Emergence of zoo of hadrons—way too many to be elementary particles
  • Strange particles (late 1940s)
  • Resonances (since early 1950s and on…)

Proton has a size (direct measurement in 1956)—yet another evidence that hadrons may not be “elementary particles”
Simple beautiful picture:

<table>
<thead>
<tr>
<th>Particles of matter</th>
<th>Particles of force</th>
<th>Odd piece</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>photon</td>
<td>neutrino (not yet seen)</td>
</tr>
<tr>
<td>Neutron</td>
<td>meson (thought to be just discovered)</td>
<td></td>
</tr>
<tr>
<td>Electron</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note that
- neutron decays to proton+electron+neutrino: \( n \rightarrow p + e^- + \bar{\nu} \)
- mesons also decayed: \( \text{meson} \rightarrow e^- + ? \)

1938 **Stückelberg** introduces new conservation law: conservation of *baryon number*\(^1\):
- *Baryon* number 1 for proton and neutron.
- Baryon number must be conserved at all times.

This would “explain” why protons/neutrons did not have the following decays, which otherwise are allowed by all known conservation laws (energy, momentum, angular momentum, charge):

\[
\begin{align*}
n & \rightarrow \text{meson}^+ + e^- + \gamma \\
 n & \rightarrow \text{meson}^- + e^- \\
 n & \rightarrow \nu + \gamma \\
p & \rightarrow e^+ + \gamma \\
p & \rightarrow \nu + \text{meson}^+ \\
\end{align*}
\]

Note that all these decays are also forbidden by the lepton conservation number, which was not yet introduced at that time

\( n \rightarrow \bar{p} + e^+ + \nu \)

This would not violate the lepton number conservation

---

\(^1\) The name *baryon* (“heavy” in Greek) was coined later in 1953 by Pais
Strange Particles (late 1940s and early 1950s)

1943  **Leprince-Ringuet, L’heritier** First sighting of yet one more charged particle, heavier than the meson, but lighter than proton. Due to the war, this was published only 1946…
Cloud chamber 75×15×10 cm³, 0.25 T, French Alps

![Diagram showing collision with angles and momenta.]

**Dessin stéréoscopique de la collision.**

Kinematics of the event: incoming fast moving charged particle, kicks out an electron that was approximately at rest. From this, one can easily deduce the mass of the incoming particle:

- Scattered electron: \( p = 1 \text{ MeV}, m = 0.5 \text{ MeV}, \) angle \( \theta_0 = 30^\circ \)
- Unknown particle: \( P = 500 \text{ MeV}, \) scattering angle \( \theta \) is very small, \( M \) is unknown

\[
\sqrt{M^2 + P^2} + m = \sqrt{M^2 + P'^2} + \varepsilon \\
P = P' \cos \theta + p \cos \theta_0 \\
0 = -P' \sin \theta + p \sin \theta_0 \\
M = P \sqrt{\frac{\varepsilon + m}{\varepsilon - m}} \cos^2 \theta_0 - 1 = 506 \pm 61 \text{ MeV}
\]
G. D. Rochester, C.C. Butler (Manchester Group) observe in their cloud chamber:

\[ \theta^0 \rightarrow \text{(positive)} + \text{(negative)} \]
\[ \theta^+ \rightarrow \text{(positive)} + \text{(neutral)} \]

The masses of these particles were estimated to be about \( \sim 900 \pm 200 \ m_e \) (450\( \pm \)100 MeV), i.e., definitely higher than the mass of mesons (\( \sim 200-300 \ m_e \), note that by that time \( \mu/\pi \) mystery was sorted out), but less than the mass of proton/neutron (\( \sim 1900 \ m_e \)):

Assuming mass of (positive), (negative), (neutral) particles equals to:

<table>
<thead>
<tr>
<th>Mass of ( \theta^0 )</th>
<th>Mass of ( \theta^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 \ m_e )</td>
<td>( 770 \pm 200 \ m_e )</td>
</tr>
<tr>
<td>( 200 \ m_e )</td>
<td>( 870 \pm 200 \ m_e )</td>
</tr>
<tr>
<td>( 400 \ m_e )</td>
<td>( 1110 \pm 150 \ m_e )</td>
</tr>
</tbody>
</table>

Decay time \( \sim 10^{-9}-10^{-10} \ s \)
1949  **C. F. Powell** (Bristol Group) reports a new heavy charged particle detected in the emulsion. It was created in a collision of a cosmic ray with nucleus and decayed into three charged particles, one which was slow and caused disintegration of nucleus in point B.

\[ \tau^+ \rightarrow \text{positive} + \text{positive} + \text{negative}, \quad \text{all signs can be reversed} \]

\[ M = 1000 \, m_e \]

**Emulsion analysis technique:**
- Density of grains \( \sim 1/v^2 \) for non-relativistic particles:
  - one can deduce that the particle was slowing down towards point of decay A
- Scale of scattering/wigging (so called multiple Coulomb scattering) \( \sim 1/p \)
  - combined with grain density measurement, one can deduce particle's mass
1950 Anderson Group (Caltech) reports V-folk events similar to those seen by Rochester+Butler Group in Manchester. The pictures are taken with a cloud chamber as well.

\[ V_0^0 \rightarrow \pi^+ \pi^- , \quad \text{mass not well determined} \]

\[ V_1^0 \rightarrow p \pi^- , \quad \text{must be quite heavier than proton!} \rightarrow \text{one more baryon?} \]

1951 C. O’Ceallaigh (Bristol Group, emulsions) reports a heavy particle decaying into (muon)+(neutrals):

\[ \kappa^\pm \rightarrow \mu^\pm + ? \]

Particle’s mass is 562±70 MeV.

1953 Thomson Group (Indiana) reports a particle decaying into two well-measured charged pions:

\[ V_2^0 \rightarrow \pi^+ \pi^- \]

Particle’s mass = 2 m_\pi + 214±5 MeV = 494±5 MeV (today’s value is 497 MeV)
1953 **Bonetti** (Bristol Group, emulsion) reports a heavy charged particle (baryon) decaying into (proton)+(neutrals):

\[ V^+_1 \rightarrow p + \text{(neutrals)} \]

1953 **York** confirms seeing a similar event

1954 **Cowan** confirms \( V^+_1 \) and also reports negatively charged baryon \( X^- \rightarrow V^{0}_1 + \pi^- \) (with \( V^{0}_1 \rightarrow p + \pi^- \))

**Bubble chambers**: note the change in the quality of pictures—since 1952, the era of bubble chambers begins! This will be discussed a bit later in this lecture.

**Cosmotron**: Cosmotron, a 1.3 GeV proton accelerator, turns on in Brookhaven in 1952 (eventually, reached 3 GeV)

**Bevatron**: Bevatron, a 6.2 GeV proton accelerator, turns on in Berkeley in 1954
Summary (early 1950s):

1953 Conference at Bagneres-de-Biggorre, France

<table>
<thead>
<tr>
<th>First seen in</th>
<th>Reported events</th>
<th>Current interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mesons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1943 (1946)</td>
<td>Charged particle with M~500 MeV</td>
<td>K⁺</td>
</tr>
<tr>
<td>1947</td>
<td>θ⁰ → π⁺π⁻ν, ν⁰₂ → π⁺π⁻</td>
<td>K⁺⁺ → π⁺π⁻</td>
</tr>
<tr>
<td>1947</td>
<td>θ⁺ → π⁺ (neutral), ξ⁺ → π⁺ (neutral)</td>
<td>K⁺⁺ → π⁺π⁻</td>
</tr>
<tr>
<td>1949</td>
<td>τ⁻ → π⁺π⁻π⁻</td>
<td>K⁺⁺ → π⁺π⁻π⁻</td>
</tr>
<tr>
<td>1951</td>
<td>κ⁺ → μ⁺ (neutrals)</td>
<td>K⁺⁺ → μ⁺ν</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Baryons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1950</td>
<td>V⁰₁ → p π⁻</td>
<td>Λ → p π⁻</td>
</tr>
<tr>
<td>1953</td>
<td>V⁺₁ → p (neutrals)</td>
<td>Σ⁺ → p π⁺</td>
</tr>
<tr>
<td>?</td>
<td>Λ⁺ → n π⁺</td>
<td>Σ⁺ → n π⁺</td>
</tr>
<tr>
<td>(1953)</td>
<td>X → V⁰₁ π⁻</td>
<td>Ξ⁻ → Λ π⁻</td>
</tr>
</tbody>
</table>

**Puzzle 1:** particles born in abundance → strong force
decay into hadrons (strongly interacting particles),
but live for too long! ~10⁻¹⁰ s (consistent with Weak Force),
instead of ~10⁻²³ s (time that would be typical for strong force)

This gave rise to the name *Strange Particles*

**Puzzle 2:**
θ⁺ → π⁺π⁻π⁻ \( J^P=0^- \)
τ⁺ → π⁺π⁻π⁻ \( J^P=0^- \)
but have the same mass:
A) different particles with the same mass (~500 MeV) and spin (J=0)?
B) same particle, but parity P can be violated in its decays?
We will discuss this puzzle later (the answer turned out to be B)
1952 Pais suggests that these new kind of particles can be produced in strong interactions, but only in pairs…

1953 Fowler indeed observes double V events obtained in the cloud chamber and 1.5 GeV $\pi$ beam at the Cosmotron accelerator—first man-made strange particles!

Gell-Mann and Nishijima independently suggested a new quantum number Strangeness (the term was coined by Gell-Mann) that would be conserved in strong and electromagnetic interaction, but not in weak

- $Q$ (electric charge, -1, 0, +1) – conserved always
- $L$ (lepton numbers, -1, 0, +1) – conserved always
- $B$ (baryon number, -1, 0, +1) – conserved always
- $S$ (strangeness, -1, 0, +1) – conserved in STRONG/EM, but no in WEAK interactions

→ severe opposition: if not always conserved, what kind of conservation law is that?
→ however, Isospin has been around already for a while; also, is not conserved in weak interactions:

- Isospin doublet ($I=1/2$): $(n, p)$ \( I_z = (-\frac{1}{2},\frac{1}{2}) \)
- Isospin triplet ($I=1$): $(\pi^-, \pi^0, \pi^+)$ \( I_z = (-1, 0, 1) \)

Gell-Mann-Nishijima formula: \( Q = I_z + (B+S)/2 \)

Decay of strange particles occurs via weak force and leads to $\Delta S=1$ and $\Delta I_z=1/2$
Strangeness assignments

**Mesons:**
- $S=0$ for $\pi^-, \pi^0, \pi^+$ (isospin triplet)
- $S=1$ for $K^0, K^+$ (isospin doublet)
- $S=-1$ for $K^-, \text{anti-} K^0$ (isospin doublet)

**Baryons:**
- $S=0$ for $n, p$ (isospin doublet)
- $S=-1$ for $\Lambda$ (isospin singlet?)
- $S=-1$ for $\Sigma^-, \Sigma^0, \Sigma^+$ (isospin triplet?, $\Lambda$ is no good as it has a too different mass):
  - $\Sigma^0 \rightarrow \Lambda \gamma$ was discovered in 1955
- $S=-2$ for $\Xi^- \rightarrow \Lambda \pi^-$ ($S=-1, I_z=-1$) ($\rightarrow I_z=-1/2$: isospin doublet?):
  - $\Xi^0 \rightarrow \Lambda \pi^0$ was discovered in 1959

These assignments would allow for: and would not allow for:

- $\pi^- p \rightarrow K^0 \Lambda$
- $K^+ \Sigma^-
- K^0 \Sigma^0$
- $K^- \Sigma^+$

The following decays with $\Delta S=1$ are allowed via weak force (resulting in long lifetimes):

- $\Lambda \rightarrow p \pi^-$
- $\Sigma^+ \rightarrow p \pi^0$
- $\Sigma^0 \rightarrow n \pi^+$
- $\Sigma^- \rightarrow n \pi^-$
- $\Xi^- \rightarrow \Lambda \pi^-$
First Resonances
(via observing bumps in cross section vs collision energy)

1952 **Enrico Fermi** Group (Chicago University Cyclotron) reports seeing enhanced cross-sections (absorption) in process $\pi^+ p \rightarrow \text{anything}$, which they suggest to interpret as a resonant stay of proton.

![Graph showing cross section vs collision energy](image)

**Fig. 1.** Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

1954 **Yuen** from Brookhaven reports clear resonance curves for both
$\pi^+ p \rightarrow \text{anything}$
$\pi^- p \rightarrow \text{anything}$

![Graph showing cross section vs collision energy](image)
Δ-resonance

All of that can be explained via a process of creating a new very short lived particle Δ (proton resonance, proton excited state) with the mass $M=1232$ MeV, $Γ=120$ MeV ($τ=1/Γ=0.5×10^{-23}$ s):

$$\sigma \sim \sigma_{\text{max}} \frac{Γ^2/4}{(E-M)^2+Γ^2/4}$$

$I_z (\pi^+ p) =3/2$, so the particle must have $I=3/2$ or higher (it is 3/2), so there must be states with $I_z=-3/2, -1/2, 1/2$.

$\pi^+ p \to Δ^{++} \to π^+ p$
$π^- n \to Δ^- \to π^- n$
$π^+ n \to Δ^0 \to π^0 p$
$π^- p \to Δ^0 \to π^0 n$
$π^- n \to Δ^- \to π^- n$

Referring to the zoo of emerging strange and resonance-like particles:

Willis Lamb in his Nobel Prize speech in 1955 said: "... the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by $10,000 fine..."

More Nucleon Resonances

Invariant mass of $πp$ system has many bumps!

Fig. 5.6  Total cross-sections for $π^± p$ scattering as a function of the total centre-of-mass energy $E_{CM}$. 
More Resonances
(via observing bumps in multi-particle invariant mass distributions)

Strange baryons:
1960 Alvarez Group (bubble chamber at Bevatron, Berkeley):
\[ K^- p \rightarrow \Lambda^+ \pi^- \pi^+ \]
invariant mass of the \( \Lambda\pi \)-system: \( \Sigma^+ \) and \( \Sigma^- \) resonances with \( M \sim 1380 \text{ MeV} \)

NOTE: a new technique of reconstructing resonances by searching for peaks in the invariant mass of decay products

Strange mesons:
1961 Alvarez Group (bubble chamber at Bevatron, Berkeley):
\[ K^- p \rightarrow \bar{K}^0 \pi^- p \]
invariant mass of the \( \bar{K}^0\pi^- \)-system: \( K^+ \) resonance with \( M \sim 880 \text{ MeV} \)

Non-strange mesons:
1961 Ervin et al. (bubble chamber at Cosmotron, Brookhaven):
\[ \pi^- p \rightarrow \pi^- \pi^0 p \]
\[ \pi^- p \rightarrow \pi^- \pi^+ n \]
invariant mass of the \( \pi\pi \)-system: \( \rho^- \) and \( \rho^- \) resonance with \( M \sim 770 \text{ MeV} \)

Three-particle resonances:
1961 Alvarez Group (bubble chamber at Bevatron, Berkeley):
\[ p p \rightarrow 2\pi^+ 2\pi^- \pi^0 \]
invariant mass of the \( \pi\pi\pi^0 \)-system: \( \omega \) resonance with \( M \sim 790 \text{ MeV} \) (fairly long lived \( \tau \sim 7 \times 10^{-23} \text{ s} \))

1968 Alvarez is awarded Nobel Prize “for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis”

\[ K^* \text{ resonance (K}\pi) \]
\[ \omega \text{ resonance (}\pi^\prime \pi\pi^0) \]
1956 McAllister and Hofstadter (Stanford linear accelerator Mark III) reported that scattering of electrons on protons deviated from the Rutherford formula (corrected for spin-1/2, Mott formula, and further corrected for proton's anomalous magnetic moment). This could be interpreted as if proton's charge was distributed over $0.7\pm0.2$ fm distances…