Introduction to physics of EIC
From Greeks to QCD

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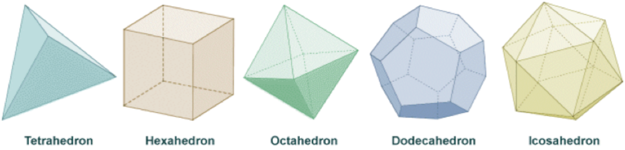
Elements

All matter is composed of a limited number of elements.

- water (Thales), air (Anaximenes), fire (Heraclitus), earth (Xenophanes)
- fire, water, earth and air (Empedocles, 450 BC)
- fire, water, earth, wood and metal (Chinese texts)
- Democritus, 460 BC - indivisable atoms and empty space
- Plato, 380 BC - atoms form 5 regular polyhedra (Platonic solids)



Sides: 4,6,8,12,20 identical polygons

- Pure speculations - no experimental clues
- Alchemists - medieval experimentalists: mercury, sulfur, salt

- XVIII century - birth of modern chemistry. 55 elements known by 1787 - gases, non-metals, metals, compounds, heat, light
- Dalton, 1804 - Law of Combining Weights: elements combine in compounds in definite proportions of masses:

$$1\,g \text{ of hydrogen} + 8\,g \text{ of oxygen} \rightarrow 9\,g \text{ of water}$$

$$H + O \rightarrow HO$$

- Gay-Lussac, 1808 - Law of Combining Volumes: gases at the same temperature and pressure combine in definite proportions of volumes

$$2 \text{ l of hydrogen} + 1 \text{ l of oxygen} \rightarrow 2 \text{ l of water vapor}$$

- Avogadro, 1811 - equal volumes of gases at the same T and p contain equal number of particles (molecules) ($pV/T = kN_A$)

$$2H_2 + O_2 \rightarrow 2H_2O$$

- Definite ratios of atomic weights:

$$H : C : N : O : S \approx 1 : 12 : 14 : 16 : 32$$

Physics in XIX

- Age of steam and electricity: termodynamics and electromagnetism
- Main experimental challenges:
  - measure the Avogadro number: $N_A \approx 6.02 \cdot 10^{23}$ molecules/mol
  - determine the nature of electricity: discovery of the electron
- Electrolysis (Faraday): $H_2O \to H^+ + OH^-$. How many units of electric charge neutralize single charged ions at battery terminals?

$$\frac{e}{m_{H^+}} \approx 10^5 \ \frac{coulombs}{g}$$

- J.J. Thomson experiments with cathod rays in vacuum tubes, 1897

$$\frac{e}{m_e} \approx 10^8 \ \frac{C}{g} \quad \longrightarrow \quad m_e \approx 10^{-3} m_{H^+}$$

- Negatively charged constituents of atoms - electrons.
- Charge quantization (Millikan, 1910): $Q = Ne$ and $e = 1.6 \cdot 10^{-19}$ C

- Discovery of radioactivity, Bequerel, P. & M. Curie - α particles
- Rutherford, 1911 - positive charge in atoms is concentrated in a nuclues, 10^4 smaller than the atom size:

$$\alpha + \mathrm{Au} \to \alpha + \mathrm{Au}$$

- Bohr, 1913 - model of hydrogen atom - energy quantization
- Rutherford, 1919 - proton discovery: $\alpha + {}^{14}\mathrm{N} \to {}^{17}\mathrm{O} + p^+$
- Chadwick, 1932 - neutron discovery: $\alpha + {}^{9}\mathrm{Be} \to {}^{12}C + n^0$

$$m_n = 939.565\ \mathrm{MeV/c^2}, \qquad \Delta m = m_n - m_p = 1.293\ \mathrm{MeV/c^2}$$

- Neutron beta decay - neutrino hypotesis, Pauli, 1930

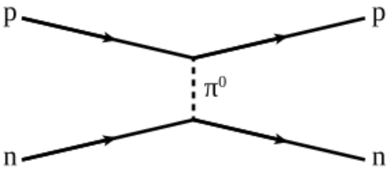
$$n \to p^+ + e^- + \bar{\nu}_e \qquad \tau = 877.75^{+0.50}_{-0.44}\ s\ (UCN\tau, 2021)$$

- Nucleus of atomic number Z and mass number A

$$\mathrm{nucleus} = Zp^+ + (A - Z)\, n^0$$

- Nucleons have spin 1/2 - fermions

- Neutrons overcome electric repulsion of protons - strong interactions
- Yukawa, 1935 - short range interactions mediated by massive pions



$$V \sim \mathrm{e}^{-r/r_s} \quad \rightarrow \quad r_s = \frac{\hbar}{m_\pi c} \simeq 2\,\mathrm{fm} \quad \rightarrow \quad m_\pi \simeq 100\,\mathrm{MeV}/c^2$$

- Charged mesons $\pi^\pm$ can also be exchanged in process

$$np \rightarrow np\,, \qquad pp \rightarrow nn\,, \qquad nn \rightarrow pp$$

π mesons

- $\pi^{\pm}$ discovered in 1947 in cosmic rays through weak decay ($\tau \sim 10^{-8} s$)

$$\pi^{+} \;\to\; \mu^{+} + \nu_{\mu} \;\to\; e^{+} + \nu_e + \nu_{\mu}$$

- Muon $\mu^{\pm}$ is a heavy electron (lepton) - discovered in 1936

$$m_{\mu} = 105.66 \ \mathrm{MeV/c^2}\,, \qquad\qquad m_e = 0.511 \ \mathrm{MeV/c^2}$$

- π^{0} discovered in 1950 at Berkeley cyclotron ($\tau \sim 10^{-17} s$)

$$\pi^{0} \to 2\,\gamma$$

- Similar masses:

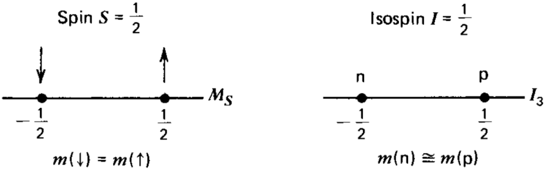
$$m_{\pi^{\pm}} = 139.57 \ \mathrm{MeV/c^2}, \qquad\qquad m_{\pi^{0}} = 134.98 \ \mathrm{MeV/c^2}$$

- Spin 0 pseudoscalar particles - bosons

Summary of the period 1900 – 1950

- The birth of Quantum Mechanics: photon, antiparticles
- The birth of Quantum Field Theory: QED
- The structure of atomic nucleus established: nucleons
- Strong (nuclear) interactions introduced: pions
- Unexpected particles: neutrino, muon
- Neutron beta decay - weak interactions - Fermi's theory, 1933:
- Idea of internal symmetry - Heisenberg, 1932:

- Strong interactions are $SU(2)$ symmetric since $m_p \approx m_n$:



- Nucleons and pions form multiplets of irreducible representations of $SU(2)$ for isotopic spin $I = \frac{1}{2}$ and $I = 1$, respectively,

$$|N\rangle = \begin{pmatrix} p \\ n \end{pmatrix}, \qquad |\boldsymbol{\pi}\rangle = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}$$

- Nucleon and pion states are eigenstates of $\hat{I}_3$:

$$|p\rangle = |\tfrac{1}{2}, \tfrac{1}{2}\rangle, \qquad |n\rangle = |\tfrac{1}{2}, -\tfrac{1}{2}\rangle, \qquad |\pi^\pm\rangle = |1, \pm 1\rangle, \qquad |\pi^0\rangle = |1, 0\rangle$$

Experimental consequence

- Isospin addition

$$|\tfrac{1}{2},\tfrac{1}{2}\rangle \otimes |\tfrac{1}{2},\tfrac{1}{2}\rangle = |1,1\rangle$$
$$|\tfrac{1}{2},\tfrac{1}{2}\rangle \otimes |\tfrac{1}{2},-\tfrac{1}{2}\rangle = \frac{|1,0\rangle + |0,0\rangle}{\sqrt{2}}$$

- Isospin (I, I_3) is conserved by strong interactions:

$$\frac{\sigma(pp \to \pi^+ d)}{\sigma(pn \to \pi^0 d)} = 2 \qquad\qquad I(d) = 0$$

- Baryon number B is always conserved

$$B(p,n) = 1 \qquad\qquad B(\pi^\pm, \pi^0) = 0$$

- New classification - baryons and mesons

Strange particles ($>$ 1947)

- New heavier K mesons were discovered,

$$K^0 \to \pi^+ + \pi^- \,, \qquad\qquad K^+ \to \pi^+ + \pi^+ + \pi^-$$

- New heavier baryons: Λ, Σ - produced copiously and decaying slowly

$$\pi^- + p^+ \to K^+ + \Lambda \,, \qquad\qquad \Sigma^+ \to p^+ + \pi^0$$

- Produced in strong interactions and decay in weak interactions
- New quantum number: strangeness S

$$S(K) = 1 \,, \qquad S(\Lambda, \Sigma) = -1 \,, \qquad S(p, n, \pi) = 0$$

- S is conserved by strong interactions but violated by weak interactions.
- CP violation in K meson decays, Cronin, Fitch, 1964 - time arrow

The Eightfold Way

- New classification based on irreducible representations of $SU(3)$ group, (Gell-Mann, Ne'eman, 1961)
- $SU(3)$ has 8 real parameters α_i associated with 8 generators $\hat{T}_i$

$$U \simeq \mathbf{1} + i \sum_{i=1}^{8} \alpha_i \hat{T}_i \,, \qquad \alpha_i \ll 1 \,, \qquad [\hat{T}_j, \hat{T}_k] = i f_{jkl} \, \hat{T}_l$$

- 2 commuting generators:

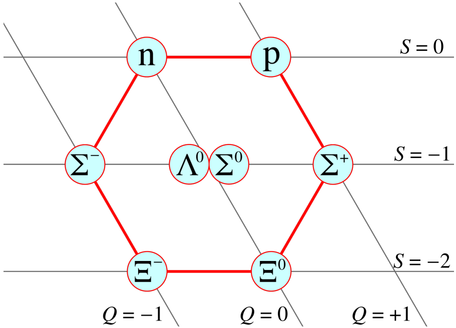
$$\hat{T}_3 = \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \hat{T}_8 = \frac{1}{2\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

- Representation space spanned by states labeled by two eigenvalues

$$|t_3, t_8\rangle = |I_3, Y\rangle \qquad Y = B + S$$

Octet of spin 1/2 baryons

- Baryons states span 8 dim. representation of $SU(3)$. In (I_3, Y) plane:

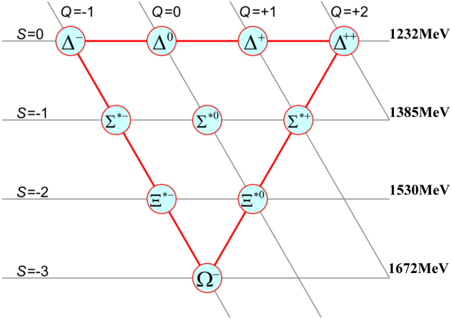


- Charges from Gell-Mann - Nishijima relation:

$$Q = I_3 + \frac{Y}{2} = I_3 + \frac{1+S}{2}$$

Decuplet of spin 3/2 baryons

- Baryon states span 10 dimensional representation of $SU(3)$



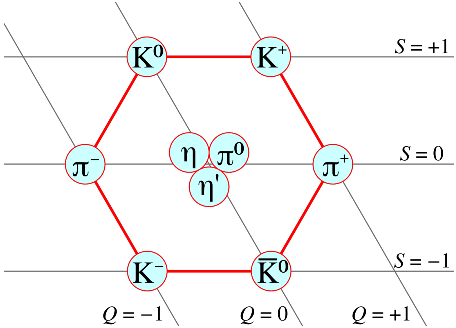
- Charges from Gell-Mann - Nishisjima relation:

$$Q = I_3 + \frac{1+S}{2}$$

- $SU(3)$ symmetry is only approximate due to mass differences.

Nonet of spin 0 mesons

- Meson states span $1 \oplus 8$ dimensional representation of $SU(3)$



- Charges from Gell-Mann - Nishijima relation:

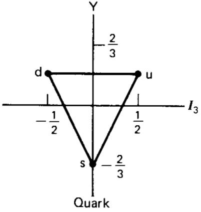
$$Q = I_3 + \frac{S}{2}$$

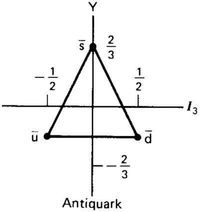
Gell-Mann - Zweig quark model (1964)

- Quarks - provide fundamental representations 3 and $\bar{3}$ of $SU(3)$

$$Q = \begin{pmatrix} u \\ d \\ s \end{pmatrix} \qquad \bar{Q} = \begin{pmatrix} \bar{u} \\ \bar{d} \\ \bar{s} \end{pmatrix}$$

- Have spin $1/2$ and baryon number $B = \pm 1/3$





- Fractional charges from $Q = I_3 + Y/2$:

Quark	I_3	B	S	$Y = B + S$	Q
u	$1/2$	$1/3$	0	$1/3$	$2/3$
d	$-1/2$	$1/3$	0	$1/3$	$-1/3$
s	0	$1/3$	-1	$-2/3$	$-1/3$

- $SU(2)$ spin addition:

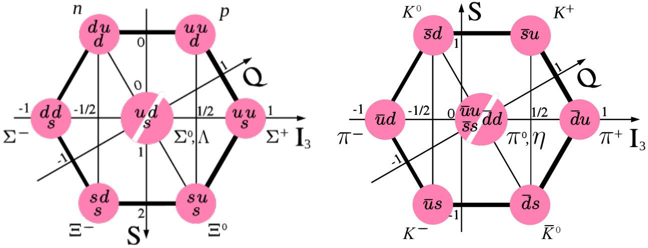
$$\tfrac{1}{2} \otimes \tfrac{1}{2} = 0 \oplus 1 \qquad \leftrightarrow \qquad 2 \otimes 2 = 1 \oplus 3$$

- $SU(3)$ addition:

$$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus \bar{8} \oplus 10 \qquad \textit{baryons } B = 1$$

$$3 \otimes \bar{3} = 1 \oplus 8 \qquad \textit{mesons } B = 0$$

- Baryon octet and meson nonet

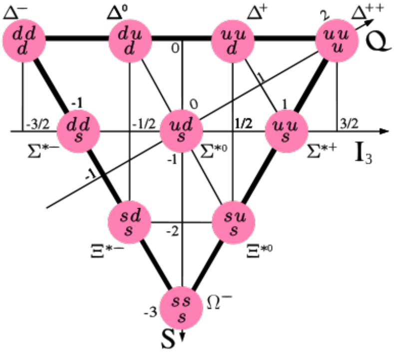


- Neutral mesons:

$$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \qquad \eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}) \qquad \eta' = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

Paradox of Δ^{++}

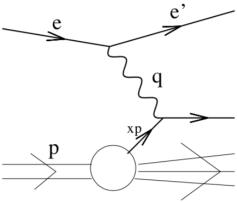
- Spin 3/2 baryon decuplet



- Fermionic state $|\Delta^{++}, J_3 = 3/2\rangle = |u\uparrow u\uparrow u\uparrow\,\rangle$ is symmetric.
- Need of additional quantum number which restores antisymmetry.

Experimental verification

- Deep Inelastic Scattering provides an evidence for quark existence



- Elastic scattering on a point-like, spin 1/2 and free particle.
- Electroweak interactions used to reveal structure of the proton.
- Quark doublets in Weinberg-Salam electroweak theory

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

- Strong interactions are flavour universal.

The theory of strong interactions which arose from the need to explain:

- additional degree of freedom to explain Δ^{++} paradox
- quark flavour universality of strong interactions
- asymptotic freedom of quarks at short distances (< 1 fm)

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ADVANTAGES OF THE COLOR OCTET GLUON PICTURE ☆

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- Quark model - Gell-Mann and Zweig, 1964
- Quark discovery in DIS - Friedman, Kendall, Taylor, 1967-69
- Electroweak unification with Higgs mechanism of mass generation - Weinberg, Salam, Glashow, 1967-74
- *QCD* and asymptotic freedom - Gross, Politzer, Wilczek, 1973
- Higgs particle discovery - CERN, 2012

STANDARD MODEL

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ Yang-Mills gauge theory