An Introduction to Cosmic Ray Physics and Research Carried Out at the Mt. Chacaltaya Laboratory in Bolivia

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Introduction

I would like to start by noting that it is quite proper that a workshop dedicated to high energy physics should include an introduction of cosmic ray physics. In this two hour lecture, it is only possible to provide a very general overview. Thus, many topics are not covered and details of those which are discussed have been omitted. On the other hand, because of the location of the School in Cusco, it is certainly proper to mention the results of scientific research carried out not very far from here, at Mt. Chacaltaya, in Bolivia. For these reasons, I thank the organizers of the School for having invited me here today.

I. Some Highlights in the History of Cosmic Rays[1]

As many phenomena, the presence of cosmic rays was detected as a consecuence of other studies. In their research on atmospheric electricity Elster[2] and Geitel[3] noted the existence of an unknown source of ions in the air. Independently, Wilson, in his studies with an ionization chamber, suspected the presence of an ionizing agent that would penetrate great depths. He speculated that this radiation could have an extraterrestrial origin[4].

In 1911, the Austrian physicist Victor Hess, installed in a balloon three electroscopes used then to measure radiation emited by radioactive substances. The observations of

[1]Resumed from S. Hayakawa. "Cosmic Ray Physics Chapter I". Monographs and Texts in Physics and Astronomy Volume XXII. Wiley - Interscience, 1969. See also G.R. Mejia y C. Aguirre. "La Radiación Cósmica". Monografía N^o 9, Serie de Física. Programa Regional de Desarrollo Científico y Tecnológico de la Organización de los Estados Americanos. Washinton DC 1973.

[2]J.Elster.- Phys. Zeits., 2, 560 (1900)

[3]H.Geitel.- Phys. Zeits. 2, 116 (1900)

[4]C.T.R.Wilson.- Proc. Camb.Phil.Soc. 11, 52 (1900) y Proc.Roy.Soc.(London) A68, 151; A69, 277 (1901)

Hess in this historical flight were resumed as follows "the results of my work can be explained on the assumption that a radiation of great penetrating power is introduced in our atmosphere from above[5]. Independent observations by Kolhorster led to the same conclusion.

During the decade following the First World War, research in cosmic rays was characterized by important events. Between 1922 and 1927, Millikan discovered the existence of a penetrating radiation in studies carried out under water in mountain lakes, whose depth corresponded to a thicknes larger than that which normally stopped the penetration of γ rays of the highest energy known then. Between 1927-29, Clay showed that the cosmic ray intensity decreased near the equator where the geomagnetic field is stronger and explained this variation as the effect of the field on cosmic rays, concluding that these were at least in part composed of charged particles[6].

At this time, new detection techniques were also developed. In 1927, Skobelzyn used a cloud chamber (associated to a magnetic field) for the study of cosmic rays. The invention and use of the "Geiger - Muller" counter permitted the detection the of passage of charged particles (Bothe and Kolhoster). The use of several of these tubes disposed geometrically constituted the first cosmic ray telecope. With the development of these and other techniques Anderson was able to establish the existence of the positron postulated in Dirac's theory. In 1934, Neddermeyer and Anderson, Street and Stevenson, proved the existence of the μ meson.

Later, two new detection techniques, the coincidence method (Rossi) and the controlled expansion of the cloud chamber (Blackett and Occhialini) produced important advances in the study of secondary cosmic rays, that is a shower (or cascade) of particles in the atmosphere (e.g. extensive air showers[7]), which are produced in the earth's atmosphere as a consecuence of the collision of a primary extraterrestrial particle with atmospheric nuclei[8]. The experimental evidences gave room to the development of the cascade theory (Bhabha and Heitler and Carlson and Oppenheimer).

By means of a shower-detecting arrangement, Rossi also observed, the frequency of showers versus the thickness of a shower producing material. The frequency-thickness curve permitted to conclude that a shower was a phenomenon involving electrons and possibly photons. In 1936, Pfotzer[9] observed intensity variations with height and established that the maximum intensity of the radiation ocurred at 15km a.s.l.

Many of the above results had an important impact on quantum electrodynamics which was being theoreticallty developed by many physicists, such as Bohr, Compton, Klein, Nishina, Dirac, Bethe.

In 1947 at Mt. Chacaltaya, Bolivia, the π meson and its decay into the μ meson was discovered[10]. In 1948, it was found that primary cosmic radiation contains heavier nuclei together with protons (Freier and collaborators). This discovery had an important

[5]V.F.Hess.- Phys.Zeits., 12, 998(1911) y Phys. Zeits., 13, 1084(1912). In 1936, Victor Hess received the Nobel Price in Physics "for the discovery of cosmic radiation". The Prize was shared with the American physicist Carl David Anderson "for his discovery of the positron".

[6]J.Clay.- Proc. Amsterdam, 30, 1115(1927).

[7]Actually discovered by P.Auger.

[8]B.Z.Rossi.- Physik, 82, 151(1933).

[9]G.Z.Pfotzer.- Physik, 102, 23(1936).

[10]C.M.G.Lattes, G.P.S.Occhialini & C.F.Powell. (H.G.Wills Physical Laboratory of the University of Bristol) "Observations on the Tracks of Slow mesons in Photographic Emulsion Plates". Nature. Vol. 160, 453 (Oct.4) and (Oct. 11), 1947.

astrophysical significance, as it revealed that there were no violent processes in the universe which could destroy nuclei in the course of their acceleration.

In the 50's theories on the origin of cosmic rays were developed. In particular, the existence and role of celestial magnetic fields were emphasized by Alfven[11]. Earlier, in 1933, Swann had proposed the acceleration of cosmic rays by a changing magnetic field. A solar origin of cosmic rays was proposed by Ritchmeyer and Teller and a galactic origin by Fermi. In the 60's. Ginzburg and Hayakawa made important contributions to the knowledge of the origin of cosmic rays by discussing the concepts of extragalactic, together with galactic and solar origins.

In 1957 Van Allen and Vernov, discovered independently the existance of rings or belts of trapped particles in the geomagnetic field. Primary electrons were detected in 1961, and so were the X-rays and their sources (Giacconi et al) in 1962. Of importance to cosmic ray studies was the discovery of the 2.7 K background blackbody radiation, interpreted as the remnant of the decoupling of matter and energy in the early stages of the big bang. In 1965 the interaction of a neutrino was observed for the first time (Reines and Cowan).

After the 60's, large air shower arrays[12] allowed the definition of the primary spectrum of cosmic rays, provided indications on their composition and allowed the establishment of some new hypothesis on their origin and the character of nuclear interactions, in particular, on the existence of new particles in nature.

During the 80's parts of cosmic ray physics were integrated into astrophysics, geophysics, space physics and other disciplines. Artificial particle accelerators forced nuclear interaction studies by cosmic rays to climb to higher energy limits.

It was in the early 50's that the Mt. Chacaltaya Cosmic Ray Physics Laboratory started its operation and has contributed since then to the advancement of this discipline. Before the Laboratory, scientists had to their disposal facilities installed at Pic du Midi in the Pirines, Jungfraujoch in the Alps or Aiguille du Midi, at Chamonix; all of them at heights between 3,000 and 3,500 meters above sea level. Chacaltaya enjoys an exceptional height between 5,200 meters and 5,600 meters at its peak, where the main Laboratory installations are located, it has an easy access and is on the geomagnetic equator. It also looks "up front" to the Galactic center. This combination of factors favours the acceptance of high energy primaries (due to the geomagnetic cut off) as well as the reduction of secondary effects, given the reduced thickness of the atmosphere (about half than that of sea level). Also at Chacaltaya, showers of large energy are at the maximun of their development thus facilitating their analysis.

[11]H.Alfven.- Cosmical Electrodynamics (1950).

[12]Volcano Ranch (1959 - 1963); Chacaltaya (1962 to present); Haverah Park (1968 - 1987); Sydney (1968 - 1979); Yakutsk (1974 to present); Akeno (1979 to present); Utah (1981 to present).

II. Some Methods of Detection and Analysis of Cosmic Rays

The treatment of cosmic rays has been traditionally separated into its geophysical, astrophysical and high energy physics characteristics. Some of the methods of detection and analysis used for their study will be highlighted here.

A. Geophysical aspects

Cosmic rays are mostly charged particles and thus subject to the effects (modulation) of magnetic fields extragalactic, galactic, solar, and terrestrial. The geophysical aspect of cosmic ray studies refer principally to the modulation (and behaviour) of cosmic rays under the action of the earth's and solar magnetic fields.

The earth's magnetic field acts as an "momentum analizer". It is convenient to define the "rigidity" by the relation

$$H\rho = \frac{p}{Ze},$$

where, H is the magnetic field, ρ is the radius of curvature and $\frac{p}{Ze}$ is the resistance of the particle to the deflexion effect of the field.

p is a function of the geomagnetic position and explains the intensity variation of cosmic rays with the geographic latitude, increasing from the equator towards the poles.

Lemaitre and Vallarta showed that the celestial sky can be divided in four regions

- The "Stormer Cone", in which particles of a given rigidity are not allowed;
- The"Principal Cone", which admits particles of a given rigidity;
- The "Penumbra" which is a region between the two above, and
- The "Shadow Cone" which is a forbiden region on the observational horizon.

The earth's magnetic field is subject to time variations (1) secular, (2) moon, (3) solar - diurnal, (4) magnetic storms. Some of the latter, which strongly influences cosmic ray intensity may last from hours up to several days. Normally during the main storm a large decrease of intensity is observed.

In the lower energy region $10^9 eV - 10^{14} eV$, cosmic radiation varies in intensity with an anisotropy defined by

$$\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

where δ is of the order of 3% for energies around $10^9 eV$ and 0.1% for energies around $10^{14} eV$.

Four types of variation exist

- "11 year", which corresponds to the solar cycle;
- 27 days, which corresponds to the sun's rotation;
- Diurnal, semidiurnal and short term, which correspond to the earth's rotation around the sun;

  and
- "Forbush", which are events of short duration originated in the sun (for example an electric storm).

Part of the observed intensity variation are due to atmospheric effects, which must be eliminated. For example, the counting rate of a detector at a given height can be corrected for pressure variations (and temperature as well), by the relation

$$N = N_{corr} e^{\alpha_0 \Delta B},$$

where ΔB is the deviation of the mean barometric value at a given height and α_o is the pressure coefficient -0.1%/milibar (for mesons) and -0.7%/milibar (for nucleons)

It is also interesting to note that the solar modulation of cosmic rays is produced by a set of phenomena, such as

- The solar corona, with a temperature of $10^6 K$, is in a continuous state of supersonic expansion and produces a "wind" of ionized H which acquires velocities of hundreds of km/hr.
- The wind wipes magnetic fields and confined gases up to 10 - 100 astronomical units ($1AU = 1.5 \times 10^{13} cm$).
- The wind fills the interplanetary space with the solar magnetic field lines, forming a spiral. - The spiral produces irregularities which depend on the wind velocity, the force lines, the temperature variation of the corona and turbulences. The wind acquires temperatures of the order of $10^4 K$ and is composed of 95% H and 5% He.

The solar wind produces several effects on cosmic rays

- It may drive them out of the solar system;
- For higher energies it decreases their density;
- The stochastic nature of particle movement in a field permits to define a statistical distribution in a large scale of cosmic rays in the solar system, through a Fokker-Plank distribution or a diffusion equation.

Some of the characteristics of the 11 year variation are

- The intensity of cosmic rays is inversely proportional to the solar activity and changes in intensity are out of phase by one year with respect to the solar cycle.
- The shape of the spectrum depends solely of the total intensity.
- Solar modulation is effective if the quantity of momentum is small and neglegible if the quantity of momentum is large (f.e. 30GeV).

In the 27-day variation, typical amplitudes are 1% to 2% at sea level and around 10% at the top of the atmosphere (40 km).

B. Composition at low energies

The composition of cosmic rays may be measured in a direct way, mostly by flying emulsions and other detectors on balloons and in an indirect way by the structure of extensive air showers. The former method is very appropriate for low energies a while the latter, as so for high energies. Table 1, shows the relative abundance of the nuclear component of cosmic rays in the energy range 0.5 GeV to 10^3 GeV per nucleon.

Several isotopes are also observed which suggests that the fragmentation of heavy nuclei in space plays an important role in the observed composition.

Besides the nuclear component,there are also low energy electrons produced by proton - proton interactions in interstellar space. The energy spectrum in the energy range $10^6 - 10^{11-12}$ eV is well determined. For energies larger than 1 GeV, the observed flux is larger by a factor of 10 to be attributed only to collisions. There exists evidence of galactic electrons produced and accelerated in the source. for energies larger than 1 TeV, point sources have been detected, f.e. VELAX.

Besides electrons, there also exist photons and high energy γ rays. Figure 1, shows the photon spectra.

Table 1 Relative abundance of the nuclear component of cosmic rays (0.5 GeV to 10^3 GeV per nucleon He = 100)

Nucleon	Observed Abundance in Cosmic Rays	Abundance in Universe
Protons	1.5×10^3	0.7×10^3
He	100	100
Li, Be, B	1.6	10^{-5}
C, N, O, F	6.7	1
Z larger than 10	25	0.1 to 0.4
Z larger than 20	0.7	0.005 to 0.02

Note Measurement errors have been omitted.

Figure 1. **Photon Spectra**

C. The cosmic ray energy spectrum

An important parameter in the study of cosmic rays is the intensity, which can be expressed as the number of particles, striking a given surface in a unit time, under specific geometric conditions. The intensity distribution can thus be represented by the cosmic ray spectrum.

Figure 2, shows a “traditional cosmic ray primary energy spectrum”, showing three clearly identifiable sections the first, in the lower energy region, determined by the latitude effect measurements; the second going into higher energies, as measured by nuclear emulsions, and the third starting at energies around 10^{13} eV deduced from extensive air shower measurements. These will be discussed in more detail in the next section.

Figure 2 **The traditional cosmic ray primary energy spectrum**

The spectrum shape has important implications in high energy physics and astrophysics. Traditionally the spectrum was viewed as following a power law a rational exponent around - 1.6 in the energy range $10^{10}eV - 10^{15}eV$, as a steepening power law-curve with exponent around - 2.0 in the energy range $10^{15} - 10^{17}$, and again as a flattening power law-curve with exponent - 1.6 for energies above 10^{17} eV. The spectrum shape at higher energies has been revised as will be discussed further.

For the intermediate energy range, the spectral shape has been primarily set by the Mt. Chacaltaya BASJE experiment. A review of the data obtained[13] shows that around $5 \times 10^{16} - 10^{17}$, the experimental set up excluded those showers falling at the center of the array, because the detectors saturated. Thus, the steepening of the spectrum in the energy range $10^{15} - 10^{17}eV$, may not be as believed.

D. Extensive Air Showers (EAS)

EAS[14] have ben studied in depth since their discovery in the 30's. It is a phenomena composed of a nucleon cascade, i.e. a series of high energy nuclear collisiones which occur at variuous depths in the atmosphere and a photon-electron cascade. A primary particle collides with an atmospheric nucleus, originating a shower of mesons and nucleons which continue towards the earth along the projected axis of the incoming particle. This central region around the axis is called the "core" of the shower. Further nuclear disintegrations are produced by these axial particles, giving rise to more mesons and nucleons (the nucleon cascade). In the initial and subsecuent collisions, the neutral π mesons decay into high energy γ rays which then initiate the photon electron cascade.

The study of EAS has been traditionally divided into two broad headings

- The longitudinal development of the shower as it proceeds down the atmosphere, and
- The lateral structure of the shower at different depths in the atmosphere.

A simple model developed by Heitler provides an idea of the longitudinal development of the photon electron component. An electron of energy E_o at depth $x_o ln2$ emits a photon of energy $E_o/2$ and retains $E_o/2$. At a new depth $x_o ln2$ emits a new photon of energy

[13] C.Aguirre.- Not published

[14] See f.e. W.Galbraith. Extensive Air Showers. Butterworths Scientific Publications. London 1958

$E_o/4$. Photons at the same time emit a pair of electrons. Thus, a given depth $tln2$ the number of particles is given by

$$N(tln2) = 2^t$$

$$N(t) = e^t$$

and the energy

$$E = E_o e^{-t}$$

Supposing that the cascade stops at $E = E_c$, then the maximun depth is given by

$$t_{max} = ls(E_o/E_c),$$

and

$$N_{max} = E_o/E_c$$

Past the point of maximun development, the cascade is absorbed as

$$N(t) = N_{max} e^{\frac{-t_1}{\lambda}}$$

where $t_1 = t - t_{max}$, and λ is called the attenuation coefficient.

Figure 3 shows in a squematic way the shower development curve. The area under the curve is called the track length and correponds to the total distance followed by the electrons.

At a given depth, the shower particles distribute themselves around the core of the shower (mainly because of multiple coulomb dispersion). The density of particles of a shower can be measured at such depth by locating a given number of detectors in a previously established area. The density of any component of the EAS at a distance r from the core is then given by

$$\delta(r) = Nf(r)$$

where N is the number of particles (the shower size) and $f(r)$ is called the lateral structure function. The number of particles can only be detrmined in terms of neergy and depth. In reality N fluctuates quite a lot, thus N is really a mean value.

The probability of finding n particles is defined as $P(n, E_o, E_c, t)$ and thus N is given by

$$N(E_o, E_c, t) = \sum_{n=0}^{\infty} nP(n, E_o, t)$$

The magnitude of the fluctuations can be represented by the variance

$$\gamma^2 = \sum_{n=0}^{\infty} n^2 P(n) - N^2$$

considering the lateral spread of the shower, and adding the coulomb dispersion, then

$$N(E_o, E, \theta, t) \;\; and \;\; N(E_o, E, r, t)$$

By definiton

$$N(E_o, E, \theta = \infty, t) = N(E_o, E, r = \infty, t) = N(E_o, E, t)$$

and the angular and lateral distributions are given by

$$f(\theta) = \frac{1}{N(\theta = \infty) sin\theta} \frac{dN(\theta)}{d\theta}$$

$$f(r) = \frac{1}{N(r = \infty) 2\pi r} \frac{dN(r)}{dr}$$

The dependance of the lateral distribution with the traversed media is eliminated by using the so called Moliere unit, defined by

$$r_M \equiv X_o(\frac{\epsilon_o}{E_s}),$$

which provides the rms spread of electrons of energy equal to a critical energy while traveling one radiation length.

The analytic solutions to the cascade equations are quite ellaborate and will not be treated here. It shall only be mentioned that the cascade process is an interesting example of a stochastic process. The analytic methods provide accurate results in light media. For heavier one, the energy dependance on the cross section and the electron back scattering play important roles and thye method becomes quite complex, except in the case of particles of energies much larger than the critical energy.

The analytic method contains two approximations. The first called Approximation A, where cross sections are expressed as fractions and ionizations loss and compton scattering are not considered and asymptotic forms for complete screening are used for radiation cross sections and pair creation. Then,

$$N_A(E_o, E, t) = E(\frac{E_o}{E}, t)$$

When E approaches the critical energy, ionization loss is important. This fact is included in the so called Approximation B, as a term of constant energy loss. Then,

$$N_B(E_o, E, t) = N(\frac{E_o}{\epsilon_o}, \frac{E}{\epsilon_o}, t)$$

With this approximation is not easy to obtain an explicit solution for finite E. The unidimensional theory for these approximations were developed by Rossi-Greisen and Belenkij.

To solve the cascade equations in three dimensions, the Landau approximation is used. It assumes a small angular divergence. Even then the mathematical procedure to obtain the structure function is quite complex. It has been obtained by Nishimura-Kamata (the N-K function) for limit cases, $E_o = \infty$ and E_o finite near the core, where the Landau approximation is not used and the structure function near shower development; when

s = 0, the shower is at the begining of its development;
s = 1, the shower is at maximun development, and
s $\geq$ 1, the shower is past maximun development and declining.

In terms of the shower age, the energy spectrum can be expressed as

$$N(E_o, E, t) \alpha E^{-s}$$

Noting that the structure function depends on rE,

$$f(r)\alpha r^{s-2}$$

and more precisely,

$$f(\frac{r}{r_M}) = C(s)(\frac{r}{r_M})^{s-2}(1+\frac{r}{r_M})^{s-4.5},$$

where $C(s)$ is a normalization factor. An approximation at $s=1$ gives

$$E = 1.9 \times 10^9 N_{max}(eV)$$

There are many other important shower parameters that can be calculated or measured with the experimental array. examples are the core position, the curvature of the shower front and the zenith angle (the arrival direction) of EAS. More recently, Hill has made important contributions to the knowledge of shower analysis which have improved the more traditional mehtods of solving the cacasde equations mentioned here.

The analysis of EAS has opened the way to the study of both the astrophysical and high energy physics aspects of cosmic rays. Examples of these two will be given further on this lecture.

III. A Brief Note on the Mt. Chacaltaya Laboratory[15]

In 1939, Ismael Escobar[16], a worker in the Spanish Air Force, arrived as a political refugee in France and in 1941 in Bolivia, where he started working as a metereologist in the Ministry of Agriculture. By 1942 he had installed a network of metereological stations, including one on Mount Chacaltaya at 5,200m.a.s.l.

In 1946, Cesar Lattes (of Brazil) arrived in Chacaltaya from Bristol, bringing newly developed nuclear emulsions. He and Ochialini were of idea of carrying emulsions to high places. Lattes had visited the Geopgraphy Departament at Bristol and "discovered" the site. It is probable that the Spanish meteorologists that knew Escobar, M. Doporto Marchori, Director of the Irish Metereological Service and Duperier, collaborator of Nobel Laureate Prof. Blackett, in London, influenced the Bristol Laboratory for its first visit to Chacaltaya.

The exposures to cosmic rays, soon revealed the importance of the technique and the site used. One of the most important discovies of the century is made the $\pi - \mu$ decay. The papaer of Lattes, Occhialini and Powell, published in Nature, made Chacaltaya known the world over. For this discovery H. Yukawa of Japan in 1949 and C.F.Powell in 1950 received the Nobel Prize in Physics.

A. Marques indicated that "for us in Brasil and Latin America the discovery had two important extensions the revitalization and stregthening of the old Laboratory, today Cosmic Ray Physics Laboratory in Chacaltaya linked to the Universidad Mayor de Saqn Andres and the creation in Rio de Janeiro of the Centro Brasilero de Pesquisas Físicas".

[15] C.Aguirre. "50 years of scientific activity at Mt. Chacaltaya" a history of cosmic ray physics in Bolivia". Essay to published in 1994 by the National Academy of Sciences.

[16] Because of his contributions to the deevlopment of physics in Bolivia, Professor Escobar was awarded in 1993, the Wheatley Award of the American Physical Society.

Taketani argues that 1947 was a year of great importance for particle physics in Japan. The discovery at Chacaltaya permited the confirmation of Yukawa's theory, the two meson hypothesis of Sakata and Tomonaga's theory. It showed their physicists that had no activities in experimental physics, because af the war, that it was possible to work originally in this discipline of science. As a consecuence a group of young swcientist was created.

Escobar proposed in 1949, to open a laboratory. The University and the Government authorized its creation late 1951 and on January 1, 1952, the Laboratory started to started to operate. Before this year several expeditions has already visited Bolivia to expose nuclear emulsions to cosmic rays, among them Maurice Shapiro (Naval Research Laboratory, Washington), Herman Yagoda (National Bureau of Standards), Marcel Schein Universidad de Chicago) and Hervasio de Carvalho (Centro Brasilero de Pesquisas Físicas).

On March 3, 1952 an aluminum hut was taken to Chacaltaya to serve as a home for scientists and workers. The first former visitor was Frank Harris who arrived in La Paz in April, just in time to spend few days underground while one of the bloodiest revolutions in Bolivia was taking place. Later this year an Agreement between the University and the Centro Brasilero de Pesquisas Físicas was signed, which today still continues to be spplied, thus making it one the oldest in America.

Within the first two years, scientific expeditions from several countries arrive in Chacaltaya. By then the the infrastructure of the Laboratory had greatly expanded, it included a power line constructed with materials donated by the government and new buildings both in the mountain and in the city. The early equipment mounted in Chacaltaya, cloud chambers and others served for initial studies on extensive air showers, the east west assymetry, etc. The first results were presented by the end of 1952 in the Laboratory's journal. Today, after 42 years, this journal is one of the oldest in Bolivia.

Since 1955 international meetings were organized in Chacaltaya. 1957 marks the initiation of six Interamerican Symposiums on Cosmic Rays. The fifth and sixth were held in La Paz. During the last one in 1970, important works were presented and the rapporteurs delivered their talks at the closing session in the mist of tear gases, bullets and general pandemonium, while the Bolivian Army occupies university premises, chasing students in a revolt initiated that same day.

The laboratory was also used for other purposes. A medical team of the Donner Laboratory of the University of California and of the US Naval Ordinance Laboratory, measured the infrared component of solar radiation. The US Naval Research Laboratory detected the first nuclear explosion in the Sahara. Later the universities of Manchester and Wisconsin carried out infrared astronomy experiments. The Bolivian High Altitude Institute used the Chacaltaya workers and scientists for their first studies on the adaptation and behaviour of men in high altitude. Also, the Laboratory started near La Paz ozone and ionosphere measurements.

In 1954, Kurt Sitte of Syracuse installed an extensive air shower array amd Gottleb and Hertzler of the University of Chicago set up one of the first "cloud chambers". Other experiments to measure the collision mean free path in coal and other elements were also set up. In 1957, the Physical Research Laboratory of Ahmedabad, India installs a cubic meson telescope to study cosmic ray modulation. Around this time a neutron monitor of the "Simpson type" is also installed. A group of the University of New Mexico sat up in an abandoned mine an experiment to measure the interaction of cosmic rays with light elements and a telescope to measure the meson intensity variation with respect to latitude.

Many other scientist participated in the early works of Chacaltaya, without trying to be exhaustive, it is possible to mention Juan Hersil of Bolivia, who actually initiated the early extensive air shower observations with the MIT group of Rossi and Clark, G. Ochialini, U. Camerini, A. marques, R. Salmeron, G.Schwachheim and A. Wataghin (from Brasil); R. Armenteros and V. Domingo (Spain), L. Mattson (USA), Jhon Bland (Great Britain).

Between 1960 and 1962 two of the most important projects in the Laboratory's history are initiated in Chacaltaya. The Bolivian Air Shower Joint Experiment (BASJE) and the Emulsion Chamber Exoeriment of the Brazil Japan Collaboration.

BASJE was born from the early contacts made by Escobar and later of Minoru Oda with Bruno Rossi at MIT and the early experiments carried out in El Alto by US and Brazilian researchers. Its main objectives were the search for gamma ray initiated air showers at energies larger than 10^{14} eV; search of heavy primaries and the study of high energy nuclear interactions. For these purposes a large scintillator arrays was constructed, accompanied by a $60m^2$ led shielded detector and Cerenkov detectors. The experiment started in 1962. Since mid 70's the cooperation has been a Bolivia-Japan endeavour. Together with the BASJE equipment, the University of Michigan operated a cloud chamber for many years.

The first results were presented in 1963[17]. Since then the number of papers, thesis and other documents have been very large. Some of the results were the establishment of the primary cosmic rays spectrum in the energy range $10^{15}eV - 10^{17}eV$; the experimental evidence of the energy dependance of the impact cross section of protons; the establishment of the surviving primary proton spectrum. BASJE contributed to clear knowledge on the origin of heavy primaries, the spectrum at energies larger than 10^{18} eV. It was the originator of gamma ray astronomy. Observations are today centered in high energy gamma ray initiated showers.

In the development of events that gave birth to the Laboratory and its later growth, the presence of the Centro Brasileiro de Pesquisas Físicas as an institution, Cesar Lattes and many other5 Brazilians as individuals stand out. The early names include Giusepe ochialini, Ugo Vamerini y Roberto Salmeron; Hervasio de Carvalho; Georges Schwachheim and Andrea Watagin; Fernando and Suzana Souza Barros. Much later, Edison Shibuya. A large part of all these effort throughout the years was carried out and closely followed up by Alfredo Marques.

One of the main results of this cooperation was the establishment of the Brasil - Japan collaboration. It was initiated from the contacts of japanese physicists led by Nobel Laureate H. Yukawa with Cesar Lattes. The project set itself to install nuclear emulsions in Chacaltaya to study interactions at around energies of 10^{14} eV. In mid 1962, Cesar Lattes and Alfredo Marques set up the first chambers. For over 30 years, the collaboration was able to describe meson multiple production processes. In particular the identification of highly exited nuclear matter (a) mirim, with rest energies around 2 - 3 GeV; (b) açu, with rest energies around 15 - 30 GeV; and (c) guaçu, with rest energies around 100 - 300 GeV. Also exotic interactions have been observed centauro,

[17] George Clark, Ismael Escobar, Kazuaki Murakami, Koichi Suga.- "Extensive Air Showers at 5200 meters above sea level and Search for High Energy Primary Gamma Rays. Pontificia Academia Scientiarum. report of the Study Week about Cosmic Rays and Interplanetary Space. Ciudad del Vaticano, 1963.

mini centauro, chiron, geminion and "clusters". Very high energy events such as the superfamily "Andromeda" were also found.

1963, Ismael Escobar left the Laboratory. The directorship was occupied afterwards by Rafael Vidaurre (1963/1967); Oscar Saavedra (1967/68); Gastón Mejia (1969/73); Carlos Aguirre (1973/77); Ricardo Anda (1978/79). Many more would come later.

An evaluation of the work was made by Linsley in the foollowing way[18] "The studies out carried out at Chacaltaya have contributed to improve knowledge of cosmic ray physics out of all proportions if compared with countries of similar development conditions". Of importance was the development of human resouces, today contributing to science, technology and other activities both in Bolivia and abroad. The Laboratory contributed to the creation of several institutions, its presence broke the isolation of the Bolivian scientific community. There were teachears of exceptional quality, capable of producing an important number scientists. recently, R.H. Schulczewski has recalled one of them, Prof. Raoul Weil[19]. The creation of working conditions at Chacaltaya were not easy. But, both at the physical and intellectual levels, Chacaltaya represented a challenge duly met. Many people have participated in this "mistic" cosmic adventure of great impact on science.

IV. Review of two Selected topics in Cosmic Ray Research

A. Energy spectrum, composition and origin of very high energy cosmic rays

An important review of several years of observations by larger air shower arrays[20] has been made by Watson[21]. These refer to the energy spectrum, composition and origin of very high energy cosmic rays, that is primary particles with energies larger than 10^{18} eV. The main conclusions of this review are given below.

1. Energy spectrum

In the energy range $10^{18}eV - 10^{19}eV$, the integral slope is larger than 2 and has increased significantly above the value close to 2 which seems to dominate the enrgy range from a few times 10^{15} eV - to 10^{17} eV (see also discussion in Part II).

Above 10^{19} eV, the spectral slope flattens again and is probably less than 2 (around 1.5 ± 0.2). On the other hand, events in the energy range 10^{20} eV do exist and there is no evidence yet of any cut-off in the spectrum.

2. Mass composition

Information on mass composition above 10^{17}eV is still a long ways from being definite. In particular, beyond 5×10^{18}eV it seems likely that discussion of this vital question will be

[18] John Linsley.- Panamerican Physics. Physics Today, Vol. 35, N^o 11, 1982.

[19] R.H.Schulczewski.- "Notas sobre el Laboratorio de Chacaltaya". La paz, 1986.

[20] See footnote 13.

[21] This part reproduced from A.A.Watson. "The Highest Energy Cosmic rays". Nuclear Physics B (Proc.Suppl.) 22B (1991) 116 - 137, North Holland.

confined for some time to consideration of two component, proton/iron model. At around 10^{19}eV very preliminary indications are that the iron component (in such a model) is less than 50%.

3. Anisotropy

Between 2×10^{18}eV and 10^{19}eV a gradual picture is being built by which it is possible to conclude that an enhanced galactic anisotropy has been observed. In terms of a simple model, it is possible that 50% of the cosmic rays are from sources associated with the galactic plane at an energy 10^{19} eV. At higher energies there is evidence of an extra-galactic anisotropy, suggestive of the site of creation of these particles lying in the Virgo Suopercluster.

As argued by Watson, unless long time exposures of much larger arrays than those of the past or in operation today take place, not much more will be said around these crucial topics. It is because of this vision that a giant array is being planned in the near future, as briefly mentioned below.

B. Very high energy nuclear interactions results of the Brasil-Japan Collaboration at Mt. Chacaltaya[22 and 23]

1. General characteristic of the experimental set up

As mentioned already, the Brasil-Japan Collaboration at Mt. Chacaltaya was initiated by a group of Japanase physicists led by H. Yukawa and Brazilian physicists led by C. Lattes. The first emulsion chamber was set up in 1962, with the initial purpose of studying multiple pion production. Several chambers followed and the experimental still continues. Figure 4 shows a schematic diagram of a latter chamber, composed of an upper chamber of $44.2m^2$ and 7cm of Pb in depth; a "producer chamber" of $5.5 \times 9m^2$ and 30cm deep of CH_2; an air space of 2.37cm and a lower chamber of $32.4m^2$ and 11cm of Pb in depth. For the experimental set up shown above, the threshold limits for detection are

- C-jets (those interactions produced in the "producer chamber" and observed at the lower chamber)

  $\sum E_\gamma = 100TeV$

  $E_o = 400TeV$, corresponding to $\sqrt{s} = 900GeV$

  In this case, the observation with this chamber entered in competition with CERN, except in the case of exotic interactions as will be discussed further.

- A-jets (produced by interactions in the atmosphere and observed in the upper chamber.

[22] Y.Fujimoto."Fire Balls in Chacaltaya Emulsion Chamber Experiment" Proceedings of the International Workshop on Super High Energy hadron Interactions. Tokyo, October, 1991.

[23] C.Aguirre et al. "Experiemnt OMEGA Observation of Multiple Particle Production, Exotic Interactions, Gamma Ray Air Showers and Heavy Primaries". Cosmic Ray research Laboratory, University of Tokyo. 1989.

$$\sum E_\gamma = 500TeV$$

$$E_o = 5,000TeV, \text{ corresponding to } \sqrt{s} = 3,200GeV$$

2. Fire Balls

One key objetive of the experiment at Chacaltaya was the observation of multiple pion production through the deacy of fire balls, as proposed by Hasegawa. The production of a fire ball as an intermediate stage in multiple pion production was outside of the theory of Yukawa and has as its modern counterpart with QCD the "quark-gluon cascade". The deacy of a fire ball into a hadron was within Yukawa's theory and its present version is hadronization. In the proposed model there are three kinds of fire balls with fixed mases one responsible for the "scaling law" and the rest responsible to scaling break down and p_t increase. table 2 resumes the general characteristics of these fire balls (with the names given during the course of the observation and analysis).

Table 2 Fire Ball Models for multiple meson production, assuming three kinds of fireballs with diffrent mass and temperature

	Name of fire-ball		
	H-quantum (heavy)	SH-quantum (super heavy)	UH-quantum (ultra heavy)
Corresponding jet	Mirim	Açu	Guaçu
Rest energy (GeV/c^2)			
Gamma ray component	1.3	5 - 10	30 - 80
Total	2 - 3	15 - 30	100 - 300
Proposed decay mode into pions first into H-quantum, and then into pions (non-legible presence of heavier mesons)			

3. Main characteristic features in multiple meson production observed with the Chacaltaya Emulsion Chamber

There are several interesting characteristic features that are important to recall. The first is the determination of the invariant mass of two γ rays from all possible combinations among those observed. the existance of the π^o peak and agreement of the background distribution between experimental data and expectation (by simulation) show the correct γ ray energy estimates that are made. the invariant mass distribution is shown in figure 5.

One other feature is the correlation between the energies of γ rays and their emission angles. Figure 6 shows the results obtained and the average values of transverse momentum obtained at the CERN collider line (a) at $\sqrt{s} = 630GeV$ and line (b) at $\sqrt{s} = 540GeV$. The integral energy distribution of C-jets in terms of fractional energy normalized by the total observed energy is shown in fig. 7. As seen from this figure, the distribution for different energy regions have the same exponencial from below $\sum E_\gamma \leq 15TeV$, while changing into regions of higher multiplicity for energies above 20 TeV.

Figure 8 shows the p_t of C-jets and modified accelerator data. Data of FNAL (p = 205 GeV/c hydrogen bubble chamber data) and CERN (minimun bias events of ISR with $\sqrt{s} = 53GeV$) are boosted to the energy region of C-jets by Monte Carlo simulation and the same experimental conditions as C-jets are imposed on the simulated events. As seen, C-jet data shows the large p_t and large rapidity density, the frequency of this latter group increasing with energy.

Other interesting features observed by emulsion chambers exposed to cosmic rays at Chacaltaya that can be compared with accelerator expeiments refer to angular distribution, showing coincidences in some energy regions. Also, the pseudo-rapidity distribution can be obtained, showing its energy dependance, i.e. scaling break down. the correlation of the number of cluster (N^*), observed in A-jets, their energy (E^* and cluster distance R^* can be also measured. The quantity, $\sum E^* R^*$ can be directly related to the fireball mass. A-jets observed with the Chacaltaya emulsion chambers are consistant with the production of large fire balls (SH-quantum).

4. Exoctic events

During the course of analysis of cosmic ray interactions with the emulsion chambers a set of exotic events have been foun. The most striking one is well know in the literature Centauro. After considering possible experimental biases it was concluded that this is real event. The main characteristics is given in Table 3 below.

After the discovery of Centauro many other exotic interactions have been observed. The Table 4 resumes them.

Several hypothesis have been sugested to explain exotic events. A group of them corresponds to the explanation of the phenomena as the product of the collission of cosmic rays in the atmosphere (exotic interactions), the second group tries to explain them rather as the collision of "exotic primaries" with atmospheric nuclei. Table 5 list some of the hypothesis in both groups.

Table 3 Main characteristic of the Centauro event	
1.	Total observed energy (after correction for detection efficiency) $\sum E_h^\gamma = 330$TeV, so the estimated primary energy is $E_o = E_h^\gamma / k_\gamma = 1,650$TeV, corresponding to $s = 1,800$TeV
2.	Production depth in the atmosphere 500g/cm^2
3.	Large multiplicity N = 80. An extrapolation of accelerator data to $s = 1,650$GeV; $n_{ch} = 34$
4.	Large transverse momentum $\langle p_t^\gamma \rangle = 0.35 \pm 0.15$ GeV/c, corresponding to $\langle p_t \rangle = \langle p_t^\gamma / k_\gamma \rangle = 1.5$ GeV/c (average values by accelerator data) $\langle p_{t\pi} \rangle = 0.45$ $\langle p_{tK} \rangle = 0.6$ and $\langle p_{tN} \rangle = 0.8$GeV/c
5.	Non existance of neutral pions

Table 4 Exotic interactions observed at Chacaltaya			
	Number of produced particles N_H	Average Transverse Momentum $\langle p_t^\gamma \rangle$GeV/c	Mass of fireball GeV/c^2
Centauro	80	0.35 - 0.15	200
Mini-centauro	15	0.35 - 0.15	30
Chiron	15 - 20	2.0 - 0.5	200
Germinion	2	2.5 - 0.4	30
Mini-cluster	-	0.01 - 0.02	?
Giant mini-cluster	-	0.1	?

V. Proposals for Future Research in the Highest Energy Region

A. Experiment OMEGA at Mt. Chacaltaya[24]

A new proposal has been put fordward to study the astrophysical and nuclear energy characteristics of very high energy cosmic rays at Mt. Chacaltaya. It is experiment OMEGA (Observation of MultipleParticle Production, Exotic Interactions, Gamma Ray Air Showers, and Heavy Primaries). The proposal is being considered by several organizations and it is hoped that observations can start soon. Some of the objectives will be reviewed here.

The proposal aims at constructing a very large chamber which will be exposed for longer periods of time. It is envisaged that a central detector will be constructed with an area of 900m^2. The central detector will consist of an emulsion chamber covered by optical (scintillation) fiber. The signal supplied will then provide information of the position and time of the event as well as the size of the electromagnetic component of the air shower. It will then be possible to withdrawn from the Chamber only those emultions which registers the event, thus allowing longer periods of exposure for those parts without interesting events. The hadron detectors will consist of plastic scintillators located below the chamber.

The central detector will be sorrounded by an air shower array of 80 plastic scintillators distributed around the central detector in a 200mm lattice. These will determine the shower density, its age, incident directions and other parametrs normally measured with such type of arragements. Table 6 shows the number of events expected by a 3,000 m^2 year exposure.

1. Exotic Interactions

As mentioned above, since the discovery of Centauro in 1972, several types of exotic interactions were detected and interpreted tentatively to be the multiple production of non pionic particles - baryons or some new particles-. It is thus of great interest to search deeper on this topic. so far, the size and time of exposure of the emulsion chambers at Chacaltaya has been a limiting factor to obtain a larger number of events at several energy regions. The proposed arragement will permit the study of a larger number of pure events

[24] See footnote 23.

(those ocurring near the chamber and the elimination of those suffering a large cascade process in the atmosphere).

Table 5 List of hypothesis put fordward to explain exotic interactions observed in the Chacaltaya emulsion chamber

Exotic interactions

Projectile	Intermediate product/mechanism	Produced particle
p	Hot spot (kT $\geq$ 1Gev/ Evaporation of quarks	quarks
A	Extended, massive multi-quark state (strange, meta stable)/ Strong nucleon decay	nucleon
π, p	Gas mixture of q, q and g/ A collapsed hadron (many quark state ofcolor singlet, zero electric charge and rich strangeness) + residues (baryon-and strangeness rich)	a collapsed hadron + baryons
p	Quark-gluon fire-ball/Precocius superfluorescent-like decay	heavier particles
A	Quark matter ($\geq 2GeV/fm^3$) with predominant nucleons/Nucleon secondaries	BB's
A	Stable or meta-stable glob (with deconfinement and chiral symmetry)/ Massless baryon state	BB's
p	New type of adronic matter/Evaporation of "strong" black-hole	baryons
p, A	Hadronic matter (1 Tev/fm^3)/Induced transition (charge bunching)	pions
p	Bubbles of nuclear matter (superdense, meta-stable)/ Excitation of $SU(3) \times U(1)$ false vacuum	Higg's KK's
p	Nucleon with diffraction excitation/Phase transition	Baryons

Exotic Primary

Exotic particle	Mechanism	Origin	Explanation for Centauro
Superdense nucleus	Pion condensation	Neutron star	-
Metaestable glob of nucleon or quark matter	MIT bang	Big bang	boil/explode to multibaryon state
Dense, invisible quark nugget (strangeness rich)	1st. order QCD phase transition strange matter	head-on collision of neutron star or decay of binary star	
Stable strangelet (baryon-number-rich glob)	Strange quark matter/Strange quark star	Cygnus X-3 (compact binary X-ray source)	

Table 6. Number of events expected by a 3,000 m^2 year exposure (corresponding to 3.4 year exposure)			
Incident energy (eV)	Above 10^{15}	above 10^{16}	above 10^{17}
Primaries	4.9×10^5	4.9×10^3	4.9×10
Protones in primaries*	2.4×10^5	2.4×10^3	2.4×10
$\lambda_{col}(p - air)(g/cm^2)$	56	48	42
$z(= 540/\lambda_{col})$	9.6	11.3	12.9
$p = e^{-z}(e^2 - 1)$	4.3×10^{-4}	7.9×10^{-5}	1.6×10^{-6}
Number of pure events	1.0×10^2	1.9×10^{-1}	
Note * proton fraction (0.49) in the primaries cosmic rays assumed independent of their energies			

2. Nuclear interactions in the energy region around 10^{15} eV

Most of the events observed in the central detector are the result of multiple meson production caused by nucleons of primary energy around 10^{15} eV. These events are to be compared with the minimun bias events observed by the present colliders (CERN SPS pp* and FNAL TEVATRON). Analysis and comparison of data will not only allow the possibility to calibrate OMEGA's detectors, buty also reveal a more complete feature of nuclear interactions, as cosmic ray observation is concerned with the features of the electromagnetic and hadronic particles produced in the forward (or fragmentation) region not easily observed by collider experiments.

3. Heavy primaries

The topic of composition is crucial from both the astrophysical and elementary particles points of view. direct observation of heavy primaries in the energy region above 10^{15}eV per nucleon is difficult due to the small frequency (around 100 particles per m^2-year. The new experiment will allow observations of nucleons of energy around 10^{14} eV, which produce air showers reaching their maximun development at Mt. Chacaltaya. In such case, energy can be more confidently determined.

4. Nuclear interactions for energies above 10^{17} eV

These energies cannot be reached by present day accelerators and probably it will take quite a while to develop the technology to construct one (and obtain the sufficient financial resources). Thus cosmic rays continue to be the only source of such particles. The project will be able to observe a large number of events in this energy region and study some of the characteristic features of interactions, such as x-distribution, p-distribution, interaction cross section, nature of produced particles, etc).

5. Ultra high energy gamma rays

Since a high energy γ rays (larger than 10^{15} eV) from Cygnus X-3 was reported some time ago, their study has become a fundamental issue in the study of high energy cosmic rays. At Mt. Chacaltaya it is possible to observe primary γ rays of a wide energy range, from about 6^{13} eV, from sources in the Galactic center and around. Some important candidates are shown in Table 7.

Finally, Table 8 shows a resume of the fenomena and possible signals that can be expected by diffrent detectors of OMEGA.

B. Giant Extensive Air Shower Array

Much can still be expected from the observation of very high enrgy cosmic rays. Along this line, in 1993, it was decided to search for a site which would permit the construction of a giant extensive air shower array covering nearly 5,000 km^2. Such a giant array would allow to collect a large number very high energy (larger than 10^{17}eV) cosmic rays. The main purpose of thiss array would be to determine the energy spectrum of primary cosmic rays, their origin, their chemical composition. Also, large energy γ rays will be looked for as well as the gross features of high energy interactions. It is expected that the design team will start its mission in Januery 1995. An appropiate site is being searched. Candidates in South America can be found in the Bolivian high lands or the Argentinian pampas or further south.

Table 7. Candidates for Ultra High Energy Gamma Rays emitters observable at Mt. Chacaltaya

Object	R.A. (hm)	Dec. (deg)	Type of Object	Min zenith angle at Chacaltaya (deg)
Crab pulsar	531	22	radio pulsar	33
Geminga	630	18	quasar	34
Vela pulsar	833	-45	pulsar	29
Vela X-1	900	-40	x-ray binary system	24
PSR0950+8	950	08	radio pulsar	24
Vir A	1228	12	radio galaxy	29
Cen A	1322	-43	radio galaxy	26
Sco X-1	1617	-15	x-ray binary system	01
X1700	1700	-38	x-ray binary system	21
X1822-37	1822	-37	x-ray binary system	20
PSR1929+10	1922	10	radio pulsar	26
X1907+09	1907	09	x-ray binary system	26
PSR1937+21	1937	21	radio pulsar	37
SS433	1909	05	x-ray binary system with strong radio jet	22

Table 8. Phenomena and possible signals that can be expected by the different detectors of OMEGA				
	Asarray	Emdetect	Hdetec	emulsioncham
Pure events	X	0	0	0
Centauro	X	X	0	0
UHE-gammas	0	0	X	X
Highest energy (larger than 10^{17} eV)	0	0	0	0
Note X-small or no signal; 0-large signal				