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Ultimate energy particles in the Universe/Particules d'énergies ultimes dans l'Univers

Identification of the primary cosmic ray

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Abstract

The nature of the primary particle giving rise to an atmospheric shower may be, to some extent, inferred from the observable properties: longitudinal profile (especially position of the maximum of the number of charged particles) or shape at ground level (lateral distribution, curvature and thickness of the shower front, muonic component). Distinguishing different nuclei cannot be performed unambiguously on a single shower, because of the random fluctuations in the first steps of the cascade; however, it is possible to study the composition of the incident flux on a statistical basis: showers from heavier nuclei have a faster development, and contain more muons. The uncertainties on the hadronic interactions at the highest energies limit the reliability of the identification. Other primaries, if they exist, could be easier to distinguish. Photons would give a slower development than protons, especially at highest energies, and a very reduced muonic component; neutrinos would be characterized by deep interactions in the atmosphere, or even within the Earth, giving almost horizontal showers with a large electromagnetic component, clearly different from the muonic tail of showers induced in the upper atmosphere by nuclei. Such 'exotic' primaries have not yet been observed. ***To cite this article: P. Billoir, P. Sommers, C. R. Physique 5 (2004).***

Résumé

Identification du rayon cosmique primaire. La nature de la particule primaire qui produit une gerbe atmosphérique peut être, dans une certaine mesure, déduite de ses propriétés observables : profil longitudinal (particulièrement position du maximum du nombre de particules chargées) ou forme au niveau du sol (distribution latérale, courbure et épaisseur du front de gerbe, composante muonique). Il est impossible de distinguer individuellement les différents noyaux, à cause des fluctuations aléatoires dans les premières étapes de la cascade ; toutefois on peut étudier statistiquement la composition du flux incident : les gerbes de noyaux lourds ont un développement plus rapide, et contiennent plus de muons. Les incertitudes sur les interactions hadroniques aux énergies les plus élevées limitent la fiabilité de l'identification. D'autres primaires, s'ils existent, pourraient être plus faciles à distinguer. Des photons donneraient un développement plus lent que les protons, en particulier aux énergies extrêmes, et une composante muonique très réduite ; des neutrinos seraient caractérisés par des interactions profondes dans l'atmosphère, ou même à l'intérieur de la Terre, donnant des gerbes presque horizontales avec une forte composante électromagnétique, clairement différentes des queues muoniques de gerbes induites dans la haute atmosphère par des noyaux. De tels primaires « exotiques » n'ont pas encore été observés. ***Pour citer cet article : P. Billoir, P. Sommers, C. R. Physique 5 (2004).***

Keywords: Chemical composition; Electromagnetic component; Muon content; Shape parameter; Photon conversion in geomagnetic field; LPM effect; Tau neutrino detection

Mots-clés : Composition chimique ; Composante électromagnétique ; Contenu en muons ; Paramètre de forme ; Conversion des photons dans le champ géomagnétique ; Effet LPM ; Détection des neutrinos-tau

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1. Introduction

The primary particle generating a shower in the atmosphere has to be stable, and, if charged, heavy enough not to lose its energy by synchrotron radiation in the galactic or intergalactic magnetic fields. This condition excludes electrons and positrons. The only remaining known candidates are nuclei, photons and neutrinos. Neutrons may also be considered at energies of the order of 10^{18} eV or more, if they have a galactic origin (or if a violation of the Lorentz invariance makes them stable at these energies). Their interaction is similar to that of protons, and proton/neutron showers would be indistinguishable. Photons above 10^{15} eV interact with the cosmological backgrounds (CMB, radio) to produce electron–positron pairs, and then are rapidly absorbed. However, due to the decrease of the cross section with energy, their range may largely exceed the Mpc scale at ultra-high energies (10^{20} eV or more). Neutrinos travel in principle freely over cosmological distances, but their interaction probability within the atmosphere is very low, even at 10^{20} eV (unless their interaction becomes strong at very high energies, as predicted by some exotic theories).

Cascade mechanisms in showers induced by various nuclei are very similar. However, the heavier the nucleus, the faster is the descent in energy in the first steps (as long as composite fragments survive). Due to shower-to-shower fluctuations, two different nuclei of the same energy may be undistinguishable, even in the extreme cases of $A = 1$ (proton) and $A = 56$ (iron). Statistically, however, each mass value A leads to a different expected distribution for certain variables that relate to the speed of shower development, especially muon production and depth of maximum $X_{\max}$. Information about the chemical composition stems from the experimental determination of such distributions.

Although photons and neutrinos are not expected to be predominant in the observed air showers (there is no evidence for them in the past observations), they are produced, in principle, by the interactions of protons and nuclei with the CMB (GZK effect), and moreover they could give a specific signature of 'top–down' models of ultra-high energy production. We describe hereafter characteristic features of photon- and neutrino-induced showers, that may allow to distinguish them from the nuclei, even if they are less abundant.

2. Mass distribution of nuclei

2.1. Surface arrays (SA)

A surface array has sensitivity to the primary mass through indirect measurement of $X_{\max}$, the electromagnetic shower's depth of maximum, and/or the abundance of muon production. Relative to proton showers, heavier nuclei showers develop faster and produce more muons.

Scintillator arrays and water Cherenkov tank arrays differ in their methods for studying the primary mass distribution. A scintillator array is essentially sensitive to the electrons and positrons of the electromagnetic cascade. It can estimate $X_{\max}$ by measuring the shape of the lateral distribution: at a given zenith angle, the steepness is an increasing function of $X_{\max}$ (the larger $X_{\max}$, the 'younger' the shower at ground level). It can also measure the curvature of the shower front (decreasing with the 'age' of the shower), and, to some extent, the time structure of the signal. To the extent that it has a good sensitivity to the shower development speed, its composition analysis power will be the same as for an ideal fluorescence detector (see below). In practice, the sensitivity is limited by statistical fluctuations of the signal, due to the finite number of incident particles on a limited detector area.

An array of water Cherenkov tanks (with a depth of the order of 1 meter or more) is sensitive to both muons (thanks to their long range) and electromagnetic particles (including photons, which have enough room to cascade within the volume of water). For near-vertical showers, the two contributions to S_{1000} (the signal at 1000 m from the shower axis) are of comparable magnitude. At large zenith angles, the muon signal is still readily measurable, while the electromagnetic cascade is extinguished (actually there is an electromagnetic component due to the decay and the radiation of the muons, which has the same shape in space and time, and then results only in a slight enhancement of the muonic signal). For showers of known total energy (or known electromagnetic energy as given by the fluorescence detector in a hybrid measurement), sensitivity to muons is especially valuable. Distinguishing individual muons is difficult in regions of high density; on the other hand, the Poisson fluctuations in regions of lower density limit the value of any muon counting technique.

An ideal surface array would have separate detectors for muons and electromagnetic particles. For reasons of economy, no large-scale array for extremely high energy cosmic rays has been built that way.

The most promising mass indicator for an array of water Cherenkov tanks is the time structure of the signal. At large core distances, muons, which travel almost in straight lines, tend to arrive before the electromagnetic particles which have gotten there after a series of multiple Coulomb scatterings. Heavy nucleus showers have a larger muon component, and a fast shower development that leads to less electromagnetic tails. A powerful way to exploit these differences is the *shape parameter* [1], defined as the ratio of the 'early signal' to 'late signal', which exploits both the difference in muon production and in electromagnetic development between light and heavy nuclei. Identifying and subtracting muon spikes in the tails of flash-ADC traces should enhance the shape parameter effectiveness. The discriminating power may be degraded at large zenith angles where the electromagnetic shower is reduced.

2.2. Fluorescence detectors (FD)

Analysis of the primary mass distribution using FD data relies on the distribution of $X_{\max}$ at fixed electromagnetic energy. Simulations with different hadronic interaction models agree to predict that the $X_{\max}$ of an iron shower is, in average, about 80 g/cm^2 less than for a proton shower. The root-mean-square (rms) width of the pure iron distribution is 22 g/cm^2, whereas the pure proton distribution rms is 66 g/cm^2. The two distributions therefore overlap, even for an ideal FD with no experimental error.

It may be unreasonable to expect any definitive conclusion about the composition at any one energy. A narrow $X_{\max}$ distribution (rms less than 66 g/cm^2) could indicate the absence of light nuclei, and especially of protons. A broad distribution (rms significantly greater than 66 g/cm^2), however, could be caused by a mixed composition and/or poor detection resolution. Even for an ideal detector, the mean $X_{\max}$ is not by itself a definitive composition indicator because it is model dependent (the different models for hadronic interactions at high energies, beyond the range covered by accelerators, disagree on $X_{\max}$ by 30 to 40 g/cm^2).

The Flys's Eye analysis [2] showed evidence for a large *elongation rate* (change in $X_{\max}$ per energy decade). There was a possible evidence that the high elongation rate begins near 3×10^{17} eV. Subsequent analyses of HiRes/MIA [3] and HiRes [4] data support the high elongation rate. In those analyses, the mean $X_{\max}$ grows from values close to what is expected for pure iron (just above 10^{17} eV) to values close to what is expected for pure proton at much higher energies. Unless the evolution of the hadronic interactions at highest energies differ strongly from the expectations, the results suggest a changing composition, perhaps from a heavy galactic population to a light extragalactic population.

2.3. Hybrid detectors

Although the hybrid data set is expected to have only 10% of the surface array (SA)-only data set, this is still a large sample for a giant observatory such as AUGER after a few years of operation. In hybrid mode, the SA and FD composition parameters can be used together for showers of known electromagnetic energy. For example, one can examine the distribution over the 2-dimensional space of $X_{\max}$ and shape parameter at fixed energy. Iron and proton showers may be better separated in that 2-D plot than in either of its 1-D projections.

As a different example, Fig. 1 shows the distribution of iron and proton showers over the variables $X_{\max}$ and S_{1000} for showers of 10^{19} at four different zenith angles. In each plot, the separation is clear, even though proton and iron overlap in either projection. This is an ideal result in the sense that there is no account of detector resolution. The FD $X_{\max}$ resolution is expected to be about 20 g/cm^2 for AUGER, and S_{1000} should be accurate to at least 10%. Even with that much degradation, it is evident that the combination of SA and FD parameters offers special power for probing the primary mass distribution.

For any one shower, its parameters cannot determine uniquely its atomic mass A, even when combining SA and FD. The measured parameters can yield a likelihood distribution over A-values, however, and an estimation of the mean value, and possibly the dispersion.

3. Identification of photons

3.1. Showers generated by photons in the atmosphere

An atmospheric shower initiated by a photon (or an electron/positron) is an almost pure electromagnetic cascade, because of the low cross section for photo-production of mesons on nuclei, compared to the pair production. As a result, the muon/electromagnetic ratio at ground level is expected to be much less than in a nucleus-induced shower.

On the other hand, the interactions in an electromagnetic cascade (Compton scattering, pair production, bremsstrahlung) give only two final objects, contrary to the large multiplicity of π^0 in hadronic interactions: with the same initial energy, the development of a photon-induced shower is expected to be slower, in the first steps, than a nucleus-induced shower. In some sense, a photon behaves as a nucleus much lighter than a proton: fewer muons, larger $X_{\max}$, larger lateral steepness, larger front curvature.

In addition, at energies beyond 10^{19} eV, the electromagnetic interactions are reduced by the Landau–Pomeranchuk–Migdal (LPM) effect [5], when the characteristic formation length of the interaction ecomes as large as the distance between atoms, so that the successive interactions cannot be considered as independent. In the upper atmosphere, the threshold for this effect is a

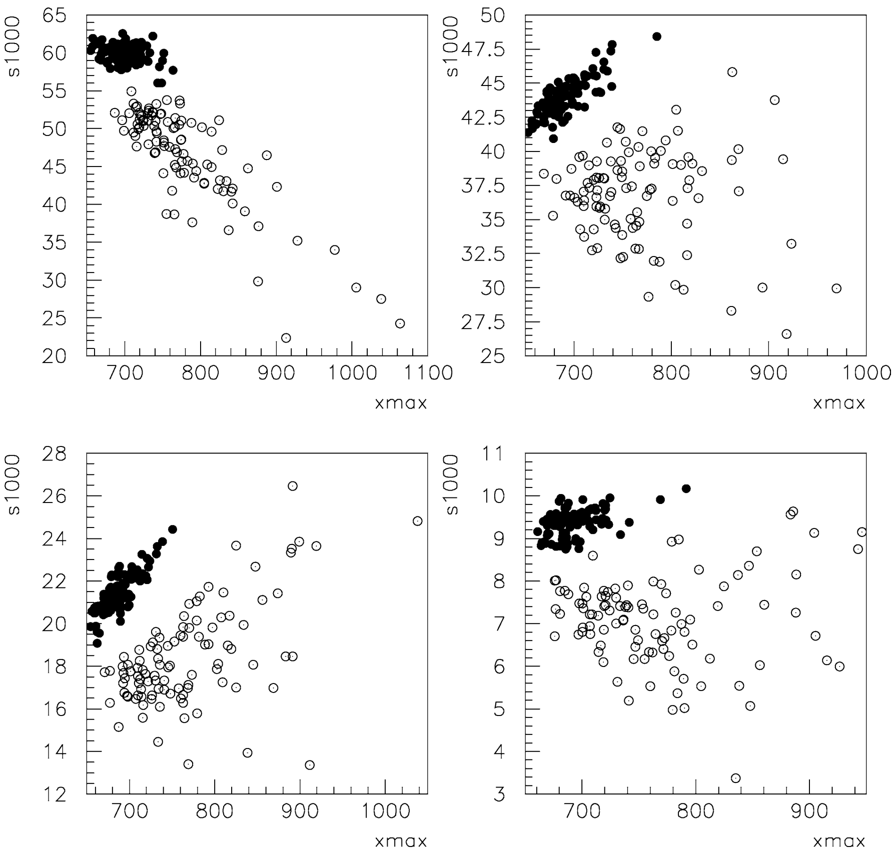

Fig. 1. Proton showers (∘) are separated from iron showers (•) in this scatter plot of S_{1000} vs $X_{\max}$. These are simulated showers of 10^{19} eV at zenith angles of 0, 37, 53 and 66 degrees (from top left to down right), using CORSIKA with QGSJET [10].

few 10^{19} eV. This threshold decreases with increasing density, so that the cascade may slow down over several steps. With a primary energy of 10^{20} eV, the result may be spectacular ($X_{\max}$ up to 1500 g/cm^2, instead of 800 to 900 for hadronic showers at the same energy), and give an unambiguous observational signature. One should note, however, that at low zenith angles, a shower with such a slow development will not reach its maximum before hitting the ground. On the other hand, it may escape detection in a ground array if it has not enough lateral extension. Zenith angles of 60 degrees or more may be needed for a complete observability.

3.2. Conversion of photons in the geomagnetic field

It was pointed out a long time ago by McBreen and Lambert [6], using a theoretical review of electromagnetic interactions in extreme conditions by Erber [7], that photons above 10^{19} eV have a large probability to convert into an e^+e^- pair in the magnetic field of the Earth before entering the atmosphere. Then the electrons produce a strong synchrotron radiation and give a large number of photons; those with highest energy give in turn secondary pairs. Both photon conversion and electron/positron radiation occur within a few thousand kilometers above the ground, in regions with a negligible density of matter. As a result, instead of a unique photon, there is a 'preshower' entering the upper atmosphere. This phenomenon has been studied in detail in [8] and the potentialities offered by an hybrid detector are discussed in [9].

Because the relevant parameter is $E B_\perp$ (where E is the energy, $B_\perp$ the field transverse to the direction of the photon), this effect is expected to depend on the arrival direction with respect to the direction of the field. Such a dependence, which is attached to the Earth frame, is a very strong signature of primary photons. Fig. 2 illustrates this dependence for the southern site of the AUGER Observatory (latitude 35 deg). Note that the pattern would be different in another site, with another direction and another amplitude of the local field.

There is a remarkable (but accidental) coincidence between the threshold energy for magnetic photon conversion in the geomagnetic field and the energy for the LPM effect in the upper atmosphere. Then preshowers produced by magnetic

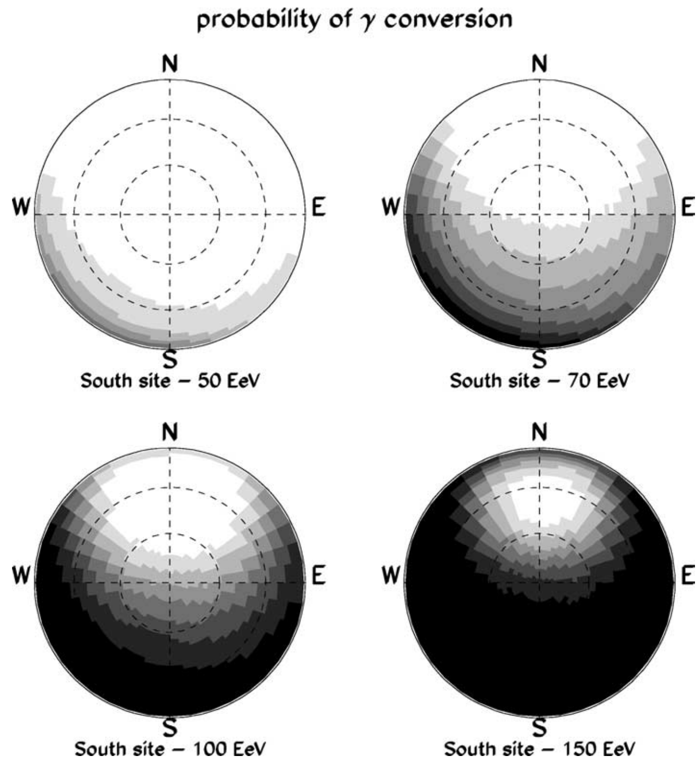

Fig. 2. Map of the photon conversion probability as a function of the direction, at the Southern Site of AUGER: eight equidistant levels from 0 (white) to 1 (black). The center represents the vertical direction, the periphery represents the horizon; the dashed circles correspond to zenith angles $\theta = 30$ and 60°.

conversion contain particles (mainly photons) below the LPM threshold; when entering the atmosphere, they generate an electromagnetic shower developing at a 'normal' rate (i.e., with $X_{\max}$ about 100 $\mathrm{g/cm^2}$ above proton showers).

3.3. Discriminating variables

With a fluorescence detector, one can measure directly $X_{\max}$ and the electromagnetic energy, both of them with a good precision, except if the maximum of the shower is not visible above ground. Fig. 3 (top) was obtained from a set of simulated protons and photons with energies ranging from 3×10^{19} to 3×10^{20} eV, and zenith angles from 0 to 90 degrees; the showers are simulated using the Monte Carlo library AIRES [11], and $X_{\max}$ is obtained by fitting a Gaisser–Hillas function [12] to the visible part of the profile. It is clear that unconverted photons are well separated from protons (and even more from heavier nuclei, which give lower values of $X_{\max}$ for the same energy), even if the maximum of the profile is not seen. The distribution of converted photons overlap with the protons, but statistically the difference is quite significant.

With a surface array, we can use other quantities related to the stage of development of the shower, for example the steepness of the lateral distribution, and the curvature of the shower front. The steepness can be estimated using a specific parametrization, for example by fitting η in the function used by the Haverah Park experiment [13]:

$$S(r) = \frac{k}{r^{\eta + r/(4\,\mathrm{km})}} \quad \text{with a multiplicative factor } \left(\frac{r}{800}\right)^{1.03} \text{ if } r > 800.$$

The radius of curvature R of the shower front is obtained from the starting times of the signals in different ground detectors. Both these quantities depend mainly on the zenith angle θ, but for a given value of θ their variation reflects the stage of evolution of the shower. Based on a realistic simulation of the detector response, Fig. 3 (bottom) shows that a good statistical separation is obtained in the (η, R) plane between nuclei and converted photons, and that most unconverted photons are unambigously distinguished.

Other measurable quantities may be used: the time structure of the signals (due to weak muon component, the signal has a larger spread), the asymmetry of the integrated signals and of their time shape.

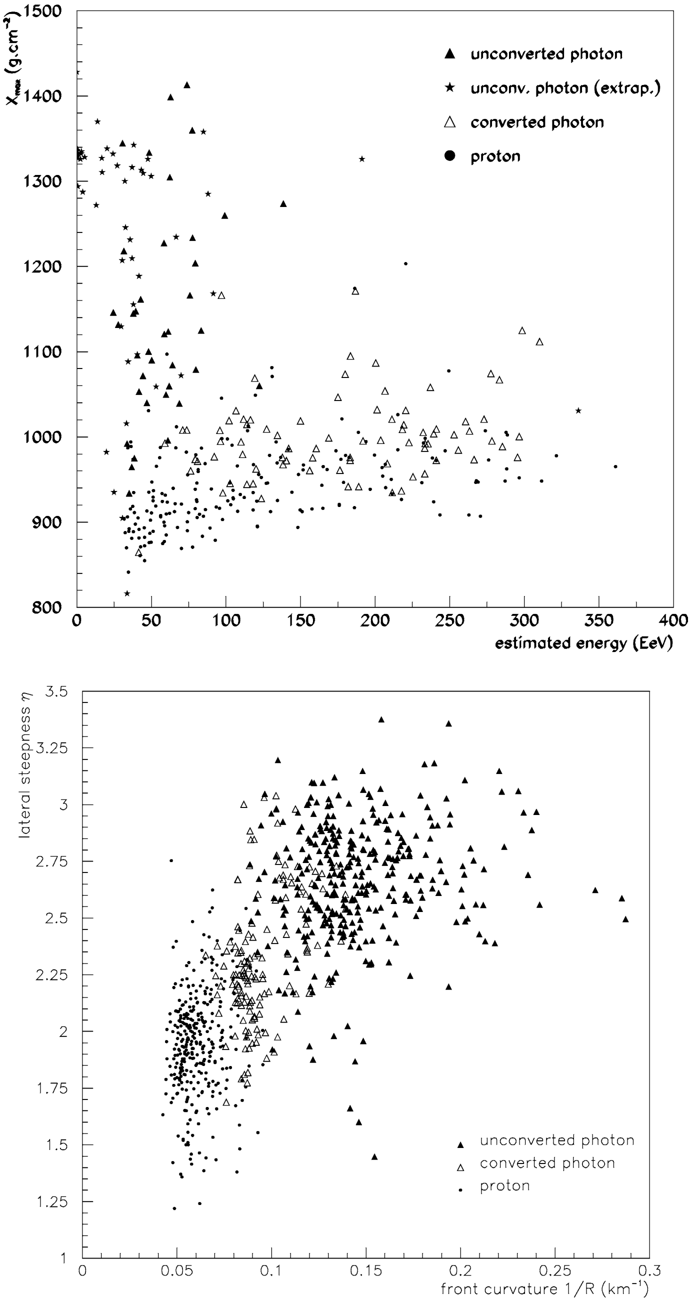

Fig. 3. Signatures of photons from discriminating variables. Top: fluorescence detector; depth $X_{\max}$ of the maximum of the longitudinal profile versus size (from a fit to a Gaisser–Hillas function), for protons and converted and unconverted photons (stars are plotted if the maximum is not visible). Bottom: surface detector; front curvature γ and lateral steepness η) for events with zenith angles $48° < \theta < 52°$.

To summarize, photons are expected to give showers which differ in many features from the nucleic ones. Moreover, the differences should be enhanced if the photons are not converted in the magnetic field: this effect produces an anisotropy related to the direction of the local field, rotating with the Earth, distinguishable from intrinsic anisotropies of the incident fluxes. The photons, if they are present at ultra-high energies, have a good chance of being recognized, even if they represent a small fraction of the fluxes.

4. Identification of neutrinos

4.1. Atmospheric interactions

Although the cross sections of neutrinos on nucleons increase with energy, they are still well below the hadronic cross sections in the range 10^{18} to 10^{21} eV (except in speculative theories which are difficult to reconcile with the present air shower observations, unless there is a sharp transition when the energy increases). As a consequence, the probability that a neutrino interacts through one atmospheric depth is small (10^{-5} to 10^{-4}), and such events should be very rare. However, another interesting consequence is that the point of interaction is distributed according to the density of matter, that is mainly in the lowest 10 km of the atmosphere, whereas the nuclei and photons have their first interactions above 20 km.

A neutrino interaction on a nucleus is essentially a hard collision with a quark in one of the nucleons. It produces a set of hadrons through the fragmentation of the interacting quark and of the rest of the nucleus. These hadrons initiate a cascade which, after a few steps, develops as an hadronic shower similar to those generated by a single primary object (mixture of an electromagnetic and a muonic component). On the other hand, a large fraction of the initial energy of the neutrino (70 to 80% on average at ultra-high energies) is taken away by the outgoing lepton. This lepton is either a neutrino, which escapes detection and has practically no chance to interact again, or, more often, a charged lepton (electron, muon or tau). An electron generates an electromagnetic shower, a muon or a tau lose generally a small fraction of their energy and do not produce an extensive atmospheric shower; a tau may decay in flight and its decay products give a mixture of electromagnetic and hadronic components, depending on their nature. To summarize, a neutrino interacting in the atmosphere gives always a shower, but the composition of this shower and the ratio of its size to the initial energy of the neutrino are subject to large variations.

At large zenith angles (in practice above 70 degrees) the nucleus-induced showers reach the ground at a very late stage, where the electromagnetic component is extinguished, and most of low energy muons have decayed: they consist in a thin and flat front of hard muons, with a shape distorted by the magnetic deviation over a long range; on the contrary, showers induced deeply in the atmosphere may be seen at ground level in their electromagnetic stage. Fig. 4 illustrates the differences between them. Although the origin of the shower is not directly visible, the reconstruction of the longitudinal profile with a fluorescence detector may be used to search for abnormally deep interactions (beyond the possible extension of photon showers mentioned above); a surface array will be sensitive to the spread in time, the lateral steepness, the curvature of the front and the absence of magnetic distortion of the shape of the distribution. However, the reconstruction of such a shower, even with precise measurements in air and/or on the ground, allows to determine only a lower limit of the energy of the primary neutrino, because an unknown (and often large) fraction of this energy escapes detection. What can be done is to compare the observations to the predictions of models including the incoming fluxes, the cross sections of neutrino interactions and the characteristics of nucleon structure and of the hadronic fragmentation.

Needless to say, an unambiguous observation of high energy neutrino interactions in atmosphere would be by itself an important achievement. Such events are expected to be very rare, even in the most optimistic scenarios. To distinguish them from the hadronic showers (at least 1000 times more abundant) is a challenging task which requires a perfect understanding of the possible sources of tails in the time structure of the signals.

4.2. Interactions of tau neutrinos in Earth

The neutrino oscillations may now be considered as a well established fact, with a large mixing of ν_μ and ν_τ [14]. Then, although ν_τ's are not produced abundantly in hadron decays, their flux after long distances is expected to be comparable to the ν_μ flux. This opens a new door for neutrino detection, through interactions in Earth (which is, of course, much more probable than an interaction in the atmosphere). If the primary neutrino is a ν_τ, it produces in most cases a charged τ lepton, which loses slowly its energy in matter, because of its large mass, and can cover a relatively large distance before decaying. With the

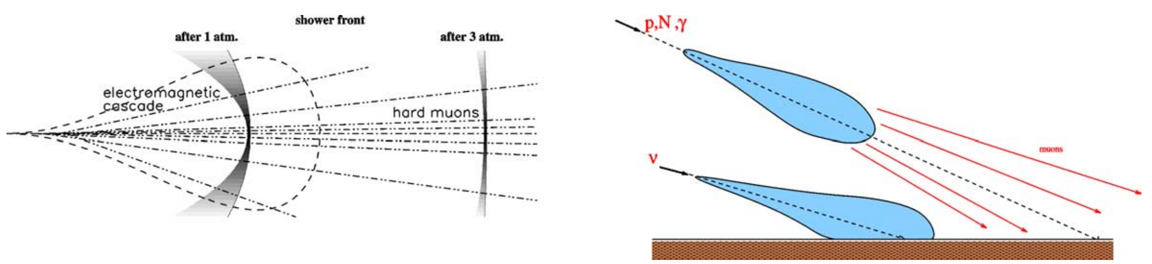

Fig. 4. Discrimination of neutrino interactions. Left: development of a shower over a large depth in air. Right: difference between a shower induced in the upper atmosphere and a 'deep' neutrino shower.

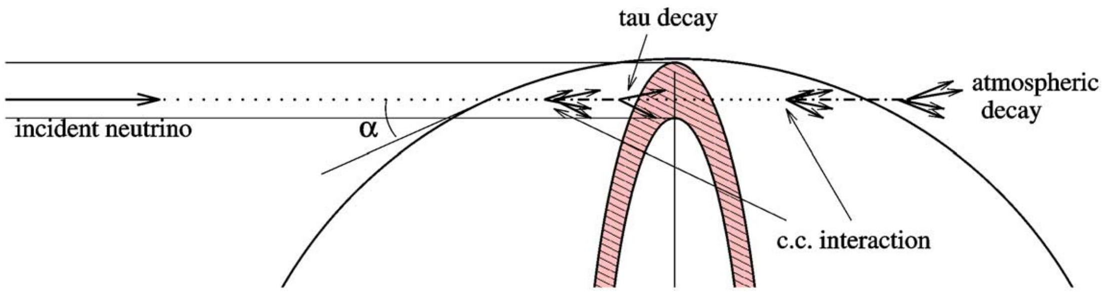

Fig. 5. Charged current interactions of ν_τ in Earth, ending in a τ decay in the atmosphere.

relativistic dilatation of times, the mean range is proportional to the energy: it is 50 km at 10^{18} eV. Then, even if the hadronic and the electromagnetic showers are fully absorbed after a few tens of meters through the earth, a τ may emerge after a few tens of kilometers and decay in the atmosphere, producing an extensive shower. There may be also intermediate interactions of the type $\nu_\tau \to \nu_\tau,\ \nu_\tau \to \tau,\ \tau \to \nu_\tau$ or $\tau \to \tau$, with more or less energy lost in byproducts, before the final interaction producing a τ ("multi-bang" processes). Fig. 5 gives an example of a detectable process.

The most favourable configuration to obtain an observable shower from an ultra-energetic neutrino is the 'earth skimming', with an incidence angle below the detector's horizon by a few degrees. In that case the trajectory of the neutrino into the Earth is not too large (otherwise it would lose most of its energy through many successive interactions), and the range in the atmosphere is large enough to contain the decay of the outgoing τ and the development of a shower. Moreover, if the core is at low altitude, the lateral expansion allows the shower to be seen in surface detectors. A study of the observability of such showers may be found in [15].

Earth-skimming interactions with subsequent detectable τ decay are expected to be more frequent than atmospheric interactions. Both have the same signature of an almost horizontal development, starting from a point of low altitude. The only difference is that earth-skimming showers go upwards. This may be seen unambiguously by a fluorescence detector while it would be more difficult with a surface detector. Unambiguous detection of up-going showers would be an indirect, but very interesting evidence for neutrino oscillations over cosmological distances.

5. Conclusion

Identifying the nature of an ultra-energetic primary particle giving rise to an atmospheric shower is a complex task. It is generally impossible to give an unambiguous answer for all showers. In the case of nuclei, there are different observables that allow a partial discrimination between light and heavy primaries: combined together, they could give a good distinction between the proton and the iron nucleus (the heaviest one with a nonnegligible abundance in the universe). If there is a continuous spectrum of mass, one can evaluate the average value (and maybe the width) of this spectrum, on a statistical basis; the most favourable situation would be a flux dominated by heavy nuclei: then the distribution of discriminating variables would be intrinsically narrow. The main limitation comes from the systematic errors due to the measurement techniques (that one can hope to eliminate with a hybrid detector) and to the uncertainties on the interactions in the first steps of the cascade.

The discrimination will be easier for the 'exotic' primaries (photons and neutrinos) if they exist, with a sufficient flux. The photons appear as 'super-light' nuclei, and this feature is enhanced at highest energies. The neutrinos, if they interact almost horizontally in the lower atmosphere or in the upper shell of the Earth, give the characteristic signature of an electromagnetic cascade still active at ground level. None of these 'exotics' have been observed up to now, but a new generation of observatories will be sensitive to them and give constraints to the theoretical models of the origin of the cosmic rays of ultra-high energy.

References

[1] J.W. Cronin, Auger technical note GAP-2003-076, http://www.auger.org/admin/GAP_Notes/.
[2] D.J. Bird, et al., Phys. Rev. Lett. 71 (1993) 3401.
[3] T. Abu-Zayyad, et al., Phys. Rev. Lett. 84 (2000) 4276.
[4] G. Archbold, HiRes Collaboration, in: Proc. 28th ICRC, Tsukuba, Japan, HE-1.3, 2003, pp. 405–408.
[5] L.D. Landau, I.Ya. Pomeranchuk, Dokl. Akad. Nauk SSSR 92 (1953) 535, 735;
A.B. Migdal, Phys. Rev. 103 (1956) 1811.
[6] L. McBreen, Phys. Rev. D 24 (1981) 2536.

[7] T. Erber, Rev. Mod. Phys. 38 (1966) 626.
[8] T. Stanev, H.P. Volkov, Phys. Rev. D 55 (1997) 1365.
[9] X. Bertou, P. Billoir, S. Dagoret-Campagne, Astropart. Phys. 14 (2000) 121.
[10] N.N. Kalmykov, S.S. Ostapchenko, Yad. Fiz. 56 (1997) 105;
N.N. Kalmykov, S.S. Ostapchenko, A.I. Pavlov, Bull. Russ. Acad. Sci. (Physics) 58 (1994) 1966.
[11] S.J. Sciutto, Auger technical note GAP-1997-029.
[12] See explications in P. Sommers, Extensive air showers and measurement techniques, C. R. Physique (2004) in press.
[13] D.M. Edge, et al., J. Phys. A 6 (1973) 1612;
R.N. Coy, et al., Proc. 17th Int. Cosmic Ray Conf., vol. 6, Paris (1981) 43.
[14] S. Fukuda, Phys. Lett. B 539 (2002) 179;
Q. Ahmad, Phys. Rev. Lett. 89 (2002) 011301.
[15] X. Bertou, et al., Astropart. Phys. 17 (2002) 183.