

Quark model of baryons: History and Developments

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Early history

- Strangeness discovered
 - K , L'Argentière, 1943, Leprince-Ringuet et al.
 - K , Λ , Pic du Midi, 1947, Rochester and Butler,
 - Λ , balloon, Hopper and Biswas (Melbourne),
 - etc.
- Strangeness introduced as a new quantum number
- Generalized isospin, **SU(3)**, rather successful,
- In particular, **equal-spacing rule** of spin 3/2 family

$$\delta = \Sigma^* - \Delta \simeq \Xi^* - \Sigma^*$$

- Prediction of the $S = -3$ member Ω^- with mass $m(\Xi^*) + \delta$
- **$\Omega^-(1672)$** discovered by N. Samios et al. at Brookhaven in 1964 with the right mass

History: quarks

- Flavor SU(3) with (p, n, Λ) as basic triplet **does not work**
- Flavor SU(3) with **Eightfold Way**
 $(p, n, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-) = \mathbf{8}$ -rep.
- Flavor SU(3) led to **quarks**, u , d and s in the modern notation
- Quarks = 3 representation, antiquarks = $\bar{3}$
- Mesons = $q\bar{q}$, baryons = qqq ,
- Somewhat paradoxically, **baryons studied first**
- Quark model of mesons really developed after the discovery of charmonium

The pioneers

A circular arrangement of names, likely representing a global or multicultural theme. The names are written in a serif font and follow the curve of a circle. Starting from the top and moving clockwise, the names are: Greenberg Dalitz Thirring, Sartor Stancu, Gromes Stamatescu, Richard Taxil Stanley Robson Lee Gaillard Rosner Lipkin Lieb Nussimov, Martin Høegasssen Dmitrasinović, Metesch Santopinto Moering, Petry Lucha Schöberl Kuti Hazenfratz Andreev Semay Silvestre-Brac Gignoux Aerts Heller ...

The harmonic oscillator model

- Greenberg (1964) problem of statistics
- **Dalitz** et al. HO and many corrections and developments
- Many other contributions: Hey, Faiman, Sartor et al., Gromes et al., etc.,
- **Isgur & Karl** made it very popular and stressed the link to QCD
- Many others
- HO based on the simple decomposition

$$\frac{p_1^2 + p_2^2 + p_3^2}{2m} + K(r_{12}^2 + r_{23}^2 + r_{31}^2) = \left[\frac{p_\rho^2}{m} + \frac{3}{2} K \rho^2 \right] + \left[\frac{p_\lambda^2}{m} + \frac{3}{2} K \lambda^2 \right] + \text{cm}$$

- Easily generalized as

$$\frac{p_1^2 + p_2^2}{2m} + \frac{p_3^2}{2M} + K(r_{12}^2 + \dots) = \left[\frac{p_\rho^2}{m} + \frac{3}{2} K \rho^2 \right] + \left[\frac{p_\lambda^2}{\mu} + \frac{3}{2} K \lambda^2 \right] + \text{cm}$$

HO: solution

$$\frac{p_1^2 + p_2^2}{2m} + \frac{p_3^2}{2M} + K(r_{12}^2 + \dots) = \left[\frac{p_\rho^2}{m} + \frac{3}{2} K \rho^2 \right] + \left[\frac{p_\lambda^2}{\mu} + \frac{3}{2} K \lambda^2 \right] + \text{cm}$$

- gives

$$E = \frac{3K}{2m}(3 + \ell_\rho + 2n_\rho) + \frac{3K}{2\mu}(3 + \ell_\lambda + 2n_\lambda),$$

- recoupling of ℓ_ρ and ℓ_λ
- remarkable degeneracies

-

$$\rho = r_2 - r_1, \quad \lambda = \frac{2r_3 - r_1 - r_2}{\sqrt{3}}, \quad \frac{1}{\mu} = \frac{2}{3M} + \frac{1}{3m}.$$

- inspiring the notation “ ρ ” excitation and “ λ ” excitation that is still used today.
- Good picture of the states already identified in the 60s and 70s

HO: a flurry of corrections

- Abundant literature
- Dalitz et al., Hey et al., Isgur and Karl, Gromes, ...
- Corrections usually treated at 1st order though large
- Central anharmonicity, e.g., $K r^2 \rightarrow \lambda r$, with $\lambda r - K r^2$ at 1st order
- Spin-spin $\propto \sigma_i \cdot \sigma_j / (m_i m_j)$ stressed by De Rujula et al., IK, ...
- In particular solve long-standing $\Sigma > \Lambda$ puzzle (Le Yaouanc et al.)
- Tensor force also gives some effects (IK, Taxil et al.)
- Spin-orbit force puzzling, see, e.g., Close, ...

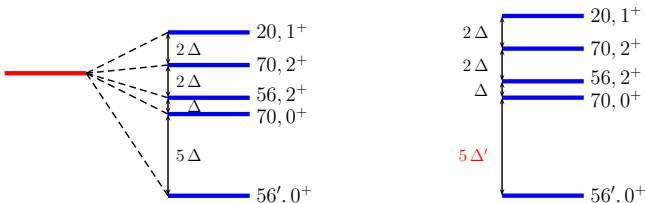
QM of three confined quarks

- Beyond first order?
- Solve the **3-quark problem** exactly in a given model?
 - **Faddeev equations** (Gignoux et al.)
 - **Hyperspherical expansion** (Giumaraes et al., Taxil et al., Santopinto, ...)
 - More and more: variational methods, in particular **Gaussian expansion**,

$$\Psi = \sum_i \gamma_i \mathcal{Y}(\hat{\rho}, \hat{\lambda}) \exp(-(a_i \rho^2 + b_i \lambda^2 + 2 c_i \rho \cdot \lambda)/2) .$$

- Variants by Hiyama et al., Varga et al., ...
- **Expansion into HO basis** $\pm$ abandoned

Roper resonance-2



- Left: splitting of the HO level $N = 2$ due to anharmonic corrections.
Right: modified splitting pattern in case of three-body forces or a more general hypercentral interaction as starting point.
- Similar studies made for $N \geq 3$
- Generalization to $V(R) + \sum v(r_{ij})$ (nearly hypercentral) where R is the hyperradius $R^2 = \rho^2 + \lambda^2 \propto r_{12}^2 + r_{23}^2 + r_{31}^2$.

Roper resonance-3

- Non perturbative study within the hyperspherical formalism (Høgaasen et al.)
- The same theorem that makes $(\ell = 0) < (\ell = 1) < (\ell = 0)^*$ for mesons makes

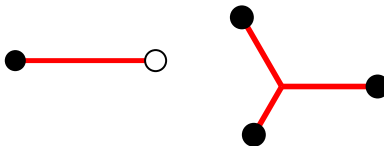
$$(0^+) < (1^-) < (0^+)^*$$

for three identical confined constituents in a symmetric, local potential, pairwise or with 3-body terms.

- Hence, to match the Roper resonance, something else needed
 - spin-dependence from the beginning
 - non-locality
 - coupling to real or virtual decay channels, ...

Three-body confinement

- 3-body forces considered from the beginning as an option
- For instance, Gromes et al. for the splitting of $N = 2$
- Also **hadronic string** (Artru, Iizuka, Dosch & Muller, Hazenfratz ...). Supported by lattice (e.g., Takahashi et al.)



$$V(Q\bar{Q}) = \lambda r, \quad V(QQQ) = \lambda \min_j (JA + JB + JC).$$

- Requires Fermat-Torricelli term in the 3-body calculation (Steiner trees methods, Melzak's trick, ..)
- **Baryon phenomenology with Y-shape confinement**
vs. (Δ shape) $\sum r_{ij}$ does **not** make dramatic changes, so far,
- But it matters for the extension to multiquarks.

Diquarks

- Debated from the very beginning
- Problem of **missing states**
- Search for **simplified dynamics**
- Avoid the 3-body problem?
- Note: **good** diquarks and **bad** diquarks (Jaffe, Wilczek, ...) fine as a handy notation for chromomagnetic effects, although the strength of chromagnetic effects depends on the surrounding (Lipkin)

Diquarks: missing states?

- At the beginning, HO and similar → **too many** states
- Isgur, . . . : the **ρ -excitations** hardly produced by pion or γ beams
- Latest experimental survey (e.g., Burkert, Eichmann and Klempt): the quark-diquark model does not produce enough states
- Hence one seemingly needs **both** ρ and λ degrees of freedom

Diquarks for high-spin states?

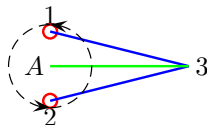
- Eguchi (1975) and many others
- Same slope for meson and baryon **Regge trajectories** (M^2 vs. J)
- Comes automatically if one **assumes** quark-diquark
- **Demonstrated** by Martin (1986) for R and NR quark models:
 - at low J symmetric rotation
 - at high J : $\ell = 0$ for a pair, and $\ell = J$ for the third quark

Quark-diquark as an approximation for the ground-state ?

- Often used blindly to avoid the 3-body problem
- Q.: Is quark-diquark a **good approximation** of a standard quark model?
- The antivariational character is often overlooked.

$$2 \langle V_A \rangle < \langle V_1 + V_2 \rangle$$

(average over a sph. distribution of #1, #2)



- For HO $\sum r_{ij}^2 \Rightarrow 3/2 \rho^2$ (exact) vs. $1 \rho^2$ (naive diquark)¹
- (For Coulomb $< \rightarrow =$, for sharper $< \rightarrow >$)
- Naive diquark approximation even more misleading in the multiquark sector

¹Note the correction is in the ρ sector

Baryons with one heavy quark

- **Charmed baryons** nicely anticipated by Gaillard, Lee and Rosner, just after the prediction of the c quark by GIM
- Several detailed studies in quark model,
- For instance, how $\Sigma_Q - \Lambda_Q$ and $\Sigma_Q^* - \Sigma_Q$ evolve
- Recent review of heavy baryons: Chen et al, 2608.20892 [hep-ph]
- As an example of reliability of quark model:
 Ω_b (bss) first found by DØ at about 6.150 GeV,
 nearly 100 MeV higher than predicted.
 Another Fermilab team, and later LHCb confirmed the quark model prediction

Baryons with two heavy quarks

- More interesting for the internal dynamics
- Analogs of H_2^+ in atomic physics
- First experimental claim by SELEX at Fermilab not confirmed
- More solid evidence from LHCb at CERN
- Diquark-quark QQq approxⁿ not too bad, but not very useful
- First excitations inside $QQ \rightarrow$ new diquark for each level
- **Born-Oppenheimer** works very well (Fleck et al.) and allows for interesting extensions (Braaten et al., Brambilla et al.) to **exotics**
- Warning: Naive BO: $E(q)$ for fixed $\mathbf{r}_1$ and $\mathbf{r}_2$
Improved BO : remove c.m. and calculate $E(q)$ for fixed r_{12}

Baryons with three heavy quarks

- QQQ named by Bjorken: *The ultimate goal of baryon spectroscopy*
- Probe the **genuine NR quark dynamics**
- For instance: radial excitation vs. orbital excitation?
- Triply-heavy analog of Roper's resonance!
- Early estimates by Hasenfratz et al. (CERN) and Heller et al. (Los Alamos) with $V(QQQ)$ calculated from variants of the bag model
- Now superseded by Lattice and elaborated quark models

Outlook

- The quark model of baryons has played a crucial role to assess the concept of **interacting quarks** inside hadrons, eventually leading to QCD.
- Though supplanted by more advanced methods such as lattice QCD and QCD sum rules, and challenged by other approaches, it remains a **guide** for
 - The classification of baryon resonances,
 - The advanced 3-body problem in the confining regime,
 - A starting point for exploring exotic multiquarks.
- Quark model will stand as a **remarkable undertaking**, carried out by a group of exceptionally talented people whom I have had the privilege of meeting, most of them.

Extra slides

From meson to baryons

- Nagging and persistent question
- Link between the $v(q\bar{q})$ of mesons and $V(qqq)$ of baryons
- Stanley & Robson, Lipkin, Nussinov, Martin & R., and many others
- If V is pairwise, $V = \sum v(qq)$, what is the relation between $v(qq)$ and $v(q\bar{q})$
- Similar to isovector and isoscalar forces in nuclear physics
- v is either color-singlet exchange or color-octet exchange or combination
- Color singlet exch. cannot confine, otherwise everything would be confined!
- Simplest solution: color-octet exchange giving

$$V = \frac{1}{2} \sum_{i < j} v_{q\bar{q}}(r_{ij})$$

- Tentatively generalized as $V \propto \sum_{i < j} \tilde{\lambda}_i \cdot \tilde{\lambda}_j v(r_{ij})$ for multiquarks

Y-shape interaction

Melzak's trick

$$JA + JB + JC = AA' = BB' = CC'$$

