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Measuring the UHE cosmic-ray composition with tracking detectors in air shower arrays

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Abstract

Measuring the angles of muons and electrons in air showers is proposed as a method for studying the primary cosmic-ray mass composition near the knee of the cosmic-ray energy spectrum at a few 10^{15} eV. Conventional tracking detectors at existing air shower arrays could serve this purpose, like the CRT detectors at the HEGRA array. When the average radial muon angles are examined as a function of shower core distance, the experimental resolution can be very well calibrated from the tangential angle distribution. The method is particularly promising for measuring changes in the average mass number of the primary cosmic rays with energy. The method is described and experimental and theoretical constraints are discussed.

1 Introduction

Despite the fact that ultra-high energy (UHE) cosmic rays are known for decades, their sources and the acceleration mechanisms are still under debate. Sources are only detectable by γ-rays produced in interactions near the sources. In the very-high energy (VHE) range near 1 TeV more and more γ-ray sources are revealed by the imaging Cherenkov technique. On the contrary, no clear source detections have been made in the UHE domain above about 100 TeV, except perhaps a few episodic cases.

Mainly for reasons of the required power, the dominant sources of cosmic rays up to about 100 TeV and probably up to the *knee* of the cosmic-ray energy spectrum at a few 10^{15} eV are believed to be supernova remnants in the Sedov phase. The change of the spectrum near the knee presumably reflects a change in the origin and the takeover of another, yet unclear type of sources at energies above the knee. A change in the cosmic-ray propagation with a decreasing Galactic containment has also been considered. In either case, the change in the slope of the spectrum should be accompanied by

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a change in the mass composition of cosmic rays. In the case of a change of sources across the knee, the composition could change dramatically. A much less spectacular change of the composition is expected in the case of decreasing containment.

Direct measurements well below the knee [1, 2] show indeed a substantial change in the mass composition already at energies around 100 TeV. In particular, the fraction of protons seems to diminish with increasing energy. Due to their small collection areas the balloon-borne direct experiments run out of statistics above several hundred TeV. Indirect methods using ground-based experiments are, so far, not able to classify individual cosmic rays unambiguously by their mass. Such methods are more appropriate for evaluating some average mass number. Most notably, the results of the Fly's Eye group [3] indicate a rather heavy composition well above the knee. If taken at face value, their results represent a composition of mainly very heavy nuclei, like iron, at 10^{17} eV.

Experiments measuring the composition right at the knee of the spectrum obtained either ambiguous or even conflicting results. Results with no significant change [4, 5] or a slight increase of heavy elements [6] have been reported. Other groups found more significant increases of heavy elements [7, 8, 9] or, on the other hand, predominantly protons [10]. Further measurements are needed, if the cosmic-ray composition should help to resolve the question where cosmic rays are accelerated.

The method proposed in this paper should be relatively easy to implement at sites where an air-shower array with an angular resolution below one degree already exists. The method is mainly a measurement of the longitudinal shower development by the angles of muons with respect to the shower axis. It does not require to measure many muons in a single shower because it uses only the *inclusive* angular distributions, nor is accurate timing required. Indeed, if several muons are measured in one event, they are treated separately.

Not only the average muon angles but also the average electron angles with respect to the shower axis are sensitive to the primary composition. Because the detector response is, in general, better understood for muon tracks than for electron tracks, this paper focuses mainly on the muons. Using the tracking detectors and the air-shower array, the method can be supplemented by traditional methods like the average μ/e ratio or the muon lateral distribution. Although one can think of complex experiments dedicated to measuring the cosmic-ray composition, like KASKADE [11], where more pieces of information are collected, the purpose of this paper is to demonstrate that even the muon angles alone provide significant information about the composition.

The proposed method relies on shower simulations to obtain an absolute value of an average mass number, just like other indirect methods. If suitable tracking detectors are used, it has the advantage that essentially all required detector parameters for the simulation can be obtained from the measured data as a function of shower size. Therefore, it can be particularly sensitive to changes in the composition across the measured shower size spectrum, even if a comparison with simulations using different interaction models may yield different absolute values.

An analysis of data taken with ten CRT detectors – tracking detectors of $2.5\,\mathrm{m}^2$ sensitive area each [12] – and the HEGRA air-shower array [13] on La Palma is in progress [14]. In the data of CRT and HEGRA both muon and electron tracks are analysed. Although the intention of this paper is to promote the method to other air-shower experiments, the simulations shown in this paper are specific to the combination of the CRT and HEGRA experiments. These simulations take into account the response of both components – the tracking detectors and the air-shower array – in much detail. After an outline of the method, the specific simulations are described to demonstrate that the method can be very well applied with existing detector technology. Experimental requirements for application of the method and limitations by shower simulations are shown in a more general context, not specific to CRT and HEGRA.

2 Outline of the method

First measurements of the angles of muons with respect to the corresponding air showers or, in alternative terms, of the apparent height of origin of the muons were done in the 1960s [15]. At that time neither the angular resolutions of air-shower arrays nor the accuracy of shower simulations were appropriate to use such measurements for investigating the mass composition of primary cosmic rays. For an early comparison of measured and simulated height of muon origin see [16].

The proposed method is based on the fact that showers initiated by heavy primaries, like iron nuclei, develop on average at smaller atmospheric depths, i.e. higher altitudes, than proton showers. Muons from showers of heavy primaries arrive, therefore, at smaller angles with respect to the shower axis for any given core distance. The proposed method is not intended to measure individual primaries but to measure accurately an average number of the composition, like $\langle \ln A \rangle$, the average logarithm of the primary mass numbers. Measuring many tracks in a single shower is, therefore, not necessary and only helps to improve statistics.

The angles of muons or other particles with respect to the shower axis are best expressed in terms of their *radial angle* and *tangential angle* components. The radial angle is the projection onto the plane defined by the geometry of the shower axis and the location of the muon detector. Throughout this paper, a negative radial angle is assigned to a particle flying away from the shower axis. In fact, at large core distances most particles have

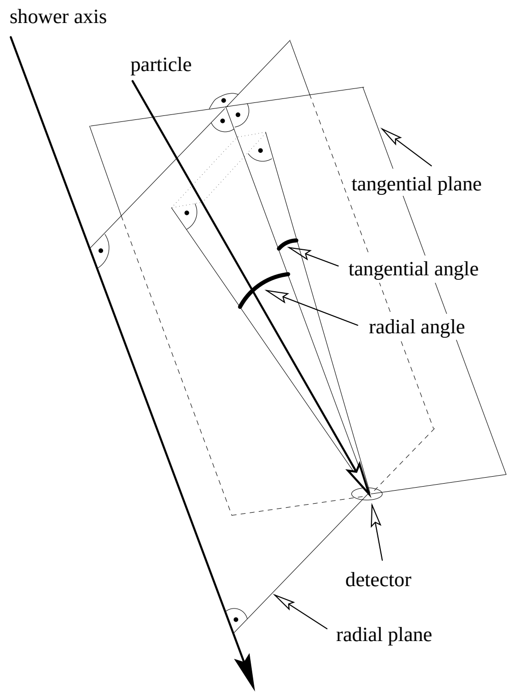

Figure 1: The geometry of radial and tangential angles between the shower axis, e.g. as reconstructed from air-shower data, and the measured track of a particle.

such a negative radial angle. The tangential angle (also called the transverse angle) is the projection onto the plane perpendicular to the 'radial' plane and parallel to the shower axis (see figure 1). For almost vertical showers a more convenient definition with projections into vertical planes defined only by the positions of the shower core and the detector is essentially equivalent.

The radial projection can be used to derive an *apparent height of origin* of a particle (figure 2). Although radial angle and apparent height of origin are almost equivalent, the radial angle is the more robust variable. This is due to the fact that a small scattering or experimental smearing around zero radial angle corresponds to $\pm\infty$ apparent height. In addition, the derived height for each muon depends directly on the resolution of the core position. In particular, the last point turns out to be a major drawback of an analysis in terms of the apparent height. The core position resolution is usually not very precisely known as a function of shower size, zenith angle, and position within the array. An analysis in terms of the apparent height is, for this reason, limited to core distances much larger than the core position resolution.

The distribution of tangential angles (see figure 3) is symmetric and its width is dominated by multiple scattering and the lateral distribution of the

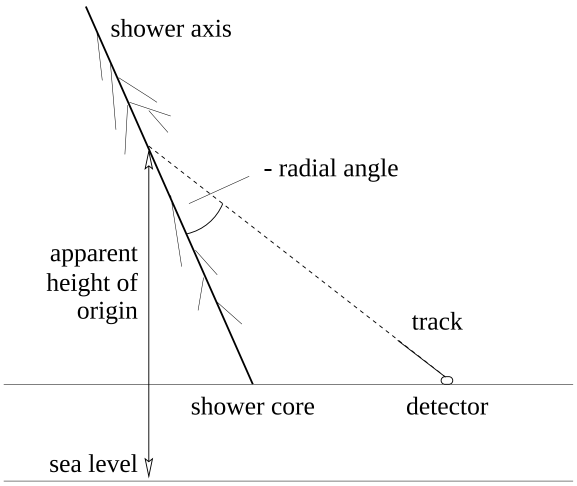

Figure 2: An apparent height of origin can be derived from the track projected onto the radial plane.

parent particle generation. For the muons in UHE air showers the intrinsic distribution is very narrow, apart from tails due to some low-energy muons. This distribution shows little difference between proton- and iron-initiated showers, even for an ideal angular resolution. Under certain experimental constraints the tangential angle can be used to measure the combined angular resolution of air-shower array and tracking detectors.

The radial angle, representing the longitudinal shower development, is the quantity sensitive to the composition. The *average* (which may be mean, median, or mode) radial angle depends in a characteristic way on the core distance. To compare the simulated average radial-angle curves with measurements requires to know the combined angular resolution of the air-shower array and tracking detectors and to some extent also the core position resolution of the array. However, the average radial angle at any given core distance changes very little with shower size or zenith angle. The figures in this paper are intended as examples. They are based on simulations using the CORSIKA code (see section 3). The simulations assume an experimental resolution as observed for CRT detectors at the HEGRA array [17]. See figure 4 for the median radial angles of different primary types. At any core distance the average radial angle is almost a linear function of $\langle \ln A \rangle$, where A is the mass number of the primary.

Although a similar difference between showers initiated by protons or iron nuclei is also present in the radial-angle curves of electrons, the electron component is less usefull for composition studies than muons. First of all, a very detailed simulation of the behaviour of the tracking detectors to electrons, gammas, muons, and hadrons is required to compare with experimental data. For muons the detector is generally much better understood,

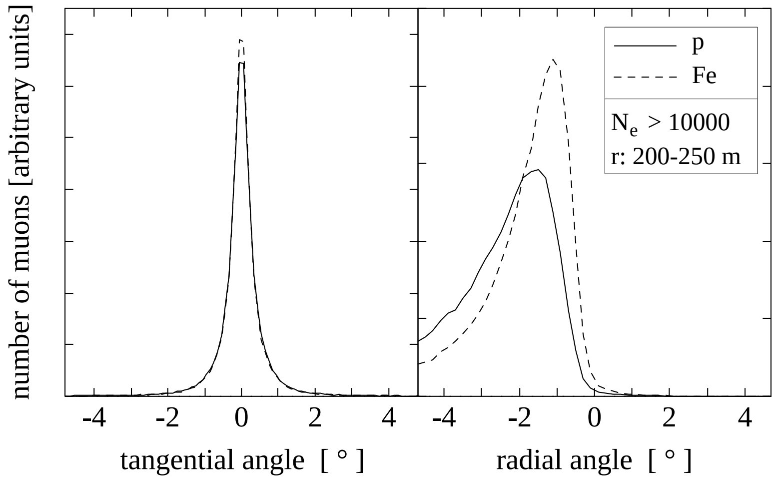

Figure 3: Distributions of tangential and radial angles of shower muons in simulated proton and iron showers, respectively, with $N_e > 10000$, at core distances of 200–250 m. Perfect angular resolution but a realistic detection efficiency as appropriate for CRT detectors is assumed.

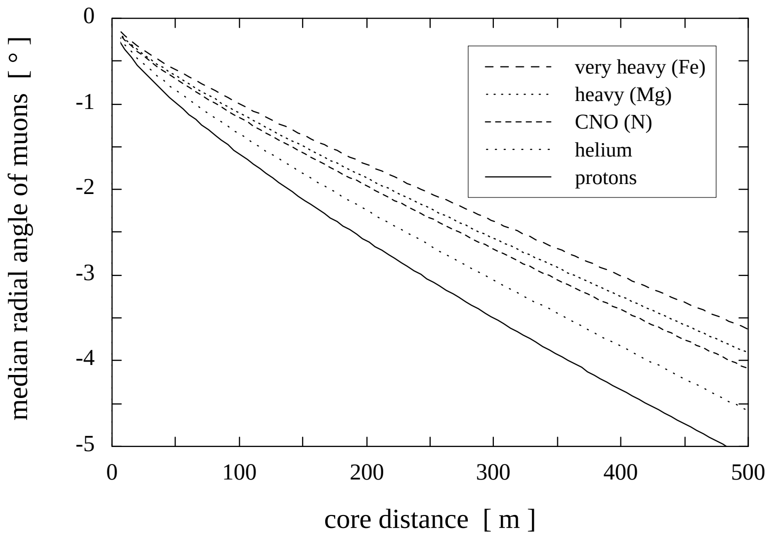

Figure 4: Median radial angle of muons in showers initiated by different primaries, for a minimum shower size of 10^4 and angular resolutions and detector responses as appropriate for CRT detectors and the HEGRA scintillator array (see section 3).

although punch-throughs of other particles have to be considered.

The second reason in favour of muons is based on the shower selection introduced by the air-shower array. To achieve the same shower size (N_e) at ground level, showers initiated by heavy primaries require a larger primary energy than proton showers. Due to the steep spectrum, conventional air-shower arrays will, therefore, mainly see proton showers at any shower size, even if protons account for only half of the mass composition at a given energy per particle. Muons can almost compensate for this bias because, at the same shower size, a proton shower contains less muons than a shower of a heavy primary.

Because of the compensation of the selection bias by the larger number of muons for heavy primaries the quantity

$$\Lambda_\mu = \frac{1}{\sum w_i} \sum_i w_i \, \frac{\langle\alpha_i\rangle - \langle\alpha_{i,\mathrm{p}}\rangle}{\langle\alpha_{i,\mathrm{Fe}}\rangle - \langle\alpha_{i,\mathrm{p}}\rangle} \tag{1}$$

is even for a mixed composition essentially proportional to $\langle\ln A\rangle$:

$$\langle\ln A\rangle \approx \Lambda_\mu \, \ln 56. \tag{2}$$

In this context $\langle\alpha_i\rangle$ is the measured (or simulated) median radial angle in the core distance interval i, $\langle\alpha_{i,\mathrm{p}}\rangle$ and $\langle\alpha_{i,\mathrm{Fe}}\rangle$ are the expected median values for pure protons and pure iron nuclei from the simulations, and the weights w_i take the statistical accuracy of measured as well as simulated average values into account. In the simplest possible formulation, ignoring statistical errors of the simulation and correlations of errors in different radial bins and taking into account only $\sigma(\langle\alpha_i\rangle)$ as the measured accuracy of $\langle\alpha_i\rangle$,

$$w_i = \Big(\sigma(\langle\alpha_i\rangle) \;/\; (\langle\alpha_{i,\mathrm{Fe}}\rangle - \langle\alpha_{i,\mathrm{p}}\rangle)\Big)^{-2}. \tag{3}$$

For compositions as reported by direct measurements, equation 2 holds to better than 0.05 at all investigated shower size intervals – at least for CRT and HEGRA to which the simulations correspond. Although this relation is quite coincidental, it is expected to hold as well for most other existing air-shower arrays in combination with tracking detectors of a low energy threshold for muons. In the case of extreme compositions like pure helium, however, the relation may be wrong by up to 0.26 in terms of $\langle\ln A\rangle$.

Figure 5 shows that the median (or mean) radial angle of muons is indeed sensitive to changes in the composition as indicated by direct measurements [1] below the knee. Even the electron radial angles can be used for that purpose (see figure 6) but a more accurate knowledge of the detector response is required in that case. In addition, Λ_e (defined in analogy to Λ_μ), is not proportional to $\langle\ln A\rangle$ but is more sensitive to the fraction of light nuclei than to heavy nuclei.

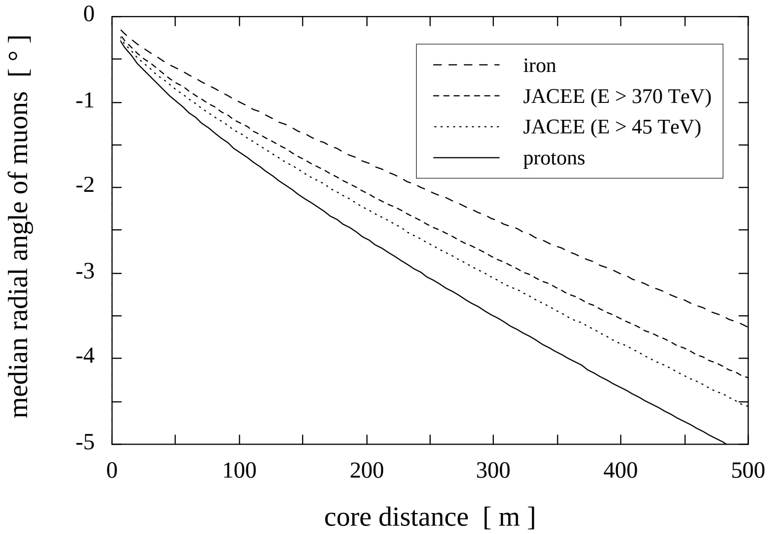

Figure 5: Median radial angle of muons in showers for different energy-independent model compositions (pure protons, pure iron, and two compositions as measured by the JACEE collaboration [1]). Simulations for $N_e > 10^4$, as in figure 4.

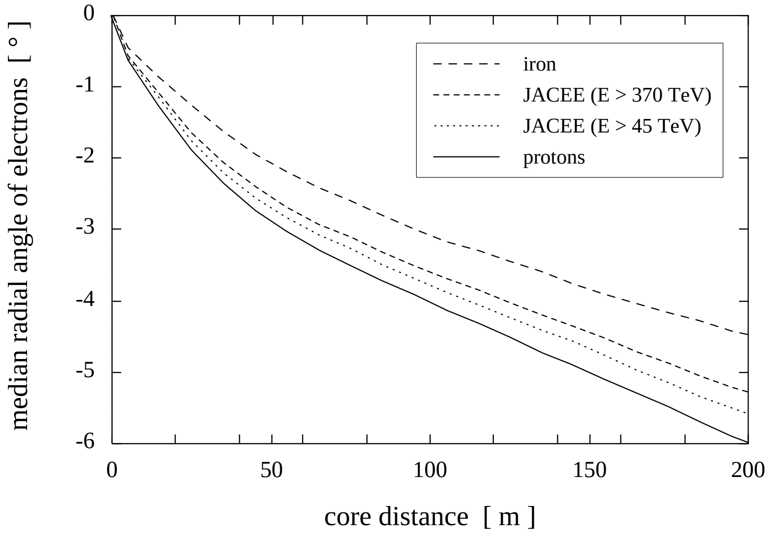

Figure 6: Simulated median radial angle of particles identified as electrons, for the same model compositions as in figure 5. $N_e > 10^4$, as in figure 4.

3 Shower and detector simulations

The scope of this paper is beyond the measurements carried out with CRT detectors and the HEGRA array. Although the simulations presented here serve only as examples, experimental effects of CRT detectors and the HEGRA scintillator array are carefully taken into account. It may be instructive to see which of these effects turn out to be the most relevant ones.

The CORSIKA simulation code [18, 19] was used in version 4.068 for all shower simulations presented in this paper. Except for tests of the accuracy of the shower simulations (see section 4) the VENUS hadron-nucleus and nucleus-nucleus interaction code [20] was used for high-energy hadronic interactions, GHEISHA [21] for hadronic interactions below 80 GeV, and EGS4 [22] for the electromagnetic component – all in the framework of CORSIKA. The simulations take also the geomagnetic field at La Palma into account. A total of 5580 showers (1860 proton showers and 930 showers for each of the other four types of primaries, He, N, Mg, and Fe) were generated isotropically in the zenith angle range 0° to 32°. The energy ranges were selected to cover approximately the same shower sizes, from 20 TeV to 2 PeV for protons increasing to 40 TeV to 4 PeV for iron nuclei. Showers were generated with a $E^{-1.7}$ differential energy spectrum to have sufficient numbers of showers at all energies and weighted by E^{-1} for the analysis. The analysis was restricted to shower sizes where contributions from showers outside the simulated energy ranges are negligible.

Concerning the CRT detectors [12], it should be mentioned that muons are identified as pairs of tracks in two drift chambers, one above and one below a 10 cm thick iron plate. The measured angles between the two tracks of an identified muon are required to be less than 2.5° in two perpendicular projections. Electrons are identified as non-muon tracks in the upper drift chamber. Results of very detailed simulations of the response of CRT detectors to various types of particles (electrons, gammas, muons, pions, and protons) – as outlined in [17] and described in detail in [23] – and the measured detector performance [17] were carefully parametrized. This includes detection efficiencies and angular resolutions as functions of particle energies, zenith angles, and track densities – independent for each particle type and for the identification as an electron track and as a muon track. As a consequence, the simulations include not only punch-through of electrons but also of hadrons. It should be noted that the energy dependence for detecting genuine muons is fully described by multiple scattering and energy loss in the iron plate [17]. CRT detectors are mainly sensitive to muons above about 1 GeV. Electrons, on the other hand, are detected above some 10 MeV. The effect of multiple scattering in the detector container and the iron plate are included in the angular resolutions.

For a detailed simulation of the HEGRA array see [24]. For the simulations presented here, a much simpler approach is sufficient because the simulations are restricted to shower sizes where the HEGRA array is fully efficient, independent of shower age, core position, and zenith angle. The resolutions for shower sizes and core positions as obtained by the detailed simulations were parametrized. The HEGRA angular resolution is implemented in the simulations in such a way that the combined angular resolution of CRT and HEGRA – as measured by the muon tangential angles as a function of shower size and zenith angle [17] – are fully reproduced.

It may be instructive to note that the median radial-angle curves presented in this paper are not significantly altered by modifying the assumed angular resolution within the experimental limits. Modifying the assumed core position resolution has an impact on the median radial angles only within a few ten meters from the core. Punch-throughs, although included in some detail, turned out to be of minor importance with CRT detectors, due to their excellent punch-through rejection. The most important experimental parameters in the simulations are the energy dependence of the detection efficiencies and the combined angular resolution of tracking detectors and air-shower array. In the case of CRT detectors and the HEGRA array both are very well known for muons and even sufficiently well known for electrons.

It appears very reasonable that the response of other types of tracking detectors and other air-shower arrays can also be understood well enough to take advantage of the radial-angle method. However, a few experimental requirements as outlined in section 5 should be observed for that purpose.

4 Accuracy of shower simulations

Apart from the detector response, a major uncertainty in the interpretation of any indirect measurement of the cosmic-ray mass composition is due to the limited accuracy of the shower simulations. Despite much progress in recent years, the nucleus-nucleus and hadron-nucleus interaction models in air-shower simulations lead to non-negligible theoretical uncertainties. The CORSIKA simulation code attempts a particularly detailed and accurate shower simulation. In the version 4.068, as used for this paper, it offers several independent interaction models.

Results for different interaction models, using the VENUS and GHEISHA options on one side and DPM on the other side, and for different fragmentation (evaporation) of the projectile nuclei have been compared in the energy range 10^{14}–10^{15} eV. Systematic differences in the average shower sizes of up to 20% are found and also differences in the shower fluctuations. If the median radial-angle curves are compared in the same ranges of shower sizes, the differences between models are very small within core distances up to about 200 m, increasing to about 10% of the proton-iron difference at a core distance of 400 m (figure 7). That increase of systematic uncertainties

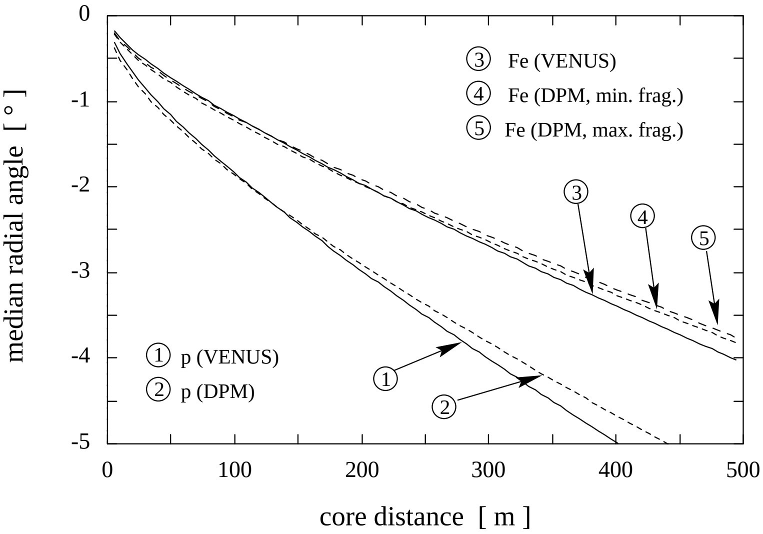

Figure 7: Median radial angle of muons in proton and iron showers with different interaction models ($10000 < N_e < 20000$, with fixed height of first interaction to keep shower-to-shower fluctuations small). 1: protons with VENUS/GHEISHA, 2: protons with DPM, 3: iron with VENUS/GHEISHA, 4(5): iron with DPM and no (full) fragmentation of the spectators in projectile nuclei.

is due to the fact that hard interactions resulting in high-p_t secondaries are not yet included very accurately. With all interaction models the shower-size dependence of the radial-angle curve is small. A 30% systematic error in the relation of simulated to measured shower sizes would result only in a systematic error of the median radial angles of 3% of the proton-iron difference. Moreover, this dependence is essentially the same for different models.

Another uncertainty in the longitudinal shower development is due to the sparse particle physics data in the very forward rapidity region at high energies. Until more such data is available and incorporated into the interaction models it seems desirable to have also indirect composition measurements in an energy range overlapping with direct measurements. When searching only for a change of the composition near the knee of the cosmic-ray spectrum, the poor knowledge of the very forward region should not be a limitation. Different parametrizations of parton densities which pose problems for shower simulations at extremely high energies [25] are not of concern near 10^{15} eV primary energy.

5 Experimental requirements

To exploit the described method for composition studies several experimental requirements should be met. These are requirements for the *particle identification* with a tracking detector and the *resolution* of angles and positions.

Because the particles of the electromagnetic shower component, $e^{\pm}$ and γ, have angular distributions much different from those of muons, a good electron rejection is important. Hadrons only matter very close to the shower core. Due to the broad muon lateral distribution it is generally not such a problem to identify muons at large core distances but more of a problem to reject random, non-shower muons. This can be easily solved by a timing information of a few hundred nanoseconds accuracy and by the angular correlation of shower muons with the shower axis. Another requirement for the muon identification is due to the fact that the radial angles are well correlated with the muon momentum, with higher-energy muons usually coming from further up in the atmosphere and being better aligned with the shower axis. The muon identification should, therefore, be well understood also as a function of momentum and zenith angle. For a high muon-energy threshold, a very good angular resolution is required, while for a low threshold the multiple scattering and magnetic deflection of muons cannot be neglected.

The combined angular resolution of air-shower array and tracking detector should be better than about 1° in each projection but has to be known as a function of shower size to compare measurements with simulations. Definitely sufficient would be a combined resolution of some 0.5° if the muon-energy threshold is as low as about 1 GeV. This would be difficult to achieve with a tracking detector entirely below thick shielding material which also scatters the muons. A good uniformity of the resolution over azimuth angles would be of advantage for the important detector calibration. Only with a uniform resolution can the angular resolution be derived from the tangential angle distribution of the same data set which is used to compare the radial angles with simulations. Otherwise, shower-size dependent systematic errors can arise.

The alignment of the tracking detectors with respect to the reference frame as defined by showers reconstructed from array data should be known to better than about 0.1°. This may require some careful calibrations but is certainly feasible.

The core position resolution which also enters into the simulations has to be determined from the air-shower array alone. Keeping selection effects of the air-shower array as small as possible demands to select only showers well contained in the array and with shower sizes well above the trigger and reconstruction thresholds. For many of the existing air-shower arrays that would correspond to threshold energies of some 80–200 TeV, just below where direct measurements are running out of statistics. Reasonable errors in the shower size and energy calibrations of the array do not compromise the method as long as the same experimental resolution is used in the simulations as seen in the data to be compared with these simulations.

With the 25 m^2 sensitive area of the CRT detectors the statistics with data of about one year would be the limit for primary energies above several 10^{16} eV. A few hundred square meters area would be sufficient in order to achieve some overlap with the Fly's Eye composition measurements.

All these requirements can be fulfilled with present technology for large-area tracking detectors and existing air-shower arrays. Although simultaneous precise (nanosecond) timing information of the muons could supplement the described method (see for example [26]), precise timing is not required and might be difficult to accomplish with large-area detectors.

6 Concluding remarks

The average radial angle of particles are sensitive to the cosmic-ray mass composition. Muons have, among other particles in air showers, many advantages. Their intrinsic angular distribution is very narrow and, thus, the tangential-angle distribution can be used to calibrate the radial-angle resolution as a function of shower size. Muons can be distinguished from other particle types very well. The larger number of muons in showers initiated by heavy primaries compensates for the N_e shower selection bias which favours light primaries.

Like any other indirect measurement of some average of the cosmic-ray composition, that method requires comparison of measured data with simulations. Compared to many other indirect methods, the muon radial-angle method has two major advantages: First, the most important detector effects to be included in the simulation can be measured very well and, second, systematic errors, for example due to the interaction model, can be easily checked by comparing measurements at low energies (a few hundred TeV) with simulations for directly measured compositions as in [1].

Despite some systematic uncertainties in the shower simulations an average mass number ($\langle \ln A \rangle$) can be derived and compared with direct measurements well below the knee. Regardless of that, the muon radial-angle method can be very sensitive to changes in the composition. The radial-angle method would not require a very large experimental effort if existing air-shower arrays are supplemented with suitable tracking detectors.

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