A new approach to inferring the mass composition of cosmic rays at energies above $10^{18}$ eV

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Abstract

We describe a new approach to establishing the mass composition at high energies. Based on measuring both the vertical and inclined shower rates, it has the potential to distinguish heavy nuclei from light nuclei. We apply the method to Haverah Park data above $10^{18}$ eV to show that, under the assumption that the Quark Gluon String Jet Model correctly describes the high energy interactions, the inclined shower measurements favour a light composition at energies above $10^{19}$ eV. The same conclusion is obtained using a variety of assumptions about the cosmic ray spectrum. To the extent that precise spectral measurements will be possible by forthcoming experiments such as the Auger observatories, the method will further constrain data on composition of the ultra high energy cosmic rays.

keywords: mass composition : ultra high energy cosmic rays

1 Introduction

Efforts to understand the origin of cosmic rays at any energy are greatly hampered by our lack of knowledge of the mass distribution in the incoming cosmic ray beam. The determination of the arrival direction of cosmic rays does not depend on knowledge of the mass of the primary and, using the fluorescence technique, the primary energy is obtainable with only a small systematic uncertainty because of the unknown mass. Even with the traditional ground arrays it has been possible to devise ways of deducing the primary energy that are reasonably independent of model and mass uncertainties, at least at the 30 % level. However use of the data on the energy
spectrum and arrival direction distribution to decide between various origin
models does require knowledge of the primary mass distribution. While there
is a common assumption that protons dominate at the highest energies, hard
experimental evidence is lacking, as it is at energies above $10^{18}$ eV.

Some models of cosmic ray origin lead to the conclusion that photons
dominate the cosmic ray beam. This hypothesis can be more readily tested
than can competing hypotheses that advocate protons or iron nucleis as the
majority primaries. This is because the shower development of a photon pri-
mary is very different from that of any hadronic primary. The difference is
larger than is expected between the showers created by proton and iron pri-
maries. For example, Halzen et al. [1] have shown that a photon is extremely
unlikely to produce a shower in the atmosphere that has a development pro-
file that looks like the famous event of $3 \times 10^{20}$ eV observed by the Fly’s
Eye Group [2]. A study of horizontal showers recorded at Haverah Park has
shown that at $10^{19}$ eV there can be no more than 40% of the primaries that
are photons [3], while a search, using the traditional idea of photon show-
ners being deficient in muons, has given a similar limit at the same energy
[4]. These analyses all assume that photons > $10^{19}$ eV have not acquired
hadron-like properties, as has sometimes been speculated.

There is no reliable evidence on the hadronic mass composition above $10^{19}$
eV. Some years ago an analysis of the Fly’s Eye data [5] pointed to a change
from an iron-dominated composition at $3 \times 10^{17}$ eV to a proton-dominated
composition near $10^{19}$ eV. This conclusion was drawn from a study of the
variation of depth of maximum with energy (the elongation rate) and from an
analysis of the spread in depth of maximum at a given energy. The elongation
rate behaviour was in agreement with an earlier, model-independent, analysis
from Haverah Park [6] and with a related study using Cherenkov light by the
Yakutsk group [7]. The conclusions on mass composition from the study of
the spread in depth of maximum were confirmed by [8] but none of these
analyses extended to energies above $10^{19}$ eV.

A different conclusion has been reached by the AGASA group based on
the variation of the muon content of showers with energy [9]. Their analysis
favours a composition that remains ‘mixed’ over the $10^{18}$ to $10^{19}$ eV decade.
Furthermore there is a difference between the conclusions reached from the
data on depth of maximum from the Fly’s Eye experiment [5] and those
reached from the HiRes prototype, operated with the MIA detector, in the
range $10^{17}$ to $10^{18}$ eV [10]. The more recent data are used to infer protons
as early as $10^{18}$ eV, if the QGSJET model [11] is correct. There is a good ev-
dence from Haverah Park data [12] that the QGSJET model is satisfactory,
at least to $10^{18}$ eV. However the HiRes/MIA conclusion is, in turn, in con-
tradiction with a new analysis of Haverah Park data [12] that suggests that
Figure 1: Compilation of data on depth of maximum as a function of energy from different experiments compared with predictions for different models. This figure was supplied by D. Heck and J. Knapp and appear in [13].
protons make up only 34% of the flux, independent of the energy, between $3 \times 10^{17}$ and $2 \times 10^{18}$ eV, with iron nuclei making up the remainder.

The addition of more data in recent years and a better understanding of what might be the optimum shower model has not helped to clarify the position: rather the reverse. In figure 1 we show a compilation of data on depth of maximum, $X_m$, as a function of energy [13]. The sensitivity of a conclusion to the choice of model is evident. The matter is thus far from being resolved and there is clearly scope for alternative approaches.

2 Outline of a new approach

It seems unlikely that a single method of deriving the mass composition will be sufficient to resolve this important issue. In this paper we argue for a new approach that is based on the study of inclined showers, and which can be added to the armoury that can be used. The method is derived from the work that led to our estimate [3] of a limit to the photon flux at $10^{19}$ eV, an estimate that has now been confirmed independently [4], as mentioned above. Our approach stems from the detailed understanding of the propagation of inclined showers that has been developed [14] and from its application to the prediction of the rate of triggering of the Haverah Park array [15]. Inclined showers induced by very high energy cosmic rays produce particle densities at ground level which are dominantly due to muons, in contrast to vertical showers that have an important component due to photons and electrons stemming from $\pi^0$ decay. Measurements of the cosmic ray rate at different zenith gives a handle on the relative number of muons in a shower, which is dependent on composition.

To find the photon limit we assumed that the energy spectrum was known, and calibrated in a mass-independent way, through the work with the Fly’s Eye detector. Using this known ’vertical’ spectrum, a prediction was made of the number of showers expected with energies above $10^{19}$ eV for photon, proton and iron primaries. We found strong evidence to reject a photon intensity at the level predicted by several super-heavy relic models [16], [17], [18]. Recent reassessment of the energy spectrum in the appropriate range [19], and the differences reported between the AGASA group and the HiRes group [20], [21], make it premature to be too firmly in favour of protons or iron above $10^{19}$ eV, but our conclusion about photons remains robust. An extensive description of our method used to derive the photon limit has been given recently [22]. In this paper we show how the technique can be used to infer the mass at energies between $10^{18}$ and $10^{19}$ eV. The conclusions, as to the mass variation with energy that we can presently draw, is constrained by
uncertainties in the form of the spectrum in this energy range, and by the assumed hadronic interaction model, rather than by statistical limitations. We present conclusions for a number of spectra, using the QGSJET model as a reference for hadronic interactions, in the expectation that the spectrum uncertainties will soon be resolved.

3 The analysis of inclined showers

The analysis of showers with zenith angles $> 60^\circ$ is not straightforward, even with an array like Haverah Park in which the detectors were deep-water Cherenkov detectors. These detectors present a significant area to inclined showers by comparison with thin scintillators. There are two major difficulties. Firstly the showers lose their near-circular symmetry very rapidly above $60^\circ$ and, secondly, the finite size of the array makes it difficult to locate the core. During the operational phase of the Haverah Park array (1967-1987) a decision was made to ignore events $> 60^\circ$ for these reasons. More recently, with the advent of the analytical techniques of Ave et al. and with the availability of much more computing power, it has proved possible to get accurate directions for the events, to estimate their energies (subject to assumptions about shower models) and to compute the flux. In this section we justify these claims.

The methods of finding the directions and of calculating the energy are described in detail in [22] for events above $10^{19}$ eV. Here we have applied the same techniques, namely an iterative process in which arrival directions are fitted to the time distributions, followed by shower energy and core position fits to the detector densities. The timing of the signals use the information on core position to account for curvature corrections. Following the same steps as described in [22], we have performed three quality cuts to eliminate uncertainties in the reconstruction procedure: (i) the distance from the central triggering detector to the core position in the shower plane is required to be below $r_{\text{max}} = 500$ m, (ii) the $\chi^2$ probability for the energy and direction fits must be $> 1\%$, (iii) the downward error in the energy determination is required to be less than a factor of 2. The chosen value of $r_{\text{max}}$ guarantees that the core position is always close to the triggering detectors in the array. Similar results, but with reduced statistics, was obtained with $r_{\text{max}} = 300$ m. This last cut is the only one that differs from those used in [22]: it ensures that the smaller showers, that are the concern of this paper, are near to sufficient detectors to allow reliable density fits. After making the cuts described above we found 385 events with $E_0 > 10^{18}$ eV and 2 events with $E_0 > 10^{19}$ eV.
Figure 2: $\chi^2$ distributions from the energy and direction reconstruction of data (stars) and artificial events (histogram), assuming proton composition and the parameterizations of the spectrum given in [24].

Again mimicking the procedure described in Ref. [22], we have generated a sample of artificial events to which we have applied the same reconstruction algorithms as used for the data. In figure 2 we show the normalised $\chi^2$ distributions for the timing fit to the 385 events above $10^{18}$ eV and for the energy estimates made, assuming proton primaries. The match between the real data and artificial data generated using the spectrum description given in [24] (from here on NW), and assuming proton primaries, is reassuring. We argue that these plots show that we have developed a good understanding of the techniques needed to analyse the directions and energies of very inclined showers.

The energy resolution for events above $10^{18}$ eV is shown in figure 3 for two energy bands. The energy error for the artificial events is the difference between the reconstructed energy $E_r$ and that of the simulated shower $E_0$. The rms spread in the relative errors for the artificial events are 0.43 and 0.40: we note the tail towards higher energies in the lower energy band.

The energy error in the data is obtained by combining in quadrature the error obtained from the maximum likelihood analysis and the error associated with the uncertainty in the zenith angle reconstruction. In figure 3 we show the upward and downward error distributions for the real data as compared with the artificial events, again generated with the NW spectrum and proton primaries. Again the agreement is very satisfactory.

In figure 3 the zenith angle distribution for events above $10^{18}$ eV is com-
Figure 3: Energy resolution integrated for all zeniths in different energy bins. A uniform energy distribution is assumed for each graph.

Figure 4: Downward and upward error distribution in the reconstructed energy from the density fits to the data (stars) and to the artificial events (histogram).
pared to real data using the NW (proton) spectrum to make the prediction. This comparison is similar to that made in our earlier work [3] but we have now developed methods to estimate the energy, most importantly including zero density measurements in the energy reconstruction fits [22]. Here we see a difference between the predictions and the data. Note that the data are not normalised. The fact that the predicted rate is above the artificial rate indicates that we are using (i) a spectrum with fluxes that are too high, or (ii) the wrong mass composition, or (iii) an incorrect hadronic interaction model. Of course a combination of all these uncertainties can also be involved.

4 Rate dependence on primary mass and spectrum assumptions

We have studied how different assumptions about the shape of primary spectrum affect the expected rates of inclined showers for both pure proton and pure iron samples. In figure 6 we show a compilation of cosmic ray data for energies above $10^{17}$ eV together with various parameterizations of the energy spectrum. The AGASA [20], Monocular HiRes (HiRes 1 and HiRes 2 [21]), HiRes-MIA [23], Haverah Park [27] and Fly’sEye Stereo [26] spectral measurements are as reported by the different groups. For the purposes of this work we have taken four recent parameterizations of the spectra represented
Figure 6: Compilation of cosmic ray data for energies exceeding $10^{17}$ eV including, recently reanalysed Haverah Park data assuming proton and iron primaries, Stereo Fly’s Eye data, Monocular HiRes data from both Eyes (HiRes1 and HiRes2), recently reanalysed AGASA data, including events up to $60^\circ$, and hybrid HiRes MIA data. The measurements are compared to spectrum parameterizations given by different authors and used in the simulation of artificial events as described in the text.
Figure 7: Integral (left panel) and differential (right panel) number of inclined events as a function of energy for the Haverah Park data set (stars) compared to the predictions for iron (dotted line), protons (continuous). The parameterization of the spectrum given in [24] is assumed.

by the lines in Fig. [3] the spectra attributed to Nagano and Watson [24], the one obtained by Szabelski et al. [19] (both of these are syntheses of various data sets), the parameterization given by HiRes experiment [21], and a parameterization based on a recent analysis of the Haverah Park data [27]. We have not used the recently reported AGASA spectrum [20] which starts above $3 \times 10^{18}$ eV. In figures [4][5][6][10] we show the sensitivity of the inferred variation of mass for reasons explained later with energy to the different input spectra. While from the Szabelski et al. input we find a mass spectrum that is iron dominated over the whole energy range ($10^{18}$-$10^{19}$ eV), with the NW spectrum one would argue for a proton dominated composition. However if we take the recently revised Haverah Park spectrum [27] we find that the mean mass lies between proton and iron near $10^{18}$ eV and possibly gets heavier as we move to energies close to $10^{19}$ eV. We note that the mean mass at the differential energy point at $2 \times 10^{18}$ eV is $<\ln A> = 1.4 \pm 0.4$. A similar conclusion can be drawn with the HiRes spectrum as an input. In the energy decade below $2 \times 10^{18}$ eV we have recently argued that $<\ln A> = 2.8 \pm 0.4$, assuming a bi-modal mass composition of proton and iron [12].

Comparing the measured data to the corresponding predictions assuming an iron only spectrum and a proton only spectrum, it is straightforward to obtain the fraction of protons in a dual mass composition model. In figure [11] the variation with energy of the predicted fraction of protons in the cosmic
Figure 8: Same as Fig. 7 but using the parameterization of the spectrum given in [19].

Figure 9: Same as Fig. 7 but using the parameterization of the spectrum given in [27].
ray beam is plotted for the four spectra. In this figure, above $10^{19}$ eV, we have included events with less stringent quality cuts ($r_{\text{max}} = 2$ km), as used in [22]. For sufficiently high energies, the number of detectors with signals increases substantially for any surface array and this allows the relaxation of the condition, while retaining reasonably constrained fits. There are large uncertainties, but a trend towards a light composition at energies above the ankle is apparent with all spectra used. We note also that if the true flux is like that in the recent analysis presented by AGASA [20], the inclined shower data would be inconsistent with even a dominantly iron composition because the predicted rate would exceed the observed rate. A heavier mass primary composition would be required.

5 Conclusion

We believe that we have demonstrated the potential of a new method for extracting the mass spectrum above $10^{18}$ eV by studying cosmic rays at high zenith angles. It is based on the difference in abundance of muons with respect to photons and electrons for different primaries. We are not making strong claims for the finality of our conclusions (see Fig. [11]) about mass composition. A definitive statement awaits a better understanding of the differences between different energy spectra above this energy and an exploration of the sensitivity of the method to different models of particle
Figure 11: Ratio of proton to total as obtained from a two component mixture of protons and irons and assuming four different energy spectra parametrizations as shown in figure 6 and described in the text.
interactions. This technique can be extended to very high energies and, assuming the interaction model is understood, we would expect to be able to extract the mass spectrum in the range $10^{19}$ to $10^{20}$ eV with data from the Pierre Auger Observatory.

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