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Chacaltaya: towards a solution of the knee ...?(*)

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Summary. — Cosmic rays physics is currently being studied with rather sophisticated detectors running in a variety of experimental conditions and atmospheric depths around the world. In this paper we describe the reasons why cosmic ray physics experiments at high altitudes like Chacaltaya are so important for resolving some of the open problems in cosmic physics. A discussion on the future prospects of the high-altitude mountain laboratories such as Chacaltaya for cosmic ray physics is presented.

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1. – Introduction

One of the most important problems in cosmic ray physics, not yet resolved after nearly 40 years, is the existence of the "knee" in the primary spectrum. And there are many other important problems in the field of cosmic rays that should be studied, in particular experimental investigations, and at high-altitude sites.

One may ask why are observations of cosmic rays at high-altitude laboratories so important? One reason is because it is possible to observe the air shower cascades produced by lower energy of primary cosmic rays than at lower altitudes, due to their attenuation in the atmospheric overburden. This is particularly relevant in the current studies of gamma-ray sources and gamma bursters. Also, to study the shower cascades of higher energies at an early stage of development where showers present a minimum of fluctuations. The atmospheric depth of Chacaltaya (540 g/cm^2) corresponds to the maximum

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development of the showers in the energy range of 10–500 TeV, giving a maximum detection probability. Moreover the fluctuations in the development of the showers are much lower at the observation level of Chacaltaya than at lower altitudes.

In this paper a possible experiment using a variety of different techniques and carried out by a wide international collaboration is also presented and discussed.

2. – The Chacaltaya Laboratory

The Chacaltaya Cosmic Ray Research Laboratory, near La Paz, Bolivia, is located at an elevation of 5220 meters above sea level corresponding to 540 $\mathrm{g/cm^2}$, equivalent to about 7 nuclear interaction mean free paths (for TeV energy protons) and 14.1 radiation lengths. Its geographic position is at 16° South latitude, 291.8° East longitude and $-4°$ of geomagnetic latitude corresponding to 13.1 GV cutoff rigidity. Its geographic location in the southern hemisphere is also important in order to observe a part of the sky where γ-astronomy is not as well developed as it is in the Northern Hemisphere. The Galactic Center, in particular, can be observed at low zenith angle.

The Chacaltaya Laboratory is the highest continuously functioning research station on the globe, and provides a unique opportunity for research on cosmic ray phenomena. At energies above 10^{14} eV, the flux of primary cosmic rays is so low that direct observation by balloon- or satellite-borne instruments (with areas of only a few square meters) is not feasible. For example, the integral primary cosmic ray flux of energies above 10^{16} eV is only one particle per $(\mathrm{m}^2 \cdot \mathrm{sr} \cdot \mathrm{y})$. Consequently, for the most sensitive indirect studies of cosmic rays with energies of and above 10^{15} eV (one PeV), it is necessary to deploy extensive detector systems at as high an elevation as possible, to reduce the atmosphere overburden.

2·1. *Hadronic intensities at Chacaltaya.* – An experiment using emulsion chambers in combination with the extensive air shower technique is being operated at Chacaltaya by the SYS collaboration. The collaboration is observing bundles of high energy gammas and hadrons in the air shower cores (with emulsion chambers) associated with air showers detected by the EAS array. The experiment employs 35 plastic scintillators, 32 emulsion chamber units and a hadron calorimeter. Each emulsion chamber unit, with dimensions of $50\ \mathrm{cm} \cdot 50\ \mathrm{cm} \cdot 15\ \mathrm{cm}$, consisting of 15 layers of 1 cm Pb plates and two sheets of X-ray films. Below each unit a scintillator detector of the same area as the emulsion chamber detects the bundle of charged particles produced in the emulsion chamber material by the hadronic component of the shower through local nuclear interactions.

The gamma "family" is connected to the hadronic component through the geometrical position, and the hadronic component is related to the air shower through the arrival time [1]. Each unit of the hadron calorimeter provides an output which is a measure of the energy released in the scintillator and is converted to the number of (minimum-ionizing) charged particles. The data produced by the air shower array and by the hadron calorimeter are recorded when at least one unit of the hadron calorimeter records a particle density $n_\mathrm{b} \geq 10^3$ (particles/0.25 m^2). 2408 events were selected during 4.6 years of data taking, during which the emulsion chambers were simultaneously active. The shower size interval for these data is $N_\mathrm{e} = 5 \cdot 10^6$–$10^7$.

The recently published results [2] can be seen in fig. 1 where the differential energy spectrum of hadrons in air showers is compared with the expectations from simulations. These simulations used different models to simulate multiple particle production; the UA5 algorithm (modified for hadron-nucleus collisions), VENUS [3], QGSJET [4] and

HDPM [5]. Atmospheric diffusion of cosmic rays is described by the code in ref. [6] for the UA5 model, and by CORSIKA 5.20 [7] for the rest. It is apparent that the average number of hadrons for shower size $N_\mathrm{e} = 5 \cdot 10^6$–$10^7$ is lower than that predicted by all these simulations. This tendency is consistent not only with the relationship between the γ families and the accompanied air showers discussed by Kawasumi *et al.* [1], but also with the conclusions of the KASCADE experiment at sea level [8], where they have also reported a hadronic flux accompanying air showers lower than the expectations based on several models. In fig. 2 the measured muon trigger rate as a function of the hadronic rate is compared with the predictions from several simulations for multiple particle production. In a more recent paper by the KASCADE group [9], this result is confirmed.

These measurements: γ families and hadrons with the SYS experiment at Chacaltaya, and hadrons at the KASCADE array at sea level, are quite independent, as they are observing with different detector systems. However they display similar problems in describing shower development through the atmosphere. If we take into account these results (*i.e.* lower hadronic intensities than expected in the KASCADE experiment [8] and at Chacaltaya [2], as well as lower intensities of γ-families [1]), it would seem that at primary energies in the range 10^{15}–10^{16} eV a larger dissipative mechanism occurs in nuclear interactions than current models predict. In fact, if we consider cosmic phenomenology, we see the "knee" problem seen in the energy spectrum of primary cosmic rays in the same energy range of the emulsion chamber families (e, γ).

2˙2. *Hadronic interaction at colliders and cosmic rays.* – The primary cosmic ray spectrum is derived from flux measurements of EAS for which energies are measured by the total number of particles in the shower. It is obvious that such measurements at energies higher than the "knee" region can be seriously affected if the characteristics of the hadronic interaction change radically.

On the other hand, due to the lack of knowledge of the high energy interactions from particle accelerators in this energy range, it is hard to make comparisons between experimental results and simulations. In fact, as has been pointed out by Jones [10], all these comparisons require the knowledge of hadronic interactions at the highest energies and over a wide angular range. The highest energy reached currently is at Fermilab collider, studied with the CDF and D0 detectors, and corresponds to ~ 2000 TeV proton collision with a stationary proton. The LHC collider currently under construction at CERN will extend this up to about $\sim 10^{17}$ eV (equivalent cosmic ray primary energy). These collider facilities will thus cover most of the EAS energy region of current interest in the contex of the "knee" and the primary composition problems. Unfortunately, this is not the case for the angular range (or rapidity) coverage. In the upper part of fig. 3 [11], the multiplicity distribution of secondary particles for different primary energies is shown, together with the rapidity range covered by the CDF experiment and UA5 experiments, which had the largest rapidity range achieved thus far among high energy collider detectors. It can be seen that most of the secondary particles are detected by both detectors. But in the lower part of fig. 3, where the energy distribution of secondary particles is displayed, it is clear that only a small fraction of the primary energy is measured by these detectors, and this fraction decreases with primary energy. This effetc is even more important in the coordinate system where one (target) nucleon is at rest, *i.e.* the cosmic ray case. Since the air shower development is dominated by the final state energy flow, *i.e.* by this missing forward region, the most important information for EAS simulation is not provided by these collider experiments.

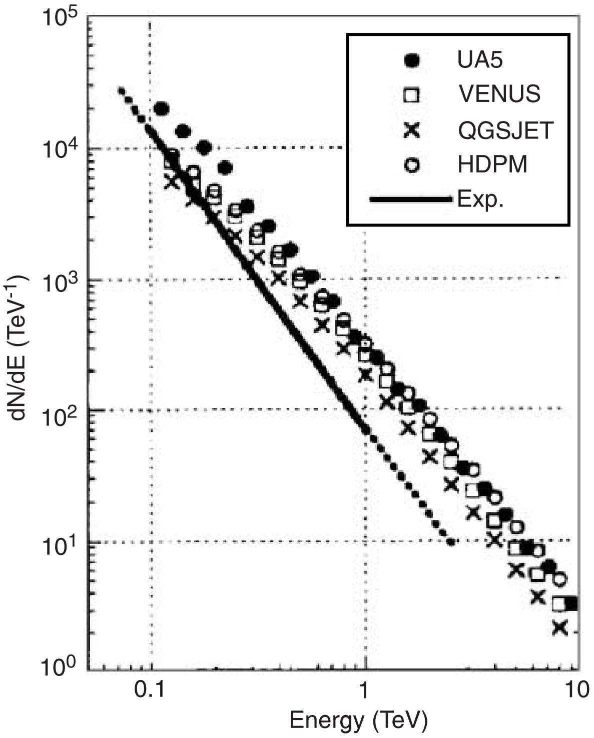

Fig. 1. – Differential energy spectrum of hadrons in air showers (solid line) and expectations from MC simulations with various interaction models (see text). The EAS size range is $N_e = 5 \cdot 10^6$–10^7.

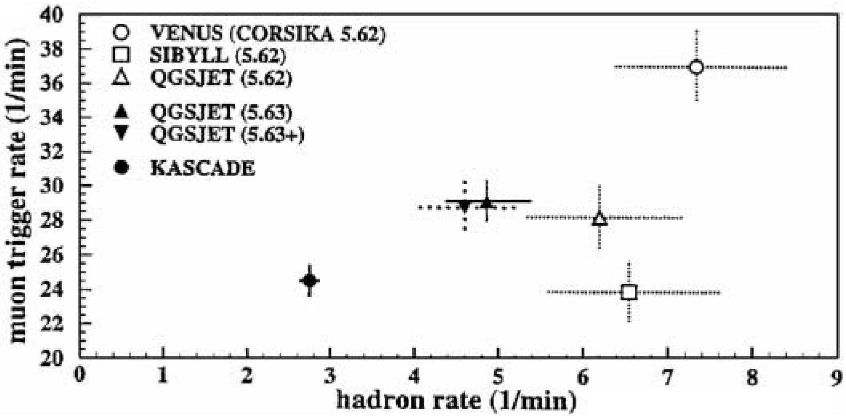

Fig. 2. – Comparison between simulated and measured integral muon trigger and hadronic rates at the KASCADE calorimeter. The experimental hadronic rate is much lower than the expectations by various simulation codes.

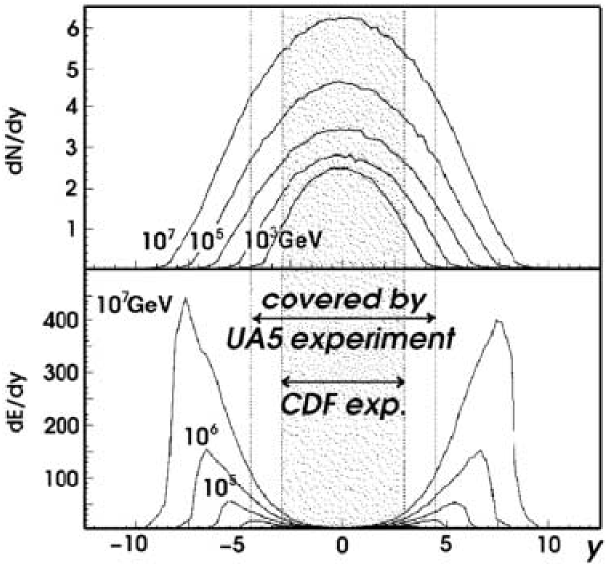

Fig. 3. – Multiplicity distributions (top) and energy distributions (bottom) *vs.* rapidity of secondary particles in high energy p-p̄ collisions for energy range 10^3–10^7 GeV in the rest system of one of the primary particles. Vertical bands show the angular acceptance of two collider experiments.

3. – Future prospects

As is well known, the energy region in the cosmic ray spectrum at primary energies of 10^{15}–10^{16} eV presents the enigmatic "knee". The origin of this change of slope of the primary cosmic rays spectrum is still unresolved, even after a great deal of efforts has been dedicated with increasingly sophisticated equipments working in a variety of atmospheric depths in the around the world. The question about the origin of the "knee" is still open. To know the reason of the existence of the knee is a major challenge faced in the very near future. Is it due to a change in production and/or acceleration mechanism at the source, propagation through interstellar space, or perhaps a change in the nature of the high energy interactions (as suggested by some emulsion experiments at high altitude laboratories)?

The current thinking is that perhaps not just one reason but two (or more) coincident mechanisms are operating in this energy region to produce the "knee". What should be the next steps for investigation of cosmic rays through this energy range? One could expect that some answers to the problems of nuclear interactions and multiple particle production will be given by the current accelerators or from the LHC experiments. However, as is shown in fig. 3, we lose information in the very forward directions with an increase in collider energy, unless different detector architectures specifically sensitive to small-angle (high rapidity) final states are utilized.

In order to fully exploit the great potential of high-altitude laboratories such as Chacaltaya, the simultaneous measurement of different observables should be undertaken. For example, consider an array built by 225 scintillation counters arranged on a 7 m grid covering an area of $\sim 10^4$ m^2. Since the atmospheric conditions at Chacaltaya for Cherenkov measurements are optimal, a wide aperture Cherenkov array could complete this EAS detector. In the central part of the array a hadronic calorimeter should be installed. This calorimeter should meet the following conditions: a) enough thickness to realiably measure the energy of hadrons of up to 100 TeV, b) large enough area to have enough statistics, for primaries of at least 10^{16} eV, for example 100 m^2, c) carpet detector on the top (streamer tubes or RPC counters) to measure the fine structure of the electromagnetic component of the associate shower, d) a tracking system in the top layers to measure the arrival direction of surviving hadrons, and e) fine-grained tracking detectors in between layers, such as a silicon array, scintillating fibers or emulsion chambers. The installation should also have muon detectors distributed around the EAS array and under the hadron calorimeter.

3˙1. *Direct measurement of survival proton spectrum up to 100 TeV*. – Up to the present the energy region up to some hundreds of TeV has been investigated by balloon- and satellite-borne instruments, and above these energies only by ground-based air shower experiments which are relatively insensitive to the primary nuclear composition. The proposal below suggests how a direct measurement of the primary proton spectrum could be achieved.

The surviving protons arriving at Chacaltaya suffer an attenuation given by $N = N_0 \cdot e^{-540/\lambda(E)}$, where $\lambda(E)$ is the nuclear interaction mean free path. The energy of such events is measured by the calorimeter and they are easily recognized by the lack of accompanying particles detected either in the carpet or in the EAS array. In addition, during moonless nights no accompanying Cherenkov light must be detected with the Cherenkov array. This confirms that no absorbed (lower energy) shower in the upper atmosphere is associated with the surviving proton. Even if this measurement is limited to lower proton energies and to a small fraction of events, the information that we can obtain is of crucial importance for background rejection.

Since only protons can reach the Chacaltaya level without interacting in the atmosphere, the final result could be the measurement of the direct primary spectrum of protons provided, all the uncertainties, both in the inelastic proton air nuclei cross-section and diffraction scattering on air nuclei be minimized. With the proposed area of the calorimeter, there would be ~ 80 events/year for $E_\mathrm{p} \geq 100$ TeV. The measurement in this energy region is of crucial importance for the calibration of the proton content in primary cosmic rays flux.

The number of expected events per 100 $\mathrm{m}^2\cdot$ year$\cdot$ sr in the energy range 1–100 TeV is shown in fig. 4. The proposed direct measurement up to 100 TeV (or higher) is needed to calibrate the indirect EAS measurement made with the same detector at Chacaltaya. In addition, these measurements of protons with good statistics can be directly compared with balloon measurements.

3˙2. *Pure events*. – "Pure events" are those that interact about 2 collision m.f.p. above the observation level and have not suffered the further complicated process of cascade development.

A two nuclear interaction m.f.p. correspond to ≈ 4 radiation lengths (r.l.), *i.e.* only ≈ 2 km above Chacaltaya. Therefore, a very collimated hadronic jet is produced and the electromagnetic cascade originated by π^0's is at a very early stage of development. Therefore, this experiment provides a great opportunity to study jet production in the very forward direction. These events are impossible to study with collider detectors up to present.

From fig. 4, it is seen that few events/year are expected at 10^{15} eV. These events

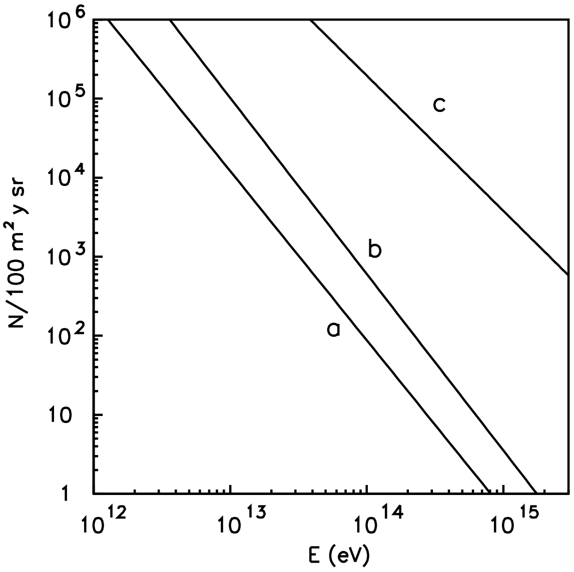

Fig. 4. – The integral spectrum of survival primary protons (a), of pure events (b) and of primary particles (c) at Chacaltaya per 100 m$^2\cdot$ year.

are also due to pure protons contained in the primary cosmic ray spectrum. In order to distinguish those events from the normal EAS background, we can use the information of the carpet detector as well as of the EAS array and (at night) the Cherenkov light detectors. In these events the electromagnetic cascade is at the very early stage of its development and would have a very steep lateral distribution; it should be well concentrated within the 100 m^2 carpet detector and not detected in the (10^4 m^2) surrounding EAS array. From fig. 4 it is seen that about 100 events per year are expected at over 200 TeV.

This would be a new approach to the study of the high energy hadronic interactions through jet production in the very forward direction together with the associated electromagnetic component.

3˙3. *Multihadron surviving events.* – The detection of multihadrons ($\geq$ 2) by the calorimeter could lead us to study the primary composition in a semi-direct way. In fact, Chacaltaya is at only $540/\lambda(E)$ interaction m.f.p. and 14 r.l. from the top of the atmosphere. Therefore the study of events with a simultaneous measurement of the hadronic energy and multiplicity, the associated EAS and the Cherenkov light seems feasible at Chacaltaya.

Moreover, special types of events, like Centauro and other exotic events like Chirons [12] having a high hadronic multiplicity and high transverse momentum with no or low electromagnetic component are still waiting to be understood. The fine granularity detector (emulsion chambers, silicon detector planes or scintillating fibers) inserted into the calorimeter will measure such events. With silicon or scintillating fibers, these events could be detected in real time, together with the associated EAS event. Up to the present, such events have only been studied with emulsion technique.

A measurement of spectra of such multihadron events with energies up to 100 TeV would be extremely helpful in order to better understand the phenomenology of these higher-energy interactions. A quantitative evaluation of such a study would be welcomed.

3˙4. *Primary composition at the "knee" region.* – As noted above, the "knee" in the energy spectrum holds a key to the understanding of the origin of cosmic ray. However, although a great effort has been dedicated to this problem over the past 40 years, confusion still reigns.

Lindner [13] proposed a method based on the analysis of Cherenkov light and particle densities registered relatively close to the shower core; he shows that the b *vs.* $X_{\max}$ relationship (where b is the "slope" of the lateral distribution of the Cherenkov light and $X_{\max}$ (g/cm^2) is the depth of the maximum development of the Cherenkov shower) does not depend on A, the primary mass, for a given model.

On the other hand, Procureur and Stamenov [14] have introduced a new parameter $\alpha(r)$ such that a shower selected with fixed values of this parameter would be generated by primaries with different masses but with the same primary energy. It is worthwhile to note that r for Chacaltaya is 35 m.

Both methods pursue an unbiased determination of the primary energy spectrum. However, in order to significantly improve the unbiased determination of the primary mass composition it has to be done by adding observables related to the non-electromagnetic shower components.

Since at Chacaltaya elevation the showers are at the minimum of their fluctuations for all components, with the proposed combined techniques (EAS and Cherenkov array and hadron-muon detector) it could be possible to face the "knee" problem in a definitive way. In particular, for lower energy showers the measurement will overlap direct results obtained by satellites or balloons. This possibility has a basic importance because, up to now, EAS data have not been calibrated against direct measurements.

4. – Conclusions

In this paper we have shown that a possible experiment could be done at Chacaltaya that would have a great potential, thanks to its high-altitude location. This presents a very great opportunity for cosmic ray physicists to exploit the unique conditions of this very high-altitude mountain laboratory.

A suitable design of a collection of detectors, perhaps modeled on that sketched here and undertaken by an international collaboration, would demostrate the unique possibility to provide very significant cosmic ray physics results.

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REFERENCES

[1] Kawasumi N. *et al.*, *Phys. Rev. D*, **53** (1996) 3634.
[2] Aguirre C. *et al.*, *Phys. Rev. D*, **62** (2000) 032003.
[3] Werner K., *Phys. Rep.*, **232** (1993) 87.

[4] Kalmykov N. and Ostapchenko S., *Yad. Fiz.*, **56** (1993) 105.

[5] Capdevielle J. N., *J. Phys. G*, **15** (1989) 909.

[6] Niihori Y. *et al.*, *Phys. Rev. D*, **36** (1987) 783.

[7] Heck D. *et al.*, FZKA report, 6019 (Fortshungszentrum Karlsruhe) 1998.

[8] KASCADE Collaboration (Risse M. *et al.*), *Proceedings of the 26th ICRC (Salt Lake City)* vol. **1** (1999) p. 135.

[9] Haungs A. *et al.*, this volume p. 599.

[10] Jones L. W., *Nucl. Phys. B (Proc. Suppl.)*, **75A** (1999) 54

[11] Schatz G., talk presented at the *Cosmolep Conference at Sodankyla, Finland, 1999.*

[12] Hasegawa S., ICRR Report, 151-87-5 (1987); Chinellato J. A. *et al.*, *Prog. Theor. Phys. Suppl.*, **76** (1983); see also Lattes C., Fujimoto Y. and Hasegawa S., *Phys. Rep.*, **65** (1980) 152.

[13] Lindner A., *Astropar. Phys.*, **8** (1998) 235.

[14] Procureurs J. and Stamenov J. N., *J. Phys. G*, **20** (1994) 1665 and *New possibilities for the Chacaltaya array*, private communication, June 1999, presented also at the Chacaltaya Meeting, La Paz, Bolivia, July 23-27, 2000, this volume, p. 519.