Atmospheric Neutrinos:
from the pioneering experiments to IMB and Kamiokande

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The idea that cosmic rays, interacting in the Earth atmosphere, should generate a large flux of neutrinos, was understood very early, and concrete ideas about possible methods to detect this flux were already formulated in the 1960s. At the same time the first theoretical estimates of the size and properties of the flux were constructed. The first detection of atmospheric neutrinos was obtained around 1965, recording in deep underground detectors the muons generated by neutrino interactions in the rock surrounding the detectors. A decade later, new detectors capable of observing the neutrino interaction vertex, and studying the final state in some detail, were developed with the main motivation to search for proton decay. This stimulated the calculation of more accurate and detailed theoretical predictions. At the end of 1980s, from the observations of the IMB (Irvine–Michigan–Brookhaven) detector in the US and soon later Kamiokande in Japan, emerged what became known as the "atmospheric neutrino anomaly", a discrepancy between data and prediction (initially in particular about the flavor ratio of the contained events). The anomaly could have several possible interpretations: (a) systematic effects in the detectors, (b) flaws in the theoretical predictions, or (c) new physics, with neutrino oscillations, the simplest (but not unique) solution. The situation was complicated by the fact that not all of the data (including measurements of neutrino–induced muons, and the observations of other proton decay detectors such as NUSEX and Fréjus) were (or appeared to be) consistent. For approximately one decade the "atmospheric neutrino anomaly" with its "hint for oscillations" was at the center of an intense scientific discussion that stimulated refinements in the calculation of the expected neutrino flux and in the modeling of the neutrino cross section, and also the construction of new physics models for the interpretation of the data.

1 Introduction

Atmospheric neutrinos are created in the Weak decays of secondary particles produced by cosmic rays (CR) in the Earth's atmosphere. The main channel of atmospheric neutrino production is the chain decay of charged pions:

$$\begin{array}{lll} \pi^+ \to & \mu^+ & \nu_\mu \\ & \searrow & e^+ \, \nu_e \, \overline{\nu}_\mu \end{array} \quad (1)$$

(and charged conjugate mode), with smaller contibutions (at the level of $\sim$ 10–20%) generated by the production and decay of kaons, in modes such as $K^+ \to \pi^0 + e^+ + \nu_e$ or $K_L \to \pi^\pm + e^\mp + \overline{\nu}_e(\nu_e)$.

The existence of the atmospheric neutrino flux was inferred from the study of cosmic rays in the 1930s and 1940s, and this story is intimately connected to the the determination of the nature of the cosmic rays (CR) and to the birth of particle physics (with the discovery of the positron, the muon and the pions).

Atmospheric neutrinos were detected for the first time in the 1960s essentially simultaneously by two detectors located in very deep mines in India and South Africa and designed to observe the muons generated by the charged current interactions of ν_μ and $\overline{\nu}_\mu$ is the rock around the detector.

Neutrino interactions inside the detector fiducial volume were later observed in large mass detectors designed to search for proton decay. These measurements resulted in the discovery by two water Cherenkov detectors (IMB and Kamiokande) of an "anomaly" in the μ/e flavor ratio for contained events, generated by the interactions of atmospheric neutrinos. After a decade of controversy and debate, the "anomaly" in the flavor ratio was finally recognized as the signature of neutrino oscillations.

This article reviews the history of atmospheric neutrinos from its beginning until the discovery of the "anomaly" in the flavor ratio. The following period, with the "solution" of the problem (and the discovery of neutrino oscillations for atmospheric ν's) is discussed in the contribution of Takaaki Kajita in these proceedings. (Also the contributions of John Learned, John LoSecco and Francesco Ronga in the proceedings discuss the history of atmospheric neutrino studies).

This article is organized as follows. In section 2 we briefly describe the developments in cosmic rays studies that lead to the understanding of the existence of the atmospheric neutrino flux. In section 3 we review the evolution of the predictions for the flux. Section 4 describes the pioneering experiments that obtained the first detection of atmospheric neutrinos. Section 5 discusses a second generation of detectors constructed with the main goal to study proton decay and that obtained detailed measurements in the GeV energy range. Section 6 introduces the discovery of an "anomaly" in the data, and the controversy about possible interpretations. The final section outlines some conclusions.

2 Understanding the existence of atmospheric neutrinos

The existence of cosmic rays [a] was first inferred from the study of the altitude dependence of the rate of ionization in gases, measured observing the discharge of electroscopes. It is common to associate the discovery of cosmic rays with the studies of Victor F. Hess who took measurements of the ionization rate during seven balloon flights that reached a maximum altitude of 5000 m, and in 1912 arrived to the conclusion [4] : "The results of my observations are best explained assuming that a radiation of very great penetrating power enters our atmosphere from above". This was the beginning of what Bruno Rossi in his classic book [1] calls "One of the most extraordinary adventures in the history of Science".

For approximately two decades, the only property of cosmic rays that was systematically studied was the ionization rate in gases, as a function of altitude and geographical position. The commonly accepted theory for the nature of the primary cosmic rays was that they were energy gamma rays. The observed ionization was then generated by the electrons produced by Compton scattering (pair production was still unknown) of these photons with the air atoms. The term "cosmic rays" was introduced in 1925 by Robert Millikan who interpreted the altitude dependence of the ionization in terms of a gamma ray spectrum formed by discrete energy bands, that he associated to the formation of nuclei in the universe (so that the cosmic rays where the "birth cries" of the elements).

[a] The early history of cosmic ray and particle physics is covered in several excellent books [1,2,3].

The dominant view that cosmic rays where high energy gamma rays was not seriously challenged until 1928–1929, when Walter Bothe and Werner Kolhörster [5,6] performed their celebrated coincidence experiments using Geiger–Müller detectors. The high coincidence rate suggested that the CR radiation was of corpuscular nature. Misteriously the radiation was very penetrating: placing a gold block with a thickness of 4.1 cm between the two counters reduced the coincidence rate by only 24%. This observation can in fact be considered as the indirect discovery of the muon [7]. In the words of Bruno Rossi [1] : "The paper of Bothe and Kolhörster came like a flash of light revealing the existence of an unsuspected world, full of mysteries, which no one had yet begun to explore."

The theory that cosmic rays were gamma rays was falsified with the discovery of the latitude effect: the intensity of the cosmic ray flux depends on the magnetic latitude of the observation point. First observations of the latitude dependence of the ionization rate had been obtained by Jacob Clay [9], but the effects was clearly demonstrated by a world–wide survey directed by Arthur Compton [10] (for a discussion of the discovery of the latitude effect and the Compton–Millikan controversy see for example [11]). The latitude dependence of the cosmic ray intensity demonstrated that a large fraction (or all) of the primary cosmic rays were electrically charged. Soon after it was also discovered that the cosmic ray flux also depends on the azimuth angle around the vertical direction (east–west effect) [12]. This demonstrated that most of the cosmic rays had a positive charge and therefore very likely were protons and ionized nuclei.

These geomagnetic effects break the isotropy of the primary cosmic ray fluxes that (for low rigidity particles) depend on the observation point and the direction. This fact is relevant in the calculation of the atmospheric neutrino flux, because the ν's observable at one point are generated over the entire surface of the Earth's.

Following these results, cosmic rays were extensively studied using new experimental tools, mainly cloud chambers (with magnetic field) and coincidence methods that improved the technique pioneered by Bothe and Kolhörster. In 1933 Carl Anderson (who three years later will share with Hess the Nobel prize in physics), using a cloud chamber immersed in a magnetic field, established the existence of the positron [13]. The new particle was immediately identified with the antiparticle of the e^- predicted by the Dirac theory.

It was also understood that most of the particles that formed the (directly observable) secondary cosmic rays where in approximately equal number electrons and positrons. The mechanism for the production of e^- and e^+ was determined when Hans Bethe and Walter Heitler [14] first calculated the cross section for the process of pair production by high energy photons in the electric field of a nucleus ($\gamma\, Z \to Z\, e^+\, e^-$) and understood that it was the main mechanism for gamma ray absorption. Soon later, Heitler together with the Indian physicist Homi Bhabha [15], and simultaneously Carlson and Oppenheimer [16] clarified the development of electromagnetic showers putting together pair production and bremsstrahlung (that is the process $e^\mp\, Z \to e^\mp\, \gamma\, Z$).

The next step in understanding cosmic rays was the discovery of the muon. Indirect evidence for the existence of the muon accumulated as it become increasingly evident that the (directly observable) secondary radiation was significantly more penetrating than the predictions constructed on the basis of the theory for electromagnetic showers. Several authors discussed the possibility that above some some threshold electrons and positrons where behaving in a theoretically unexpected way. In 1934, Hans Bethe quotes [17]: "The experiments of Anderson and Neddermeyer on the passage of cosmic ray electrons through lead are extremely valuable for theoretical physics. They show that a large fraction of the energy loss by electrons in the energy range round 10^8 V is due to the emission of gamma radiation rather than to collisions, but still the radiative energy loss seems far smaller than that predicted by theory. Thus the quantum theory apparently goes wrong for energies of about 10^8 V, and it would be of special value for any future quantum electrodynamics to know exactly at which energy the present theory begins to fail, in other words to have much more experimental data on the energy loss of fast electrons (energy 10^7 to 5×10^8 V) passing through matter." And Oppenheimer summarized the situation writing[18]: "It is possible to do justice to the great penetration of cosmic rays only by admitting that the formulae are wrong, or by postulating some other and less absorbable component of the rays to account for their penetration."

Evidence for the existence of a new particle was soon obtained. In 1937 Anderson and Neddermeyer[19] demonstrated that particles of the same magnetic rigidity existed in two distinct types. One group of particles ($e^{\pm}$) were easily absorbed, in agreement with the theory for electrons, while a second group was losing only a small fraction of their energy traversing lead. From the rate of energy loss (that had been worked out by Bethe[20]) Anderson and Neddermeyer concluded that these particles had a mass much larger that the electron, but significantly smaller than the proton.

Soon later Street and Stevenson[21] working at Harvard university used a cloud chamber immersed in a magnetic field and triggered with Geiger Müller counters to increase the number of pictures with a penetrating particle stopping in the chamber obtained more precise measurements of the ionization density along the tracks to infer the mass of the new particle (of order 200 m_e).

The new particle (the μ "meson") was erroneously identified as the particle predicted by Yukawa in 1935[22] as the carrier of the strong interaction. The mass of the predicted particle was associated to the range of the nuclear forces, and therefore of order 100 m_e. Yukawa also predicted that the new particle should be unstable, decaying into an electron and a neutrino, with a lifetime of order 10^{-6} sec. This estimate stimulated experimental studies to observe the decay of the muon.

In the following years several teams of physicists from different european countries (England, France, Germany and Italy) measured the muon flux at various altitudes, and using different absorbers obtained puzzling results. It was understood that this could be a method to measure the muon lifetime (if the new particle was indeed unstable). For example, the same amount of mass contained in a layer of water or air corresponds to length that differ by a factor of approximately one thousand. For a muon lifetime of order microseconds, the probability of decay is negligible in water, but significant in air. This method (that was also a beautiful application of relativistic effects) was studied by several groups. For example Bruno Rossi[23] who had moved to the Unites States after the promulgation of the racial laws in Italy, in 1940 performed measurements in Chicago and in Colorado at different altitudes counting μ particles both with and without an absorbing layer of graphite and estimated the lifetime of muons at approximately two microseconds.

The decay of the "mesotron" was finally directly detected by Williams and Roberts[24] who succeeded in obtainig the first photographs of the decay of a μ particle that had stopped in the gas of a cloud chamber. The decay was generating one electron, that (to conserve energy and momentum) had to be accompanied by one (or perhaps more than one) invisible particle(s). Atmospheric neutrinos were now known to exist.

The interpretation of the μ as the "Yukawa particle" (that is the mediator of the nuclear interactions) was falsified by experiments performed in Italy in the years 1945–1947 by Conversi, Pancini and Piccioni[25,26]. The japanese physicists Tomonaga and Araki[27] had pointed out that positive and negative muons should behave in characteristically different ways after coming to rest in matter, because the negative particles can be captured by the nuclei generating nuclear disintegrations, while all positive particles decay.

Conversi, Pancini and Piccioni measured the probability of nuclear capture for negative muons at rest in iron and graphite and inferred a characteristic time for nuclear capture many orders of magnitudes longer than the prediction of Tomonaga and Araki (based on the strong interaction postulated by Yukawa). The "muon" was interacting weakly[28].

The strongly interacting "Yukawa particle" was discovered at approximately the same time when the leptonic nature of the μ "meson" was established. The discovery of the pion was obtained using the technique of photographic emulsions to detect charged particles. This technique was pioneered by two women physicists from Vienna: Marietta Blau and Hertha Wambacher [b]. In 1937 they announced the discovery [30] (made studying emulsions exposed at an altitude of 2300 m in the austrian alps) of "nuclear disintegration stars", the first evidence of cosmic ray hadronic interactions. The "stars" were formed by the (slow and strongly ionizing) fragments of a target nucleus struck by a CR particle, while the sensitivity of the emulsion was insufficient for the detection of ultrarelativistic particles at ionization minimum.

The results of Blau and Wambacher intrigued Heitler and Powell in Bristol, who confirmed the results about the nuclear stars exposing a batch of Ilford emulsions at the Jungfraujoch in Switzerland (3500 m). Work on emulsion was interrupted during the war, but continued later. In 1945 Powell was joined by Giuseppe Occhialini, and one year later by his brasilian student Cesar Lattes. They realized that it was necessary to improve the sensitivity of the emulsions increasing the concentration of silver bromide. New, more sensitive emulsions (prepared in collaboration with Ilford) were exposed at the Pic du Midi in the French Pyrenees and showed a remarkable improvement in sensitivity. According to Powell [31]: " [...] a whole new world had been revealed. [...] It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished and all kinds of exotic fruits had ripened in great profusion." The study of the emulsions (also used by Donald Perkins in London) revealed the first events of nuclear capture with a stopping particle generating a nuclear disintegration star. The mass of the captured particle could be estimated from the study of multiple scattering as a function of the residual range indicating a mass somewhat larger than m_μ. Soon later the first two events where a meson was stopping in the emulsion giving rise to a second particle [32] were found.

In order to obtain a larger data sample, a batch of the emulsions were exposed at very high altitude at mount Chacaltaya in the Bolivean Andes (5300 m). Ten more two–mesons decay were found [33] where the secondary particle came to rest in the emulsion. The range of the secondary particle was constant (approximately 600 μm) indicating that the parent particle (that they called π) was decaying in a two–body final state. The invisible neutral particle that accompanied the muon in the final state had a very small mass (consistent with zero). A new component had been added to the atmospheric neutrino flux.

The fact of the ν's generated in $\pi^\pm$ are not identical to those created in β decay could only be established fifteen years later in 1962, in the celebrated (and Nobel prize winning) accelerator experiment of Lederman, Schwartz and Steinberger (see below Sec.3.5).

It was soon also verified that the π meson was behaving as the particle predicted by Yukawa as one half of the stopping π's (those with negative electric charge) was generating nuclear disintegrations while the other half was decaying, as predicted for a strongly interacting particle.

The main properties of muon decay were also established at the end of the 1940s. Experimental studies of the energy distribution of the electrons emitted in μ decay performed with absorbers [34] and with a cloud chamber in a magnetic field [35] demonstrated that the spectrum was continuous, with a maximum energy equal within errors to one half of the muon, giving strong evidence that the final state contained two neutrinos (and therefore that the μ had spin 1/2). At the same time also Hinks and Pontecorvo [36] in Canada obtained the result that the electron spectrum in muon decay is not monochromatic. Muon decay could then be seen as analogous to the β decay of neutrons, and the shape of the spectrum could be studied to obtain information about the structure of the interaction between four spin 1/2 particles [37].

Once the two main components of the secondary cosmic radiation [the soft electromagnetic one formed by ($e^\pm$, γ), and the hard one formed by muons (and accompanied by the invisible neutrinos)] had been discovered, it remained the problem to understand how they were generated from the primary radiation. The solution was to predict [38,39] the existence of a neutral partner

[b] Marietta Blau was forced out of Austria in 1938 because of racial persecution and her role as a pioneer in cosmic ray studies is too often forgotten. For a discussion of her role see chapter 3 in Galison's book [29]. Hertha Wambacher was Blau's student. Their stories soon diverged. Wambacher had joined the NSDAP (the nazist party) already in 1934 at a time when it was still illegal in Austria.

for the Yukawa particle (the π^0 meson) with a dominant decay mode into two photons ($\pi^0 \to \gamma\gamma$). The pions (in their three charge states) were created in the collisions of the primary CR particles with the air nuclei. The electromagnetic component of the cosmic rays was generated by the gamma rays produced in π^0 decay, while the decay of the charged states ($\pi^\pm$) was the source of muons (and neutrinos). The neutral pion was soon observed [40] produced in accelerator experiments in proton nuclei–collisions.

The open problem were now on one hand the properties of nuclear interactions, and on the other the spectrum (and composition) of the primary particles.

The study of the nuclear interactions with cosmic rays yielded the discovery of strange particles [kaons and lambdas, with kaon decay generating one more (subdominant) contribution to the neutrino fluxes] [41,42].

3 Predictions for atmospheric neutrino observables

By the end of the 1940s, the study of cosmic rays had established (indirectly but beyond any doubt) that they were the source of large flux of neutrinos, and the main channels of ν production had been identified. The detection of this flux appeared as very difficult, but this did not stop physicists to speculate about methods to detect it (see next section).

This discovery also indicated fascinating possibilities for neutrino astronomy. The idea that the neutrino (a neutral, stable particle that travels along straight lines) could be used as an "astrophysical messenger" was in fact expressed very soon after the proposal of its existence as a product of β–decay by Pauli. The existence of the atmospheric ν flux was however indicating concrete possibilities for the sources of astrophysical neutrinos. The sites where CR were produced should in fact also be sources of high energy neutrinos, generated by the same mechanism that create the atmospheric flux. The relativistic particles in the source can interact with some target producing secondaries that decay into neutrinos. This simple concept remains in fact the basis for high energy neutrino astronomy also today [c].

3.1 The muon flux

The first method to estimate the atmospheric neutrino flux was to "extrapolate" from the observations of the muon flux. The μ and ν fluxes are intimately related because they are both generated in the decay of the same parent particles [see Eq. (1)].

Muons are unstable, with a lifetime of 2.2 μs, that corresponds (including relativistic effect and for $\beta \simeq 1$) to a decay length $\ell_\mu \simeq 6.2\ E_{\rm GeV}$ km. Since the atmosphere has a thickness of order 20 km, this implies that muons above few GeV reach the ground before decay, while muons created with lower energy decay. It is relatively straightforward to extrapolate from the muon spectrum to the spectrum of $(\nu_\mu + \overline{\nu}_\mu)$ for energies $E \gtrsim 10$ GeV, because each $\mu^\pm$ is accompanied by a $\nu_\mu(\overline{\nu}_\mu)$ created in the $\pi^\pm$ same decay. The muon and neutrino flux are however not identical, because one has to take into account some simple kinematical effects.

The main factor that must be taken into account to relate the μ and ν fluxes is the fact in the decay of a charged pion the muon and the neutrino take fractions $(1 \pm (m_\mu/m_\pi)^2)/2$ of the parent energy [that is 0.79 and 0.21], and this results in a ratio μ/ν much larger than unity. For the energy spectrum of the parent pions that is steeply falling (reflecting the cosmic ray spectrum $\phi_p(E) \propto E^{-2.7}$) this corresponds to a ratio $\phi_\mu(E)/\phi_\nu(E) \approx 8.5$. Corrections can be introduced to take into account muon decay (that suppresses the muon flux and generates more neutrinos) and to take into account the contributions of kaons.

Several measurements of the muon flux underground were performed at the end of 1940s and at the beginning of the 1950s, from shallow depths up to a maximum of 3000 m.w.e. (meter water equivalent). A summary of the results available in 1952 can be found in the review of

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[c] For the history of the development of neutrino astronomy see [43,44].

Barrett et al. [45] (and is also shown in Fig. 1). For an underground measurement, the column density X (along a certain direction) corresponds to a minimum muon energy $E_{\min}(X)$, and therefore the depth–intensity relation can be transformed into an energy spectrum.

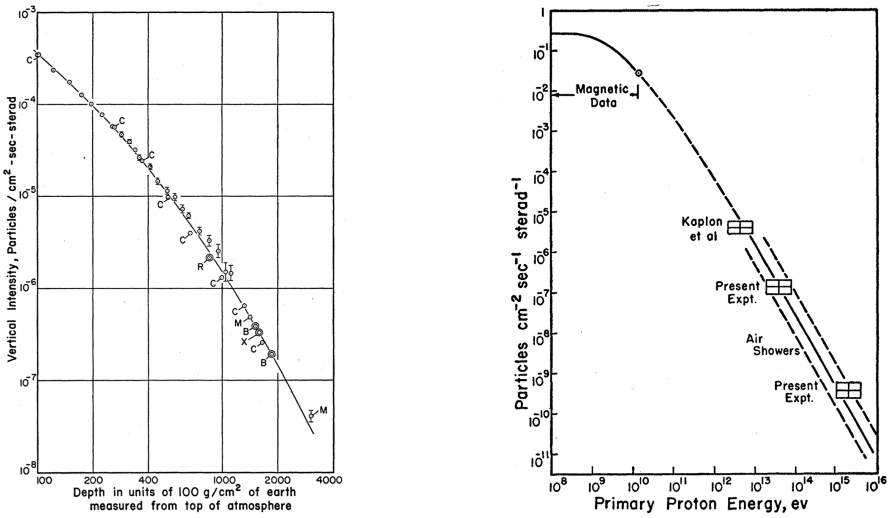

Figure 1 – The left panel shows measurements of the underground muon flux available in 1952. The right panel shows the primary flux inferred from the muon measurements, and estimates of the primary cosmic ray flux from measuremts at the surface (with Extensive Air Showers and emulsions chambers at high altitude). Both figures are taken from reference [45].

The observations of the muon flux showed that the high energy muon (and therefore also neutrino) flux was falling approximately as a power law $\propto E^{-2.8}$ (that is in good agreement with modern measurements [46,47,48]).

The most remarkable result of the atmospheric muon measurements was the fact that the spectrum was extending to very high energy (of order 10 TeV), and the data was used to infer the primary cosmic ray spectrum (with simple assumptions about the properties of nuclear interactions) up to an energy of 10^{15} eV (see Fig. 1).

The data were also giving information about the zenith angle distribution of the muon flux. At high energy (when μ decay is negligible) the flux was observed to grow with zenith angle. This effect was consistent with the hypothesis that the muons were generated by charged pion decay, taking into account for their finite lifetime (measured in accelerator experiments and corresponding to a decay length $\ell_\pi \simeq 55.9\ E_{\rm GeV}$ m) and the competition between interaction and decay. At high energy the primary particle, the secondary parent pion and the muon are all collinear. For inclined direction, the π creation point (that is at the same column density for all zenith angles) is at higher altitude, and the particle travels in a lower density air medium, so that the probability of decay (before interaction) is larger, and the μ (and ν) fluxes are enhanced.

3.2 First ideas for the detection of atmospheric neutrinos

The idea to detect atmospheric (and possibly also astrophysical) neutrinos, in spite of its obviously extraordinary difficulty, started to be discussed already in the 1950s. Kenneth Greisen [50,51] published in 1960 one of the first calculations of the atmospheric neutrino flux, and also discussed explicitely a detector concept: a large volume of water (a sphere with a diameter of 15 m) sourrounded by Cherenkov counters, that could detect and separate electron and muon neutrinos. This is remarkably similar to what was constructed decades later.

Studies of atmospheric and astrophysical neutrinos were also performed in the Soviet Union[d]). Estimates of the neutrino flux were calculated by Zatsepin and Kuzmin [53], and Markov and

[d] The personal recollection of Igor Zheleznykh about these very early studies can be found in reference [52].

Zheleznykh [54] who also proposed to install detectors [54] deep in a lake or in the sea, using Cherenkov radiation to detect charged particles, and argued that "a reasonable counting rate could be obtained with available equipment". They also discussed that the most easily detectable signal from atmospheric neutrinos should be associated to the muons generated by the charged current interactions of ν_μ and $\overline{\nu}_\mu$ outside the detector, and that the main uncertainty for the prediction of the rate was the energy dependence of the neutrino cross section [see below].

Similar calculations of the atmospheric neutrino flux where also performed in India by Ramanath Cowsik and collaborators [55].

3.3 The geometry of atmospheric neutrinos

The atmospheric ν flux observable at one point is formed by particles created over the entire surface of the Earth, and the pathlength L traveled by a neutrino observed (at sea level) with zenith angle [e] θ_z is:

$$L = -R_\oplus \ \cos\theta_z + \sqrt{R_\oplus^2 \cos^2\theta_z + 2\, H\, R_\oplus + H^2} \tag{2}$$

where $R_\oplus$ is the radius of the Earth, and H the altitude of the ν creation point. The altitude (above sea level) of neutrino creation extends to a maximum of approximately 30 km (only 1.3% of the air mass is at higher altitude) with an average (that has a weak energy and direction dependence) of order $\langle H \rangle \simeq 15$–20 km. The pathlength L is therefore very well correlated with the ν direction, and varies in a very broad energy range, between a maximum of an Earth diameter $L_{\rm max} \simeq 2\,R_\oplus \simeq 12,700$ km (for vertical up–going ν's) to a minimum $L_{\rm min}$ of order few km (for vertical down–going particles). The ν pathlength changes very rapidly with angle for quasi–horizontal particles ($\theta_z \simeq 90^\circ$) when L is around the value $L \simeq \sqrt{2 \langle H \rangle\, R_\oplus} \simeq 500$ km.

A very important property of atmospheric ν's is that a neutrino observed at sea level with an upgoing trajectory of zenith angle $\theta_z^{\rm obs} > \pi/2$ has penetrated the volume of the Earth in the opposite hemisphere on a down–going trajectory with zenith angle: $\theta_z^{\rm in} = \pi - \theta_z^{\rm obs}$. Assuming spherical symmetry and negligible absorption (and no unusual propagation properties, such as oscillations, for the neutrinos) it follows (see the left panel in fig. 2) that the atmospheric ν fluxes (that by hypothesis are independent from the observation point), are also up–down symmetric, that is they have the the property:

$$\phi_{\nu_\alpha}(E, \cos\theta_z) = \phi_{\nu_\alpha}(E, -\cos\theta_z)\ . \tag{3}$$

It is evident that this an ideal situation to study the existence of neutrino oscillations that depend on the ν pathlength and break the up–down symmetry of Eq. (3).

In fact, at low energy the generation of the neutrino fluxes is not spherically symmetric because of the geomagnetic (latitude and east–west) effects first discovered by Compton, Alvarez and others (see sec. 2). The geomagnetic field bends the trajectories of the electrically charged primary particles so that only particles of sufficiently high rigidity can reach the surface of the Earth. The latitude effect implies that the down–going neutrino flux in observation points near the magnetic equator is smaller that the flux observed at points closer to the magnetic poles, and also introduces corrections to the upgoing neutrino flux that depends on the detector position and the ν direction. The geomagnetic effects can therefore mimic or mask those generated by neutrino oscillations.

To take into account for these geomagnetic effects precise predictions for the atmospheric neutrino flux must be constructed specifically for the geographical position of each detector, and use a description of the geomagnetic field as accurate as possible. In a reasonable good first approximation the geomagnetic field can be described as a dipole. In this case, neglecting the

[e] The zenith angle is defined as the angle between the particle 3–momentum and the versor $-\hat{z}$ toward the center of the Earth, so that a down–going (up–going) particle has $\cos\theta_z = +1$ (-1).

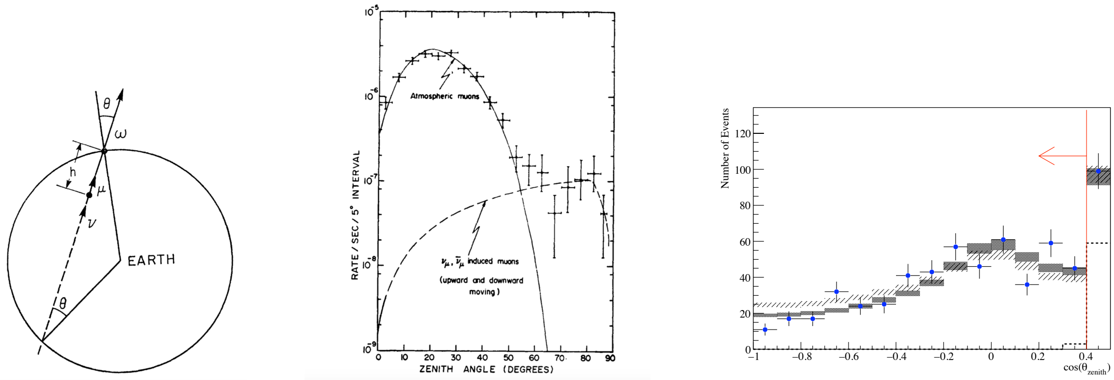

Figure 2 – The left panel shows a scheme of the geometry of atmospheric neutrino detection (for ν induced muons) [taken from [49]]. The central panel shows the zenith angle distribution of the muons seen at the KGF detector (without resolving the up–down ambiguity) with the two components of atmospheric and ν–induced muons [taken from [92]]. The right panel shows the measurements of deep underground muons taken by SNO [48], where the μ direction is well determined.

so called "penumbra effect", one has an exact analytic solution for the minimum rigidity that can reach the surface of the Earth as a function of position (magnetic latitude) and direction. This solution was developed by the norwegian mathematician Carl Størmer and then used [56] to interpret the results on geomagnetic effects by Compton and others in the 1930s. The Størmer solution was used in the calculations of the atmospheric neutrino fluxes available in the 1980s. Later, the predictions calculated the geomagnetic effects more accurately using detailed models of the Earth's magnetic field (in the form of a multipole expansion), and computing with numerical integrations the trajectories of charged particles in the field model, to identify "allowed" and "forbidden" ones.

3.4 Calculations of the atmospheric neutrino flux

The method of extrapolating from the muon observations to estimate the neutrino flux has limited validity for low energy neutrinos (because low energy muons decay in air) and for ν_e and $\overline{\nu}_e$. It then becomes necessary (and more attractive) to perform a "direct calculation" of the neutrino fluxes, starting from measurements of the primary cosmic rays flux. From 1980 until today [f] several authors have published calculations of the atmospheric neutrino fluxes of increased detail and complexity [58,59,60,61,62,63,64,65,66,67,68,69,70,71,72].

Calculations of the atmospheric neutrino fluxes performed after 1988 were done with the knowledge that the observations of the IMB and Kamiokande appeared to be in conflict with the existing predictions, and great efforts were taken to search for possible errors, improve the accuracy of the prediction and verify its robustness.

A direct calculation of the atmospheric neutrino flux is based on the following elements:

(A) A description of the primary cosmic ray fluxes.

(B) A model for the hadronic interactions of relativistic protons and nuclei with air that describes the multiplicity, composition and energy spectra of the particles in the final states of the collisions.

(C) A model for the Weak decays of the unstable particles ($\mu^\pm$, $\pi^\pm$, $K^\pm$, ...) created in the CR showers that have neutrinos in the final state.

(D) A calculation scheme to put together the elements listed above, and obtain the neutrino flux as a function of flavor, energy and direction.

A calculation of the atmospheric neutrino flux will also necessarily give as output the flux of atmospheric muons (that can be measured). Therefore the comparison of the muon prediction

[f] A review of the current status of these calculations (that remain an important element for the interpretation of atmospheric neutrino observations) can be found in [57].

with the data is an important method to test, and in some cases also adjust, the prediction of the atmospheric neutrino flux.

At a fundamental level the important sources of uncertainty in the calculation of the atmospheric neutrino fluxes are the two elements (A) and (B) in the list above: the description of the primary cosmic rays spectra, and the modeling of the properties of hadronic interactions.

The primary cosmic ray fluxes can be studied experimentally at lower energy with detectors on balloons or satellites and and higher energy interpreting the data of air shower detectors. As new data became gradually available, the predictions did improve in accuracy.

The modeling of the hadronic collisions of the primary particles (and of secondary particles during shower propagation) had to be constructed phenomenologically using the data obtained in experiments performed at accelerators. In fact even today the theory of the strong interactions Quantum Chromo Dynamics (QCD) remains "the dark side of the Standard Model", and the properties of particle production in hadronic collisions cannot be calculated from first principles. Uncertainties in the description of nuclear interactions remain in fact the main source of uncertainty in the prediction of the atmospheric neutrino fluxes for the most recent calculations [see for example [73]].

Point (C), that is the description of the Weak decays, should not have been a source of uncertainty, because after the development of the Standard Model the relevant physics was very well understood. A subtle but significant error was however present in all calculations of the atmospheric neutrino fluxes performed before 1988.

The error, first noticed by Volkova [74], was the neglect of the polarization of the muons generated in the two–body decays of charged pions and kaons: $\pi^+(K^+) \to \mu^+ \nu_\mu$ and charge conjugate modes. Volkova understood that the inclusion of the muon polarization resulted is the suppression of the spectra of ν_μ and $\overline{\nu}_\mu$, and an enhancement of the spectra of ν_e and $\overline{\nu}_e$, going in the direction of explaining the "anomaly" in the flavor ratio observed by IMB and Kamiokande (see Sec. 6).

It is straightforward to see that muons created together with a neutrino in a two–body decay must be polarized. Discussing for simplicity the case of the decay into the state $\mu^+\nu_\mu$, one has that in the rest frame of the parent meson (where the final state particles have collinear and anti–parallel momenta) the μ^+ is created in a state of left helicity. This is a simple consequence of the conservation of angular momentum, because the parent particle has spin zero, and the accompanying ν_μ is left–handed. After transforming to the laboratory frame one finds that high energy μ^+ (emitted in the direction of the parent momentum, with E_μ close to E_π) are left–handed, while low energy particles (emitted in the opposite direction) are right–handed. The net effect (for a rapidly falling energy spectrum) is that on average μ^+ are partially polarized with the spin antiparallel to the momentum. This fact has significant consequences on the ν spectra generated in the following muon decay, because (for the channel $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$) the $\overline{\nu}_\mu$ (ν_e) is emitted preferentially in the same (opposite) direction of the muon spin. For left–helicity muons, more of the energy is going to the ν_e, and less to the to the $\overline{\nu}_\mu$. Because of CP symmetry, muon polarization in the chain decay of π^- and K^- has the identical effect of enhancing the $\overline{\nu}_e$ flux and suppressing the ν_μ flux.

Detailed calculations of the muon polarization effects where soon performed [75] showing that they were indeed significant but could account for only a small part of the flavor ratio anomaly.

The calculation of the atmospheric neutrino fluxes has been performed using with different methods to model and combine the different necessary elements (primary spectra, cross sections, decays properties, energy losses, ...). Some calculations have used numerical integrations of the shower equations that describe the evolution along each line of sight of the flux for all particle types. The most detailed calculations use Monte-Carlo methods, constructing simulated showers for a large number of primaries. The neutrino flux is then estimated from an ensemble of individual ν's (each associated to a primary shower) that can be binned to estimate smooth energy and angular distributions.

All calculations[g] of the neutrino flux performed before 1999 made the simplifying assumption that the neutrinos are collinear with the parent particle. In a Monte-Carlo calculation this can be obtained rotating the 3–momenta of particles in the final state of an interaction (or decay) to align them to the momentum of the projectile (parent) particle.

The use of this approximation allows to save a very large factor in the computation time for a Monte-Carlo prediction. As discussed above, to take into account geomagnetic effects a calculation of the atmospheric neutrino flux must be performed for each detector site. However the neutrinos observable at one point are generated in the entire volume of air of the Earth's atmosphere. A fully 3D Monte-Carlo calculation is therefore very inefficient, because only a small fraction of the neutrinos arrives close to the detector point.

The availability of more computer power made a fully 3D calculation possible. The results[69] showed that at low energy ($E \lesssim 1$ GeV) the "3D effects" are not entirely negligible and their importance grows when E decreases and the average angle between the neutrino and the primary particle becomes larger. The 3D effects generate a small change of the absolute normalization of the low energy neutrino fluxes and distort their angular distribution (enhancing the flux of horizontal neutrinos), but has a small effect on the μ/e flavor ratio.

In summary, calculations of the atmospheric neutrino fluxes of increasing detail and complexity where performed starting from the 1960s. The appearance of the "flavor anomaly" stimulated a careful critical study of existing calculations and the development of new ones. These efforts essentially confirmed the early results (with a small but non–negligible correction associated to the inclusion of the muon polarization effects). Better input on the primary cosmic ray spectra, and the possibility of a complete 3D calculations allowed to improve the accuracy of the predictions.

3.5 Neutrino cross section

The prediction of observables related to atmospheric neutrinos requires a knowledge of the neutrino cross sections in a broad energy range. In fact an important motivation for the detection and study of atmospheric neutrinos has been the measurement of the ν cross section, and the study of the properties of the Weak interaction at high energy.

The situation changed when it became possible to construct artificial neutrino beams at accelerators. The idea of creating such a ν beam was developed around 1960 by Pontecorvo[76] and Schwartz[77], and was then implemented[78,79] when the group led by Leon Lederman, Melvin Schwartz and Jack Steinberger managed to form a neutrino beam using the then brand-new Alternating Gradient Synchrotron (AGS) at Brookhaven. The beam of protons of the AGS was sent to a steel target to produce charged pions that decayed into neutrinos, that could then interact in a neon filled spark chamber. The experiment demonstrated that the neutrinos created in pion decay could only produce muons, and therefore that two different types (or flavors) of neutrinos existed (the ν_e and the ν_μ).

Neutrino beams were also obtained at CERN at the end of the 1960s and used to perform studies of the quasi–elastic[80] ($\nu_\mu + n \to \mu^- + p$ and $\overline{\nu}_\mu + p \to \mu^+ + n$) and single pion production[81] processes. A reasonably good understanding of quasi–elastic scattering (with also measurements of the relevant form factors) was soon obtained as summarized in the review of Llewellyn Smith[82].

The description of the neutrino cross sections at higher energy required an understanding of the structure of the nucleon. The first fundamental step was obtained in 1969 when the group lead by Jerome Friedman, Henry Kendall and Richard Taylor performed its celebrated e^-p scattering experiment[83,84] that revealed the parton structure of the proton. The implications for the neutrino cross section were quickly developed (for example by Bjorken and Paschos[85]). Measurements of the deep inelastic ν–nucleon cross sections were soon obtained, demonstrating that the total inelastic cross sections for ν_μ and $\overline{\nu}_\mu$ were both growing linearly with E_ν up to the

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[g] The only exception was the calculation of Lee and Koh[64]. The 3D effects were however not included correctly in this calculation.

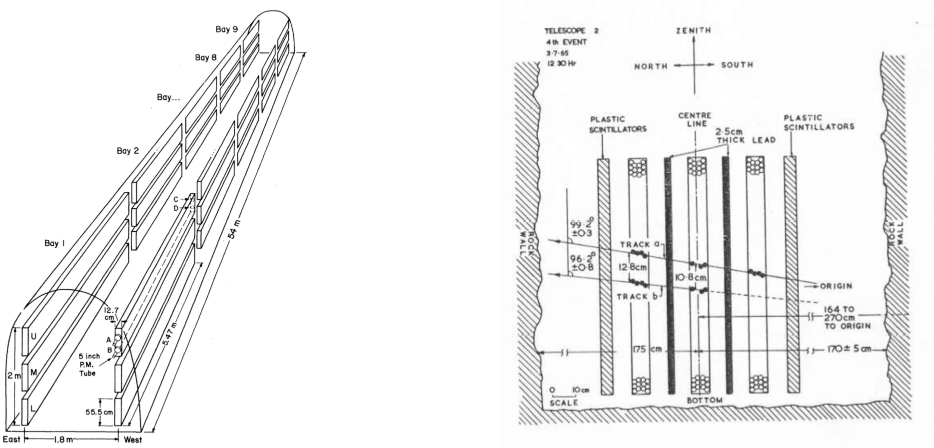

Figure 3 – The left panel is a scheme of the CWI detector [taken from [98]]. The right panel shows one intriguing event detected by the KGF detector with two up–going tracks that originate from the same point (in the rock (or in the air near the rock) to the right of the figure) [taken from [92]].

maximum energy available at the time (of order 70 GeV). The existence of neutral currents [86] (a crucial prediction of the SU(2)⊗U(1) newly developed (future) standard model) was later demonstrated by measurements performed at CERN by Gargamelle [87], and then confirmed and in the US at the National Accelerator Laboratory [88].

The neutrino beams at CERN and at Fermilab also obtained improved measurements of the ν and $\overline{\nu}$ cross section in an energy range that extended at higher energy [89,90,91].

With good theoretical control of the Weak interactions the main uncertainty for the extrapolation of the neutrino cross section at higher energy was the mass of the W and Z bosons that were obtained at CERN in 1983.

4 First observation of atmospheric neutrinos

The first direct observations of atmospheric neutrinos were obtained essentially at the same time by two experiments using very similar methods, performed in two very deep mines in India and South Africa.

The method used to observe the neutrino flux was the observations of the muons generated in the charged current interactions of ν_μ and $\overline{\nu}_\mu$ in the rock around the detector. The long range of muons allows to use a large volume of rock as target for the neutrino interactions, increasing significantly the event rate with respect to events where the neutrino interact inside the detection volume.

The detection concept is illustrated in the left panel of Fig. 2 that is taken from a paper of 1963 [49] (where the up–down symmetry of the neutrino flux is already discussed). The detectors were not able to separate down–going and up–going muon direction, and could therefore only measure the sum $\phi_\mu(E,\theta_z)+\phi_\mu(E,\pi-\theta_z)$. The observation of the neutrino induced component was however possible selecting horizontal tracks in very deep detectors (see central panel in Fig. 2).

The first requirement for the detection of atmospheric ν's is the need to suppress the background generated by the flux of secondary cosmic rays. This can be achieved placing the detector deep underground, where the main source of background is due to atmospheric muons. At depth larger than approximately 1 km of rock, only muons with $E \gtrsim 1$ TeV can arrive. At these energies radiative processes such as bremsstrahlung (that for muons are suppressed by factor $(m_e/m_\mu)^2$ with respect to electrons) become dominant for energy loss, and absorption is more rapid. A muon flux that has a power law energy spectrum at the surface, results in a depth–intensity curve that falls exponentially with X.

The deepest site available for the study of the muon flux in the 1960s was the Kolar Gold Field mine in India. Experiments performed there (for a review of the programs in India see [92]) reached a depth of more that 3 km (8400 m.w.e.) observing an exponential suppression of the flux. The Indian physicists [93] argued that the reduced background could allow the observation of “naturally occurring neutrinos” and suggested a simple design for an experiments capable to detect “cosmic ray produced and extra terrestrial neutrinos”. The simple idea was to “take coincidences between large area detectors parallel to each other and in the vertical plane”. The rate of these coincidences would measure the (approximately horizontal) flux of ν–induced muons that was predicted to be much larger than the flux of muons generated by pion decay in the atmosphere. The two component of the muon flux could be disentangled because of their very different angular distributions (with the pion decay component strongly peaked on the vertical, and the ν induced component much closer to isotropic).

The group of Fred Reines [h] learned about the studies performed at the Kolar Gold Field site and realized that there was a concrete possibility to carry out a measurement of the atmospheric neutrino flux. Reines visited India, but somehow an agreement with the Indian physicist could not be reached, and two experiments of similar design were therefore planned, one in India, in the Kolar Gold Field mine, and the other one in a deep mine in South Africa.

Constructing and operating these experiments in a particularly difficult environments was a remarkable effort, but both projects were successful, announcing the observations of ν–induced muons at approximately the same time in 1965 [94,95].

The detector at the Kolar Gold Field (KGF) mine was located at a depth of 7500 m.w.e. (approximately 2.3 km of depth) and consisted of two walls of plastic scintillators (viewed by PMT’s) with in the middle three trays of flash tubes separated by layers of lead with a thickness of 2.5 cm (see Fig. 3). A summary of the results of the Kolar Gold Field experiment is given in an article of 1971 of Krishnaswamy et al. [97].

The South Africa experiment [Case–Witwatersrand–Irvine (CWI)] constructed a detector formed by two walls of segmented liquid scintillator at a depth of 8800 m.w.e (see Fig. 3), a geometry that is optimized to detect horizontal muons. The detector was set into operation (one element at the time) starting in September 1964, and registered the first ν–induced muon the 23$^{\rm rd}$ of February 1965. The first publication of the Collaboration [95] reported the detection of 7 candidate (ν generated) events, selected in an angular region where the background of atmospheric muons was estimated to be $\ll 1$.

A larger statistics (35 candidate events) was presented [98] and interpreted [99] in 1971. The paper obtained an estimate of of the ν–induced muon flux, and discussed the result in terms of limits on the mass of the W boson. The experiment gave a lower limit on the mass ($M_W \gtrsim$ 2.9 GeV) because models [100] predicted the copious production of W bosons in ν interaction for small mass W. Interestingly Reines and the other authors [99] also gave a (1 σ) upper limit for the mass of the W boson ($M_W \lesssim 45$ GeV) because the observed rate was smaller than the central value predicted assuming no suppression of the cross section associated to the W propagator (that is in the limit $M_W \to \infty$).

Final results for the experiment were published in 1978 [101], reporting a flux of neutrino induced muons (averaged in direction) of $I = (2.23 \pm 0.20) \times 10^{-13}$ (cm^2 s sr)$^{-1}$, in “fair agreement with predictions”.

The results of the experiment where also used to set limits [99,101] on a possible neutrino flux from extraterrestrial sources, expressed as one half of the flux atmospheric neutrinos.

A third experiment was capable to observe the ν–induced muon flux using a magnetized iron detector in a salt mine in Utah [102]. This experiment was placed at a relatively shallow depth of 1500 m.w.e., so that the horizontal μ–flux was still dominated by the atmospheric muons. The experiment could however measure the directionality of the neutrino with water Cherenkov detectors. A data taking of a total (live) time of 830 (603) days yielded 10^6 atmospheric muons

[h] The story of the efforts of the Reines group are described in [96]

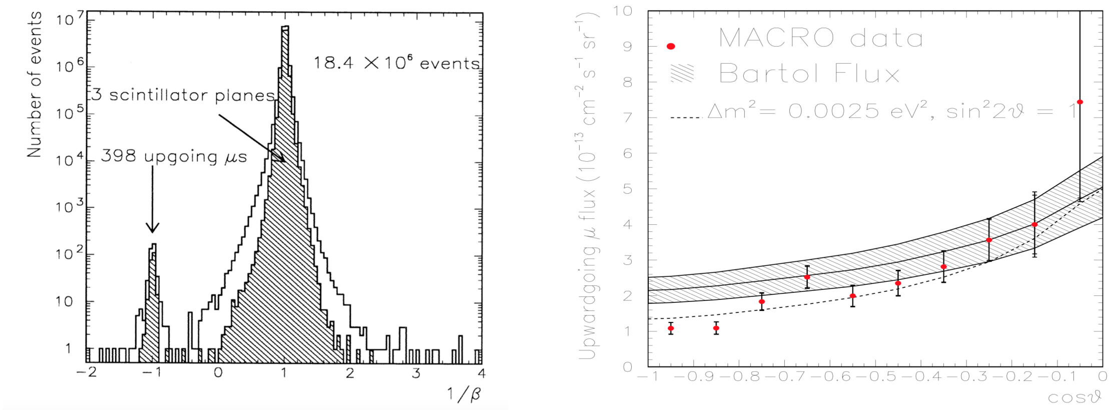

Figure 4 – Figures taken from the MACRO 1998 paper [106]. The left panel shows the distribution of $1/\beta$ of the muon tracks observed by the detectors. A negative value of $1/\beta$ corresponds to up–going trajectories. The shaded part of the distribution corresponds to the subset of events where three scintillators were hit. The right panel gives the zenith angle distributions of up–going muons with energy greater than 1 GeV for data and Monte Carlo for the combined MACRO data. The solid curve shows the expectation for no oscillations and the shaded region shows the uncertainty in the expectation. The dashed line shows the prediction for an oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2.

and 5 ν–induced muons. The results were interpreted with a lower limit on the mass of the W boson of 10 (3) GeV at the 1 (3) σ level.

In the Soviet Union there was no deep mine suitable to perform a muon experiment. However a gallery was excavated in the Baksan valley, in the Caucasus, with liquid scintillators to determine the muon directionality via a time of flight measurement. The results became however available only much later [103,104]. The same idea of using scintillator detectors to measure the muon direction and identify the ν–induced component was later used by the MACRO detector in the Gran Sasso underground laboratory [105,106,107,108]. In 1998, the detector presented results that showed a distortion of the zenith angle distribution of the up–going muons consistent with oscillations (see Fig. 4). For more discussion on the MACRO results see [109].

5 Proton Decay Experiments

The first experimental search for proton decay was performed [110] by Reines, Cowan and Goldhaber in 1954. Reines and his collaborators soon obtained much improved limits [111,112] using the scintillation detectors in the deep South Africa mine to look for the fragments of proton decays in the rock around the detector. They established limits [112] of 2×10^{28} to 8×10^{29} years, depending on the assumed decay mode. It was recognized that atmospheric neutrinos were the major source of background that limited the sensitivity of the experiment.

The study of proton decay received a very powerful stimulus with the development of Grand Unified Theories (GUT) in the 1970s [113,114,115]. The interest exploded especially after the publication of the work of Georgi and Glashow [115] in 1974 “Unity of All Elementary Particle Forces”, where they make the fascinating conjecture that the strong, electromagnetic, and weak forces arise from a single fundamental interaction based on the gauge group SU(5). This implies the existence of vector bosons that connects quarks and leptons, and can therefore mediate the decay of the proton. The observation of proton decay emerged as a crucial method to confirm the idea of unification.

The lifetime of the proton in GUT is connected to the mass M of the new, superheavy vector bosons ($\tau_p \propto M^4/m_p^5$). Georgi, Quinn and Weinberg [116] estimated a mass of order $M = 5 \times 10^{15}$ GeV, that implied a proton lifetime of about 6×10^{31} yrs, setting a clear goal for experimental searches.

This immediately stimulated new and more refined analyses of the data of existing detectors

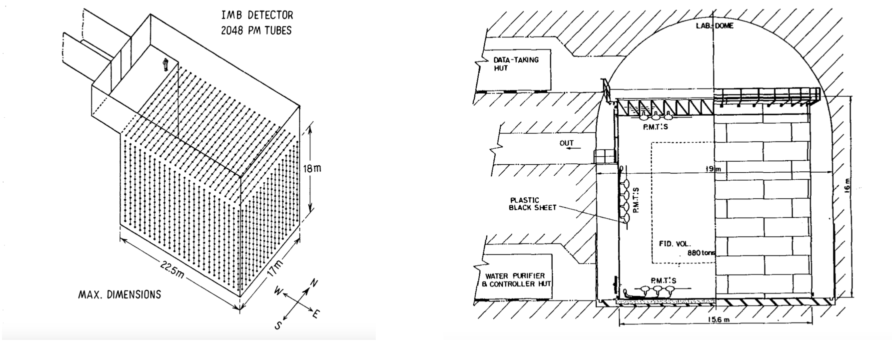

Figure 5 – The water Cherenkov detectors IMB (Irvine–Michigan–Brookhaven) and Kamiokande.

(such as those discussed above in India and South Africa). Reines and collaborators presented new limits on baryon conservation violation [117] (reaching an improved lower limit $\tau_p > 2 \times 10^{30}$ yr for favorable decay modes). Similarly new measurements in the KGF mine in India [118] resulted in limits of the same order.

New experiments capable of improving the limits on the proton lifetime were quickly proposed and constructed.

The proton decay experiments were constructed using two different designs. A first class of detectors (such as NUSEX [119], Fréjus [120] and Soudan [121]) was formed by fine grained iron calorimeters, where most of the mass is provided by sheets of steel or iron, and the charged particles generated in proton decay (or in neutrino interactions) are detected by sensitive elements (such as drift tubes) distributed in the detector volume.

A second type of experiment, represented by IMB in the US and Kamiokande in Japan (see fig. 5) was formed by a large mass of purified water, instrumented with photon detectors (Photon Multiplier Tubes or PMTs). Relativistic particles ($\beta \gtrsim 0.75$) traveling in water emit Cherenkov radiation. Water is transparent for the Cherenkov photons, that are observed by an ensemble of PMTs placed on the surface of the detector volume (looking inside). An outer layer of water (observed with a second set of outward looking PMTs) is also used as a veto system.

Some examples of atmospheric neutrino interactions in the detector fiducial volume are shown in fig. 6. Iron calorimeters (see the top part of fig. 6) have a good space resolution and can relatively easily identify events where a $\mu^{\mp}$ (a particle that propagates losing gradually energy by ionization) or an $e^{\mp}$ (a particle that generates an electromagnetic shower) is created.

Water Cherenkov detectors allow to instrument a larger mass, but the space resolution is less good, and the threshold ($\beta \gtrsim 0.75$) is higher. In these detectors, the Cherenkov photons generated by a particle that is created and stops inside the fiducial volume form a "ring" on the (see the bottom part of fig. 6). This is because, for charged particles with $\beta \simeq 1$, the Cherenkov photons are emitted at an angle of approximately 41° with respect to the particle direction. The geometry of the ring gives the particle direction, and the number of photons the energy of the particle. The separation of muon and electron events is possible from a study of the shape of the ring if the PMTs cover a sufficiently large fraction of the detector surface.

6 The "Anomaly"

The first "hint" of a discrepancy between data and predictions for the atmospheric neutrino flux appeared inside a paper of the IMB Collaboration [123], that had as main goal a description of the modeling of the atmospheric neutrino background for nucleon decay searches. The paper reported a discrepancy between the measurement of the fraction of contained events with an identified muon decay, with the Monte-Carlo prediction. The simulation predicted that $(34 \pm 1)\%$ of the events should have an identified muon decay, while the IMB data gave the result: $(26 \pm 3)\%$ (the total number of contained events was 401, and 104 events had an observed muon decay).

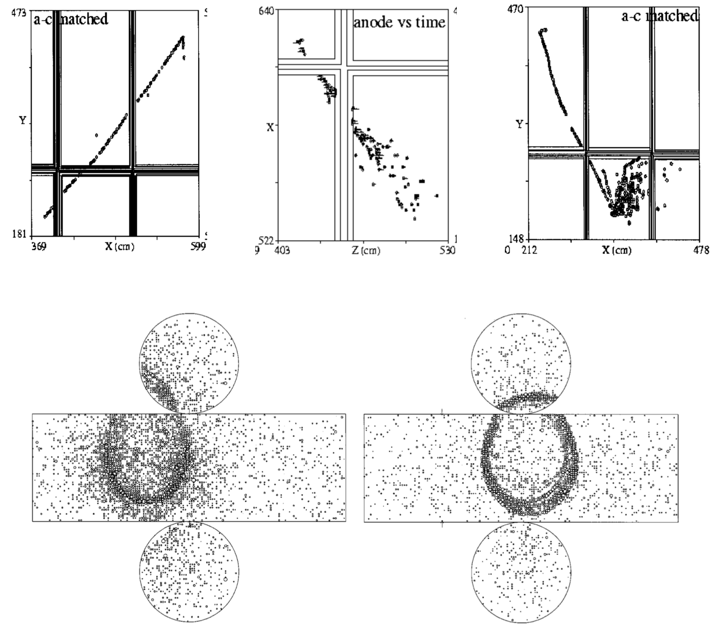

Figure 6 – The top part of the figure shows three events observed in the iron calorimeter Soudan–II (from [122]). The first one (left panel) is a quasi–elastic interaction $\nu_\mu + n \to \mu^- + p$ (note the visible recoil proton). The second one (center) is the quasi–elastic interaction of a ν_e or $\overline{\nu}_e$. The third one (right) shows the inelastic (or "multiprong") interaction of a ν_μ ($\overline{\nu}_\mu$. The bottom part of the figure shows two examples of "single ring" neutrino interaction events in the (second generation) water Cherenkov detector SuperKamiokande (from [150]). The even display shows the the outer surface of the cylindrical detector indicating the PMTs that have recorded a signal. The event on the left (right) is classified as e–like (μ–like) event.

It can be interesting to state in full length the relevant paragraph in the IMB paper [123] that discusses possible interpretations for the "anomaly"in the flavor ratio:

> "This discrepancy could be a statistical fluctuation or a systematic error due to: (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as–yet–unaccounted–for physics."

One can immediately see that this indeed covers all possible explanations for the "anomaly". The discrepancy between data and prediction was at the level of three standard deviations, and it was not entirely possible to exclude a statistical fluctuations. Excluding the fluctuation hypothesis, one has indeed three possibilities to explain the result (i) some mistake in constructing the prediction for the flavor ratio, (ii) a systematic error in the modeling of the detector, and finally (iii) some new physics effect. John LoSecco, who was a coauthor of the IMB paper [123] has recently published [124,125] an interesting recollection and critical analysis of the discussion internal to the IMB Collaboration before the publication of the anomaly.

It is (as it was already in 1986) straightforward to see that neutrino oscillations could account in a very simple and economic way for the effect (both in the channels $\nu_\mu \leftrightarrow \nu_\tau$ and and $\nu_\mu \leftrightarrow \nu_e$). This requires that a large fraction of the neutrinos must undergo a flavor transition, and therefore that the oscillation length of the neutrinos (with energy $E \sim 1$ GeV) had to be shorter than approximately 1000 km (some fraction of the Earth radius) and the mixing parameter ($\sin^2 2\theta$) of order unity.

The same flavor ratio "anomaly" was present also in the early Kamiokande data [126], but the result received a more intense attention when the Kamiokande [i] experiment published [127] a study of atmospheric neutrino interactions in the detector with an exposure of 2.87 kton yr,

[i] For a more in depth discussion of the Kamiokande results see [128].

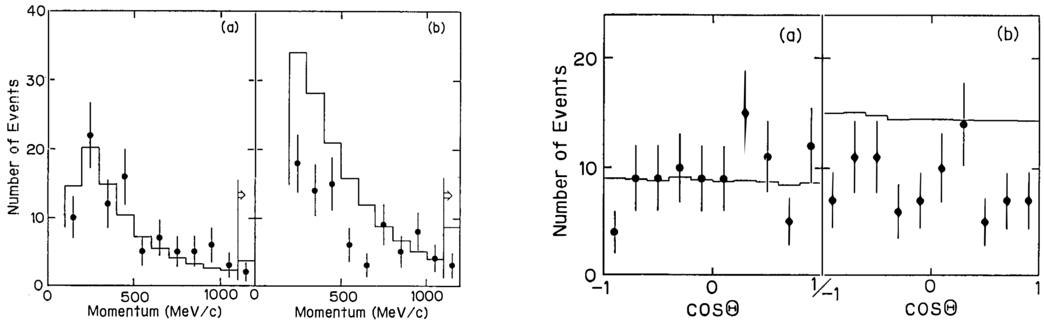

Figure 7 – Figures taken from the Kamiokande 1988 paper [127] reporting on an exposure of 2.87 kton yr and 277 fully–contained events. The left (right) panel shows the momentum (zenith angle) distributions of the 190 "single ring" events that are classified as electron–like and muon–like. In both panels (a) indicates electron-like events and (b) muon-like events. The histograms show the distributions expected for atmospheric neutrino interactions (no–oscillations). A large deficit ($\simeq 40\%$) of muon–like events is present.

with a total of 277 fully contained events. For "single ring" events, where only one particle is observed in the final state, (190 in total) the Kamiokande Collaboration was able to separate them into e–like and μ–like classes, and reported that the μ–like events were only $(59 \pm 7)\%$ (statistical error only) of the total, while the number of e–like events was in agreement with the prediction.

The deficit of muon–like events observed by Kamiokande is shown in Fig. 7. The abstract of the paper was stating clearly: "We are unable to explain the data as a result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes", explicitely pointing to an explanation in terms of some new, non–standard properties of neutrinos. The conclusion of the paper includes the terse statement: "Neutrino oscillations might be one of the possibilities which could account for the data.".

A few years later also the IMB detector [j] presented results [129] on the flavor content of contained neutrino events from an exposure of 7.7 kton yr (for a total of 935 contained events), and confirmed a relative suppression of the non–showering events. Of the 610 single Cherenkov ring events the fraction of non-showering events was 0.36 ± 0.02 (stat)± 0.02(syst), while the expected fraction was 0.51 ± 0.01(stat)± 0.05(syst). This deficit of non–showering events was consistent with the analysis of muon decay signals reported previously [123], and now repeated with larger statistics. In the same sample 33 ± 2(stat)% of events were accompanied by a muon decay, with a prediction of 43 ± 1(stat)%. The deficit of muon–like events observed by IMB is shown in the left panel of Fig. 8.

A complication in the interpretation of the data was the fact that the observations of the iron calorimeters NUSEX [119] and Fréjus [120] while having smaller statistics were reporting a ν_μ/ν_e ratio of the contained events consistent with predictions, in significant tension (if not open conflict) with the results of the Water Cherenkov detectors.

Another result that appeared in conflict with the simple interpretation of the effect in terms of neutrino oscillations was the paper published by the IMB detector on neutrino induced muons [130]. According to this paper the observations of ν–induced muons was consistent with predictions excluding therefore the region of parameter space that could explain the deficit on μ–like contained events. The conflict is shown in the right panel of Fig. 8.

The Kamiokande Collaboration in the following years released additional data [132,133] for a larger exposures, that strengthened the case for the flavor oscillations. Of particular interest was the presentation of "multi–GeV" events for which the direction of the interacting neutrino can be reconstructed with a smaller error. The data showed indications of zenith angle dependence of the muon deficit, that was supported an interpretation in terms of neutrino oscillations (see

[j] For a more in depth discussion of the IMB results see [131].

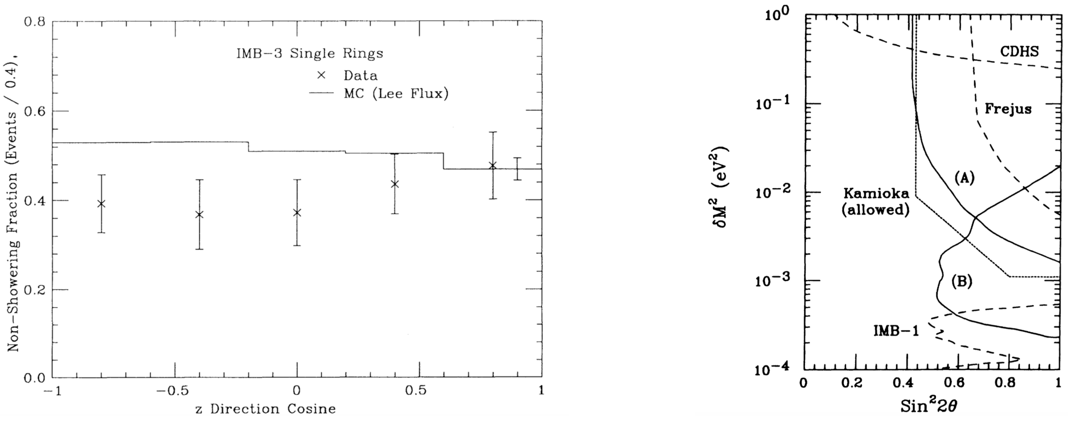

Figure 8 – The left panel shows a figure from the IMB Collaboration 1992 paper [129] (corresponding to a 3.4 kton yr exposure). The points show the fraction of fully contained non–showering (muon–like) events. The line is the Monte-Carlo prediction (with the statistical error also shown). The right panel is from the 1992 IMB paper [130], and shows 90% C.L. exclusion region limits for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations from the total rate (A) and from the stopping fraction of ν–induced up–going muons (B). The dotted curve shows the allowed region estimated by Kamiokande [132]. The other curves show exclusion limits by IMB–1 [134], Fréjus [120], and CERN–Dortmund–Heidelberg–Saclay (CDHS) [135].

fig. 9).

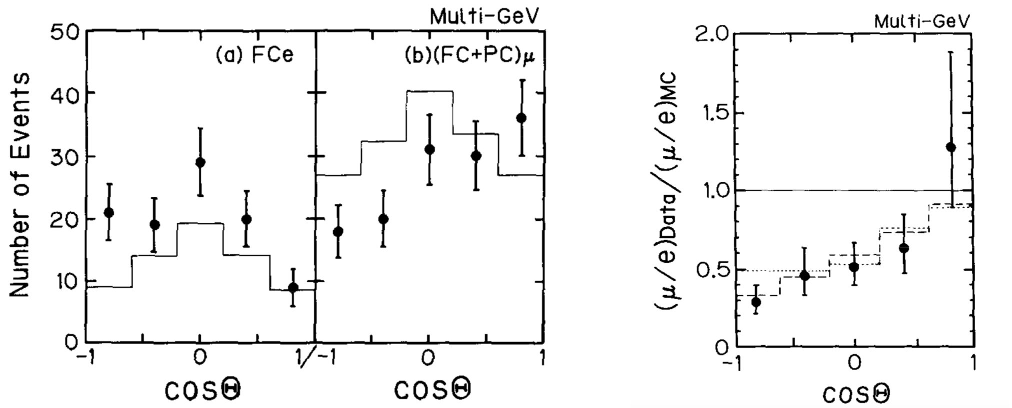

Figure 9 – Figures taken from the Kamiokande 1994 paper [133] on "multi–GeV" events. The data corresponds to an exposure of 8.3 kton yr. The multi–GeV events are selected as having a visible energy $E_{\rm vis} > 1.33$ GeV, fully contained or partially contained (one track exiting the detector). The left panel shows the zenith-angle distributions for (a) e–like events (fully contained) and (b) μ–like events (fully-contained and partially-contained combined). The histogram shows the (no–oscillations) Monte-Carlo (MC) prediction. The right panel shows the zenith-angle distribution of the ratio $(\mu/e)_{\rm data}/(\mu/e)_{\rm MC}$. The lines show expectations of the MC simulations for two choices of ν–oscillations parameters $\{\Delta m^2, \sin^2 2\theta\}$ that are the best fits to the data. The dashed line is for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations $\{1.8 \times 10^{-2}$ eV^2, 1.0$\}$. The dotted line is for $\nu_\mu \leftrightarrow \nu_e$ oscillations $\{1.6 \times 10^{-2}$ eV^2, 1.0$\}$.

6.1 Interpretations

The report of the anomaly in the flavor of the contained events generated a very lively debate.

It is probably true that many (if not most) physicists remained skeptical about the result, however it is clearly very difficult to demonstrate (or argue) for the existence of systematic effects in an experiment. Several people however noticed that the indications of the anomaly were present in the data of water Cherenkov detectors, while the iron calorimeters, that had in principle a better spatial resolution, and therefore better particle identification capabilities, were not reporting discrepancies between observations and predictions.

Papers written by Olga Ryazhskaya argued that the anomaly was generated by the presence of a background of events generated by neutron penetrating in the detector from muon interactions in the rock outside [136,137].

Several physicists have remarked that the skepticism encountered in accepting the explanation of the anomaly in terms of neutrino oscillations was the fact that it required very large mixing between neutrinos, in contrast with theoretical expectations (where the mixing between neutrinos had a similar structure to the one observed for quarks). The attitude of most theorists was essentially to "wait and see whether these claims are confirmed" before starting to construct models of the neutrinos masses and mixings that had large mixing between different flavors. Some (among many) examples of this attitude (before the release of the Super-Kamiokande data) can be found in reviews of Guido Altarelli [138] and Jonathan Ellis [139].

On the other hand several efforts were performed to interpret the results in terms of new physics. Standard flavor oscillations were a simple possibility. Given the uncertainties in the absolute normalization of the neutrino fluxes both (2–flavor mixing) channels ($\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_e$) were possible. On the other hand several other possibilities were introduced.

Also oscillations into sterile neutrinos were considered [140,141,142]. In this case the difference with respect to the $\nu_\mu \leftrightarrow \nu_\tau$ channel is the absence of τ production events (that are however kinematically forbidden below a threshold energy $E_{\rm th} \simeq 3.5$ GeV) and of neutral currents events, but also the presence of matter effects.

Other possibilities where neutrino decay [143,144], decoherence effects [145] and violations of the equivalence principle [146].

One proposal was proton decay in the channel $p \to e^+\nu\nu$ [147], with a lifetime $\tau_p/B \approx 4{\times}10^{31}$ yr (in this case clearly the effect was understood as an excess of ν_e limited to the energy range $E < m_p/2$).

7 Conclusions

The existence of atmospheric neutrinos was inferred during an extraordinary (one could say "heroic") decade (1937–1947) of studies of the cosmic ray radiation that saw the discovery of the muon and the charged pions, and the observation of their decay modes.

Speculations about possible methods of direct detection of atmospheric neutrinos started very early. In the decade of the 1960s the main motivation for this direct detection was the investigation of the properties of Weak Interactions at high energy (extrapolating from the measurements of atmospheric muons, the neutrino flux had to extend up and beyond energies of several TeV). The possible discovery of signatures for the existence of the intermediate W boson was in fact considered as a major goal for the planning and construction of atmospheric neutrino detectors. Two experiments located in deep mines in India and South Africa obtained the first direct observations of the flux of atmospheric ν_μ and $\overline{\nu}_\mu$ detecting the muons generated by charged current neutrino interactions in the rock around the detector.

The development of Grand Unified Theories, in the 1970s, with the prediction of proton decay with a lifetime observable by ambitious but possible projects stimulated the design of construction of very large mass detectors, that were perfectly suited to study the interactions of neutrinos with energy around 1 GeV. This energy range around the proton mass is also where in good approximation atmospheric neutrino interactions are most frequent (folding a rapidly falling spectrum with a cross section that grows with E).

The concept that the measurement of atmospheric neutrinos could explore flavor oscillations for an interesting range of parameters was by then well understood, but atmospheric neutrino interactions were mostly considered as a source of background for the search for proton decay.

It is in this context that the "anomaly" in the flavor ratio for contained events was observed by the two water Cherenkov detectors IMB and Kamiokande.

A generally accepted "solution" for the origin of the anomaly, and the recognition that is was the effect of flavor oscillations required more than a decade of studies and the construction of a second generation, larger mass water Cherenkov detector (Super-Kamiokande).

Peter Galison, in a paper about the discovery of neutral currents in neutrino interactions [148] (and more in general in his book "How Experiments End"), argues that it is often impossible to identify the "instant of discovery", and that one has rather a "process of discovery" as the available data (and all possible sources of systematic errors) are critically scrutinized, and the possible interpretations are analyzed. Given the large size of the experimental collaborations and the great complexity of the instruments used to perform the measurements, this "process" happens not only in the wider scientific community, but also inside the experimental collaborations, where different physicists make different judgements and have different level of skepticism [k]

A review of the controversies, discussions, hypothesis making about the flavor anomaly in atmospheric neutrinos (and how this effect was a "hint" for oscillations or other forms of new physics in neutrino propagation) during the time interval 1986–1998 can in fact be very interesting and instructive to study the "process of discovery" and see how Science is concretely made (the "Flesh and Blood" of research).

During the time interval 1986–1988 more data on atmospheric neutrinos were obtained (or made public), and more refined predictions were calculated. Some physicists became gradually convinced that new physics had been discovered, while others remained skeptical.

In this case it is however possible to identify quite clearly an "instant" when the "hint" became "evidence" (at least for physicists outside the collaboration), and this is the moment when the Super-Kamiokande experiment finally released its first 1.5 years of data taking (33 kton yrs of exposure) during the Neutrino–1998 conference in Toyama [128]. The strength of the Super-Kamiokande result was not simply the smaller statistical errors but also the broader range in energy that the larger exposure made possible. Neutrino Flavor oscillations have very characteristic dependences of the ν pathlength and energy, and this in principle allows a clear, unambiguous identification of the existence of this phenomenon, if the observations cover with sufficiently good resolution a sufficiently large part of the region in the plane $\{L, E_\nu\}$ where the flavor transition probabilities are non trivial.

The data of Super-Kamiokande [149,150], in particular the zenith angle dependences of the muons events, were strikingly supporting the neutrino oscillation hypothesis. Additional support to the flavor oscillation hypothesis was also coming from the study of (ν–induced) up–going muons that showed a zenith angle dependence distorted with respect to the no–oscillation prediction (a result that was also independently confirmed by the MACRO detector data [106]).

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