Time structure of the shower front as measured at Haverah Park above 10^{19} eV

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Abstract

The time structure of the air shower front observed with any particle detector is largely defined by the development of the shower in the atmosphere. Shower front structure can thus be correlated with the mass of the initiating primary particle. We have extended previous work on this topic, using the Haverah Park array, to explore these features in events of mean energy 2×10^{19} eV. We compare the measurements with Monte Carlo calculations made using the CORSIKA/QGSGET model. Data and simulations show clear azimuthal asymmetries in the time structure, which relate to the cosmic ray mass composition. The observed time structure can be best understood if iron primaries are dominant at these energies, but this conclusion is model dependent.

1. Introduction

Although the Haverah Park array was closed in 1987, the database has continued to be a rich source for new insights into the properties of high-energy cosmic rays [3,4]. In part, this is because of the availability of increased computational power and improved shower models. In [4] we showed how these resources could be used to infer the mass composition from 2×10^{17} to 3×10^{18} eV from accurate measurements of the lateral distribution of signals in large area water-Cherenkov detectors. An additional mass sensitive parameter that was measured at Haverah Park was the thickness of the shower front observed at the four central 34 m^2 detectors. With these detectors, the first evidence of shower-to-shower fluctuations was obtained [10] and later, using an improved recording system, detailed measurements on over 7000 showers led to an inference of the elongation rate above 3×10^{17} eV [9].

Here we describe an extension of the earlier work on the shower front, focusing on the highest energy events. The parameter measured was the 10-50% risetime ($t_{1/2}$), as before, but, to obtain a consistent data set, all the pulse shapes were remeasured for events $>10^{19}$ eV and zenith angle $<45°$, from a set of records made with a single recording system, as used in [10]. The integrated signals from

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each 34 m^2 detector were recorded photographically from an oscilloscope. The signal at 1029 m from the core of a shower of 6×10^{19} eV is shown in figure 1A. A total of 266 pulses from 100 showers were measured. At 1000 m from the core of a 10^{19} eV event from near the vertical, a typical risetime is ~250 ns. The risetimes can be measured to ±4 ns: details of the procedure will be given elsewhere.

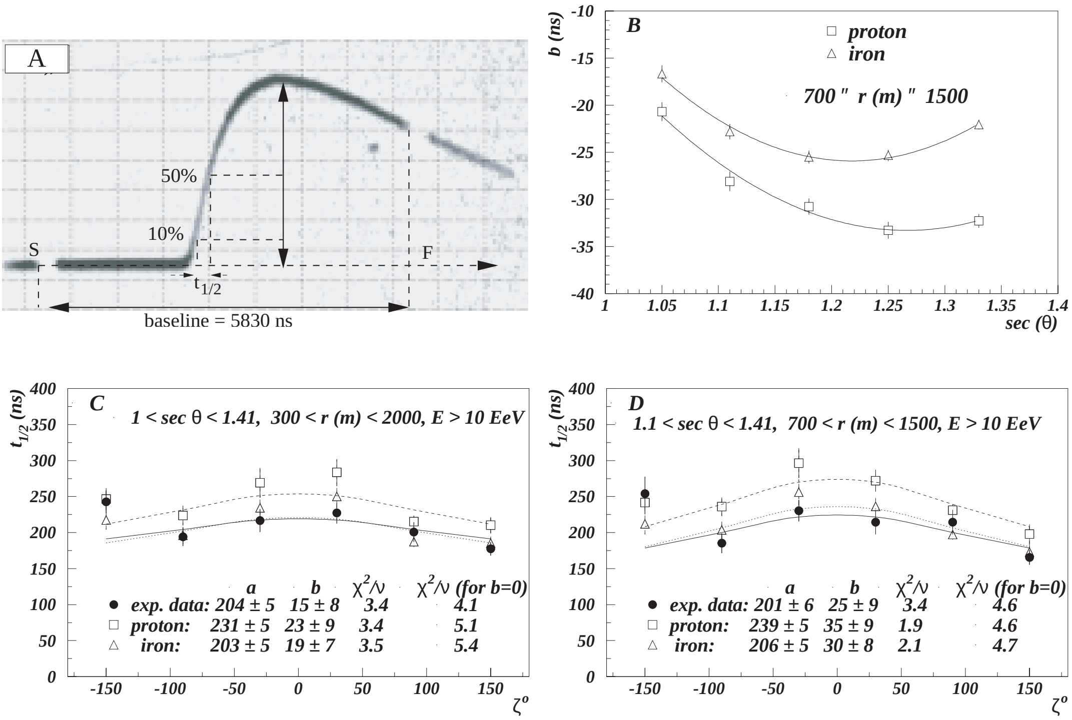

Fig. 1. A: pulse of a typical event recorded at the Haverah Park array: $E = 6 \times 10^{19}$ eV, $\rho \simeq 18$ m^{-2}, $\theta = 30°$ and $t_{1/2} = 260$ ns. The 10% and the 50% levels of the pulse are shown along with the start (S) and the finish (F) of pulse of a defined 5830 ns baseline.
B: variation of b as function of sec θ for core distance range $700 \leq r \leq 1500$ m.
C: $t_{1/2}$ vs ζ for experimental data (266 pulses) and Monte Carlo.
D: same as C but with $700 \leq r \leq 1500$ m and $1.1 \leq \sec\theta \leq 1.4$ in both data (60 pulses) and Monte Carlo.

2. Results of the measurements

The measurements were parameterised as a function of core distance, r and zenith angle, θ. The shower-to-shower differences were explored using the analysis of variance, as in the original work [10]. This analysis showed that shower-to-shower differences are larger than can be accounted for by experimental uncertainties. The experimental uncertainties in the risetime measurements come from the measurement uncertainty mentioned above, and from the sampling of the shower front by detectors of finite size. For a density of ∼2 m^{-2} in a near vertical shower at 1000 m, the sampling uncertainty, even on a 34 m^2 detector, is ∼28 ns, very much larger than the measurement error. The overall uncertainty is so large that, for the small sample of events available, it is only meaningful to work with average values.

3. Comparison of average values of risetimes with shower models

It has been known for many years that asymmetries can arise in the density distribution of air showers because of the magnetic field [1,2,3,5]. In addition, at Haverah Park, attenuation of the density signal as the shower crossed the array was observed in a small number of events with well-located cores [7]. More recently, within the Auger Collaboration, considerable attention has been given to asymmetries, both because of their importance in the reconstruction of the parameter from which the primary energy is derived and because the magnitude of the time asymmetry predicted for various descriptors of the shower front thickness is sensitive to the mass composition [6].

It is convenient to group the pulses for which there are measurements as a function of r, θ, E and ζ, the azimuthal angle in the shower plane, where $\zeta = 0°$ is chosen to lie in the direction of the incoming shower. A detector lying at $\zeta = 180°$ will record signals from a part of the shower that has travelled through more atmosphere than one at $\zeta = 0°$. A suitable parameterisation of $t_{1/2}$ for real data and for Monte Carlo predictions, as a function of ζ is given by $t_{1/2} = a + b \cos \zeta$. The behaviour of the average $t_{1/2}$ for the 266 measurements is shown in figure 1C.

Since the data set is sparse and compiled from a range of r, θ, E and ζ, comparison of it with the Monte Carlo results, which are made for showers of specific energy, zenith angle and mass, is not straightforward. We have used the CORSIKA code with QGSJET01 [8] with proton and iron primaries for the simulations. Then we have parameterised the coefficients a and b, from the simulations, as a function of r, θ, E and ζ, so that the comparisons with the data sample can be done as exactly as possible. In figure 1B a typical variation of b with sec θ is shown and similar interpolations have been formed for a and b with the other variables. It is thus possible to make a prediction of $t_{1/2}$, for p and Fe primaries, using a simulated set of pulses that has identical r, θ, E and ζ to that of the events. Additionally, the choice of binning to maximise the possibility of observing an asymmetry in ζ can be guided by these interpolations. In figure 1C, the comparison of all data with the Monte Carlo results is displayed. In figure 1D, a comparison between data and simulations for a restricted range of angle and distance (60 pulses) is made.

The first point to note is that the predicted average properties of the shower pulses are clearly different for p and Fe showers at the large distances used here.

This is in contrast to the conclusion in [4] where for the relevant distance range, $250 < r < 500$ m the sensitivity of the risetime technique for the extraction of mass information was shown to be rather limited. However, as pointed out there, the technique is expected to have promise for mass separation when used at larger r, as demonstrated here. Secondly, it is clear from figures 1C and 1D that the data are better described using Fe primaries. However, before claiming this as a firm conclusion, it is necessary to explore the sensitivity of it to the choice of different shower models. As noted before, the data are too sparse to make use of fluctuations, as was possible for the lateral distribution work at lower energy [4].

We look forward to seeing this technique developed, with high statistics, using the data expected from the Pierre Auger Observatory.

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