Muon lifetime measurement from muon nuclear capture process

F. I. G. Da Silva, **C. R. A. Augusto**, **C. E. Navia**, **M. B. Robba**

Instituto de Física, Universidade Federal Fluminense, 24210-346, Niterói RJ. Brazil

E-mail: navia@if.uff.br

(Received 26 February 2008, accepted 7 April 2008)

Abstract

We report the results from a search for cosmic muon decay through muon nuclear capture process measured at sea level by the Tupi muon telescope. The method denominated "frozen images" has been used and it requires a relatively small active volume, such as a plastic scintillator with its outlying system, a photomultiplier with its power supply. The data acquisition system is constituted on the basis of a 100 MHz oscilloscope with trigger and stop. The method of frozen images allows us to separate the two (ordinary and radiative) muon decay modes in the data set. The muon lifetime as well as the branching ratio for the radiative muon decay are obtained in this survey. They are in relative agreement with the results reported by the Data Particle Group.

Keywords: Cosmic Rays, Particle Physics, Particle detectors teaching.

Resumen

Reportamos los resultados de una búsqueda para el decaimiento de muones cósmicos mediante el proceso de captura nuclear de muones medidos al nivel del mar mediante el telescopio de muón Tupi. Se ha utilizado el método denominado "imágenes congeladas" que requiere de un pequeño volumen relativamente activo, tal como un *scintillator* plástico con su sistema periférico, un fotomultiplicador con su fuente de poder. El sistema de adquisición de datos está constituido mediante un osciloscopio de 100 MHz con disparador y con pausa. El método de imágenes congeladas nos permite separar los dos modos de decaimiento del muón (ordinario y radiativo) en el conjunto de datos. En esta revisión son obtenidos el tiempo de vida del muón así como también la razón de ramificación para el decaimiento radiativo del muón. Esto coincide relativamente con los resultados reportados por el Grupo de Datos de Partículas.

Palabras clave: Rayos Cósmicos, Física de Partículas, Enseñanza de detectores de partículas.

PACS: 13.30.Ce, 01.50.Pa, 13.85.Tp **ISSN 1870-9095**

I. INTRODUCTION

The fundamental constituent of the matter consists of two categories: hadrons and leptons. The hadrons are defined as the particles that interact through strong interaction and they are constituted by quarks.

Quarks are bounded up into hadrons, forming the baryons (semi-integer spin) such as protons and neutrons and the mesons (integer spin) such as the pions and kaons. The other fundamental constituent of matter is the leptons. Leptons include the electrons, the muons and their associated neutrinos, as the electrons, the muons can carry a positive or negative electric charge (μ^+ or μ^-). Muons are produced in the atmosphere by cosmic-ray induced air showers, and because they are quite penetrating, they can reach the ground, enter the laboratory through the walls or roof of the building, and be detected with a suitable apparatus.

Muons were first detected and investigated by Bruno Rossi in the 1930s and 1940s [1] and in 1947 by Neddermeyer and Anderson [2] in surveys on cosmic rays. The mass of the muons was estimated in ~ 200 times the mass of the electron. Initially the muon particle was associated with the Yukawa particle postulate in 1935, the Yukawa's mesotron (later denominated as π meson), a force carrier of the strong interaction. But, it was demonstrated in 1947 that the muon did not interact through the strong interaction. Consequently, the muons could not be the Yukawa π meson. The discovery of the Yukawa's particle, the π meson was made in 1947 by Lattes, Ochianilli, and Powel [3] in the cosmic rays using emulsion techniques. Around one year later Lattes at Chacaltaya-Bolivia (5200 m above sea level) obtained the first experimental evidence of the $\pi \to \mu$ decay [4].

The search for muon nuclear capture process ($\mu^- N \to e^- N$, where N is a nucleus capturing a muon) was initially made by Steinberg in 1948 [5] and by Lagarrigue and Peyrou in 1952 [6]. The study of the capture process was improved when muons became artificially produced at accelerators by Steinberg and Wolfe in 1955 [7].

Nowadays, our understanding of modern elementary particle physics is based on the Standard Model (SM), which is a gauge theory of the strong and electroweak interactions. The formulation of the SM was made in the 1960s and 1970s by many authors as Leite Lopes [8], Weinberg [9], Salam [10], and Glashow [11].

Recently, considerable interest has arisen in the study of muon decay as a signature of Lepton Flavor Violation (LFV) process based on supersymmetric (SUSY) extension of the SM model [12]. So far, the SM predictions are in agreement with several experimental tests. However, the Higgs boson, essential in the electroweak theory, has not yet been observed.

In particular supersymmetric grand unified theories (SUSY-GUT) [13] predict the conversion processes $\mu^+ \rightarrow e^+ \gamma$ and $\mu^- \rightarrow e^-$. So far, there are no experimental evidences for these conversion processes, and only their upper limits are known.

On the other hand, the knowledge of the muon flux at sea level is essential in neutrino experiments, since one of the natural sources of neutrinos is through muon decay. All these facts justify a study of the muon decay, besides providing material for the teaching of elementary particle physics which is only done in theoretical form in most of the cases.

In this paper, we report an experimental determination of the muon lifetime. The method, based on frozen images, has been used, and it allows us to separate the two (ordinary and radiative) of muon decay modes in the data set.

It was presented by one of the authors (F.I.G. da Silva) on the Science and Technology week established by the Brazilian government (October 2005) and it was the winner of the Vasconcelos Torres of Scientific Initiation award of the "Universidade Federal Fluminese".

The paper is organized as follows: In Section 2, the muon source at Earth is described; in Section 3 the experimental setup is presented. The muon decay time distribution on the basis of the frozen images method is presented in section 4. In section 5 results of the radiative muon decay are presented and finally Section 6 contains our conclusions.

II. MUON SOURCE AT EARTH

The upper layers of the Earth's atmosphere are bombarded by a flux of cosmic charged particles called as primary cosmic ray particles. The chemical composition of these primary cosmic particles depends on the energy region. In the low energy region (above 1 GeV to several TeV), the dominant particles are protons (~ 80%). The primary cosmic rays collide with the nuclei of air molecules and produce an air shower of particle that include nucleons, charged and neutral pions, kaons etc. These secondary particles then undergo electromagnetic and nuclear interactions to produce yet additional particles in a cascade process, as shown in Fig.1. Of particular interest is the fate of charged pions produced in the cascade. Some of these will interact via the strong interaction with air molecule nuclei but other will spontaneously decay via the weak interaction into a muon plus a neutrino or anti-neutrino following the scheme

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu} \ . \qquad (1)$$

The muon does not interact with matter via the strong interaction but only through the electromagnetic and weak

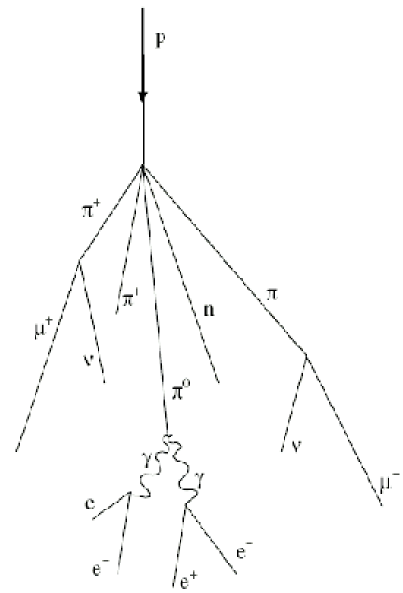

FIGURE 1. A typical nuclear and electromagnetic cascade induced by a high energy cosmic proton striking an air molecule nucleus.

Interactions. It travels a relatively long distance (muons are quite penetrating and they can reach the ground) while losing its energy and decays by the weak interaction into an electron plus a neutrino and an anti-neutrino

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_{\mu} \ , \qquad (2)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_{\mu} \ . \qquad (3)$$

The branching ratios for these modes (called as normal modes) are near 100%. Even so, there are some experimental evidences for other modes as the radiative muon decay observed specially in negative muons with energies above 10 MeV

$$\mu^- \rightarrow e^- + \overline{\mu}_e + \nu_{\mu} + \gamma \ , \qquad (4)$$

with a branching ratio around 1.4%. There are also other (SUSY-GUT) decay modes called as exotic. In this case, only the upper bound of the branching ratios has been observed, and they are less than 10^{-11} at 90% confidence level.

Not all of the particles produced in the cascade in the upper atmosphere survive down to sea level due to their interaction with the atmosphere nuclei and their down spontaneous decay. The muon flux at sea level is around 1 per minute per cm^2 with a mean energy of ~ 4 GeV.

III. EXPERIMENTAL SETUP

The Tupi telescope is a tracking telescope and detect muons at sea level with energies greater than the ~0.2-0.3 GeV required to penetrate the two flagstone or walls surrounding the telescope.

The Tupi muon telescope is sensitive to primary particles (including photons) with energies above the pion production energy. In the case of charged particles, the minimal primary energy must be compatible with the (Niteroi-Brazil) geomagnetic cut-off (= 9.8 GV or 9.8 GeV for proton). Due to its limited aperture (9.5 degrees of opening angle), the Tupi telescope is on the boundary between telescopes with a very small field of view, like the air Cherenkov telescopes, and the small air shower arrays, characterized by a large field of view.

The Tupi muon telescope has four plastic scintillator panels each 50 cm long, 50 cm wide and 3.0 cm thick. Two detectors are installed telescopically and in coincidence as is show in Fig.2. Each scintillator is viewed by a 7.0 cm Hamamatsu photomultiplier according to the scheme shown in Fig.3. Details of the experimental setup of the Tupi telescope including results can be found elsewhere [14-16].

FIGURE 2. General layout of the Tupi telescope, constituted by four scintillator detectors, of which two are installed in coincidence and forming a tracking telescope.

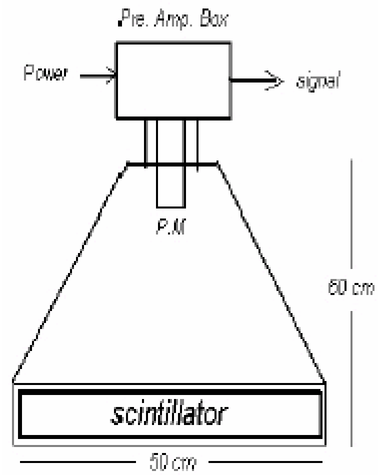

FIGURE 3. General layout of a detector unit, built on the basis of a square (50 cm x 50 cm x 3.5 cm) plastic scintillator, a 7.0 cm Hamamatsu RS21 photomultiplier and a linear pre-amplified unit (80 times). The system requires high (for the photomultiplier) and low (for the pre-amplified) stable power supplies.

In the present survey, we have used only the active volume (plastic scintillator) of a detector. Plastic scintillator is transparent organic material made by mixing together one or more flours with a solid plastic solvent in an aromatic ring structure. A charged particle passing through the scintillator will loss its kinetic energy by ionization and atomic excitation of the solvent molecules. Some of this deposited energy is then transferred to the flour molecules whose electrons are then promoted to excited states. Upon radiative de-excitation, light in the blue and near UV portion of the electromagnetic spectrum is emitted with a typical decay time of few nanoseconds.

IV.MUON DECAY TIME DISTRIBUTION

In the SM framework, the muon lifetime, τ_μ, is related to the Fermi coupling constant, G_F, and it is a measure of the strength of the weak force. The interaction is described by the vector-axial (V-A) interaction, assuming the general four-fermion interaction and whose Feymman diagram is shown in Fig.4.

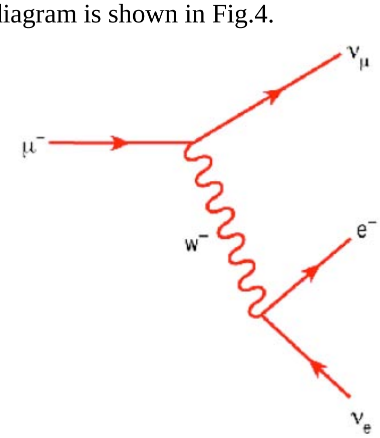

FIGURE 4. Feymman diagram for the muon decay process. The interaction is described by the V-A interaction, assuming the Fermi general four-fermion interaction.

In a first approximation, the relation between G_F and τ_μ can be expressed as [17]

$$\tau_\mu = \frac{192\pi^3\hbar^7}{G_F^2 m_\mu^5 c^4}. \tag{5}$$

The last expression does not include the radiative corrections. Even so, it is a very good approximation.

Just as it happens in the study of radioactive elements in nuclear physics, the change $dN_\mu(t)$ of a population of muons is proportional to the number of muons N_μ at time t and it can be expressed as $dN_\mu(t) = -N_\mu(t)\lambda t$, where λ is a constant called as "decay rate". The lifetime τ of muons is the reciprocal of λ, $\tau = 1/\lambda$. Integrating the last expression, the number of surviving muons is just

$$N(t) = N_0 \exp(-t/\tau). \tag{6}$$

On the other hand, the probability for nuclear capture of a stopped negative muon by one of the scintillator nuclei is proportional to Z^4, where Z is the atomic number of the nucleus. A stopped muon captured in an atomic orbital will make transitions down the K-shell on a time scale short compared to its time for spontaneous decay. Its Bohr radius is roughly 200 times smaller than that of an electron due to its much larger mass.

However, after a time τ_μ the muon captured decays, according to the process $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ as above explained. As in our experiment the neutrinos are not detected the muon capture process is related only as $\mu^- + N \to e^- + N$ and schematized in Fig.5.

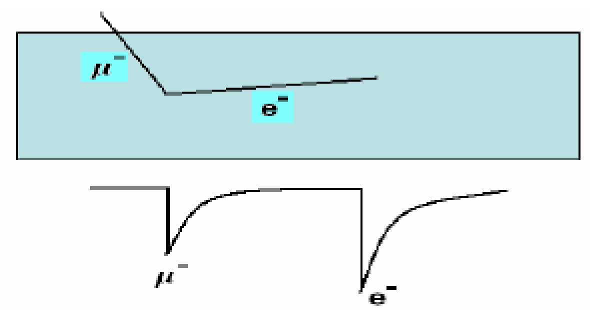

FIGURE 5. Typical signature of the nuclear (scintillator) capture of a negative muon followed by its decay emitting an electron (plus two neutrinos). The two serial (inverse) peaks correspond to the signal of the muon and electron respectively.

So, if we can stop a muon, we can measure essentially its rest lifetime in the material. Both the muon and electron can interact with scintillation material and the typical signature for muon nuclear capture process are two consecutive light pulses. The first pulse is due to muon interaction in the scintillator and the second pulse is due to electron interaction in the scintillator. The difference of time between these two inverse peaks is proportional to the muon lifetime.

Fig.6 shows two examples for this signature on the muon nuclear capture and decay in scintillator, observed on the screen of an oscilloscope like the Tektronix TDS 210 working at a rate of 100 MHz. Every time that appears an event with several picks (two or more) the image in the screen is frozen. This apparatus has a tool that allows to position two vertical cursors in different points and to obtain automatically the time difference between these two points (see Fig.6).

Strictly speaking, this method provides a measure of an effective time, τ_{eff}, and it is correlated to τ_μ as

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_\mu} + \frac{1}{\tau_c}, \tag{7}$$

where τ_c is the nuclear capture time estimated in several ns. According to reference [18], an analysis in muon capture leads to a correction of 3.4% for τ_μ .

The data provided here consist of 442 double peak events, and the time distribution obtained from there is shown in Fig.7. On a semi-log scale, the data fit is a straight line and whose equation is

$$\log N = \log N_0 - \frac{1}{\tau_{eff}} t, \tag{8}$$

Given a τ_{eff} =2.38 ± 0.05 μs and after the correction due to nuclear capture time we obtain τ_μ = 2.30 ± 0.05 μs. This value is around 4% higher than the muon lifetime reported by the Particle Data Group as 2.19703 ± 0.00004 μs [19].

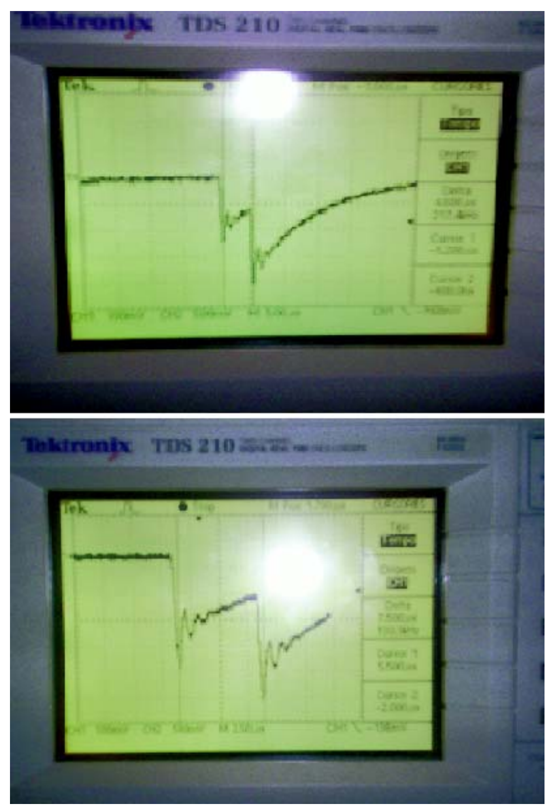

FIGURE 6. Two real examples of the muon capture and decay processes as described in the caption of Fig.5 and observed on the screen of an oscilloscope.

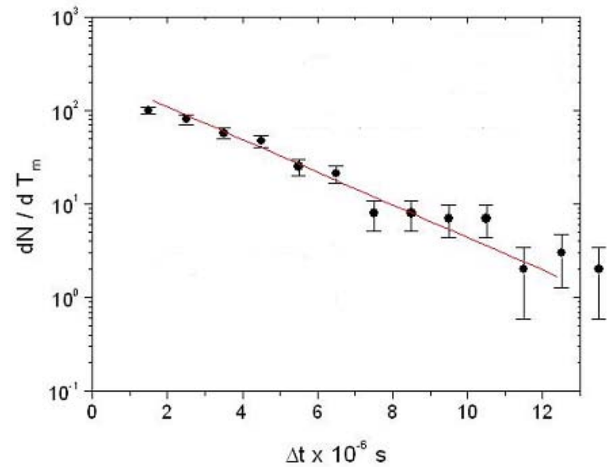

FIGURE 7. Muon decay time distribution. The straight line (in the semi-logarithmic scale) represents a fit obtained by the method of least squares on the experimental data. The inclination of this straight line is proportional to the mean muon lifetime.

V. RADIATIVE MUON DECAY

There are also experimental evidences for a radiative muon decay, as well as, within the framework of the V-A interaction, there are two radiative channels for muon decay

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \nu + \gamma, \tag{9}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \nu + e^{+} + e^{-}. \tag{10}$$

However, only the first process has a large branching ratio of 1.4%. We look for this process in our data whose signature is expected as three consecutive peaks.

The first is due to muon on the scintillator, the second is due to electron emission, and the third due to photon. In addition, the high energy photons first lose their energy by e^+e^- pair production, and these electrons e^+e^- give signal in the scintillator. Consequently, the signal produced by the photon comes after the signal of the emitted electron.

Four examples for radiative muon decay are summarized in Fig.8. The three serial (inverse) peaks correspond to the signal of the muon, electron and photon (gamma) respectively. In 447 events analyzed here, we have 5 events consistent with the radiative muon decay signature, giving a branching ratio of 1.12% in relative agreemnet with the branching ratio reported by the Data Particle Group as 1.4%.

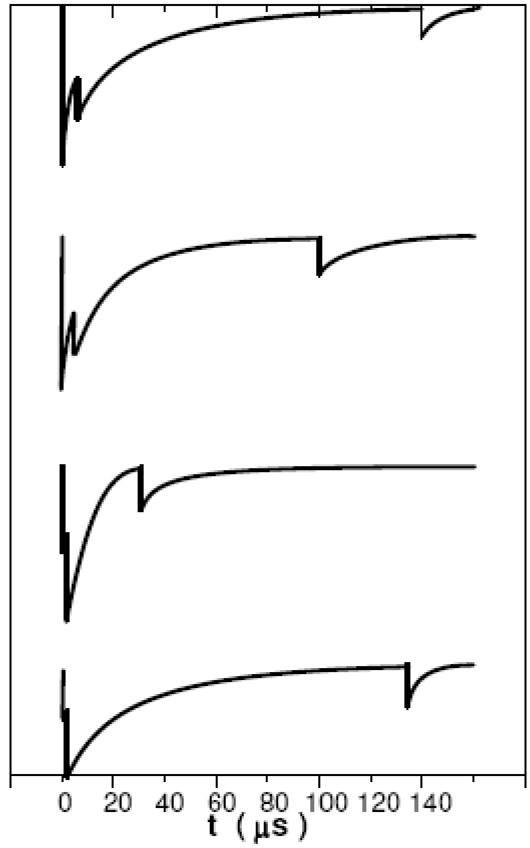

FIGURE 8. Typical signature, as is observed on the screen of a oscilloscope, of a negative muon nuclear (scintillator) capture followed by its radiative decay emitting an electron and a photon (plus two neutrinos). The three serial (inverse) peaks correspond to the signal of the muon, electron and photon (gamma) respectively.

VI. CONCLUSIONS

The primary objective of the present work is to introduce undergraduate students in Physics to experimental techniques of the elementary particle physics besides the theoretical treatments. In this sense, results on measurement of the muon lifetime through muon nuclear capture process using a detector of the Tupi telescope have been presented. We have used the method of frozen images on the screen of an oscilloscope as data acquisition system, which permits us discriminate the two modes (ordinary and radiative) of muon decay in a data set.

Both, the mean lifetime of muons and the branching ratio of the muon radiative decay obtained are τ_{μ} =2.30 ± 0.03 μs and 1.2% respectively and they are in relative agreement with results reported by the Particle Data Group.

ACKNOWLEDMENTS

This work is supported by the CNPq and FAPERJ in Brazil. We want to thank to the Vasconcelos Torres Foundation of the "Universidade Federal Fluminense" for the "Scientific initiation" award granted to this work in

2005. We are grateful to the K. H. Tsui for reading the manuscript.

REFERENCES

[1] Rossi, B., *High Energy Particles* (Prentice-Hall, Inc. New York, 1955).
[2] Neddemeyer, S. H. and Anderson, C. D., Phys. Rev. **51**, 884 (1937).
[3] Lattes, C. M. G., Occhialini, G. P. S. and Powell, C. F., Nature **160**, 453 (1949).
[4] Lattes, C. M. G., Occhialini, G. P. S and Powell, C. F. , *A determination of the ratio of the masses of pi-meson and mu-meson by the method of grain-counting*, Proceedings of The Physical Society **61**, 173-183 (1948).
[5] Steinberg, J., Phys. Rev. **74**, 500 (1948).
[6] Lagarrigue, A. and Peyrou, C., Acad. Sci. Paris **234**, 873 (1952).
[7] Steinerg, J. and Whole, H. B., Phys. Rev. **100**, 1490 (1955).
[8] Leite Lopes, J., Nucl. Phys. **8**, 234 (1958).
[9] Weinberg, S., Phys. Rev. Lett. **19**, 1264 (1967).
[10] Salam, A., *Elementary Particle Theory*, p.367 (Almquist and Wiksells, Stockholm, 1969).
[11] Glashow, S. L. *et al.*, Phys. Rev. D **2**, 1285 (1970).
[12] Nilles, H. P., Phys. Rep. **110**, 1 (1984).
[13] Barbieri, R. and Hall, L. J., Phys., Lett. B **228**, 212 (1994).
[14] Navia, C. E., Augusto, C. R. A., Robba, M. B., Malheiro, M. and Shigueoka, H., Ap. J, **621**, 1137 (2005).
[15] Augusto, C. R. A. Navia, C. E. and Robba, M. B., Phys. Rev. D **71**, 103011 (2005).
[16] Navia, C. E., Augusto, C. R. A., Tsui, K. H. and Robba, M. B., Phys. Rev. D **72**, 103001 (2005).
[17] Konishita, T. and Sirlin, A., Phys. Rev. **113**, 1652 (1959).
[18] Galviati, C. and Beacon, J., Phys. Rev. C **72**, 025807 (2005).
[19] Particle Data Group, J. of Phys. G, 33, 33 (2006).