

The Discovery of Color

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Outline

- I Discovery of hidden color charge
- II Response of community
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- IV Introduction of gauged $SU(3)$ color
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I Discovery of hidden color charge

1964

- Crucial year for the discovery of quarks and color.

Introduction of quarks

- Gell-Mann—"quarks"—current quarks.
- Zweig—"aces"—constituent quarks.
- Why only qqq and $q-q\bar{q}$?
- No reason in the original models.

Background, Princeton, Fall 1964

- Relativistic $SU(6)$, Gurnsey and Radicati
- Generalization of Wigner's nonrelativistic nuclear physics idea to combine $SU(2)_I$ with $SU(2)_S$ to get an $SU(4)$ to classify nuclear states.
- Gurnsey and Radicati combined $SU(3)_f$ with $SU(2)_S$ to get an $SU(6)$ to classify particle states.

SU(6) classifications

$$q \sim (u, d, s), \text{ in } SU(3)_f$$

$$(1/2) \sim (\uparrow, \downarrow)$$

$$\mathbf{6} = (q, 1/2) \sim (u_\uparrow, u_\downarrow, d_\uparrow, d_\downarrow, s_\uparrow, s_\downarrow) \text{ in } SU(6)_{fS}$$

$$SU(6)_{fS} \rightarrow SU(3)_f \times SU(2)_S = (u, d, s,) \times (\uparrow, \downarrow)$$

Mesons

$$6 \otimes 6^* = 1 + 35$$

$$35 \rightarrow (8, 0) + (1 + 8, 1)$$

$$(K^+, K^0, \pi^+, \pi^0, \pi^-, \eta^0, \bar{K}^0, \bar{K}^-)$$

$$(K^{*+}, K^{*0}, \phi^0, \rho^+, \rho^0, \rho^-, \omega^0, \bar{K}^{*0}, \bar{K}^{*-})$$

Baryons

$$6 \otimes 6 \otimes 6 = 56 + 70 + 70 + 20$$

$$56 \rightarrow (8, 1/2) + (10, 3/2)$$

$$(p^+, n^0, \Lambda^0, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-)$$

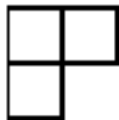
$$(\Delta^{++}, \Delta^+, \Delta^0, \Delta^-, Y_1^{*+}, Y_1^{*0}, Y_1^{*-}, \Xi^{*0}, \Xi^{*-}, \Omega^-)$$

Statistics paradox

- 56



- 70



- 20



Magnetic moment ratio

- Beg, Lee, and Pais μ_p/μ_n

$$|p_{\uparrow}^+\rangle = \frac{1}{\sqrt{3}}u_{\uparrow}^{\dagger}(u_{\uparrow}^{\dagger}d_{\downarrow}^{\dagger} - u_{\downarrow}^{\dagger}d_{\uparrow}^{\dagger})|0\rangle$$

$$|n_{\uparrow}^0\rangle = \frac{1}{\sqrt{3}}d_{\uparrow}^{\dagger}(u_{\uparrow}^{\dagger}d_{\downarrow}^{\dagger} - u_{\downarrow}^{\dagger}d_{\uparrow}^{\dagger})|0\rangle$$

$$\mu_B = \langle B_{\uparrow}|\mu_3|B_{\uparrow}\rangle$$

$$\mu_3 = 2\mu_0 \sum_q Q_q S_q, \quad Q_q = \left(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}\right)$$

$$\mu_p = 2\mu_0 \cdot \frac{1}{3} \left\{ 2 \left[\frac{2}{3} \cdot 1 + \left(-\frac{1}{3}\right) \cdot \left(-\frac{1}{2}\right) \right] + \left[\left(-\frac{1}{3}\right) \cdot \frac{1}{2} \right] \right\} = \mu_0$$

$$\mu_n = -\frac{2}{3}\mu_0 \qquad m_N/2.79 = 336 MeV$$

Previous calculations of magnetic moments

- Complicated calculations using pion clouds failed.
- Nobody even realized that the ratio was so simple.

Significance of the magnetic moment calculation

- A simple one-line calculation gave the ratio accurate to 3%.
- Very convincing additional argument for the quark model.
- Quarks have concrete reality.

The spin-statistics theorem

- Particles that have integer spin must obey Bose statistics
- Particles that have odd-half-integer spin must obey Fermi statistics.

Generalized spin-statistics theorem

- Not part of general knowledge:
- Particles that have integer spin must obey parabose statistics and particles that have odd-half-integer spin must obey parafermi statistics.
- Each family is labeled by an integer p ; $p=1$ is ordinary Bose or Fermi statistics.

Parafermi quark model, 1964

- Suggested a model in which quarks carry order-3 parafermi statistics.
- This allows up to three quarks in the same space-spin-flavor state without violating the Pauli principle, so the statistics paradox is resolved.
- This leads to a model for baryons that is now accepted.

Resolution of the statistics paradox

- Exhilarated—resolving the statistics problem seemed of lasting value.
- Not interested in higher relativistic groups; from O’Raifeartaigh’s and my own work I knew that combining internal and spacetime symmetries is difficult or impossible..

Baryon spectroscopy

- Hidden parafermi (color) degree of freedom takes care of the required antisymmetry of the Pauli principle.
- Quarks can be treated as Bosons in the visible space, spin and flavor degrees of freedom.

Table of excited baryons

- Developed a simple bound state model with s and p state quarks in the 56, $L=0$ and 70, $L=1$ supermultiplets.

Table II. Low-lying states in paraquark model of baryons.^a

Orbitals configuration	L	Parity	Young diagram	(SU(3), J) decomposition	Total multiplicity	Total no. of I multiplets
s^3 (pure)	0	+	(3)	$(\underline{8}, J = 1/2)$ $(\underline{10}, J = 3/2)$	56	8
$s^2 p^1$ (spurious)	1	-	(3)	$(\underline{8}, J = 1/2, 3/2)$ $(\underline{10}, J = 1/2, 3/2, 5/2)$	168	20
$s^2 p^1$ (pure)	1	-	(2, 1)	$(\underline{1}, J = 1/2, 3/2)$ $(\underline{8}, J = 1/2, 3/2, 5/2)$ $(\underline{10}, J = 1/2, 3/2)$ $(\underline{8}, J = 1/2, 3/2)$	210	30
$s^1 p^2, s^2 d^1$ (mixed)	2	+	(3)	$(\underline{8}, J = 3/2, 5/2)$ $(\underline{10}, J = 1/2, 3/2, 5/2, 7/2)$	280	24
$s^1 p^2, s^2 d^1$ (mixed)	2	+	(2, 1)	$(\underline{1}, J = 3/2, 5/2)$ $(\underline{8}, J = 1/2, 3/2, 5/2, 7/2)$ $(\underline{10}, J = 3/2, 5/2)$ $(\underline{8}, J = 3/2, 5/2)$	350	34
$s^1 p^2, s^2 d^1$ (mixed)	1	+	(2, 1)	$(\underline{1}, J = 1/2, 3/2)$ $(\underline{8}, J = 1/2, 3/2, 5/2)$ $(\underline{10}, J = 1/2, 3/2)$ $(\underline{8}, J = 1/2, 3/2)$	210	30
$s^1 p^2$ (pure)	1	+	(1, 1, 1)	$(\underline{8}, J = 1/2, 3/2)$ $(\underline{1}, J = 1/2, 3/2, 5/2)$	60	11
$s^1 p^2, s^2 d^1$ (mixed)	0	+	(3)	$(\underline{8}, J = 1/2)$ $(\underline{10}, J = 3/2)$	56	8
$s^1 p^2, s^2 d^1$ (mixed)	0	+	(2, 1)	$(\underline{1}, J = 1/2)$ $(\underline{8}, J = 3/2)$ $(\underline{10}, J = 1/2)$ $(\underline{8}, J = 1/2)$	70	13
$p^3, s^1 p^1 d^1, s^2 f^1$ (mixed)	3	-	(3)	$(\underline{8}, J = 5/2, 7/2)$ $(\underline{10}, J = 3/2, 5/2, 7/2, 9/2)$	392	24

Later developments of baryon spectroscopy

- OWG, Resnikoff
- Dalitz, and collaborators
- Isgur and Karl
- Riska and collaborators

II Response of community

Initial skepticism about PT

- The response to the suggestion of a hidden degree of freedom carried by unseen quarks with fractional charge was similar to the initial skepticism about Carl's PT symmetry as an alternative to hermiticity.

How did the physics community react?

- J. Robert Oppenheimer
- Steven Weinberg

Gave Oppenheimer a preprint in Princeton

- Met him at a conference in Maryland
- *“Greenberg, it’s beautiful!”*

Oppenheimer's response, (continued)

- *“but I don’t believe a word of it.”*

Weinberg, "The making of the standard model"

- *"At that time I did not have any faith in the existence of quarks." (1967)*

Sources of skepticism

- Quarks had just been suggested.
- Fractional electric charges had never been seen.
- Gell-Mann himself was ambiguous.

Gell-Mann's comments

- *"It is fun to speculate ...if they were physical particles of finite mass (instead of purely mathematical entities as they would be in the limit of infinite mass)....A search ... would help to reassure us of the non-existence of real quarks."*

Skepticism, continued

- Assuming a hidden degree of freedom on top of the fractionally charged unseen quarks seemed to stretch credibility to the breaking point.
- Some felt that parastatistics was inconsistent.

III Other attempts to resolve paradox

Attempts to make a higher-dimensional relativistic theory

- $U(6,6)$
- $U(12)$
- $GL(12, \mathbb{C})$
- Pais, Salam, et al, Freund, et al.
- Pais, Rev. Mod. Physics 38, 215 (1966).

No-go theorems

- Later work of Coleman and Mandula and of Haag, Lopuszanski and Sohnius showed that the only way to combine internal and spacetime symmetries in a larger group is supersymmetry.

Attempt to avoid a new degree of freedom

- Dalitz preferred a complicated ground state that would avoid the statistics problem.
- As rapporteur Dalitz always put a model with Fermi quarks first.
- The first rapporteur who preferred the parastatistics model was Harari, Vienna, 1968.

Arguments for a simple ground state

- General theorems lead to an s-wave ground state.
- The simplest antisymmetric polynomial in the quark coordinates is

$$(x_1^2 - x_2^2)(x_2^2 - x_3^2)(x_3^2 - x_1^2)$$

Arguments for a simple ground state (continued)

Then not clear what to choose for excited states.

- The polynomial $\mathbf{x}_1 \times \mathbf{x}_2 \cdot \mathbf{x}_3$

vanishes because the coordinates are linearly dependent.

Adding $q\bar{q}$ pairs leads to unseen “exploding SU(3) states” that are not seen.

Arguments for a simple ground state (continued)

- Zeroes in the ground state wave function would lead to
 - zeroes in the proton electric and magnetic form factors, which are not seen.

Other models

- Baryonettes, in which 9 objects (baryonettes) compose a hadron.
- Many other models.

If quarks are not “real?”

- If quarks are just mathematical constructs, then their statistics is irrelevant.

IV Introduction of gauged $SU(3)$ color

Nambu; Han-Nambu

- Explicit color $SU(3)$ —
Nambu, Han-Nambu, 1965;
- Used three dissimilar triplets in order to have integer charges.
- *“Introduce now eight gauge vector fields which behave as $(1,8)$, namely as an octet in $SU(3)$ ”.*

Nambu's paper in Weisskopf festschrift

- In Preludes in Theoretical Physics,
(North Holland, 1966).
- Discussed mass formula based on octet
gluon exchange.
- Very overlooked paper

Color & electromagnetism commute

- Identical fractional electric charges allow color & electromagnetism to commute.
- Allows color to be an exact, unbroken, symmetry.
- Crucial part of understanding of quantum chromodynamics, QCD.

v The period of dormancy

Saturation

- Why are hadrons made from just two combinations,

qqq and $q\bar{q}$

Work with Zwanziger, 1966

- Surveyed existing models, constructed new models to account for saturation.
- Only models that worked were parafermi model, order 3, and equivalent 3-triplet or color $SU(3)$ models.

Equivalence as classification symmetry

States that are bosons or fermions in
parafermi model, order 3,
are in

1-to-1 correspondence with states that are
color singlets in $SU(3)$ color model.

Gradual diffusion of ideas

Greenberg, Zwanziger, 1966
parastatistics for bosons and fermions
equivalent to color

Bjorken, scaling prediction, 1966, 1968

Feynman, parton model, 1969

Callan, Gross, spin of partons is $\frac{1}{2}$, 1968

Anomaly; electroproduction

- Adler, Bell-Jackiw, π^0 decay, 1969
- Cabibbo, Parisi, Testa,
 $e^+ e^-$ to hadrons, 1970

Relations and differences between the models

$$\pi^0 \rightarrow \gamma\gamma$$

$$\sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$$

't Hooft Wilson

- Quantization of gauge theory, 't Hooft, 1967
- Renormalization group, Wilson, 1971

Conflicting issues

- Quarks, fiction, mathematical, confined, or real?
- Quark charges, integral or fractional?

Quark statistics, fermi, para, explicit color?

- Gluons, singlets or octets?

Evidence for color

- 1964, O.W. Greenberg, baryon spectra
- 1969, S. Adler, J. Bell & R. Jackiw explained π to 2 gamma decay rate.
- From 1964 to 1969 baryon spectroscopy was the only experimental evidence for color.

VI The discovery of asymptotic freedom and the writing of the QCD Lagrangian

Asymptotic freedom

D. Gross and, F. Wilczek

Phys. Rev. Lett. 30, 1343 (1973).

H.D. Politzer

Phys. Rev. Lett. 30, 1346 (1973).

Both write the QCD Lagrangian.

Reconciles quasi-free quarks of parton model with confined quarks of low-energy hadrons

Advantages of the color octet

- H. Fritzsch, M. Gell-Mann and H. Leutwyler
Phys. Lett. 47B, 365 (1973).

Very influential paper.

Properties that require gauge theory

- Confinement
- S. Weinberg, 1973
- D.J. Gross and F. Wilczek, 1973
- H. Fritzsch, M. Gell-Mann and H. Leutwyler, 1973

Properties that require gauge theory (continued)

- Asymptotic freedom,
Gross, Wilczek, 1973
Politzer, 1973
- Reconciles quasi-free quarks of the parton model with confined quarks of low-energy hadrons

Properties that require gauge theory (continued)

- Running of coupling constants and precision tests of QCD.
- Jets in high-energy collisions.

VII Summary

Two facets of strong interaction

1 Color as classification symmetry & global quantum number

- parafermi model (1964)
- was first introduction of color as global quantum number.

Two facets of strong interaction

2 $SU(3)$ color as local gauge theory

- Han-Nambu model (1965) was first introduction of gauged $SU(3)$ color.

General acceptance of color

3 General acceptance required a surprizingly long dormancy period in which many new ideas were assimilated.

Concluding remarks

I have reviewed the discoveries and ideas connected with the color degree of freedom in particle physics.

We are all looking forward to the next round of discoveries.