

## II. Leptons, quarks and hadrons

❖ *Leptons* are spin-1/2 fermions, not subject to strong interaction

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

$$M_e < M_\mu < M_\tau$$

- ⊙ Electron  $e^-$ , muon  $\mu^-$  and tau-lepton  $\tau^-$  have corresponding neutrinos  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$ .
- ⊙ Electron, muon and tau have electric charge of  $-e$ . Neutrinos are neutral.
- ⊙ Neutrinos have *very small* masses (were thought to be massless).
- ⊙ For neutrinos, only weak interactions have been observed so far.

- ❖ Antileptons are: positron  $e^+$ , positive muon  $\mu^+$ , positive tau-lepton  $\tau^+$ , and antineutrinos:

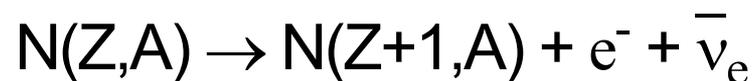
$$\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}, \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}, \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$

- ❖ Neutrinos and antineutrinos differ by the *lepton number*. Leptons possess lepton numbers  $L_\alpha=1$  ( $\alpha$  stands for e,  $\mu$  or  $\tau$ ), and antileptons have  $L_\alpha=-1$ .

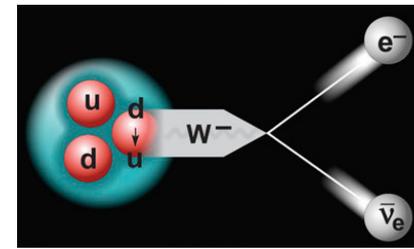
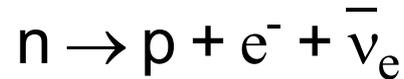
- ❖ *Lepton numbers are conserved in all interactions!*

Neutrinos can not be directly registered by any detector, there are only indirect measurements of their properties.

- 🕒 First indication of neutrino existence came from  $\beta$ -decays of nuclei, N:



$\beta$ -decay is simply one of the neutrons decaying:



⊙ Experimentally, only proton and electron can be observed, and a fraction of energy and angular momentum is “missing”. W. Pauli in 1930 suggested that these are carried out by an undetectable neutral particle, a neutrino.

❖ Note that for the sake of the lepton number conservation, electron must be accompanied by an electron-type antineutrino!

The  $\bar{\nu}_e$  mass can be estimated from the electron energy in the  $\beta$ -decay:

$$m_e \leq E_e \leq \Delta M_N - m_{\bar{\nu}_e}$$

Current results from the tritium decay indicate a very small upper limit:



❖ Recently observed neutrino mixing suggests *non-zero* mass

- ❖ An inverse  $\beta$ -decay (neutrino “capture”) also takes place:



or



However, the probabilities of these processes is very low, therefore to register any, one needs a very intense flux of neutrinos

### Reines and Cowan experiment (1956)

- ❖ Reactions of type (22) or (23) provide direct evidence of neutrinos.
- ❖ By “capturing” antineutrinos produced in a nuclear reactor, it is possible to obtain around 2 events of type (23) per hour.
- ❖ To separate the signal from background noise, the “delayed coincidence” scheme was used: signal from neutron comes later than one from positron.

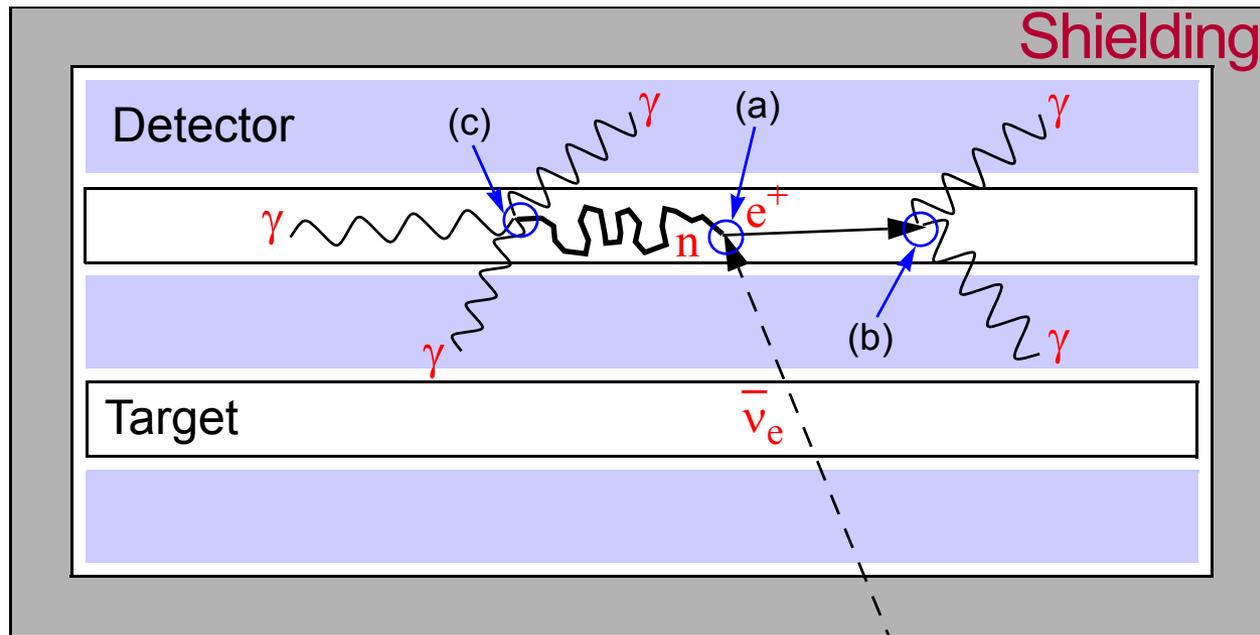


Figure 16: Schematic representation of the Reines and Cowan experiment. Aqueous solution of  $CdCl_2$  used as the target ( $Cd$  captures neutrons).

- (a) Antineutrino interacts with a proton in water (hydrogen nucleus), producing neutron and positron
- (b) Positron annihilation with an atomic electron produces fast photon  $\gamma$ ; Coulomb scattering gives rise to softer photons
- (c) Neutron is captured by a  $Cd$  nucleus, releasing more photons.

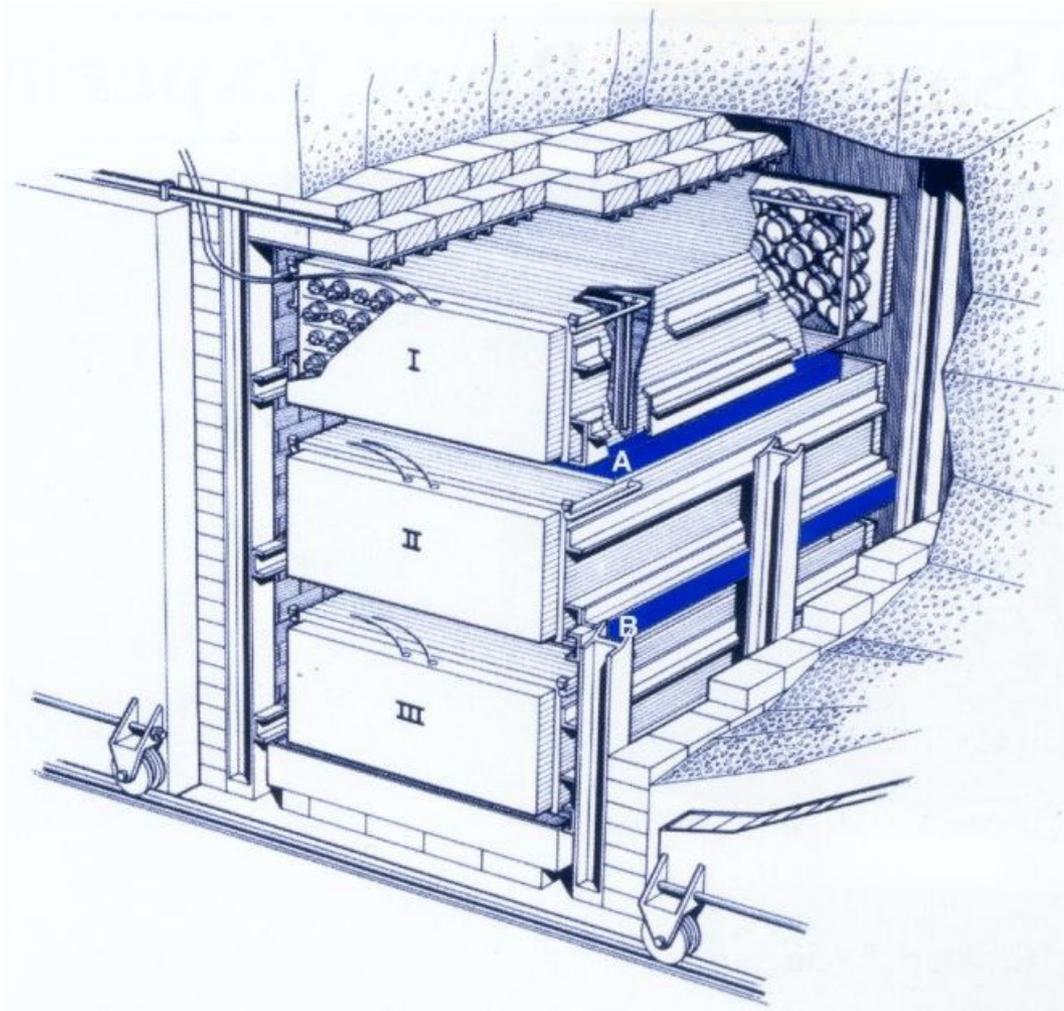
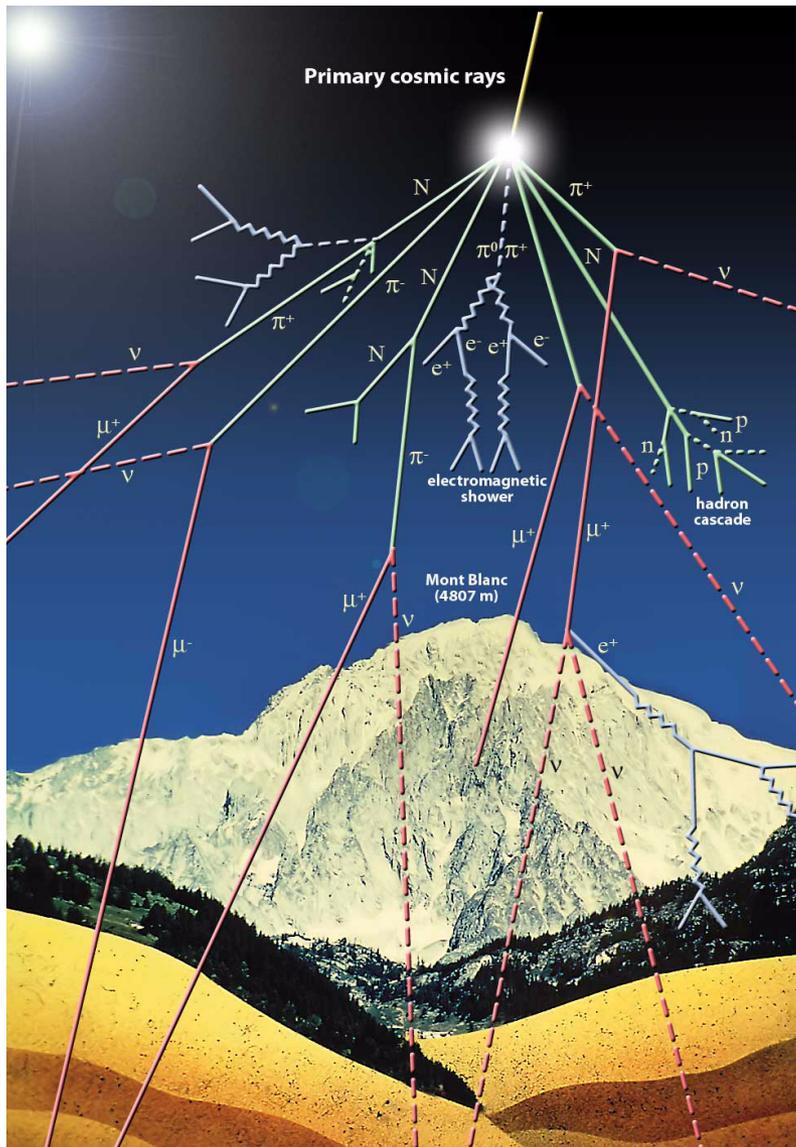


Figure 17: The Savannah River neutrino detector which registered neutrinos in 1956



❖ Muons were first observed in 1936, in *cosmic rays*

Cosmic rays have two components:

- 1) *primaries*, which are high-energy particles coming from the outer space, mostly hydrogen nuclei
- 2) *secondaries*, the particles which are produced in collisions of primaries with nuclei in the Earth atmosphere; muons belong to this component

Figure 18: Schematic representation of cosmic rays

- ◎ Muons are 200 times heavier than electrons and are very penetrating particles.
- ◎ Electromagnetic properties of muon are identical to those of electron (except the mass difference)

❖ Tau is the heaviest lepton, discovered in  $e^+e^-$  annihilation experiments in 1975

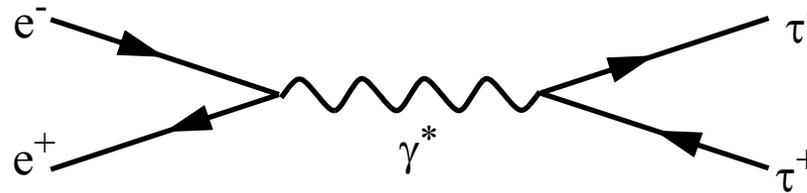


Figure 19:  $\tau$  pair production in  $e^+e^-$  annihilation

❖ Electron is a stable particle, while  $\mu$  and  $\tau$  have finite lifetimes:

$$\tau_{\mu} = 2.2 \times 10^{-6} \text{ s} \quad \text{and} \quad \tau_{\tau} = 2.9 \times 10^{-13} \text{ s}$$

Muon decays in a purely leptonic mode:

$$\mu^{-} \rightarrow e^{-} + \bar{\nu}_e + \nu_{\mu} \tag{24}$$

Tau has a mass sufficient to decay into hadrons, but it has leptonic decay modes as well:

$$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau \quad (25)$$

$$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau \quad (26)$$

- ❖ **Note: lepton numbers are conserved in all reactions ever observed**
- ❖ Fraction of a given decay mode with respect to all possible decays is called *branching ratio*, denoted by B.
- ❖ *Decay rate*:  $\Gamma = B/\tau$ , where  $\tau$  is decaying particle's lifetime.

Branching ratio of the process (25) is 17.84%, and of (26) – 17.37%.

### Important assumptions:

- ❖ Weak interactions of leptons are identical, just like electromagnetic ones (*“universality of weak interactions”*)
- ❖ One can neglect final state lepton masses for many basic calculations

Decay rate  $\Gamma$  of a muon is given by the expression:

$$\Gamma(\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu) = \frac{G_F^2 m_\mu^5}{195\pi^3} \quad (27)$$

where  $G_F$  is the Fermi constant and  $m_\mu$  is muon mass.

Substituting  $m_\mu$  with  $m_\tau$  in (27), one obtains decay rates of leptonic tau decays.

- ⊙ Since only decaying particle mass enters (27), decay rates are equal for processes (25) and (26).
- ⊙ It explains why branching ratios of these processes have such close values.

Lifetime of a lepton can be calculated using measured decay rate:

$$\tau_l = \frac{B(l^- \rightarrow e^- \bar{\nu}_e \nu_l)}{\Gamma(l^- \rightarrow e^- \bar{\nu}_e \nu_l)} \quad (28)$$

Here  $l$  stands for  $\mu$  or  $\tau$ .

Since muons have basically only one decay mode,  $B=1$  in their case. Using experimental values of  $B$  and formula (27), one obtains the ratio of muon and tau lifetimes:

$$\frac{\tau_\tau}{\tau_\mu} \approx 0.178 \cdot \left( \frac{m_\mu}{m_\tau} \right)^5 \approx 1.3 \times 10^{-7}$$

This again is in a very good agreement with independent experimental measurements

❖ Universality of lepton interactions is proved to a great extent. That means that there is basically no difference between lepton generations, apart of the mass and the lepton numbers.

❖ *Quarks* are spin-1/2 fermions, subject to **all** interactions. Quarks have fractional electric charges.

Quarks and their bound states are the only particles which interact strongly (via strong force).

Some historical background:

- ⊙ Proton and neutron (“nucleons”) were known to interact strongly.
- ⊙ In 1947, in cosmic rays, new heavy particles were detected (“hadrons”).
- ⊙ By 1960s, in accelerator experiments, many dozens of hadrons were discovered
- ⊙ An urge to find a kind of “periodic system” led to the “Eightfold Way” classification, invented by Gell-Mann and Ne‘eman in 1961, based on the SU(3) symmetry group and describing hadrons in terms of “building blocks”.
- ⊙ In 1964, Gell-Mann invented quarks as the building blocks (and Zweig invented “aces”).

❖ The quark model: *baryons* and *antibaryons* are bound states of three quarks, and *mesons* are bound states of a quark and antiquark.

❖ *Hadrons* is a common name for baryons and mesons.

Like leptons, quarks and antiquarks occur in three generations:

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} \bar{d} \\ \bar{u} \end{pmatrix}, \begin{pmatrix} \bar{s} \\ \bar{c} \end{pmatrix}, \begin{pmatrix} \bar{b} \\ \bar{t} \end{pmatrix}$$

Name ("Flavour")	Symbol	Charge (units of e)	Mass
Down	d	-1/3	4-8 MeV/c <sup>2</sup>
Up	u	+2/3	1.5-4.0 MeV/c <sup>2</sup>
Strange	s	-1/3	80-130 MeV/c <sup>2</sup>
Charmed	c	+2/3	1.15-1.35 GeV/c <sup>2</sup>
Bottom	b	-1/3	4.1-4.9 GeV/c <sup>2</sup>
Top	t	+2/3	≈178 GeV/c <sup>2</sup>

## ❖ Despite numerous attempts, free quarks could never be observed

There is an elegant explanation for this:

- ❖ Every quark possesses a new quantum number: the *colour*. There are three different colours, thus each quark can have three distinct colour states. Colours are called *red (R)*, *green (G)* and *blue (B)*.
- ❖ Coloured objects can not exist as free observable particles.
  - ☉ Therefore quarks must confine into colourless hadrons.
- ❖ Colourless (“blank”) combinations are: 3-colour states  $RGB$  ( $\overline{RGB}$ ), or colour-anticolour states  $R\overline{R}$ ,  $G\overline{G}$ ,  $B\overline{B}$ , and their linear combinations.
  - ☉ Baryons are bound states of three quarks *of different colours*. Mesons consist of *colour-anticolour* quark pairs.
- ❖ Each quark flavour is associated with a different quantum number, which is conserved in strong and electromagnetic interactions, but **not in weak ones**.

Quark quantum numbers are defined as: *strangeness*  $S = -1$  for s-quark; *charm*  $C = 1$  for c-quark; *beauty*  $\tilde{B} = -1$  for b-quark.

- ⊙ top-quark has lifetime too short to form hadrons before decaying, thus *truth*  $T = 0$  for all hadrons
- ⊙ Up and down quarks have nameless quantum numbers

**Some examples of baryons:**

Particle	Mass (GeV/c <sup>2</sup> )	Quark composition	Q (units of e)	S	C	$\tilde{B}$
p	0.938	uud	1	0	0	0
n	0.940	udd	0	0	0	0
$\Lambda$	1.116	uds	0	-1	0	0
$\Lambda_c$	2.285	udc	1	0	1	0

Baryons are assigned own quantum number  $B = (N(q) - N(\bar{q}))/3$ , which gives  $B = 1$  for baryons,  $B = -1$  for antibaryons (for mesons,  $B = 0$ ).

- ⊙  $B$  is conserved in all interactions, thus the lightest baryon, proton, is stable.

## Some examples of mesons:

Particle	Mass (Gev/c <sup>2</sup> )	Quark composition	Q (units of e)	S	C	$\tilde{B}$
$\pi^+$	0.140	$u\bar{d}$	1	0	0	0
$K^-$	0.494	$s\bar{u}$	-1	-1	0	0
$D^-$	1.869	$d\bar{c}$	-1	0	-1	0
$D_s^+$	1.969	$c\bar{s}$	1	1	1	0
$B^-$	5.279	$b\bar{u}$	-1	0	0	-1
$Y$	9.460	$b\bar{b}$	0	0	0	0

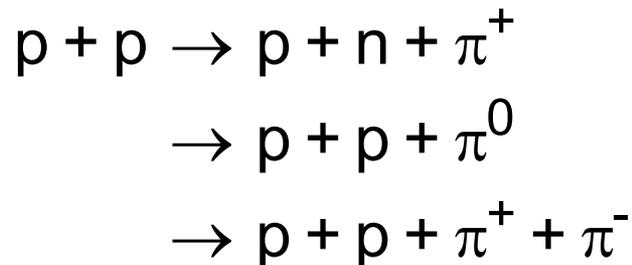
- Majority of hadrons are unstable and tend to decay by the strong interaction to the state with the lowest possible mass (lifetime about  $10^{-23}$  s).
- Hadrons with the lowest possible mass for each quark number (S, C, etc.) may live significantly longer before decaying weakly (lifetimes  $10^{-7}$ - $10^{-13}$  s) or electromagnetically (mesons, lifetimes  $10^{-16}$  -  $10^{-21}$  s). Such hadrons are called *long-lived particles* (sometimes even “stable”).
- The only truly stable hadron is proton – that is, if baryon number conservation is not violated.

## Brief history of hadron discoveries

- ◎ First known hadrons were proton and neutron.
- ◎ The lightest are pions  $\pi$  (“pi-mesons”). There are charged pions  $\pi^+$ ,  $\pi^-$  with mass of  $0.140 \text{ GeV}/c^2$ , and neutral ones  $\pi^0$ , mass  $0.135 \text{ GeV}/c^2$ .
- ❖ Pions and nucleons are the lightest particles containing u- and d-quarks only.

Pions were discovered in 1947 in cosmic rays, using photoemulsions to detect particles.

Some reactions induced by cosmic rays primaries:



Same reactions can be reproduced in accelerators, with higher rates, although cosmic rays may provide higher energies.

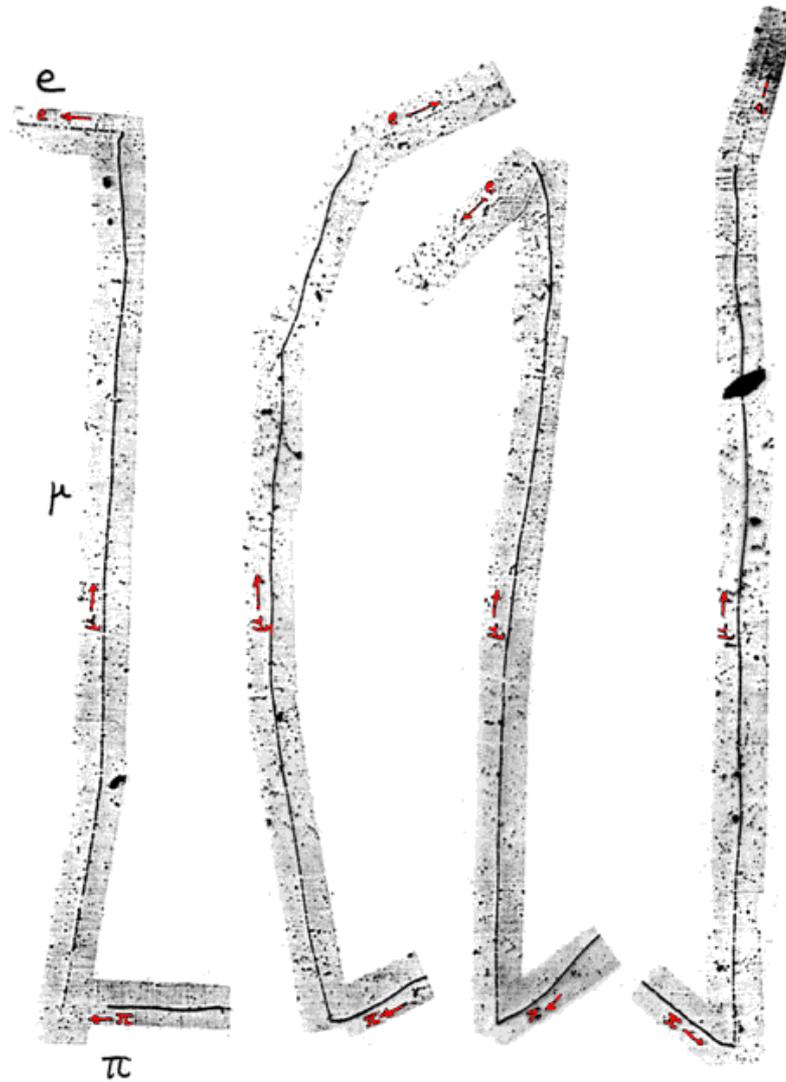


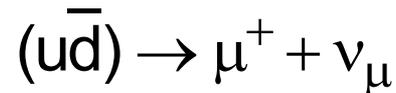
Figure 20: First observed pions: a  $\pi^+$  stops in the emulsion and decays to a  $\mu^+$  and  $\nu_\mu$ , followed by the decay of  $\mu^+$ . In emulsions, pions were identified by much more dense ionization along the track, as compared to electron tracks.

Figure 20: examples of the reaction



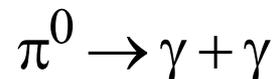
where the pion comes to rest, producing muons which in turn decay by the reaction  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ .

- ❖ Charged pions decay mainly to the muon-neutrino pair (branching ratio about 99.99%), having lifetimes of  $2.6 \times 10^{-8}$  s. In quark terms:



- ☉ The decay occurs through weak interaction, hence quark quantum numbers are not conserved.  $B$  and  $L$  are conserved.

- ❖ Neutral pions decay mostly by the electromagnetic interaction, having shorter lifetime of  $0.8 \times 10^{-16}$  s:



Discovered pions were fitting very well into Yukawa's theory – they were thought to be responsible for the nuclear forces:

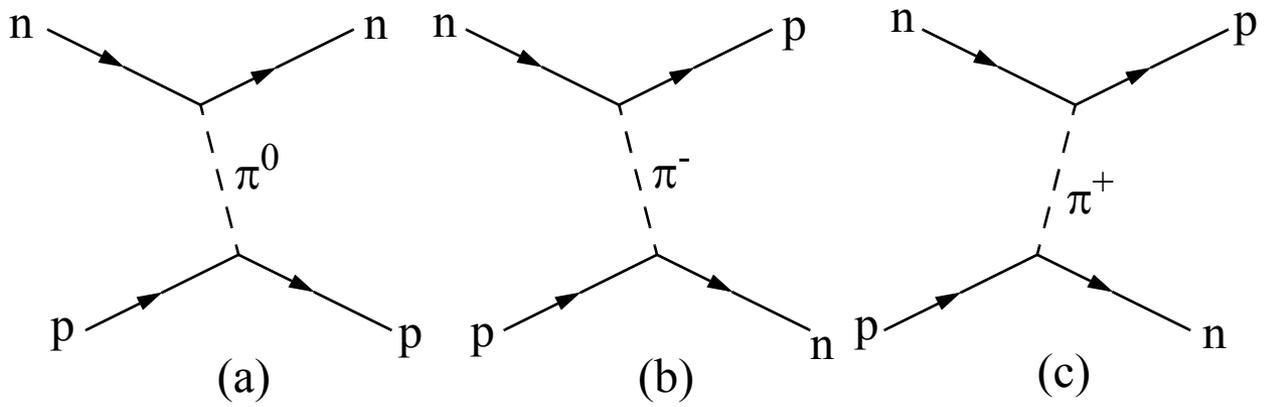


Figure 21: Yukawa model of direct (a) and exchange (b,c) nuclear forces

- ⊙ The resulting potential for this kind of exchange is of Yukawa type (19), and at the longest range reproduces observed nuclear forces very well, including even spin effects.
- ⊙ However, at the ranges comparable with the size of nucleons, this description **fails**, and the internal structure of hadrons must be taken into account.

## Strange mesons and baryons

were called so, because they were produced in strong interactions, and yet had quite long lifetimes, and decayed weakly.

The lightest particles containing s-quarks are:

- ⊙ mesons  $K^+$ ,  $K^-$  and  $K^0$ ,  $\bar{K}^0$ : "kaons", lifetime of  $K^+$  is  $1.2 \times 10^{-8}$  s
- ⊙ baryon  $\Lambda$ , lifetime of  $2.6 \times 10^{-10}$  s

Principal decay modes of strange hadrons:

$$K^+ \rightarrow \mu^+ + \nu_\mu \quad (B=0.64)$$

$$K^+ \rightarrow \pi^+ + \pi^0 \quad (B=0.21)$$

$$\Lambda \rightarrow \pi^- + p \quad (B=0.64)$$

$$\Lambda \rightarrow \pi^0 + n \quad (B=0.36)$$

The first decay is clearly a weak one. Decays of  $\Lambda$  have too long lifetime to be strong: if  $\Lambda$  were  $(udd)$ , the decay  $(udd) \rightarrow (d\bar{u}) + (uud)$  should have had a lifetime of order  $10^{-23}$  s.  $\Lambda$  cannot be  $(udd)$  like the neutron.

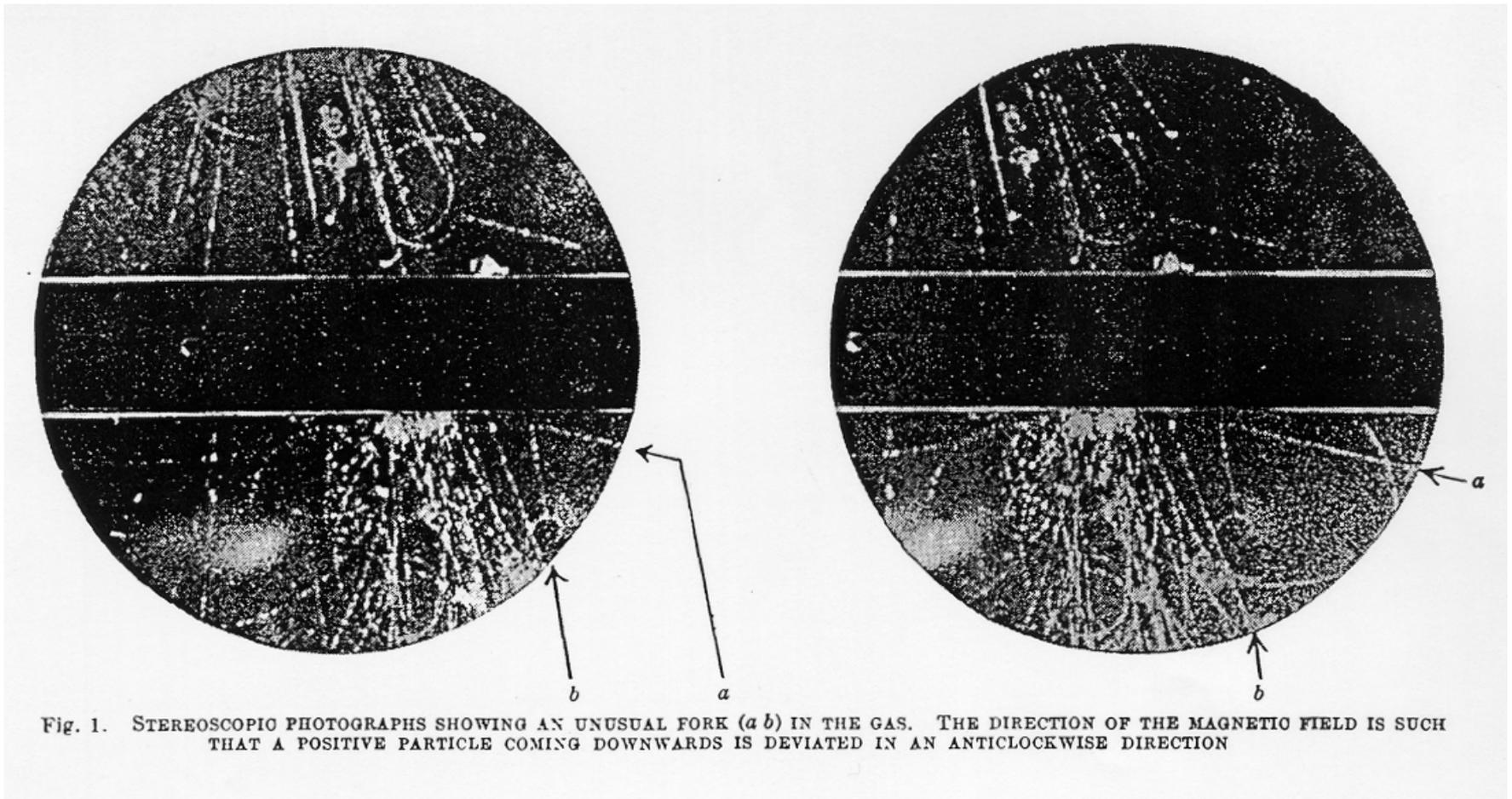


Figure 22: “Strange” particle discovery (neutral kaon) by Rochester and Butler, 1947

**Solution:** to invent a new “*strange*” quark, bearing a new quark number, “*strangeness*”, which does not have to be conserved in weak interactions

$S = 1$	$S = -1$
$\bar{\Lambda} (1116) = \overline{uds}$	$\Lambda (1116) = uds$
$K^+(494) = u\bar{s}$	$K^-(494) = s\bar{u}$
$K^0 (498) = d\bar{s}$	$\bar{K}^0(498) = s\bar{d}$

❖ In strong interactions, strange particles have to be produced in pairs in order to conserve total strangeness (“*associated production*”):



In 1952, *bubble chambers* were invented as particle detectors, and also worked as *targets*, providing, in particular, the proton target for reaction (30).

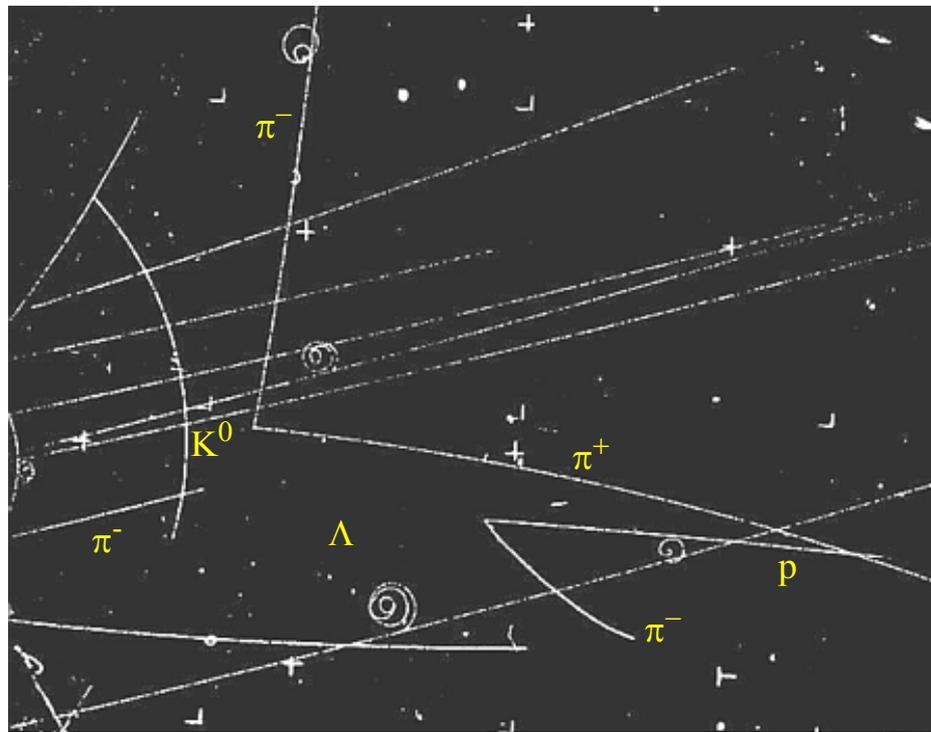


Figure 23: A bubble chamber picture of the reaction (30)

- A bubble chamber is filled with a liquid (hydrogen, propane, freons) under pressure, heated above its boiling point.
- Particles ionize the liquid along their passage.
- Volume expands  $\Rightarrow$  pressure drops  $\Rightarrow$  liquid starts boiling along the ionization trails.
- Visible bubbles are stereo-photographed.

❖ Bubble chambers were great tools in particle discoveries, providing physicists with numerous hadrons, all of them fitting u-d-s quark scheme until 1974.

🕒 In 1974, a new particle was discovered, which demanded a new flavour to be introduced. Since it was detected simultaneously by two groups in Brookhaven (BNL) and Stanford (SLAC), it received a double name:  $J/\psi$  (3097), a  $c\bar{c}$  meson

The new quark was called “*charmed*”, and the corresponding quark number is *charm*,  $C$ . Since  $J/\psi$  itself has  $C=0$ , it is said to contain “hidden charm”.

Shortly after that particles with “open charm” were discovered as well:

$$D^+(1869) = c\bar{d}, D^0(1865) = c\bar{u}$$

$$D^-(1869) = d\bar{c}, \bar{D}^0(1865) = u\bar{c}$$

$$\Lambda_c^+(2285) = udc$$

Even heavier charmed mesons were found – those which contained strange quark as well:

$$D_s^+(1969) = c\bar{s}, D_s^-(1969) = s\bar{c}$$

Lifetimes of the lightest charmed particles are of order  $10^{-13}$  s, well in the expected range of weak decays.

❖ Discovery of “charmed” particles was a triumph for the electroweak theory, which demanded number of quarks and leptons to be equal.

In 1977, “*beautiful*” mesons were discovered:

$$Y(9460) = b\bar{b}$$

$$B^+(5279) = u\bar{b}, B^0(5279) = d\bar{b}$$

$$B^-(5279) = b\bar{u}, \bar{B}^0(5279) = b\bar{d}$$

and the lightest b-baryon:  $\Lambda_b^0(5461) = udb$

And this is the limit: top-quark is too unstable to form observable hadrons