misura della vita media del μ

argomenti da trattare a lezione

http://wwwusers.ts.infn.it/~martin/d_labfnsn/aa0809/

- introduzione: i μ e loro vita media
- raggi cosmici
  - storia ed esperimenti
  - caratteristiche
- decadimento
- apparato sperimentale - eventi attesi
- sistema di acquisizione dei dati
- metodi di analisi dei dati

introduction: the μ lifetime

μ charged lepton

leptons: elementary particles with spin 1/2 (fermion) that do not experience the strong force

form a family of elementary particles that is distinct from the other known family of fermions, the quarks

	e^- / e^+	μ^- / μ^+	τ^- / τ^+
mass	**0.511 MeV/c^2**	**105.6 MeV/c^2**	**1777 Mev/c^2**
lifetime	**$> 4.6\cdot10^{26}$ yr**	**$2.2\cdot10^{-6}$ s**	**$2.9\cdot10^{-13}$ s**
	$\nu_e / \bar{\nu}_e$	$\nu_\mu / \bar{\nu}_\mu$	$\nu_\tau / \bar{\nu}_\tau$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

~100% of cases, **$2.2\cdot10^{-6}$ s**

"**lifetime:** time elapsed between some reference time and the decay of a particle/nucleus (muon) in the rest frame of the particle

mean lifetime: arithmetic mean of the individual lifetimes"

?

introduction: the μ lifetime

the decay has a statistical nature

the lifetime has a well defined distribution function

$\mathbf{N_0}$ particles at $\mathbf{t=0}$

$\mathbf{N(t)}$ particles at $\mathbf{t}$

λ decay probability per unit time (the same for all particles)

$\mathbf{dp=\lambda dt}$ decay probability in $\mathbf{dt}$

in $\mathbf{dt}$ the number of particles decreases: $\mathbf{dN = -N(t)\cdot\lambda\, dt}$

integrating over $(\mathbf{0,t})$, particles at $\mathbf{t}$ $\mathbf{N(t) = N_0\, e^{-\lambda t}}$

exponential decay law
"radiactive"

(normalised) **lifetime distribution function** $\mathbf{g(t) = \lambda\, e^{-\lambda t}}$

mean lifetime τ = < t >

$$\mathbf{<t> = \frac{\int_0^\infty t\, N(t)\, dt}{\int_0^\infty N(t)\, dt}}$$

$$\tau = \frac{1}{\lambda}$$

$$\mathbf{<t> = \int_0^\infty t\, g(t)\, dt = \int_0^\infty \lambda\, t\, e^{-\lambda t}\, dt = \lambda}$$

introduction: the μ lifetime

the decay has a statistical nature

the lifetime has a well defined distribution function

N_0 particles at $t=0$ $N(t)$ particles at t

λ decay probability per unit time (the same for all particles)

$dp=\lambda dt$ decay probability in dt

in dt the number of particles decreases: $$dN = -N(t) \cdot \lambda \, dt$$

integrating over $(0,t)$, particles at t $$N(t) = N_0 \, e^{-\lambda t}$$

exponential decay law
"radiactive"

(normalised) **lifetime distribution function** $$g(t) = \lambda \, e^{-\lambda t}$$

mean lifetime $\tau = \langle t \rangle$

$$\tau = \frac{1}{\lambda}$$

decay probability in $(t,t+dt)$

$$dP = P_0 dp = e^{-\lambda t} \lambda dt$$

$$f(t) = \lambda e^{-\lambda t}$$

introduction: the μ lifetime

mean lifetime $\tau = \dfrac{1}{\lambda}$

λ decay probability per unit time

The most precise determination of G_F is based on the mean life of the positive muon, τ_μ. It has long been known that in the Fermi theory, the QED radiative corrections are finite to first order in G_F and to all orders in the electromagnetic coupling constant, α [6]. This provides a framework [3] for extracting G_F from τ_μ,

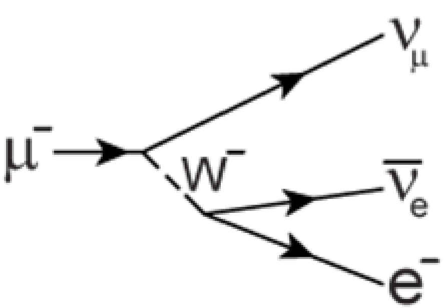
$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1 + \Delta q)\,, \tag{2}$$

where Δq is the sum of phase space and both QED and hadronic radiative corrections, which have been known in lowest-order since the 1950s [7]. Relation 2 does not

The Fermi constant G_F is related [3] to the electroweak gauge coupling g by

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}(1 + \Delta r)\,, \tag{1}$$

where Δr represents the weak-boson-mediated tree-level and radiative corrections, which have been computed to second order [4]. Comparison of the Fermi constant ex-



introduction: the μ lifetime

Improved Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant

D.B. Chitwood,[1] T.I. Banks,[2] M.J. Barnes,[3] S. Battu,[4] R.M. Carey,[5] S. Cheekatmalla,[4] S.M. Clayton,[1] J. Crnkovic,[1] K.M. Crowe,[2] P.T. Debevec,[1] S. Dhamija,[4] W. Earle,[5] A. Gafarov,[5] K. Giovanetti,[6] T.P. Gorringe,[4] F.E. Gray,[1,2] M. Hance,[5] D.W. Hertzog,[1] M.F. Hare,[5] P. Kammel,[1] B. Kiburg,[1] J. Kunkle,[1] B. Lauss,[2] I. Logashenko,[5] K.R. Lynch,[5] R. McNabb,[1] J.P. Miller,[5] F. Mulhauser,[1] C.J.G. Onderwater,[1,7] C.S. Özben,[1] Q. Peng,[5] C.C. Polly,[1] S. Rath,[4] B.L. Roberts,[5] V. Tishchenko,[4] G.D. Wait,[3] J. Wasserman,[5] D.M. Webber,[1] P. Winter,[1] and P.A. Żołnierczuk[4]

(MuLan Collaboration)

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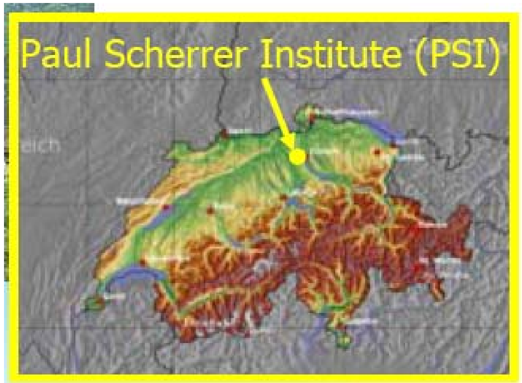
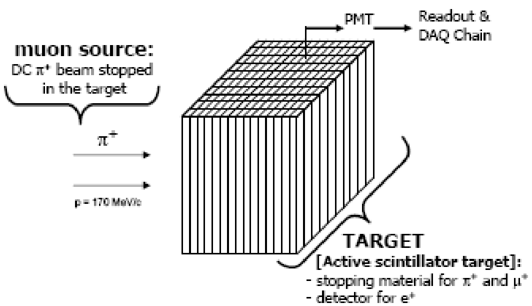
The mean life of the positive muon has been measured to a precision of 11 ppm using a low-energy, pulsed muon beam stopped in a ferromagnetic target, which was surrounded by a scintillator detector array. The result, $\tau_\mu = 2.197\,013(24)\ \mu s$, is in excellent agreement with the previous world average. The new world average $\tau_\mu = 2.197\,019(21)\ \mu s$ determines the Fermi constant $G_F = 1.166\,371(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$ (5 ppm). Additionally, the precision measurement of the positive muon lifetime is needed to determine the nucleon pseudoscalar coupling g_P.



introduction: the μ lifetime

THE FAST EXPERIMENT



SIGNATURE FOR AN EVENT [π→μ→e] :

- $\pi^+ \to \mu^+ \nu_\mu \; (\tau_\pi \sim 26ns)$ $\quad E_\mu^{kin} \sim 4\ MeV$, $\rho_\mu \sim 1.5\ mm$
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \; (\tau_\mu \sim 2.2\mu s)$

Signature:
- π^+ & μ^+ close in time & space [high pulses]
- e^+ track [mip's]

Size of the statistical sample → max achievable

$$\frac{(\delta\tau)_{stat}}{\tau} = \frac{1}{\sqrt{N_\cdot}}$$

$$\frac{\delta\tau_\mu}{\tau_\mu} \sim 2 \text{ ppm} \Rightarrow N_\cdot$$

PARALLELISATIC
i.e. treat more π→μ
the same time insic

- High granularity of t
- Tracking capabilitie
- Ability to disantangl events

- High beam rate
- Huge data rate thro

- Systematics under

RESULTS & CONCLUSIONS

arXiv hep-ex_0707.3904 & submitted to PLB

- first precise measurement of the positive muon lifetime with the FAST experiment:

$$\boxed{\tau_\mu = [2197.083 \pm 0.032\ (\text{stat}) \pm 0.015\ (\text{syst})]\ \text{ns}}$$

$$\boxed{\frac{\delta\tau_\mu}{\tau_\mu} = 16\ \text{ppm}}$$

  - run 2006 [3 weeks data taking, Nov-Dec06]
  - data sample : 1.073 10^{10} μ^+ decay events
  - precision comparable to PDG, value compatible with PDG
  - uncertainty dominated by the statistics

$$\boxed{\frac{\delta G_F}{G_F} = 8\ \text{ppm}}$$

- FAST measurement of the Fermi coupling constant G_F

$$\boxed{G_F = [1.166353 \pm 0.000009] \times 10^{-5}\ \text{GeV}^{-2}}$$

  - not yet in the regime where the effects of M_W starts to be visible:
    - G_F : Fermi model + $O(\alpha^2)$ 1.16635319 x 10^{-5} GeV^{-2}
    - G_F : Fermi model + $O(\alpha^2)$ + M_W 1.16635258 x 10^{-5} GeV^{-2}
    - present uncertainty 0.000009 x 10^{-5} GeV^{-2}

Cosmic Rays a brief history

1800: "atmospheric electricity"
an electroscope is "spontaneously" discharged

1896, Henri Becquerel: discovery of radioactivity

→ atmospheric electricity is caused by radiation from radioactive elements in the ground

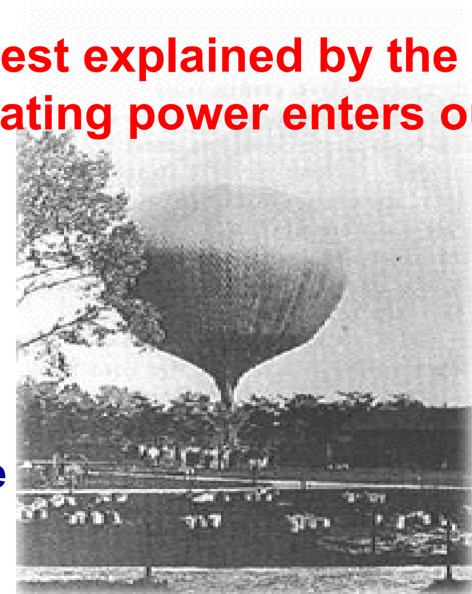
1900-1910: measurements of ionization rate at increasing heights above the ground : it decreases, as expected!

1912, V. Hess: carried three electrometers to an altitude of 5300 meters in a balloon flight and found that the ionization rate increased approximately four-fold over the rate at ground level

"The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."

Nobel Prize in Physics in 1936 for his discovery of "cosmic rays"

…- 1925: they are not of solar origin
and they are coming from above

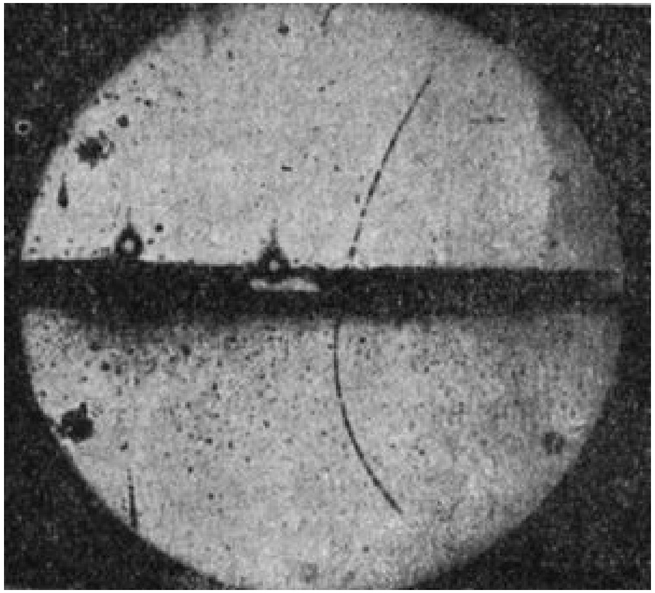


Cosmic Rays a brief history

1932, C. Anderson: unexpected particle tracks in cloud chamber photographs, created by a particle with the same mass as the electron, but with opposite charge:

the positron

predicted in 1928 by Paul Dirac



1932, B. Rossi: cosmic rays at ground level "soft component" easily absorbed plus "hard component" of penetrating particles

1936, S. Nedermeyer and C. Anderson: discovery of a new particle in cosmic rays with mass between the electron and the proton mass: the "muon"

1937, J. C. Street and E. C. Stevenson: with a cloud chamber measured $m_\mu = 207\ m_e$

1935, H. Yukawa: an intermediate mass "meson" is responsible for the nuclear strong force mass of about 100 MeV/c^2

the muon (mesotron) ?

Cosmic Rays a brief history

1939, Rossi, Van Norman Hilbery: study of absorption in different materials $\rightarrow$ muon decay and **indirect measurement of $\tau_\mu \sim 2\ \mu s$**

1940, Rossi and Hall: muon decay used to verify relativistic **time dilation**

→ *Introduzione alla Fisica Nucleare e Subnucleare*

1940, Williams and Roberts: **observation of the decay of a muon in a e^+**

1941, Rasetti: $\tau_\mu = 1.5 \pm 0.3\ \mu s$ **first direct measurement** from muon decay

1942, Nereson and Rossi: with time-to-amplitude converter,

$$\tau_\mu = 2.3 \pm 0.2\ \mu s$$

1947-1948, Conversi, Pancini, Piccioni: muon capture

from muon decay in different materials, the **capture in light materials** is not as relevant as in case of strong interactions

the muon does not interact strongly with nuclei, it can not be the Yukawa particle

Bethe and Marshak suggested that the muon might be the decay product of the particle needed in the Yukawa theory

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu, \quad \pi^- \longrightarrow \mu^- + \bar{\nu}_\mu.$$

1947: first evidence of $\pi \rightarrow \mu x$ - discovery of the **pion**

mass 139.6 MeV/c^2, mean life of 2.6×10^{-8} seconds

Experimental Determination of the Disintegration Curve of Mesotrons

BRUNO ROSSI AND NORRIS NERESON
Cornell University, Ithaca, New York

(Received September 17, 1942)

The disintegration curve of mesotrons has been experimentally determined by investigating the delayed emission of disintegration electrons which takes place after the absorption of mesotrons by matter. Within the experimental errors, the disintegration curve is exponential and corresponds to a mean lifetime of 2.3 ± 0.2 microseconds.

THE purpose of the experiment described in the present paper was to determine the disintegration curve of mesotrons at rest. The experiment was performed by investigating the delayed emission of the disintegration electrons, which takes place after the absorption of mesotrons by matter.

We have succeeded in increasing the selectivity and the statistical accuracy of the method considerably by recording all decay electrons and measuring the time interval between the arrival of each mesotron and the emission of the corresponding electron. The circuit used for this measurement will be referred to as the *time circuit*.

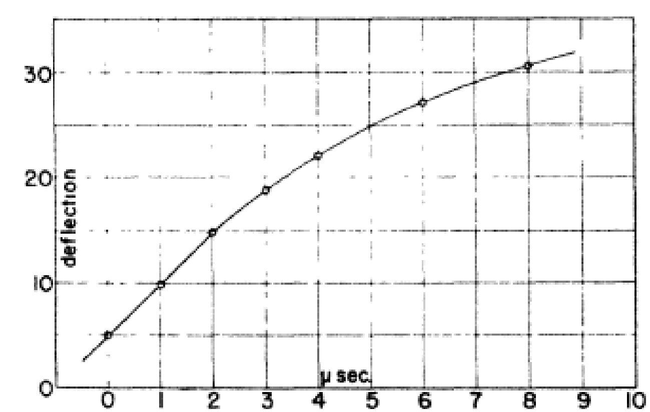
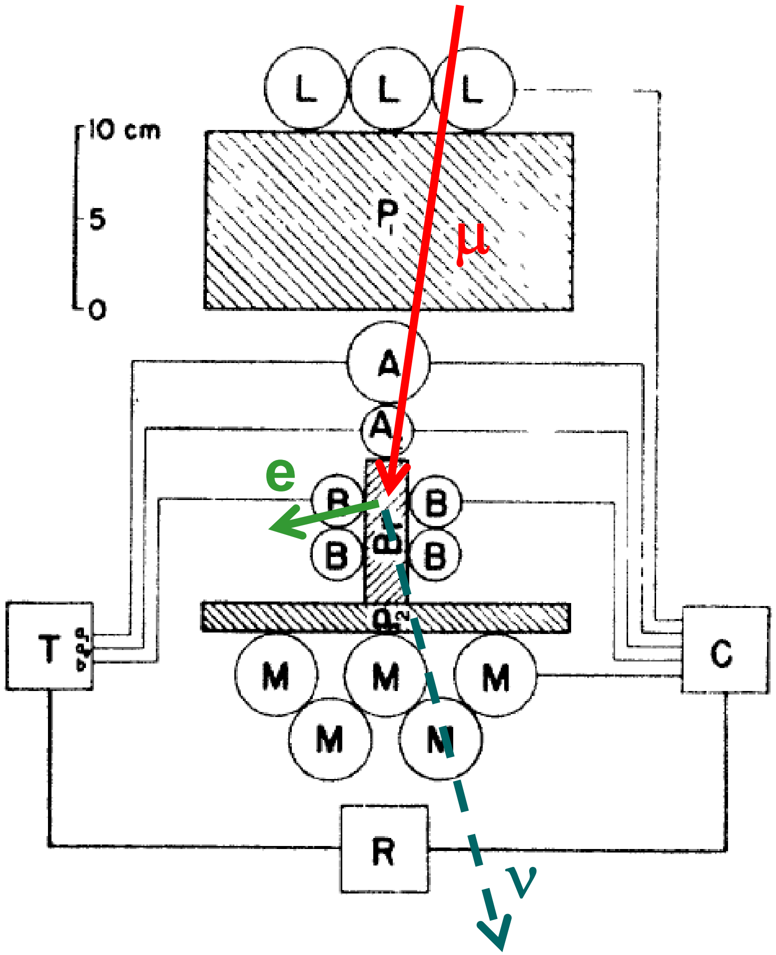


FIG. 1. Calibration curve of the time circuit.

Nereson Rossi



L, A, B, M: Geiger-Muller counters

the 4 counters L are connected in parallel (OR)

the same for the 4 counters B and the 5 counters M

Br: brass plate 25.5x8x2.3 cm

compromise: rate of muon decays vs probability of detecting the electron

good event:

muon gives signal in L, A1, A2

decays in Br → no signal in M, B

decay electron gives a signal in B

P1: 9 cm of lead

to cut the electron component

P2: lead plate 1.4 cm thick

to decrease the probability of having a decay electron signal in M

C gives a signal which activates R if

$L \cdot A1 \cdot A2 \cdot B \cdot \overline{M}$ (10^{-4} s)

R registers the amplitude of the signal from T prop to Δt between A and B

Nereson Rossi

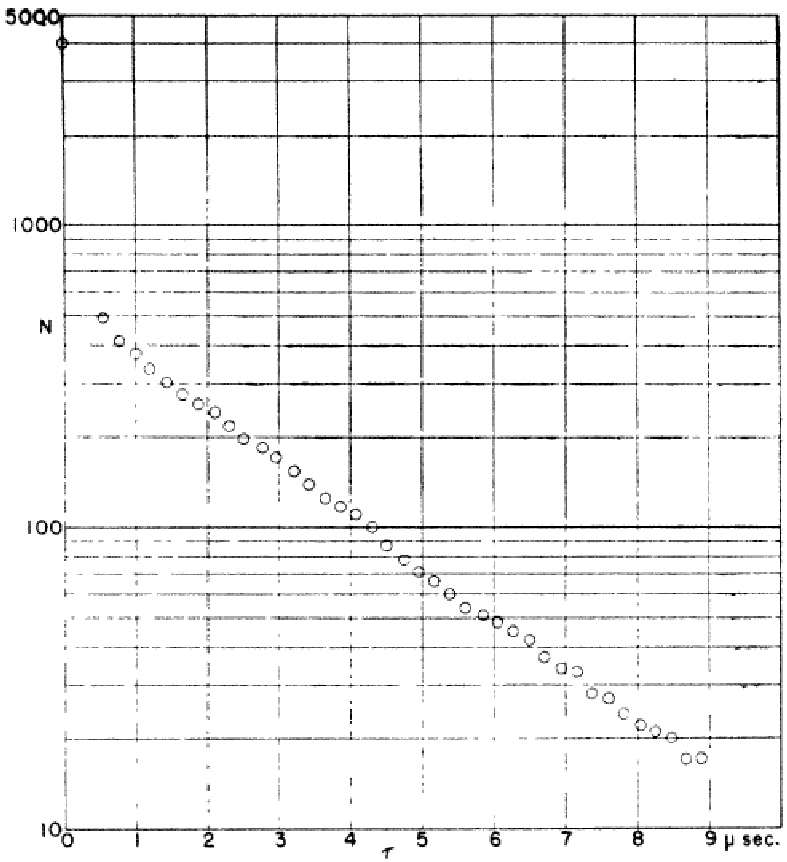


FIG. 5. Experimental disintegration curve of mesotrons. The abscissa τ is the delay recorded by the time circuit, the ordinate is the logarithm of the number N of anti-coincidences accompanied by delays larger than the corresponding abscissa (Exp. A).

semi-logarithmic scale in Fig. 5. The experimental points lie on a straight line as closely as one can expect considering the statistical fluctuations, with the exception, of course, of the point at $\tau=0$ and possibly the one at 0.55 μsec. Hence the disintegration of mesotrons follows an exponential law as does any ordinary disintegration process.

For the evaluation of the lifetime τ_0 we shall use the following equation:

$$\begin{aligned}\rho &= [N(\tau_1)-N(\tau_2)]/[N(\tau_2)-N(\tau_3)] \\ &= [\exp(-\tau_1/\tau_0)-\exp(-\tau_2/\tau_0)]/ \\ &\qquad [\exp(-\tau_2/\tau_0)-\exp(-\tau_3/\tau_0)], \qquad (1)\end{aligned}$$

where $N(\tau)$ is the number of mesotrons surviving at the time τ after their absorption in the brass plate. If we take $\tau_1=0.99$ μsec., $\tau_2=4.95$ μsec., $\tau_3=8.91$ μsec., then $\tau_2-\tau_1=\tau_3-\tau_2=\Delta\tau=3.96$ μsec. Equation (1) reduces to

$$\rho=\exp(\Delta\tau/\tau_0),$$

and the experimental data set forth in Table I yield

$$\tau_0=2.3\pm0.2\ \mu\text{sec.},$$

where the error indicated is the standard statistical error.

Conversi, Pancini, Piccioni

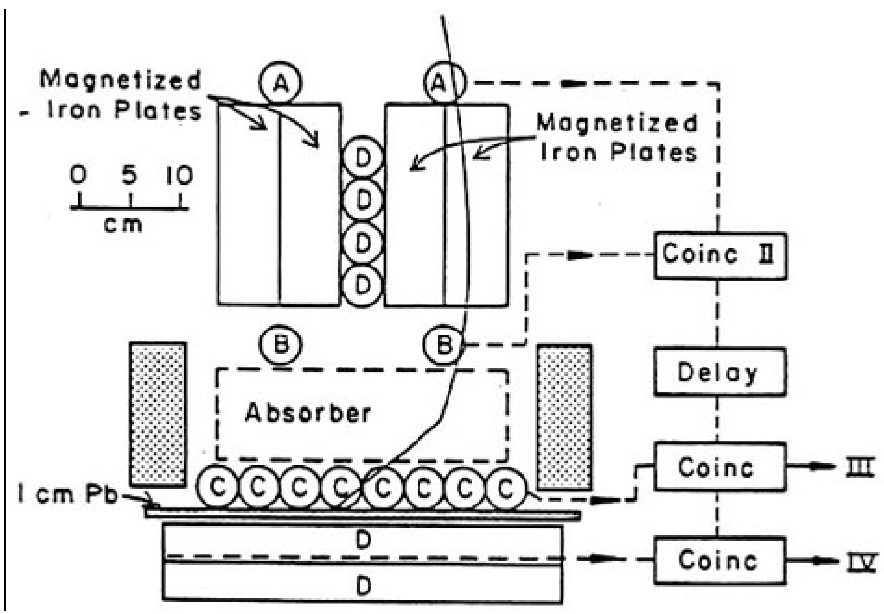
PHYSICAL REVIEW 71, 1947

On the Disintegration of Negative Mesons

M. Conversi, E. Pancini, and O. Piccioni*

Centro di Fisica Nucleare del C. N. R. Istituto di Fisica dell'Università di Roma, Italia

December 21, 1946



We alternated the following three measurements:

A. Negative mesons with 4 cm C and 5 cm Fe,
B. Negative mesons with 6.2 cm Fe (6.2 cm Fe is approximately equivalent to 4 cm C+5 cm Fe as far as energy loss is concerned.
C. Positive mesons with 4 cm C.

Conversi, Pancini, Piccioni

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TABLE I. Results of measurements on β-decay rates for positive and negative mesons.

Sign	Absorber	III	IV	Hours	M/100 hours
(a) +	5 cm Fe	213	106	155.00′	67 ±6.5
(b) −	5 cm Fe	172	158	206.00′	3
(c) −	none	71	69	107.45′	−1
(d) +	4 cm C	170	101	179.20′	36 ±4.5
(e) −	4 cm C+5 cm Fe	218	146	243.00′	27 ±3.5
(f) −	6.2 cm Fe	128	120	240.00′	0

The great yield of negative decay electrons from carbon shows a marked difference between it and iron as absorbers. Tomonaga and Araki's calculation also give for carbon a much higher ratio of capture to decay probability for negative mesons, so we are forced to doubt their estimation. It is possible that a suitable dependence of the capture cross section, σ_c, on the nuclear charge, Z, might explain these results; however, if the ratio of the capture to decay probability also depends on the density as Tomonaga and Araki pointed out, then it would require a very irregular dependence on Z to also explain the cloud-chamber pictures of some authors[6] showing negative mesons stopped in the chamber without any decay electrons coming out.

Further experiments on this subject are now in progress, in an attempt to calculate the capture cross section, and to know how it depends on Z.

Cosmic Rays some info from PDG

The cosmic radiation incident at the top of the atmosphere includes all stable charged particles and nuclei (lifetimes ~10^6 years or longer)

Most of the cosmic radiation comes from outside the solar system

Technically: "primary" and "secondary" cosmic rays

those particles accelerated at astrophysical sources

electrons, protons and helium, as well as carbon, oxygen, iron, and other nuclei synthesized in stars

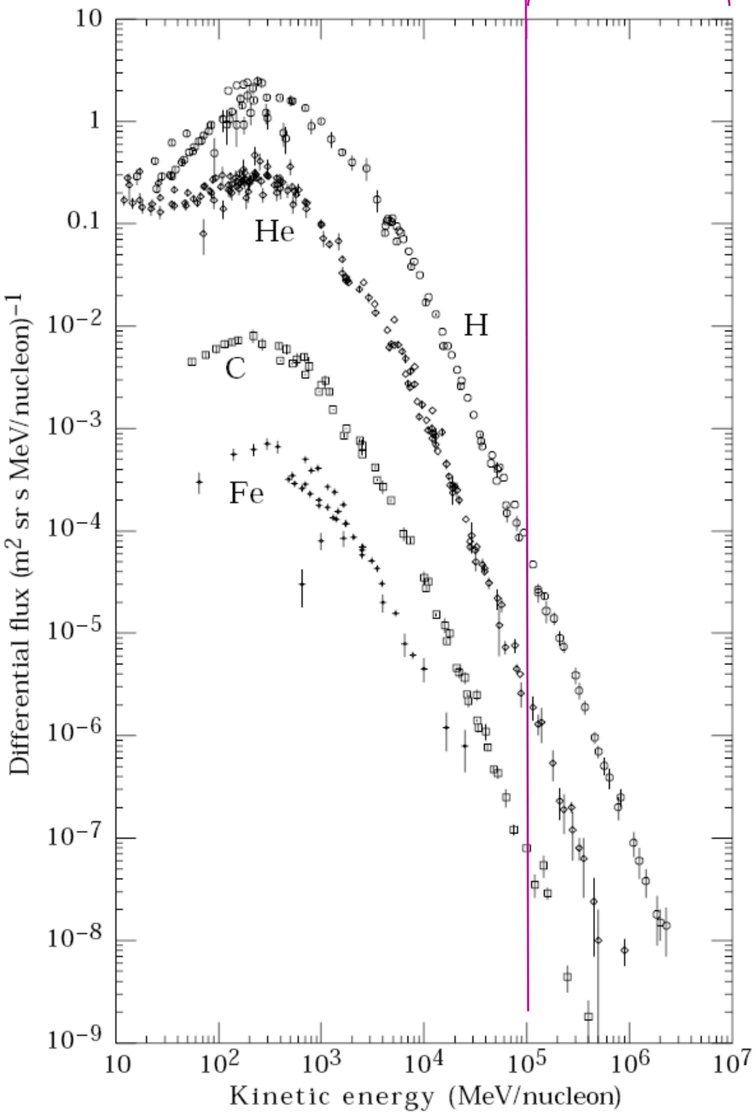
Table 23.1: Relative abundances F of cosmic-ray nuclei at 10.6 GeV/nucleon normalized to oxygen ($\equiv 1$) [7]. The oxygen flux at kinetic energy of 10.6 GeV/nucleon is 3.26×10^{-6} cm^{-2} s^{-1} sr^{-1} (GeV/nucleon)$^{-1}$. Abundances of hydrogen and helium are from Ref. [5,6].

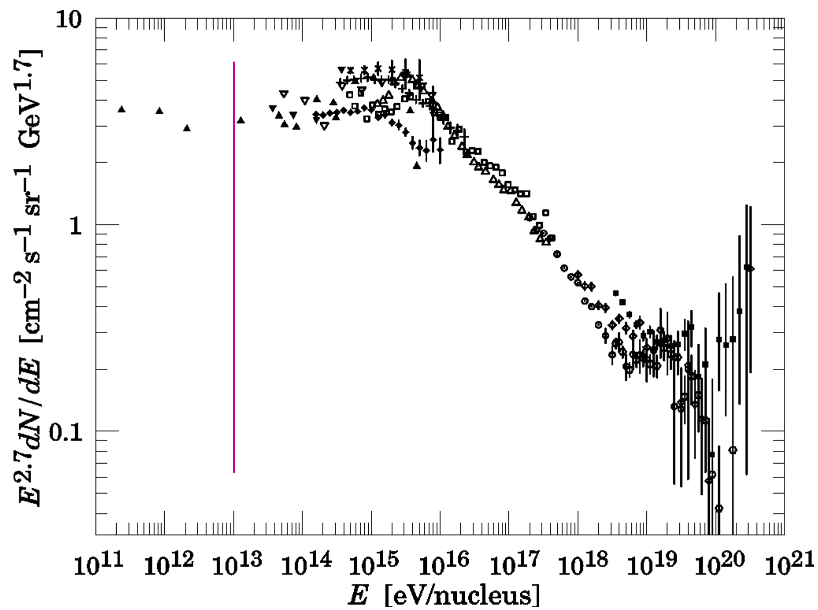
Z	Element	F	Z	Element	F
1	H	540	13–14	Al-Si	0.19
2	He	26	15–16	P-S	0.03
3–5	Li-B	0.40	17–18	Cl-Ar	0.01
6–8	C-O	2.20	19–20	K-Ca	0.02
9–10	F-Ne	0.30	21–25	Sc-Mn	0.05
11–12	Na-Mg	0.22	26–28	Fe-Ni	0.12

protons 79%

Cosmic Rays some info from PDG

"primary" cosmic rays

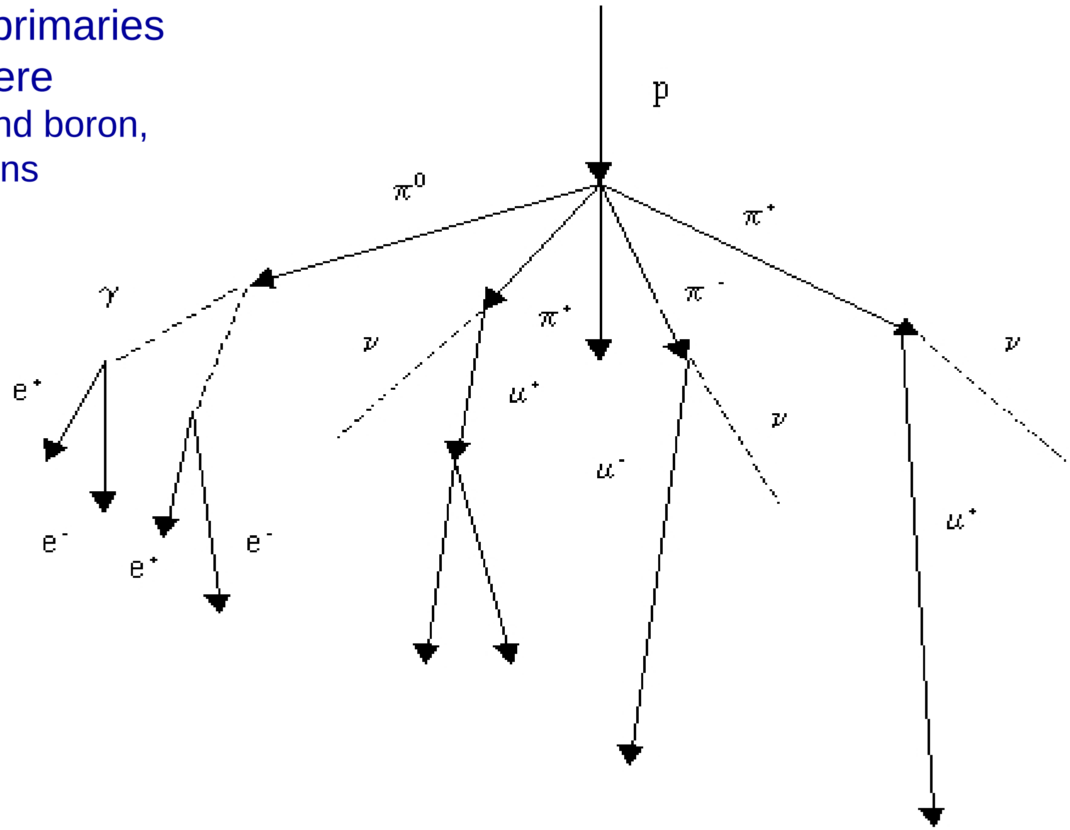




Major components of the primary cosmic radiation

Cosmic Rays some info from PDG

"**secondaries**" are those particles
produced in interaction of the primaries
with interstellar gas / atmosphere
nuclei such as lithium, beryllium, and boron,
most of the antiprotons and positrons
pions



$$\pi^\pm \to \mu^\pm \nu$$

"hard" component

$$\pi^0 \to 2\gamma$$

em showers

"soft" component

$$e^+, e^-, \gamma$$

B. Rossi

Cosmic Rays in the atmosphere some info from PDG

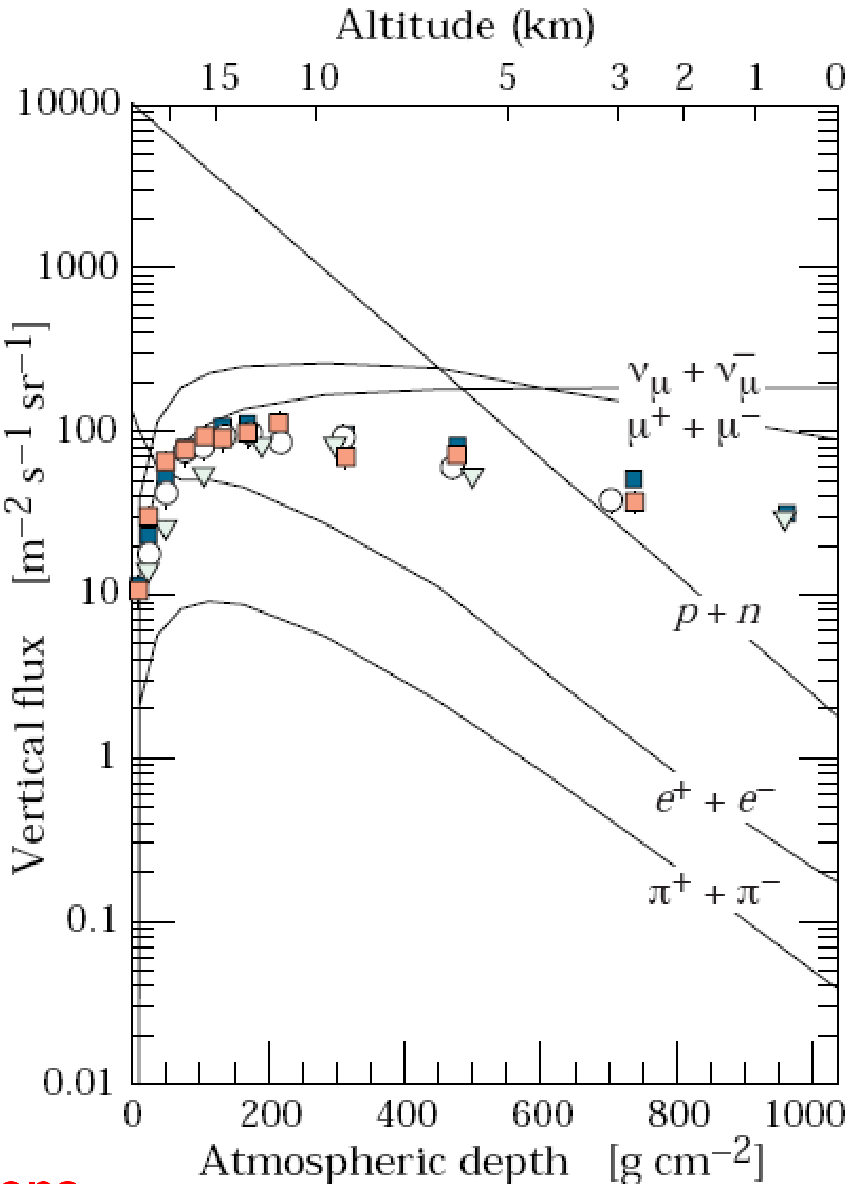
vertical fluxes of the major cosmic ray components in the atmosphere in the energy region where the particles are most numerous (except for electrons)

$$\Phi_v = \frac{d^3N}{dS\,dt\,d\Omega} \qquad m^{-2}\,s^{-1}\,sr^{-1}$$

except for protons and electrons near the top of the atmosphere, **all particles are produced in *interactions of the primary cosmic rays in the air***

muons and neutrinos are products of the *decay of charged mesons*

electrons and photons originate in *decays of neutral mesons*

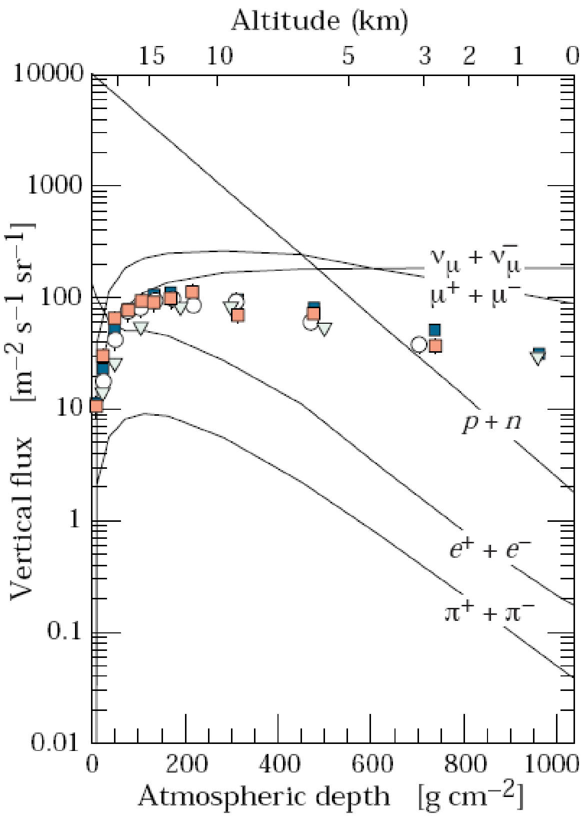


muons, electromagnetic component, protons

Cosmic Rays at the surface some info from PDG

MUONS are the most numerous charged particles at sea level

most muons are produced high in the atmosphere (typically 15 km) and lose about 2 GeV to ionization before reaching the ground



the integral intensity of vertical muons above 1 GeV/*c* at sea level is $I \approx 70$ m^{-2} s^{-1} sr^{-1} ($I \approx 1$ cm^{-2} min^{-1} for horizontal detectors)

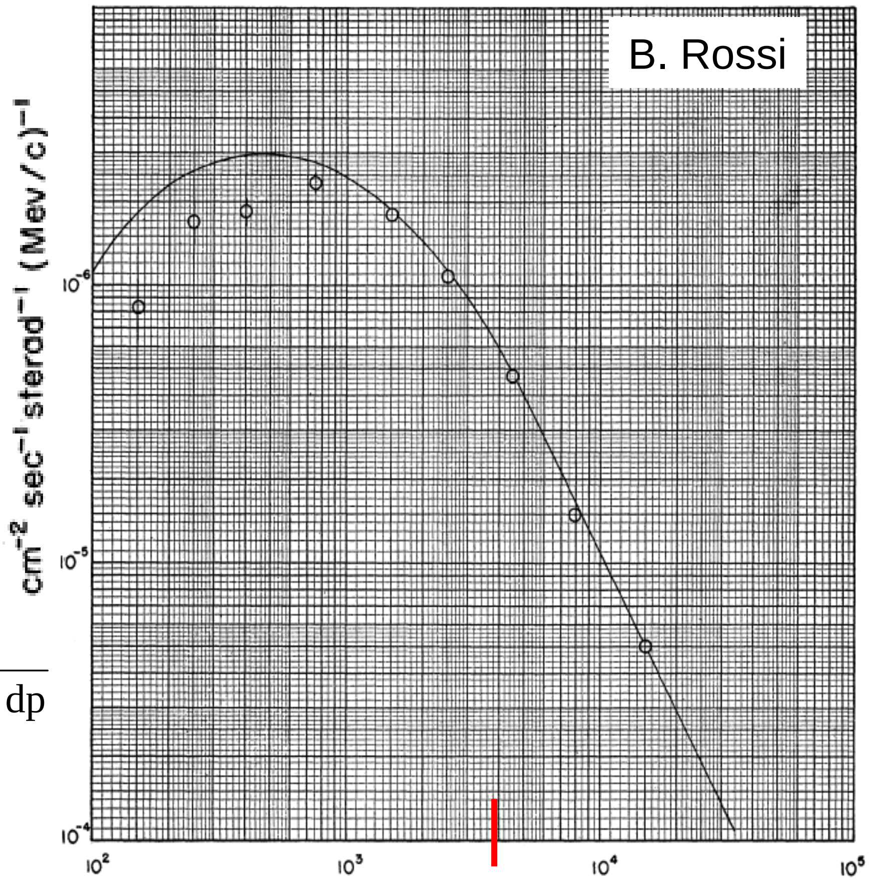
their energy and angular distribution reflect a convolution of production spectrum, energy loss in the atmosphere, and decay

Cosmic Rays at the surface some info from PDG

MUONS

the mean energy of muons at the ground is ≈ 4 GeV

the energy spectrum is almost flat below 1 GeV, steepens gradually to reflect the primary spectrum in the 10–100 GeV range



$$\Phi = \frac{d^4 N}{dS\, dt\, d\Omega\, dp}$$

The overall angular distribution of muons at the ground is ~ $\cos^2\theta$, which is characteristic of muons with E_μ ~ 3 GeV.

at lower energy the angular distribution becomes increasingly steep, while at higher energy it flattens (at large angles low energy muons decay before reaching the surface)

Cosmic Rays at the surface   some info from PDG

MUONS

the muon charge ratio is between 1.1 and 1.4 from 1 GeV to 100 GeV

it reflects

- the excess of π+ over π− in the forward fragmentation region of proton initiated interactions
- the fact that there are more protons than neutrons in the primary spectrum.

protons

nucleons above 1 GeV/*c* at ground level are degraded remnants of the primary cosmic radiation.

at sea level, about 1/3 of the nucleons in the vertical direction are neutrons

the integral intensity of vertical protons above 1 GeV/*c* at sea level is ≈ 0.9 $m^{-2}\ s^{-1}\ sr^{-1}$ (70 for muons)

Cosmic Rays at the surface some info from PDG

Electromagnetic component

At the ground, this component consists of **electrons**, **positrons**, and **photons** primarily from electromagnetic cascades initiated by decay of neutral and charged mesons

Muon decay is the dominant source of low-energy electrons at sea level

Decay of neutral pions is more important at high altitude or when the energy threshold is high

The ratio of photons to electrons plus positrons is approximately 1.3 to 1.7, depending on the energy

The angular dependence is complex because of the different altitude dependence of the different sources of electrons

The **integral vertical intensity** of electrons plus positrons is very approximately 30, 6, and 0.2 $m^{-2}\ s^{-1}\ sr^{-1}$ above 10, 100, and 1000 MeV respectively