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SCHOOL ON
NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

FROM DISCOVERY OF COSMIC RAYS (1912)
TO DISCOVERY OF HYPERFRAGMENTS (1953)

by
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CONTENT OF LECTURES

COVERED PERIOD - 40 YEARS:

FROM DISCOVERY OF COSMIC RAYS (1912)

TO DISCOVERY OF HYPERFRAGMENTS (1953)

ONLY APPROXIMATELY HISTORIC PRESENTATION OF MAIN IDEAS AND EVENTS THAT PRECEDED THE DEVELOPMENT OF LARGE ACCELERATORS

EMPHASIS ON ITEMS MOST RELEVANT FOR THE DEVELOPMENT OF PARTICLE PHYSICS

DETAILS ONLY OCCASIONAL (PERSONAL RECOLLECTIONS)

REFERENCES:

a) The Birth of Particle Physics, based on a Fermilab Symposium, Edited by L.M.Brown and L.Hoddeson (Cambridge University Press, 1983).

b) International Colloquium on the History of Particle Physics, in Journal de Physique, Colloque C8, Supplement au n° 12, décembre 1982. Specifically: Ch. Peyrou talk from page C8-7: The Role of Cosmic Rays in the Development of Particle Physics.

c) Proceedings of 1984 "Wingspread Confer." on "50 years of weak interactions". Specifically: Rochester's report on The Discovery of the V-particles

DISCOVERY OF COSMIC RAYS etc.

PREHISTORY

1900: STUDY OF CONDUCTIVITY OF AIR BY ELECTROSCOPES (J.ELSTER, H.GEITEL, C.T.R. WILSON, ...)

RESIDUAL CONDUCTIVITY PRESENT EVEN AFTER 10 cm Pb SHIELDING. HYPOTHESIS OF PENETRATING RADIATION OF UNKNOWN EXTRATERRESTR. ORIGIN FIRST ADVANCED AS A POSSIBILITY

1909: HYPOTHESIS SOMEWHAT REINFORCED BY THE FACT THAT ELECTROSCOPES IN BALLOON AT 4000 m ALTITUDE DISCHARGE MORE QUICKLY THAN AT SEA LEVEL (A.GOKKEL, ...)

1911-12: V.F.HESS AND SHORTLY AFTERWARDS W.KOLHORSTER DEMONSTRATE THAT IONIZATION FIRST DECREASES FROM GROUDD TO ~ 700 m, THAN INCREASES STEADTLY WITH ALTITUDE. HESS SHOWS ABSENCE OF DIURNAL EFFECTS AND PUT FORTH HYPOTHESIS OF EXTREMELY PENETRATING "COSMIC" RADIATION, FOR MANY YEARS BELIEVED TO CONSIST OF H.E. GAMMAS (GAMMAS FROM RADIOACTIVE SUBSTANCES KNOWN TO BE FAR MORE PENETRATING THAN "CORPUSCULAR RAYS"). Penetrating power demonstrated by measurements under 10 m of water first, 10 m Pb later

WORK INTERRUPTED DURING WORLD WAR I NOT RESUMED AFTER THE WAR UNTIL ~ 1922

Millikan proposes the name of COSMIC RAYS

1927: DISCOVERY LATITUDE EFFECT (J.CLAY)

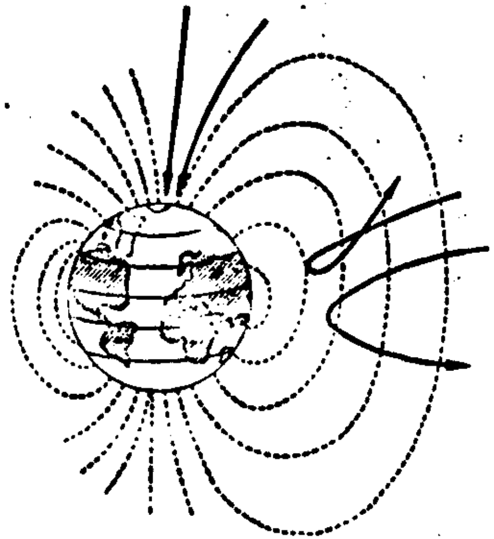
~ 10% MEASURED EFFECT AT SEA LEVEL (A.H.COMPTON et al. , 1933)

HENCE: PRIMARY C.R. ARE CHARGED

THEORY OF AURORA BOREALIS (C.STOERMER)

~ 5000 hours of calculations and many Kg. of paper for 120 trajectories

THE LATITUDE EFFECT



IOMENTUM THRESHOLD AT LATITUDE L FOR
'RIMARY PARTICLE OF CHARGE $q = z \cdot e$:

$$_t = 300 \cdot (Mz/4R^2) \cdot \cos^4 L = 15 \cdot z \cdot \cos^4 L \text{ GeV} \quad /z$$

EING $M \equiv |\vec{M}| = \sim 8.1 \times 10^{25}$ gaussxcm^3
ND $R = 6.37 \times 10^8$ cm

ESPECTIVELY THE MAGNETIC MOMENT AND THE
'ERAGE RADIUS OF THE EARTH.

Bowen, Millikan + Neher, 1936

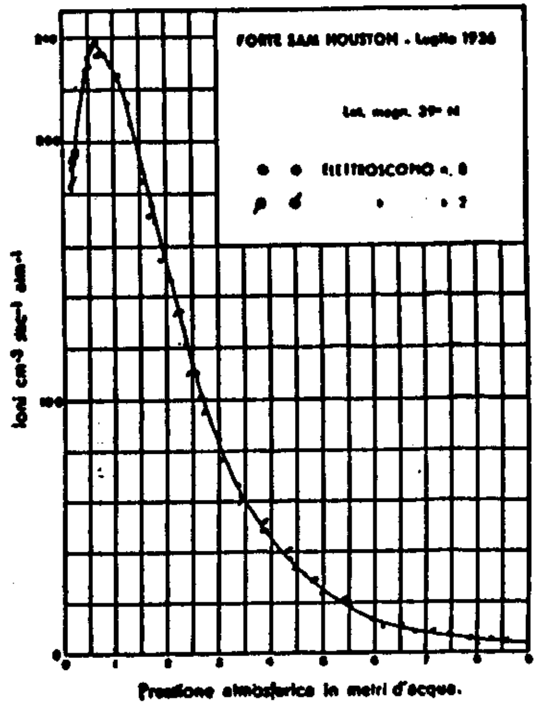


Fig. nn. - Curva di ionizzazione in funzione dell'altitudine. Il numero degli ioni per c.c. è stato ridotto ad una atmosfera; la pressione è misurata in metri d'acqua a partire dalla sommità (1 atm. = 10 m. d'acqua).

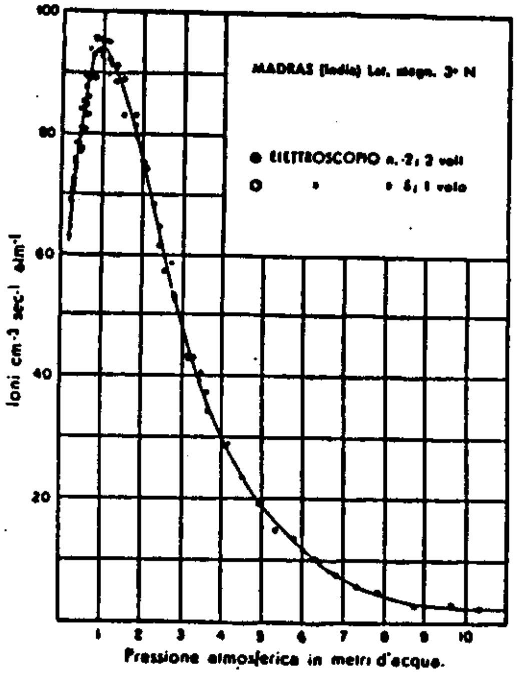


FIG. 21. - Curva di ionizzazione in funzione dell'altitudine, relativa a Madras (India).

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ENERGY SPECTRUM OF PRIMARY COSMIC RAYS

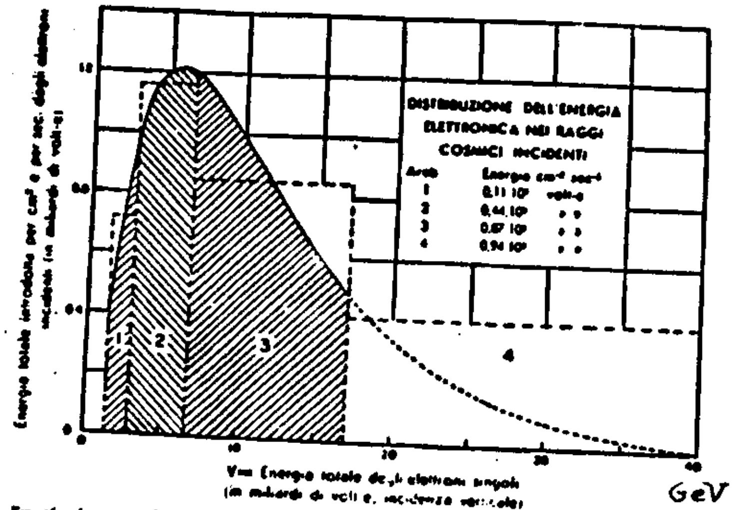


FIG. 26. - Le aree A, B, C di figura 25 sono situate tra i corrispondenti limiti dell'energia V (incidenza verticale). Le ordinate danno l'energia totale portata sulla terra dagli elettroni di energia individuale compresa fra V e V+dV.

EAST-WEST EFFECT PREDICTED BY ROSSI (1930); OBSERVED BY T.H. JOHNSON and BY ALVAREZ + COMPTON (1933): PRIMARY PARTICLES ARE POSITIVE – WORK of M. SCHEIN and others (1940): PRIMARY PARTICLES ARE MOSTLY PROTONS

PRIMARY C.R.'s KNOWN TODAY TO BE COMPOSED BY

- ~ 80% protons
- ~ 15% α particles
- ~ 5% heavier nuclei + (~ 1%) e^-

WITH AN ENERGY INTEGRAL SPECTRUM

$$N(E) = (A+E)^{-n}$$

with A (of ≈ 1 if E is in GeV) and n (≈ 2) change slightly in various energy regions

HARD AND SOFT COMPONENTS OF COSMIC RAYS NEAR SEA LEVEL

1927: FIRST INVESTIGATIONS OF C.R. WITH CLOUD CHAMBER
FIRST EVIDENCE FOR SHOWER (D.SKOBELZYN, 1928-29)

1928: DEVELOPMENT OF GEIGER-MULLER COUNTER

1929: USING GM COUNTERS AND PRIMITIVE TIME COINCIDENCES BOTHE AND KOLHOESTER DEMONSTRATE THAT ~75% OF C.R. NEAR SEA LEVEL ARE CHARGED PARTICLES CAPABLE OF TRAVERSING 4 cm THICK GOLD BLOCK (HARD COMPONENT OF C.R.)

1930: DEVELOPMENT OF "ROSSI ELECTRONIC COINCIDENCES" APPLICATION TO PROVE THAT 60% OF C.R. FILTERED AT SEA LEVEL WITH 25 cm Pb PENETRATE AN ADDITIONAL THICKNESS OF 1 m Pb

1932: OBSERVATION OF "ROSSI TRANSITION CURVE" WITH "TRIANGULAR" ARRANGEMENT OF GM-COUNTERS.
SOFT AND HARD COMPONENTS OF C.R.

1932: COUNTER CONTROLLED CLOUD CHAMBER (P.M.S.BLACKETT AND G.P.S.OCCHIALINI)

1932 ... "THE LUCKY YEAR": DISCOVERY OF THE NEUTRON; FIRST ARTIFICIAL NUCLEAR REACTION and

DISCOVERY OF THE POSITRON

COMMUNICATED IN "SCIENCE", SEPTEMBER 1932, BY C.D. ANDERSON, AS THE OBSERVATION OF "A POSITIVELY CHARGED PARTICLE COMPARABLE IN MASS AND MAGNITUDE OF CHARGE WITH AN ELECTRON"

1933: PROMPT CONFIRMATION BY BLACKETT AND OCCHIALINI WHO OBSERVE SHOWERS INITIATED BY NEUTRALS IN THE MIDDLE PLATE OF THEIR MAGNETIC COUNTER CONTROLLED CLOUD CHAMBER, MADE OF e^- AND e^+

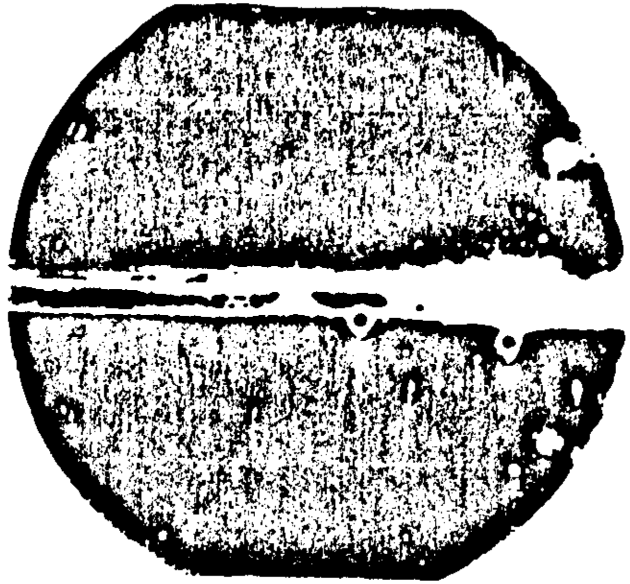


Fig. 1 The positive electron. The particle comes from the bottom, losing energy in the lead plate. This direction and the one of the magnetic field shows that the sign is positive. The ionization is much too weak for a proton.

PARTICLE COMES FROM BOTTOM AS IT CAN ONLY LOSE ENERGY IN TRAVERSING THE Pb PLATE
PARTICLE IS THEREFORE POSITIVE
ITS IONIZATION IS MUCH TOO WEAK FOR A PROTON
ITS MASS IS $< 20\ m_e$

CONCLUSIVE EVIDENCE FOR A NEW PARTICLE (e^+) FROM 1 EVENT

(... await until the discovery of the Ω^-, which was expected however from SU3)

Fig. 2 A shower coming from the top in the first counter triggered cloud chamber. The overall aspect is symmetric between negative particles (electrons) and positive (positrons) their ionisation is too small for protons.

Simmetric aspect of + and −
Ionization too small for protons

PRODUCTION OF e^+e^- PAIRS COULD HAVE BEEN DISCOVERED WITH γ RAYS FROM RADIOACTIVE SOURCES....

THE DECADE PRECEDING THE DISCOVERY OF THE MESOTRON

1927: First C.R. investigations with cloud chambers
First observation of "showers" (Skobeltzin 1928-29)

1928: Development of Geiger Müller counter

1929: Bothe + Kolhörster discover charged penetrating C.R. using GM counters and Bothe's "time coincidences"

1932: Anderson discovers the positron

1933: Blackett + Occhialini discover e^+e^- pairs

1932-3: Rossi's transition curve

1934: Bethe + Heitler develop theory of QED (bremsstrahlung + pair production)
Doubts for its validity at high energies (≥ 300 MeV)

1935: B. Rossi + Auger clarify existence of two distinct components in C.R.'s : "soft" + "hard"

1935: Yukawa's theory of nuclear forces

1937: Bhabha + Heitler and Carlson + Oppenheimer develop theory of cascade showers.
"Soft" component of C.R. well understood

What about the nature of the "hard" penetrating component?

DISCOVERY OF THE MESOTRON (I)

NOT SUDDEN + UNEXPECTED AS THAT OF THE e^+

I (Anderson + Neddermeyer 1934-37) Observations of C.R. particles, at sea level and at 4500 m a.s.l., in counter controlled cl.chamber in strong magnetic field, with a plate across the middle to allow measurements of p and -dp/dx. Plot p vs dp/dx. →

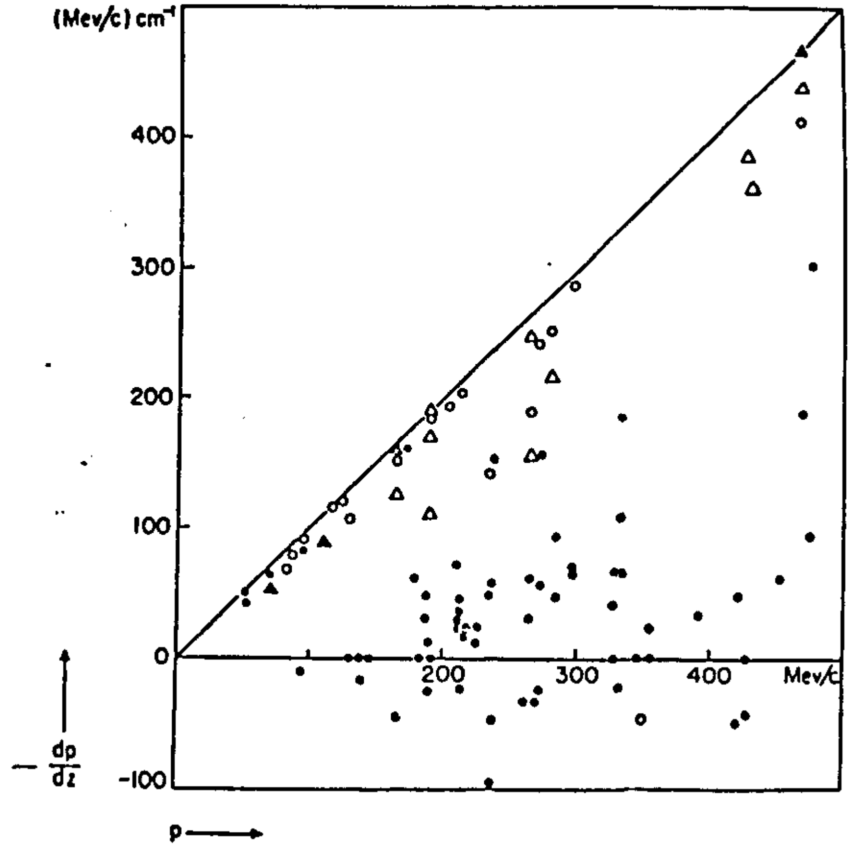
Striking different behaviour of "shower-particles" and "single-particles"

a) $-\frac{dp}{dx}$ { increases ~ linearly for shower-particles; ~ constant for single particles

b) shower production { yes for shower particles; no for single particles

c) altitude variation: much greater for shower particles

Conclusions: Shower-particles are $e^{\pm}$ (soft component of C.R.) Single-particles (hard component) have a mass $\mu >> m_e$; but they cannot be protons because: 1) energy distribution of knock-on e^-; 2) many single-particles with p < 1 GeV/c are minimum ionizing; 3) ionization-curvature relations; 4) there should be many negative protons. They are therefore particles of intermediate mass, $100\ m_e < \mu < 300\ m_e$.
Name "mesotron" proposed.



● "single-particles"
▲,o,Δ "shower-particles"

(From Neddermeyer + Anderson, 1937)

DISCOVERY OF THE MESOTRON (II + III)

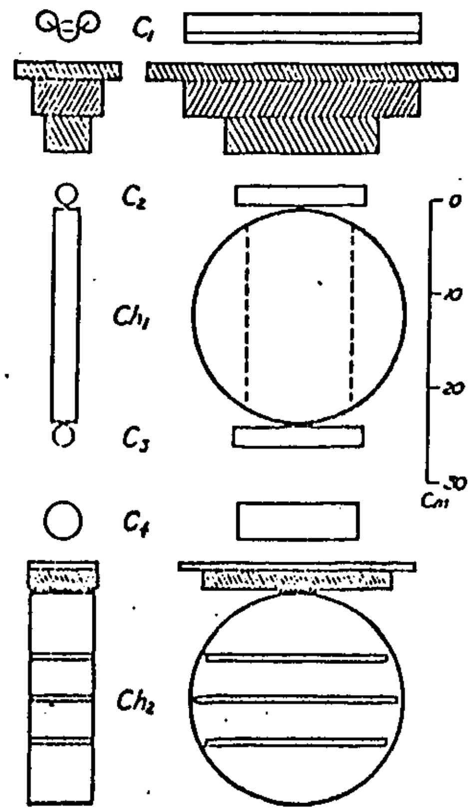
II Work of Nishima, Takeuki + Ichimiya (August 28, 1937)
Similar technique - Similar conclusions

$$M_p/10 < \mu < M_p/7$$

- Very strong evidence but of a "negative nature" (observations not to be explained except by assuming such new particles).

- More direct evidence from observation of tracks of momentum and ionization providing a value of μ incompatible with m_e and M_p.

III Photo of Street + Stevenson (October 8, 1937)
Counter controll. cluod ch. with 1s delayed expansion
$J = 6\ J_{min}$; $H\rho = 9.6\ 10^4$ G cm. Hence $\mu = \sim 125\ m_e$ (± 25%).



The double chamber system of Street and Stevenson: at the top the magnetic chamber, at the bottom the multiplate chamber. G.M. counters for triggering

Fig. 5 Street and Stevenson's first mesotron. The particule, if coming from the top, is negative. Curvature and ionization give a mass of 130 ± 25% m_e.

Fig. 7 This picture was published by Kunze in 1933 with the remarks that the blacker track ionizes more than an electron and less than a proton.

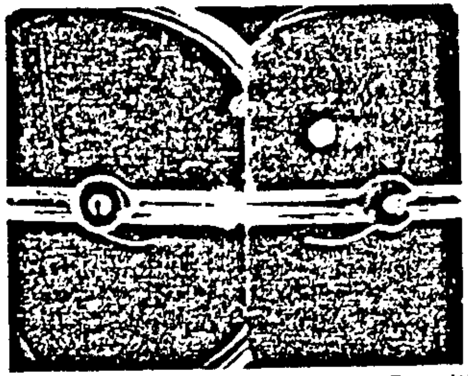


Fig. 6 The classical picture of Neddermeyer and Anderson. The positive mesotron crosses a Geiger counter inside the chamber and stops underneath in the gas. Curvature and range give a mass of ~ 240 m_e, no errors quoted (N.B. The chamber was relatively insensitive, the decay electron, which should have been seen, is not).

Williams and Roberts, 1940

Fig. 8 The first mesotron decay photographed in a high pressure cloud chamber by Williams and Roberts.

1st direct observation of a $\mu^+ \to e^+$ decay in a high pressure cloud chamber

- Existence of unstable mesotron definit. established
- All efforts directed to check whether its properties fit predictions of "MESON THEORY" started by Yukawa

YUKAWA AGENT OF NUCLEAR FORCES, THE MESON

1935: Yukawa proposes that short range nuclear forces involve exchange of "heavy quanta" (mesons, y) not observed in nuclear reactions because energy required for their creation (~ 100 MeV) not available.

Mass $\mu \sim 200\ m_e$ ($\mu c^2 \sim 100$ MeV) from relation

$$\lambda_{Compton} \sim R_{nucl.}$$

Virtual process $N \rightarrow N + y$ (+, - or 0)
in times $\tau \sim \hbar/\mu c^2$ over distances $\sim c\tau = \lambda_{Compton}$

Discovery of y ($\equiv \pi$) made at Bristol in 1947.
Mesotron erroneously identified with meson, as proposed by Yukawa himself in 1937.

To explain ß decay y has to be unstable, with meanlife $\tau \sim 1\ \mu s$ (first estimate by Yukawa et al. 1938).

WORK OF TOMONAGA AND ARAKI (1940)

Material	lead	aluminium	air
Capture probability of neg. mesons per sec	$2.5\ 10^{12}$	$1.2\ 10^{11}$	$3\ 10^{7}$

Probability of spontaneous decay, $4.5\ 10^5\ s^{-1}$, <<

Experimental investigation of behaviour of μ^+ and μ^- at rest needed to check assumed identity of mesotron and meson

MASS OF MESOTRON, μ

For several years not clear whether experimental data interpretable in terms of a unique mass value, μ.

In 1946 Bethe points out importance of scattering in cloud-chamber gas. When this is taken into account, all existing data compatible with $\mu \sim 200\ m_e$.

By momentum-range method applied to large number of cloud-chamber photos Fretter (1946) finds

$$\mu = (202 \pm 5)\ m_e$$

Today value

$$\mu = 206.77\ m_e$$

ANOMALOUS ABSORPTION OF HARD COMPONENT OF C.R. IN AIR

1937 (Ehmert; Auger et al.):
Nr. of penetrating particles at sea level smaller than that measured at high altitude with compensating "equivalent" absorber of dense material ("anomalous" absorption in air).

1938: Kulenkampf, and Euler + Heisenberg, suggest that the penetrating particles are Yukawa unstable particles and that anomaly is a relativistic effect due to the decay of mesotrons in flight: a mesotron of mass μ, meanlife τ (at rest) and momentum $p = \beta c \mu \gamma$ $(\gamma = 1/\sqrt{1-\beta^2})$ has ~~in empty space (~ air)~~ a decay mean free path

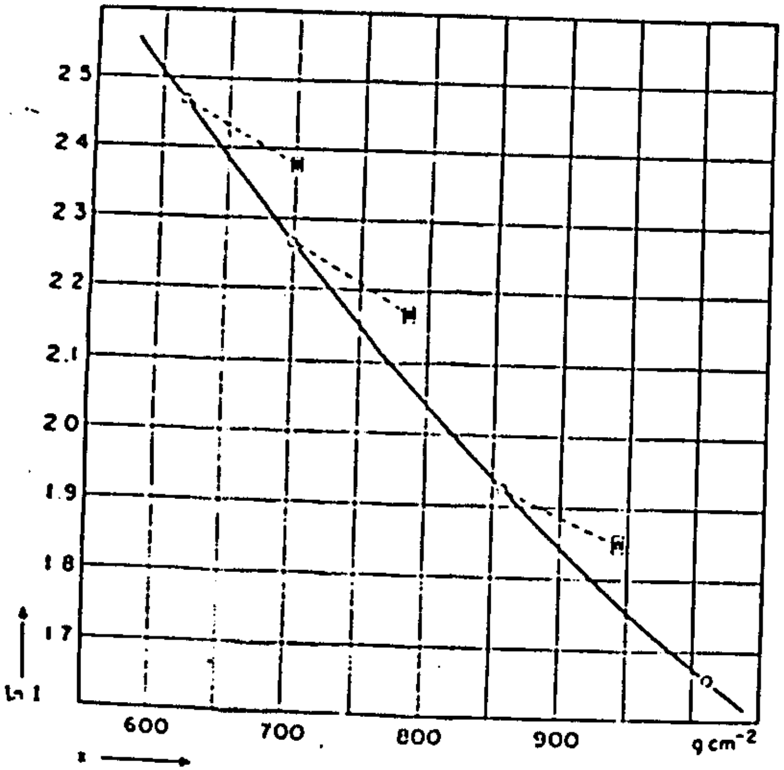
$$\lambda = \beta c \gamma \tau = p(\tau/\mu)$$

Hence the nr. of mesotrons of momentum p travelling over a length h is attenuated by the ~~measurable~~ factor

$$\exp(-h/\lambda) = \exp(-h/p)(\mu/\tau)$$

and the ratio τ/μ can be derived from attenuation measurements if the momentum spectrum of the penetrating particles is known.

ANOMALOUS ABSORPTION OF C.R. MESOTRONS



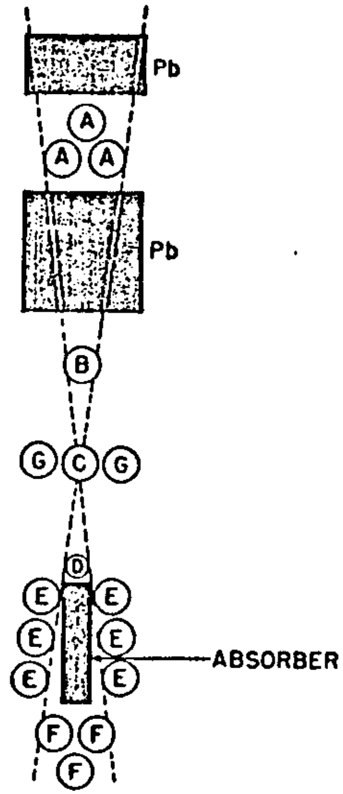
Meson intensity (I) vs atmospheric depth (x)
Dashed lines: results of absorption measurements in a graphite absorber (From Rossi et al. 1940).

$\tau \approx 2\ \mu s$ if $\mu \approx 200\ m_e$

DIRECT MEASURE OF MESOTRON MEANLIFE

First unsuccessfull attempts (Montgomery et al. 1939) indicated the problems to overcome

First successfull measure (Rasetti 1941): $\tau = 1.5 \pm 0.3\ \mu s$ based on the assumption of exponential decay (τ derived from logarithmic decrease relative to two points of decay curve).
Excellent geometry at the price of low counting rate.
"Decay counters" out of μ beam.
Three prompt coincidences with resolving times of .95, 1.95, 15 μs.
Since ~ all'μ's decay before 15μs one finds $1/\tau = \ln(D_1/D_2)\ \mu s^{-1}$
if $D_1 \equiv$ rate (15μs)-rate (0.95μs)
$D_2 \equiv$ rate (15μs)-rate (1.95μs)



Spurious delays of counter pulses responsible for small value of τ found in this and subsequent experiment of Auger et al. (1941) who reported $\tau = 1.3\ \mu s \pm 50\%$.

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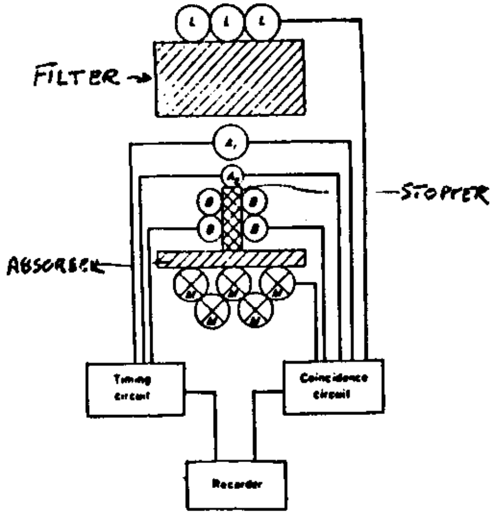
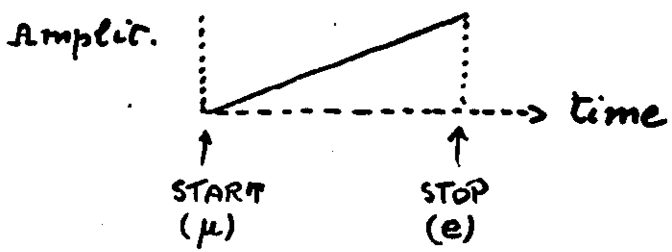


FIG. 4. Apparatus of Rossi and Nereson for measuring delays of electrons from μ-meson decay [13].

Rossi and Nereson (1942)

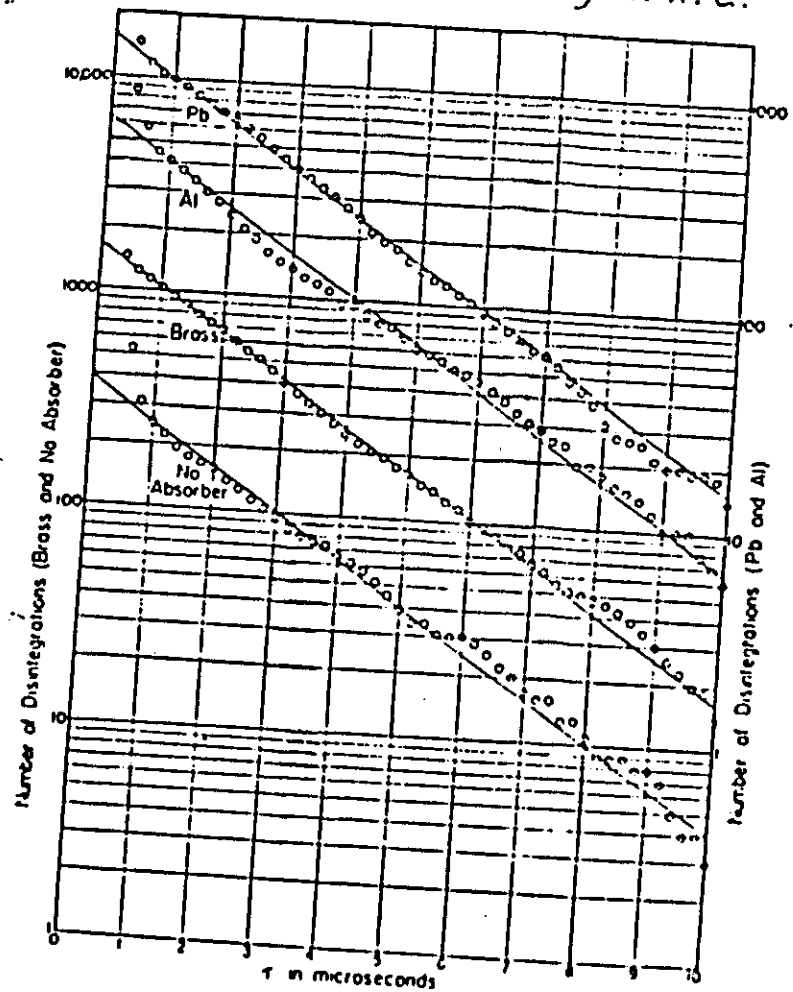
Introduction of T.A.C. to measure delays of $e^{\mp}$ from $\mu^{\mp}$ on single $\mu \rightarrow e$ events.



EXPONENTIAL CURVES FROM MESOTRON DECAY

(Nereson + Rossi 1943)

Delays of single μ-decays measured by T.A.C.



$\tau = 2.15 \pm 0.07\ \mu s$

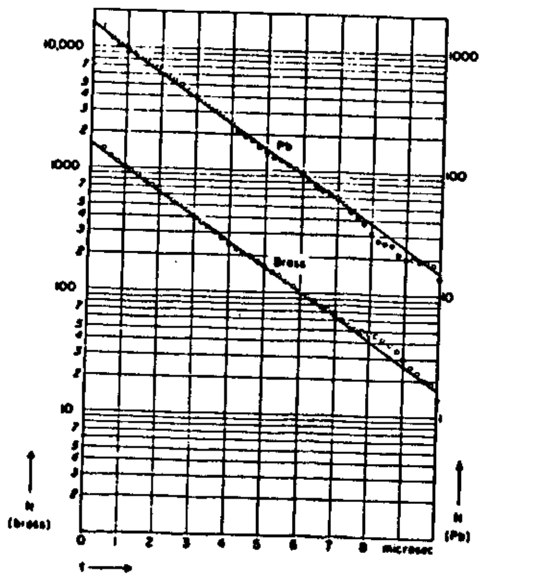


Fig. 4.2.4. Integral disintegration curves of mesons in lead and brass. Each point represents the observed number, N, of decay events for which the delay is greater than t. From N. Nereson and B. Rossi (NNG43).

Rossi and Nereson : Decay curves of C.R. mesons in lead + brass

$$\tau_\mu = (2.15 \pm 0.07)\,\mu s$$

↓

1984 value:

$$\tau_\mu = (2196.950 \pm 0.060)\ ns$$

<World value> = ↓ = (2197.035 ± 0.040) ns

(BERTIN VITALE 1984 Bo Conf.)

$$G_F = \frac{192\pi^3}{m_\mu^5}\frac{1}{\tau_\mu} = 1.03 \cdot 10^{-5}/M_p^2$$

M. C. + O. Piccioni (1943)

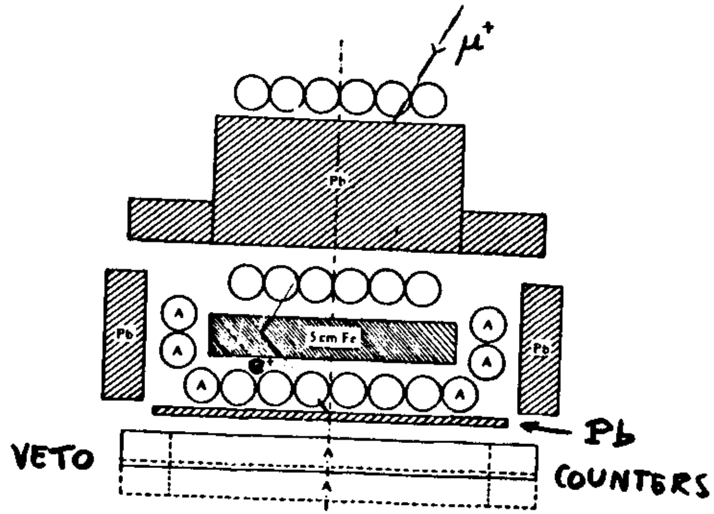


Figure 13.3. Layout of Geiger-Müller counters and absorbers for our experiments 1 and 2.[8,11] From top, the first and second sets of six counters detect an incoming muon. If the muon stops in the absorber (5 cm of iron in the figure) and emits an electron at a later time, a delayed coincidence is counted. The A counters veto a count if the muon crosses them. The thin lead slab prevents the decay electrons from vetoing themselves. From M. Conversi and O. Piccioni in *Phys. Rev.* 70 (1946), 861, Fig. 1.

First:

$$\tau_\mu = 2.3\,\mu s \pm 6.5\%$$

from a best fit through 4 measured points of the decay curve.

(Convinced to be the first to record the expon. decay curve of a free particle ..... total lack of communication with USA)

Next : Test of predictions of Tomonaga + Araki → 0.6 cm thick Fe abs. → OK

Next : Put on magnetic lenses ...

WORK WITH "MAGNETIC LENSES"

Early attempts to deflect cosmic rays by means of magnetized iron bars:
Skobeltzyn 1929; Rossi 1931; Mott-Smith 1932

• Large effect expected assuming an "interior field" $H_i = B$ since charged C.R. were believed to be all e^-. • No effect observed

Hence the question $H_i \sim H$ or $H_i \sim B$?

Answer in favour of B on theoretical ground
(Weizsäcker 1933)

Answer apparently against $H_i = B$ from specific experiments:
Alvarez 1934 ($H_i < B/3$); Danford + Swann (1936)

Rossi-Puccianti
Magnetic lenses
used by Rossi
in 1931

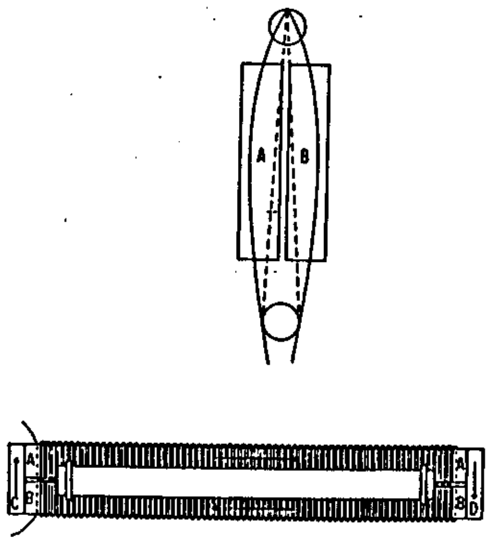
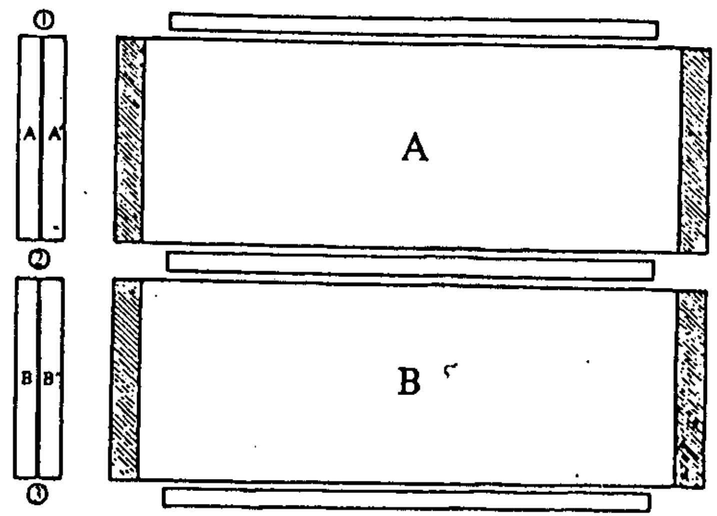


Figure 13.5. Rossi-Puccianti lenses.[13] The side view (at top) shows the trajectory of a "wanted" charge sign (solid line) and of an "unwanted" one. The top view shows the direction of the magnetic field and the position of the top Geiger-Müller counter. From B. Rossi, in *Nature 128* (1931), 300.



"Doublet" of magnetic lenses used in 1940 (Bernardini + Conversi 1940) to demonstrate the effect of the magnetic field on the penetrating cosmic rays. 1, 2, 3 are GM counters. The number, N, of threefold coincidences (1 2 3) was recorded in two configurations:

a) magnetic field parallel in lenses A and B
b) field antiparallel in lenses A and B

A 35% effect was recorded for $(N_a-N_b)/(N_a+N_b)$ showing that the "Interior field" acting on the charged penetrating particles has a value close to B.

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M. Conv. and E. Scrocco (1943)

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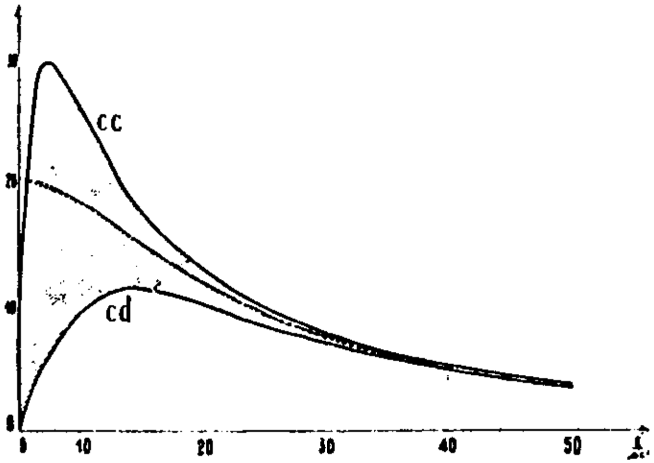

Red curve: Energy spectrum of C.R. mesons at sea level computed assuming a primary power spectrum E^{-n} $(n = 2.87)$ and

$\tau_\mu / m_\mu c^2 = 2 \cdot 10^{-8}$ s/MeV

Top curve (cc'): Energy spectrum as emerging from the "lens doublet" for parallel $\vec{B}$ (17 kgauss) in the two magnetic lenses

Bottom curve (cd'): En. spectr. ...... for anti-parallel $\vec{B}$ in the two magnetic lensens

M.C. and E. Scrocco (1943)

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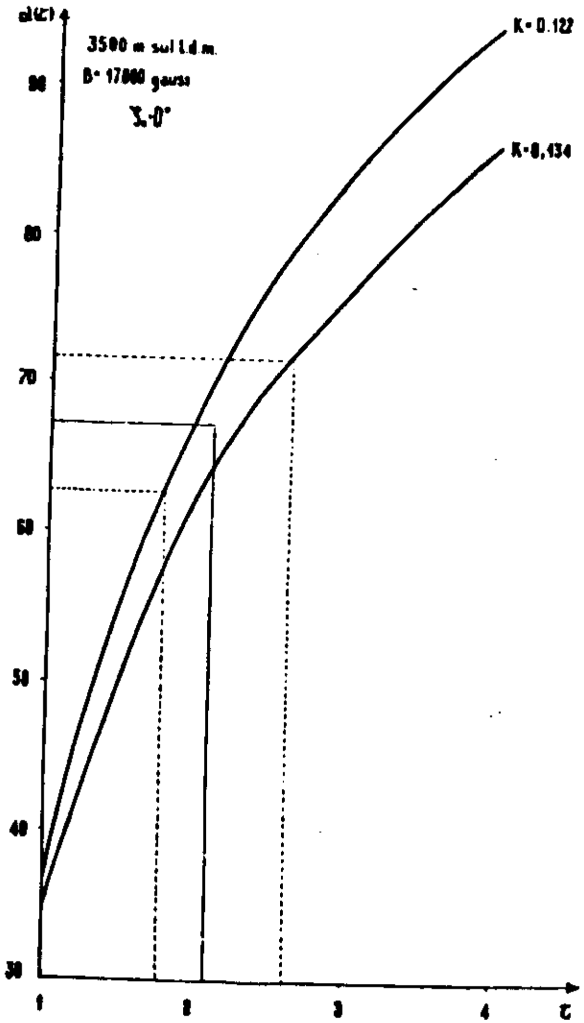


Fig. 12.

$$\tau_\mu / m_\mu c^2 = \sim 2.1 \times 10^{-8} \text{ s/MeV} \pm \sim 20\%$$

To-day value: $\tau_\mu / m_\mu c^2 = 2.0793 \cdot 10^{-8}$ s/MeV

SOME RELEVANT EVENTS IN THE RECENT HISTORY OF ITALY

20 bis

13a)

10 JUNE 1940: Declaration of war to France + England

19 JULY 1943: Rome bombed by American aircraft

25 JULY 1943: Fall of fascist government

8 SEPT. 1943: Italian separate armistice: start of German occupation

5 JUNE 1944: Allied Troops liberate Rome

25 April 1945: Liberation of Northern Italy

RECOLLECTION OF WORK AT THE "VIRGILIO"

FOUR CONSECUTIVE EXPERIMENTS:

1 - Direct measurement of τ
2 - Measure of $\eta \equiv \mu$-decays/μ-stops } C. + Piccioni (1944)

and, with magnetic lenses:

3 - Test of T-A theory in iron
4 - Test of T-A theory in carbon } C.+ Pancini + Piccioni (1945-6)

First Experiment (prepared at the University but carried-out at the "Virgilio" after Rome bombing of July 19, 1943) provided the basis of all subsequent work. Four points of the decay curve of cosmic-ray μ's were obtained giving

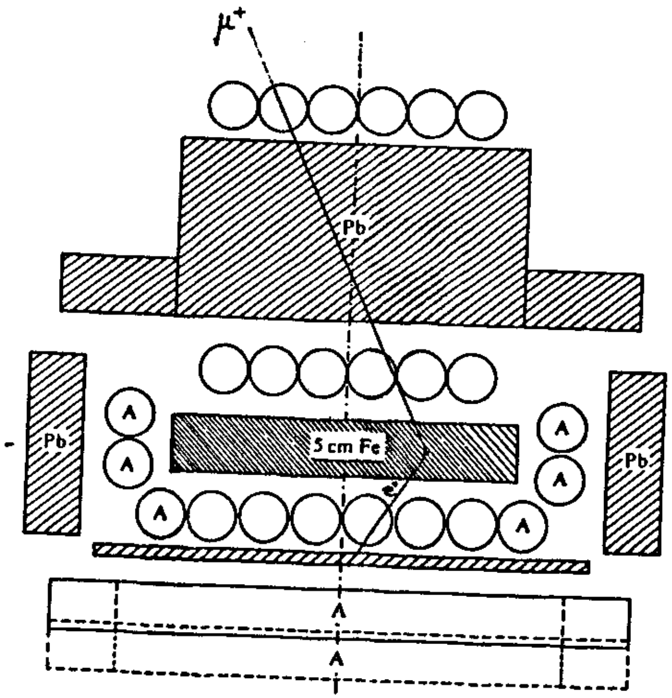
$$\tau = 2.3\ \mu s \pm 6.5\ \%$$

for the mesotron meanlife

Second Experiment aimed at testing T-A predictions.
If only μ^+ decay (μ^- being captured) then one expects:
$\eta \equiv \mu$-decays/μ-stops = 0.55 taking into account a 20% excess of μ^+
We found $\eta = 0.49 \pm 0.07$, with an upper limit of

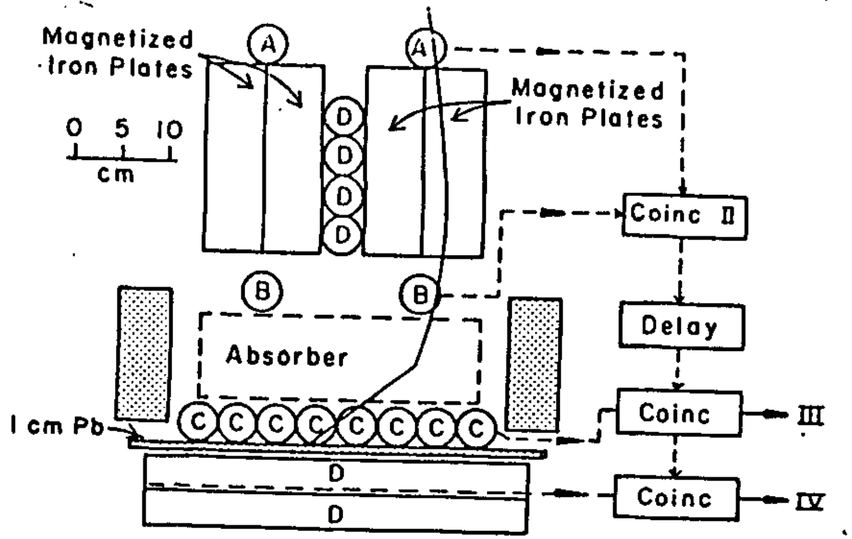
$$\eta = 0.56 \pm 0.08$$

well consistent with T-A predictions



Layout of Geiger-Müller counters and absorbers for experiments 1 and 2. From top, the first and second sets of six counters detect an incoming muon. If the muon stops in the absorber (5 cm of iron in the figure) and emits an electron at a later time, a delayed coincidence is counted. The A counters veto a count if the muon crosses them. The thin lead slab prevents the decay electrons from vetoing themselves.(From M.Conversi and O.Piccioni, 1946). /4

OPPORTUNITY OF 3rd EXPERIMENT WITH MAGNETIC LENSES PROJECTED AT THE "VIRGILIO"; CARRIED OUT IN THE Phys. Inst.



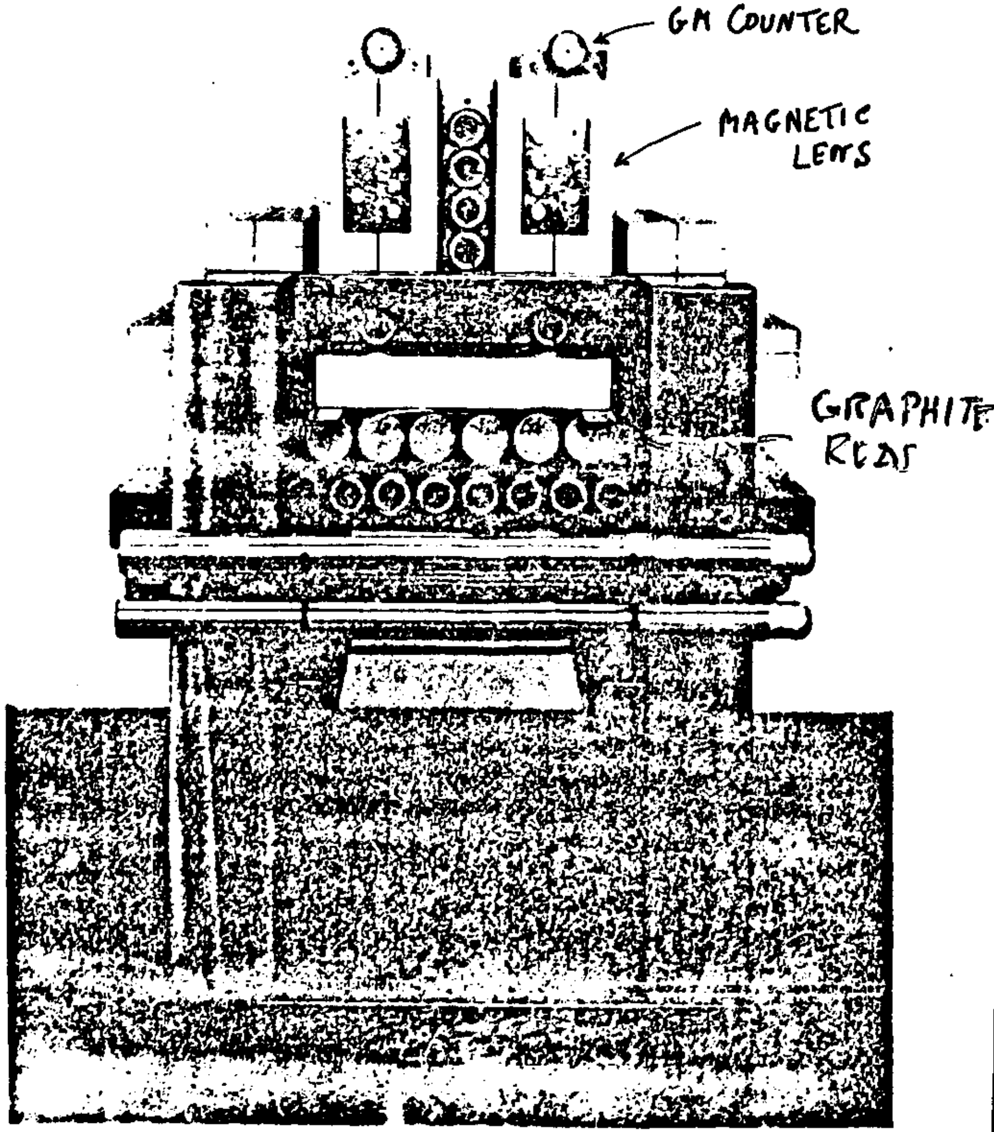
Apparatus used in experiments 3 and 4. *Result of 3rd experim.: 0.33 ± 0.04 μ^+/hr against 0.07 ± 0.02 μ^-/hr (3 cm Fe absorb.)*

Results of measurements on decay rates for positive and negative mesons at rest in various absorbers *(4th experim.)*

Sign	Absorber	III	IV	Hours	M/100 hr
a) +	5 cm Fe	213	106	155.00′	67 ± 6.5
b) −	5 cm Fe	172	158	206.00′	3 (± 2.5)*
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 (+ 4 − ?)*

- 5 cm Fe on top of 4 cm C (row e) to guard against very low energy μ^- which might destroy magnetic selection
- 6.2 cm Fe "equivalent" to 4 cm C + 5 cm Fe
- Unexpected effect (non capture in C) from last two rows (e and f)

MODEL OF EXPERIMENT
c/o Smithsonian Museum



CHOICE of CARBON ABSORBER
(in my personal recollections)

To extend check of theor. predict.s to low Z (so large $\hbar^2/Ze^2m_\mu$)

To search for possible γ from μ^- capture (later done by Piccioni in USA)

To clarify uncertain indication of previous exp. in Al (Maze + Chaminade) that > 1/2 μ decay

MEANING + CONSEQUENCES of EXPERIMENT

Discrepancy of 10^{12} with theoret. predic.s (Fermi, Teller + Weisskopf, 1947)

Two-meson hypothesis (Sakata + Inoue, 1946) (Marshak + Bethe, 1947)

Z^4 "Wheeler law" (Wheeler, 1947)

Idea of Univ. Fermi Interaction (Pontecorvo, 1947; Tiomno + Wheeler 1948; Puppi; Klein, 1948; ....) → $\theta_{Cabibbo}$

Start of new field of "mesic atoms"

C.R. meson as "heavy e^-" (2^{nd} charged lepton)

↓

discovery of τ (Perl et al.)

High energy μ scattering (e.g. E. Amaldi, G. Fidecaro, etc.)

INTERPRETATION + MAIN CONSEQUENCES OF ROME EXPERIMENT

Fermi seminar in December 1946 at University of Chicago

Factor 10^{12} discrepancy (Fermi, Teller + Weisskopf 1947)
Slowing down and atomic capture times $<< \tau = 2.2\ \mu s$
The mesotron cannot be the Yukawa particle

What is the mesotron? Where is the Yukawa particle?

Before answer came from Bristol, following steps were made

(i) Two-meson hypothesis: Marshak + Bethe (1947). Sakata + Inoue (1946), before result of Rome experim.

(ii) Idea of universal Fermi interaction [Pontecorvo, 1947 and, from 1948: Klein; Lee, Rosenbluth + Yang; Puppi, especially Tiomno + Wheeler]

(iii) Z^4 Law (Wheeler 1947) of μ^- capture

Other consequences of Rome experiment

(iv) Concept of mesic atom

(v) Lepton concept

GENESIS of concept of Universal Fermi Interac.

June 47 (before pion discovery):

Pontecorvo points out that because of the result of the Rome experiment:

- The Yukawa theory of β decay is untenable
- β decay is to be described as originally proposed by Fermi (4-fermion interaction)
- β decay and muon capture have ~ the same strength if allowance is made for phase space and size of Bohr orbit.
- The muon has spin 1/2 and is absorbed with the emission of one neutrino ($\mu^- p \to n\nu$)
- Perhaps $\mu \to e + \gamma$ (a process later searched for together with Hincks)

This is the first presentation of the concept of Universal Fermi Interaction elaborated with subsequent contributions from Klein, Puppi, Tiomno and Wheeler, ~~etc~~ Lee, Rosenbluth and Yang ....

What about muon decay ?

Z DEPENDENCE OF μ^- CAPTURE

"Mesic atom" from μ^- capture in K orbit around nucleus (Z, A) has radius

$$r_\mu = h/Z\mu e^2_{(\text{muon mass})} = \sim 250/Z \text{ fermi}$$

In light elements always $r_\mu >> r_{nucl} = \sim 1.75 \sqrt[3]{Z}$ fermi so that ψ (at nucleus) $\approx \psi(0) \sim Z^{3/2}$

Hence the capture probability

$$\Lambda_c \equiv \frac{1}{\tau_c} = \sim |\psi|^2 V_{nucl} \sim Z^3 Z = Z^4 \quad \text{(Wheeler)}$$

can be written as

$$\frac{1}{\tau_c} = \frac{1}{\tau_\mu}\left(\frac{Z}{Z_o}\right)^4 \text{ with } Z_o \text{ empirically} = \sim 11$$

(muon lifetime)

The probability of disappearence of μ^- at rest is then

$$\Lambda_- = \frac{1}{\tau_-} = \frac{1}{\tau_\mu} + \frac{1}{\tau_c} = \frac{1}{\tau_\mu}\left[1 + (Z/Z_O)^4\right]$$

(competing probabilities) (Ticho, Rossi + Valley)

Fraction of spontaneous decays

$$\frac{1}{\tau_\mu} / \frac{1}{\tau_-} = \frac{\tau_-}{\tau_\mu} = \frac{1}{1 + (Z/Z_o)^4} = \begin{cases} 92\% \text{ in C } (Z = 6) \\ 3\% \text{ in Fe } (Z = 26) \end{cases}$$

in agreement with experiments

After the Bristol discovery of the π meson + $\pi \to \mu\nu$ decay the best interpretation of the Rome experiment was that π's are strongly interacting particles decaying into weakly interacting μ's.

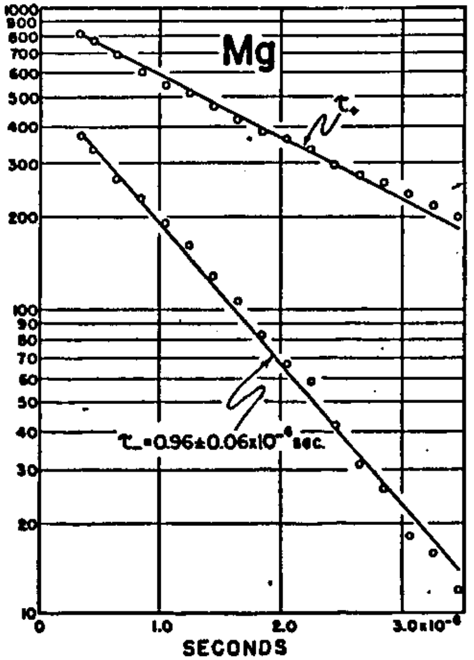
Every difficulty seemed to be solved, but ...
a) The π could not be the mediator of ß decay
b) What was the role of the μ ?

Nature was much more complex than believed in those days:
(i) The problem of nuclear forces was not solved by the π discovery
(ii) The π has a $q\bar{q}$ structure and is only the ligthest of many similar structures
(iii) What about the muon? A "heavy electron", as slowly clarified, ~ 200 times more "costly" than the e^-.

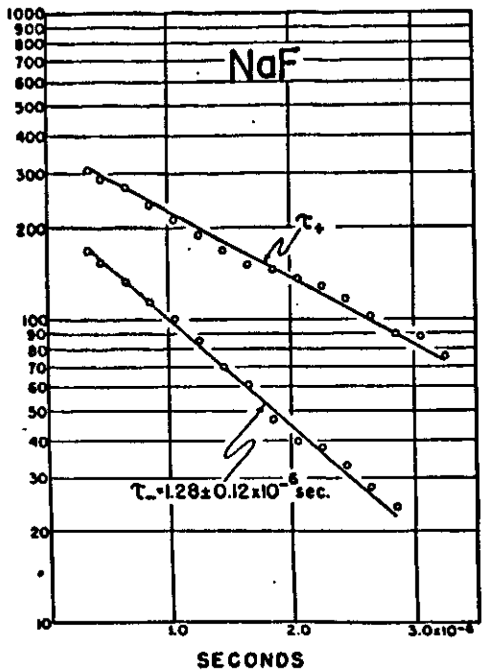
- So from the Rome experiment slowly arose the concept of a "lepton world": the family of structureless elementary particles immune from the strong interaction
- The identification of the μ as a lepton represents the discovery of the second charged lepton after the electron.
- ~ 30 years elapsed before the discovery of a third charged lepton, τ (Perl et al. 1975) at Stanford.

To complete this early story of the μ, what about its decay mode? $\mu \to e\,\gamma$ searched for, with negative result, since 1948.

Indications in favour of three-body decay from Anderson et al. (1947) and Fowler et al. (1948). First evidence from Steinberger (1948-49).



Z = 12



Z = 10.1

<u>After the Bristol discovery</u> of the π meson + $\pi \rightarrow \mu\nu$ decay the best interpretation of the Rome experiment was that π's are strongly interacting particles decaying into weakly interacting μ's.

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On the Range of the Electrons in Meson Decay

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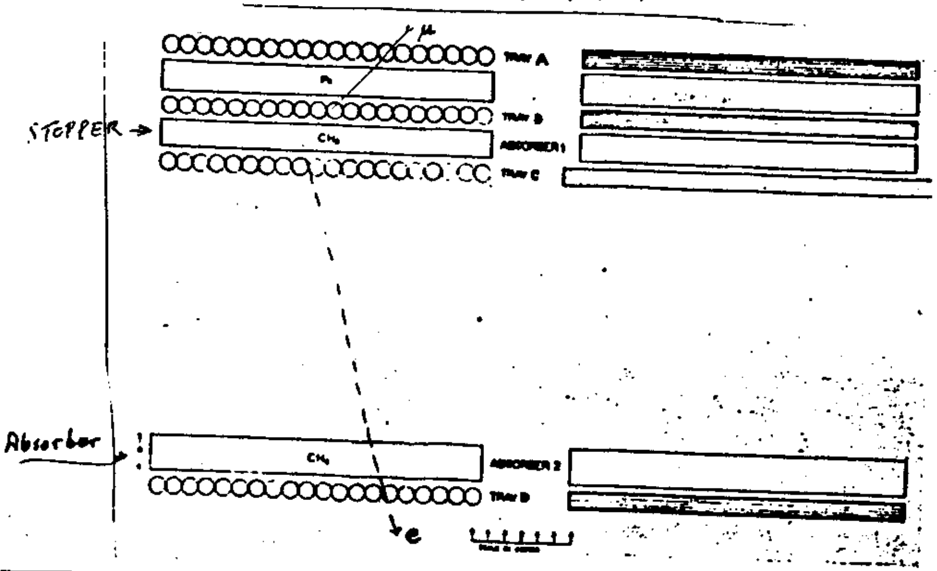
The Institute for Nuclear Study, University of Chicago, Chicago, Illinois

(Received January 10, 1949)



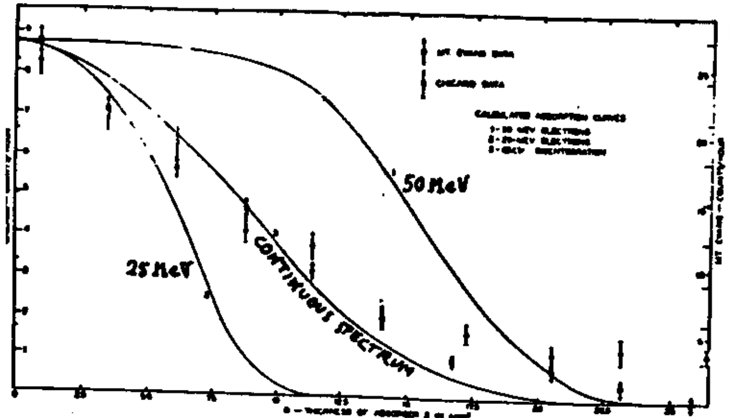
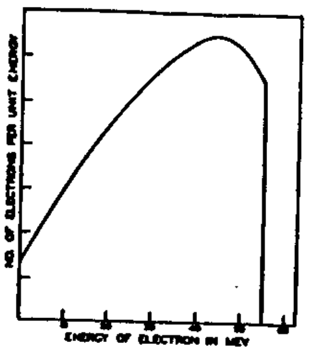
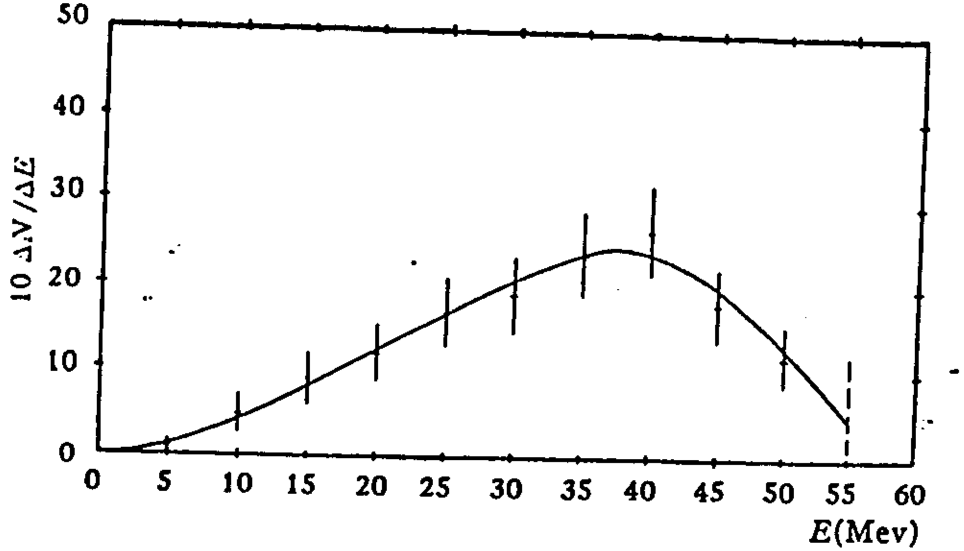


Fig. 8. The experimental points represent the data obtained in Chicago and on Mt. Evans. The indicated ror is the standard deviation. The full curves 1 and 2 represent the calculated absorption curves for 50 d 25 Mev, respectively. Curve 3 is the absorption curve calculated for electrons emitted in a continuous ectrum. The spectrum is calculated from Eq. (2), taking $\mu c^2 = 100$ Mev.



Differential energy spectrum



The first spectrum of the electron energy in μ, e decay obtained in a cloud chamber. (As we know now the curve dips much too much towards zero at the high energy end, but the measured points demonstrate clearly the existence of a spectrum).

CONCLUSIONS AS A SUMMARY OF THE "TANGLED TALE" OF THE MUON

First observed as constituent of the hard component of cosmic rays

Then as an unstable particle of intermediate mass

For long erroneously identified with the Yukawa carrier of the strong nuclear force

Subsequently recognized as a "heavy electron" (the first heavy lepton is today's words)

Subject to the weak processes of spontaneous decay and nuclear capture similar to ß decay (U.F.I.)

Then found at Bristol as daughter particle of the strongly interacting π meson

Finally identified as a fermion subject to the three-body decay process $\mu \rightarrow e\nu\nu'$

CONCENTRATED NUCLEAR EMULSIONS

Developed by Demers in Canada and especially by the Ilford Co. in England (Waller + Woosley) in cooperation with Bristol (Powell, Occhialini, etc)

→ 1944 patent for the special treatment of "Concentrated Nuclear Emulsions" produced commercially by the Ilford. Co.

These emulsions contain an amount of Silver halide ~ 8 times larger than previous emulsions. Their development greatly amplified the range of applicability of the photographic emulsion technique to the experimental study of elementary particles.

WORK AT BRISTOL WITH NUCLEAR EMULSION

as commercially developed by Ilford Co. with Powell + Occhialini

First important work published by

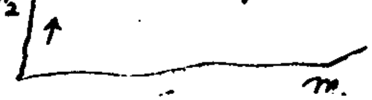
LATTES, MUIRHEAD, OCCHIALINI, POWELL

(Nature, May 1947)

soon after observation (by Perkins and by Occhialini + Powell) that slow cosmic ray mesons "can enter nuclei" of emulsion exposed at high altitude "and produce disintegrations with the emission of heavy particles"

Mass of slow particles, derived from grain counting and range in emulsion calibrated with fast protons, Method capable to recognise a "meson", when combined with multiple scattering measurements

Out of 65 mesons stopping in emulsion 2 give rise to the emission of a secondary meson



FIRST TWO EXAMPLES OF π → μ DECAYS (May 1947)

Fig. 10 The first published π, μ decay.

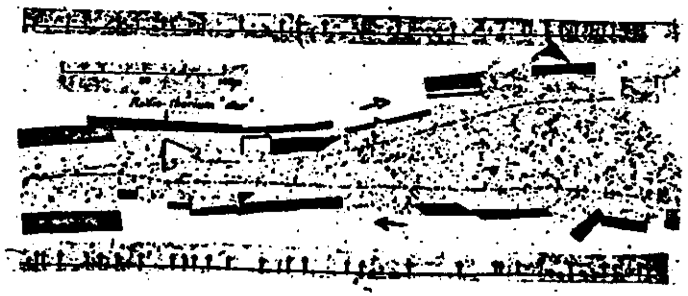


Fig. 11 The second π, μ decay. The μ quits just before stopping but is clearly at the end of its range.

2nd fondamental work published by October

LATTES, OCCHIALINI + POWELL (1947)

FIG. 56. Typical rho mesons stopping uneventfully, observed by Powell and coworkers.

"ρ-mesons" interpreted as C.R. μ (muons) entering and stopping uneventfully in the nuclear emulsion

LATTES, OCCHIALINI + POWELL (1947)

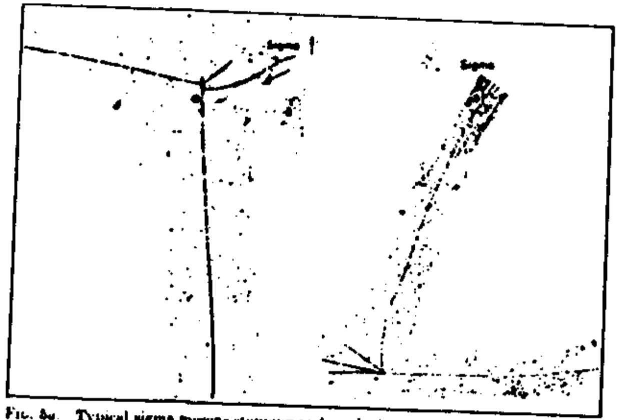


FIG. 5x. Typical sigma mesons stopping and producing a star. Observed by Powell and coworkers.

"σ-mesons", interpreted as π^- mesons captured in matter at the end of their range, where the produce a "star"

This table reproduces table I of the original publication of Lattes, Occhialini, Powell. It shows that the secondary μ, have a unique range in the π, μ decay.

Event No.	Range in emulsion in microns of Primary meson	Secondary meson
I	133	613
II	84	565
III	1040	621
IV	133	591
V	117	638
VI	49	595
VII	460	616
VIII	900	610
IX	239	666
X	256	637
XI	81	590

<u>Mean range $\bar{614} \pm 8\ \mu$.</u> Straggling coefficient $\sqrt{\Sigma \Delta_i^2 / n} = 4.3$ per cent, where $\Delta_i = R_i - \bar{R}$, R_i being the range of a secondary meson, and $\bar{R}$ the mean value for n particles of this type.

LATTES, OCCHIALINI + POWELL (1947)

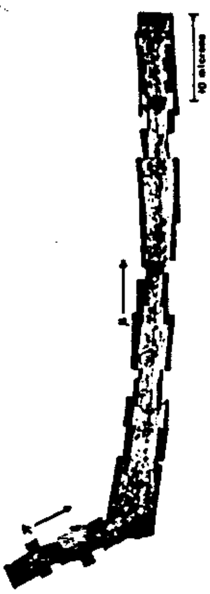


Fig. 4.8.1. Mosaic of microphotographs showing a $\pi \to \mu$ decay in Ilford C2 emulsion. From Lattes *et al.* (LCM47.1).

Fig. 4.8.2. Mosaic of microphotographs showing a $\pi \to \mu \to e$ decay. Kodak NT4 electron-sensitive emulsion. From Brown *et al.* (BR1149.2).

Discovery of $\pi^+ \to \mu^+$ decays

↓

constant range

↙

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\hookrightarrow (e^+ + \nu_e + \bar{\nu}_\mu)$$

a)

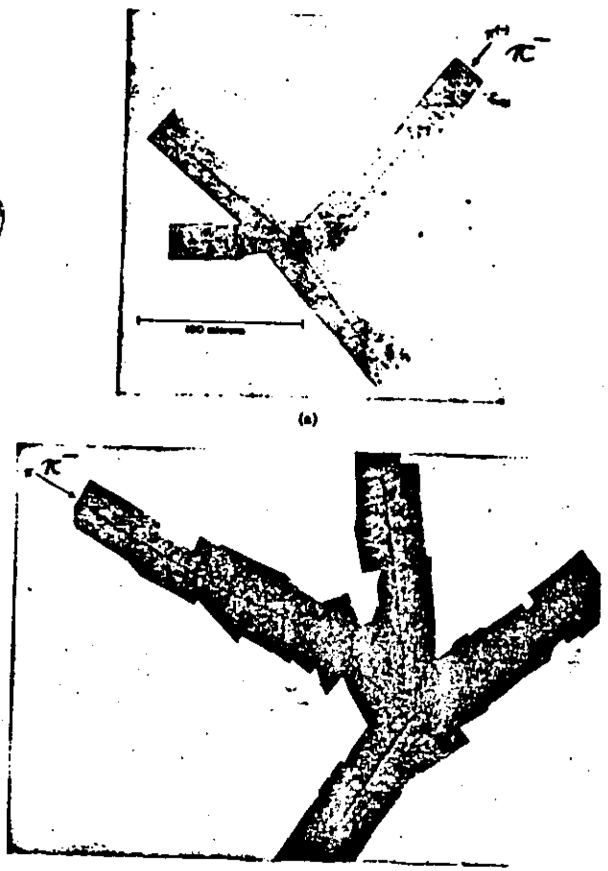


Fig. 4.9.8. Disintegrations produced by the nuclear absorption of negative π-mesons. (a) D. H. Perkins, Ilford B1 emulsion (PDH47). (b) Powell, Ilford C2 emulsion (PCF49).

a) FIRST OBSERVATIONS OF NUCLEAR DISINTEGRATIONS FROM π^- ABSORPTION IN EMULSION OBSERVED BY PERKINS IN 1947

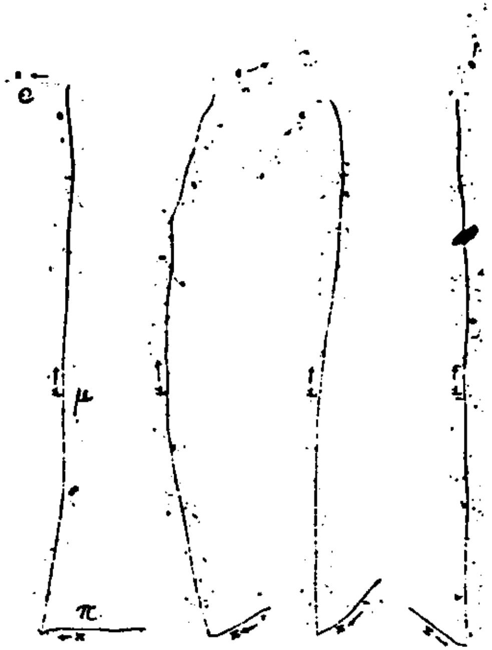


Fig. 1.1 Examples of the decay sequence $\pi \to \mu \to e$ in nuclear emulsion. Note that the constancy of range of the muon track implies that the pion decays at rest into two particles of unique masses $\pi \to \mu + \nu$. The electron emitted in the β-decay of the muon, $\mu \to e + \nu + \bar{\nu}$ was not observed in the early experiments, which employed less sensitive emulsion. (Courtesy, University of Bristol.)

Four examples of the decay sequence

$$\pi \to \mu \to e$$

as observed in electron sensitive nuclear emulsions

CONCLUSIONS from "EMULSION WORK" at Bristol

1) There are two 'mesons': π and μ

2) $\pi \to \mu + \nu$ because R_μ = cost.

3) Best interpret. of Rome exp. is to assume that π is the "Yukawa particle"

4) If the $\pi \to \mu$ decay is fast enough the bulk of p.p. C.R. are μ's

5) Mesons producing stars (σ) are π^-'s

6) Mesons stopping in emulsion uneventfully (ρ) are μ^+ or μ^- (decay electrons still unobservable)

So everything O.K.? The Yukawa particle has been found, even though with other properties than expected (it decays into a μ, NOT into an e!: Yukawa theory does not explain β decay!).

What about the μ?

Which role plays it in particle physics?

"Who ordered it?"

DISCOVERY OF V-PARTICLES

POSITIVE PARTICLE OF MASS 990 m_e $\pm$ 12% AS DERIVED FROM THE COLLISION, SUPPOSED ELASTIC, WITH AN e^- OF THE GAS OF A CLOUD CHAMBER (LEPRINCE RINGUET, LHERITIER, 1944).

V-PARTICLE WORK AT MANCHESTER GREW OUT OF AN EXPERIMENT DESIGNED TO INVESTIGATE CREATION OF P.P. BY COUNTER TECHNIQUE (JANOSSY AND INGLEBY, 1939).

CLOUD CHAMBER INCORPORATED ALLOWED TO CONCLUDE IN 1943 (IN AGREEMENT WITH SCHEIN'S CONCLUSIONS, - 1940) THAT THE "PENETRATING SHOWERS" WERE ORIGINATED BY PRIMARY PROTONS + NEUTRONS.

END OF THE WAR - BLACKETT BACK IN MANCHESTER SUPPORTS IMPROVEMENTS OF CLOUD-CHAMBER SYSTEM.

ROCHESTER AND BUTLER UTILIZE BIG "BLACKETT MAGNET" AND NEW CLOUD CHAMBER WITH 3 cm Pb PLATE ACROSS.

1st V^0 EVENT OBSERVED IN OCTOBER 1946 (K^0 DECAY)
1st V^+ EVENT " " MAY 1947 (K^+ DECAY)

BOTH APPEAR AS DECAY IN FLIGHT OF SHORT LIVED PARTICLES OF ESTIMATED MASS ~ 1000 m_e (IF NO NEUTRALS EMITTED IN V^0 DECAY)

FIRST V° EVENT OBSERVED AT MANCHESTER BY ROCHESTER AND BUTLER (OCTOBER 1946)

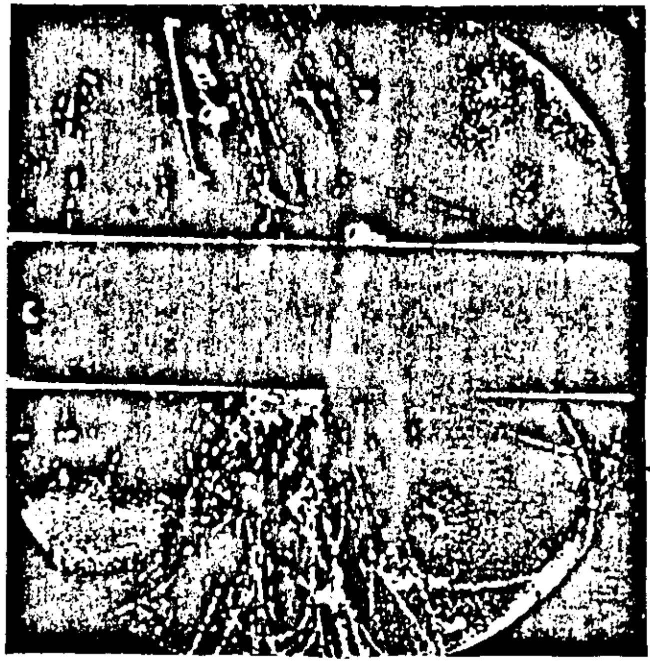


Fig. 1. – Prima fotografia di evento V° ottenuta da ROCHESTER e BUTLER, nel 1947, con camera di Wilson immersa in campo magnetico di 3500 gauss. Pochi millimetri al disotto della lastra contenuta nella camera una particella neutra decade in volo in due particelle cariche che producono le due tracce « V » visibili nella parte destra inferiore della foto. [Fotografia riprodotta per gentile concessione del prof. G. D. ROCHESTER].

- No blob of recoil nucleus at vertex of V
- However small the mass of the secondary p. is assumed to be, the mass of the primary is > 800 m_e
- If the secondary p. are mesons then $m_{prim.} \approx 1000\ m_e$

FIRST EXAMPLE of $K^0 \to \pi^+ + \pi^-$

FIRST "τ MESON" ($K_{\pi 3}$)
(Bristol group, 1949)

K →

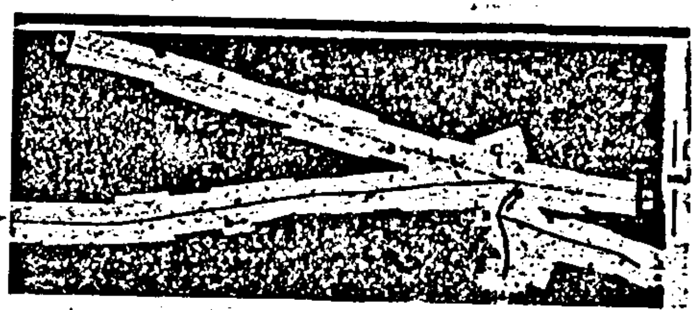


Fig. 16 The first τ (K_{π}) the primary heavy meson (called κ on the picture) comes from left to right and stops. A slow π^- comes down and makes a two-prong star. Two others lightly ionising particle are emitted from the first stopping point.

A HEAVY PARTICLE (K), BUT LIGHTER THAN A PROTON, STOPS IN EMULSION ($m_K \sim 1000\ m_e$ from ionization-range + scattering-range). Three coplanar tracks arise from the stop: one due to a slow π^- which stops producing a "star"; the other due to mesons (μ's or π's) as seen from measurements of ionization and scattering. If the three secondaries are pions then

$$m_K = \sim 985\ m_e$$

DISTINCTION BETWEEN Λ^0 AND K^0 (I)

ACHIEVED THROUGH WORK CARRIED OUT IN THE EARLY 1950's WITH LARGE MAGNETIC CLOUD CHAMBERS BY

- MANCHESTER GROUP (ARMENTEROS et al) AT PIC DU MIDI
- CALTECH GROUP (LEIGHTON et al.)
- INDIANA GROUP (THOMPSON et al.)
- BERKELEY GROUP (FRETTER et al.)
- M.I.T. GROUP (BRIDGE et al.)

MOSTLY REPORTED AT THE BAGNÈRE DE BIGORRE CONFERENCE

THE CALTECH GROUP (ANDERSON GROUP) WAS THE FIRST TO CONFIRM THE DISCOVERY OF ROCHESTER AND BUTLER REPORTING 34 SIMILAR EVENTS (V PARTICLES)

THE MANCHESTER GROUP MOVED THE APPARATUS ON THE PIC DU MIDI IN 1950 AND IN MARCH 1951 REPORTED THE OBSERVATION OF 36 V^0 + 7 $V^{\pm}$. IN 4 OF THE 36 V^0 THE POSITIVE TRACK APPEARED TO BE VERY LIKELY THAT OF A PROTON; THE NEGATIVE ONE THAT OF A MESON (NEXT TRANSPARENCIES)
IN SOME CASES, HOWEVER, THE POSITIVE PARTICLE WAS CLEARLY LIGHTER THAN A PROTON. HERE WERE THE FIRST INDICATIONS FOR THE DECAY MODES $V_1^0 \to p\pi^-$; $V_2^0 \to \pi^+\pi^-$ ONLY LATER ESTABLISHED DEFINITIVELY.

FIRST EXAMPLE OF V_1^0 DECAY ($\Lambda^0 \to p + \pi^-$)

Fig. 17 The first V_1^0, the heavy ionisation of the positive is clearly seen.

FROM EXPOSURE AT PIC DU MIDI
(Armenteros et al. 1951)

EXAMPLE OF $V_1^0 \rightarrow p + \pi^-$ OBSERVED AT CALTECH BY LEIGHTON et al. (1953)

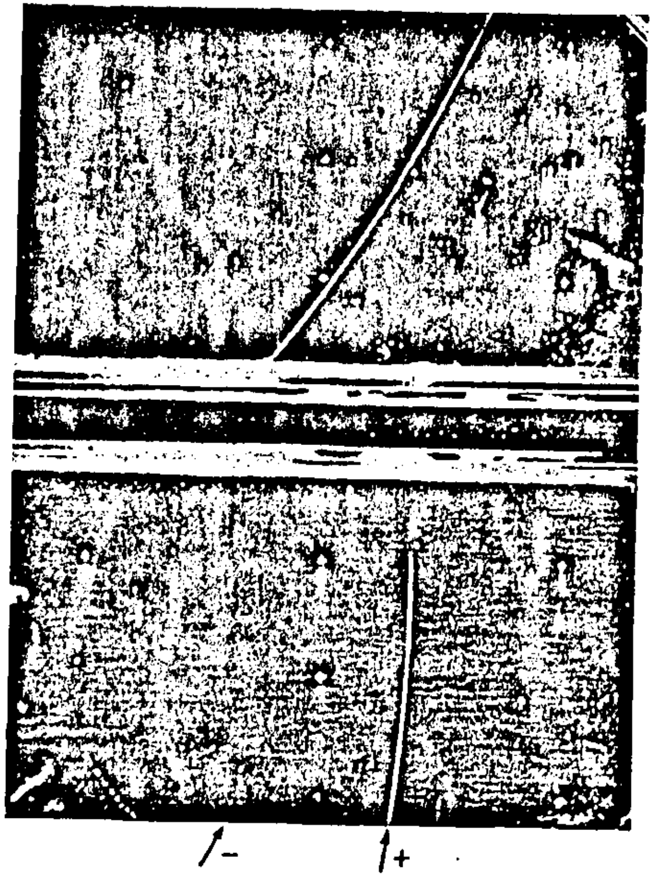


Fig. 3. – Esempio di evento V_1^0 ottenuto da LEIGHTON *et al.* con camera di Wilson in campo magnetico di 5000 gauss. La particella positiva (a destra) è identificata per un protone; la massa di quella negativa (a sinistra) è compresa tra 230 e 430 m_e [21].
[Fotografia riprodotta per gentile concessione del prof. C. D. ANDERSON].

EXAMPLE OF $V_2^0 \rightarrow \pi^+ + \pi^-$ OBSERVED AT INDIANA BY THOMPSON et al. (1951)

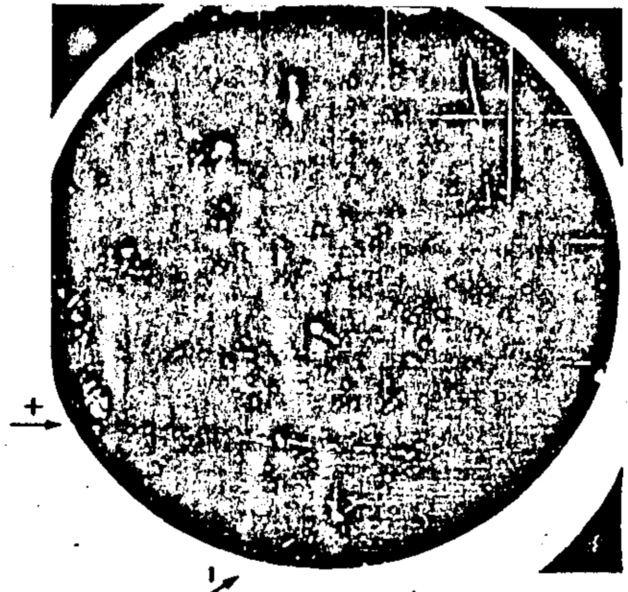


Fig. 4. – Esempio di evento che non può essere interpretato con lo schema (I) perchè il secondario positivo ha una massa quasi certamente non superiore a quella del pione. Ciò si deduce dalle misure della ionizzazione e della curvatura della traccia. La fotografia è stata ottenuta da THOMPSON *et al.* in camera di Wilson immersa in campo magnetico di 3100 gauss [39]. [Fotografia riprodotta per gentile concessione del prof. R. W. THOMPSON].

The positive secondary cannot be a proton: from curvature and ionisation measurements its mass is $\sim m_\pi$ providing evidence for the decay scheme

$$V_2^0 (K^0) \rightarrow \pi^+ \pi^-$$

DISTINCTION BETWEEN Λ^0 AND K^0 (II)

a) Use of parameter $\alpha = (p_1^\ell - p_2^\ell)/(p_1^\ell + p_2^\ell)$

introduced by Armenteros + Podolansky to test level of symmetry in decay

$$M \rightarrow m_1 + m_2$$

Since
$$\alpha = \frac{m_1^2 - m_2^2}{M^2} + \frac{2}{\beta}\frac{p^* \cos\theta^*}{M}$$

$$\bar{\alpha} = 0 \text{ only if } m_1 = m_2$$

Results from expos. at Pic du Midi provided first evidence for two groups of events:

1) events giving $\bar{\alpha} = 0.69$ ($V_1^0 \rightarrow p\pi^-$; Q = 37 MeV)
2) " " $\bar{\alpha} = 0$ ($V_2^0 \rightarrow \pi^+\pi^-$; Q = 214 MeV)

although it was not yet proved that they came indeed from two different particles as indicated [A unique neutral particle undergoing the decay modes $\rightarrow p + \pi^- +$ neutral, $\rightarrow n + \pi^+ + \pi^-$ could not be excluded]

Proof of a two-body decay ($V_1^0 \rightarrow p + \pi^- + (37 \pm 2)$ MeV) reported at 3rd Rochester Conf. by M.I.T. group

b) Use of ~~Thomp~~ Thompson $P_t(\alpha)$ ellipses and Q-surface

High accuracy results presented at Bagnères de Bigorre
Conclusion that there are particles of same mass ~ 965 m_e with different decay modes. Here initiated the "θ-τ puzzle" which ultimately led to the recognition of the BREAKDOWN OF PARITY CONSERVATION IN WEAK INTERACTIONS

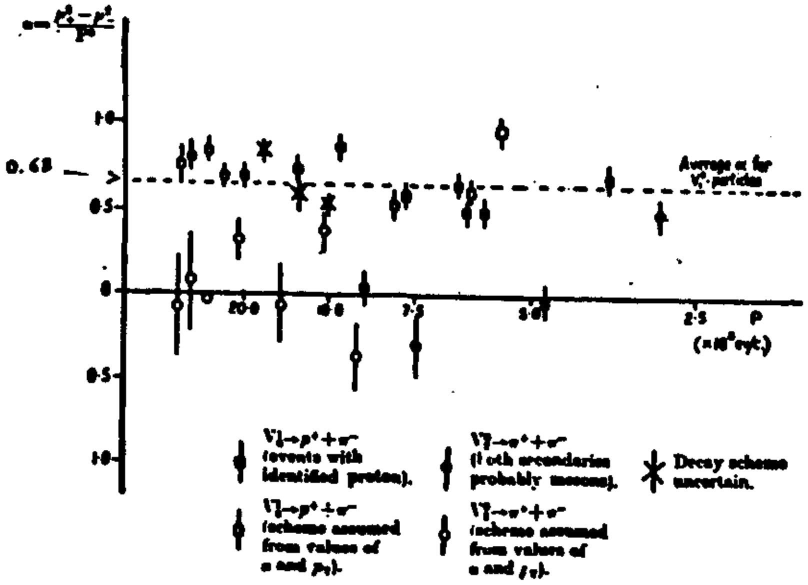


Fig. 19 The 1/p, α plot of the Manchester events. The grouping in two decay modes is clearly seen.

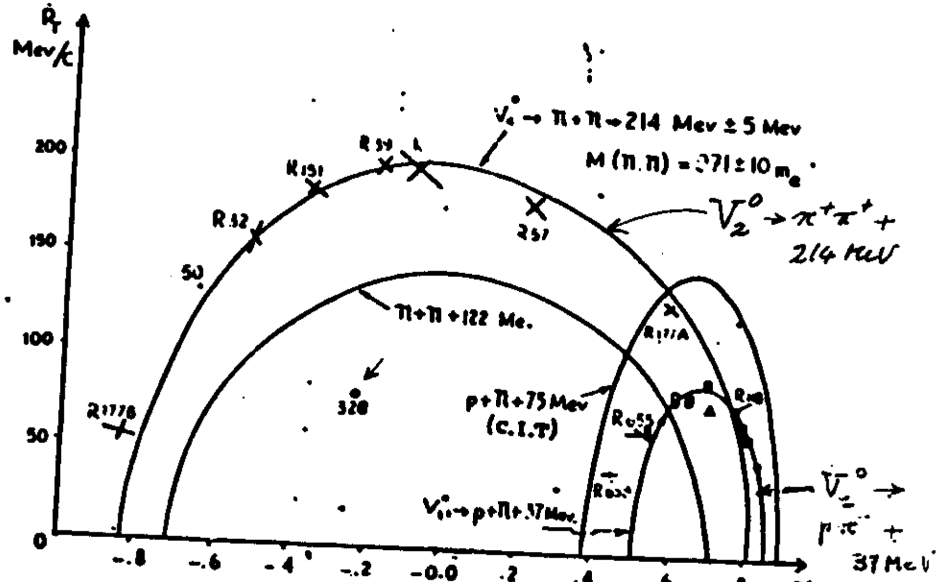


Fig. 22 The α, PT plot of Thompson. The grouping on the ellipses of two-body decays for the V_1 and V_2 is evident. One point in the middle is a first example of anomalous V_2 (K_L).

↙ FIRST example of anomalous V_2^a (K_L^0)

CHARGED STRANGE PARTICLES

Discovery of the Ξ^- ($\to \Lambda^0 \pi^-$, $\Lambda^0 \to p\pi^-$)

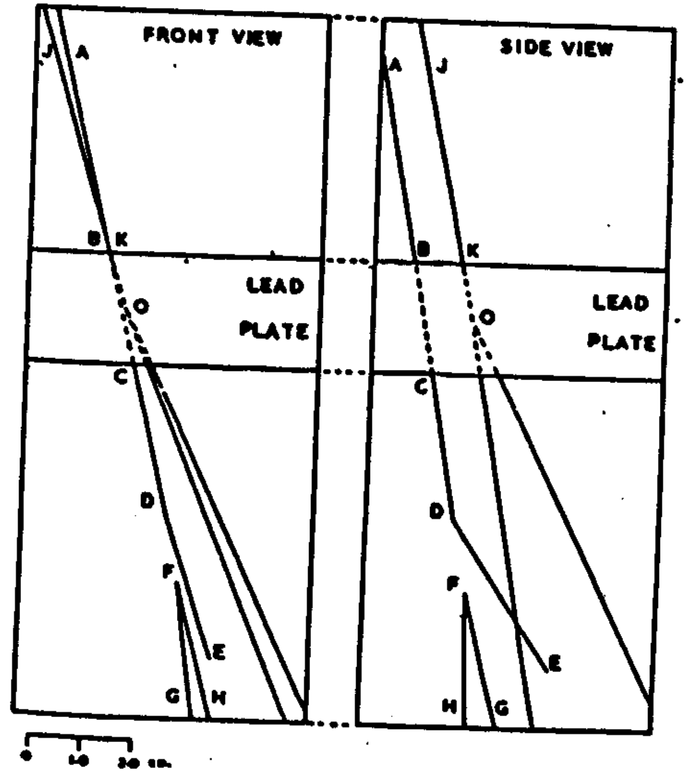


Fig.23 A geometric reconstruction of the first Ξ^- (cascade particle) photograph taken at the Pic du Midi by the Manchester group. (1952)

$V^- \to V^0 +$ meson

↙ Ξ^- (decay point of V^- in plane of secondaries of V^0)

Three similar events reported at Bagnère de Bigorre by Leighton provided conclusive evidence for the existence of this negative "cascade hyperon" (a negative baryon)!

FIRST EXAMPLE OF $\Sigma^+ \to p + \pi^0$

(MILAN + GENOA Group, Nov. 1953)

(Bonetti et al.)

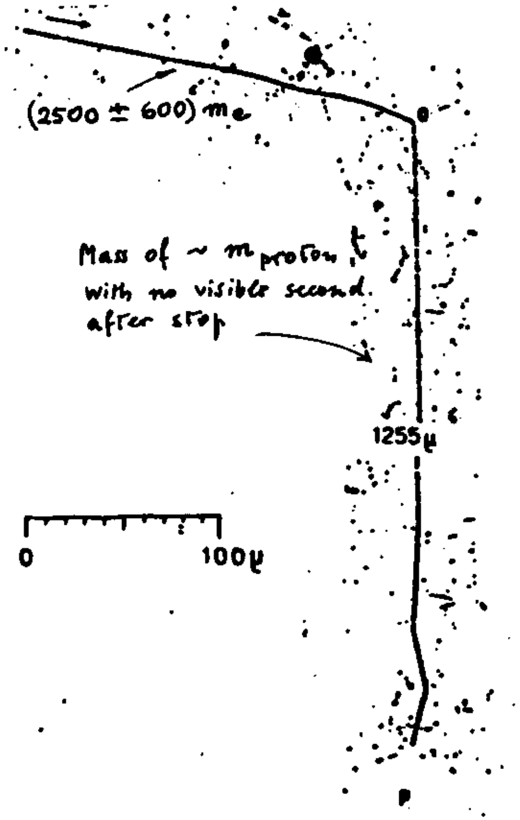


Fig. 26 The first $\Sigma^+ \to p + \pi^0$ recorded in emulsion by the Milano, Genova Group.

Previous example of possible "superprotons" ↳ [$\Sigma^+ \to n + \pi^+$]
already reported at Bagnère
de Bigorre, without providing conclusive evidence
Mass of Σ^+ much too large to consider Σ^+ as an
isospin partner of the Λ^0 ?

DISCOVERY OF HYPERFRAGMENTS

(Danysz and Pniewski, 1953)

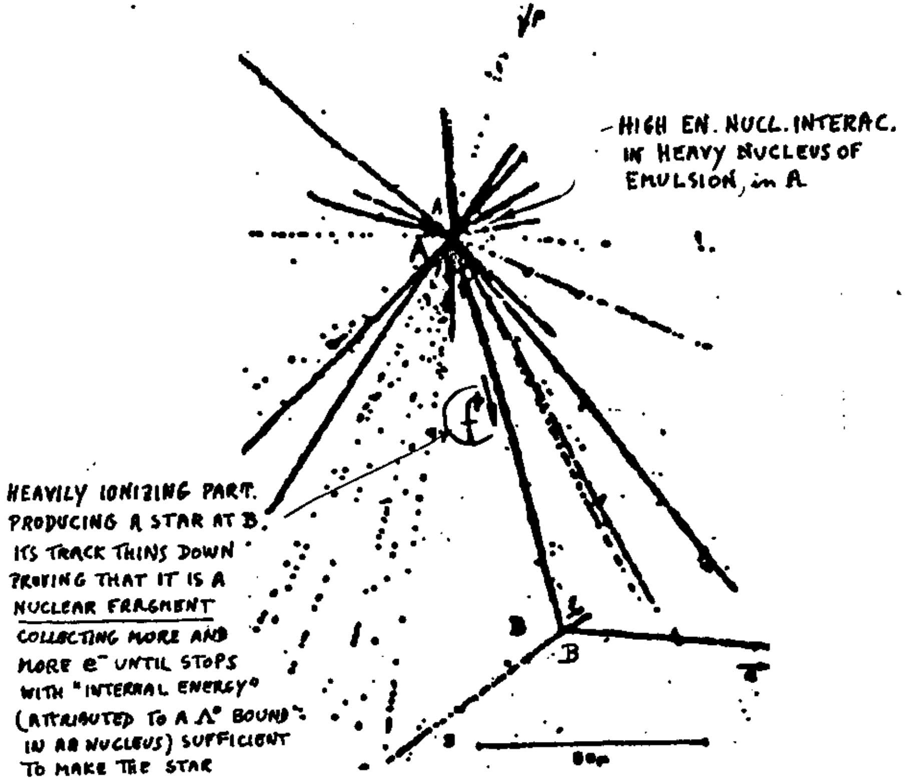


Fig. 25 The first hyperfragment. The track f is a heavy fragment which thins down at the end of its range and then explodes. The explosion is due to the decay of a bound Λ^0.

STRANGE PARTICLES IN COSMIC R.
(a summary)

1946	Rochester + Butler	$V^0 \to V_1^0 \to \theta^0 \Rightarrow K_1^0 \to \pi^+\pi^-$	Mag. Cl. Ch.
1947	" "	$V^+ \Rightarrow K^+$	" "
1949	Bristol group	$\tau \Rightarrow K^+ \to \pi^+\pi^+\pi^-$	Emulsion
1951	Manchester gr.	$V_1^0 \Rightarrow \Lambda^0 \to p\pi^-$	Mag. Cl. Ch.
1951	O'Ceallaigh	$K \Rightarrow (K_{\mu_3})$	Emulsion
"	"	$K_\mu \Rightarrow (K_{\mu_2})$	"
1952	Manch. gr. CASCADE PART.	$\Rightarrow \Xi^- \to \Lambda^0\pi^-$, $\hookrightarrow p\pi^-$	Mag. Cl. Ch.
1953	Thompson ANOMALOUS	$V_2^0 \Rightarrow K_2^0 \to \pi^+\pi^-\pi^0$	" "
1953	Milan Genoa gr. SUPERPROTON	$\Rightarrow \Sigma^+ \to p\pi^0$	Emulsion
1954	Menon + O'Ceallaigh	$\chi \Rightarrow (K_{\pi_2})$	

Discoveries ~ equally shared between two techniques: Magnetic Cl. Chamber and Nuclear Emulsion

CONCLUDING REMARKS

Of Two reasons for high en. in particle phys.

a) creation of new particles
b) exploitation of microscopic structure by probing distances of $\sim c\hbar/E$

only a) exploited in Cosmic Rays
Nevertheless COSMIC RAYS OPENED THE FIELD OF PARTICLE PHYSICS through

- FIRST DISCOVERY OF ANTIMATTER — the positron
- DISCOVERY OF NEW e.m. PROCESSES — pair production
- DISCOVERY OF CASCADE PROCESSES — e.m. cascade
- DISCOVERY OF FIRST "HEAVY LEPTON" — the muon
- CONCEPT OF UNIVERSAL FERMI INTERACTION
- DISCOVERY OF FIRST "YUKAWA MESON" — the pion
- DISCOVERY OF NEW LAYER OF HADRONIC MATTER: Strange particles + hyperfragments

ALL THAT DONE BY SINGLES OR SMALL GROUPS, WITH LIMITED FINANCIAL SUPPORT, WITH NO OTHER THAN THE "INTELLECTUAL PRESSURE" OF KNOWING NATURE, IN A "FAMILY STYLE" TYPE OF WORK BELONGING TO AN ERA ~~WHERE~~ WITH NO NEED OF "MANAGERIAL TALENT"