The Constituent Quark Model-History and New Challenges for QCD

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In 1960 particle physicists believed that the nucleon and pion were elementary

Like the electron and the photon

Nuclei were bound by a pion-exchange force

Like atoms were bound by a photon-exchange force

Today we know that hadrons are made of quarks which we believe are elementary

Hadrons are bound by a gluon exchange force.

The journey from nucleons and pions to quarks and gluons

First stage - there were too many hadrons

1. Gell-Mann and Ne'eman classified the nucleon and pion into SU(3) octets.
2. No reason for the number 3 in SU(3); No reason for octets
3. No reason why mesons and baryons should both be in octets
4. Mesons and baryons were very different, like electron and photon

The Ω^- convinced the consensus that symmetry made sense

Predicted by Glashow and Sakurai; Found at Brookhaven

A Historical Perspective

The conflict between “Grand Unification” and “Compositeness”

Each stage began with “known” fundamental constituents of matter or “elements”

Experimental discoveries of too many elements led to:

1. Unifying elements while still considered elementary,

Mendeleev Periodic Table; Symmetry classifications

2. Build from a smaller fundamental building blocks.

Bohr model of atom; Quark Model of hadrons

In 1950 N and π were considered fundamental constituents of hadronic matter.

1. Evidence for composite structure was resisted by the establishment
2. Attempts to unify all the new “elementary” particles as equally elementary
3. Concepts like nuclear democracy or higher symmetry.

Today - back to square one at a deeper level

Grand unification or compositeness explanations of too many elementary objects

Moved from nucleon-pion level to quark-gluon level.

The Meson Octet

K^o————K^+

π^-————π^o, η————π^+

K^-————$\bar{K}^o$

The Baryon Octet

$$\begin{tikzcd} n \arrow[r, dash] & p \end{tikzcd}$$

$$\begin{tikzcd} \Sigma^- \arrow[r, dash] & \Sigma^o, \Lambda \arrow[r, dash] & \Sigma^+ \end{tikzcd}$$

$$\begin{tikzcd} \Xi^- \arrow[r, dash] & \Xi^o \end{tikzcd}$$

Second stage - From hadrons to quarks

Search for symmetry to connect meson and baryon octets

1. Barbaryons $SU(3) \times SU(3)$ supersymmetry?
2. Fundamental triplets Goldberg-Ne'eman; Gell-Mann-Zweig

Absence of Exotics - An Early Clue to QCD

No K^+N resonances found! Called the "Goldhaber Gap"

The Goldhaber Gap - killed Barbaryons - led Gell-Mann to quarks

Quark model led to understanding hadron structure

Basis of QCD - But no relation between mesons and baryons

Third stage - November revolution and heavy quarks

Charmonium, the hydrogen atom of particle physics

Flavor dependence of relation between mesons and baryons not understood

Fourth Stage - Present challenge to QCD

How does QCD make hadrons from quarks and gluons

Constituent quark model - QCD phenomenology - now with five flavors

1. Nuclear physics aproach - same n,p in H, He, U
2. Same constituent (u,d,s) in N, π, ρ, Δ, Λ, Σ, Σ^*,etc

Barbaryon Supersymmetry

$$\begin{tikzcd}B\downarrow \arrow[r, dash] & B\uparrow\end{tikzcd}$$

$$\begin{tikzcd}V\downarrow \arrow[r, dash] & V_o, P \arrow[r, dash] & V\uparrow\end{tikzcd}$$

$$\begin{tikzcd}\bar{B}\downarrow \arrow[r, dash] & \bar{B}\uparrow\end{tikzcd}$$

STATIC HADRON PROPERTIES WITH QUARKS

\- **The Very Early Successes**

1. Difference between the quark structures of the meson and baryon octets
2. Explained striking regularities beyond SU(3) in low-lying hadron spectrum
3. Baryon octets and decuplets; meson nonets and no meson decuplets
4. No ninth baryon suggested by some SU(3) models
5. Spin-parity quantum numbers $J^P = 0^-,\ 1^-, 1/2^+,\ 3/2^+$.

Introduce U(3) rather than SU(3); Break SU(3) at the quark level

Setting $m_s > m_u$ immediately gave experimentally observed mass inequalities

$M_\Xi > M_\Sigma \approx M_\Lambda > M_N; \quad M_\eta > M_{K^+} \approx M_{K^-} > M_\pi$

Not bad baryon mass inequality from assuming same baryon and meson octets

$M_\Lambda > M_N \approx M_\Xi > M_\Sigma$

Many open questions remained

1. **Spin and statistics**
2. **Reason for decuplet classification for the spin-3/2 baryons**
3. **Reason for the $\Lambda - \Sigma$ mass difference**
4. **Were next excited states orbital excitations or more $\bar{q}q$ pairs**

HADRON REACTIONS IN THE QUARK MODEL

Further evidence for a quark structure of hadrons

1. **The additive quark model for hadron reactions**
2. **The so-called ideal mixing pattern of vector and tensor mesons,**
3. **Mysterious topological quark diagram selection rule now called OZI**
4. **Peculiar systematics in energy behavior of certain hadron σ_{tot}.**

The Additive Quark Model, Duality, etc.

The simple additive quark model (AQM) of Levin and Frankfurt

Explained the ratio of 3/2 between $\sigma_{tot}(NN)$ and $\sigma_{tot}(\pi N)$

Showed mesons and baryons to be made of the same quarks.

Further refinements successfully described many other experiments.

σ_{tot} in exotic channels do not have sharply decreasing energy behavior

Described in the AQM by $\bar{q}q$ annihilation amplitudes

Combined in Regge picture with exchange degeneracy of trajectories.

$\bar{p}p$ Annihilation - First Evidence for Quarks

Pion multiplicity in $\bar{p}p$ annihilation experiments.

5.3 ± 0.4 **found; 2 or 3 predicted by statistical models,**

No $e^+ - e^-$ pairs seen at level predicted by QED.

Unacceptable heretical explanation -mesons and baryons composite

Made from same constituents carrying baryon number,

Rearrangement of 3q and 3$\bar{q}$ in $p\bar{p}$ into 3 mesons gave pion multiplicity 5.25.

Quark-rearrangement model ridiculed when proposed in 1966

Establishment prejudice against quarks created serious difficulties

For obtaining appointments and promotions for young people in our group.

Deans and committees influenced by letters from well-known physicists

Condemning people who rush into print with such quark garbage.

The universality of additive quark couplings to mesons and baryons

Arose again and again in different contexts.

S-matrix Regge approach beginning with finite-energy sum rules

The duality revolution and the Veneziano model

1. **Same states appear as s-channel resonances and t-channel exchanges**
2. **Dual resonance models beginning with the Veneziano model.**
3. **Quark-model constraints on Reggeon couplings**
4. **Provided powerful input with predictive power.**
5. **Absence of exotics as resonances and t-channel exchanges led to OZI**

Exchange degeneracy and $\bar{q}q$ annihilation dominance of of σ_{tot}

Led naturally to duality diagrams.

Energy constant part of cross section, later found to be slowly rising

Related to diffraction, described by Pomeron exchange

Coupling given by Levin-Frankfurt quark-counting recipe.

Neutral Meson Mixing and OZI

First use of the additive quark model to obtain OZI relations

Selection rule forbidding reactions like

$$\sigma(\pi^- p \to N\phi) = 0$$

and its SU(3) rotation predicting the equality

$$\sigma(K^- p \to \Lambda\omega) = \sigma(K^- p \to \Lambda\rho^o)$$

The ρ^o and ω mesons produced equally.only via their $u\bar{u}$ component

The Pre-History of QCD

Andrei Sakharov took quarks seriously in 1966.

“Λ and Σ made of same quarks. Why are masses different?”

Sakharov and Zeldovich *anticipated* **QCD**

Showed mesons and baryons made of same quarks.

Quark model - flavor dependent linear mass term

Two-body force - flavor-dependent hyperfine force

$$v_{ij} = v^{o}_{ij} + \vec{\sigma}_i \cdot \vec{\sigma}_j v^{hyp}_{ij}$$

Two surprising meson - baryon mass relations

$(m_s - m_u)_{Bar} = M_\Lambda - M_N = 177\,\mathrm{MeV}$

$$(m_s - m_u)_{Mes} = \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi)}{4} = 180\,\mathrm{MeV}$$

$$1.53 = \frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61$$

Nambu universal meson - baryon mass formula (1966)

Colored quarks and non-abelian SU(3) gauge field

Predicted only (qqq) and $(\bar{q}q)$; NO EXOTICS!

Surprising agreement with experiment.

Nambu solved the exotics problem in 1966!

Nambu's Theorem: Only lowest color singlets are stable

Color-exchange two-body potential

$V_{cx}(r_{ij}) = V \cdot \lambda_c^i \cdot \lambda_c^j \cdot v(r_{ij})$; $\vec{\lambda}_c$ **color SU(3) generator**

In lowest order neglecting color-space and color-spin correlations

For color singlet states having N quarks and antiquarks

$$\langle V_{cx}(tot)\rangle = \sum_{i\neq j} \frac{V\lambda_c^i \cdot \lambda_c^j}{2} \cdot \langle v(r)\rangle = \frac{V}{2} \cdot \left[\sum_i (\lambda_c^i)^2\right] \cdot \langle v(r)\rangle = \frac{NV}{2}(\lambda_c^i)^2 \cdot \langle v(r)\rangle$$

All color singlet states with N constituents

1. **Have same potential energy**
2. **Gain kinetic energy by breaking up into color singlets**

Nambu's Theorem Prediction: Only bound states are

Mesons made of $(q\bar{q})_1$ and baryons containing $(qq)_{\bar{3}}$ diquarks

Agrees with experiment and mass spectra

Nobel for QCD - Sakharov, Zeldovich and Nambu

Basis of QCD already published in 1966.

- **Lagrangian with right degrees of freedom**

Colored quarks and non-abelian SU(3) gauge field

- **Balmer formula, Bohr atom, Schroedinger equation**

Sakharov-Zeldovich (1966) Mesons and baryons made of same quarks

Mass formula - effective masses and hyperfine interaction

- **Mesons and baryons made of same quarks**

Nambu (1966) Non-Abelian gauge theory

- **Colored quarks and bosons - Mesons, baryons and no exotics**

WE knew quarks had the right physics already in 1966.

Surprising agreement with experiment must lead somewhere

Establishment refused to recognize new physics

- **None so blind as those who don't want to see.**
- **All subsequent developments - New fancy names**
- **Chromodynamics, color, confinement - no new physics**

Some Words of Wisdom from David Gross

Third Symposium on the History of Particle Physics at SLAC, June 1992.

“It was a pity that particle theorists at that time, for the most part,

totally ignored condensed matter physics.

There were of course notable exceptions, such as Nambu,

and the last of the true universalists, Landau....

This attitude was largely a product of arrogance. ..

Particle physicists thought that they had little to learn

From ‘squalid state physics’

This attitude was unfortunate.

We would have profited much from deeper study of superconductivity

The preeminent advance in condensed matter physics in this period.

Not only insight into broken gauge symmetry stressed by Philip Anderson

Clues to QCD from information in experimental data

Mesons and baryons are made of the same quarks.

Flavor SU(3) accidental; misses two additional flavors

Need to describe five flavor meson-baryon universality

Only the constituent quark model does this

What are constituent quarks - A BCS Approach

Learn from John Bardeen - Implications of BCS

Quarks are Quasiparticle degrees of freedom describing

Low-lying elementary excitations of hadronic matter.

In 1960 John Bardeen noted Nambu's interesting work

Applying superconductivity ideas to particle physics.

But particle physicists showed no interest in Nambu's work on symmetry breaking

BCS theory was not gauge invariant - so what?

Bardeen knew it had the right physics - didn't worry

Anderson explained it - found the Higgs mechanism

Particle physicists don't recognize Anderson found Higgs

An underlying dynamics describes many meson and baryon properties

Primarily in terms of constituent quarks same in mesons and baryons.

$$\langle m_s - m_u \rangle_{Bar} = M_\Lambda - M_N = 177\,\mathrm{MeV} =$$

$$= \frac{M_N + M_\Delta}{6} \cdot \left(\frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} - 1 \right) = 190\,\mathrm{MeV}.$$

$$\langle m_s - m_u \rangle_{mes} = \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi}{4} = 180\,\mathrm{MeV} =$$

$$= \frac{3M_\rho + M_\pi}{8} \cdot \left(\frac{M_\rho - M_\pi}{M_{K^*} - M_K} - 1 \right) = 178\,\mathrm{MeV}.$$

Mass difference $m_s - m_u$ **has the same value** $\pm 3\%$ **from baryon and meson masses.**

Same approach gives

$\langle m_b - m_c \rangle_{Bar} = M(\Lambda_b) - M(\Lambda_c) = 3356\,\mathrm{MeV},$

$\langle m_b - m_c \rangle_{mes} = \frac{3(M_{B^*} - M_{D^*}) + M_B - M_D}{4} = 3338\,\mathrm{MeV}.$

Ratio $\frac{m_s}{m_u}$ - same value ±2.5% for mesons and baryons.

$$\left(\frac{m_s}{m_u}\right)_{Bar} = \frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = 1.53 = \left(\frac{m_s}{m_u}\right)_{Mes} = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61$$

Three magnetic moments - no free parameters

$$\mu_\Lambda = -0.61\,\text{n.m.} = -\frac{\mu_p}{3} \cdot \frac{m_u}{m_s} = -\frac{\mu_p}{3} \frac{M_{\Sigma^*} - M_\Sigma}{M_\Delta - M_N} = -0.61\,\text{n.m.}$$

$$-1.46 = \frac{\mu_p}{\mu_n} = -\frac{3}{2}$$

$$\mu_p + \mu_n = 0.88\,\text{n.m.} = \frac{M_p}{3m_u} = \frac{2M_p}{M_N + M_\Delta} = 0.865\,\text{n.m.}$$

Nobody knows how to connect QCD with experiment

How does QCD make hadrons from quarks and gluons?

DOES QCD make hadrons from quarks and gluons?

Do we need more than the standard model?

Do we need another symmetry or supersymmetry?

Clues from the hadron spectrum

Mesons and Baryons are made of same quarks!

Simple meson - baryon transformation (KL 2006)

$M(\bar{q}Q_i) \leftrightarrow B([qq]_S Q_i)$

q **denotes light** u **or** d **quark,** Q_i **any quark of flavor** i

$[qq]_S$ **- two light quarks coupled to total spin** S**.**

Light color-$\bar{3}$ antiquark goes into light color-$\bar{3}$ diquark

Surprising Experimental Result!

Mass change independent of quark flavor i

For all four flavors (u, s, c, b)

When hyperfine interaction energy of Q_i **is removed**

Simple Experimental Tests

For any two quark flavors i and j,

Remove hyperfine energy of Q_i in vectors $|V_i(Q_i\bar{q})\rangle$ and pseudoscalars $|P_i(Q_i\bar{q})\rangle$

$$\tilde{M}(V_i) \equiv \tfrac{3M(V_i)+M(P_i)}{4}$$

Removing hyperfine in baryons with spin-one diquarks gives

$$\tilde{M}(\Sigma_i) \equiv \tfrac{2M_{\Sigma_i^*}+M_{\Sigma_i}}{3}; \quad \tilde{M}(\Delta) \equiv \tfrac{2M_\Delta+M_N}{3}$$

Relations for Baryon-Meson Mass Differences

$$\tilde{M}(B_i) - \tilde{M}(V_i) = \tilde{M}(B_j) - \tilde{M}(V_j)$$

For baryons with spin-zero diquarks and mesons,

$$M(N) - \tilde{M}(\rho) = M(\Lambda) - \tilde{M}(K^*) = M(\Lambda_c) - \tilde{M}(D^*) = = M(\Lambda_b) - \tilde{M}(B^*)$$

$$326 \text{ MeV} = 323 \text{ MeV} = 312 \text{ MeV} = 310 \text{ MeV}$$

For baryons with spin-one diquarks and mesons,

$$\tilde{M}(\Delta) - \tilde{M}(\rho) = \tilde{M}(\Sigma) - \tilde{M}(K^*) = \tilde{M}(\Sigma_c) - \tilde{M}(D^*) = \tilde{M}(\Sigma_b) - \tilde{M}(B^*)$$

$$517 \text{ MeV} = 512 \text{ MeV} = 524 \text{ MeV} = 512 \text{ MeV}$$

Relating Baryon and Meson Hyperfine splittings

For mesons and baryons related by

$M(\bar{q}Q_i) \leftrightarrow B([qq]_S Q_i)$

Equal ratios of $\bar{q}Q$ $[qq]Q$ hyperfine splittings for two different quark flavors

$$\frac{V_{hyp}(Q_i[qq]))]}{V_{hyp}(Q_j[qq])} = \frac{V_{hyp}(Q_i\bar{q}))]}{V_{hyp}(Q_j\bar{q})}$$

$$\frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = 1.53 = \frac{V(qqd)}{V(qqs)} \approx \frac{V(\bar{q}d)}{V(\bar{q}s)} = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61$$

$$\frac{M_{\Sigma^*} - M_\Sigma}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 2.84 = \frac{V(qqs)}{V(qqc)} \approx \frac{V(\bar{q}s)}{V(\bar{q}c)} = \frac{M_{K^*} - M_K}{M_{D^*} - M_D} = 2.81$$

$$\frac{M_\Delta - M_p}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 4.36 = \frac{V(qqd)}{V(qqc)} \approx \frac{V(\bar{q}d)}{V(\bar{q}c)} = \frac{M_\rho - M_\pi}{M_{D^*} - M_D} = 4.46$$

$$\frac{M_\Sigma^* - M_\Sigma}{M_{\Sigma_b^*} - M_{\Sigma b}} = 9.1 = \frac{V(qqb)}{V(qqs)} \approx \frac{V(\bar{q}b)}{V(\bar{q}s)} = \frac{M_{K^*} - M_K}{M_{B^*} - M_B} = 8.7$$

New four-flavor type of meson - baryon mass relation

Relates ratios of $V_{hyp}(ud)$, $V_{hyp}(us)$and $V_{hyp}(uc)$ or $V_{hyp}(ub)$ in mesons and baryons,

$\Sigma - \Lambda$ mass difference due to difference between $V_{hyp}(ud)$ and $V_{hyp}(us)$

$\Sigma_c - \Lambda_c$ mass difference due to difference between $V_{hyp}(ud)$ and $V_{hyp}(uc)$

$$\frac{M_{\Sigma_c} - M_{\Lambda c}}{M_\Sigma - M_\Lambda} = 2.2 = \frac{(M_\rho - M_\pi) - (M_{D^*} - M_D)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.1$$

The meson and baryon relations agree to $\pm 2.5\%$.

A similar relation for Λ_b and then yet unmeasured Σ_b

$$\frac{M_{\Sigma_b} - M_{\Lambda b}}{M_\Sigma - M_\Lambda} = \frac{(M_\rho - M_\pi) - (M_{B^*} - M_B)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.51$$

Predictions $M_{\Sigma_b} = 5814\,\mathrm{MeV}$ and $M_{\Sigma_b} - M_{\Lambda b} = 194\,\mathrm{MeV}$

Confirmed by the experimental values,

5808 MeV and 5816 MeV of newly discovered Σ_b^+ and Σ_b^-