Muon lifetime and Conversi Pancini Piccioni experiments

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Muon group seminars

22^{nd} January 2024

Outline

- Scientific landscape at the time.
- Muon lifetime.
- Yukawa's theory and the Tomonaga&Araki hypothesis.
- Conversi, Pancini, Piccioni experiments.

Scientific landscape

- 1928: Dirac's equation describes relativistic motion of electrons.
- 1930: Bethe-Bloch (and Bohr): energy loss by ionization.
- 1930: Pauli postulates the existence of a new particle (neutrino) to explain the continuous energy spectrum in β decays.
- 1934: Fermi publishes his theory for β decay.
- 1934: Bethe-Heitler energy loss by *bremsstrahlung* (braking radiation).

Known particles

electron (1897) neutron (1932)

proton (1917) positron (1932)

see Elia's seminar

1937: Mesoton → Mesotron → μ meson → Muon

- Mesoton: Anderson
- Mesotron: Millikan and everybody else
- μ meson: Everybody until a few years later
- Muon: Everybody today

diagram stolen from Lorenzo's seminar

$$m_e < m < m_p$$

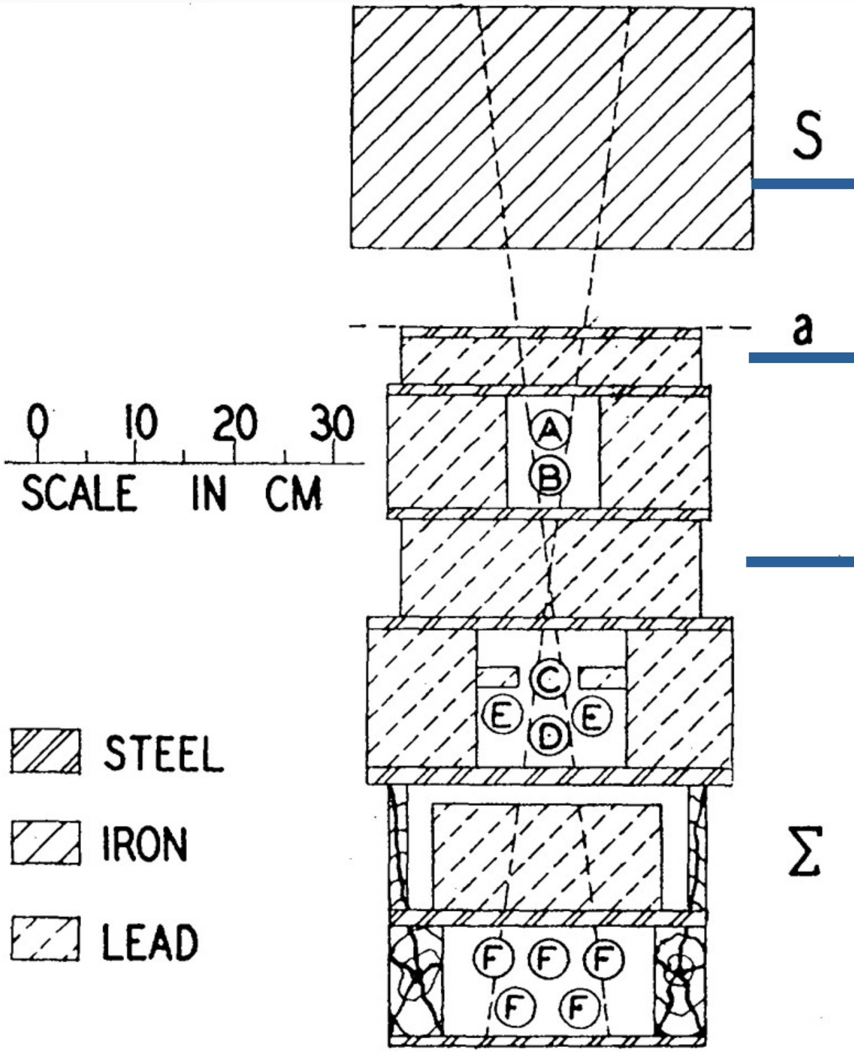
$$m \sim 100\,\mathrm{MeV}$$

Studying the new particle...

- Late '30 – first '40: It was well established that the hard component of cosmic rays is composed of mesotrons.
- Anomalous absorption of mesotrons in the atmosphere is observed by several groups around the world.
  It can be explained assuming the mesotron decay: $\mu \rightarrow e^{-} \nu$
- Several groups measure the mesotron lifetime with <10% precision, using different techinques:
  - B. Rossi, D.B. Hall;
    B. Rossi, K. Greisen, J.C. Stearns, D.K. Froman (Colorado);
  - F. Rasetti (Canada);
  - W.N. Nielsen, C.M. Ryerson, L.W. Nordheim, K.Z. Morgan (North Carolina);
  - G. Bernardini, B.N. Cacciapuoti, B. Ferretti, O. Piccioni, G.C. Wick (Italy);
  - M. Conversi, E. Pancini, O. Piccioni (Italy).

Mesotron lifetime: Rossi and Hall

Phys. Rev. 59, 223 (1941)



Fe absorber

5 cm Pb

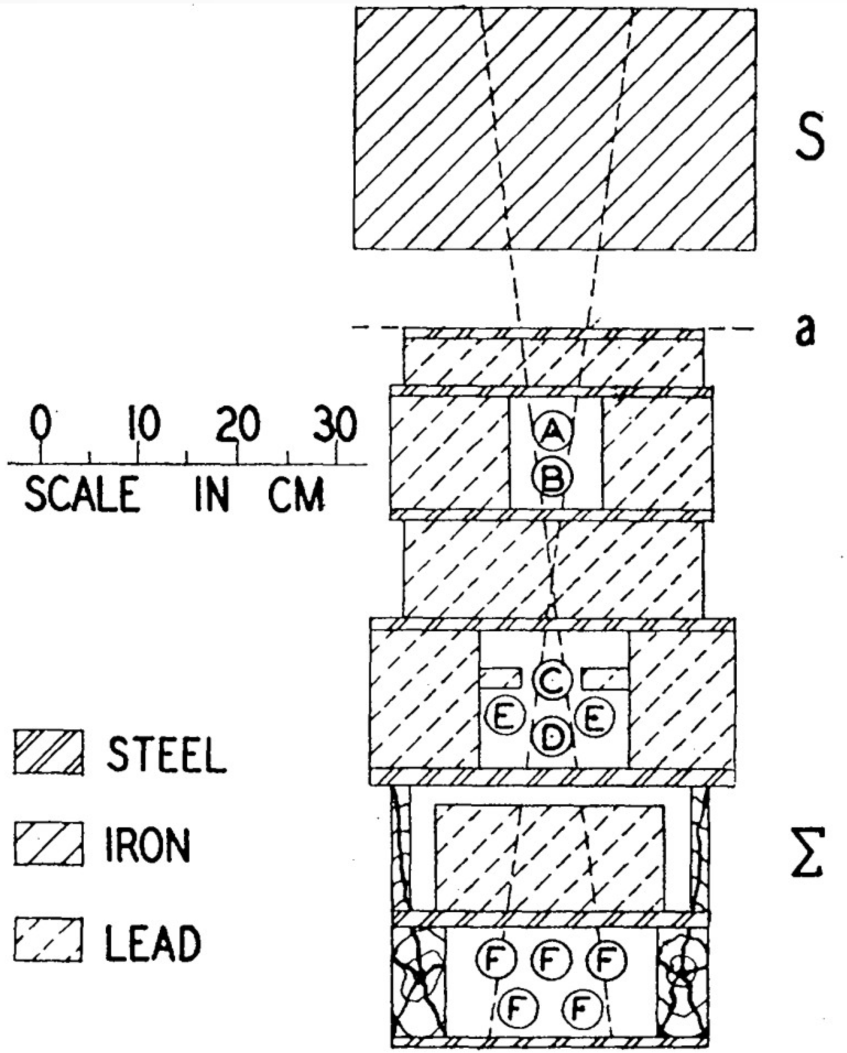
Equivalent to 196 g/cm^2

10 cm Pb

115 g/cm^2 Pb (~10 cm)

Mesotron lifetime: Rossi and Hall

Phys. Rev. 59, 223 (1941)



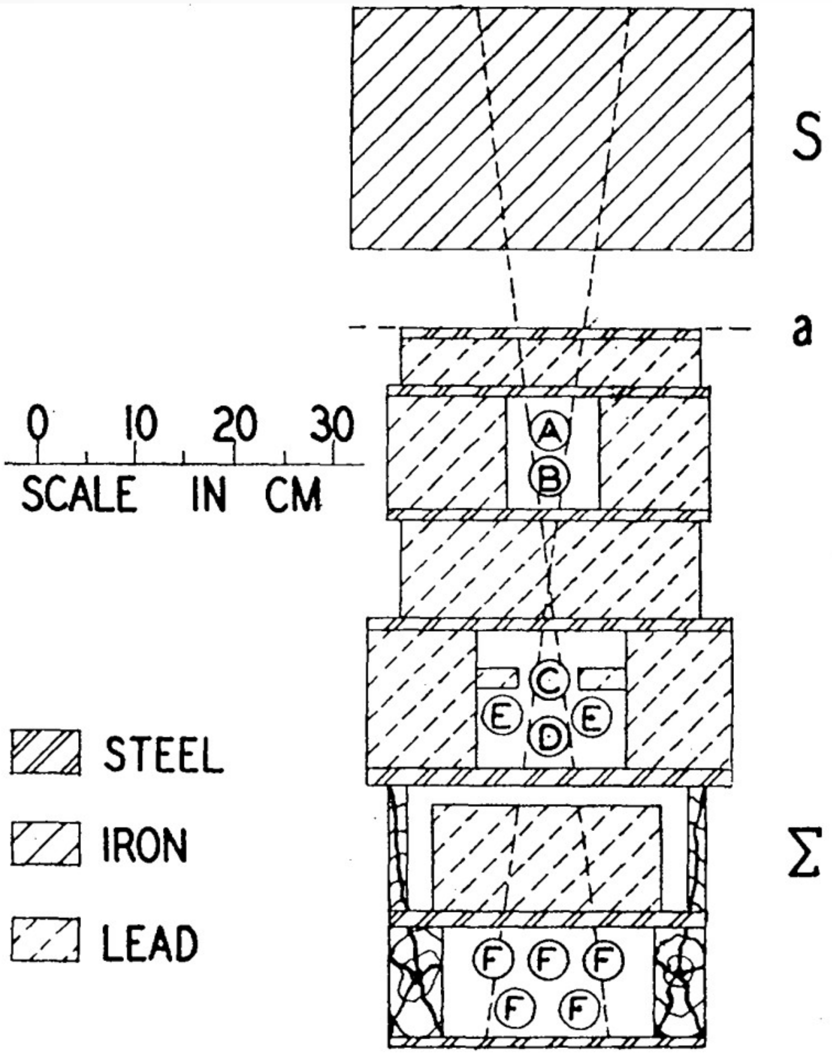
A, B, C, D, E, F: Geiger counters.

Goal:
select a specific momentum range to determine the mesotron lifetime through the relativistic expression

$$L = \beta\gamma c\tau = \frac{p}{m}\tau$$

Mesotron lifetime: Rossi and Hall

Phys. Rev. 59, 223 (1941)



Measurements in 2 locations:

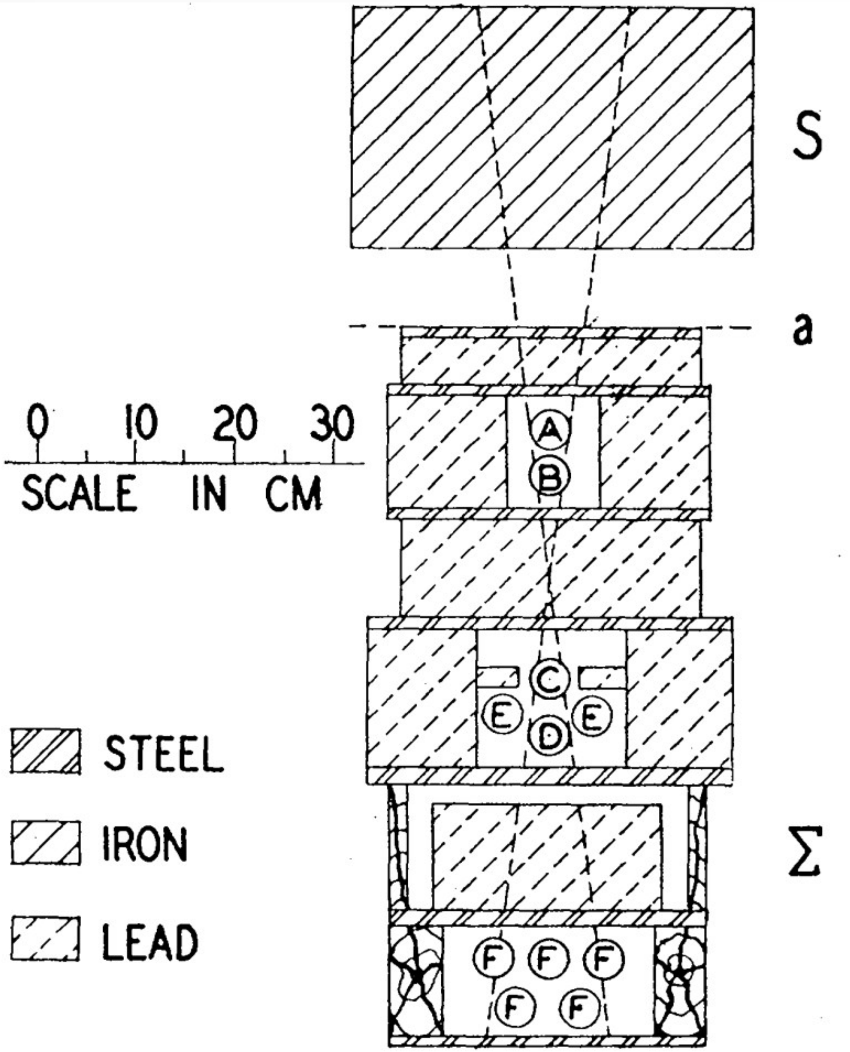
- Echo Lake (z_1 = 3240 m) with S.
- Denver (z_2 = 1616 m) without the absorber S.

Two run conditions in each location:

- Without the absorber Σ (mesotrons with penetration range < 196 g/cm^2)
- With the absorber Σ (mesotrons with penetration range < 311 g/cm^2)

Mesotron lifetime: Rossi and Hall

Phys. Rev. 59, 223 (1941)



Record the coincidences

$$ABCD(\overline{E||F})$$

- Mesotrons stopped between D and F.
- Hard mesotrons not detected by F.
- Chance coincidence of ABCD.

$N_{\Sigma} - N_{\text{no}\,\Sigma} = N(\text{range } [196, 311]\ \text{g/cm}^2)$

Mesotron lifetime: Rossi and Hall

Use the Bethe-Bloch to find the corresponding momentum range:

$$-\frac{dp}{dx} = \frac{2\pi r_0^2 N Z m_e}{\beta^3}\left(\ln \frac{W_m m_e \beta^2}{I^2 Z^2 (1-\beta^2)} + 1 - \beta^2\right)$$

Integrate to get Range(*p*):

Range in [196, 311] g/cm^2 ⟷ *p* in [310, 450] MeV

Further correction to take into account the momentum loss in the atmosphere:

p in [440, 580] MeV

Average effective momentum: *p* = 500 MeV

Mesotron lifetime: Rossi and Hall

Extract *L* from the
probability of survival between Echo Lake and Denver:

$$w = \frac{N(\text{range } [196,\, 311]\ \text{g/cm}^2\ @\ \text{Denver})}{N(\text{range } [196,\, 311]\ \text{g/cm}^2\ @\ \text{Echo Lake})} = e^{-(z_1 - z_2)/L}$$

$$L = \frac{p}{m}\tau$$ → τ = (2.4 ± 0.3) μs

Disclaimer:
they set m = 80 MeV

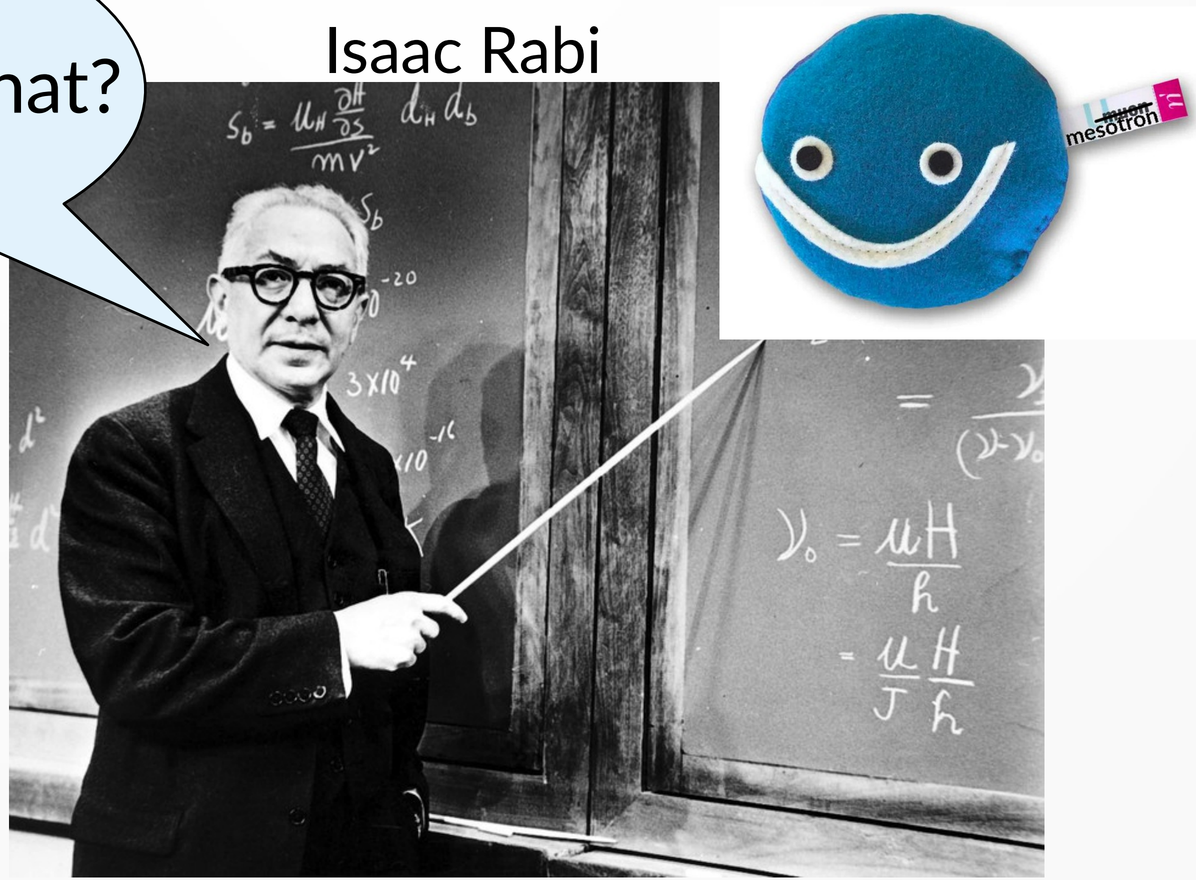
τ(105 MeV) = 3.2 μs

All the τ measurements from several different groups where within [1, 3] μs, with <10% precision.

1 million $ question

Who ordered that?

Isaac Rabi

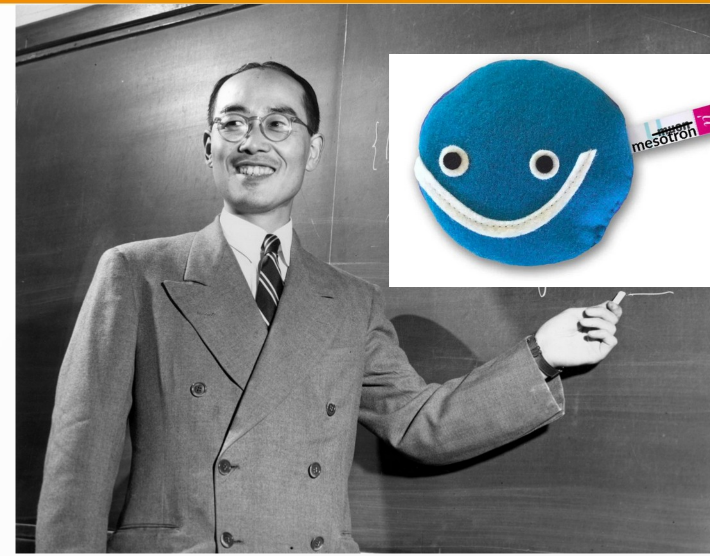


1 million $ question

Hideki Yukawa

Yukawa's theory (1935)

New particle:
mediator of nuclear interactions



- Must exists in 3 charge states (to explain *pn* and *nn* interactions).
- Must be a boson.
- Must be responsible of the β decay.

What's the mass of the new particle?

EM interactions:
infinite range

$$V_{em} \propto \frac{1}{r} \longrightarrow m_\gamma = 0$$

Nuclear interactions:
limited range

$$V_{nucl} \propto \frac{e^{-r/r_0}}{r} \quad r_0 \sim \frac{\hbar c}{mc^2} \quad m \sim 200\,\mathrm{MeV}$$

$$r_0 \sim 1\,\mathrm{fm}$$

Tomonaga and Araki's hypothesis

Yukawa's particles (Yukons) at rest in matter
behave differently depending to their electric charge.

Positive Yukons

Do not interact with nuclei because of Coulomb repulsion.

↓

They have enough time to decay.

Negative Yukons

Coulomb interaction with nuclei.

↓

"Mesotronic" atom with nuclei and absorption in $t << \tau$

$$\eta_{TA} = \frac{M}{A} \sim 0.5 \div 0.6$$

M = N(decayed Yukons)

A = N(Yukons stopped in the material)

Conversi, Pancini and Piccioni

Marcello Conversi

Ettore Pancini

Oreste Piccioni

Conversi, Pancini and Piccioni

- They want to study the mesotron,
  and determine if it’s actually the Yukawa’s particle.

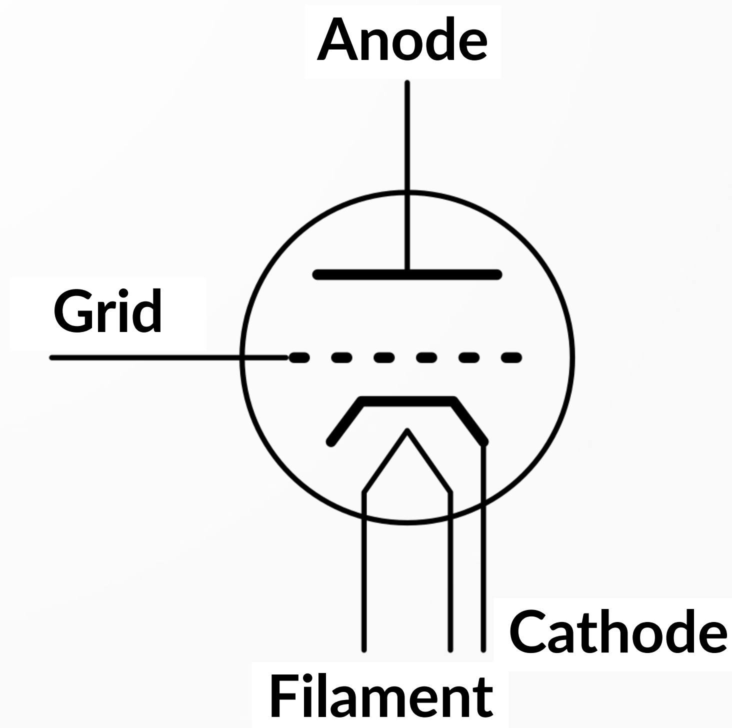
- Late ‘30 – first ‘40:
  they develop state of the art electronic circuits
  with delayed coincidences. Their circuits are based on:
    - Termionic valves.
    - Monostable circuits.

- Geiger counters to detect particles.

Thermionic valve (vacuum tube)

First active component in electric circuits
(precursor of transistors).

- Heat the filament, which emits electrons due to thermionic effect.
- If $V_{grid} > V_{cathode}$, then the current on the anode is amplified.
- If you send a signal on the grid, it will be amplified on the anode.

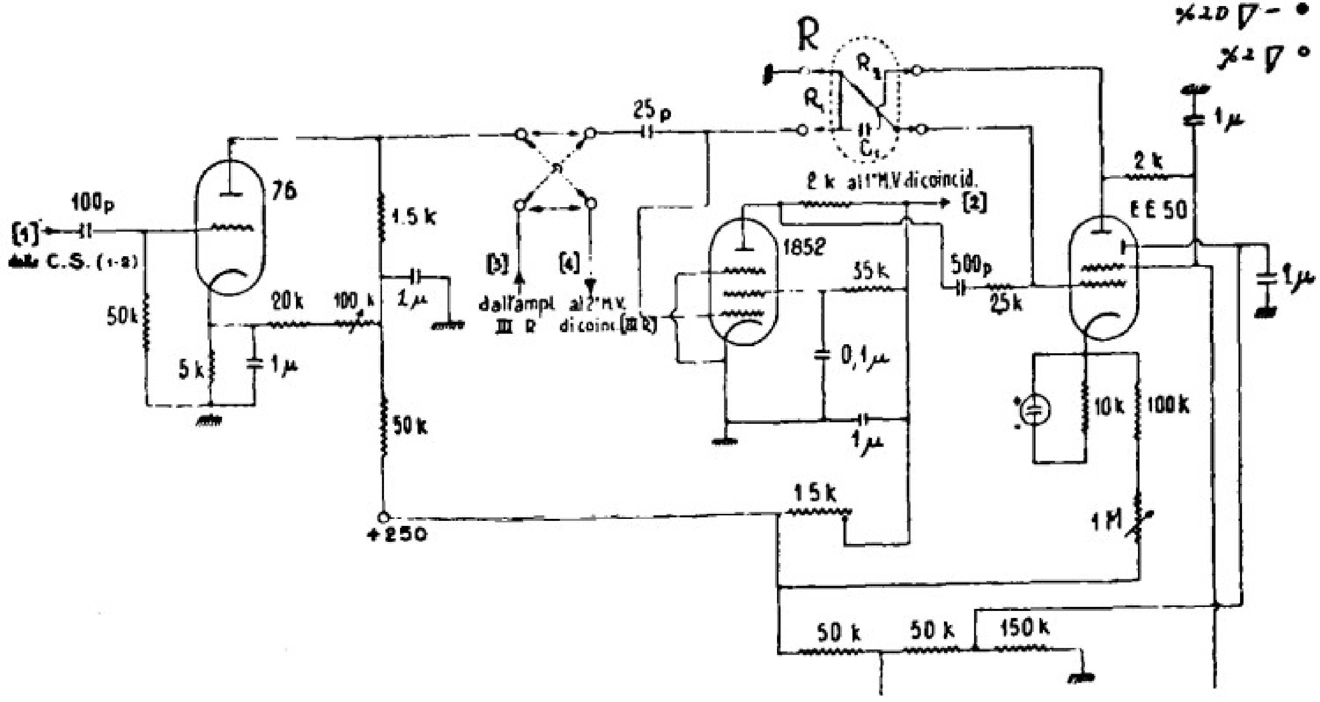


Monostable circuits

Input: signal with irregular shape.

Output: rectangular signal with known time length.

Fundamental improvement to implement coincidence circuits.



Related history

CPP experiments at Rome during the Second World War (1943-46).

- 1943-44: 1st Conversi Piccioni experiment: mesotron lifetime.
- 19/07/1943: bombing in San Lorenzo (Rome).
  CP apparatus was moved from “La Sapienza” University to a high school close to Vatican (Liceo Virgilio).
  Pancini got injured during the bombing. He sought refuge in Venice, where will join the partisans to fight for the liberation of Italy.
- 09/1943: Piccioni tried to join the Allies in the south of Italy, but he got imprisoned by the Germans in Frosinone. He will be set free after 10 days.
- 1944: 2nd Conversi Piccioni experiment: absorption of mesotrons at rest.
- 1945-1946: Conversi Pancini Piccioni experiment:
  clarify the nature of negative mesotrons.

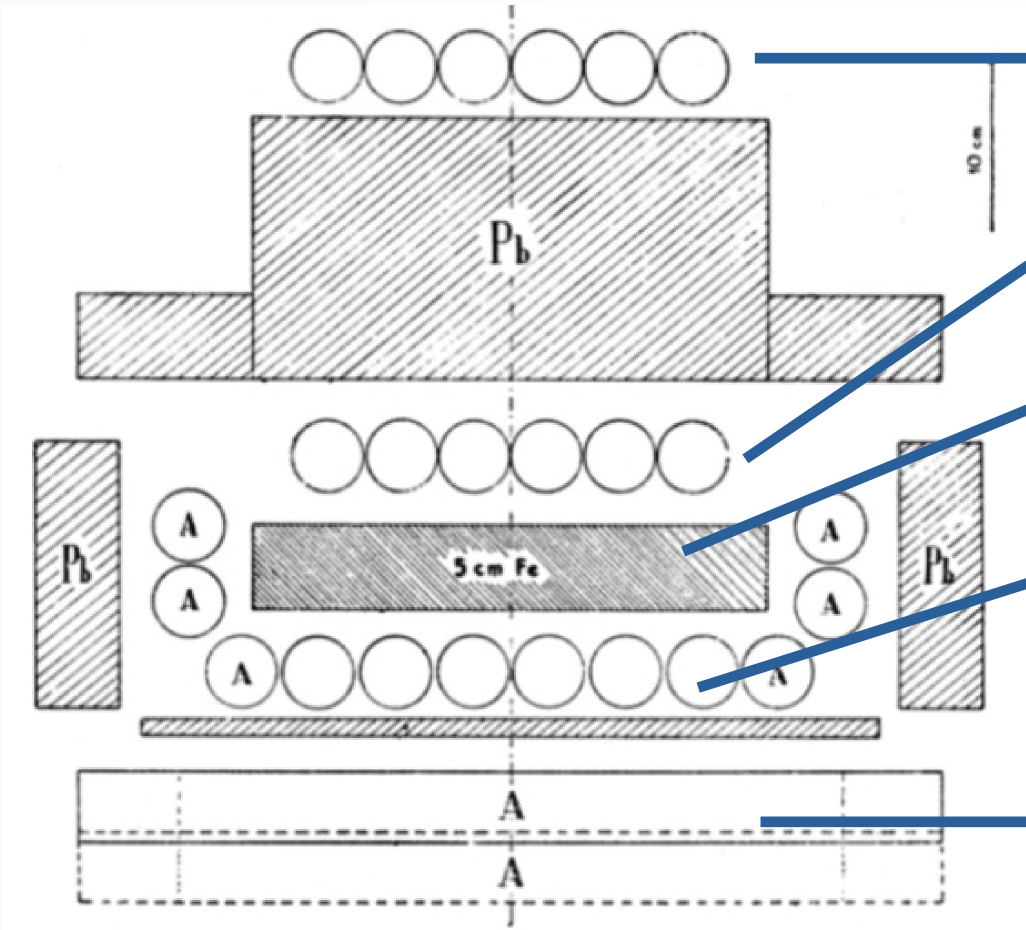
1st Conversi – Piccioni experiment

Marcello Conversi

Oreste Piccioni

1st Conversi – Piccioni experiment

Direct measurement of mesotron lifetime



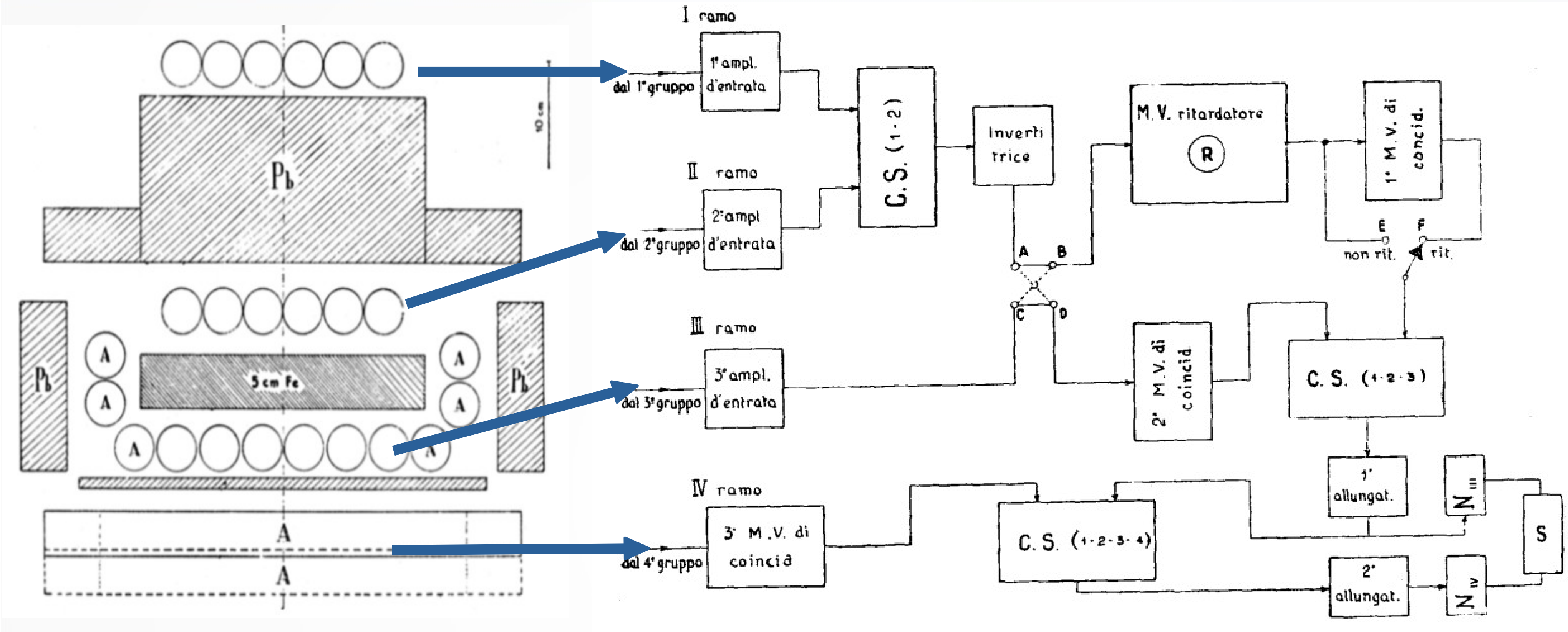
Geiger counters (I group)

Geiger counters (II group)

Absorber: 5 cm Fe

Geiger counters (III group)
(detect decayed electrons)

Geiger counters (IV group)
(quadruple coincidence to
reject chance coincidence).



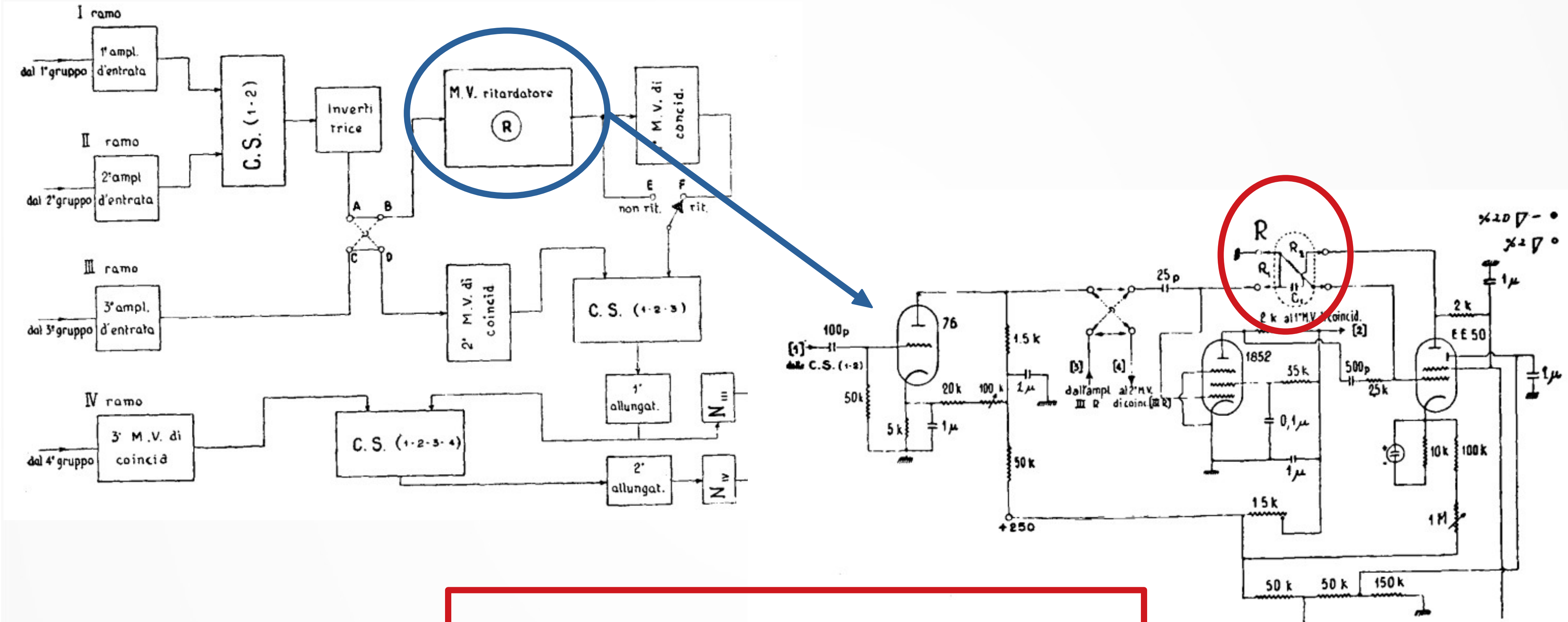
CS 1-2:
the particles reach
the absorber.

CS 1-2-3:
delayed
coincidences.

Mesotron
decay

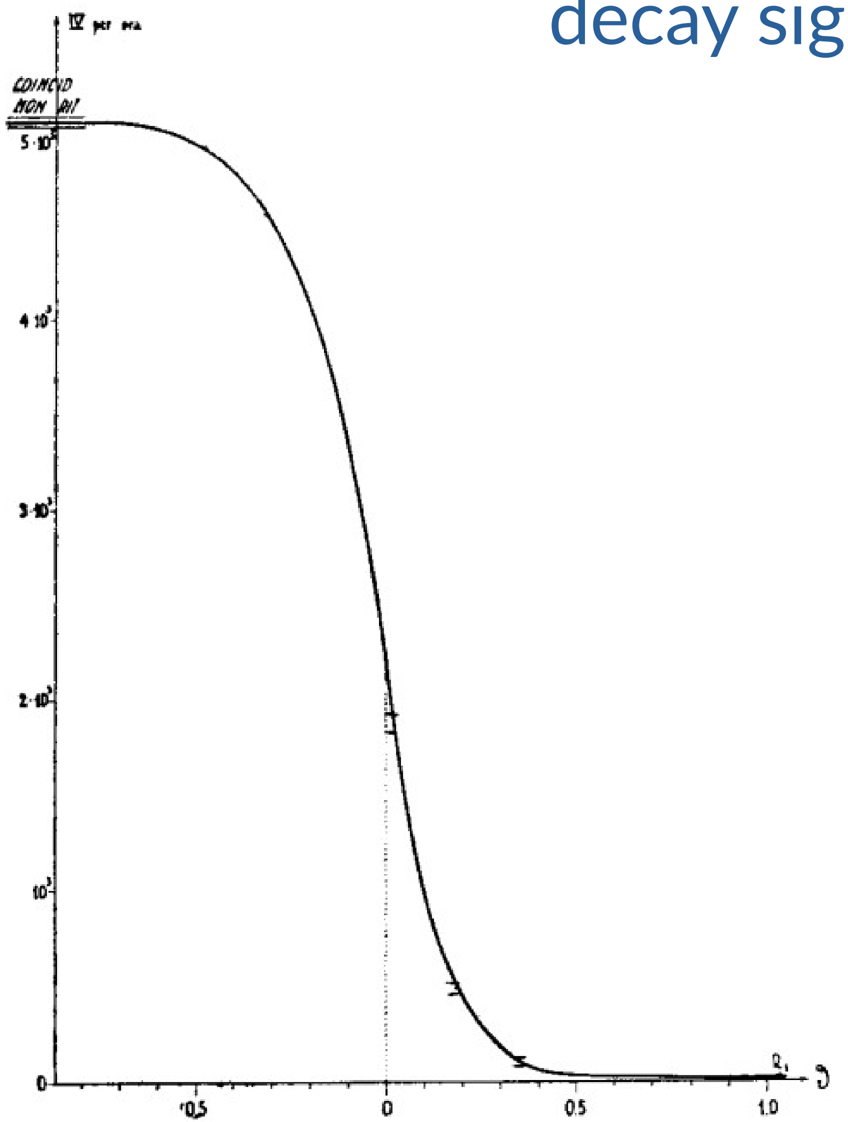
CS 1-2-3-4: delayed coincidences,
to determine the number of chance coincidences.

How to sample the decay rate in multiple points?



Modify the delay between
CS 1-2 (double coincidence)
and group 3 (decayed mesotron)
by changing R_1, R_2 and C.

How to calculate the delay between CS 1-2 and the decay signal (III group)?



Plot the delay curve for the quadruple coincidences.

The inflection point corresponds to zero delay.

1st Conversi – Piccioni experiment

Number of
decayed mesotrons (M):

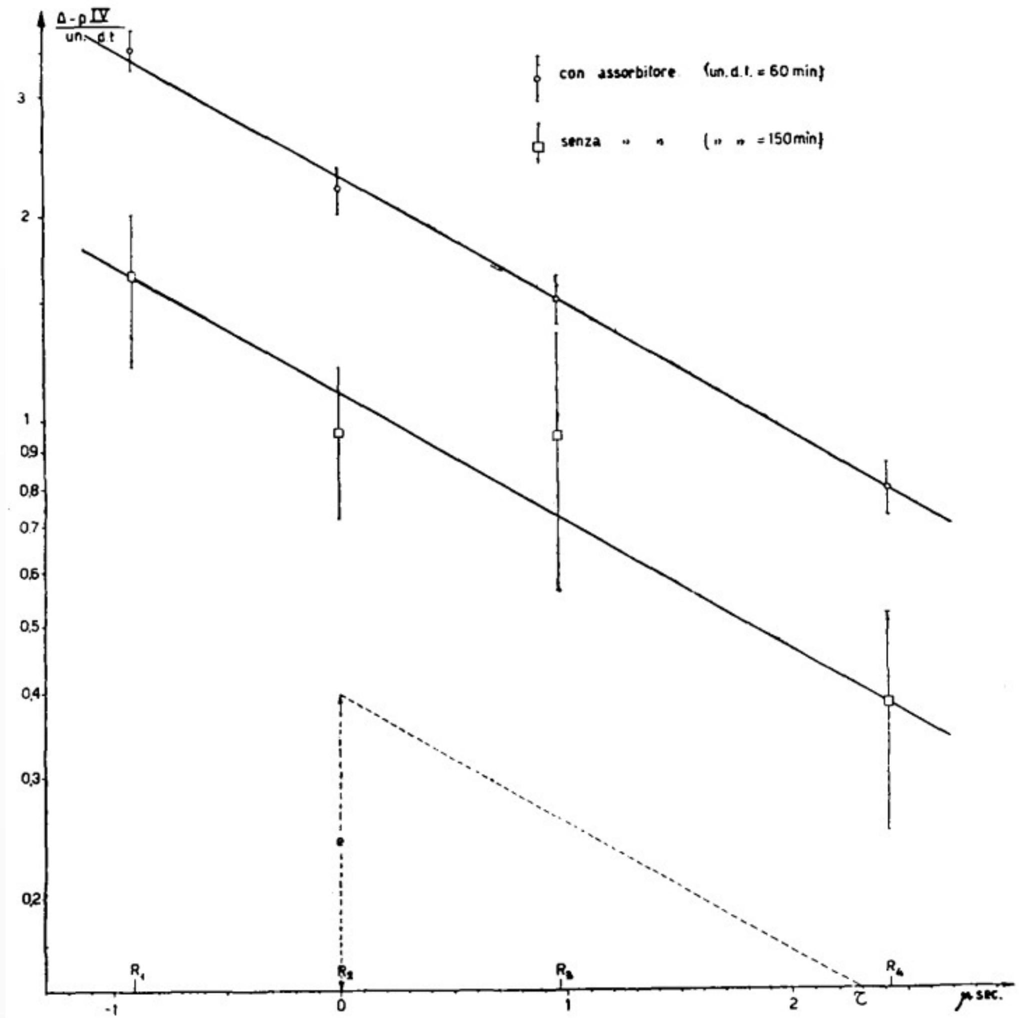
$$M = T - (1 + p)Q$$

T = CS 1-2-3 (delayed coincidences)

Q = CS 1-2-3-4
(delayed random coincidences)

pQ = correction to take into account the efficiency of CS 1-2-3-4.

$$\tau = 2.3\ \mu s \pm 7.5\%$$



2nd Conversi – Piccioni experiment

CP want to verify Tomonaga&Araki hypothesis
about the mesotrons absorption in matter.

Positive Yukons → Slow absorption, they can decay.

Negative Yukons → Fast absorbtion in the material.

CP measure the number of decayed mesotrons (M)
and the number of mesotrons absorbed in 5 cm of Fe (A):

$$\eta_{CP} = \frac{M}{A} = 0.56 \pm 0.08$$

The result is in agreement with
Tomonaga&Araki hypothesis.

2nd Conversi – Piccioni experiment

Is the mesotron the Yukawa particle?

Un'esperienza atta a fornire una risposta presumibilmente definitiva sull'argomento in questione, è stata da tempo suggerita dal dott. ETTORE PANCINI; essa doveva consistere nel misurare le coincidenze ritardate prodotte da elettroni di disintegrazione, concentrando alternativamente i mesoni positivi e quelli negativi per mezzo di blocchi di ferro magnetizzati. Purtroppo questa esperienza, in seguito alle attuali contingenze, non si è ancora potuta realizzare.

An experiment aimed at providing a conclusive answer to this issue has been suggested since a long time by Dr Ettore Pancini. It consists in measuring the delayed coincidences produced by the decayed electrons, focusing alternately positive and negative mesotrons in the apparatus by means of magnetized iron blocks. Unfortunately, due to the current circumstances, this experiment couldn't be performed yet.

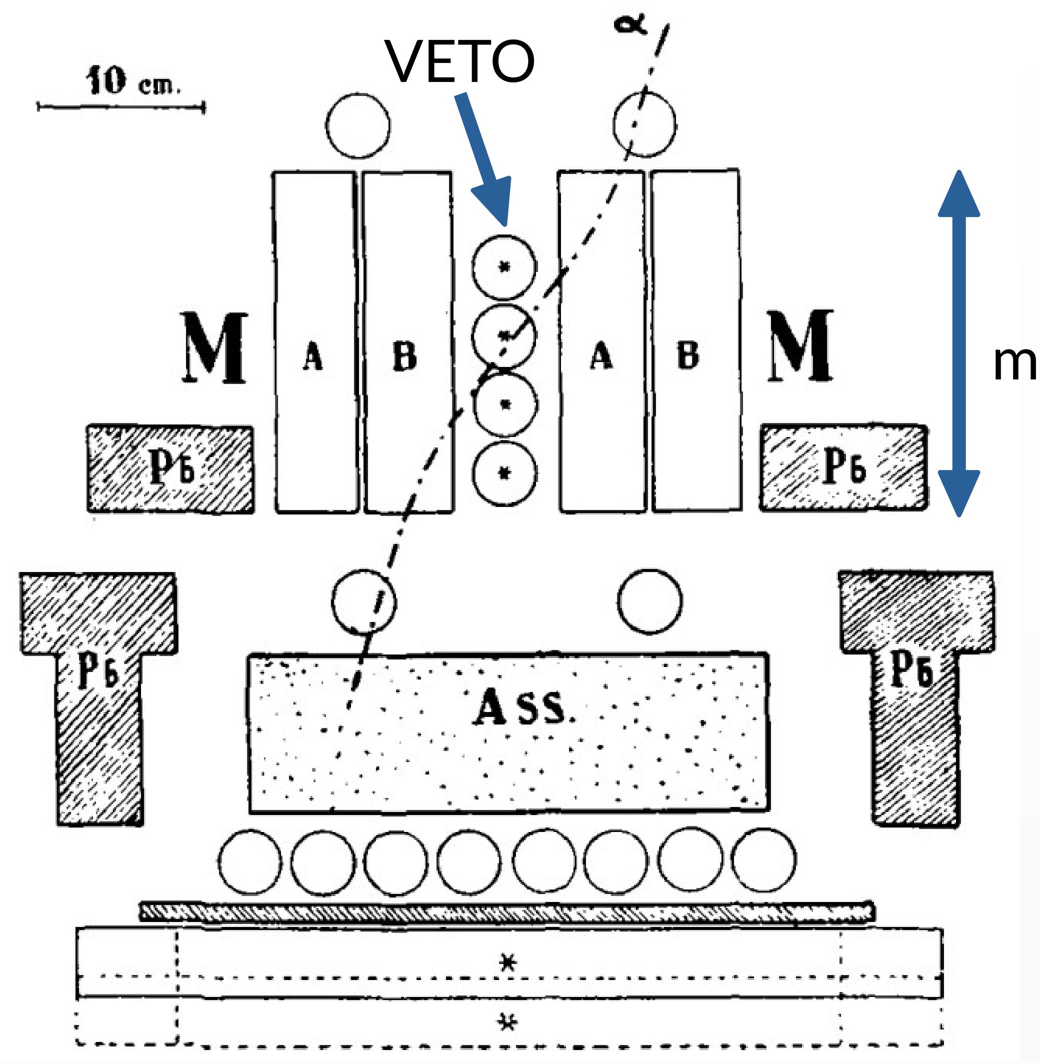
Conversi – Pancini – Piccioni experiment

Marcello Conversi

Ettore Pancini

Oreste Piccioni

Conversi – Pancini – Piccioni experiment



20 cm
magnetized Fe

Magnets are designed to stop mesotrons with E ~ 400 MeV

$$\vec{B} = 1.54\,\mathrm{T}$$

Absorber: 5 cm Fe

M = (III – IV) - pIV

Segno	Assorbitore	III	IV	t	IV/ora	M	$\frac{M_-}{M_+}$
+	5 cm Fe	213	106	155^h —	0,69 ± 0,07	0,67 ± 0,065	
—	5 cm Fe	172	158	206^h —	0,77 ± 0,06	0,03	0,048
—	Assente	71	69	$107^h 45'$	0,64 ± 0,08	— 0,01	

Negative mesotrons **DO NOT** produce any count. → Further confirmation of the Tomonaga&Araki hypothesis.

Next step: understand what's the absorption process.

Gian Carlo Wick suggests

$p\ \mu^- \rightarrow n\ \gamma$ with $E_\gamma = m_\mu$

Absorber: 4 cm C

In order to test Wick's suggestion, CPP use a light absorber to detect the emitted photon: graphite cylinders, 4 cm thick (equivalent to 1.2 cm Fe).

They start studying the delayed coincidences with the new absorber before instrumenting the apparatus to detect photons.

Segno	Assorbitore	III	IV	t	IV/ora	M	$\frac{M_-}{M_+}$
+	4 cm C	170	101	$179^h 20'$	0,56 ± 0,055	0,36 ± 0,045	
—	4 cm C + 5 cm Fe	218	146	243^h —	0,60 ± 0,05	0,27 ± 0,035	0,75
—	6 cm Fe	128	120	240^h —	0,50 ± 0,045	0,008	

Negative mesotrons:
Use (4 cm C + 5 cm Fe) vs 6 cm Fe, for a comparison in the same energy range of the previous measurements.

Absorber: 4 cm C

Segno	Assorbitore	III	IV	t	IV/ora	M	$\frac{M_-}{M_+}$
+	4 cm C	170	101	$179^h 20'$	0,56 ± 0,055	0,36 ± 0,045	
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—	6 cm Fe	128	120	240^h —	0,50 ± 0,045	0,008	

Clear evidence of decays coming from the negative mesotrons: this is **AGAINST** Tomonaga&Araki hypothesis.

A comment by Piccioni, 1984

Obviously our results contradicted Tomonaga and Araki,
because they had calculated exactly what we should observe.

We were very happy about that:
it is always fun for experimentalists to prove theorists wrong.

But none of us understood that our data showed that the cosmic ray mesotrons were not the Yukawa particles. In fact, such an assertion is not in our publication. It would have meant that we had understood some nonobvious points faster than a long list of theorists, including N. Bohr…

Conversi – Pancini – Piccioni experiment

CPP transmit confidentially their result to Edoardo Amaldi, who was in the USA.

A few weeks later Fermi, Teller and Weisskopf calculate the absorption time of Yukawa mesons in C and Fe:

$$\tau_{ass}^{C} \sim 10^{-18}\ \mathrm{s} \qquad \tau_{ass}^{Fe} \sim 10^{-20}\ \mathrm{s}$$

CPP found some decays from the negative mesotrons:

$$\tau_{ass} \sim \tau_{dec} \sim \mu\mathrm{s}$$

→ The mesotron can't be Yukawa's particle.

How to explain the different results between Fe an C?

The absorption of μ⁻ in the nucleus occurs in 2 steps:

1) K capture: μ⁻ falls into an excited Bohr orbit, then emits radiation until it reaches the K orbit:

$$r_B^\mu \simeq \frac{r_B^{e^-}}{200}$$

For heavy atoms:

$$r_B^\mu < R_N$$

The μ⁻ wave function overlaps with the nucleus

2) μ⁻ absorbed by the nucleus: $\mu^- \; p \rightarrow n \; \nu$

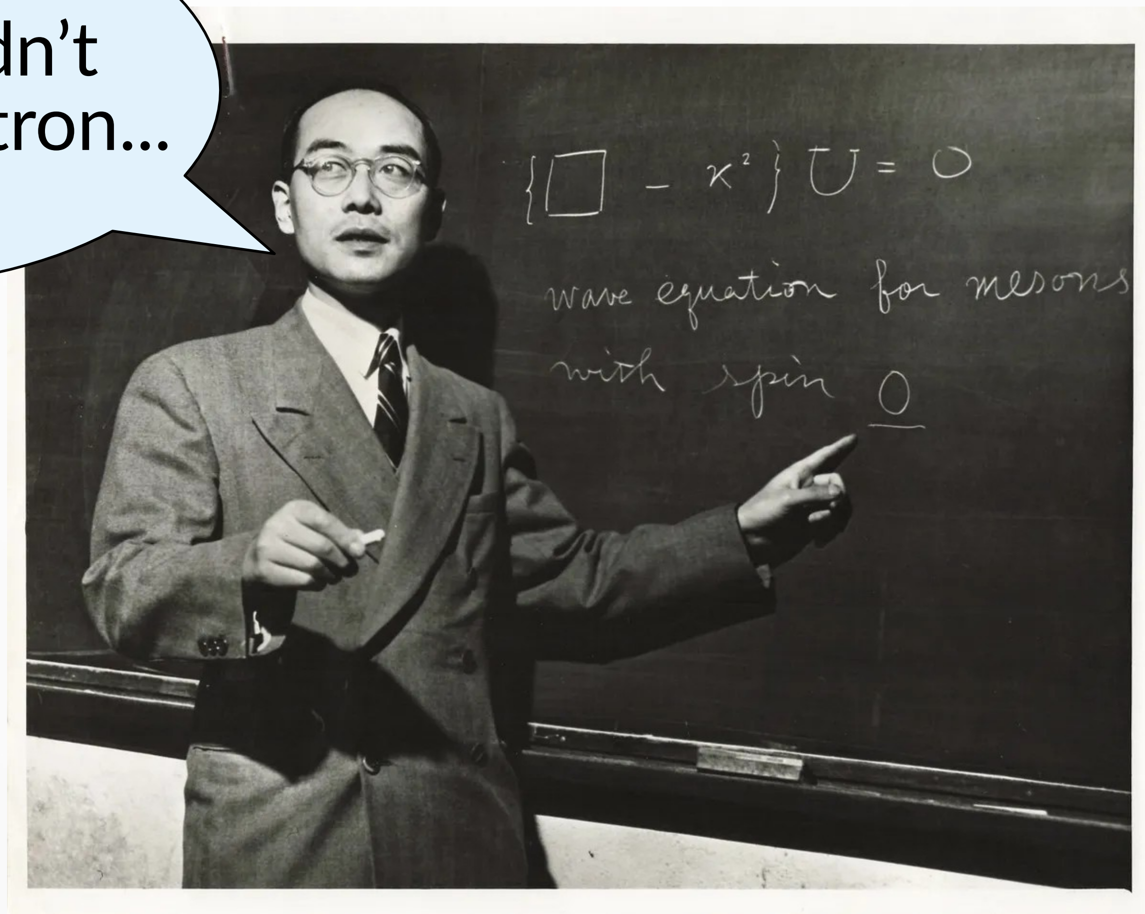
The absorption and the decay will compete

$$\tau_{ass} \sim \tau_{dec} \sim \mu\mathrm{s}$$

$$P_{abs} \propto Z^4 \qquad \frac{P_{abs}^{\mathrm{Fe}}}{P_{abs}^{\mathrm{C}}} \sim \left(\frac{Z_{\mathrm{Fe}}}{Z_{\mathrm{C}}}\right)^4 \sim 350$$

What is Yukawa’s particle?

Maybe I didn’t order a mesotron...



What is Yukawa’s particle?

Maybe I ordered
a pion!