Historical introduction to Elementary Particles: Particle Zoo and Quark Model

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- Griffiths, 2nd ed., 1.6-1.8, 4.3
- Recommend reading about quark model in other books (e.g. D.H.Perkins Introduction to High Energy Physics, 4th ed., 4.3-4.11)
Pion discovery 1946

- **C.F. Powell** distinguished muons from charged pions in 1946 in cosmic rays
  - Pion is the particle Yukawa had predicted as carrier of strong interactions in nuclei
  - Yukawa received Nobel prize in 1947, Powell in 1950

- Except for “spurious” muon, it seemed in 1947 that our understanding of elementary ingredients of matter was complete

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass MeV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.5</td>
</tr>
<tr>
<td>µ</td>
<td>105.7</td>
</tr>
<tr>
<td>π⁻</td>
<td>139.6</td>
</tr>
<tr>
<td>p</td>
<td>938.3</td>
</tr>
<tr>
<td>n</td>
<td>939.6</td>
</tr>
</tbody>
</table>
Discovery of strange particles - 1947

- Studying cosmic rays with a cloud chamber at Manchester University in late 1947, G.D. Rochester and C.C. Butler observed a neutral particle decaying to $\pi^+\pi^-$ with mass about half of nucleon mass – meson. Nowadays we call it a neutral kaon ($K^0$).
- Charged kaon was first observed in cosmic rays in 1949 via $K^+ \rightarrow \pi^+\pi^-\pi^+$.
- In 1950 another “V$^0$ particle” was observed in cosmic rays: $\Lambda^0 \rightarrow p\pi^-$ (V.D. Hopper, S. Biwas, Univ. of Melbourne; also Anderson group in Caltech).
- They were completely unexpected and had very strange lifetimes (see next).
First accelerators

• In 1952 first modern particle accelerator came to operation at Brookhaven National Lab: Cosmotron (3.3 GeV p beam)

Bubble chamber photograph

Kaons also live “strangely” long
**Particle Zoo - Meson**

- Lots of new particles were discovered at accelerators.
- Lightest mesons:

<table>
<thead>
<tr>
<th>Particle</th>
<th>Spin</th>
<th>Mass (width = $\hbar/\tau$)</th>
<th>Main decay mode</th>
<th>Lifetime $\tau$</th>
<th>$c\tau$</th>
<th>Decay type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm$</td>
<td>0</td>
<td>140 MeV</td>
<td>$\mu^\pm\nu_\mu$</td>
<td>2.6x10^{-8} s</td>
<td>7.8 m</td>
<td>weak</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>0</td>
<td>135 MeV</td>
<td>$\gamma\gamma$</td>
<td>8.5x10^{-17} s</td>
<td>2.5 10^{-8} m</td>
<td>electromagnetic</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0</td>
<td>548 MeV</td>
<td>$\gamma\gamma$</td>
<td>3.1x10^{-18} s</td>
<td>9.5 10^{-10} m</td>
<td>electromagnetic</td>
</tr>
<tr>
<td>$\rho^0,\rho^\pm$</td>
<td>1</td>
<td>775 MeV (149 MeV)</td>
<td>$\pi^+\pi^-, \pi^\pm\pi^0$</td>
<td>2.8x10^{-23} s</td>
<td>8.3 10^{-15} m</td>
<td>strong</td>
</tr>
<tr>
<td>$\omega$</td>
<td>1</td>
<td>783 MeV (8.2 MeV)</td>
<td>$\pi^+\pi^-\pi^0$</td>
<td>4.9x10^{-22} s</td>
<td>1.5 10^{-13} m</td>
<td>strong</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>0</td>
<td>958 MeV (0.2 MeV)</td>
<td>$\pi^+\pi^-\eta$</td>
<td>2.1x10^{-20} s</td>
<td>6.3 10^{-12} m</td>
<td>strong</td>
</tr>
<tr>
<td>$K^0_s$</td>
<td>0</td>
<td>498 MeV</td>
<td>$\pi^+\pi^-, \pi^0\pi^0$</td>
<td>8.9x10^{-11} s</td>
<td>0.027 m</td>
<td>weak</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>0</td>
<td>494 MeV</td>
<td>$\mu^\pm\nu_\mu$</td>
<td>1.2x10^{-8} s</td>
<td>3.7 m</td>
<td>weak</td>
</tr>
<tr>
<td>$K^{<em>0},K^{</em>\pm}$</td>
<td>1</td>
<td>892 MeV (~50 MeV)</td>
<td>$K^+\pi^-, K^{\pm}\pi^0$</td>
<td>8.3x10^{-23} s</td>
<td>2.5 10^{-14} m</td>
<td>strong</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1</td>
<td>1020 MeV (4.3 MeV)</td>
<td>$K^+K^-$</td>
<td>9.6x10^{-22} s</td>
<td>2.9 10^{-13} m</td>
<td>strong</td>
</tr>
</tbody>
</table>

*Why $K^0_s$ does not decay strongly to $\pi^+\pi^-$? [next slide]*
Conservation of strangeness - Pais

- Abraham Pais suggested:
  - new quantity “strangeness”:
    - $S(\text{strange particle e.g. } K^+) = +1$
    - $S(\text{strange antiparticle e.g. } K^-) = -1$
    - $S(\text{non-strange particle}) = 0$
  - total strangeness ($\Sigma S_i$) is conserved in strong and electromagnetic interactions
  - weak interactions can violate strangeness

- Lightest strange particles must decay weakly, and therefore live long

\[
\begin{align*}
K^0_s &\rightarrow \pi^+\pi^- \\
\Sigma_i S_i &\quad 1 \quad 0+0=0 \quad \text{weak} \\
K^*0 &\rightarrow K^+\pi^- \\
\Sigma_i S_i &\quad 1 \quad 1+0=1 \quad \text{strong} \\
\phi &\rightarrow K^+K^- \\
\Sigma_i S_i &\quad 0 \quad 1+(-1)=0 \quad \text{strong}
\end{align*}
\]

With particles being produced via proton beam incident at nuclear target (strong interactions!), strange particles can only be produced in strange – antistrange pairs

\[
\begin{align*}
pA \quad \text{strong} &\rightarrow \ldots \\
\Sigma_i S_i &\quad 0+0=0 \quad 0
\end{align*}
\]
**Particle Zoo - Baryons**

- **Lightest baryons:**

<table>
<thead>
<tr>
<th>Spin</th>
<th>Strangness</th>
<th>Mass (width= $\hbar / \tau$)</th>
<th>Main decay mode</th>
<th>Lifetime $\tau$</th>
<th>$c\tau$</th>
<th>Decay type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$1/2$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>$1/2$</td>
<td>0</td>
<td>$p e^- \nu_e$</td>
<td>$8.8 \times 10^{-2}$ s</td>
<td>$2.6 \times 10^{+8}$ m</td>
<td>weak</td>
</tr>
<tr>
<td>$\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$</td>
<td>$3/2$</td>
<td>0</td>
<td>$\sim 1232$ MeV ($\sim 117$ MeV)</td>
<td>$3.5 \times 10^{-23}$ s</td>
<td>$1.1 \times 10^{-16}$ m</td>
<td>strong</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$1/2$</td>
<td>-1</td>
<td>1116 MeV</td>
<td>$p \pi^-, n \pi^0$</td>
<td>$2.6 \times 10^{-10}$ s</td>
<td>$0.079$ m</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>$1/2$</td>
<td>-1</td>
<td>1189 MeV</td>
<td>$p \pi^0, n \pi^+$</td>
<td>$0.8 \times 10^{-10}$ s</td>
<td>$0.024$ m</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>$1/2$</td>
<td>-1</td>
<td>1193 MeV</td>
<td>$\Lambda \gamma$</td>
<td>$7.4 \times 10^{-20}$ s</td>
<td>$2.2 \times 10^{-11}$ m</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>$1/2$</td>
<td>-1</td>
<td>1197 MeV</td>
<td>$n \pi^-$</td>
<td>$1.5 \times 10^{-10}$ s</td>
<td>$0.044$ m</td>
</tr>
<tr>
<td>$\Sigma^{*-}, \Sigma^{<em>0}, \Sigma^{</em>+}$</td>
<td>$3/2$</td>
<td>-1</td>
<td>1383 MeV ($\sim 36$ MeV)</td>
<td>$\Lambda \pi$</td>
<td>$1.2 \times 10^{-22}$ s</td>
<td>$3.5 \times 10^{-14}$ m</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>$1/2$</td>
<td>-2</td>
<td>1315 MeV</td>
<td>$\Lambda \pi^0$</td>
<td>$2.9 \times 10^{-10}$ s</td>
<td>$0.087$ m</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>$1/2$</td>
<td>-2</td>
<td>1322 MeV</td>
<td>$\Lambda \pi^-$</td>
<td>$1.6 \times 10^{-10}$ s</td>
<td>$0.049$ m</td>
</tr>
<tr>
<td>$\Xi^{*-}, \Xi^{*0}$</td>
<td>$3/2$</td>
<td>-2</td>
<td>$\sim 1532$ MeV ($\sim 9$ MeV)</td>
<td>$\Xi \pi$</td>
<td>$4.5 \times 10^{-22}$ s</td>
<td>$1.3 \times 10^{-13}$ m</td>
</tr>
</tbody>
</table>

1) Why proton doesn’t decay (e.g. $e^+ \gamma$)? Pions do. [see next slide]
2) $\Lambda, \Sigma$ are strange as seen from lifetimes of their lightest versions
3) $\Xi$ are doubly strange, since their decay to singly strange baryons is weak (i.e. slow)
Conservation of baryon number - Stueckelberg

- Ernst Stueckelberg introduced baryon number (~1938) as a conserved quantity to explain why proton does not decay
  - **baryon number**
    - $A(\text{baryon e.g. } p) = +1$
    - $A(\text{antibaryon e.g. } p) = -1$
    - $A(\text{not a baryon}) = 0$
  - **total baryon number ($\sum_i A_i$)** is conserved in all interactions
  - For nuclei baryon number is equal to their mass number (justifies use of “A” for the baryon number)

- Lightest baryon ($p$) cannot decay

- All baryons discovered in cosmic rays and at accelerators obey this rule, thus subsequent decays of baryons all eventually lead to a proton (unless baryon interacts with a nucleus in a material of apparatus before it decays)

  \[ \Xi^* \rightarrow \Xi^0 \pi^- , \Xi^0 \rightarrow \Lambda \pi^0 , \Lambda \rightarrow p \pi^- \]

- Please note, there is no conservation of meson number!

Notice, that decay of a meson to baryon-antibaryon pair is possible and does happen e.g.

\[ B^0 \rightarrow p\bar{\Lambda}\pi^-, \quad \sum_i A_i = 0 \]
Terminology related to strange baryons

- $\Lambda$ : “Lambda”
- $\Sigma$ : “Sigma”
- $\Xi$ : “Xi” or “cascade”
- Any strange baryon ($\Lambda, \Sigma, \Xi$) : “hyperon”
**Particle Zoo**

- In addition to the lightest mesons and baryons listed on the previous slides, many more, usually short lived, particles were discovered in 1950ies.

  ```
  ![Particle Catalog Image]
  ```

  Contemporary catalog at http://pdg.lbl.gov

  Way out of crisis - build “periodic table of elements”
**Isospin symmetry - 1932**

- Neutron was discovered in 1932:
  - p and n had almost identical masses
  - p and n interact in nucleus the same way
- Heisenberg proposed to think about p,n as the same particle (nucleon), different via projections of spin-like quantum number “isospin” onto quantization axis:
  
  Nucleon $I= \frac{1}{2}$ , $I_z = +\frac{1}{2}$ (p), $-\frac{1}{2}$ (n)

Just like electron ($J= \frac{1}{2}$ ) with spin projection ($J_z$) $+\frac{1}{2}$ is not considered to be a different particle than electron with spin projection $-\frac{1}{2}$ (two different quantum states of the same particle)

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Lagrangian symmetrical under</th>
<th>Conserved quantity</th>
<th>Intrinsic particle quantum number</th>
<th>Possible values</th>
<th>Describe particle properties under rotation in</th>
</tr>
</thead>
<tbody>
<tr>
<td>any</td>
<td>rotation in real space</td>
<td>Angular momentum</td>
<td>Spin ($J$)</td>
<td>0, $\frac{1}{2}$, 1, $\frac{3}{2}$, 2,…</td>
<td>real space</td>
</tr>
<tr>
<td>strong</td>
<td>rotation in isospin space</td>
<td>Isospin</td>
<td>Isospin ($I$)</td>
<td>0, $\frac{1}{2}$, 1, $\frac{3}{2}$, 2,…</td>
<td>Isospin space</td>
</tr>
</tbody>
</table>

*The difference in n,p masses was blamed on electric charge of p*

Nuclei have well defined isospin (often called *isobaric spin*), which is a sum of nucleon isospins. Nuclear reactions conserve isospin – very useful concepts in nuclear physics.
Particle Zoo and isospin symmetry - baryons

- Newly discovered baryons clearly formed isospin multiplets:

| particle      | Isospin \((I)\) | Members of isospin multiplet \((2I+I)\):  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(I_z), symbol, (mass in MeV)</td>
<td></td>
</tr>
</tbody>
</table>
| nucleon       | 1/2             | -1/2 n (940)  
|               |                 | 1/2 p (938)            |
| Delta baryon  | 3/2             | -3/2 \(\Delta^-\)  
|               |                 | -1/2 \(\Delta^0\)  
|               |                 | 1/2 \(\Delta^+\)  
|               |                 | 3/2 \(\Delta^{++}\)            |
| Lambda        | 0               | 0 \(\Lambda\) (1116)            |
| Sigma         | 1               | -1 \(\Sigma^-\) (1197)  
|               |                 | 0 \(\Sigma^0\) (1192)  
|               |                 | 1 \(\Sigma^+\) (1189)            |
| Cascade       | 1/2             | -1/2 \(\Xi^-\) (1322)  
|               |                 | 1/2 \(\Xi^0\) (1315)            |

The mass differences within multiplets were “blamed” on electromagnetic interactions  
- though mechanism for that was never really explained and would have been inconsistent

Empirical formula for electric charge (Gell-Mann Nishijima):
\[ Q = I_z^+ \frac{1}{2} (A+S) \]

Antibaryons exist for each above e.g.: \(\Sigma^+ \neq \Sigma^-\), \(\Sigma^0 \neq \Sigma^0\)
Particle Zoo and isospin symmetry - meson

- Mesons formed isospin multiplets as well:

<table>
<thead>
<tr>
<th>particle</th>
<th>Isospin $(l)$</th>
<th>Members of isospin multiplet $(2l+1)$: $I_z$, symbol, (mass in MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pion</td>
<td>1</td>
<td>$-1 \pi^- (139)$, $0 \pi^0 (135)$, $1 \pi^+ (139)$</td>
</tr>
<tr>
<td>rho meson</td>
<td>1</td>
<td>$-1 \rho^- (766)$, $0 \rho^0 (769)$, $1 \rho^+ (766)$</td>
</tr>
<tr>
<td>eta meson</td>
<td>0</td>
<td>$0 \eta (548)$</td>
</tr>
<tr>
<td>omega</td>
<td>0</td>
<td>$0 \omega (782)$</td>
</tr>
<tr>
<td>eta' meson</td>
<td>0</td>
<td>$0 \eta' (958)$</td>
</tr>
<tr>
<td>kaon</td>
<td>1/2</td>
<td>$-1/2 K^0 (498)$, $+1/2 K^\pm (494)$</td>
</tr>
</tbody>
</table>

Empirical formula for electric charge (Gell-Mann Nishijima):

$$Q = I_z + \frac{1}{2} (A+S)$$

A=0 for all above

Antiparticles already included above e.g.: $\overline{\pi^+} = \pi^-$, $\overline{\pi^0} = \pi^0$
“Eightfold Way” symmetry - 1961

- **Gell-Mann** proposed in 1961 a higher level of symmetry (incorporating Isospin symmetry):
  - Lightest mesons and baryons formed “octets” in space of \( Y = A + S \) (“hypercharge”) vs \( I_z \)

The differences in masses are now much larger than in isospin multiplets, but there were some regularities within [do related problems 1.4 and 1.5]
Nevertheless, this symmetry seemed to “explain” why there were no other (pseudo)scalar mesons or spin \( \frac{1}{2} \) baryons in these mass ranges.
Multiplet of spin-3/2 baryons

- Hypercharge vs $I_z$ space organized spin-3/2 baryons into a “decouplet” with one empty spot:

Gell-Mann predicted mass of the missing triple-strange particle $\Omega^-$
[do related problem 1.6]
Experimental discovery of $\Omega^-$ – 1964

- Discovered in 1964 at Brookhaven in a bubble chamber experiment with kaon beam
- It convinced physicists that Gell-Mann was on the right track
- However, fundamental principles behind the Gell-Mann multiplets were not understood – the situation was like with the Mandeleev’s period table of elements
Quark-model - 1964

- Symmetry proposed by Gell-Mann (nowadays called SU(3)-flavor symmetry) has a simpler fundamental multiplet representation:

\[
\begin{array}{c|c|c}
Y & \text{I}_z & \text{I} \\
\hline
1 & 0 & -1 \\
0 & 1 & 0 \\
-1 & -1 & 1 \\
\end{array}
\]

\[
\begin{align*}
\text{Spin} &= \frac{1}{2} \\
\text{A} &= \frac{1}{3} \\
\text{Q} &= \pm \frac{2}{3} \\
\text{S} &= 0
\end{align*}
\]

Gell-Mann proposed that elementary particles corresponding to this representation exist (he called them “quarks” - q), and that they were building blocks of all baryons (qqq) and mesons (qq̅)

(Carl Zweig independently proposed the same idea)
Mesons is quark model

- Quark-antiquark combinations: $q\bar{q}$ (together “nonent”)
- In group theory: $3 \otimes \bar{3} = 8 \otimes 1$ i.e. octet $\otimes$ singlet
- The singlet is fully symmetrical under exchange of quarks:
  \[ \eta_0 = \frac{1}{\sqrt{3}} (dd - uu + ss) \quad (I=0) \]
- Octet contains isospin singlet (symmetrical under exchange of $u,d$), which is orthogonal to SU(3)$_i$ singlet
  \[ \eta_8 = \frac{1}{\sqrt{6}} (dd + uu - 2ss) \quad (I=0) \]
- Octet contains isospin triplet built from $u,d$. Its $I=0$ member is antisymmetric with respect to exchange of $u,d$ (orthogonal to both $\eta_0$ and $\eta_8$)
  \[ \pi^0 = \frac{1}{\sqrt{2}} (dd - uu) \quad (I=1, I_z=0) \]
  \[ \pi^+ = ud \quad \pi^- = \bar{u}d \quad (I=1, I_z=+1, -1) \]
- Octet also contains isospin doublets:
  \[ K^+ = u\bar{s} \quad K^0 = d\bar{s} \quad (I=\frac{1}{2}, I_z=+\frac{1}{2}, -\frac{1}{2}) \]
  \[ K^- = \bar{u}s \quad \bar{K}^0 = \bar{d}s \]
Mesons in quark model – SU(3)\(_f\) breaking

- **Isospin symmetry** is nearly exact, \(m_u = m_d\)
- Strange quark is heavier, \(m_s > m_{u,d}\) which breaks SU(3)\(_f\) symmetry:
  - this makes states with \(s\) quark (kaons and singlets) heavier
  - It also makes physical \(\eta\) mesons become mixtures of \(\eta_0\) and \(\eta_8\):

\[
\begin{pmatrix}
\cos \theta_P & -\sin \theta_P \\
\sin \theta_P & \cos \theta_P \\
\end{pmatrix}
\begin{pmatrix}
\eta_8 \\
\eta_1 \\
\end{pmatrix}
= \begin{pmatrix}
\eta \\
\eta' \\
\end{pmatrix}
\]

- In practice, the mixing angle is small for the pseudoscalar mesons:

\[
\theta_P = -11.5^\circ
\]

\[
\eta = 0.98 \eta_8 - 0.20 \eta_0 \\
\eta' = -0.20 \eta_8 + 0.98 \eta_0
\]

- The original “Eightfold Way” symmetry had no accommodation for \(\eta'\). The quark model with SU(3)\(_f\) explained existence of this state.
Vector mesons in quark model

- Spin of a meson (J) is a sum of total quark spin (S=S_q+S_\bar{q}) and orbital angular momentum between quarks (L).
- In pseudoscalar mesons the quark spins (½) align for S=0. There is also no orbital angular momentum between them (L=0).
- For vector mesons the quark spins align for total quark spin of 1 (S=1). There is still no orbital angular momentum between the quarks (L=0).

\[ J = 1 \]

- The mixing angle between isospin singlets is large for the vector mesons: \[ \theta_V = 40^\circ \]
- \( \sin\theta_V=0.64 \) is close to \( 1/\sqrt{3}=0.58 \) which would correspond to “ideal mixing”:
  \[ \phi = s\bar{s} \]
  \[ \omega = \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) \]
Higher excitations of $q\bar{q}$ pairs

$n^{2S+1}L_J$

$q\bar{q}$ excitations  
$n$ – radial quantum number  
$S$ – total quark spin (=0 or 1)  
$L$ – orbital angular momentum between quarks  
.  
(i.e. (=S, P, D, …))  
$J$ – meson spin

From Griffiths Fig 1.10

Be aware:  
1) Particles repeated in different nonets are not the same; they have different masses  
2) Many particle names in this figure have new names

- All these are for $n=1$. Then, there are nonets also for $n=2$, 3, …  
- Particle Zoo stems from different excitations of quark-antiquark system.  
- Spectrum of expected baryons is even richer – more degrees of freedom between 3 quarks.
Baryons in quark model

\[ 3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A. \]

Decuplet is symmetric under exchange of any quark e.g.

\[ \Delta^0 = \frac{1}{\sqrt{3}}(d \uparrow d \uparrow u \uparrow + u \uparrow d \uparrow +d \uparrow u \uparrow d \uparrow) \]

\[ \Omega^- = s \uparrow s \uparrow s \uparrow \]

Octet has a mixed symmetry e.g.

\[ p = \frac{1}{\sqrt{18}}(2u \uparrow u \uparrow d \downarrow +2d \downarrow u \uparrow +2u \uparrow d \downarrow u \uparrow \]

\[ -u \downarrow d \uparrow + u \uparrow -u \uparrow d \uparrow -u \downarrow u \uparrow d \uparrow \]

\[ -d \uparrow u \downarrow -u \uparrow d \uparrow -d \uparrow u \downarrow -d \uparrow u \uparrow u \downarrow) \]
Quark model view at ...

• **Weak interactions** of hadrons (particles made out of quarks):
  – Really happen between quarks (**quarks have weak charge!**).
  – Weak decays of mesons are 4-fermion interactions, like any other weak interaction. More on this later.

• **Conservation of strangeness in strong interactions:**
  – Only weak decays can turn one quark to the other.
  – In strong interactions, strange quarks can be created and annihilated only in ss pairs.

• **Conservation of baryon number:**
  – Quarks don’t turn to leptons. Thus “quark number” is conserved in all interactions.

• **Isospin symmetry:**
  – All quarks have the same strong interactions. Masses of u and d quarks are nearly identical (we don’t know why).
  – u and d quark masses **are not** identical; **Isospin violation does happen!** Isospin violating effects (e.g. mass differences in isospin multiplets) are small and often negligible.

• **SU(3) flavor symmetry:**
  – All quarks have the same strong interactions (**flavor independent**). s quark mass is only slightly different from u,d masses (again don’t know why).
  – The difference between s and u,d masses is significantly larger than u-d mass difference. **SU(3)_f violations are not negligible!**
Deep inelastic scattering of electrons on protons

- In late 1960s electron beam with sufficient energy to penetrate a proton became available at Stanford Linear Accelerator Center (SLAC).
- The experiments showed evidence for hard scattering centers inside proton (called “partons”) – analog of Rutherford’s experiment.
- Gell-Mann gets Nobel Prize in 1969.
- There was still some skepticism if partons were the same as quarks. Some people did not believe in quarks since none of experiments revealed isolated quarks.
- More on quarks and strong interactions next time.