Mid-1930s

Elementary particle list is very short and seems to explain nearly everything:

- proton
- neutron
- electron
- photon

Protons, neutrons, and electrons were spin-½ particles and had anti-particles, as suggested by Dirac's equation.

A few problems:

1) a new force was needed to hold together protons inside nuclei

2) unlike α-decays and γ-decays, β-decays seemed not to conserve the energy…
   or something else was escaping nuclei together with electrons and remained undetected…

The first problem led to the hypothesis of Yukawa's particles, discovery of pions (and muons), and an eventual design of the strong force theory.

The second problem led to the hypothesis of neutrino particles, a weak force, and eventual discovery of the neutrino and carriers of the weak force, W and Z-bosons, and construction of the electroweak theory…

Yukawa particle

1935 **Yukawa** hypothesized about existence of massive particles to account for the short-range strong force between protons and neutrons and proposed a formalism to describe such fields/particles (see lecture 9).

1. New force is needed to keep protons and neutrons together in nucleus—thus, the name "nuclear force".

2. It must be stronger than Coulomb's force to overcome repulsion of protons.

3. Its range cannot be much shorter than the typical distance between nucleons; otherwise, it would not be able to hold them together:

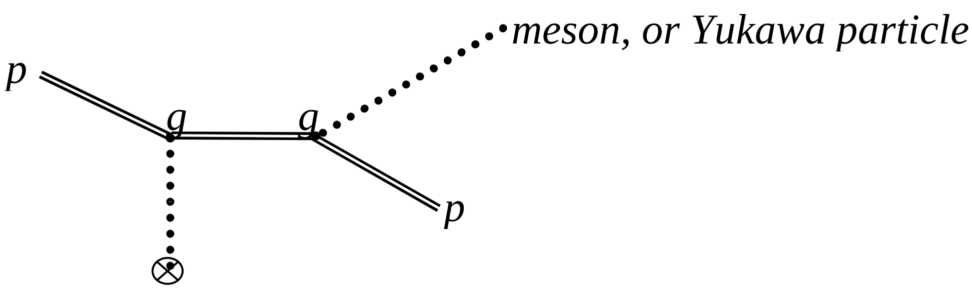
   $r_0 > 1 \text{ fm} \quad \rightarrow \quad m < 1/r_0 \sim 200 \text{ MeV}$

   Question for further study: how did Yukawa know about the distance between protons and neutrons?

4. It must give in to electrostatic forces at larger distances—there are no elements much heavier than uranium (A~240)

   $R_U \sim \sqrt[3]{240} r_0 \sim 6 \text{ fm} \quad \rightarrow \quad m > 1/R_U \sim 30 \text{ MeV}$

5. Yukawa made a brave assumption that one could produce such particles via Bremsstrahlung radiation of, for instance, protons in the strong force field of nuclei similarly to electromagnetic Bremsstrahlung radiation of electrons in the electric field of nuclei; therefore, such hypothetical strong force particles may be present in cosmic rays—the only source of sufficiently high energy particles at that time.



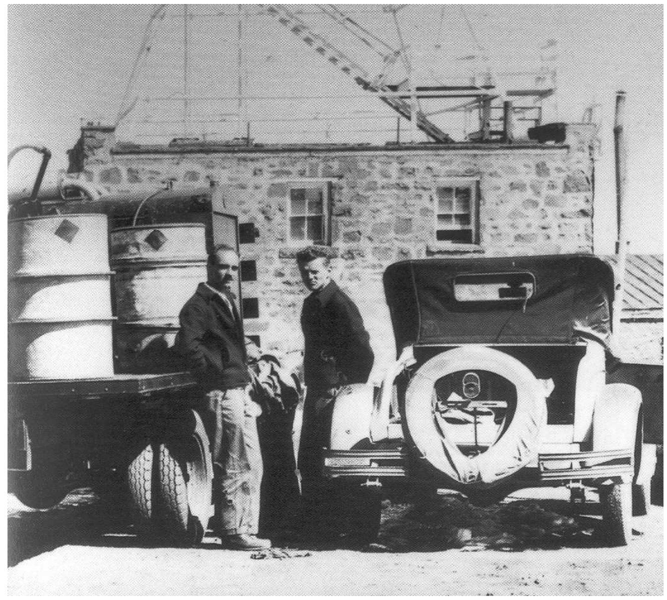
6. The name meson comes from *middle* in Greek, implying that such particles should have a mass somewhere between proton and electron masses.

7. After some initial period of confusion with muons, such particles were finally discovered in 1947.

8. In the framework of the today's Standard Model, the carriers of the true strong forces are massless gluons with a non-trivial structure of "color" charges. Proton and neutron contain three quarks with the total "color" charge zero and the nuclear force between them can be paralleled to the van der Waals forces between electrically neutral atoms/molecules. The Yukawa meson, now known as a pion, is also "color"-neutral object made from a quark-antiquark pair. Remarkably, at large distances and small momenta transfers, the force between protons and neutrons indeed can be often approximated as a force due to an exchange with pions (as well as some other resonances).

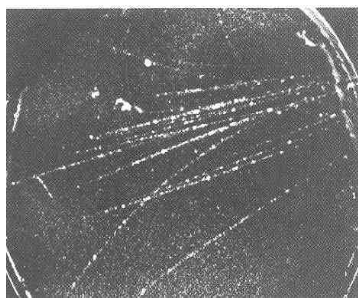
1949 **Yukawa** receives the Nobel Prize "for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces"

Great confusion: discovery of muons ($\mu^{\pm}$)

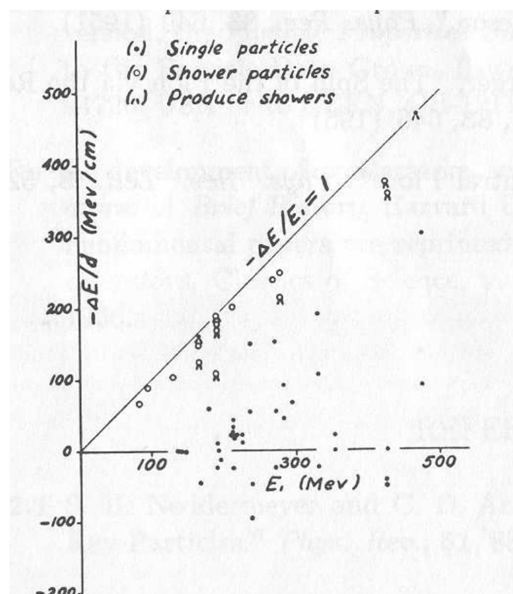


1937 **Anderson and Neddermeyer**

- Cloud chamber, 1 cm platinum plate, magnetic field
- Special selection of photos of low momentum particles (100-500 MeV)
- Measure their momenta before and after they pass through the plate and, thus, evaluate the fraction of energy they lose…
- Observed two kinds of particles:
    - o "showering" particles (either as they enter the cloud chamber or after passing the platinum plate)
    - o "penetrating" single-track particles



→ Showering particles lost their energy/momentum according to shower losses ($\Delta E \sim E$)
→ Penetrating particles did not seem to lose much energy at all (and produced thin tracks consistent with minimal dE/dx losses in the volume of the cloud chamber)
→ These penetrating particles could not be protons: protons of 100-500 MeV momenta would be very slow and have very short range due to the standard ionization losses and, also, produce very dense thick ionization $dE/dx \sim 1/v^2$.
→ Note: earlier observations of penetrating particles could not exclude protons as they mostly were higher momentum tracks.
→ Note: also, physicists at that time had some doubts whether Bethe+Heitler formula could be applied to higher energy particles—after all it was already known that relativistic equations are plagued with divergencies…



→ THE ONLY VIABLE EXPLANATION IS EXISTENCE OF PARTICLES WITH INTERMEDIATE MASS BETWEEN MASSES OF PROTON AND ELECTRON (10-100 MeV?).
→ IS IT YUKAWA PARTICLE?

→ In about 10 years it would become clear that the answer was NO. WHAT THEY ACTUALLY OBSERVED WAS MUONS, heavy siblings of electrons!

→ Muons have a mass of **106 MeV** and lifetime of **2.2 μs**.

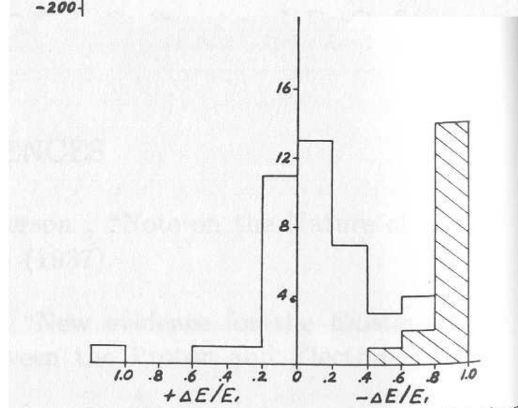


FIG. 2. Distribution of fractional losses in 1 cm of platinum.

1937 **Street and Stevenson**

- Experimental setup:
  - cloud chamber C in magnetic field sandwiched between 1+2+3+(4) counters
  - absorb "soft" component of cosmic rays → piece of lead L
  - trigger on stopping particles: coincidence of the counters of 1, 2, 3 in anti-coincidence with the counters (4)
  - measure particles' velocities by evaluating ionization losses near stopping in the gas (count amount of condensation drops per unit of track length)
  - measure particles' momenta by measuring its bending curvature
  - and deduce particles' masses

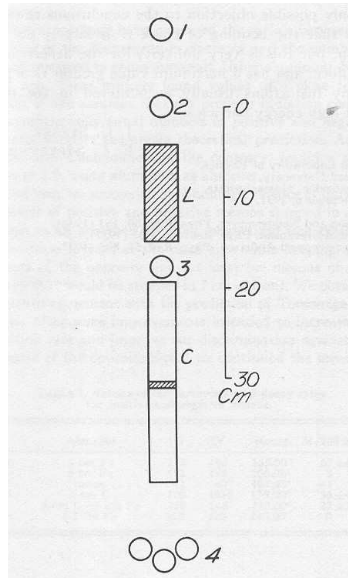


Fig. 1. Geometrical arrangement of apparatus.

→ observed a bunch of penetrating particles with $m \sim 130 \pm 30\ m_e$ *(should've been ~106 MeV, or 210* m_e *…)*
→ ARE THEY YUKAWA PARTICLES??? (the answer again turned out to be NO)

1939 **Franco Rassetti, Rossi+Nerson, Chaminade+Freon+Maze,**

Observe delayed decay of stopped mesons, the lifetime being about 2 µs.

$$\tau_0 = \begin{cases} 1.5 \pm 0.4 \mu S & \text{Rasetti} \\ 2.2 \pm 0.2 \mu s & \text{Maze} \\ 2.15 \pm 0.15 \mu s & \text{Rossi} \\ 2.33 \pm 0.15 \mu s & \text{Conversi} \end{cases}$$

1940 **Tomonaga + Araki**

Positive and negative Yukawa particles would behave very differently if stopped inside a chunk of matter:
  - Positive particles should stop and decay.
  - Negative particles should stop, get captured on the lowest orbit in atoms; being so heavy the redius of such orbit would be very small, and the wave function of these particles would strongly overlap with the nucleus; being subject to strong nuclear force, these particle would immediately interact with the nucleus before having a chance to decay.

1939-45 WORLD WAR II disrupts further studies…

1946 **Conversi + Pancini + Piccioni**

Conduct an experiment suggested by Tomonaga and Araki:
  - When carbon was used as an absorber, both negative and positive mesons would just decay—in full contradiction to what was expected from Yukawa particles…

→ These mesons are NOT Yukawa particles

→ THESE MESONS AT THE END BEHAVED JUST LIKE HEAVY ELECTRONS.

Famous exclamation by Rabi: "**Who ordered that**?"

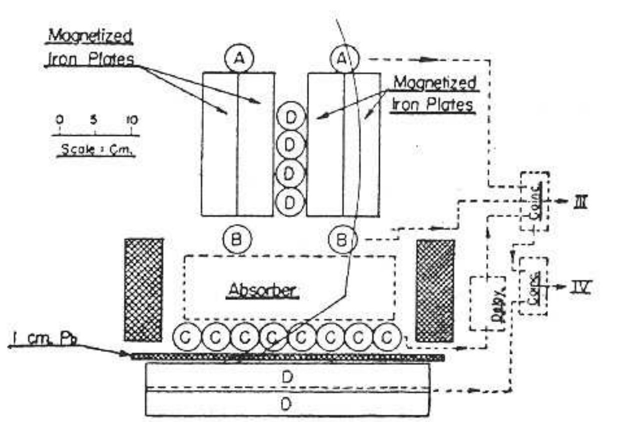


Fig. 1. Disposition of counters, absorber, and magnetized iron plates. All counters "D" are connected in parallel.

Confusion resolved: discovery of charged pions ($\pi^{\pm}$)

1940s EMULSION: a new technique of detecting particles

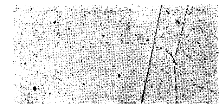


Fig. 1 *a*. PHOTOMICROGRAPH OF CENTRE OF STAR, SHOWING TRACK OF MESON PRODUCING DISINTEGRATION. (LEITZ 2 MM. OIL-IMMERSION OBJECTIVE. × 500)

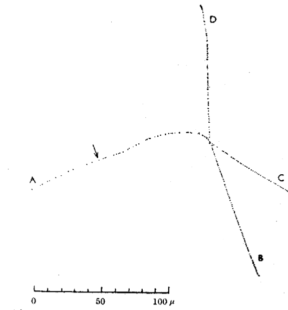


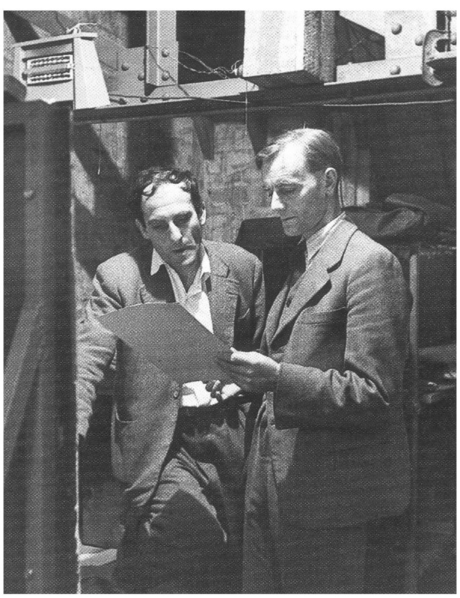
Fig. 1 *b*. TRACE OF COMPLETE STAR ON SCREEN OF PROJECTION MICROSCOPE, SHOWING PROJECTION OF THE TRACKS IN THE PLANE OF THE EMULSION. TRACK *A* CANNOT BE TRACED WITH CERTAINTY BEYOND THE ARROW

1947 **Perkins**

Emulsion showing how a stopping meson disintegrates a nucleus—the behavior in accord with the expected properties of negatively charged Yukawa particles. The emulsions are exposed to cosmic rays <u>at high altitudes in mountains.</u>

1947 **Lattes, Occhialini, <u>Powell</u>**

Many emulsions exposed <u>in mountains</u> showed that there were two kinds of mesons, the heavier meson decaying into the light one and something invisible. The decay seemed to be a two-body decay, since all the lighter mesons had the same range. The lighter mesons decayed in what appeared to be electrons and again something invisible. They named the heavier mesons **π-mesons** (pions) and the lighter ones as **μ-mesons** (muons).



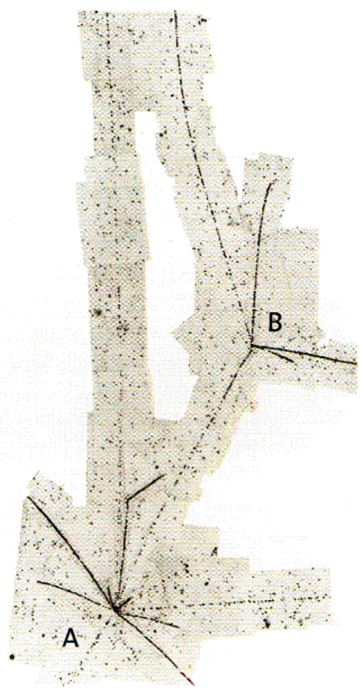


Fig. 5.9 The birth (A) and death (B) of a pion are recorded in this photograph taken by César Lattes, Occhialini, and Powell in 1947. It was one of the first observations of the creation of a pion. The distance between points A and B is about 0.11 mm

Fig. 4.25 *With the development of electron-sensitive emulsions, Powell was able to record the complete decay chain of a charged pion in images such as this one taken in October 1948. The pion comes in to the top of the picture from the left, leaving a strong track. It decays to a muon and an invisible neutrino. The muon proceeds down the page and then itself decays into an electron and a second neutrino. Again the neutrino remains invisible; the electron, however, leaves a faint but clear track. Notice how the muon's track, which is about 0.6 mm long, becomes denser as it slows down before it decays.*

1950 **Powell** receives the Nobel Prize "for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method"

Further investigations showed that charged pions ($\pi^{\pm}$) have a mass of **140 MeV** and lifetime of **2.6×10^{-8} s**.
Since they interact strongly (with nuclei of air), they don't get a chance to reach the sea level…
Pions decay ~99% of time to a muon and a muon neutrino: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

Discovery of neutral pions (π^0)

1938 **Kemmer** suggested π^0 in his paper on isospin symmetry… (to be discussed later)

???? **Lewis, Oppenheimer, Wouthuysen** suggested that "soft" electromagnetic component of cosmic ray showers might be due to neutral pions decaying into photons…

1950 **Bjorkland, Crandall, Moyer, York** observed a large yield of photons in the reaction

$$p + p \rightarrow \gamma + \text{anything}$$

after the energy of protons, accelerated at the 350-MeV proton synchrocyclotron commissioned at Berkeley in 1948, exceeded the threshold energy of ~230 MeV. Just before that Lattes and Gardner observed charged pions appearing after protons reached the same threshold energy. The γ's observed by Bjorkland et al. peaked at 70 MeV, indicating that they probably observed the reaction as follows:

$$p + p \rightarrow p + p + \pi^0, \quad \pi^0 \rightarrow \gamma + \gamma$$

π^0 became the first particle discovered at a man-made accelerator…

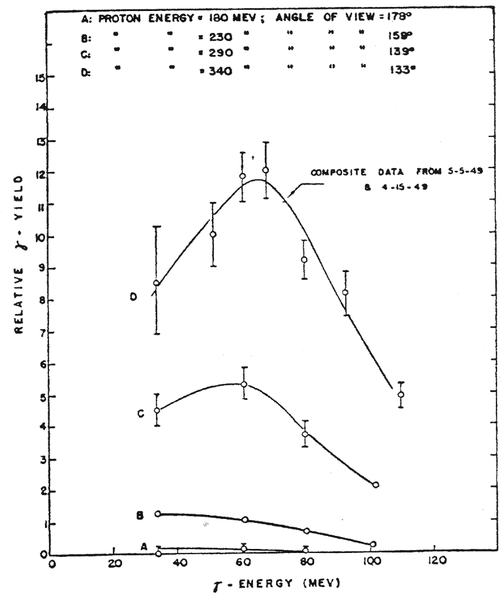


Figure 2.2: Gamma-ray yields from proton–carbon collisions at 180 to 340 MeV proton kinetic energy. The marked increase with increasing proton energy is the result of passing the π^0 production threshold. The π^0 decays into two photons. (Ref. 2.6)

1950 **Carlson, Hooper, King** observed $\pi^0 \rightarrow \gamma + \gamma$, with both gammas converting into electron-positron pairs by exposing emulsions to cosmic rays (high altitude balloon ascends). They were able to set the limit on pion lifetime being less than $5 \cdot 10^{-14}$ s.

Further studies showed that π^0 had a mass of about **135 MeV** and lifetime $\mathbf{0.8 \cdot 10^{-16}}$ **s**.

Note: Such lifetime is extremely difficult to measure: it is too short to see significant displacement between the points of pion's birth and decay, and too long to give a measurable effect on the particle's width… The lifetime was first measured indirectly in 1965—it was inferred from measuring inclusive π^0 production cross-section by bombarding nuclei with 1 GeV gammas.

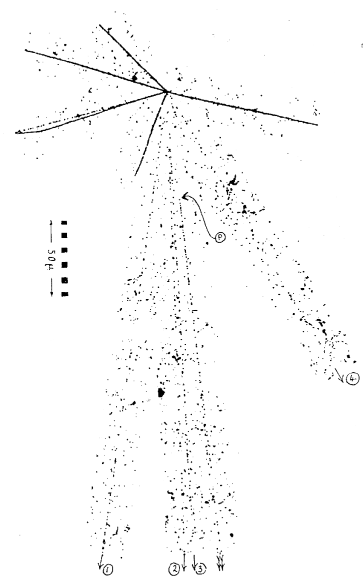


Figure 2.3: An emulsion event showing an e^+e^- pair created by conversion of a photon from π^0 decay. The conversion occurs at the point marked P. (Ref. 2.7)

1951 **Steinberger, Panofsky, Steller** showed that the π^0 indeed decays into two photons, by performing a detailed analysis of the angular and energy distributions of decay gammas.

Just another nice picture showing its decay into photons…

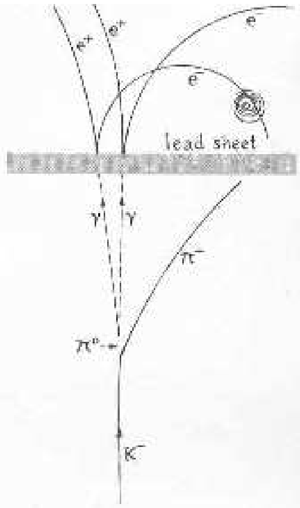


Fig. 7.2 A negative kaon (K^-) decays in a bubble chamber at the Lawrence Berkeley Laboratory, producing a negative pion (π^-) and a neutral pion (π^0). The neutral pion immediately decays into two gamma rays (γ) whose paths are marked by the dotted lines in the diagram. The gamma rays strike a lead sheet in the chamber and each turns into an electron (e^-) and a positron (e^+). The bubble chamber's magnetic field curls the negative particles clockwise, the positive ones anticlockwise. The tight spiral towards the end of the track of the lower electron is another electron, which has been knocked out of an atom in the bubble chamber liquid; other extraneous tracks have been removed.