

Fundamental interactions

Particles' history

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M.Sozzi - Fundamental Interactions - Università di Pisa



Dipartimento di Fisica "E. Fermi"
UNIVERSITÀ DI PISA

Why?

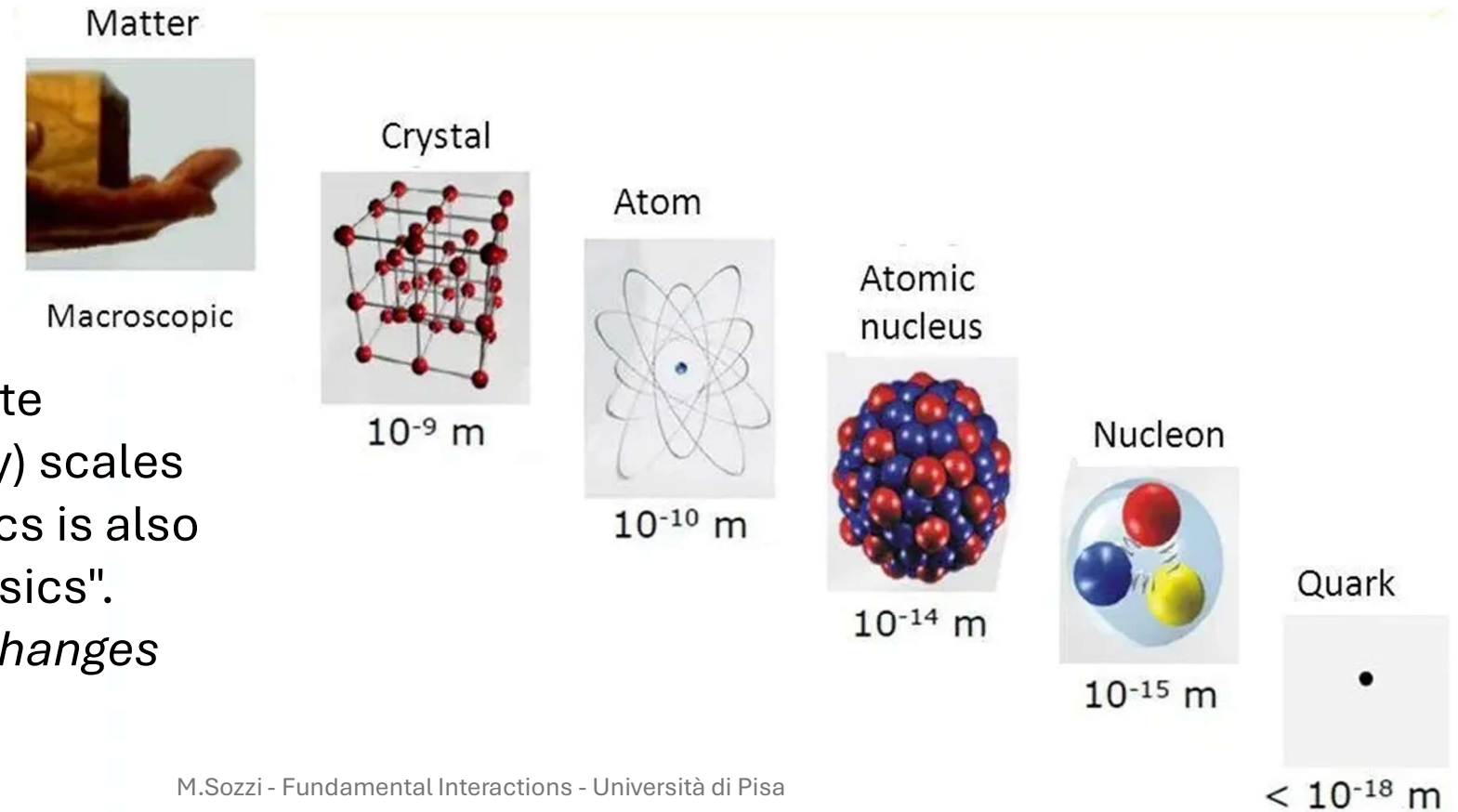
As mentioned, while for an "active" branch of science this might be possible, we will not follow a strictly historical approach in the course

However

- We discussed the difference between learning "what" and learning "why or how"
- Science is built upon experimental observations, crucial ones must be known
- An "axiomatic" presentation of the concepts might leave students baffled and look a little bit as "magic"
- There are quite many concepts and particles to learn about, knowing how they came to be helps assimilating and remembering them (you must know and memorize the basic properties of the main particles, as these correlate to concepts)
- It's useful to get a bird's eye overview before delving into the details

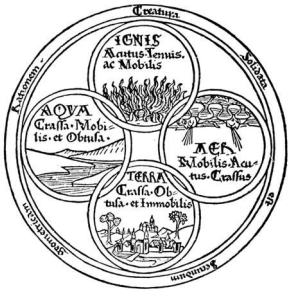
What about?

"Fundamental" interactions are the known ways in which "fundamental" constituents of matter relate to each other. *The meaning of "fundamental" changes with time.*

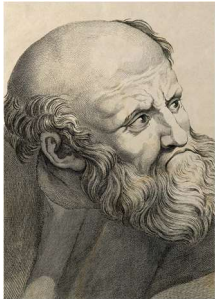


Distance scales translate into momentum (energy) scales $\lambda = h/p$, so particle physics is also called "high-energy physics". *The meaning of "high" changes with time.*

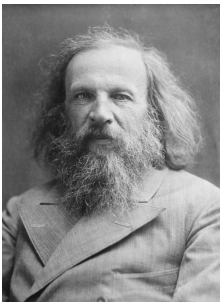
Spectroscopies: e pluribus unum



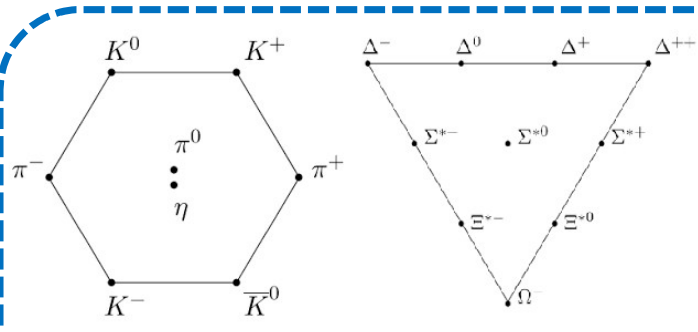
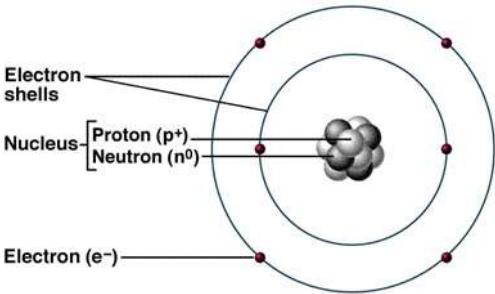
Empedocles (550 B.C)



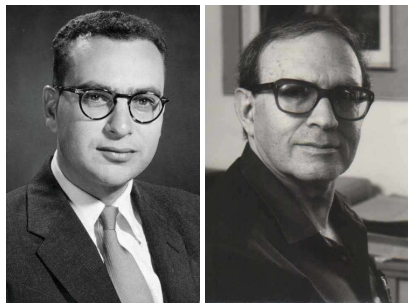
Mendeleev (1870)



Rutherford + many others (1900-1932)



Gell-Mann, Ne'eman (1961)



Gell-Mann, Zweig (1964) + many others (to 1995)

2.4 MeV/c ² $\frac{2}{3}$ u up	1.27 GeV/c ² $\frac{2}{3}$ c charm	171.2 GeV/c ² $\frac{2}{3}$ t top
4.8 MeV/c ² $-\frac{1}{3}$ d down	104 MeV/c ² $-\frac{1}{3}$ s strange	4.2 GeV/c ² $-\frac{1}{3}$ b bottom

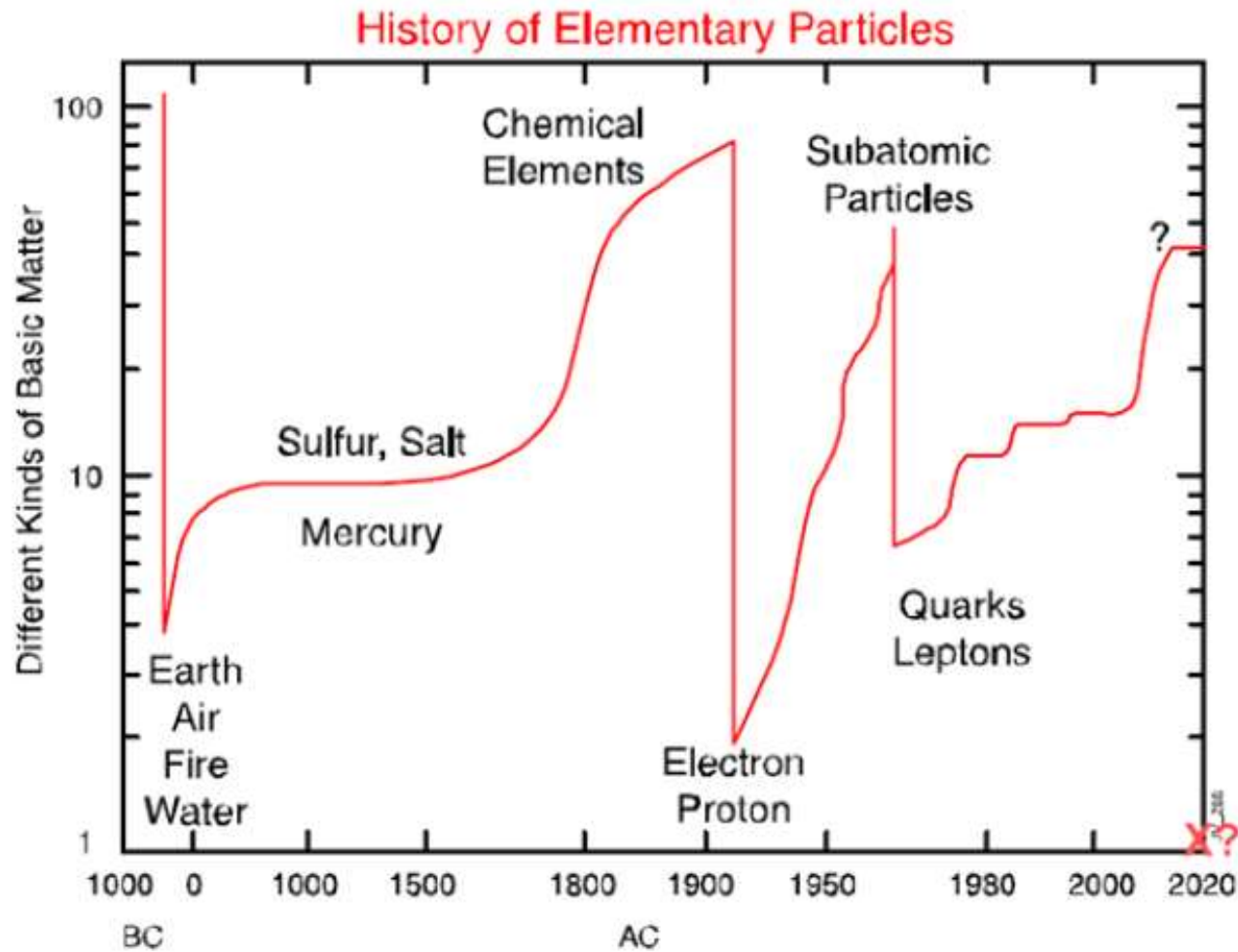
This course

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The end?

Elementary particles?



Elementary particles?

J	Symbol	Generic name
0	$\pi^{\pm,0}, K^{\pm,0,\bar{0}}, \dots$	(P)Scalar mesons
1/2	$e, \mu, e_{\mu}, \nu_{\mu}$ $p, n, \Lambda, \Sigma \dots$	Leptons Baryons
1	γ $\rho, \omega \dots$	Photon Vector mesons
3/2	$\Delta^{++,+,0,-}, \dots \Xi^{-,0} \dots$	Baryons

Around 1960



J	Symbol	Generic name
0	H	Higgs scalar
1/2	$e, \mu, \tau, \nu_e, \nu_{\mu}, \nu_{\tau}$ u, d, c, s, t, b	leptons quarks
1	γ g_j^i $W^{\pm}, Z^0$	photon gluon (8) vector bosons
2		graviton

Around 2020



Particle discoveries

Particle	Year	Discovered	Technique
e^-	1897	Thomson	Discharge in gases
p	1919	Rutherford	Radioactivity
n	1932	Chadwick	Radioactivity
e^+	1933	Anderson	Cosmic-rays
$\mu^{+/-}$	1937	Neddermeyer, Anderson	Cosmic-rays
$\pi^{+/-}$	1947	Powell, Occhialini, Lattes	Cosmic-rays
$K^{+/-}$	1947	Rochester, Butler	Cosmic-rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic-rays
Λ^0	1950	Hopper	Cosmic-rays
anything else	1955 $\rightarrow$ today	various groups	Accelerators



The classical era (1897-1932)

Photon

1905 Bern

Einstein proposes that Planck's light quanta behave as particles to explain the photoelectric effect

A. Einstein -
Ann. Phys. 17 (1905) 132

1914 Chicago

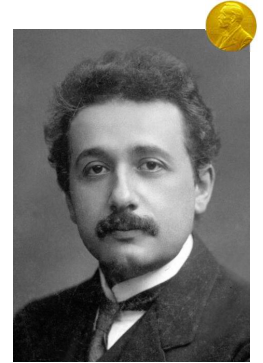
R. Millikan confirms Einstein's photoelectric law

R. Millikan -
Phys. Rev. 4 (1914) 73

1923 S. Louis

A. Compton observes the frequency change of scattered X rays

A. H. Compton -
Phys. Rev. 21 (1923) 483



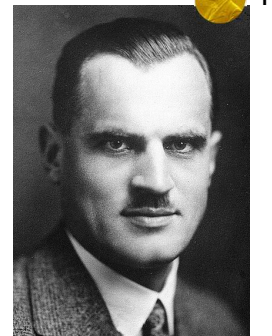
1921

Albert Einstein
(1879-1955)



1923

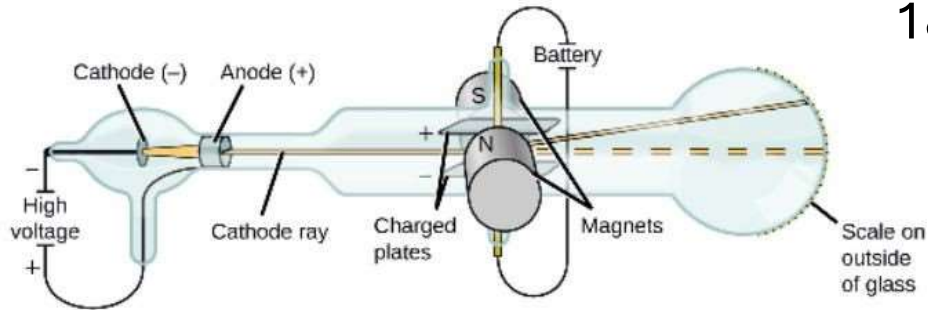
Robert Millikan
(1868-1953)



1927

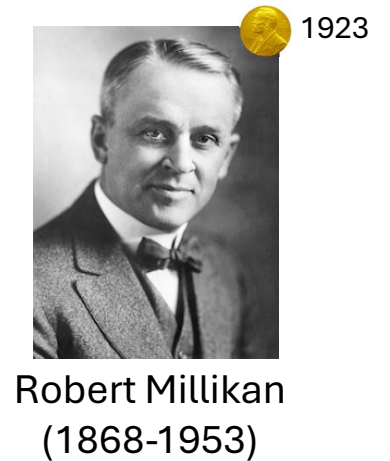
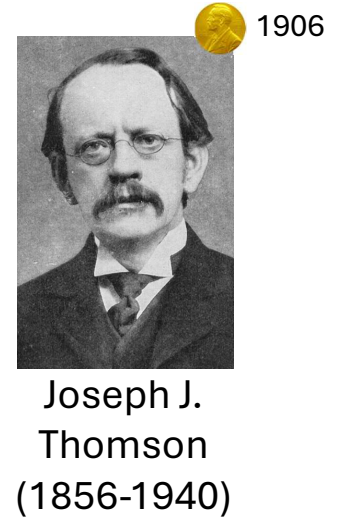
Arthur H. Compton
(1892-1962)

Electron



1897 Cambridge
Cathode rays deflected by electric field.
Use of crossed electric and magnetic fields indicates $e/m \sim 1800$ times that of lightest ion

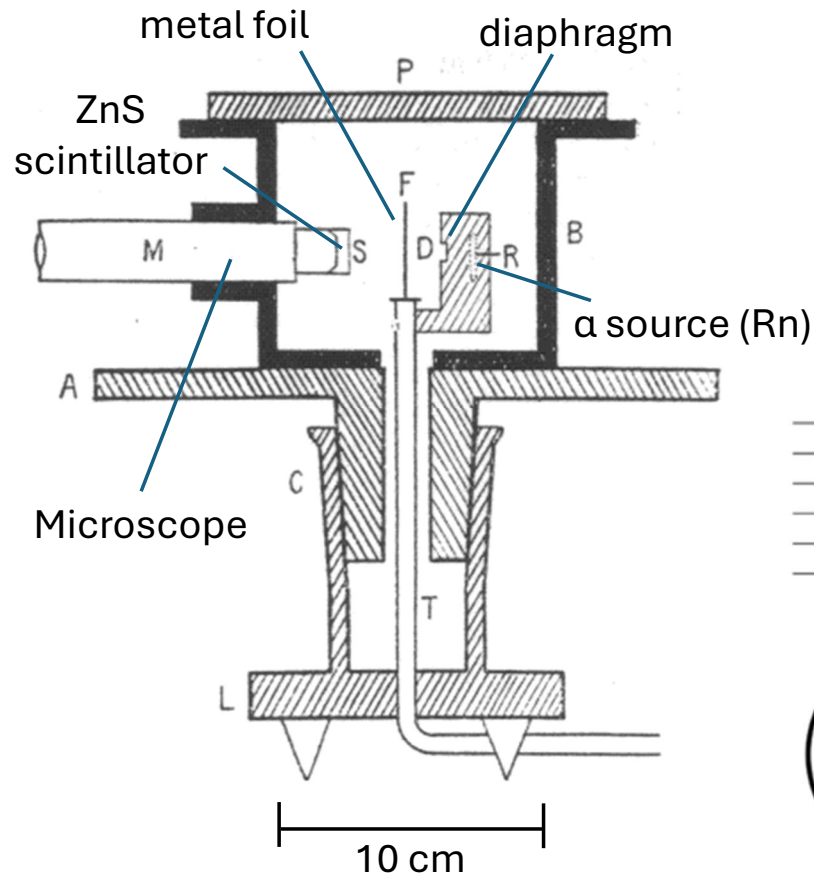
J.J. Thomson –
Phil. Mag. 44 (1897) 293



1909 Chicago
Measurement of electron charge
58 oil droplets for 60 days
(determination of electron mass)

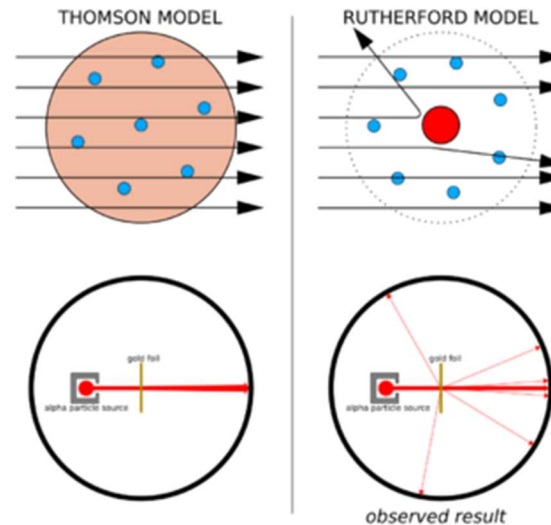
R.A. Millikan –
Science. 32 (1910) 436

Nucleus



H. Geiger, E. Marsden –
Proc. R. Soc. A 82 (1909), 495

1909 Manchester
Deflection of α particles
at large angles
indicates positive
charge with $R < 10^{-14}$ m



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Hans Geiger
(1882-1945)



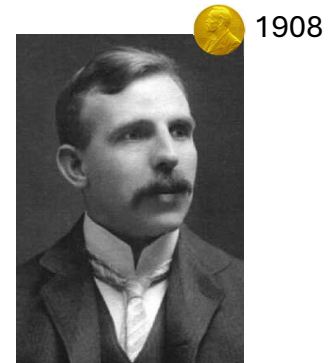
Ernst Marsden
(1889-1970)

On a Diffuse Reflection of the α -Particles.

By H. GEIGER, Ph.D., John Harling Fellow, and E. MARSDEN, Hatfield
Scholar, University of Manchester.

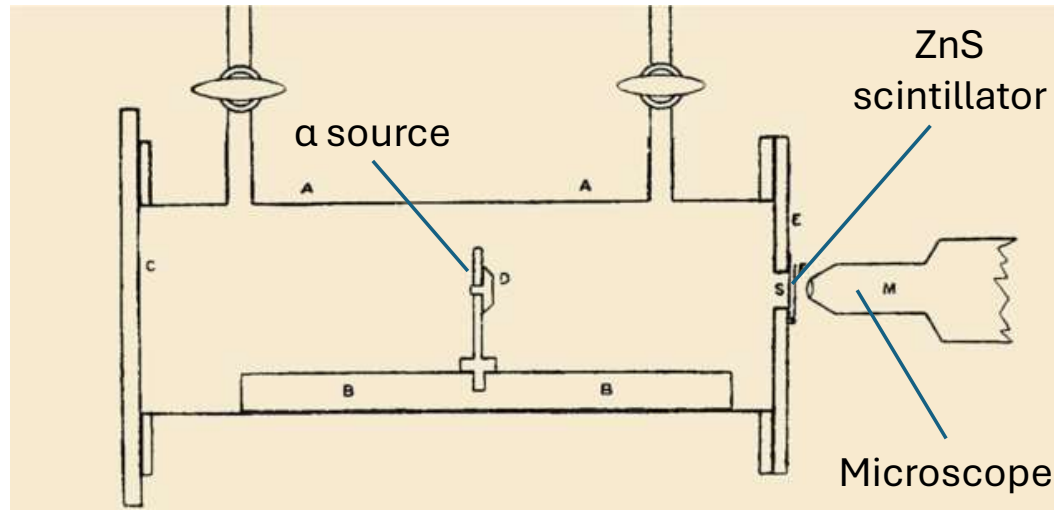
(Communicated by Prof. E. Rutherford, F.R.S. Received May 19,—Read
June 17, 1909.)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4(\theta/2)}$$

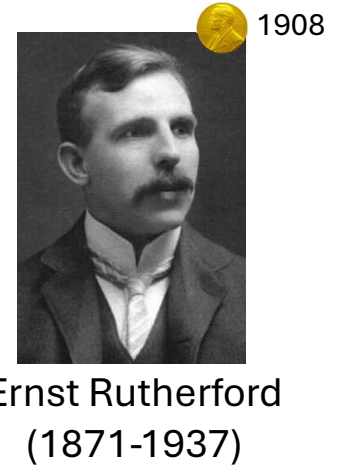


Ernst Rutherford
(1871-1937)

Proton



1919 Cambridge
Recoil hydrogen
particles emitted by
bombarding metal with
α particles increase
when N₂ is present



E. Rutherford –
Phil. Mag. 37 (1919) 581

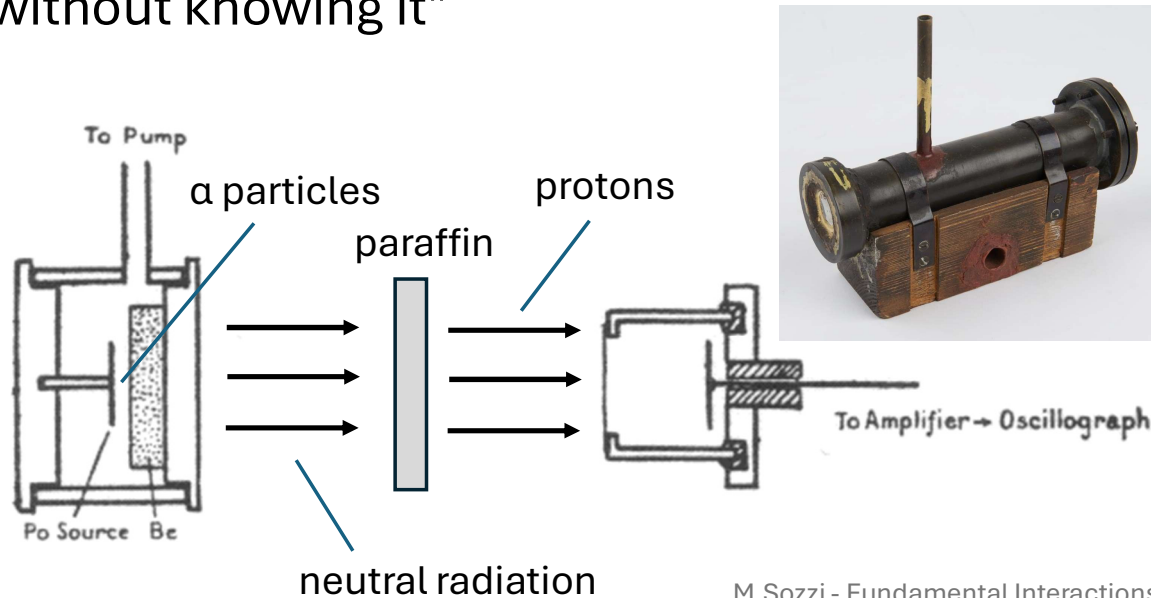
Neutron

1932 Paris

Penetrating neutral radiation produced by α particles on Be was known to eject 5 MeV protons from paraffin: interpreted as photons.

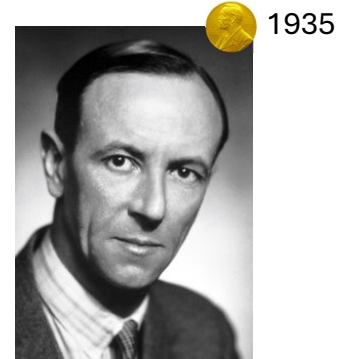
1932 Roma

E. Majorana: "they discovered the neutron without knowing it"



1932 Cambridge

Measurement of ionization (velocity) of other emitted ions is not compatible with 50 MeV photons



James Chadwick
(1891-1974)

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons.

Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. Chadwick –
Nature 129 (1932) 312

Particles 1

Particle	Mass (MeV/c ²)	Charge (e)	Spin ($\hbar/2$)	Lifetime (s)	Decay modes
electron (e ⁻)	0.511	-1	1/2	stable	N/A
photon (γ)	0	0	1	stable	N/A
proton (p)	938	+1	1/2	stable	N/A
neutron (n)	939	0	1/2	880	pe ⁻ ...

Nomenclature initially based on mass: **leptons** ("light") vs. **baryons** ("heavy")
to which **mesons** were added in the middle

Beware: no longer the correct meaning of these words!



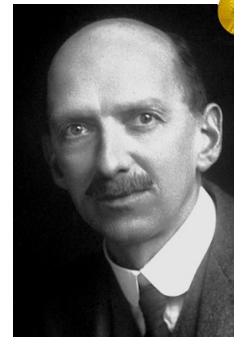
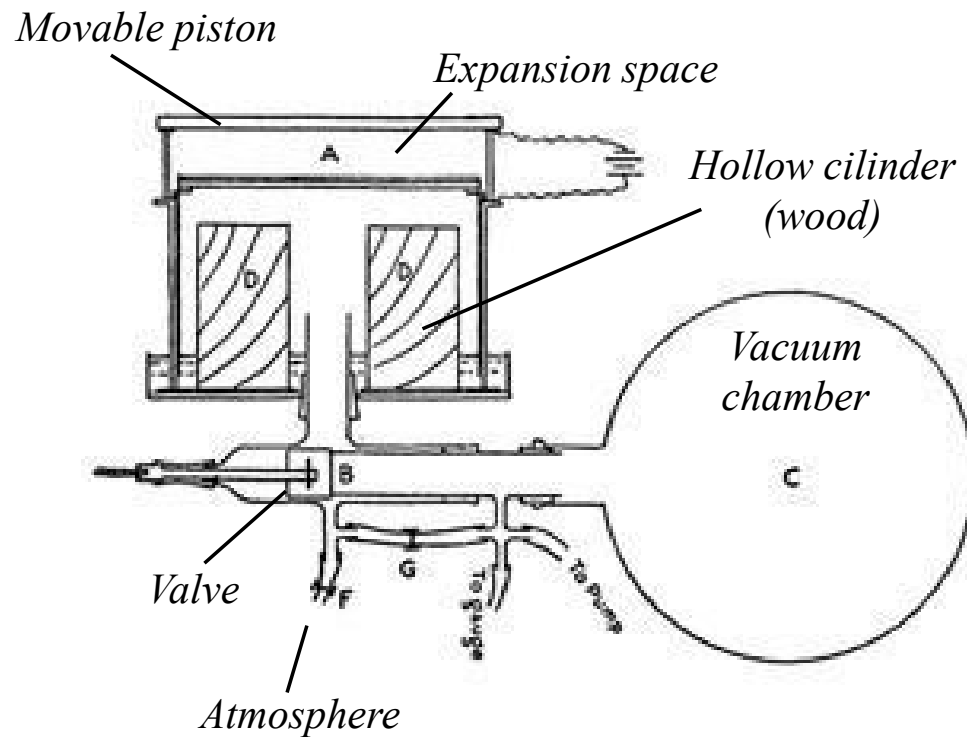
Antiparticles (1932-1956)

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Cloud chamber

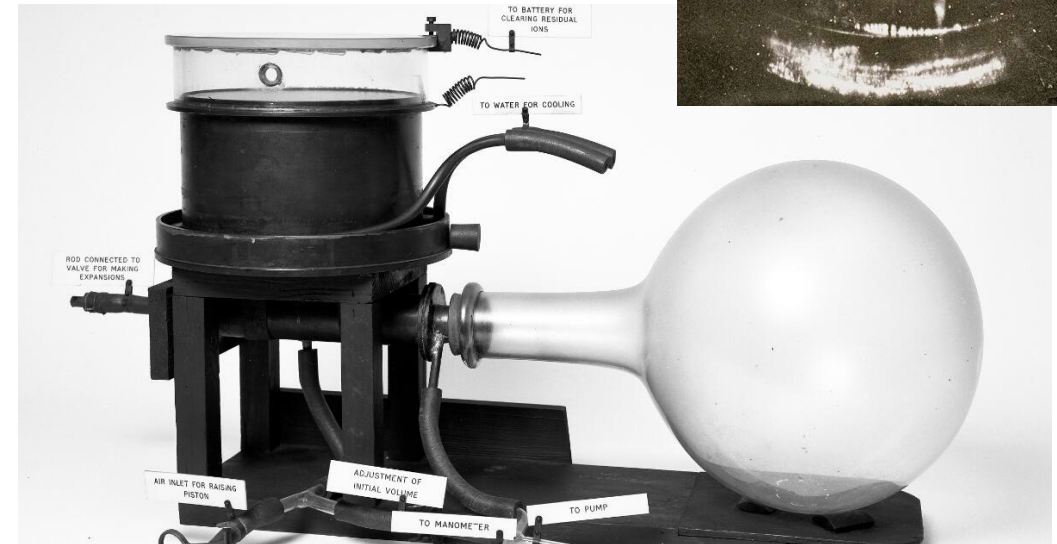
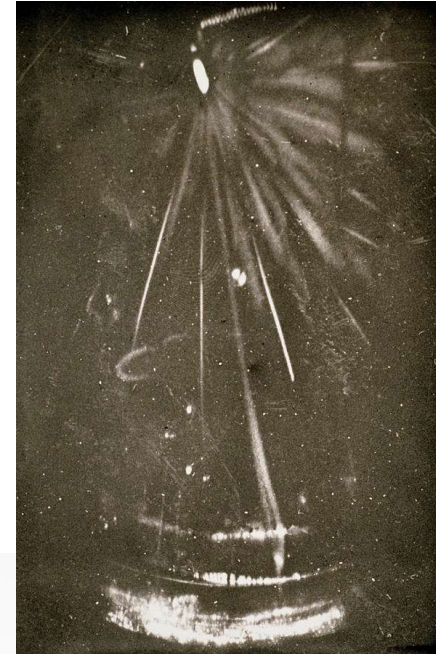
1899-1912 Cambridge

Adiabatic expansion results in a supersaturated gas and the formation of droplets around ionization centres



1927

Charles Wilson
(1869-1959)



Cosmic rays

1930-1936 Pasadena, Pike's Peak

Observation of cosmic rays in cloud chamber,
estimate of their momentum (by magnetic
deflection) and their energy (by range)

VOL. 50, No. 4

AUGUST 15, 1936

SECOND SERIES

Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level

CARL D. ANDERSON AND SETH H. NEDDERMEYER, *Norman Bridge Laboratory of Physics, California Institute of Technology*
(Received June 9, 1936)

C.D. Anderson, S.H. Neddermeyer –
Phys. Rev. 50 (1936) 263

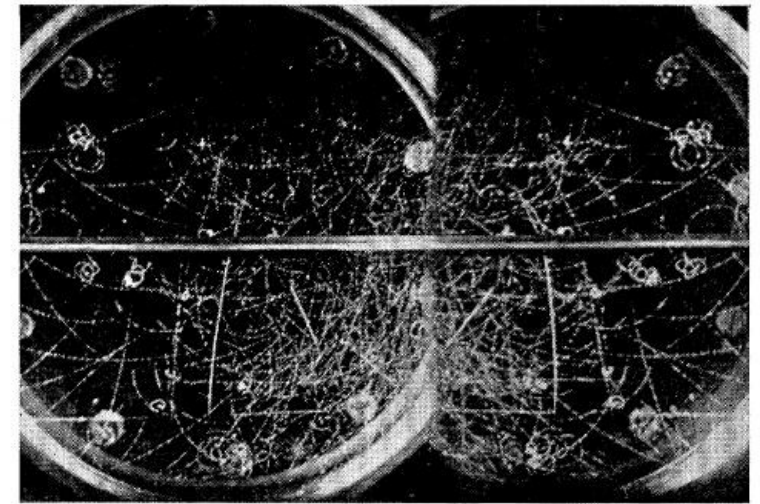


FIG. 13. Pasadena, 4500 gauss. A complex electron shower not clearly defined in direction, and three heavy particles with specific ionizations definitely greater than that of electrons. The sign of charge of two of these heavy particles represented by short tracks cannot be determined, but the assumption that they represent protons is consistent with the information supplied by the photograph. The third heavy track appears above the 0.35 cm lead plate where it has a specific ionization not noticeably different from that of an electron. It penetrates the lead plate and appears in the lower half of the chamber as a nearly vertical track near the middle. Below the plate it shows a greater ionization than an electron, and is deviated in the magnetic field to indicate a positively charged particle. Its $H\rho$ is apparently at most 1.4×10^5 gauss cm, which corresponds to a proton energy of 1 MEV and a range of only 2 cm in the chamber, whereas the observed range is greater than 5 cm. A difficulty of the same nature was discussed in the description of the previous photograph.

Anti-particles ?

1926 Leningrad

Add a magnetic field to a cloud chamber
for observing cosmic rays

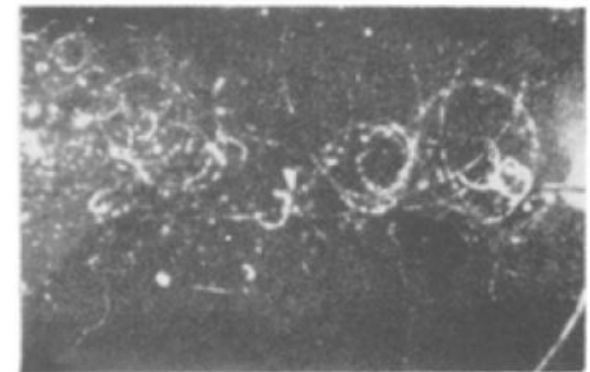
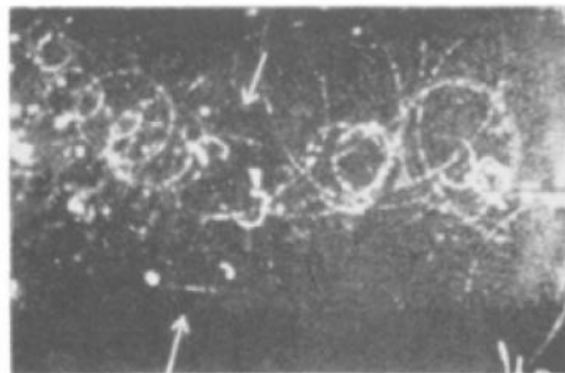
Observed some tracks which looked like
electrons but curved in the wrong direction

Also I. Curie and F. Joliot, and C. Chao

Not understood



Dmitri V. Skobeltsyn
(1892-1990)



Anti-electron

1932 Pasadena, Pike's Peak
Observation of a particle with
the same mass as the electron
but positive charge

1936



Carl Anderson
(1905-1991)

The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*
(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the

curvatures and ionizations produced require the m less than twenty times the electron mass. These will be called positrons. Because they occur in association with other tracks it is concluded that they be secondary particles ejected from atomic nuclei

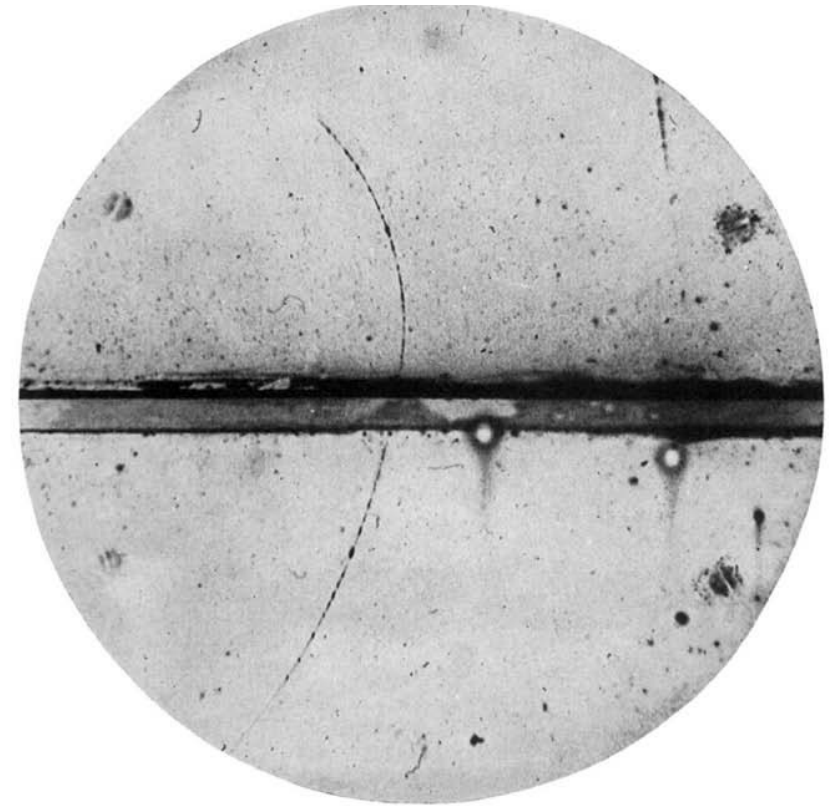


FIG. 1. A 63 million volt positron ($H\rho=2.1\times10^6$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho=7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Particle accelerators

	Year	Where	Diameter (or length)	Particle	Energy
Lawrence's cyclotron	1931	Berkeley	11 cm	p	80 keV
60' cyclotron	1939	Berkeley	152 cm	p	16 MeV
184' cyclotron	1946	Berkeley	470 cm	p	350 MeV
Cosmotron	1953	Brookhaven	23 m	p	3 GeV
Bevatron	1954	Berkeley	39 m	p	13 GeV
Proton synchrotron	1959	CERN	144 m	p	28 GeV
AGS	1960	Brookhaven	258 m	p	33 GeV
Stanford linear	1966	Stanford	3 km	e ⁻	30 GeV



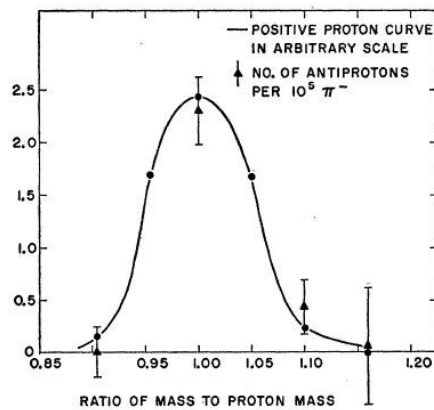
Berkeley's Bevatron (1954)
13 GeV protons

Anti-proton

1955 Berkeley

Negative 1.19 GeV/c beam

Velocity: TOF, $\check{C} \rightarrow m$



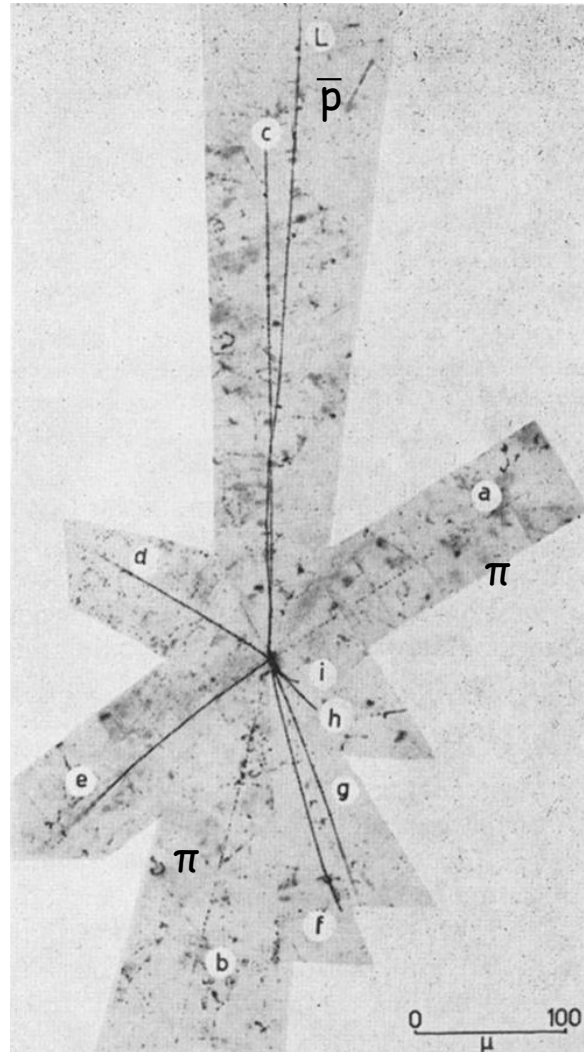
Observation of Antiprotons*

OWEN CHAMBERLAIN, EMILIO SEGRÈ, CLYDE WIEGAND,
AND THOMAS YPSILANTIS

*Radiation Laboratory, Department of Physics, University of
California, Berkeley, California*

(Received October 24, 1955)

O. Chamberlain et al. –
Phys. Rev. 100 (1955) 947

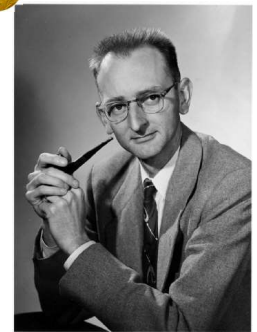


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1959



E. G. Segre
(1905-1989)



O. Chamberlain
(1920-2006)

Antiproton Star Observed in Emulsion*

O. CHAMBERLAIN, W. W. CHUPP, G. GOLDBABER, E. SEGRÈ, AND
C. WIEGAND, *Radiation Laboratory, Department of Physics,
University of California, Berkeley, California*

AND

E. AMALDI, G. BARONI, C. CASTAGNOLI, C. FRANZINETTI, AND
A. MANFREDINI, *Istituto di Fisica della Università, Roma
Istituto Nazionale di Fisica Nucleare,
Sezione di Roma, Italy*

(Received December 16, 1955)

O. Chamberlain et al. –
Phys. Rev. 101 (1956) 909

Particles 2

Particle	Mass (MeV/c ²)	Charge (e)	Spin ($\hbar/2$)	Lifetime (s)	Decay modes
positron (e^+)	0.511	+1	1/2	stable	N/A
antiproton ($\bar{p}$)	938	-1	1/2	stable	N/A
neutron ($\bar{n}$)	939	0	1/2	880	$\bar{p}e^+\dots$

Nomenclature initially considered different names ("positron" and "negatron") but then reverted to anti-XXX

The symbol normally has an overline, and sometimes the charge

Which one is particle and which one is anti-particle is arbitrary (assume world is made of matter: e^- , p , n are particles)

Baryon number

The proton does not decay (e.g. $p \rightarrow e^+ \dots$ $p \rightarrow \pi^+ \dots$)

Its lifetime is currently measured to be $> 10^{34}$ years

Baryons always decay into other baryons

1938 Geneva

Hypothesis of a conserved quantity ("heavy charge") counting baryons

$$B(p) = B(n) = B(\Lambda) = B(\Sigma) = \dots = +1$$

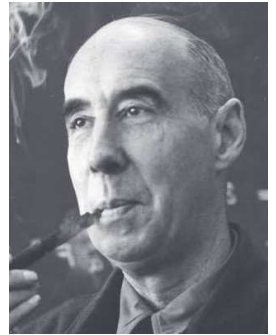
$$B(\bar{p}) = B(\bar{n}) = B(\bar{\Lambda}) = B(\bar{\Sigma}) = \dots = -1$$

$$B(e) = B(\mu) = B(\pi) = \dots = 0$$

- The proton is stable because it is the lightest baryon
- Baryons and anti-baryons are different ($\bar{n} \neq n$)

Baryon number conservation appears to be valid for all interactions

Note that there is no conserved "meson number"



Ernst Stueckelberg
(1905-1984)



Mesons (1934-1947)

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Yukawa's hypothesis

1935 Osaka, Geneva

Idea that strong interactions are mediated by the exchange of particles ("U-quanta") which transform neutron into proton and viceversa

On the Interaction of Elementary Particles. I.

By Hideki YUKAWA.

(Read Nov. 17, 1934)

§ 1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction of elementary particles. Heisenberg considered the interaction of "Platzwechsel" between the neutron and the proton to be of importance to the nuclear structure.⁽¹⁾

Recently Fermi treated the problem of β -disintegration on the hypothesis of "neutrino"⁽²⁾. According to this theory, the neutron and the proton can interact by emitting and absorbing a pair of neutrino and electron. Unfortunately the interaction energy calculated on such assumption is much too small to account for the binding energies of neutrons and protons in the nucleus.⁽³⁾

H. Yukawa –
Prog. Theor. Phys. Suppl. 1 (1935) 1

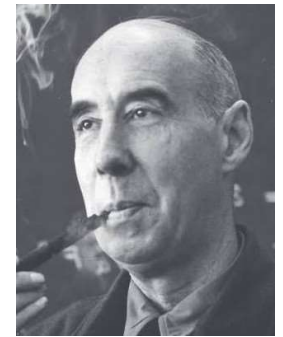
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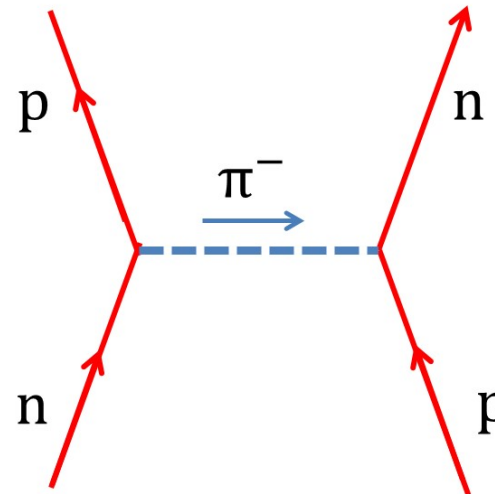
Hideki Yukawa
(1907-1981)



1949



Ernst Stueckelberg
(1905-1984)



Mass estimate:

$$R \sim \frac{\hbar}{Mc}$$

$$R \sim 1 \text{ fm}$$
$$M \sim O(200) m_e$$

Anderson, Neddermeyer discovery

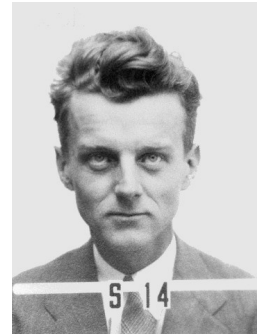
1936 Pasadena, Pike's Peak

Identification of cosmic ray particles with intermediate mass between the electron and the proton ones

1936



Carl Anderson
(1905-1991)



Seth Neddermeyer
(1907-1988)

Note on the Nature of Cosmic-Ray Particles

SETH H. NEDDERMEYER AND CARL. D. ANDERSON
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

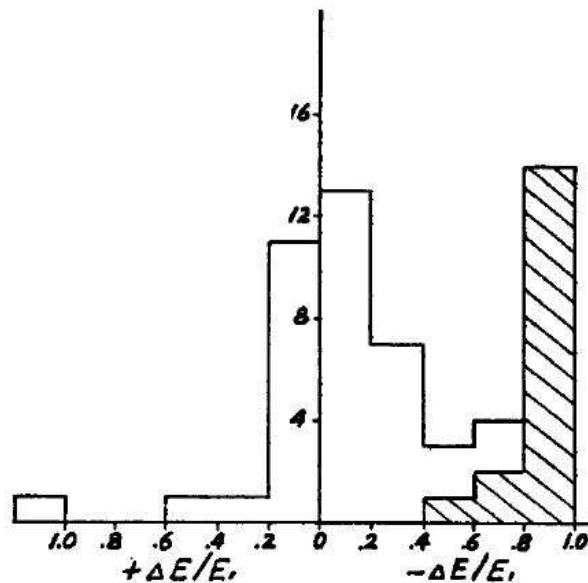


Figure 2: Distribution of fractional losses in 1 cm of platinum.

The nonpenetrating particles are readily interpreted as free positive and negative electrons. Interpretations of the penetrating ones encounter very great difficulties, but at present appear to be limited to the following hypotheses: (*a*) that an electron (+ or -) can possess some property other than its charge and mass which is capable of accounting for the absence of numerous large radiative losses in a heavy element; or (*b*) that there exist particles of unit charge, but with a mass (which may not have a unique value) larger than that of a normal free electron⁷ and much smaller than that of a proton; this assumption would also account for the absence of numerous large radiative losses, as well as for the observed ionization. Inasmuch as charge and mass are the only parameters which characterize the electron in the quantum theory, assumption (*b*) seems to be the better working hypothesis.

Conversi, Pancini and Piccioni experiment



Marcello Conversi
(1917-1988)



Ettore Pancini
(1915-1981)



Oreste Piccioni
(1915-2002)

1945-46 Roma

Comparison of absorption and decay
for positive and negative mesotrons

Actually, a negative particle can be captured by a nucleus and, if it is the quantum of nuclear forces, quickly interacts with it rather than decaying. In contrast, a positive particle is repelled by a nucleus and will decay as in vacuum. The two iron blocks, F_1 and F_2 in the upper part of Fig. 2.1, are magnetised in opposite directions normal to the drawing and are used to focus the particles of one sign or, inverting their positions, the other. The 'trigger logic' of the experiment is the following. The Geiger counters A and B , above and below the magnetised blocks, must discharge at the same instant ('fast' coincidence); one of the C counters under the absorber must fire not immediately but later, after a delay Δt in the range $1\ \mu\text{s} < \Delta t < 4.5\ \mu\text{s}$ ('delayed' coincidence). This logic guarantees the following: first that the energy of the particle is large enough to cross the blocks and small enough to stop in the absorber; second that, in this energy range and with the chosen geometry, only particles of one sign can hit both A and B ; and finally that the particle decays in a time compatible with the lifetime value of Rossi and Nereson.

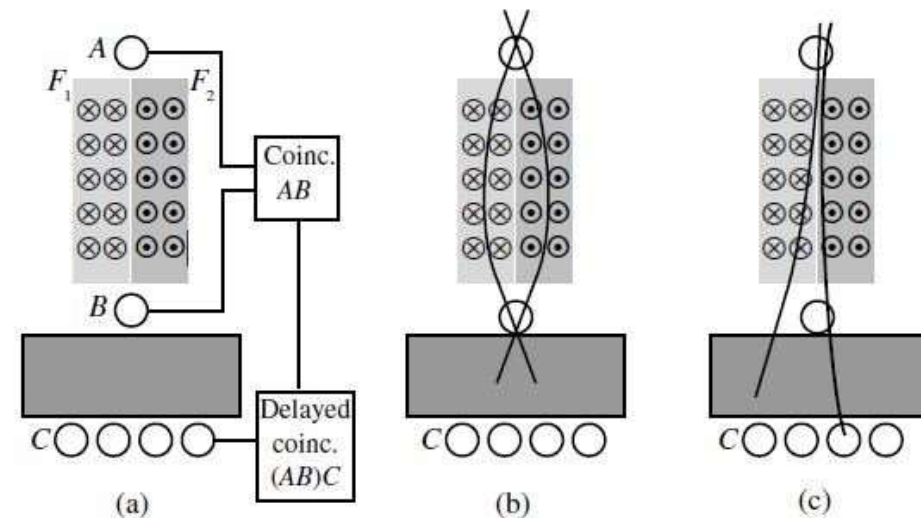


Fig. 2.1. A sketch of the Conversi, Pancini, Piccioni experiment.

The "mesotron" is not the Yukawa particle

**Sull'assorbimento e sulla disintegrazione dei mesoni
alla fine del loro percorso.**

M. CONVERSI, E. PANCINI ed O. PICCIONI

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

M. Conversi, E. Pancini, O. Piccioni –
Nuovo Cim. 3 (1946) 372

1946 Roma

While in Fe negative mesotrons are indeed absorbed before decay, in C they are not and do decay just as positive ones: interaction is many orders of magnitude too small

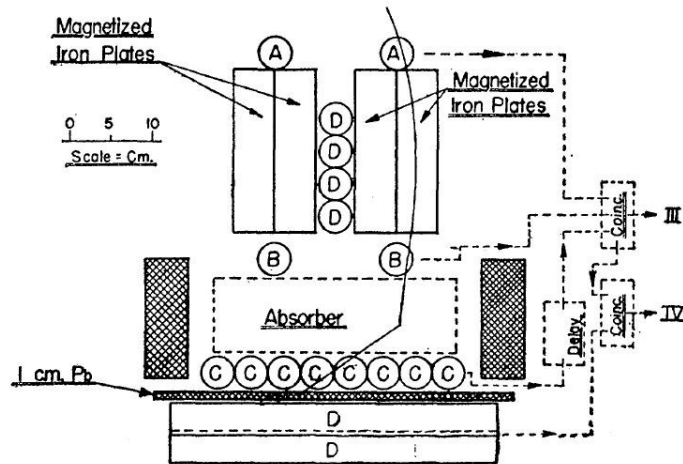


TABELLA I. - Risultati delle misure.

Serie	Se- gno	Assorbitore	III	IV	t	IV/ora	M	$\frac{M_-}{M_+}$
2°	+	5 cm Fe	213	106	155 ^h —	$0,69 \pm 0,07$	$0,67 \pm 0,065$	0,048
	—	5 cm Fe	172	158	206 ^h —	$0,77 \pm 0,06$	0,03	
	—	Assente	71	69	107 ^h 45'	$0,64 \pm 0,08$	—0,01	
3°	+	4 cm C	170	101	179 ^h 20'	$0,56 \pm 0,055$	$0,36 \pm 0,045$	0,75
	—	4 cm C + 5 cm Fe	218	146	243 ^h —	$0,60 \pm 0,05$	$0,27 \pm 0,035$	
	—	6 cm Fe	128	120	240 ^h —	$0,50 \pm 0,045$	0,008	

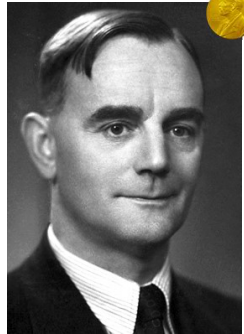
Lattes, Occhialini, Powell experiment



Cesare Lattes
(1924-2005)



Giuseppe Occhialini
(1907-1993)



Cecil Powell
(1903-1969)

1950

1947, Andes

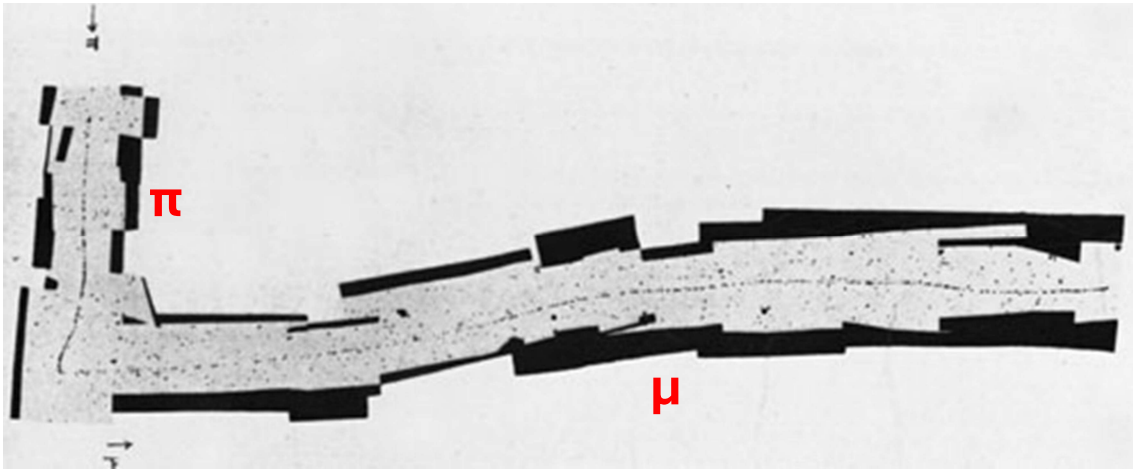
Observation of a π meson decaying into a penetrating μ particle in nuclear emulsions

OBSERVATIONS ON THE TRACKS OF SLOW MESONS IN PHOTO- GRAPHIC EMULSIONS*

By C. M. G. LATTES, DR. G. P. S. OCCHIALINI
and DR. C. F. POWELL

H. H. Wills Physical Laboratory, University of Bristol

C.M.G. Lattes, G.P.S. Occhialini, C.F. Powell –
Nature 160 (1947) 453



Yukawa's meson is the π which in cosmic rays decays in the atmosphere into a μ , which reaches ground and is much more penetrating

Particles 3

Particle	Mass (MeV/c ²)	Charge (e)	Spin ($\hbar/2$)	Lifetime (s)	Decay modes
muon ($\mu^\pm$)	105.6	± 1	1/2	$2.2 \cdot 10^{-6}$	$e^\pm \dots$
pion ($\pi^\pm$)	139.6	± 1	0	$2.6 \cdot 10^{-6}$	$\mu^\pm \dots$

Leptons: not affected by strong interactions

They all have spin 1/2

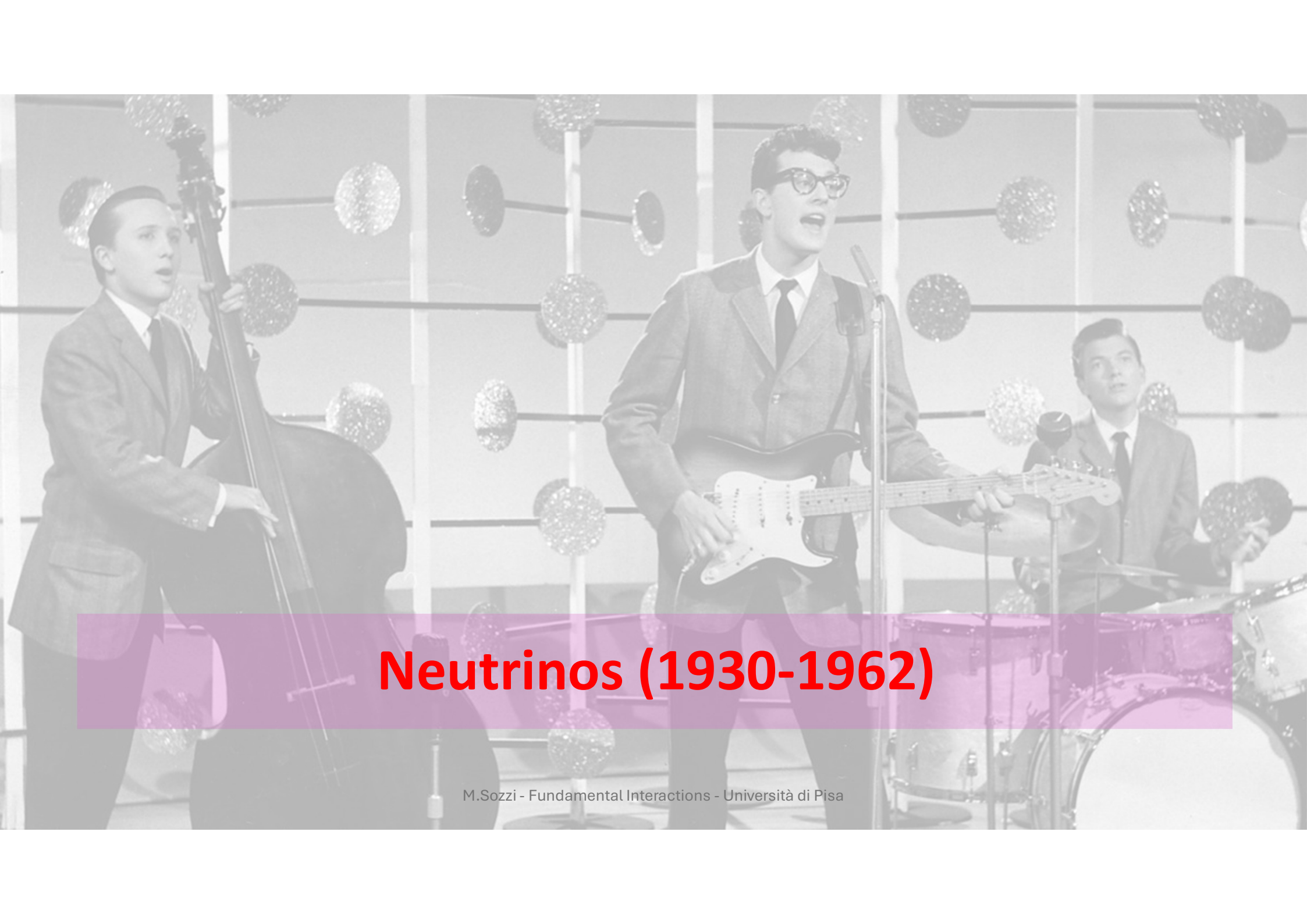
Hadrons: affected by strong interactions

They either have half-integer spin: **baryons**

or integer spin: **mesons**

The muon is not a meson but a (heavier) lepton

The pion is a meson and a hadron



Neutrinos (1930-1962)

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Beta decay: monochromatic ?

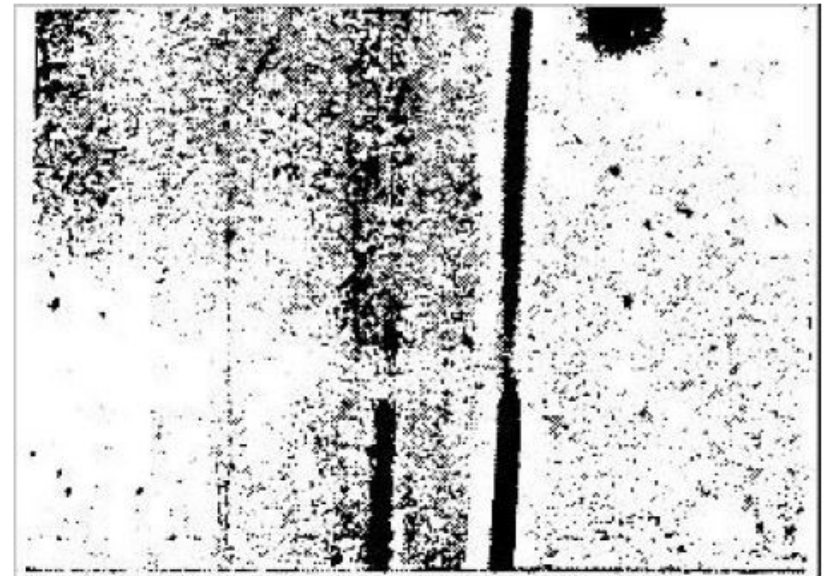
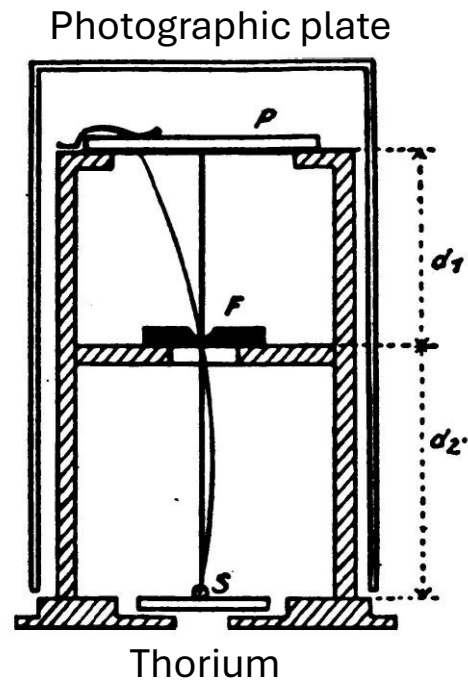
1944



Otto Hahn (1879-1968) Lise Meitner (1878-1968)

1911 Berlino

Single line detected on plate:
monochromatic electrons
(two lines for two radioactive species)



Beta decay: continuous?

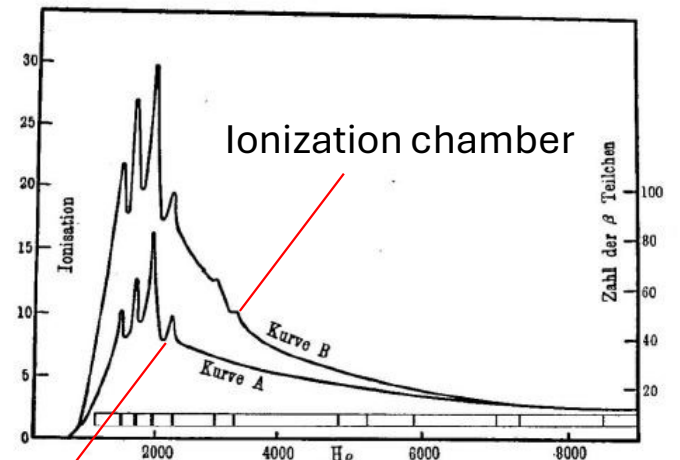
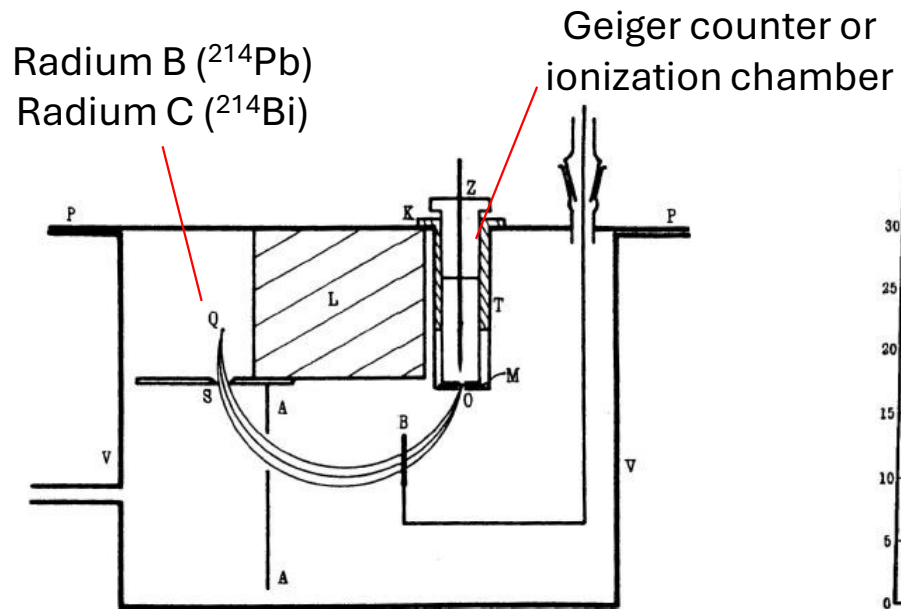


1935

James Chadwick
(1891-1974)

1914 Berlino

Continuum spectrum detected



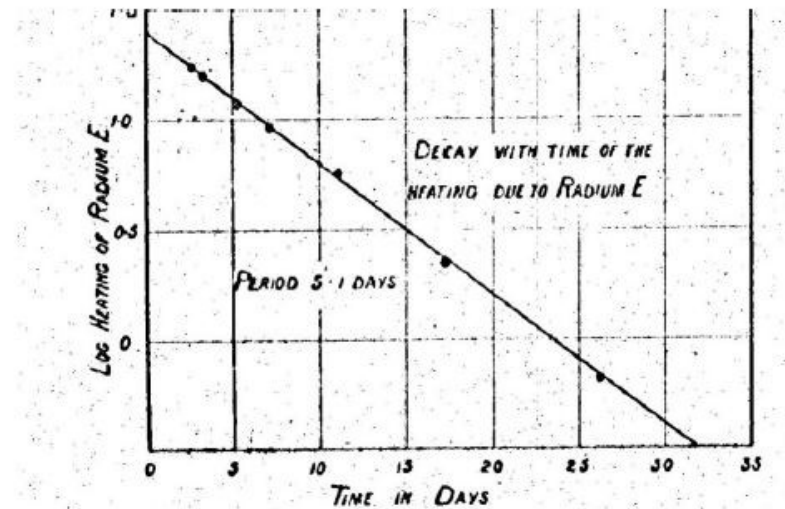
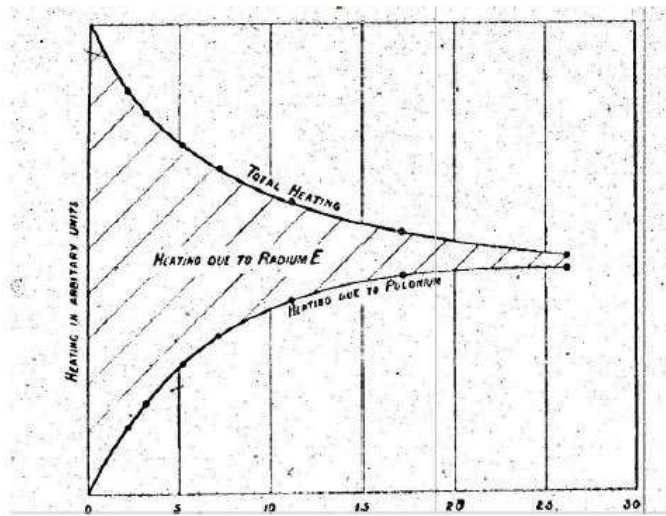
Geiger counter

J. Chadwick - Verhandl. Dtsch. Phys.
Ges. 16 (1914) 383

Beta decay: continuous!

1927 Cambridge

Calorimetric measure of heating effect of electrons: 10^{-3} degrees temperature differences, contamination from Po α decay separated due to different lifetime. Heating effect (total energy) equal to average of observed energy spectrum, which is therefore not due to energy losses.



The neutrino hypothesis (1930)



1945

Wolfgang Pauli
(1900-1958)

Dear radioactive ladies and gentlemen,

[...] I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr. Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tübingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. [...]

Your humble servant

W. Pauli

*Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.
Abschrift
Phys. Institut
zwischen Hochschule
und Herren;*

Zurich – 4 December 1930

*Zürich, 4. Dez. 1930
Oliviastrasse*

*den ich halbvollst
andererseits wird, bin ich
A- und Li-6 Kerne, sowie
einen verweifelten Answeg
Statistik und den Energiesatz
s könnten elektrisch neutrale
L, in den Kernen existieren,
schliessungsprinzip befolgen und
dadurch untercheiden, dass sie
m. Die Masse der Neutronen
wie die Elektronenmasse sein und
Protonenmasse. Das kontinuierliche
sich unter der Annahme, dass beim
eils noch ein Neutron emittiert
Energien von Neutron und Elektron*

Muon decay & neutrinos

π decays into μ and invisible particle (neutrino?)
 μ also decay into e and invisible particles (neutrinos?)
Decay spectrum indicates a multi-body decay
(e.g. 2 neutrinos)

Direct observation of neutrinos very difficult
due to tiny interaction cross sections $O(10^{-18})$ barn
Requiring:

(1) very intense flux

Atomic bombs



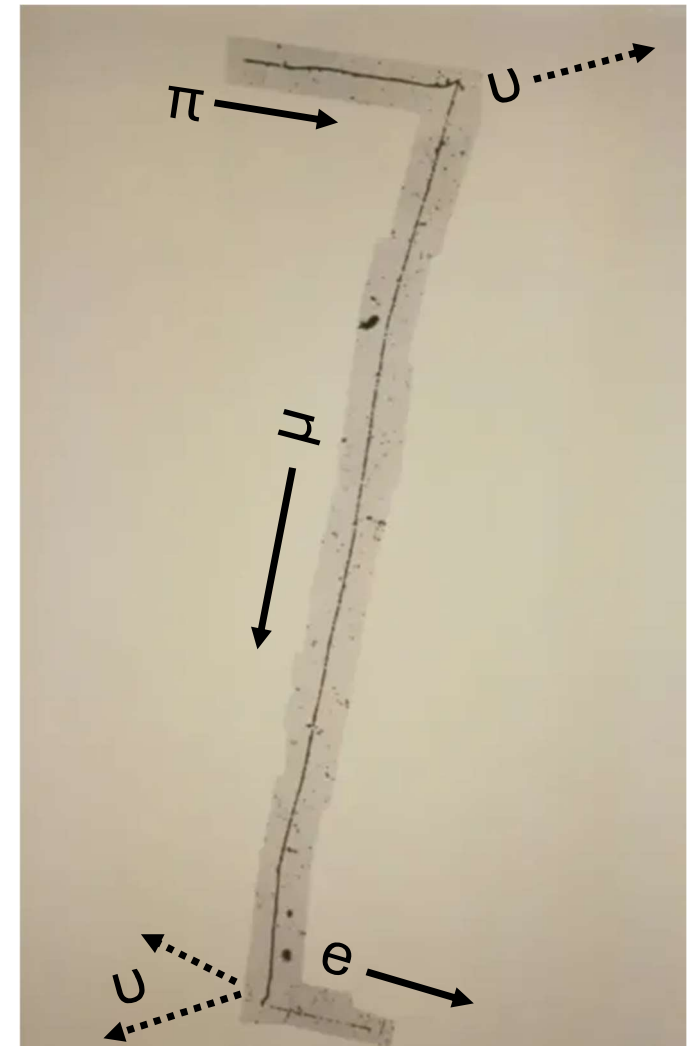
Nuclear reactors (lots of β decays)

(2) very massive target



Cheap water tanks with Cl

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C. Powell (1948)

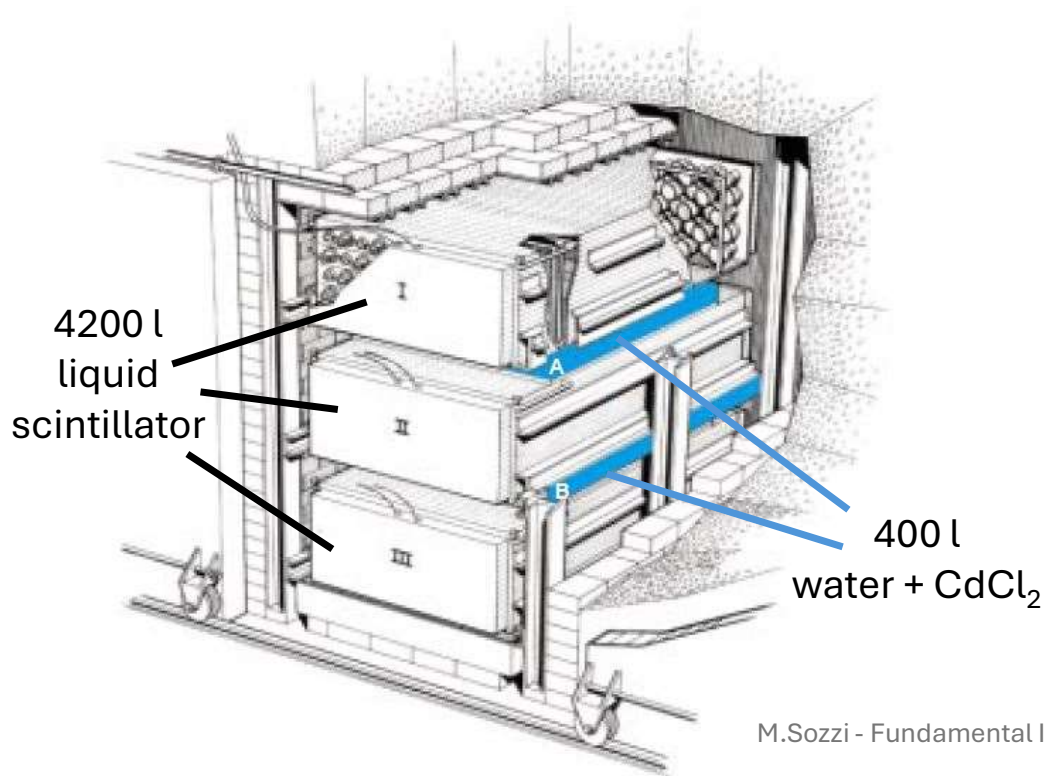
Neutrino observation

1956 Savannah River reactor

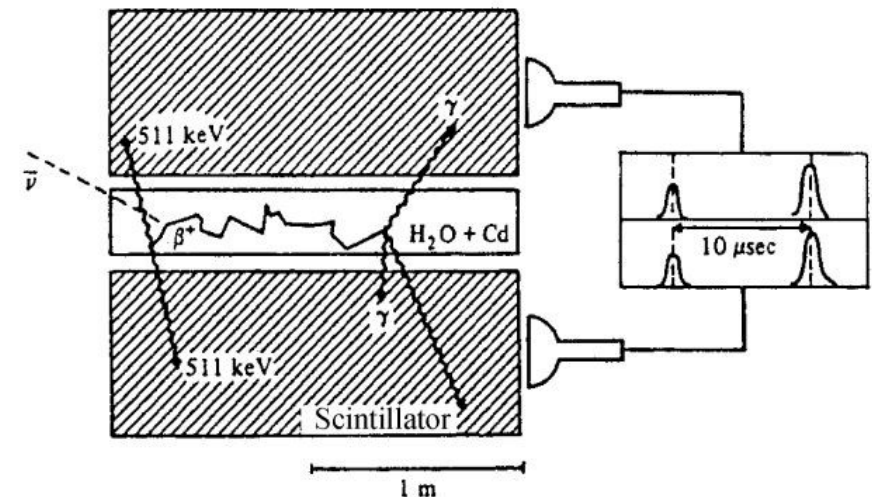
Exploit "inverse beta decay" $\bar{\nu}p \rightarrow ne^+$

n slowed in water, captured by $n^{113}\text{Cd} \rightarrow ^{114}\text{Cd} \gamma$ (9.1 MeV delayed)

e^+ annihilates with electron producing prompt $\gamma\gamma$ (2x 511 keV)



Frederick Reines (1918-1998) Clyde Cowan (1919-1974)



F. Reines, C.L. Cowan *et al.* –
Phys. Rev. 117 (1960) 159

Anti-neutrino

Beta decay: $n \rightarrow p e^- \text{ neutrino}$

One might expect also: $\text{neutrino } n \rightarrow p e^-$

e.g. $\text{neutrino } {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar } e^-$

which can be detected via radiochemical analysis
but this was not observed at reactors



Bruno Pontecorvo
(1913-1993)

Relativistic neutrinos and anti-neutrinos are different:

$n \rightarrow p e^- \bar{\nu}$ Beta decays at reactors produce anti-neutrinos

~~$\bar{\nu} n \rightarrow p e^-$~~ Not observed

$\nu n \rightarrow p e^-$ Observed

CROSSING SYMMETRY

Lepton number

1953 Konopinski & Mannoud introduce a conserved lepton number to count leptons:

L = +1 for electron, negative muon, neutrinos

L = -1 for positron, positive muon, antineutrinos

L = 0 for other particles

$$n \rightarrow p e^{-} \bar{\nu} \quad (0) = (0) + (+1) + (-1)$$

$$\bar{\nu} n \rightarrow p e^{-} \quad (-1) + (0) \neq (0) + (+1)$$

$$\nu n \rightarrow p e^{-} \quad (+1) + (0) = (0) + (+1)$$

Pion and muon decays involve different number of neutrinos/antineutrinos:

$$\pi^{-} \rightarrow \mu^{-} \bar{\nu} \quad (0) = (+1) + (-1) \quad \pi^{+} \rightarrow \mu^{+} \nu \quad (0) = (-1) + (+1)$$

$$\mu^{-} \rightarrow e^{-} \nu \bar{\nu} \quad (+1) = (+1) + (+1) + (-1) \quad \mu^{+} \rightarrow e^{+} \nu \bar{\nu} \quad (-1) = (-1) + (+1) + (-1)$$

More neutrinos

$\mu^- \rightarrow e^- \gamma$ would be allowed by lepton number conservation, but it does not occur



Bruno Pontecorvo
(1913-1993)

1957 Dubna

B. Pontecorvo and others suggest that different types of neutrinos exist. Separately conserved lepton family numbers

$$\begin{aligned} \pi^- &\rightarrow \mu^- \bar{\nu}_\mu & \pi^- &\rightarrow e^- \bar{\nu}_e \\ \pi^+ &\rightarrow \mu^+ \nu_\mu & \pi^+ &\rightarrow e^+ \nu_e \\ \mu^- &\rightarrow e^- \nu_\mu \bar{\nu}_e & \mu^+ &\rightarrow e^+ \bar{\nu}_\mu \nu_e \end{aligned}$$

$$L = L_e + L_\mu$$

Particle	L	L_e	L_μ
e^-	+1	+1	0
ν_e	+1	+1	0
e^+	-1	-1	0
$\bar{\nu}_e$	-1	-1	0
μ	+1	0	+1
ν_μ	+1	0	+1
μ^+	-1	0	-1
$\bar{\nu}_\mu$	-1	0	-1

More neutrinos

1962 Brookhaven

Existence of two different types of neutrinos proven

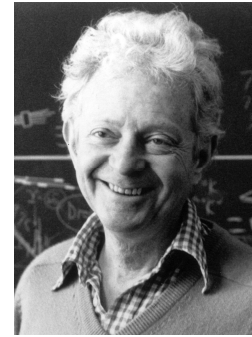
Neutrinos are produced at accelerators by π decays which produce almost only muon-type neutrinos and antineutrinos

When these interact with particles they only produce muons, never electrons

$$\nu_{\mu} n \rightarrow \mu^{-} p$$

$$\bar{\nu}_{\mu} p \rightarrow \mu^{+} n$$

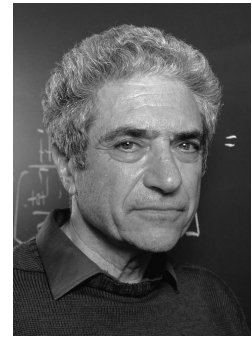
~~$$\nu_{\mu}, \bar{\nu}_{\mu} \rightarrow e^{-}, e^{+}$$~~



Leon Lederman (1922-2018)



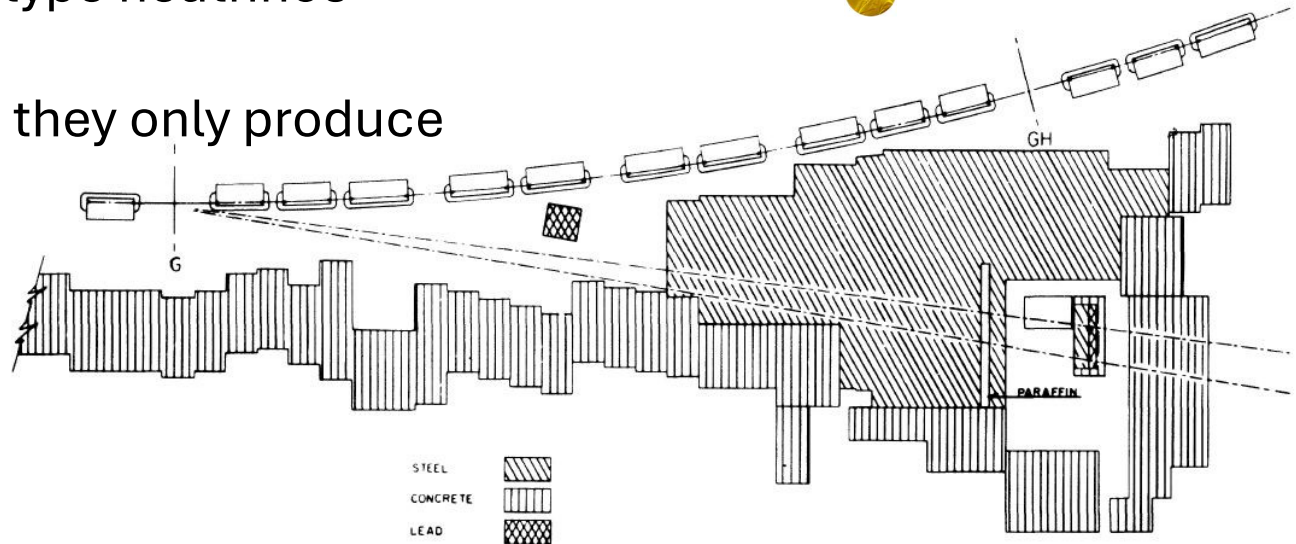
Melvin Schwartz (1932-2006)



Jack Steinberger (1921-2020)



1988



Particles 5

Particle	Mass (MeV/c ²)	Charge (e)	Spin ($\hbar/2$)	Lifetime (s)	Decay modes
neutrino e (ν_e)	O(10 ⁻⁶)	0	1/2	stable	N/A
neutrino μ (ν_μ)	O(10 ⁻⁶)	0	1/2	stable	N/A
neutrino τ (ν_τ)	O(10 ⁻⁶)	0	1/2	stable	N/A

Neutrinos do have non-zero, different masses,
but they are extremely tiny ($< 1 \text{ eV}/c^2$) and not yet measured

It is not actually known whether antineutrinos coincide with neutrinos



More hadrons (1947-1960)

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Particle accelerators

1930 Berkeley

Invention of the cyclotron

1940s Berkeley

Increasingly larger accelerators

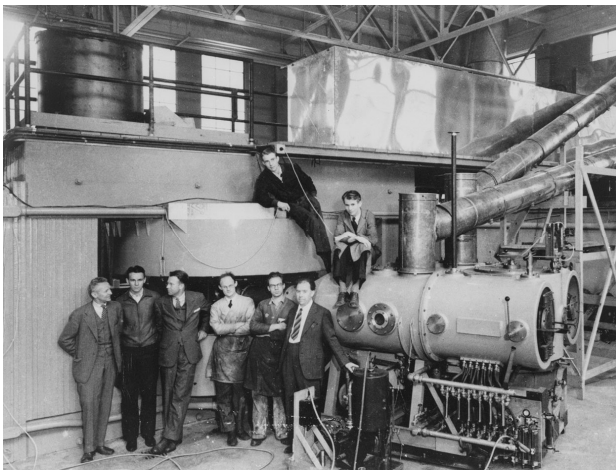
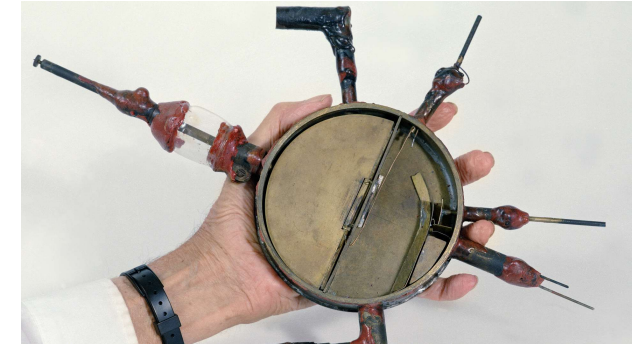
1952 Brookhaven Cosmotron (3.3 GeV)

1954 Berkeley Bevatron (6.5 GeV)

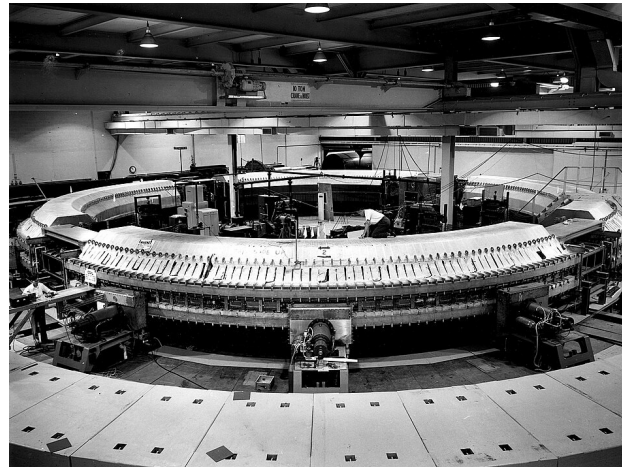
1939



Ernest Lawrence
(1901-1958)



60-inch cyclotron (1939): 25 MeV deuterons



23-m Cosmotron (1952): 3.3 GeV protons

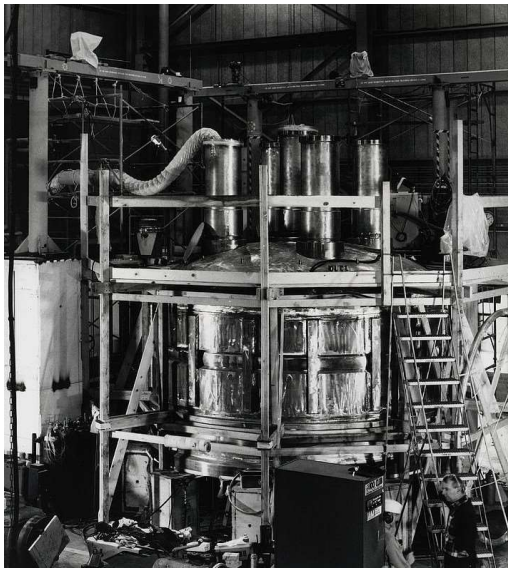


55-m Bevatron (1954): 6.5 GeV protons

Bubble chamber

1952 Ann Arbor

Fast expansion results in a superheated liquid and create bubbles around ionization centres



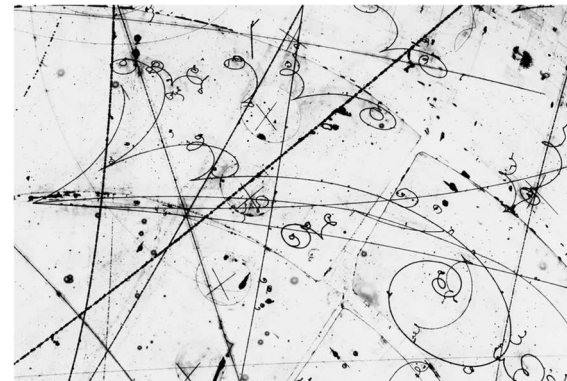
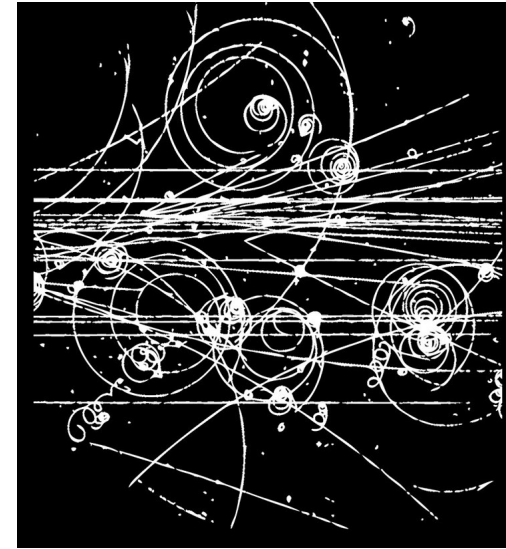
12-foot liquid hydrogen bubble chamber (1969) at Argonne Lab



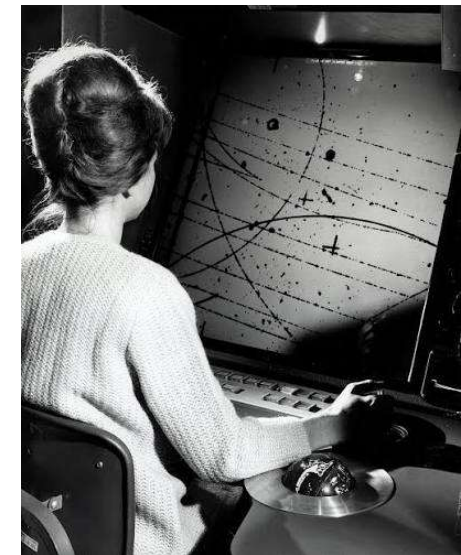
Big European Bubble Chamber (1973-1984) at CERN



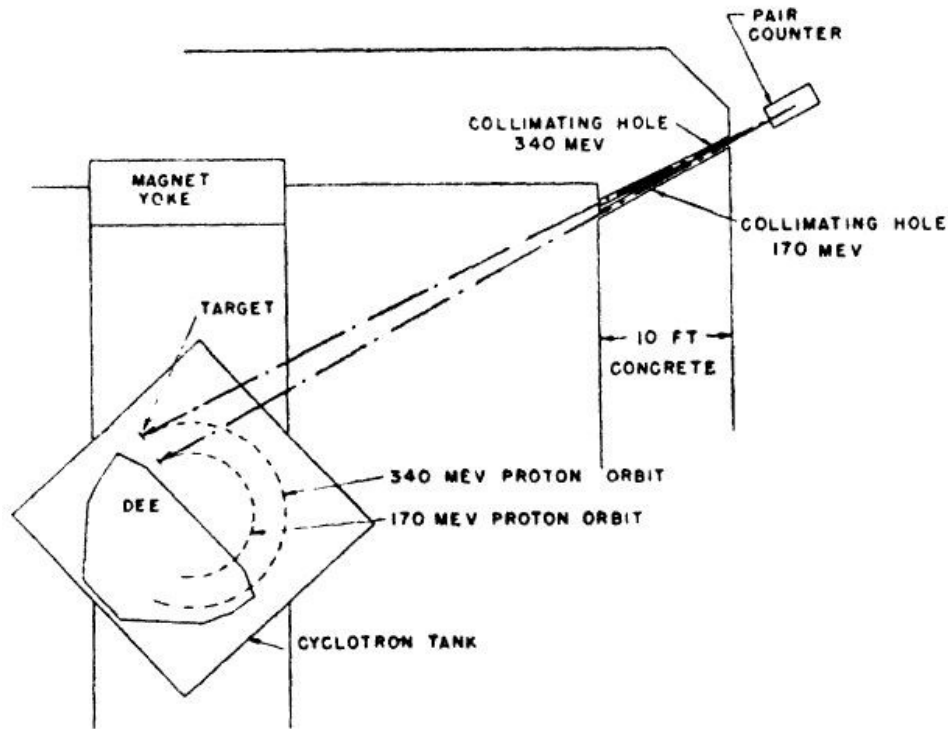
Donald Glaser
(1926-2013)



6.3 million photographs
(3000 km film)



The neutral pion



On the basis of this assumption, the observations lead to mass of about 300 electron masses for the neutral meson involved. A particle of this type, with a half-life of less than 10^{-11} sec., fits all of our present observations.

R. Bjorklund *et al.* –
Phys. Rev. 77 (1950) 213

1949 Berkeley

High energy (>200 MeV) photons produced in collisions of protons with $E > 175$ MeV

High Energy Photons from Proton-Nucleon Collisions

R. BJORKLUND, W. E. CRANDALL, B. J. MOYER, AND H. F. YORE

Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received September 19, 1949)

The neutral meson hypothesis is also in agreement, as is also the isobar hypothesis, with the experimental observation that the energy of the peak of the photon spectrum occurs at approximately the same value, independent of the proton energy, when transformed to the proper coordinate system.

The existence of a neutral meson is clearly not required at the present stage of the experiments, but is the only one of the above five hypotheses which seems to fit the experimental data.

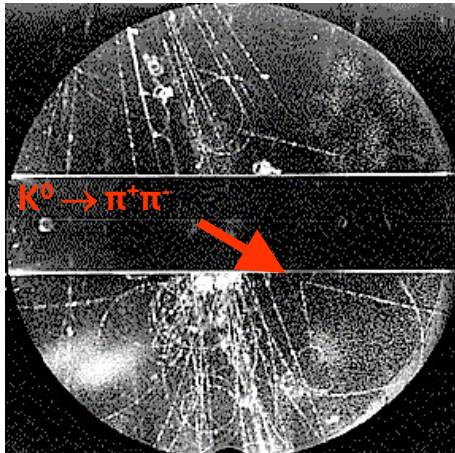
Strange particles

1947 Manchester

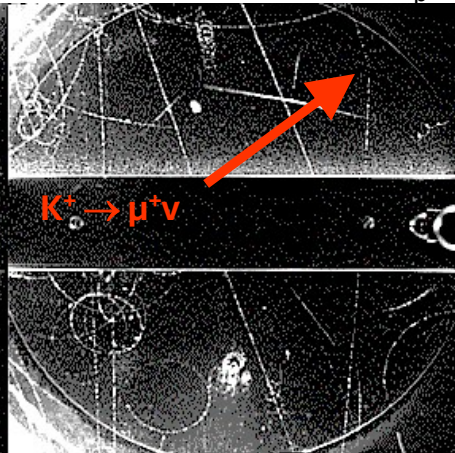
Cloud chamber on cosmic rays with single absorber plate (no electrons or positrons, only penetrating particles).

2/5000 pictures (1500h):

Neutral "V-particle"
mass 393 to 818 MeV/c^2



Charged particle
mass 500 MeV/c^2 to m_p

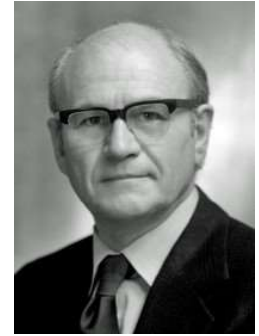


Now called K^0 and K^+ ("kaons")

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George D. Rochester (1908-2001)



Clifford C. Butler (1922-1999)

December 20, 1947 NATURE
EVIDENCE FOR THE EXISTENCE
OF NEW UNSTABLE ELEMENTARY
PARTICLES

By DR. G. D. ROCHESTER
AND
DR. C. C. BUTLER
Physical Laboratories, University, Manchester

G.D. Rochester, C.C. Butler –
Nature 219 (1947) 855

"Strange" particles
not present on Earth

"Strangeness"

A. Pais - Phys. Rev. 86 (1952) 663
M. Gell-Mann - Phys. Rev. 92 (1953) 833
T. Nakano, K. Nishijima - Prog. Theor. Phys. 10 (1953) 581

“Strange” behaviour:

♦ **copious production**: $\sigma(\pi^- p \rightarrow K^0 \Lambda) \approx 1 \text{ mb} \approx \sigma_{\text{tot}}/40$ (STRONG)

BUT

♦ **long lifetime**: $\tau(K^0 \rightarrow \pi^+ \pi^-) \approx 10^{-10} \text{ s} \gg 10^{-23} \text{ s} \sim r_p/c$ (WEAK)

Strangeness (S) hypothesis :

new quantum number conserved by strong interactions but NOT by weak ones:

- **Associate production (STRONG)**:

$$\pi^- p \rightarrow K^- p \quad \text{not seen} \quad (0)+(0) \neq (-1)+(0)$$

- **Strangeness-violating decay (WEAK)**

$$K^0 \rightarrow \pi^+ \pi^- \quad \text{occurs, but very slowly} \quad (1) \neq (0)+(0)$$

Other strange particles

	Particles			Anti-particles			
	Particle	S	B	Particle	S	B	
Particles	K^+	+1	0	K^-	-1	0	Strange mesons
	K^0	+1	0	$\bar{K}^0$	-1	0	
	Λ^0	-1	+1	$\bar{\Lambda}^0$	+1	-1	Hyperons
	$\Sigma^\pm, \Sigma^0$	-1	+1	$\bar{\Sigma}^\pm, \bar{\Sigma}^0$	+1	-1	
	Ξ^-, Ξ^0	-2	+1	$\bar{\Xi}^+, \bar{\Xi}^0$	+2	-1	
	Ω^-	-3	+1	$\bar{\Omega}^+$	+3	-1	

All other particles encountered so far have $S=0$
Hyperons are strange baryons (half-integer spin)