Pions and Muons

Conversi, Pancini, Piccioni (CPP) experiment

Marcello Conversi

Ettore Pancini

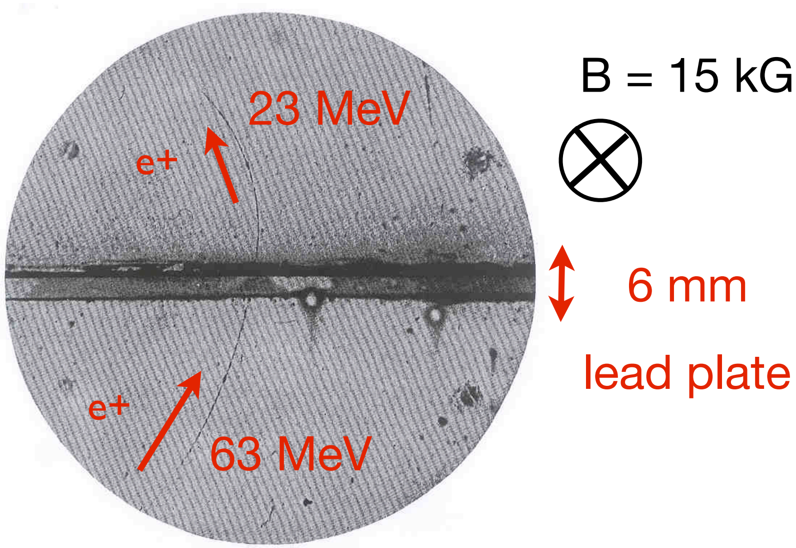
Oreste Piccioni

Historical introduction

1912 Discovery of cosmic rays (V. Hess)

1932 Discovery of positron (C. Anderson)

predicted by Dirac in 1928



Measurement of the curvature of the track

Range not compatible with proton hypothesis (~5 mm in Air)

From ΔE infer upper limit on particle mass (< 20 mass electron)

Historical Introduction II

1935 Yukawa theory for strong interaction

predicts mediator particle with mass ~ 100 MeV. Yukawa meson is supposed to decay into electron and neutrino with decay time of ~1 μs

1937 Discovery of the “mesotron” (C. Anderson, S. Neddermeyer)

mass ~110 MeV → associated with Yukawa particle

1940 Decay and absorption properties of Yukawa mesons (S. Tomonaga, G. Araki)

Yukawa meson - strong interaction with matter

nuclear capture and decay rates are different for positive and negative mesons at rest. Different interaction with positive nuclei.

Decay of the mesotron

1940 Observation of mesotron decays into positrons (William, Roberts)

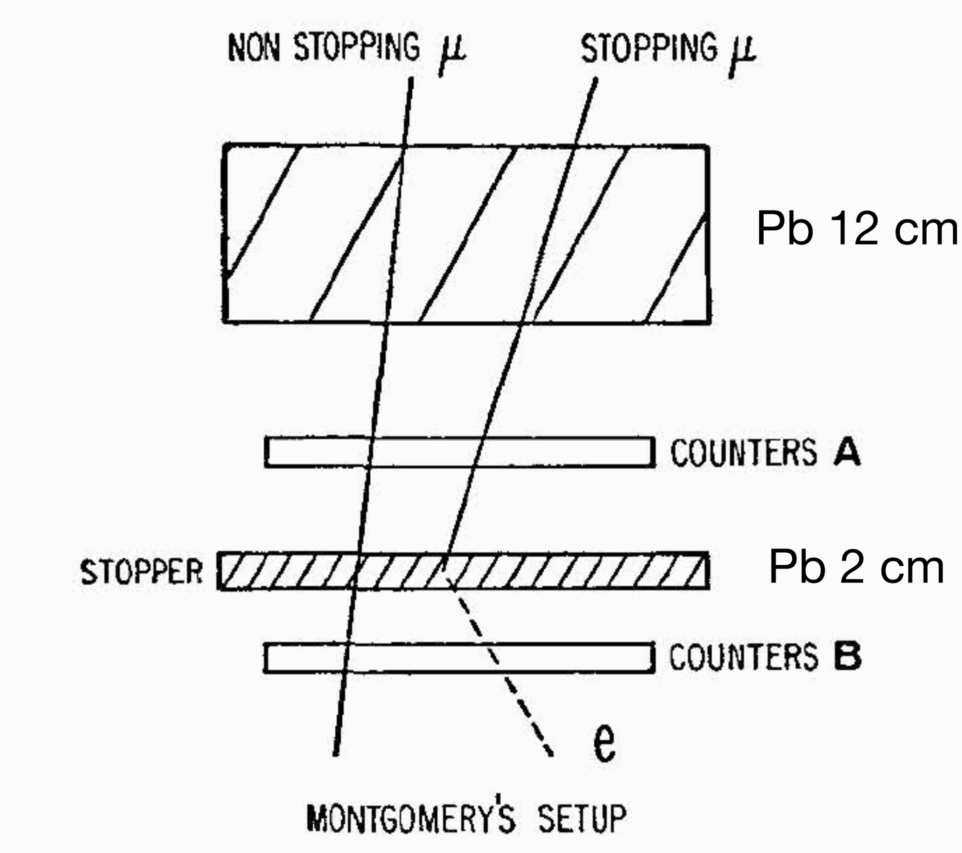
1941 Measurement of decay time (Rasetti) $\tau = (1.5 \pm 0.3)\mu s$

1941 Piccioni and Conversi decided to work together and improve the precision on the decay time measurement...

Piccioni ed io, quando sul finire del 1941 decidemmo di lavorare insieme, avevamo in mente la determinazione diretta della vita media del mesotrone. Piccioni, con alcuni anni di esperienza più di me, aveva una profonda conoscenza ed un grande entusiasmo per l'elettronica, e la maggior parte dello sviluppo che ne seguì fu dovuto alla sua grande competenza ed ingegnosità in questo campo." (M.C.)

Pioneer experiments for decay time measurement

1939 C. Montgomery, W. Ramsey, D. Cowie, D. Montgomery



Pb 12 cm

Pb 2 cm

Register delayed coincidence between A and B, after a time interval t_1 and before t_2

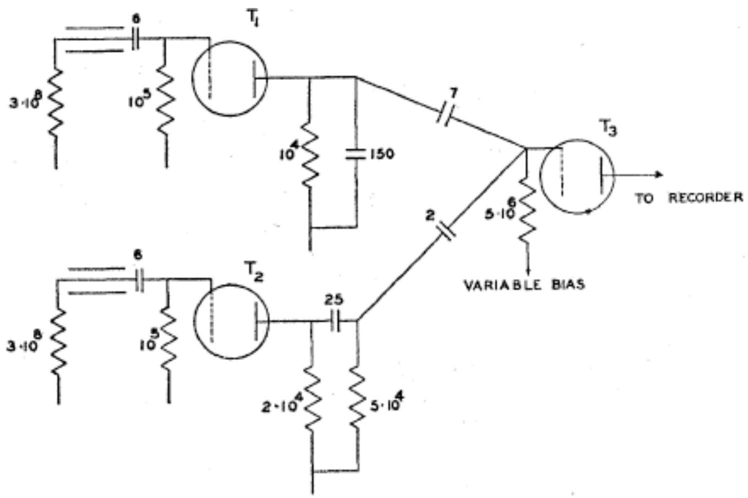


FIG. 2. Circuit for selecting the delayed coincidences.

Extract decay time from intensities of delayed coincidences with and without stopper.
Too spurious coincidences in counter B.
Experiment was not successful

Mesotron decay time measurement

1940 F. Rasetti

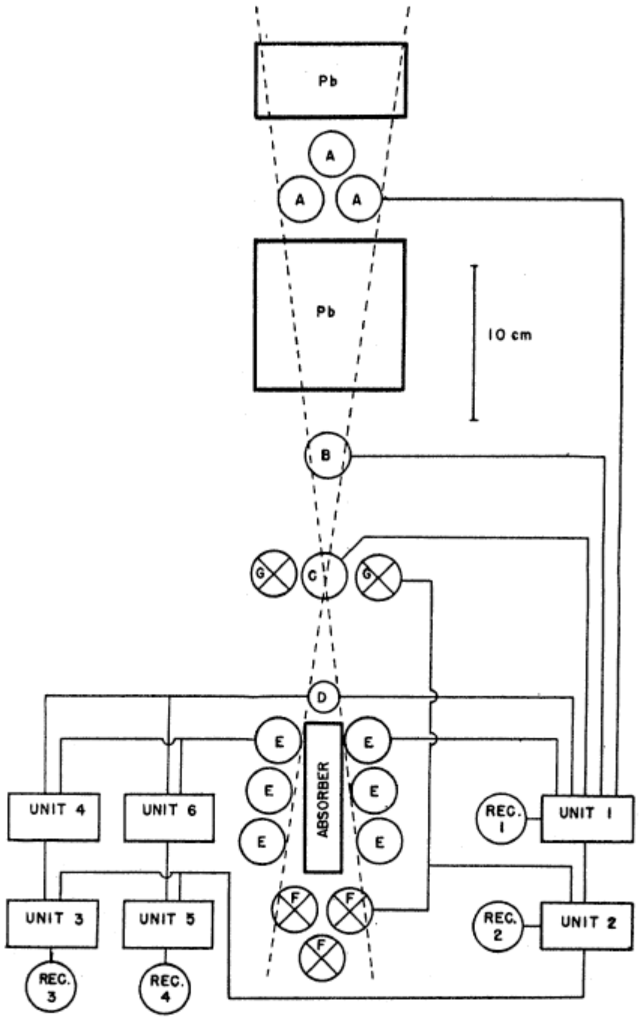


FIG. 1. Arrangement of counters, illustrating connections to amplifier units.

Experimental Procedure

Define a beam of mesotrons with the coincidence (ABCD)
Anticounter G (anticoincidence) discriminates against e.m. showers
Anticounter F selects mesotrons stopped in the absorber
Counter E detects particles emitted in the absorber

Signal events in Rasetti experiment

No delayed coincidences but “prompt” coincidences with different resolving times.

Signal + Noise events

n_2: defined by 5 the coincidence and 1 anticoincidence (ABCDE-F). Resolving time t_2=12μs

Noise events

n_3, n_4: defined by (ABCDE-F) (in coincidence with (DE), {(ABCDE-F) (DE)}. Resolving time of (DE), t_3= 1.95μs, t_4= (0.95, 0.76) μs.

It is not possible to prove the existence of an exponential decay.

The mean life τ of the disintegration process is calculated from the differences of the numbers of counts, according to the formula:

$$\exp\left(-\frac{t_3-t_4}{\tau}\right)=\frac{n_2-n_3}{n_2-n_4}$$

coincidence resolving times

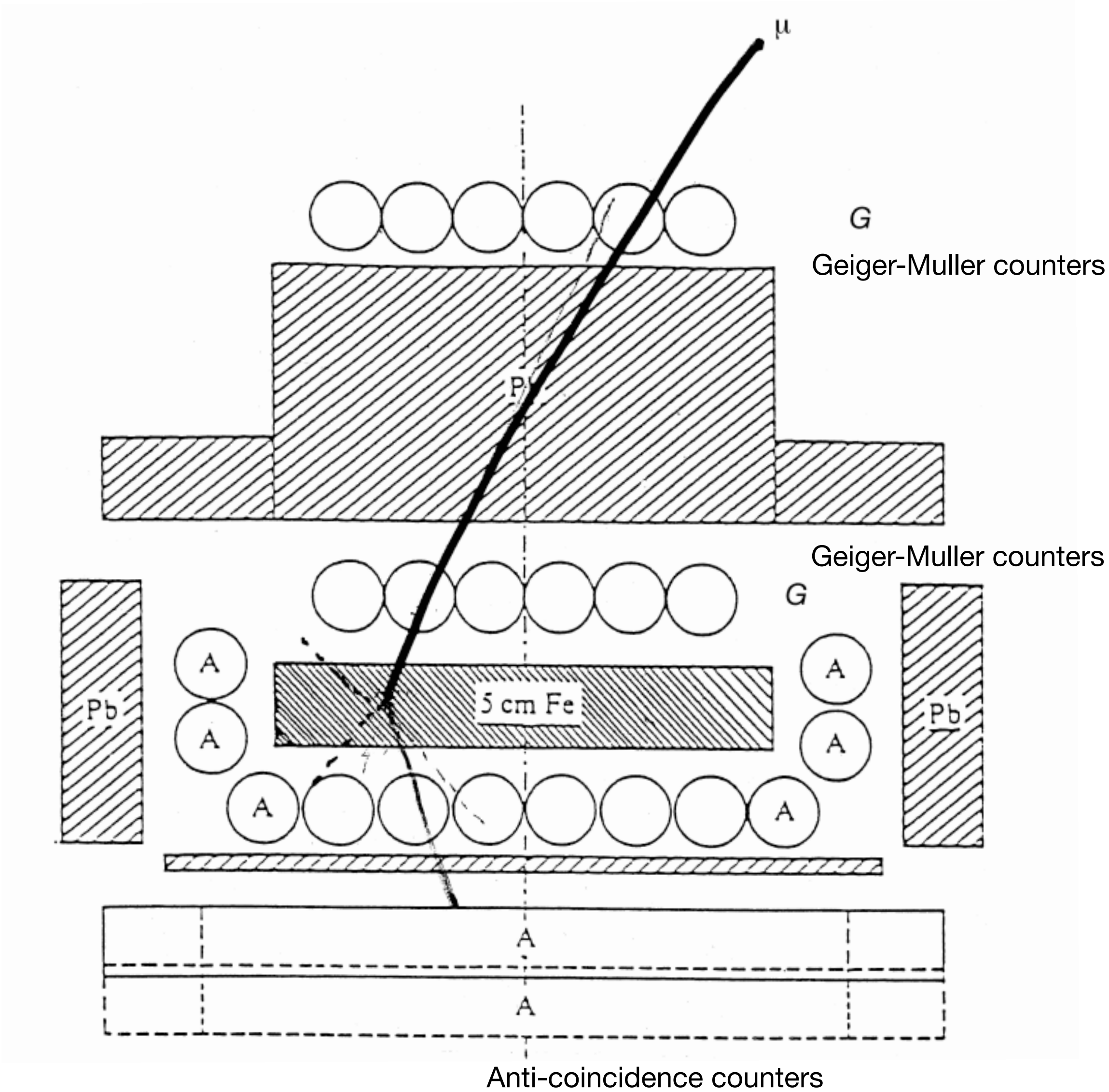
registered events

$$\tau = (1.5 \pm 0.3)\mu s$$

Piccioni e Conversi appreciated Rasetti measurement and in 1941 started working together to design an improved experiment.

Mesotron decay time, improved measurement

1942 M. Conversi, O. Piccioni



"*Il compito di sviluppare una tecnica adeguata era già arduo di per sé e venne reso ancora più gravoso, ovviamente, dalle condizioni particolari imposte dalla guerra*." (M.C.)

Signal events

a mesotron stops in the absorber (Fe) and then decay.

Use of delayed coincidences between top and bottom counters and anti-coincidences (A).

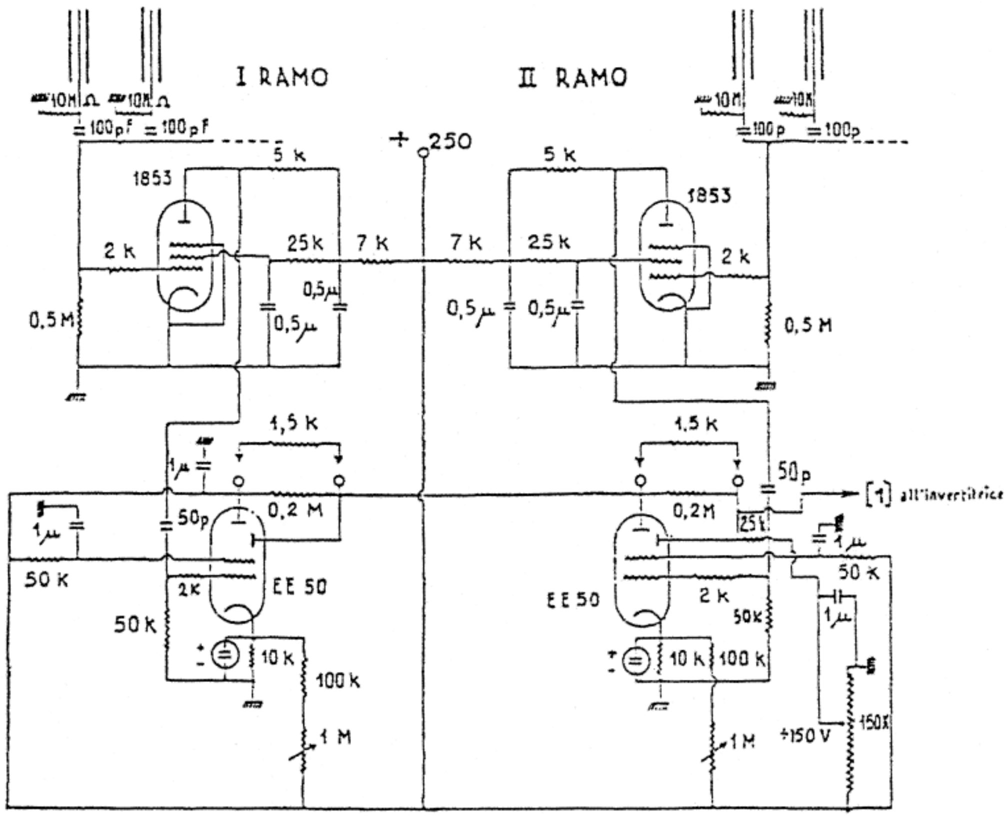
Electron are stopped by the Pb absorber.

Anti-coincidence signal reject the event.

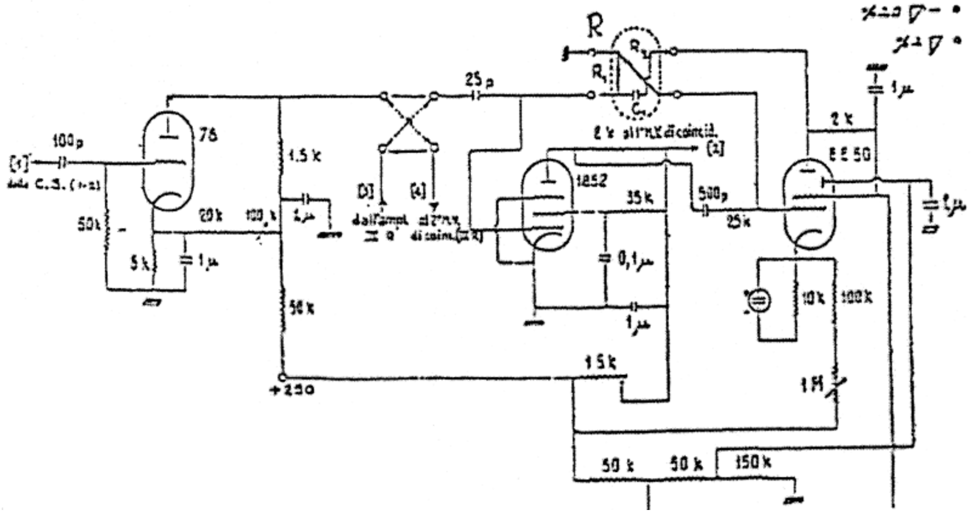
Design of precise and fast electronics by Piccioni and Conversi

M. Conversi, 1943. *Sul ritardo degli impulsi nei contatori di Geiger-Müller.* Atti della SIPS, Roma.
M. Conversi, O. Piccioni, 1943. *Sulle registrazioni di coincidenze a piccoli tempi di separazione.* Nuovo Cimento, 1; 279 ss.

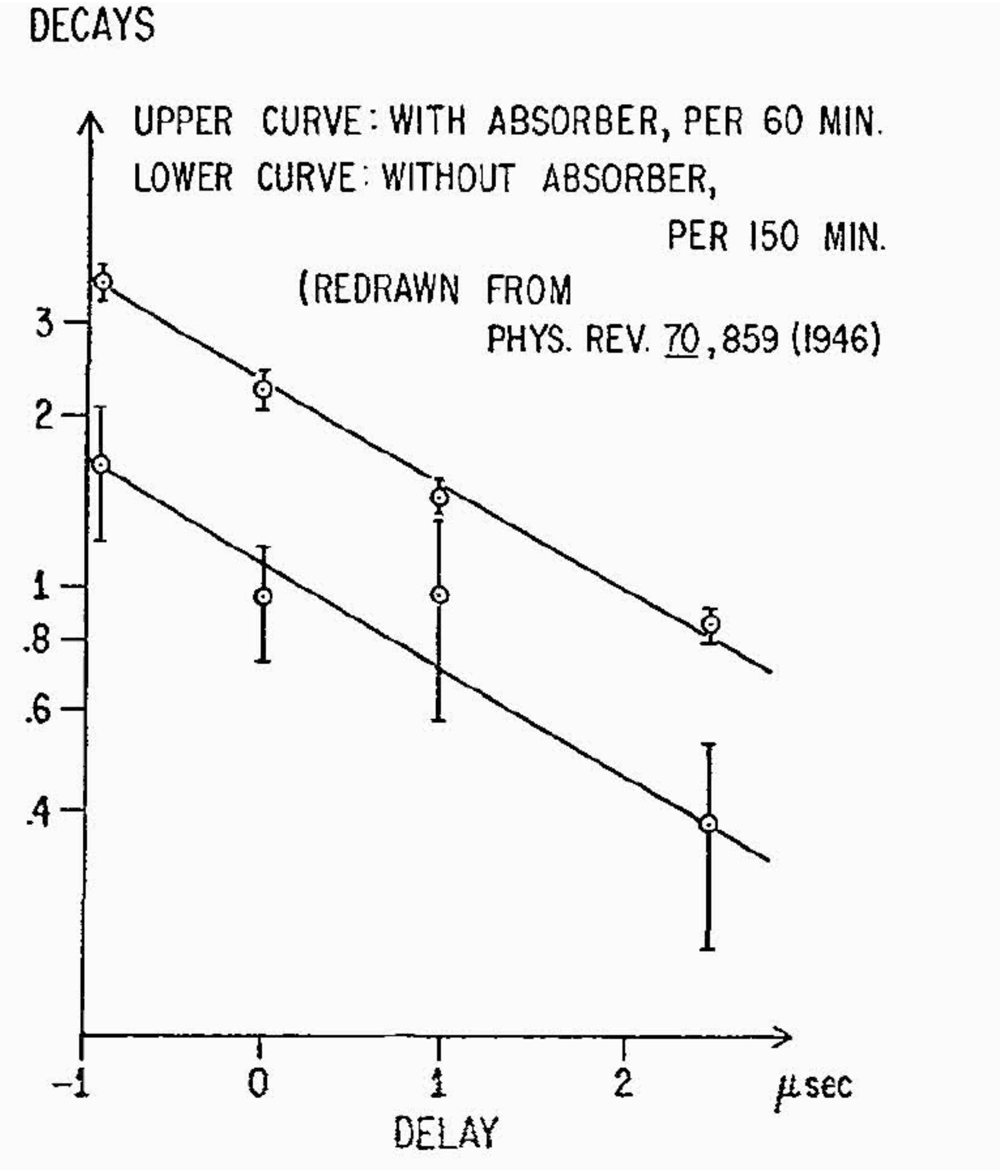
Input amplifiers designed by Piccioni and Conversi



Original scheme of the electronic circuit for the measurement of the coincidence delays



Results



First experimental evidence of exponential decay of the mesotron. Rossi and Nerenson obtained similar results independently.

Extract the decay time value from the slope of the distribution of the counts vs coincidence delay

$$N(t) = N_0 e^{-t/\tau}$$

$$\tau = (2.33 \pm 0.15)\mu s$$

Test of Tomonaga - Araki theory

S. TOMONAGA - G. ARAKI, Effect of the Nuclear Coulomb Field on the Capture of Slow Mesons.
Phys.Rev., 58, 1940, 90-91.

In consequence of the Coulomb attraction the capture probability will increase for negative mesons, while for positives it will be greatly reduced by the potential barrier. The competition between nuclear capture and spontaneous disintegration must in this way be different for mesons of different signs.

Since the probability for negative mesons being captured is seen always to be larger than the probability of disintegration, which is of the order of 10^6 sec.$^{-1}$, the negative mesons will be much more likely captured by nuclei than disintegrate spontaneously,

Strong interaction

Yukawa meson interacts with nucleus mainly via strong interaction.
According to calculations, the nuclear capture depends mildly from the Z value of the material

Nuclear capture process

slow positive mesotrons are repulsed by positive nuclei, while slow negative mesons can be captured

Decay process

slow positive mesotrons can only decay

The CPP experiment and the previous tests

"*La moderna fisica delle particelle ebbe inizio durante gli ultimi giorni della seconda guerra mondiale, quando un gruppo di giovani italiani, Conversi, Pancini e Piccioni, iniziarono un notevole esperimento*" (L. Alvares, Nobel Lecture 1968).

1944 First test of T-A theory

use same apparatus as for the previous decay time measurement. Thinner absorber (0.6 cm Fe instead of 5 cm) to improve electron detection efficiency. Measure ratio of mesotrons that decay inside Fe, $h = 0.49 \pm 0.07$ in agreement with predicted value $h=0.55$ due to 20% excess of positive mesotrons at sea level from cosmic rays.

1945 The CPP experiment

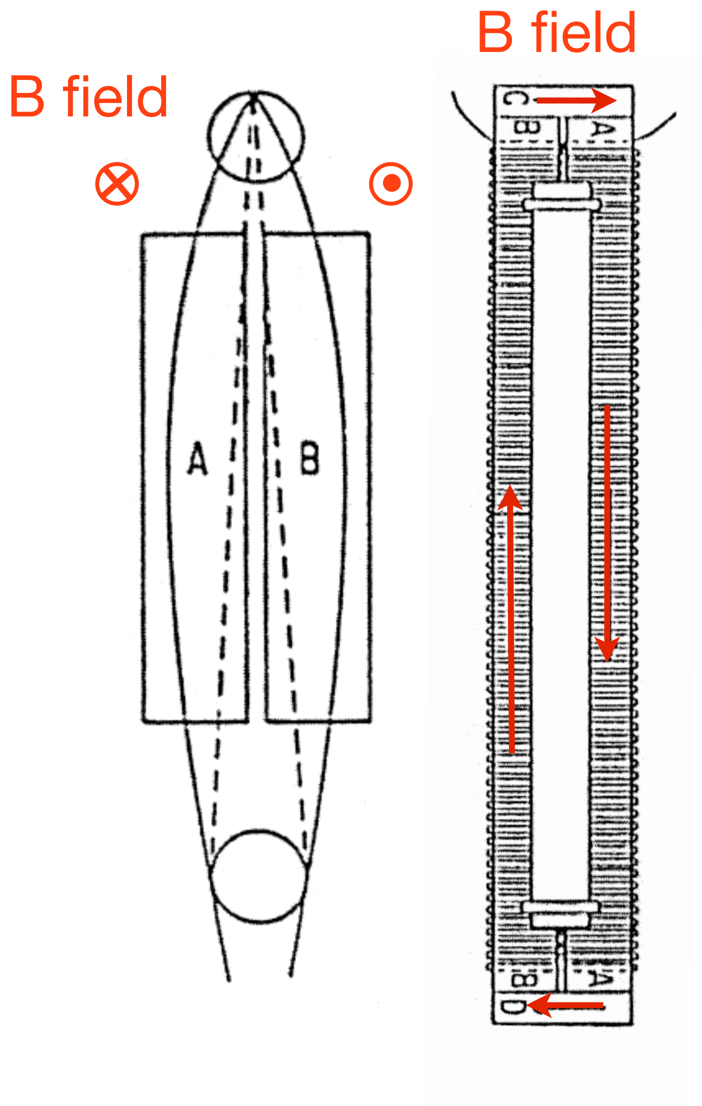
improved apparatus with magnetic lens for separation of negative and positive mesotrons. Use Fe (high Z material) as absorber. Confirmation of T-A theory.

1946 The CPP experiment

Use carbon (low Z) as absorber, for *experimental completeness sake.* Also for detecting photons emitted from nuclear capture of negative mesotrons. Results are in disagreement with the T-A theory.

Magnetic lens

1930 B. Rossi

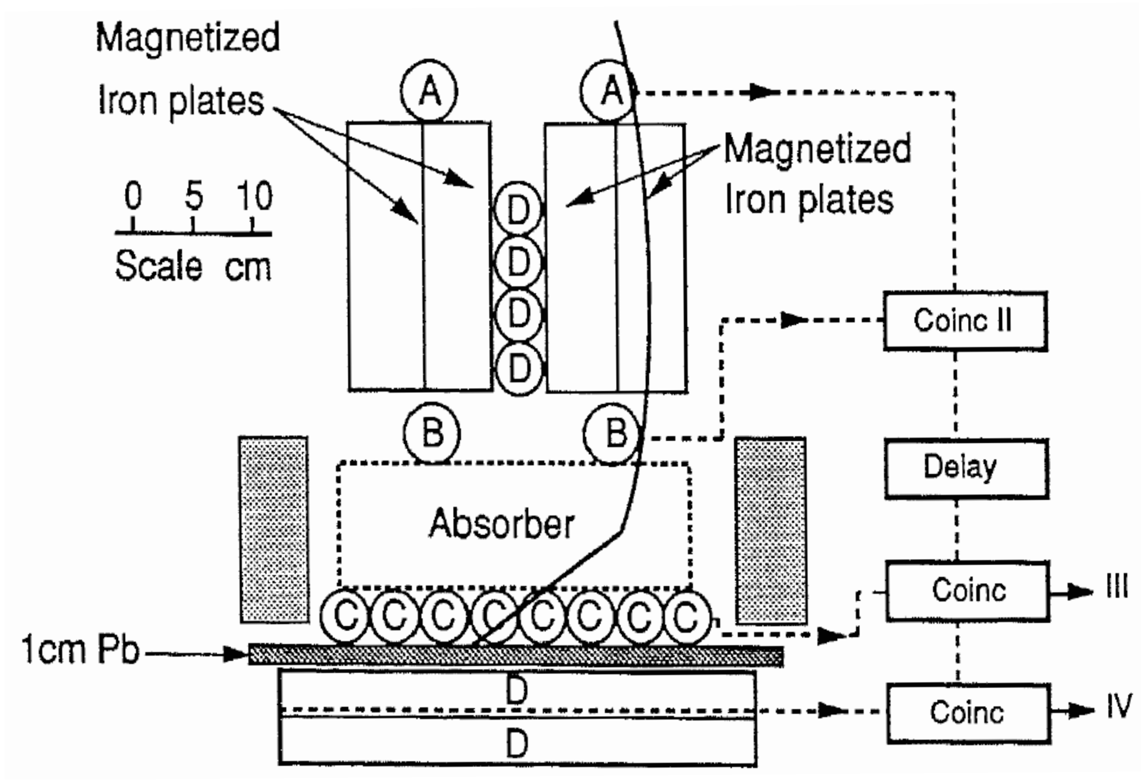


Closed magnetic circuit made of iron plates with coils wound around to produce a magnetic field

According to the direction of the B field the magnets focussed in one plane either negative or positive particles

1931 Rossi, Puccianti measured the relative abundance of positive (55%) and negative (45%) particles in cosmic rays.

Experimental setup



B field 15 kGauss to select negative and positive particles

Magnetic lens ~ 20 cm of Fe

Absorber Fe (5 cm), C (4 cm) graphite cylinders

III 3-fold delayed coincidence,
IV 4-fold delayed coincidence.
Signal = III - IV (decay electrons)

Delay: 1 - 4.5 μs

Pb (1cm) absorber for electrons from decays

1. Which is the typical energy for muons that are focussed and then stopped in the absorber?

2. Contamination from opposite sign particles selected by the magnetic lens is negligible. Use approximate measurements from the drawings and show how it depends on the geometry of the lens.

3. Which kind of events can fire the delayed 4-fold coincidence IV?

Main result of the CPP experiment

carica dei muoni fermati	assorbitore	frequenza di disintegrazione (eventi / 10 ore)
positiva	5 cm Fe	6.7 ± 0.65
negativa	5 cm Fe	0.3 ± 0.25
negativa	nessuno	-0.1
positiva	4 cm C	3.6 ± 0.45
negativa	4 cm C + 5 cm Fe	2.7 ± 0.35
negativa	6.2 cm Fe	0

The decay rate in Fe for negative particles is compatible with zero. Negative particles are captured by the nuclei before they decay

Decay rate of negative particles in C is different from zero and similar to positive particle rate

Results are in disagreement with T-A calculations for a strongly interacting Yukawa particle

Fermi and the CPP experiment

Fermi (with Teller and Weisskopf) concluded that there were about 12 orders of magnitude difference between the predicted capture time for a negative Yukawa particle and the results of the experiment for negative particles

The mesotron is not the strongly interacting Yukawa particle (today pion)

The mesotron was renominated the μ "meson"

«La prima volta (continua Piccioni) che io sentii questa affermazione fu da Enrico Fermi, nel suo studio in Chicago. Marcello era arrivato da poco a Chicago, ed era anch'egli presente, come anche Wick. Wick chiese a Fermi come egli si rappresentasse matematicamente la cattura del muone, e Fermi rispose con estrema naturalezza "con un potenziale immaginario". Quando uscimmo dallo studio di Fermi, Marcello mi disse di essersi goduto la mia faccia terrorizzata davanti a quelle parole. Forse esagerò; ma è vero che la mia innocenza in meccanica quantistica era al di là di ogni elogio (*it*

Problem 5: When the muon was originally discovered back in the 30s, people thought that this was the Yukawa particle. The Yukawa particle was considered then to be the mediator of the strong interaction. This incorrect interpretation of the nature of the muon was due to the fact that the muon mass (106 MeV) was not very different from the expected mass of the particle predicted by Yukawa. Later on it turned out that the Yukawa particle was the pion which was discovered in the 40s at Bristol.

This problem[2] relates to the calculations done by Tomonaga and Araki who predicted that if the muon was the mediator of the strong interaction then negative muons passing through matter would be more likely to be captured by the nuclei rather than decay.

(a) Show that a negative muon captured in an S-state by a nucleus of charge Ze and mass A will spend a fraction $f \simeq 0.25 A(Z/137)^3$ of its time inside the nuclear matter and that in time t it will travel a total distance $fct \quad (Z/137)$ in the nuclear matter. The hydrogen atom ground state wave function can be used in these calculations with modifications to account for the fact that the muon mass is of the order of 200 times larger than the electron mass:

$$\Psi_{100} = \frac{1}{\sqrt{\pi}}\left(\frac{Z}{\alpha_0}\right)^{3/2} e^{-\frac{Zr}{\alpha_0}} \text{ where } \alpha_0 = \frac{\hbar^2}{M_R e^2} \text{ and } M_R = \frac{m_p m_\mu}{m_p + m_\mu}$$ is the reduced mass of the proton muon system. The proton and muon masses are $m_p = 938\,MeV$ and $m_\mu = 106\,MeV$.

(b) The law of radioactive decay of free muons is $dN/dt = -\Gamma_d N$, where $\Gamma = 1/\tau$ is the decay constant (width) and the lifetime is $\tau = 2.16\,\mu\,sec$. For a negative muon captured in an atom Z the decay constant is $\Gamma_{TOT} = \Gamma_d + \Gamma_c$, where Γ_c is the width for nuclear capture i.e. the probability per unit time of nuclear capture. For aluminium $(Z = 13, A = 27)$ the mean lifetime of negative muons is $\tau = 0.88\,\mu\,sec$. Calculate Γ_c and using he expression for f in (a), compute the interaction mean free path Λ for a muon in nuclear matter.

(c) From the magnitude of Λ estimate the magnitude of the coupling constant of the interaction that caused the nuclear capture $\mu^- + p \rightarrow n + \nu$ given that the strong interaction coupling constant is α_S and corresponds to a mean free path of $1\,fm$.

Conversi, Pancini and Piccioni[3] did experiments in Rome in the 40s to test Tomonaga's and Araki's hypothesis and found that positive muons traversing different materials always decay rather than being captured (not surprising). They also found that negative muons undergo nuclear capture in iron. However, in carbon negative muons decay and do not get captured by the nucleus in direct contradiction of the Tomonaga-Araki hypothesis. Hence, the muons have nothing to do with the strong interaction.

Answers:

(b) 26.5 cm

(c) 10^{-7}

Finally the pion discovery

1947 Hypothesis of existence of the pion and the muon (Marshak, Bethe)

the Yukawa particle (the pion) is produced high in the atmosphere and decay into the muon which arrives on the earth

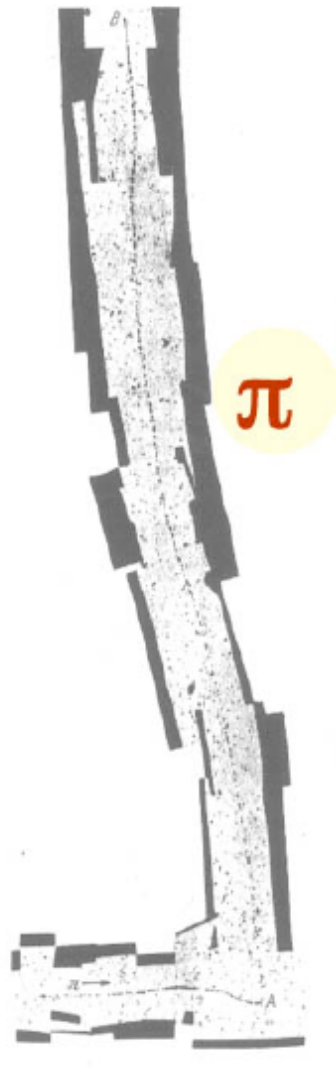
1947 Nuclear capture theory for muons (Wheeler)

$$\mu^- + p \to n + \nu_\mu$$

nuclear capture probability for muons is proportional to Z^4 (atomic number). Carbon (Z=6) has smaller capture probability than Fe (Z=26) in agreement with CPP experiment results.

1947 Discovery of the pion (Lattes, Muirhead, Powell, Occhialini,)

evidence of pion into muon decays in photographic plates



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