Experimental foundation of the quark-structure

### E1A History

1887: $e^-$ (J.J. Thomson) \[\Rightarrow\text{Slide 2}\]
1917: $p$ (E. Rutherford) \[\Rightarrow\text{Slide 3}\]
1932: $n$ (J. Chadwick) \[\Rightarrow\text{Slide 4}\]

(with preparational work from Bohl & Beck and Joliot-Curie)

1933: $\mu^+$ (C. Anderson) \[\Rightarrow\text{Slide 5}\] (cosmic rays)
1933-1940: $e^\pm, \mu^\pm$

With the advent of particle accelerators a new source of particles was available.

1950: $\pi^0$

... and many more new unstable and quasi-stable particles. \[\Rightarrow\text{Slide 6}\]

At the same time the isospin concept was introduced to sort particles with same (similar) mass.

- $p \leftrightarrow n$
  - $I = \frac{1}{2}$, $I_3 = \pm \frac{1}{2}$
  - $m_p = 938.3\,\text{MeV}$, $m_n = 939.6\,\text{MeV}$

Isospin Triplets: $\pi^+\pi^0\pi^-$, $I = 1$, $I_3 = 0$

Only with the introduction of the quark model it was transformed to $e = \frac{1}{2}$, $\bar{e} = \frac{1}{2}$, $\mu = \frac{1}{2}$, $\bar{\mu} = \frac{1}{2}$.
Isospin symmetry is not exact due to different mass of u, d quarks. I, I_s are conserved quantum numbers (QG) in the strong and em. I_A (not in weak I_A!)

Intermediate: Naming of (ground state) mesons

\[
\begin{array}{cccccc}
\bar{u} & \pi^0 & \pi^- & K^- & D^0 & \bar{B}^- \\
\bar{d} & \pi^+ & \pi^0 & \bar{K}^0 & D^+ & \bar{B}^0 \\
\bar{s} & K^+ & K^0 & \bar{D}_s^+ & \bar{B}_s^- \\
\bar{c} & \bar{D}^0 & D^- & \bar{D}_s^- & \bar{D}_s^+ & \bar{B}_s^- \\
\bar{t} & B^+ & \bar{B}_s^- & B_s^+ & Y \\
\end{array}
\]

Heavyest quark determines the name
tops are too heavy to form bound states

Thadronisation \( \sim 10^{-26} \) s
\( T_{\text{top}} \sim 6 \times 10^{-25} \) s

1.2. Discovery of "strange" particles

Reminder kaon system \( K^+ = 1u\bar{d}, K^- = 1d\bar{u} \)

Flavour eigenstates \( K^0 = 1d\bar{s}, \bar{K}^0 = 1\bar{d}s \)

Mass(eigenstate) eigenstates \( K_L, K_S \) (linear combination of \( K^0, \bar{K}^0 \))

\[
\begin{align*}
    m_{K^+} &= 494 \text{ MeV} \\
    T_{K^+} &= 12.4 \mu \text{s} \\
    m_{K^0} &= 498 \text{ MeV} \\
    T_{K^0} &= 900 \text{ ps} \\
    T_{K_S} &= 52 \text{ ns}
\end{align*}
\]

Decay time of pure \( K^0 \) beam
A large number of subsequent cosmic ray experiments led to the discovery of further "unstable particles" with typical lifetimes of $10^{-9}$ to $10^{-10}$ s (e.g., $\pi^+ + K^+ \rightarrow \pi^+ + \pi^- + \pi^+$).

Not clear which of the new particles are the same but different decays and which are really different.

**Famous example:** $\Theta^\pm$ puzzle

Two particles with same mass, but different parity:

\[
\Theta^+ \rightarrow 2\pi^- \\
\Theta^+ \rightarrow 2\pi^- \\
\]

T. D. Lee and Yang proposed that $\Theta^+$ and $\Sigma^+$ are the same particle but $\Theta$ is not conserved in weak decays.

\Rightarrow \text{discovery of } \Theta \text{ violation by Wu}

With first proton synchrotron it was possible to produce "strange" particles copiously with other strange partners, e.g., $\pi^+ + p \rightarrow K^+ + \bar{K^0} + p$
From the large production cross-section it was concluded that the lifetime must be only \( O(10^{-20}) \) s if the new particle decays strongly.

Introduction of new additive quantum number (strangeness) which is conserved in strong \( \Lambda \) but violated in weak decays.

The new quantum number together with the isospin concept opened the way to flavors, see (3) classification of hadrons and to the introduction of the static quark model as the fundamental representation by Gell-Mann + Zweig.

1.3. Gell-Mann: The 8folded Way

Using isospin and strangeness, Gell-Mann was able to order the known spin \( \frac{1}{2}, \frac{3}{2} \) baryons and the spin \( 0, \frac{1}{2} \) mesons in octets.

\[ \begin{align*}
  S = 0 & \quad \pi^+ \quad \pi^- \\
  S = -1 & \quad \Sigma^+ \quad \Sigma^- \quad \Sigma^0 \quad \Lambda \\
  S = -2 & \quad \Xi^- \quad \Xi^0 \quad \Xi^+ \\
  \end{align*} \]

\( S = \frac{1}{2} \) baryons \quad \( S = 0 \) mesons

[74 slide 8]
Gell-Mann discovered that the underlying symmetry group is a SU(3) group.

Analysing the baryon decouplet resulted in predicting in 1962 one missing particle: $\Sigma^- (\frac{5}{2}, Q = -1)$

The $\Sigma^-$ was discovered in 1964! Triumph of the Symmetry Ansatz! [⇒ Slide 97]

Gell-Mann + Zweig (1964): The regularities of the hadron multiplets can be accounted for by the introduction of 3 types of fermion constituents of the hadron = quarks ($u, d, s$)

<table>
<thead>
<tr>
<th>Quark Flavor</th>
<th>$\bar{3}$</th>
<th>$\frac{1}{2}$</th>
<th>$\frac{1}{2}$</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>0</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td>$d$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>$-\frac{1}{2}$</td>
<td>0</td>
<td>$-\frac{1}{3}$</td>
</tr>
<tr>
<td>$s$</td>
<td>$\frac{1}{3}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$-1$</td>
</tr>
</tbody>
</table>

Quark flavor symmetry $\bar{3} I I_3 5$ of $\frac{1}{2} - \frac{1}{2} (3 + 5)$

The symmetry between the hadrons is nowadays understood as the $SU(3)$ quark flavor symmetry between $u, d, s$ quarks.
4.1.4 The prediction of the 4th quark

Experimental findings analysing "weak decays" of hadrons found that $\Delta s = 1$ transitions are suppressed with respect to $\Delta s = 0$ decays by a $20 \text{ (phase space corrected)}$

\[ \Rightarrow \text{Cabibbo Theory} \]

\[
\begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix} \approx 
\begin{pmatrix}
1 - \theta^2 & \theta \\
\theta & 1 - \theta^2
\end{pmatrix}
\]

\[\text{mit } \theta = 13^\circ, \sin^2 \theta = 0.05 \Rightarrow \text{suppression}\]

A quark couples to $\bar{d}'$, which is linear combination of $d$ and $s$.

However, an experimental puzzling result was the very tiny $B_2$ of $K_\ell^0 \rightarrow \mu^+ \mu^-$

\[B_2 = (6.84 \pm 0.11) \times 10^{-9}\]

In 3 quark model one would expect:

\[K_\ell^0 \rightarrow \mu^+ \mu^-\]


Introduction of heavy $c$-type quark to
complete a new 2nd quark doublet fulfilling flavour symmetry

\[
\begin{pmatrix}
e' \\
g'
\end{pmatrix}
\begin{pmatrix}
c' \\
\sin \theta \cos \theta
\end{pmatrix}
\begin{pmatrix}
l' \\
\sin \theta \sin \theta
\end{pmatrix}
\begin{pmatrix}
s' \\
\cos \theta
\end{pmatrix}
\begin{pmatrix}
a \\
\end{pmatrix}
\]

With the new c'-quark there exist a 2nd amplitude to \( K^0 \to \pi^- \pi^+ e^+ e^- \), \( \Rightarrow \text{side 10} \)

\[
K^0 \rightarrow \pi^- \pi^+ e^+ e^- \quad \text{UC} = -G_F (\cos \theta \sin \theta)
\]

In the limit of perfect flavour symmetry (massless quarks), the two amplitudes cancel out \( \Rightarrow \beta^2 (K^0 \to \pi^- \pi^+ e^+ e^-) = 0 \)

\( \Rightarrow \) 4 quark model

**Remark**: In the same paper GIM also analysed the neutral kaon mixing

\[
K^0 \leftrightarrow \bar{K}^0 \quad K^0 \rightarrow e^+ e^- \quad \bar{K}^0 \rightarrow \mu^+ \mu^-
\]

Mixing frequency \( \delta m \approx G_F (-\cos^2 \theta \sin \theta \psi (m_u) \quad + \cos^2 \theta \sin \theta \psi (m_c)) \)

for \( m_c \gg m_u \)

\( \delta m \approx 2G_F m_c \cos^2 \theta \sin \theta \psi \)

From measurements of the mixing frequency they concluded that \( m_c \) must not be larger than 3-4 GeV.

From similar arguments Gaillard & Lee predicted
mc \approx 1.5 \ldots 2 \text{ GeV}

Although this is an impressive prediction, the evaluation is probably wrong (non-negligible higher-order terms).

However, it is interesting to note that the story repeated for the prediction of the top quark mass: from the observation of the \(3\eta\bar{\eta}\) oscillation, one was able to conclude that \(m_t > 35 \text{ GeV}!\)

E1.5 Discovery of the charm quark

1974: "November revoaction"

3. Ting et al. at BNL: \(p(28.6 \text{ GeV}) + \text{Be} \rightarrow e^+e^-X\) sharp narrow resonance

3. Richter et al. at SLAC: \(e^+e^- \rightarrow e^+e^-\) at 3.16 GeV

Interpretation: CE Resonance

Both experiments were very different but discovered the same particle

\(\text{SLAC-exp. also found excited CE-states } \eta(1S), \eta(2S), \eta(3S)\)

The particle is today called \(\eta'/\eta\) (only lowest \(\eta\)-state)

[\Rightarrow \text{slide 11}]

E.1.6 Discover of the $b$-quark (1973)

Analyzing the general structure of the quark mixing matrix, Kobayashi-Maskawa concluded that in order to explain CP violation in hadron decays (discovered in 1964 in neutral kaon decays) one needs at least 3 quark generations.

In general, mixing matrix for $N$ generations has $\frac{1}{2}N(N-1)$ real parameters (angles) $\frac{1}{2}N(N-1)(N-2)$ phases => necessary to generate CPV!

=> Nobel prize in Physics in 2008

$b$-quark discovery: New narrow resonance at 9.46 GeV

L. Lederman et al, Fermilab 1977

\[ p(400 \text{ GeV}) + (\text{C}u, 76) \rightarrow \ell^+\ell^- + X \]

\[ \text{K}_{\text{S0}} \text{rane} \]

E.1.7: Discovery of the top quark

From indirect measurements: $m_t > 35 \text{ GeV}$

$\beta\beta$ oscillations

$m_t > 173 \text{ GeV}$. Precision electroweak data is (~1991) sensitive to radiative corrections
modifies tree level relation between $m_{\tau}$ and $\sin^2 \theta_W$

$$\text{Tree level: } \sin^2 \theta_W = 1 - \frac{m_{\tau}^2}{M_{\tau}^2}$$

The only machine with sufficient energy to discover the top quark was Tevatron pp at 2001 GeV

How to discover the $t\bar{t}$-quark? There is no $t\bar{t}$ resonance

$\Rightarrow$ Need to reconstruct the top-quark via its decay products!

Discovery of Tevatron (1995) [Slide 13]

E 1.8 limits on possible "sequential quark" generation

i) From $e^-e^-$ cross-section one knows the number of active quark flavors.

$$\text{Rate: } \frac{\sigma(\text{ee}^{-}\text{hadrons})}{\sigma(\text{ee}^{-}\text{e+e-})} = N_e \ \frac{E_{\text{e}^-} \ \text{eV}^2}{E_{\text{e}^-}}$$
- no additional low mass quark family

2) Constraints on heavy 4th generation from Higgs production

main Higgs-production channel at LHC is gluon-fusion.

\[ t \rightarrow t H \]

Presence of additional heavy quarks will increase effective \( ggW \) coupling by a factor 3,

i.e. we would expect an enhanced Higgs production rate w.r.t. to SM.

Observed Higgs rate excludes the existence of a heavy 4th generation by \( 5.6 \sigma \)