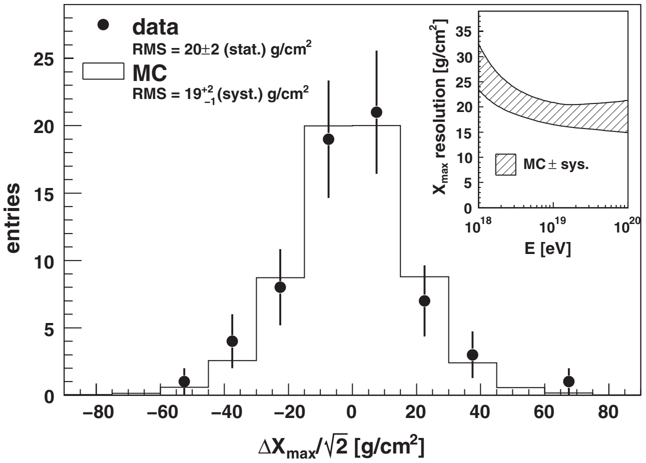

FIG. 1. Difference between $X_{\max}$ measured in showers simultaneously at two FD stations ($\langle \mathrm{lg}(E/\mathrm{eV})\rangle = 19.1$). The $X_{\max}$ resolution is displayed as a function of energy in the inset.

A fit of the measured $\langle X_{\max}\rangle$ values with a constant elongation rate does not describe our data ($\chi^2/\mathrm{Ndf} = 34.9/11$), but as can be seen in Fig. 2, using two slopes yields a satisfactory fit ($\chi^2/\mathrm{Ndf} = 9.7/9$) with an elongation rate of $(106^{+35}_{-21})\ \mathrm{g/cm^2/decade}$ below $10^{18.24\pm0.05}$ eV and $(24 \pm 3)\ \mathrm{g/cm^2/decade}$ 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 $\Delta D_{10} = (82^{+35}_{-21})\ \mathrm{g/cm^2/decade}$ would imply a change in the energy dependence of the composition around the

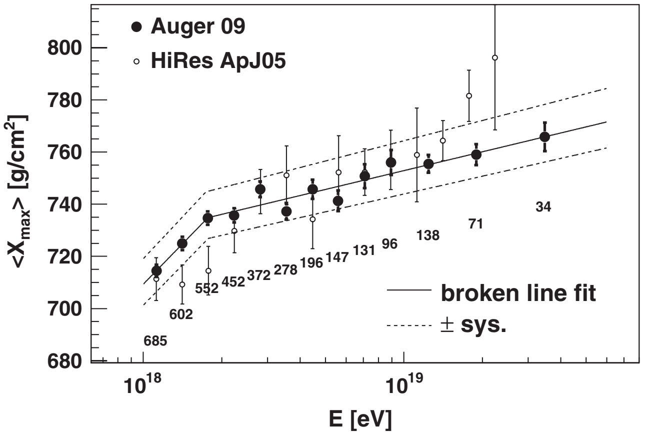

FIG. 2. $\langle X_{\max}\rangle$ as a function of energy. Lines denote a fit with a broken line in $\mathrm{lg}E$. The systematic uncertainties of $\langle X_{\max}\rangle$ are indicated by a dashed line. The number of events in each energy bin is displayed below the data points. HiRes data [10] are shown for comparison.

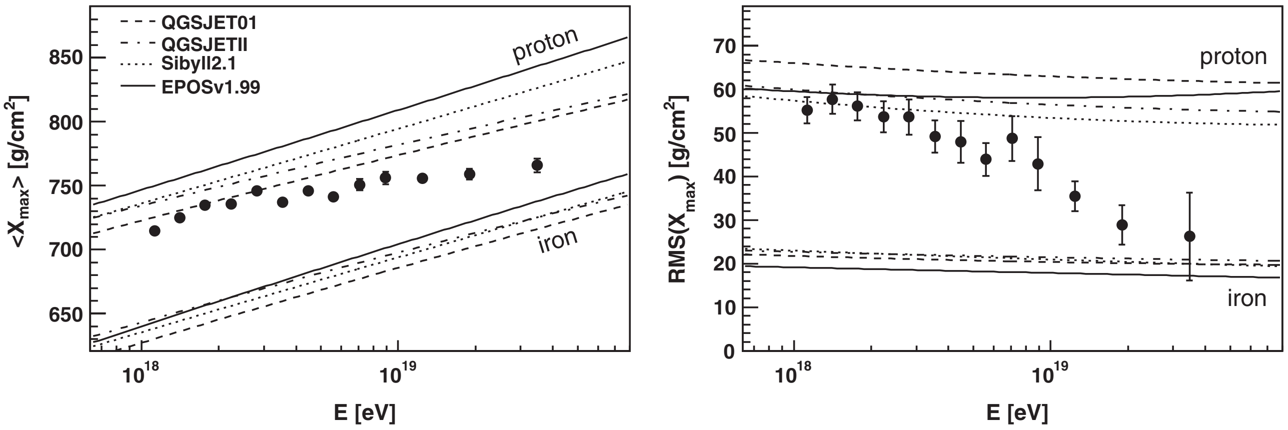

FIG. 3. $\langle X_{\max} \rangle$ and rms($X_{\max}$) compared with air shower simulations [20] using different hadronic interaction models [21].

ankle, supporting the hypothesis of a transition from galactic to extragalactic cosmic rays in this region.

The $\langle X_{\max} \rangle$ 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 χ^2/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, rms($X_{\max}$), are obtained by subtracting the detector resolution in quadrature from the width of the observed $X_{\max}$ distributions resulting in a correction of ≤ 6 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 $\langle X_{\max} \rangle$ and rms($X_{\max}$) a comparison to air shower simulations is needed. As can be seen in Fig. 3, there are considerable differences between the results of calculations using different hadronic interaction models. These differences are not necessarily exhaustive, since the hadronic interaction models do not cover the full range of possible extrapolations of low energy accelerator data. If, however, these models provide a realistic description of hadronic interactions at ultrahigh energies, the comparison of the data and simulations leads to the same conclusions as above, namely, a gradual increase of the average mass of cosmic rays with energy up to 59 EeV.

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*Deceased.

[1] A. M. Hillas, Phys. Lett. 24, 677 (to be published); V. S. Berezinsky and S. I. Grigor'eva, Astron. Astrophys. **199**, 1 (1988); D. Allard, E. Parizot, and A. V. Olinto, Astropart. Phys. **27**, 61 (2007); R. Aloisio, V. Berezinsky, P. Blasi, and S. Ostapchenko, Phys. Rev. D **77**, 025007 (2008).

[2] R. Abbasi *et al.* (HiRes Collaboration), Phys. Rev. Lett. **100**, 101101 (2008); J. Abraham *et al.* (Pierre Auger Collaboration), Phys. Rev. Lett. **101**, 061101 (2008).

[3] D. Allard *et al.*, J. Cosmol. Astropart. Phys. 10 (2008) 033.

[4] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1954); J. Matthews, Astropart. Phys. **22**, 387 (2005).

[5] T. Wibig, Phys. Rev. D **79**, 094008 (2009); R. Ulrich *et al.*, arXiv:0906.0418 [Proc. 31st ICRC (to be published)].

[6] T. Pierog, R. Engel, and D. Heck, Czech. J. Phys. **56**, A161 (2006); J. Bluemer, R. Engel, and J. R. Hoerandel, Prog. Part. Nucl. Phys. **63**, 293 (2009).

[7] J. Linsley, *Proceedings of the 15th ICRC*, Vol. 12, p. 89 (Hungarian Academy of Sciences, Budapest, 1977); T. K. Gaisser *et al.*, *Proceedings of the 16th ICRC*, Vol. 9, p. 275 (Institute for Cosmic Ray Research, Tokyo, 1979); J. Linsley and A. A. Watson, Phys. Rev. Lett. **46**, 459 (1981).

[8] J. Engel *et al.*, Phys. Rev. D **46**, 5013 (1992).

[9] D. J. Bird *et al.* (Fly's Eye Collaboration), Phys. Rev. Lett. **71**, 3401 (1993).

[10] R. U. Abbasi *et al.* (HiRes Collaboration), Astrophys. J. **622**, 910 (2005).

[11] J. Abraham *et al.* (Pierre Auger Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **523**, 50 (2004); J. Abraham *et al.* (Pierre Auger Collaboration), arXiv:0907.4282 [Nucl. Instrum. Meth. (to be published)]; I. Allekotte *et al.* (Pierre Auger Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **586**, 409 (2008).

[12] P. Sommers, Astropart. Phys. **3**, 349 (1995); B. R. Dawson *et al.*, Astropart. Phys. **5**, 239 (1996).

[13] C. Bonifazi *et al.* (Pierre Auger Collaboration), Nucl. Phys. B, Proc. Suppl. **190**, 20 (2009).

[14] M. Unger *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **588**, 433 (2008).

[15] M. D. Roberts, J. Phys. G **31**, 1291 (2005); D. Gora *et al.*, Astropart. Phys. **24**, 484 (2006); F. Nerling *et al.*, Astropart. Phys. **24**, 421 (2006); B. R. Dawson, M. Giller, and G. Wieczorek, *Proceedings of the 30th ICRC* (2007); B. Keilhauer *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **597**, 99 (2008).

[16] J. Abraham *et al.* (Pierre Auger Collaboration), arXiv:0906.2358 [Proc. 31st ICRC (to be published)].

[17] T. K. Gaisser and A. M. Hillas, *Proceedings of the 15th ICRC*, Vol. 8, p. 353 (1977).

[18] J. Abraham *et al.* (Pierre Auger Collaboration), arXiv:0906.2189 [*Proc. 31st ICRC* (to be published)].

[19] M. Unger (Pierre Auger Coll.), Nucl. Phys. B, Proc. Suppl. **190**, 240 (2009); J. A. Bellido (Pierre Auger Coll.), arXiv:0901.3389 [Proc. XXth Rencontres de Blois (to be published)].

[20] T. Bergmann *et al.*, Astropart. Phys. **26**, 420 (2007).

[21] N. N. Kalmykov and S. S. Ostapchenko, Phys. At. Nucl. **56**, 346 (1993); S. S. Ostapchenko, Nucl. Phys. B, Proc. Suppl. **151**, 143 (2006); T. Pierog and K. Werner, Phys. Rev. Lett. **101**, 171101 (2008); E. J. Ahn *et al.*, Phys. Rev. D **80**, 094003 (2009).