PROPERTIES OF COSMIC RAY INTERACTIONS AT PEV ENERGIES

A.D. Erlykin 1,2, A.W. Wolfendale 2

(1) Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK
(2) P. N. Lebedev Physical Institute, Leninsky Prospekt, Moscow 117924, Russia

Abstract

An analysis has been made of the present situation with the high energy hadron-nucleus and nucleus-nucleus interaction models. As is already known there are inconsistencies in the interpretation of experimental data on the primary mass composition, which appear when different EAS components are used for the analyses, even for the same experiment. In the absence of obvious experimental defects, there is a clear need for an improvement to the existing models; we argue that the most promising way is to introduce two effects which should be present in nucleus-nucleus collisions and have not been allowed for before. These are: a few percent energy transfer into the EAS electromagnetic component due to electron-positron pair production or electromagnetic radiation of quark-gluon plasma and a small slowdown of the cascading process in its initial stages associated with the extended lifetime of excited nuclear fragments. The latter process displaces the shower maximum deeper into the atmosphere.

1. Introduction

Among the most popular interaction models which are used for the analysis of experimental data in the PeV region and beyond are QGSJET, SYBILL, NEXUS, DPMJET, VENUS and HDPM, coupled with CORSIKA and partly with the AIRES simulation codes (see [1, 2] and references therein for a description of the models). Early versions of these models differed significantly in their description of the development of the atmospheric cascades. One of the possible ways to evaluate the quality of a model is to derive the primary mass composition from the analysis of different observables: a good model should obviously give the same composition for any set of observables. We used this approach to interpret the data on the maximum development depth of the electromagnetic cascades $X_{\text{max}}$ and on the ratio of muon to electron sizes $N_\mu/N_e$ in terms of the mean

1Corresponding author: Erlykin A.D., e-mail: A.D.Erlykin@durham.ac.uk
logarithm of the primary mass \( \langle \ln A \rangle \); the best consistency was obtained for the QGSJET model \([3]\). A later analysis of the EAS hadron component confirmed this conclusion \([4]\).

Since then the models have been improved and the differences between their predictions reduced \([1]\). The precision of experimental data has been also improved and this offers the hope of further testing the models and of determining the actual value of \( \langle \ln A \rangle \). Some of the new measurements in which Cherenkov light in the atmosphere is detected have given a deeper \( X_{\text{max}} \) and hence a lighter mass composition than before \([5, 6]\). The extensive set of measurements on the ground and relevant simulations made by the KASCADE collaboration indicated that there is a difference in the estimate of \( \langle \ln A \rangle \) derived from different sets of observables \([7]\). At lower energies it was also difficult to get a consistent explanation of the measured muon and hadron trigger rates \([8]\). All these facts provide evidence that further improvements to the models are urgently needed.

Meanwhile, a few calls for a quite radical change of the interaction model have appeared, inspired mostly by the existence of the well known knee in the primary cosmic ray \( \text{(CR)} \) spectrum at PeV energies. We discuss first the need for such a radical change and follow this with our own suggestion for modifications to the model for a better description of the modern experimental data \( \text{(i.e. KASCADE, DICE, BLANCA et al.)} \).

2. The possibility of a radical change in the interaction model

2.1. The possibilities and general remarks

A number of possibilities arise, and they will be considered in turn. Essentially they are of two types. The first considers that the primary spectrum \( \text{(represented in the usual way by a power law)} \) has an energy-independent exponent valid both below and above the PeV region where there is the knee in the spectrum inferred from the detected particles ‘low’ in the atmosphere \( \text{(electrons, muons, hadrons)} \). The change in the interaction mechanism is then sudden \( \text{(at} \approx 3 \text{ PeV)} \) for CR-air nucleus interactions. The second is of the same philosophy i.e. that the original production spectrum has a unique exponent, but the interactions are in the interstellar medium \( \text{(ISM)} \) or even in the intergalactic medium \( \text{(IGM)} \) and not with air nuclei so that the spectrum of CR incident on the atmosphere already has the knee in it; there is no further radical change in the interaction mechanism for CR-air nucleus collisions.
The general argument against all these ideas is based on the observed anisotropy of the arrival directions of cosmic rays. The measured amplitude and phase of the anisotropy change in the vicinity of the knee and this gives support for its astrophysical origin \cite{9, 10, 11}, i.e. that the spectral shape arises because several sources, or types of source, contribute.

Of relevance, too, is the cosmological aspect, viz the effect of a proposed radical interaction change in the early Universe when the average energy of all 'particles' was in the PeV region. As we have pointed out already \cite{8} there are sound cosmological arguments against a radical change for P-P reactions in the PeV region. Some $10^{-14}$ sec after the Big Bang the average temperature of the primordial plasma was about $10^{16}$K and the mean energy per 'particle' was of the order of a TeV in the centre of mass system, which corresponds to PeV energies in the laboratory system. If a radical change of the interaction occurred at this energy changes to the subsequent evolution of the Universe would have taken place \cite{12}. Now the contemporary model (i.e. without a radical change) fits the observed data on the relative abundance of the light elements and it is difficult to imagine this being the case were there to have been a radical change of the interaction at $10^{-14}$ s.

Despite 'the case against' the possibility of such a radical change it would have such important implications for particle physics that we make a detailed examination of some of the recent radical interaction models put forward to explain the knee.

2.2. A radical change for the CR - air nucleus interaction

Nikolsky has argued extensively that there is such a radical change. The latest idea \cite{13} is close to that of his paper of 1995 \cite{14}. The author assumes that at a primary energy of about 3-5 PeV the multiplicity of secondary particles increases dramatically. The attenuation of the cascade speeds up and the intensity of showers in the lower half of the atmosphere falls, thereby forming the knee. There is actually no detailed model to be checked, because no numerical estimates have been given of the basic interaction parameters and their energy dependence, therefore it is difficult to assess the idea quantitatively.

One remark should be made, however. There is a difference between the previous and present pictures of the interaction advocated by the author. The 1995 model had the need
to withdraw a part of the cascade energy and to put it into some unobservable components (high energy muons, neutrinos etc.) in order to form the knee. Now, in 2001, on the other hand, more energy is transferred to low energy particles of the hadronic cascade in the initial stages of its development. In our mind this is a backward step. The suggested increase of the energy transferred into the hadronic cascade in the atmosphere should be seen in the spectra of muons and Cherenkov light emitted by the charged particles in the atmosphere as an 'inverse knee or ankle', i.e. as a decrease of the spectral slope. Nothing like that is actually observed. EAS muon size spectra at mountains: Tien-Shan [15, 16], EAS-TOP [17, 18] and at sea level: Ohya [19], KASCADE [20, 21] and MSU [22] all show the 'ordinary' knee, i.e. an increase of the spectral slope. To the existing 5 Cherenkov light spectra: TUNKA [23], HEGRA [24], DICE [5], BLANCA [6] and CACTI [25] has been added another one which is based on the combined use of Cherenkov light and EAS electron size measurement [26]. All 6 demonstrate clearly the existence of the knee just like that in the particle size spectrum with a sharp increase of slope, which rules out the possibility of radical increasing the energy fraction deposited by the cascade in the atmosphere.

The possibility of having no knee in the primary spectrum and hiding the missing energy in high energy muons and neutrinos (an apparently attractive idea) has also been discussed by Petrukhin [27]. The proposed model suggests the production at threshold of one or a few hypothetical heavy particles in each interaction, which then decay into muons and neutrinos. The energy flux contained in his muon spectra is less than the missing energy flux, needed to form the knee, by a factor of about 20 even for the case of the maximum flux of high energy muons. This means that the bulk of the missing energy should be carried away by neutrinos. The author succeeds in making the energy spectrum of muons from the hypothetical decay much harder than that of the background muons from $\pi, K$ decays and prompt muons. In this way it is possible to make the missing energy visible only as a very low flux of extremely high energy muons. However, such a model of the 'new physics' ignores everything we know about the multiple production at high energies (small cross-section for the production of heavy particles, conservation of lepton number in weak decays, etc.) and seems hardly credible.

Another model of 'new physics' discussed by Kazanas and Nicolaidis [28], in spite of
some theoretical arguments, is actually purely phenomenological. In it one opens a new
channel for multiple production and puts part of the primary energy into some unobserved
particles ( technihadrons, gravitons ), then, if one fits the energy dependence of the cross-
section for the new channel and the energy fraction contained in the new particles, one
can get a reasonable fit to the observed primary cosmic ray energy spectrum, including
the knee. It is difficult to argue against the fit, but there seems to us to be no support
for such speculation.

2.3. Radical changes in the interactions in the interstellar medium

It is, in principle, possible that the knee is due to interactions of some form beyond the
atmosphere - in the ISM or IGM. If, as might be assumed by analogy with the 'X-particles'
produced by cosmic strings, the electromagnetic component is a prominent end-product
of this interaction, then this hypothesis can be ruled out because the ensuing cascade in
the Universe ( inverse compton scattering on the cosmic microwave background ) would
produce a gamma ray intensity in excess of that measured ( see, e.g. [29] for the related
cosmic string arguments ). However, there are other possibilities for the radical change
of the interaction, which can now be considered.

The possibility of finite neutrino mass has given birth to models in which the knee is
caused by the interaction of the primary protons with massive relic neutrinos. Assuming
that the mass of the electron antineutrino is 0.4 eV/c², Wigmans [30] converts some of the
primary protons by inverse β-decay reaction into neutrons and positrons, starting from
an energy of about 4 PeV. Indeed, protons will disappear from the primary flux, but we
ourselves argue that even if the shower from a secondary positron misses the detector,
the shower produced by the neutron will be practically indistinguishable from a proton-
initiated shower, because neutrons preserve more than 99% of the primary proton energy;
thus EAS measurements would not see a knee. Taking into account the problem of the
very small cross-section for the neutrino induced reactions, which requires us to assume a
very dense halo of neutrinos gravitationally attracted to the cosmic ray source region ( be
it the Galaxy or source within the Galaxy ), one should remark that the PeV neutron will
decay again into a proton and a positron within tens of parsecs and the model loses its
value.
Another model of the intermediate type was proposed by Ehrlich [31]. He used some theoretical ideas that the electron neutrino is a tachyon, which in fact does not contradict the existence of a finite neutrino mass. In this case, starting from the same energy of 4 PeV, the primary proton has the possibility to decay into a neutron, a positron and an electron neutrino. This decay might create a narrow peak of neutrons in the primary cosmic ray flux in the region close to 4.5 PeV, which can perhaps imitate the knee. All the scepticism put forward in the previous paragraph is applicable also in this case, however.

The common deficiency of all the models on the radical change of the interaction is that no attempts have been made to reconcile it with the multitude of other experimental data, different from those used for the motivation of the model. The conclusion which can be drawn from this survey is that at the present time there is neither a reasonable model nor solid argument which justifies a radical change of the interaction. We conclude that such a change as is necessary for the interaction model should not be radical and not responsible for the origin of the knee, but only responsible for restoring consistency for all cosmic ray measurables.

3. What kind of the modification of the interaction model do we need?

The variety of observed EAS components and precise measurements of their characteristics by the KASCADE experiment allowed this collaboration to derive the primary mass composition using the multivariate analysis of data. Remarkably, as has been pointed out already, it was found that not only do different methods applied to the same set of observables give different results, but that there is a systematic difference between the results obtained using the same method, but different components. In Figure 1 the mean logarithm of primary mass $\langle \ln A \rangle$ derived from different sets of observables is shown vs. the so called truncated muon number $N_{\mu}^{tr}$ (the figure is taken from [7]). $N_{\mu}^{tr}$ is the number of low energy muons ($>0.25$ GeV) contained between 40 and 200 m from the shower axis and is an observable adopted by the KASCADE collaboration as a measure of the primary energy, independent of the primary mass. They also use the number of higher energy muons ($>2.4$ GeV) $N_{\mu}^{*}$ as well as some observables related to the hadron component for the analysis of the mass composition [4]. The fundamental problem is, of course, that all the $\langle \ln A \rangle$ values should be the same, at the same value of $N_{\mu}^{tr}$, and they are not.
Figure 1: (a,b, taken from [7]). Mean logarithmic mass $\langle \ln A \rangle$ from the analysis of different sets of observables vs. $\lg N^\mu_{tr}$ (QGSJET prediction). The two dashed lines indicate alternative predictions of the Single Source Model [3], with the upper line being our latest and 'best estimate'. The sets displayed in (b) do not include the observable $N_e$. It is seen that omitting $N_e$ results in a heavier mass composition. (c) The ratio of mean values of $\langle \ln A \rangle$ from sets (b) and (a). We argue, in the text, that the 'true' value of $\langle \ln A \rangle$ is a little below the crosses in Figure 1b.
A number of features are of interest and, presumably, of some importance.

(i) The dispersion of the individual $\langle \ln A \rangle$ values about smooth lines through them indicates that non-systematic errors are $\approx \pm 0.05$. 

(ii) The use of the electron size $N_e$ results in an average lighter composition (Fig. 1a). On the other hand, omitting electrons and using just muons and hadrons results in a heavier composition (Fig. 1b).

(iii) Considering the mean values from the two sets of data (filled-in circles), the ratio of $\langle \ln A \rangle$ for (b) to (a) increases smoothly with $\log N_\mu^*$, i.e. the discrepancy between (b) and (a) rises with increasing primary energy (Fig. 1c).

(iv) Within each of (a) and (b) the differences between the $\langle \ln A \rangle$ values using different combinations of data ($N_e, N_\mu^*$ etc.) are systematic and real (see (i)).

(v) In both (a) and (b), the highest estimated $\langle \ln A \rangle$ values are for the cases where $N_\mu^*$ is absent - i.e. not used in the analysis. The lowest values of $\langle \ln A \rangle$ are where $N_\mu^*$ has the greatest weight in the analysis, i.e. the number of parameters (2 in 1a and 3 in 1b) is a minimum. It is an indication that the higher energy muons ($>2.4 GeV$) in the observed showers are in the greater deficit compared with model predictions [21].

(vi) With respect to (v), taking only the two sets (one in 1a and one in 1b) which did not use $N_\mu^*$, it is interesting to note that the former points are close to our lower variant (lower dashed curve) in 1a and close to our ’best estimate’ (upper dashed curve) in 1b. The differences are, therefore, significant.

The difference in the $\langle \ln A \rangle$ values derived using different observables (Fig. 1) points to inadequacies in the models used for the analysis of the experimental data and provides an impetus to correct them. However, as remarked already, it is sure that the corrections should not be radical, because the difference between the $\langle \ln A \rangle$ is not large, typically $\delta \langle \ln A \rangle \approx 0.2 - 0.4$ or, in terms of the ratio of the mean $\langle \ln A \rangle$ values from Figures 1b and 1a, an increase from 1.12 to 1.37. Below, we show that the mentioned systematic difference between the $\langle \ln A \rangle$ values can be an indication that the energy distribution between the different shower components is slightly different from that in the models: specifically, the actual mean number of electrons $N_e$ in EAS appears to be higher, that of muons $N_\mu$ slightly lower and that of hadrons $N_h$ lower still than in the models.

It is well known from the present models that for the same primary energy the number
of muons in nuclei-induced showers is higher than in proton-induced ones. On the other hand the number of electrons and hadrons in nuclei-induced showers observed in the lower half of the atmosphere is lower than in proton ones [32]. If one has an opportunity to measure the primary energy, by muons, Cherenkov light or another technique, and finds that the shower has a low \( N_\mu \) or a high \( N_e \) ( actually the ratio \( \frac{N_\mu}{N_e} \) is important ) the conclusion will be that this shower is initiated by a proton or light nucleus. On the contrary, if one finds that the shower has a low \( N_h \) the conclusion will be the opposite, i.e. that the shower is initiated by a heavy nucleus. This is exactly what is observed in the showers at sea level. In order to get a better consistency between the \( \langle lnA \rangle \) values obtained using \( N_e, N_\mu^{tr} \) and \( N_h \) ( Fig.1 ) the model should have higher \( N_e/N_\mu^{tr} \) and smaller \( N_h/N_\mu^{tr} \) ratios. This situation could be achieved if the corrections give a reduction of \( N_h \), a smaller reduction of \( N_\mu^{tr} \) and an increase in \( N_e \).

The same conclusion on the improvement of the model can be drawn from an analysis of KASCADE event rates [8]. Both the muon and hadron trigger rates, observed by KASCADE, are lower than expected from the model calculations. This discrepancy indicates again that the actual numbers of muons and hadrons in EAS are lower than in the models, although the energy region responsible for the trigger rates is lower than that analysed for the mass composition around the knee. The argument that the lower trigger rates might be due to a lower primary intensity is disproved by the fact that the ratio of hadron to muon trigger rates, which is independent of the absolute intensity, is also lower than in the calculations [33]. To get agreement the predicted muon trigger rate should be reduced by a factor \( 0.89 \pm 0.06 \), and the hadron rate by \( 0.54 \pm 0.08 \) compared with the rates given by the QGSJET model. This analysis is of value because it indicates that the needed reduction of the number of muons in the model should be about 6\%, for hadrons it is bigger - about 29\%. Because muons and hadrons are the products of hadronic cascades, it is evident from the energy balance that to reduce the energy contained in the hadronic cascade one has to increase the energy transferred to the electromagnetic cascade. At this stage it can be remarked that an increase in this energy is predicted by theory ( although it appears not to have been included into the models hitherto ).
4. Numerical estimates

4.1. The balance between the EAS components

To evaluate the effect of the proposed change of the balance between different cascade components we applied the semi-quantitative analytical approach. We assumed that there are only nucleons (N), pions (π), muons+neutrinos (µν) and the electromagnetic component (eγ) in the cascade. The total and partial inelasticity for nucleons: \( K^N_{\text{tot}} \) and \( K^N_\gamma \) and for pions \( K^\pi_{\text{tot}} = 1 \) and \( K^\pi_\gamma \), interaction mean free paths for nucleons \( \lambda_N \) and for pions \( \lambda_\pi \) were taken to be energy independent, i.e. constant. The system of kinetic equations, describing the longitudinal development of the nucleon, pion, muon+neutrino and the electromagnetic energy of the cascade has been taken as

\[
\frac{dE_N}{dX} = -\frac{E_N}{\Lambda_N} \\
\frac{dE_\pi}{dX} = -(\frac{1}{\Lambda_\pi} + \frac{E_\pi}{\langle E_\pi \rangle X})E_\pi + \frac{K^N_\gamma - K^N_\pi}{\lambda_N}E_N \\
\frac{dE_\mu}{dX} = \frac{E_\mu}{\langle E_\pi \rangle X}E_\pi \\
\frac{dE_e}{dX} = \frac{E_e}{\Lambda_{\pi N}} + \frac{K^N_\pi}{\lambda_N}E_N
\]

Here \( X \) is the atmospheric depth, \( \Lambda_N = \frac{\Lambda_N}{K^N_{\text{tot}}} \), \( \Lambda_\pi = \frac{\Lambda_\pi}{K^\pi_{\text{tot}}} \), \( E_{cr} \) - the critical energy for pion decay in the air, \( \langle E_\pi \rangle \) - the mean energy for pions. The boundary condition at \( X = 0 \) is

\[
E_N = E_0
\]

where \( E_0 \) is the total energy of the cascade. The solution of the system of equations is

\[
E_N = E_0 e^{\exp\left(-\frac{X}{\Lambda_N}\right)} \\
E_\pi = E_0 \frac{K^N_\gamma - K^N_\pi}{\Lambda_N} e^{\exp\left(-\frac{X}{\Lambda_\pi}\right)} \int_0^X \left(\frac{\Lambda_\pi}{\Lambda_N}\right) e^{\exp\left(-\frac{y}{\Lambda_{\pi N}}\right)} dy \\
E_\mu = \int_0^X \frac{E_\mu(y)}{\langle E_\pi \rangle Y} dy \\
E_e = \int_0^X \frac{E_e(y)}{\Lambda_\pi} dy + \frac{E_0 K^N_\pi}{\Lambda_N K^\pi_{\text{tot}}} (1 - e^{\exp\left(-\frac{X}{\Lambda_N}\right)})
\]

Here \( \Lambda_{\pi N} = \frac{\Lambda_\pi \Lambda_N}{\Lambda_\pi - \Lambda_N} \).

We calculated also the longitudinal development of the electron size of the shower \( N_e \) as

\[
N_e(X) = \int_0^X \frac{dE_e}{dy} \tilde{N}_e(X - y) dy
\]

The longitudinal profile of the electromagnetic cascade has been taken as

\[
\tilde{N}_e(t) = \frac{E_{\gamma t}}{E_{\text{cr}}} e^{\exp(t - t_{max} - 2tnS)}, \text{where the atmospheric depth } y \text{ is measured in units of the radiation length } t_0: t = \frac{y}{t_0}, t_{max} = 1.7 + 0.76ln\left(\frac{E_{\gamma t}}{\beta}\right), S = \frac{2t}{t + t_{max}} [3]. \text{Here } E_{\gamma t} \text{ is the total energy of the electromagnetic cascade, } t_0 = 37.1 \text{ g cm}^{-2} \text{ and } \beta \text{ is the critical energy}
\]
for the electromagnetic cascade in air, equal to 0.081 GeV. Although this approximation is recommended for nuclear cascades, its use for the electromagnetic cascades is more appropriate for our energy-balance approach, since it gives the correct estimate of the depth of the shower maximum ($X_{\text{max}} \approx 610\text{gcm}^{-2}$) and its elongation rate ($ER \approx 65\text{gcm}^{-2}$).

The integrals for $E_\pi$, $E_\mu$ and $E_{e\gamma}$ were calculated numerically. The basic parameters for the calculation were taken as $K_{N}^{N}=0.60$, $K_{\gamma}^{N}=0.20$, $K_{\gamma}^{\pi}=0.33$, $\lambda_{N}=90\text{gcm}^{-2}$, $\lambda_{\pi}=120\text{gcm}^{-2}$, $E_{cr}=90\text{GeV}$, $\langle E_{\pi} \rangle = 300\text{GeV}$.

The results of the calculation are shown in Figure 2 by the full line. According to our suggestion, we increased the energy fraction transferred by nucleons into the electromagnetic component, leaving all the other characteristics untouched. We increased $K_{\gamma}^{N}$ from 0.20 to 0.26 (the reason for this particular value will be clear later). The result is shown in Figure 2 by the dashed line: the muon energy at sea level ($1000\text{gcm}^{-2}$) decreased by $\sim 6\%$, the hadron energy decreased by $\sim 23\%$, the energy transferred into the electromagnetic component increased by $\sim 2\%$.

4.2. The triangle diagrams

The balance of the energy contained in the major components of the shower is convenient to analyse using the so-called “triangle diagrams” [35, 36]. If the height of an equilateral triangle is equal to 1, then for each point inside this triangle the sum of the distances to its sides is equal to 1. If we know the energy fractions carried by the electromagnetic ($\delta_{e\gamma}$), muon ($\delta_\mu$) and hadron ($\delta_h$) components of the shower at the observation level, so that $\delta_{e\gamma} + \delta_\mu + \delta_h = 1$, then each shower can be presented by a single point inside the triangle. Our basic shower (Figure 2, full line) is shown in Figure 3 by a full circle ($\delta_{e\gamma}=0.394, \delta_\mu=0.505, \delta_h=0.101$). The desired direction for the shift of the energy balance in the modified model is shown by the straight arrow in Figure 3b.

However, despite the increase of the energy transferred into the electromagnetic component, the preserved electromagnetic energy and the electron size of the shower $N_e$ at sea level decreased by 14% due to its faster development and then faster attenuation of the cascade. The point in the triangle diagram moved in the different direction (open circle). The shift is similar to the case when we increase the total inelasticity $K_{tot}^N$ and $K_{\gamma}^N$ with $K_{\gamma}^N = \frac{1}{3} K_{tot}^N$. 
Figure 2: The longitudinal development of 1 PeV cascades in the atmosphere: (a) Fractions of the total energy carried by nucleons (N), pions (π), muons (μ) and transferred into the electromagnetic (eγ) component; (b) Electron Size of the shower \( N_e \). Basic parameters of the calculation are given in the text. Full line: \( K_N^N = 0.20, ER_{em} = 65 \text{ gcm}^{-2} \); dashed line: \( K_N^N = 0.26, ER_{em} = 65 \text{ gcm}^{-2} \); dotted line: \( K_N^N = 0.26, ER_{em} = 71 \text{ gcm}^{-2} \).
Figure 3: Triangle diagram for a 1 PeV shower at the sea level: $\delta_h, \delta_\mu, \delta_e\gamma$ are fractions of energy carried by the hadron, muon and electromagnetic components of the shower, respectively. • - $K_N^\gamma = 0.20, \text{ER}=65\text{gcm}^{-2}$; ○ - $K_N^\gamma = 0.26, \text{ER}=65\text{gcm}^{-2}$; △ - $K_N^\gamma = 0.26, \text{ER}=71\text{gcm}^{-2}$. (a) Large scale diagram with the inset magnifying the indicated region. (b) Small scale part of the full diagram. The straight arrow to the left of the full circle indicates the desired modification of the EAS energy balance.
If we were to assume a larger fluctuation $\sigma(K_N^N)$ compared with those in the model this would result in a wider distributions of $N_e$, $N_\mu$ and $N_h$ and in a bigger value of $\sigma(lnA)$. Within our approach we cannot give the numerical estimates, but we expect that the mean energy balance would not move in the desired direction and the mean value $\langle lnA \rangle$ would not change significantly. Therefore, an increase of the mean value or increased fluctuations of $K_N^N$ cannot give the required result.

4.3. Data from mountain laboratories

We should remark that the conclusion about the decrease of $N_e$ relates only to measurements at sea level. At mountain altitudes the increase of $K_N^N$ results in an increase in $N_e$ as seen in Figure 2, however it is not enough here, either. The best complex EAS array at mountain altitude was at Tien-Shan and the data there also indicated the need for the model to be improved [37]. The problem was with the so-called 'observed' mass composition, i.e. the mass composition of primary particles responsible for showers at the observation level selected by one of their parameters. The Tien-Shan array is at a depth of 690 gcm$^{-2}$, i.e. PeV-showers are definitely observed beyond their maximum. The $N_e$-selected showers have to be enriched by showers initiated by protons and light nuclei, while in contrast the $N_\mu$-selected showers have to be enriched by heavy nuclei initiated showers. However, in fact, the 'observed' composition at Tien-Shan was about the same for these two selections [15, 37]. The consistency can be restored by the same way as in KASCADE, i.e. by changing the balance between the muon and electromagnetic components in the models, in favor of the latter.

4.4. Slowing down the cascade

We have concluded that the mere increase of the energy fraction $K_N^N$ transferred into the electromagnetic component does not change the balance properly, although it does help in some respects and, as we have stated, it must be present. We now argue that another effect that should be present will bring about the desired effect: the slowing down of the development of the cascade in its initial stages. The physics behind this modification will be discussed later. Here we just demonstrate the validity of this argument in a semi-qualitative way. For illustration purposes we slow down the development of the hadronic and electromagnetic cascade by increasing the elongation rate $ER$ from 65 gcm$^{-2}$ to 71 gcm$^{-2}$, preserving $K_N^N = 0.26$. The result is shown in Figure 2 by dotted lines and in
Figure 3 by an open triangle. The direction of the shift is correct and its magnitude can be adjusted to achieve consistency in the mass composition.

Thus we conclude that the increase of the energy transferred into the electromagnetic component (\( K_N^N \)) combined with the slowing down of the development of cascades in their initial stages is the most realistic way to improve the particle interaction model and to achieve a consistent estimate of the primary mass composition.

5. Theoretical arguments

5.1. General remarks

All the arguments hitherto were purely phenomenological. However, there are theoretical arguments too which lend support to the phenomenological consideration as will be demonstrated. At the moment nearly all the models for hadron-nucleus (\( hA \)) interactions implemented in CORSIKA are well developed and theoretically justified. Nucleus-nucleus (\( AA \)) interactions are considered within the framework of the Glauber approach, which reduces the \( AA \)-collision to the sum of a few \( hA \)-collisions. No new processes are assumed to occur in \( AA \)-collisions. However, there are processes which must be present but which have not been included hitherto, and we think that both effects: the increase of \( K \gamma \) and the slowing down of the cascade development refer to processes, intrinsic for \( AA \)-collisions, which will cause at least near-equality of the \( \langle \ln A \rangle \) values in Figures 1a and 1b.

5.2. The increase of \( K \gamma \)

At PeV energies, when the Lorenz-factor of the projectile nucleus approaches \( \sim 10^6 \) and its charge \( Z \) is \( \sim 10 - 30 \), the density of virtual photons in the contracted coulomb field is so high that when the projectile collides with a nitrogen (\( Z = 7 \)) nucleus of the air and the impact parameter is small (central collision) the probability of electron-positron pair production including multiple pair production becomes quite appreciable \[38, 39, 40\]. Using the numerical estimates made by Erlykin \[38\] for p-air collisions, we can extrapolate them to Fe-air collisions and expect an increase of \( K_{Fe-air}^{Fe} \) for the average collision at PeV energies by 0.05-0.13. For specific central collisions the effect will be even higher. Our 0.06 of §4.1 was thus rather conservative. We also emphasize the fact that ordinary \( K_{AA}^{AA} \) value in AA-collisions is not very high. Typically for Fe-air collisions the average number of wounded nucleons \( n_w \) is about 7-8 and \( K_{Fe-air}^{Fe} \approx K_{AA}^{PA} \frac{n_w}{A_{Fe}} \approx 0.03 \). Therefore even a few percent increase of \( K_{AA}^{AA} \) in the first interaction can be essential for the subsequent
development of the atmospheric cascade.

Experimental results confirm the intense production of electron-positron pairs in $AA$ collisions. In the CERES/NA45 experiment the number of $e^+e^-$ pairs in the low invariant mass region $m_{e^+e^-} < 200\text{MeV}/c^2$ exceeds the number in the higher mass region of $m_{e^+e^-} > 200\text{MeV}/c^2$ by a factor of $\sim 10^4$. For the CERES/NA45 collaboration it is just a background, because they are interested in dileptons with high invariant mass \cite{1, 2} as a signature of an elusive quark-gluon plasma. We believe that to check our assumption the study of the dilepton production should be concentrated preferentially in the region of invariant mass below $10\text{MeV}/c^2$.

An additional energy transfer into an electromagnetic component can arise also from an excess of direct photons, which has been predicted theoretically as a signature of the quark-gluon plasma \cite{13} and is now observed in AA-collisions both at low and high transverse momenta \cite{14, 15}.

Another theoretical possibility is to increase the transfer of the energy into the electromagnetic component, by way of $hA$-interactions; this could be connected with the breaking of the diquark and its subsequent recombination into $3\pi^0$-mesons \cite{16, 17}.

5.3. Slowing down of the cascade development

The theoretical motivation of the second assumption is also connected with the properties of AA-interactions, but relates mainly to peripheral collisions. It is known that even at high energies a projectile nucleus does not fully disintegrate into constituent nucleons in the first interaction but fragment into few pieces of different mass \cite{18}. Some of these fragments are excited and, after the de-excitation, if it occurs in space, give rise to MeV gamma-ray lines, observed from ‘discrete’ sources and the interstellar medium \cite{19}. The lifetime of the excited fragments varies from a ‘nuclear’ time $\sim 10^{-23}$ sec to millions of years. For AA-interaction at PeV energies both the lifetime before de-excitation and the energy of emitted gamma-quanta are extended by the factor of $\sim 10^5 - 10^6$ due to relativistic effects. As a consequence one can expect an additional sub-PeV electromagnetic cascade to be initiated a few hundred meters below the point of the first interaction. This effect will slow down the development of the electromagnetic cascade and shift its maximum.

In general the shift is limited to no more than 1-2 mean free paths for the inelastic
interaction of the fragments. However, there might be an additional effect which is, it
must be admitted, speculative. It is based on the so-called “sling” effect [50, 51] and is
connected with the deformation of the shape of the nuclear fragment, which rotates with
a high spin [52]. As a result of such deformation one can expect an increase in the mean
free path for inelastic interaction which enables the excited nuclear fragments to penetrate
deeper into the atmosphere, slowing down the cascade development and resulting in a
further shift of $X_{\text{max}}$. There will be an additional increase of $N_e$ for nucleus-induced
cascades like that shown in Figure 2b by the dotted line.

All the consequences of the ‘sling’ effect: polarisation of the secondary nuclear frag-
ments, deformed shape of the nuclei rotating with a high spin and cross-section fluctua-
tions of the excited nuclei are true effects observed at low energies [53]. The problem is
whether they still hold at higher energies. However, even if they don’t, the de-exitation
of the nuclear fragments itself will give the needed shift of $X_{\text{max}}$ if their lifetime is not
less than $10^{-12}$ sec.

It is difficult to make reliable numerical estimates of the shift since there is not enough
experimental data and no good theory of the effect. We think that to check our assumption
the study of the properties of the secondary nuclear fragments should be made in high
energy AA-collisions with different nuclear beams.

6. Discussion

6.1. Application of the new model to PeV energies

6.1.1. The mass composition problem

In order to get better consistency of the results on the primary cosmic ray mass
composition, the combination of two effects is needed. The increase of only $K^{AA}_{\gamma}$ is not
enough because although it results in a decrease of $N_\mu$ and $N_h$ it also leads to a fall in $N_e$
if the measurements are made at sea level, whereas we need an increase in $N_e$. The slowing
down of the electromagnetic cascade alone does not change the ratio between muons and
hadrons. The slowing down of just the nuclear and electromagnetic cascades ( e.g. by
increasing the mean free path for nucleon interaction $\lambda_N$ without increasing $K^{N}_{\gamma}$ ) results
in an increase in both $N_e$ and $N_h$. Only the combination of both effects: the increase of
$K^{N}_{\gamma}$ and the slowing down of the development of the electromagnetic cascade changes the
energy balance in the needed direction: $N_\mu$ and $N_h$ decreased, $N_e$ and $X_{\text{max}}$ increased
The required changes of $K_{\gamma}^{AA}$ and $X_{\text{max}}$ are small, because the sensitivity of the energy balance to these changes is rather high.

The result should be a coming together of the $\langle \ln A \rangle$ values in Figures 1a and 1b. There will be an increase in the values in Figure 1a and a small reduction in those in Figure 1b. In view of the problems associated with $N_\mu^*$ (see §3) most of the predictions in Figure 1b should be disregarded; the 'best estimate' is then just a little below the crosses in Figure 1b - these values are reassuringly close to our latest estimate indicated by the upper dashed curve in Figure 1.

6.1.2. The $X_{\text{max}}$ controversy

Although the $X_{\text{max}}$ aspect for EAS is one of some complexity we discuss it briefly. The assumption of a slowing down of the cascade development and the consequent shift of $X_{\text{max}}$ in $AA$-interactions helps us to understand the striking difference between the mass composition derived recently by Swordy and Kieda and Fowler et al., using Cherenkov light measurements and those by Roth et al. and others, without. Those with Cherenkov light give a significantly lighter mass composition and lower intensity of the primary energy spectrum than those obtained without the use of $X_{\text{max}}$. If there is indeed a shift of $X_{\text{max}}$ and a consequent increase of $N_e$ the shower looks more like that initiated by proton and its primary energy, based on the on-ground measurements is underestimated. Insofar as the $N_e$ values are most in doubt, from the prediction standpoint the real mass composition should be closer to that derived by using direct measurements in the stratosphere or using EAS muons and hadrons on the ground (Fig.1b).

6.2. Application of the new model to higher energies

If the increase of $K_{\gamma}^{AA}$ and the slowing down of the development of the cascade are due to electron-positron pair production, and de-excitation of nuclear fragments, there will be significant further consequences of the model because of its charge and energy dependent QED effect and the displacement of the depth of shower maximum. Both these effects will grow with increasing collision energy. In this case it is not surprising that the inconsistency in the estimates of the primary mass composition grows with energy, as noticed by Roth et al. and indicated in Figure 1c.

Of greatest importance is the mass composition at the highest energies, where, due to the low anisotropy and the rapid growth of $X_{\text{max}}$ with energy, particles are generally con-
sidered to be extragalactic (EG). There is controversy, here, between those who subscribe to the common view that the EG particles are protons (e.g. [55, 56, 57] and ourselves (e.g. [58], following much earlier work by Tkaczyk et al. [59]). A later publication will deal with this aspect in detail but a few brief remarks here are in order.

(i) The change of $K_{\gamma}^{AA}$ will be even bigger at the highest energies (say above $10^{10}$ GeV) and the result will be an increase in the mean primary mass: this follows from the analysis of Ave et.al. [57], in which inclined muon showers were detected - the corresponding primary energy will now be higher and the rates more in accord with expectation for a significant fraction of primary iron nuclei, a recent recalibration of Haverah Park energies [57] leads to a reduction in primary energy and an even further increase in the iron fraction.

(ii) The displacement of the depth of maximum to greater values will, again, lead to an increase in the mean primary mass as indicated by the $X_{\text{max}}$ values from the experimental data (see Fig.1b).

7. Conclusions

Our analysis of the present situation with the high energy interaction models indicates that there is no support for the introduction of a radical change of the models, sometimes proposed to explain the origin of the knee in the primary cosmic ray energy spectrum. However, the inconsistencies in the interpretation of the experimental data on the primary mass composition, obtained when different EAS components are used for the analysis, indicate the need for some improvement to the models which were used hitherto. We propose that the most promising way is to introduce an additional (a few percent) energy transfer into the EAS electromagnetic component combined with a slowing down of the cascade development at its initial stages, which is followed by a small ($\sim 20 - 30 gcm^{-2}$) shift of $X_{\text{max}}$ into the deeper atmosphere and the consequent increase of $N_e$. The most likely processes which can be responsible for such changes (e.g. electron-positron pair production including multiple pairs, direct photons from the hypothetical quark-gluon plasma, excitation of the secondary nuclear fragments) are those which occur in nucleus-nucleus collisions and they should indeed be present at some level. The importance of these processes is expected to grow with energy and offer the hope of resolving some controversies at very high energies.
Acknowledgements

The authors are greatful to the UK’s Particle Physics and Astronomy Research Council and to The Royal Society for financial support. Also we thank Professors G.Schatz, H.Rebel, K.H.Kampert, J.Kempa and R.Chapman for useful discussions.

References

[1] Heck D. et al., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 1 ( 2001 ) 233
[2] Sciutto S.J., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 1 ( 2001 ) 237
[3] Erlykin A.D., Wolfendale A.W., Astropart. Phys., 9 ( 1998 ) 213
[4] Antoni T. et al. J. Phys.G: Nucl., Part. Phys., 25 ( 1999 ) 2161
[5] Swordy S.P., Kieda D.B., Astropart. Phys., 13 ( 2000 ) 137
[6] Fowler J.W. et al., Astropart. Phys., 15 ( 2001 ) 49
[7] Roth M. et al., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 1 ( 2001 ) 88; astro-ph/0102443
[8] Antoni T. et al., astro-ph/0106494 ( 2001 )
[9] Clay R.W. et al., Publ. Astron. Soc. Aust., 15 ( 1998 ) 208
[10] Erlykin A.D., Lipsky M., Wolfendale A.W., Astropart. Phys., 8 ( 1998 ) 283
[11] Erlykin A.D., Wolfendale A.W. Adv. Space Res., 27 ( 2001 ) 803
[12] Berezinsky V.S., Nucl. Phys. B380 ( 2002 ) 478
[13] Nikolsky S.I. Proc. 27th Int. Cosm. Ray Conf., Hamburg, 4 ( 2001 ) 1389
[14] Nikolsky S.I. Nucl. Phys. B ( Proc. Suppl.), 39A ( 1995 ) 228
[15] Stamenov J.N. et al., Proc. 18th Int. Cosm. Ray Conf., Bangalore, 2 ( 1983 ) 111
[16] Romakhin V.A., private communication ( 1995 )
[17] Navarra G., Nucl. Phys. B (Proc. Suppl.), 60B (1998) 105
[18] Aglietta M. et al., Astropart. Phys., 10 (1999) 1
[19] Mitsui K. et al., Astropart. Phys., 3 (1995) 125
[20] Glasstetter R. et al., Proc. 26th Int. Cosm. Ray Conf., Salt Lake City, 1 (1999) 222
[21] Haungs A. et al., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 1 (2001) 63
[22] Fomin Yu.A. et al., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 1 (2001) 80
[23] Gress O. et al., Nucl. Phys. B (Proc. Suppl.), 75A (1999) 299
[24] Arqueros F. et al., Astron. Astrophys., 359 (2000) 682
[25] Paling S., PhD Thesis, University of Leeds (1997) (unpublished)
[26] Knurenko S. et al., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 1 (2001) 145
[27] Petrukhin A.A., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 5 (2001) 1768
[28] Kazanas D., Nicolaidis A., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 5 (2001) 1760; astro-ph/0103147, hep-ph/0109247
[29] Chi X. et al., Astropart. Phys., 1 (1993) 239
[30] Wigmans R., astro-ph/0107263 (2001)
[31] Ehrlich R., Phys. Rev. D, 60 (1999) 73005
[32] Knapp J., Heck D., Schatz G. Wissenschaftliche Berichte FZKA 5828 (1996)
[33] Risse M. et al., Proc. 26th Int.Cosm.Ray Conf., Salt Lake City, 1 (1999) 135
[34] Catalano O. et al., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 2 (2001) 498
[35] Danilova T.V., Erlykin A.D., Proc. 18th Int. Cosm. Ray Conf., Bangalore, 5 (1983) 262
[36] Danilova T.V. et al., Journ. Phys. G: Nucl., Part. Phys., 19 (1993) 429
[37] Erlykin A.D., Proc. 1st Int. Symp. on Cosm. Ray Phys. in Tibet, Lhasa, (1994) 74

[38] Erlykin A.D., Proc. 14th Int. Cosm. Ray Conf., München, 7 (1975) 2173

[39] Baur G. et al., Journ. Phys. G: Nucl., Part. Phys. 24 (1998) 1657; nucl-th/9606011; hep-ph/0112211

[40] Lee R.N. et al., hep-ph/0108014 (2001)

[41] Agakishev G. et al., Nucl. Phys. A, 661 (1999) 23

[42] Filimonov K. et al., nucl-ex/0109017 (2001)

[43] Feinberg E.L., Nuovo Cim. 34A (1975) 391

[44] Aggarwal M.M. et al., Phys. Rev. C56 (1997) 1160

[45] Peitzmann T., Thoma M.H., hep-ph/0111114 (2001)

[46] Capella A., Nucl. Phys. B, 60 (1998) 138

[47] Capdevielle J.N. et al., Proc. 27th Int. Cosm. Ray Conf., 1 (2001) 319

[48] Giorgini M., Manzoor S., hep-ex/0104019 (2001)

[49] Ramaty R. et al., Astrophys. J. Suppl., 40 (1979) 487

[50] Dremin I.M., Man’ko V.I., N.Cim., 111A (1998) 439

[51] Erlykin A.D., Wolfendale A.W., Nucl. Phys. B (Proc. Suppl.), 75A (1999) 209

[52] Lo Iudice N., La Rivista del Nuovo Cimento, 9 (2000) 1

[53] Satchler G.R., Introduction to Nuclear Reactions, Macm. Press Ltd., NY (1980)

[54] Hörandel J.R., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 1 (2001) 71

[55] Bird D.J. et al., Phys. Rev. Lett., 71 (1993) 3401

[56] Abu-Zayad T. et al., astro-ph/9911144 (1999)

[57] Ave M. et al., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 1 (2001) 381 and 390
[58] Wibig T., Wolfendale A.W., Proc. 27th Int. Cosm. Ray Conf., Hamburg, 5 ( 2001 ) 1987

[59] Tkaczyk W. et al., Journ. Phys. A, 8 ( 1975 ) 1518