Murray GELL-MANN

Memorial Conference

Colymbari, August 2019

John Iliopoulos

ENS Paris

Murray GELL-MANN

Born: Sept. 15, 1929 in Lower Manhattan
Died: May 24, 2019 at Santa Fe

- A precocious child, High School valedictorian at age 14
- A polymath-nicknamed "the Walking Encyclopedia."
- Studied Physics "by accident"
- BSc: Yale 1948, PhD: MIT (V. Weisskopf) 1951
- Received the 1969 Nobel Prize in Physics

- He never published his thesis on strong interaction corrections to the nuclear shell model.
  Coupling Strength and Nuclear Reactions
  Murray Gell-Mann (MIT). Jan 1951. 85 pp.

- He never published his thesis on strong interaction corrections to the nuclear shell model.
  Coupling Strength and Nuclear Reactions
  Murray Gell-Mann (MIT). Jan 1951. 85 pp.

- *His first paper*

PHYSICAL REVIEW VOLUME 84, NUMBER 2 OCTOBER 15, 1951

Bound States in Quantum Field Theory

MURRAY GELL-MANN AND FRANCIS LOW
Institute for Advanced Study, Princeton, New Jersey
(Received June 13, 1951)

The relativistic two-body equation of Bethe and Salpeter is derived from field theory. It is shown that the Feynman two-body kernel may be written as a sum of wave functions over the states of the system. These wave functions depend exponentially on the energies of the states to which they correspond and therefore provide a means of calculating energy levels of bound states.

The first field-theoretic derivation of the Bethe-Salpeter equation.
A long-lasting collaboration with Francis Low.

He covered practically all fields in particle physics

He covered practically all fields in particle physics

- Bethe-Salpeter equation
- Meson-Baryon dynamics
- The theory of scattering
- Nuclear Physics
- The renormalisation group
- Formal Quantum Field Theory
- Strangeness
- The $K^0 - \bar{K}^0$ system
- Systematics of the new particles
- Properties of a degenerate electron gas
- The $V - A$ theory
- The σ-model
- Gauge Theories

- $SU(3)$ - The eightfold way
- Current Algebras
- Regge Poles and applications
- Quarks
- Higher groups
- Non-compact groups, Infinite dim. algebras
- Light cone current algebra
- *QCD*
- Grand-Unified Theories
- Supergravity theories
- Superstrings
- Quantum Cosmology, Foundations of Q. M.
- Non-equilibrium statistical mechanics

The renormalisation group

PHYSICAL REVIEW VOLUME 95, NUMBER 5 SEPTEMBER 1, 1954

Quantum Electrodynamics at Small Distances*

M. GELL-MANN† AND F. E. LOW
Physics Department, University of Illinois, Urbana, Illinois

(Received April 1, 1954)

The renormalisation group

PHYSICAL REVIEW VOLUME 95, NUMBER 5 SEPTEMBER 1, 1954

Quantum Electrodynamics at Small Distances*

M. GELL-MANN† AND F. E. LOW
Physics Department, University of Illinois, Urbana, Illinois
(Received April 1, 1954)

- The concept of the RG was invented by:
  E.C.G. Stueckelberg de Breidenbach and A. Petermann, *"Normalization of constants in the quanta theory", Helv. Phys. Acta* **26**, *499 (1953)*

The renormalisation group

PHYSICAL REVIEW VOLUME 95, NUMBER 5 SEPTEMBER 1, 1954

Quantum Electrodynamics at Small Distances*

M. GELL-MANN† AND F. E. LOW
Physics Department, University of Illinois, Urbana, Illinois
(Received April 1, 1954)

- The concept of the RG was invented by:
  E.C.G. Stueckelberg de Breidenbach and A. Petermann,
  "Normalization of constants in the quanta theory", Helv. Phys. Acta ***26****, 499 (1953)*

- $\Gamma^{(2n)}(p_1, \ldots, p_n; \lambda; m; \mu) \qquad \mu \to \rho\mu$

  $$[\mu\frac{\partial}{\partial\mu} + \beta\frac{\partial}{\partial\lambda} + \gamma_m m\frac{\partial}{\partial m} - n\gamma]\Gamma^{(2n)}(p_1, \ldots, p_n; \lambda; m; \mu) = 0$$

  Apparently, only technical interest

The renormalisation group

Gell-Mann and Low were the first to understand that:

- In the kinematic regions in which $\lim_{m\to 0}\Gamma^{(2n)}(p_1,\ldots,p_n;\lambda;m;\mu)$ exists
- The large μ limit can be translated into a large p one.

  $\Rightarrow$ We can obtain the short distance behaviour of the Green functions.
- Applications :

  (i) Critical phenomena
  K. Wilson (Murray's student)

  (ii) High Energy Physics

Strangeness

Strangeness

- Already in the early 1940s new particles were found in cosmic rays
  (L. Leprince-Ringuet and M. Lhéritier, 1944)
  which turned out to have a "strange" behaviour:
  - Copiously produced $\Rightarrow$ strong interactions
  - Long life-times $\Rightarrow$ weak interactions

Strangeness

- Already in the early 1940s new particles were found in cosmic rays
  (L. Leprince-Ringuet and M. Lhéritier, 1944)
  which turned out to have a "strange" behaviour:
  - Copiously produced $\Rightarrow$ strong interactions
  - Long life-times $\Rightarrow$ weak interactions
- Many ingenious proposals to explain this schizophrenic phenomenon
  (A. Pais, D.C. Peaslee, ...)

Strangeness

- Already in the early 1940s new particles were found in cosmic rays
  (L. Leprince-Ringuet and M. Lhéritier, 1944)
  which turned out to have a "strange" behaviour:
  - Copiously produced $\Rightarrow$ strong interactions
  - Long life-times $\Rightarrow$ weak interactions
- Many ingenious proposals to explain this schizophrenic phenomenon
  (A. Pais, D.C. Peaslee, ...)
- Gell-Mann, and, independently, K. Nishijima, found the answer.

Strangeness

Isotopic Spin and New Unstable Particles

M. Gell-Mann
Department of Physics and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 21, 1953)

Phys. Rev. 92, 833 (1953)

Until this time we had:
- Half-integer isospin baryons (the nucleons)
- Integer isospin mesons (the pions)

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

Gell-Mann proposed to decouple these three quantities for the new particles, thus allowing the introduction of integer isospin baryons and half-integer isospin mesons.

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

The $K^0 - \bar{K}^0$ system

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. GELL-MANN,* *Department of Physics, Columbia University, New York, New York*

AND

A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

- Parity assumed to be conserved.
- We were still talking about the θ-particles.
- The first time that quantum oscillation phenomena are introduced in particle physics.

Systematics of the new particles

HYPERONS AND HEAVY MESONS
(SYSTEMATICS AND DECAY[1])

BY MURRAY GELL-MANN
Department of Physics, California Institute of Technology, Pasadena, California

AND

ARTHUR H. ROSENFELD
Department of Physics and Radiation Laboratory, University of California Berkeley, California

1. INTRODUCTION

We attempt, in this article, to summarize the information now available, both experimental and theoretical, on the classification and decays of hyperons and heavy mesons. Our principal emphasis is on the "weak interactions" responsible for the slow decays of these particles. The "strong interactions" involved in production and scattering phenomena form a separate topic, which we do not discuss at length. We do, however, mention the hyperfragments, the study of which bears on both kinds of interactions.

Ann.Rev.Nucl.Part.Sci. 7, 407 (1957)

Rosenfeld continued these publications

⇒ Rosenfeld Tables ⇒ Particle Data Group

Properties of a degenerate electron gas

PHYSICAL REVIEW VOLUME 106, NUMBER 2 APRIL 15, 1957

Correlation Energy of an Electron Gas at High Density*

MURRAY GELL-MANN, *Department of Physics, California Institute of Technology, Pasadena, California*

AND

KEITH A. BRUECKNER, *Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania*

(Received December 14, 1956)

The quantity ϵ_c is defined as the correlation energy per particle of an electron gas expressed in rydbergs. It is a function of the conventional dimensionless parameter r_s, where r_s^{-3} is proportional to the electron density. Here ϵ_c is computed for small values of r_s (high density) and found to be given by $\epsilon_c = A \ln r_s + C + O(r_s)$. The value of A is found to be 0.0622, a result that could be deduced from previous work of Wigner, Macke, and Pines. An exact formula for the constant C is given here for the first time; earlier workers had made only approximate calculations of C. Further, it is shown how the next correction in r_s can be computed. The method is based on summing the most highly divergent terms of the perturbation series under the integral sign to give a convergent result. The summation is performed by a technique similar to Feynman's methods in field theory.

In electronic systems, terms in the perturbation approach of the Coulomb potential which were divergent, could be summed up to give a finite, physical result.
Not surprising from somebody who had understood the summing up of logarithms in the RG.

For some reason, in later times Gell-Mann developed little respect for condensed matter physics "squalid state physics"

Gauge Theories

ELSEVIER

Annals of Physics

Volume 15, Issue 3, September 1961, Pages 437-460

Gauge theories of vector particles ☆

Sheldon L Glashow, Murray Gell-Mann

California Institute of Technology, Pasadena, California, USA

Received 12 June 1961, Available online 27 September 2004.

Gauge Theories

ELSEVIER

Annals of Physics

Volume 15, Issue 3, September 1961, Pages 437-460

Gauge theories of vector particles ☆

Sheldon L Glashow, Murray Gell-Mann

California Institute of Technology, Pasadena, California, USA

Received 12 June 1961, Available online 27 September 2004.

- It extends Yang-Mills to $G_1 \times G_2 \times \ldots$
  One coupling constant for every factor.

Gauge Theories

ELSEVIER

Annals of Physics
Volume 15, Issue 3, September 1961, Pages 437-460

Gauge theories of vector particles ☆

Sheldon L Glashow, Murray Gell-Mann

California Institute of Technology, Pasadena, California, USA

Received 12 June 1961, Available online 27 September 2004.

- It extends Yang-Mills to $G_1 \times G_2 \times \ldots$
  One coupling constant for every factor.
- The seed of Grand Unification
  "The remarkable universality of the electric charge would be better understood were the photon not merely a singlet, but a member of a family of vector mesons comprising a simple partially gauge invariant theory."
  (note: "partially gauge invariant" = massive gauge bosons)

Gauge Theories

- Application to strong interactions:
  Attempt to identify the 1^- vector bosons with gauge bosons.

Gauge Theories

- Application to strong interactions:
  Attempt to identify the 1^- vector bosons with gauge bosons.

- Application to the Glashow $SU(2) \times U(1)$ model of weak interactions:
  It correctly identifies the problems related to the absence of strangeness changing neutral currents and the small value of the $K_1^0 - K_2^0$ mass difference.

  It addresses the problem of universality in the framework of the Sakata model:
  "Observe that the sum of the squares of the coupling strengths to strangeness-saving charged currents and to strangeness-changing charged currents is just the square of the universal coupling strength. Should the gauge principle be extended to leptons - at least for the charged currents - the equality between G_V and G_μ is no longer the proper statement of universality, for in this theory $G_V^2 + G_\Lambda^2 = G_\mu^2$ "

$SU(3)$ - The eightfold way

The Eightfold Way: A Theory of strong interaction symmetry

Murray Gell-Mann (Caltech)

Mar 1961 - 49 pages

CTSL-20, TID-12608

The paper which forced particle physicists to learn group theory

Unpublished!! NOT very cited!!

$SU(3)$ - The eightfold way

The Eightfold Way: A Theory of strong interaction symmetry

Murray Gell-Mann (Caltech)

Mar 1961 - 49 pages

CTSL-20, TID-12608

The paper which forced particle physicists to learn group theory
Unpublished!! NOT very cited!!

- With the introduction of strangeness it was natural to look for hadron classification schemes larger than isospin $SU(2)$.

$SU(3)$ - The eightfold way

The Eightfold Way: A Theory of strong interaction symmetry

Murray Gell-Mann (Caltech)

Mar 1961 - 49 pages

CTSL-20, TID-12608

The paper which forced particle physicists to learn group theory

Unpublished!! NOT very cited!!

- With the introduction of strangeness it was natural to look for hadron classification schemes larger than isospin $SU(2)$.
- Several attempts : $SU(2) \times SU(2)$, $O(4)$, G_2, ...

$SU(3)$ - The eightfold way

The Eightfold Way: A Theory of strong interaction symmetry

Murray Gell-Mann (Caltech)

Mar 1961 - 49 pages

CTSL-20, TID-12608

The paper which forced particle physicists to learn group theory
Unpublished!! NOT very cited!!

- With the introduction of strangeness it was natural to look for hadron classification schemes larger than isospin $SU(2)$.
- Several attempts : $SU(2) \times SU(2)$, $O(4)$, G_2, ...
- $SU(2) \Rightarrow SU(3)$ the simple-minded way:

$$\begin{pmatrix} p \\ n \end{pmatrix} \Rightarrow \begin{pmatrix} p \\ n \\ \Lambda \end{pmatrix}$$

S. Sakata, Prog. Theor. Phys. 16, 686 (1956) It does not work!

$SU(3)$ - The eightfold way

- The eightfold way : Gell-Mann (and, ind. Y. Ne'eman)
  The triplet is missing! Use **8** and **10**

$SU(3)$ - The eightfold way

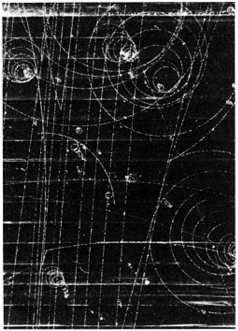
- The eightfold way : Gell-Mann (and, ind. Y. Ne'eman)
  The triplet is missing! Use **8** and **10**

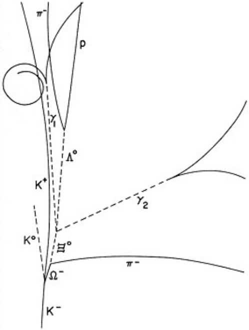
- $SU(3)$ must be strongly broken. Assumption : H_{Br} belongs to an octet $\Rightarrow$ Gell-Mann (and, ind. Okubo) mass formula.

$SU(3)$ - The eightfold way

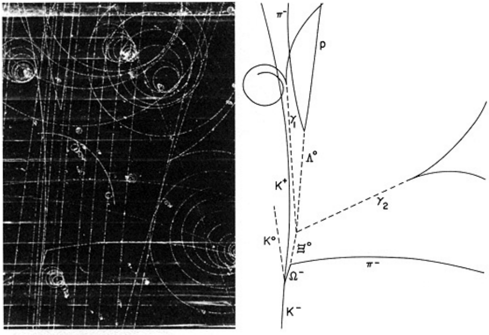
- The eightfold way : Gell-Mann (and, ind. Y. Ne'eman)
  The triplet is missing! Use **8** and **10**
- $SU(3)$ must be strongly broken. Assumption : H_{Br} belongs to an octet $\Rightarrow$ Gell-Mann (and, ind. Okubo) mass formula.
- Prediction of Ω^-

$SU(3)$ - The eightfold way





$SU(3)$ - The eightfold way



- $SU(3)$ and weak interactions :

  N. Cabibbo : The weak currents belong to an octet.

Current Algebras

Probably, the subject in which Gell-Mann concentrated most of his efforts and obtained the most profound and most seminal results.

Weak and electromagnetic interactions are interactions among currents.
The problem : Use the observed properties of these currents in order to guess the symmetries of strong interactions.

Current Algebras

Probably, the subject in which Gell-Mann concentrated most of his efforts and obtained the most profound and most seminal results.

Weak and electromagnetic interactions are interactions among currents.
The problem : Use the observed properties of these currents in order to guess the symmetries of strong interactions.

- $V - A$ theory (with R.P. Feynman) - 1957

Current Algebras

Probably, the subject in which Gell-Mann concentrated most of his efforts and obtained the most profound and most seminal results.

Weak and electromagnetic interactions are interactions among currents.
The problem : Use the observed properties of these currents in order to guess the symmetries of strong interactions.

- $V - A$ theory (with R.P. Feynman) - 1957
- Weak interactions : leptonic modes - 1958

Current Algebras

Probably, the subject in which Gell-Mann concentrated most of his efforts and obtained the most profound and most seminal results.

Weak and electromagnetic interactions are interactions among currents.
The problem : Use the observed properties of these currents in order to guess the symmetries of strong interactions.

- $V - A$ theory (with R.P. Feynman) - 1957
- Weak interactions : leptonic modes - 1958
- Vector Interaction in beta Decay - 1958

Current Algebras

Probably, the subject in which Gell-Mann concentrated most of his efforts and obtained the most profound and most seminal results.

Weak and electromagnetic interactions are interactions among currents.
The problem : Use the observed properties of these currents in order to guess the symmetries of strong interactions.

- $V - A$ theory (with R.P. Feynman) - 1957
- Weak interactions : leptonic modes - 1958
- Vector Interaction in beta Decay - 1958
- The axial vector current in beta decay (with M. Lévy) (The σ-model) - 1960

Current Algebras

Probably, the subject in which Gell-Mann concentrated most of his efforts and obtained the most profound and most seminal results.

Weak and electromagnetic interactions are interactions among currents.
The problem : Use the observed properties of these currents in order to guess the symmetries of strong interactions.

- $V - A$ theory (with R.P. Feynman) - 1957
- Weak interactions : leptonic modes - 1958
- Vector Interaction in beta Decay - 1958
- The axial vector current in beta decay (with M. Lévy) (The σ-model) - 1960
- On the renormalization of the axial vector coupling constant in β-decay (with J. Bernstein and L. Michel) - 1960

Current Algebras

- Conserved and partially conserved currents in the theory of weak interactions - 1960

Current Algebras

- Conserved and partially conserved currents in the theory of weak interactions - 1960
- Group U(6) x U(6) generated by current components (with R.P. Feynman and G. Zweig) -1964

Current Algebras

- Conserved and partially conserved currents in the theory of weak interactions - 1960
- Group U(6) x U(6) generated by current components (with R.P. Feynman and G. Zweig) -1964
- Current-generated algebras (with Y. Ne'eman) - 1964

Current Algebras

- Conserved and partially conserved currents in the theory of weak interactions - 1960
- Group U(6) x U(6) generated by current components (with R.P. Feynman and G. Zweig) -1964
- Current-generated algebras (with Y. Ne'eman) - 1964
- THE SYMMETRY GROUP OF VECTOR AND AXIAL VECTOR CURRENTS*

  MURRAY GELL-MANN

  California Institute of Technology, Pasadena, California

  (*Received* 25 *May* 1964)

  Abstract

  We review, modify slightly, generalize, and attempt to apply a theory proposed earlier of a higher broken symmetry than the eightfold way. The integrals of the time components of the vector and axial vector current octets are assumed to generate, under equal time commutation, the algebra of SU(3) × SU(3). *The energy density of the strong interactions is assumed to consist of a piece invariant under the algebra, a piece that violates conservation of the axial vector currents only and belongs to the representation* (3, 3*) *and* (3*, 3), *and a piece that violates the eightfold way and probably belongs to* (1, 8) *and* (8, 1). *Assuming*

  Physics 1, 63 (1964)

Current Algebras

- Many papers, with different collaborators, between 1964 and 1970

Current Algebras

- Many papers, with different collaborators, between 1964 and 1970

Representation of Local Current Algebra at Infinite Momentum

Roger Dashen, Murray Gell-Mann (Caltech)

Aug 8, 1966 - 3 pages

Phys.Rev.Lett. 17 (1966) 340-343
DOI: 10.1103/PhysRevLett.17.340

-

Current Algebras

- Many papers, with different collaborators, between 1964 and 1970
- **Representation of Local Current Algebra at Infinite Momentum**

  Roger Dashen, Murray Gell-Mann (Caltech)

  Aug 8, 1966 - 3 pages

  Phys.Rev.Lett. 17 (1966) 340-343
  DOI: 10.1103/PhysRevLett.17.340

- **Current Algebra**

  M. Gell-Mann (Caltech)

  1966 - 29 pages

  Note: Strong and Weak Interactions, Present Problems (New York, NY: Academic Press, 1966), pp. 173-201

Current Algebras

- Many papers, with different collaborators, between 1964 and 1970
- **Representation of Local Current Algebra at Infinite Momentum**
  Roger Dashen, Murray Gell-Mann (Caltech)
  Aug 8, 1966 - 3 pages
  Phys.Rev.Lett. 17 (1966) 340-343
  DOI: 10.1103/PhysRevLett.17.340
- **Current Algebra**
  M. Gell-Mann (Caltech)
  1966 - 29 pages
  Note: Strong and Weak Interactions, Present Problems (New York, NY: Academic Press, 1966), pp. 173-201
- **Behavior of current divergences under SU(3) x SU(3)**
  Murray Gell-Mann (Caltech), R.J. Oakes (Northwestern U.), B. Renner (Caltech)
  1968 - 5 pages
  Phys.Rev. 175 (1968) 2195-2199
  DOI: 10.1103/PhysRev.175.2195

Current Algebras

Numerous applications and by-products of the Current Algebra scheme:

Current Algebras

Numerous applications and by-products of the Current Algebra scheme:

- The Adler-Weisberger relation

Current Algebras

Numerous applications and by-products of the Current Algebra scheme:

- The Adler-Weisberger relation
- Pion scattering lengths

Current Algebras

Numerous applications and by-products of the Current Algebra scheme:

- The Adler-Weisberger relation
- Pion scattering lengths
- Many relations and Sum Rules

Current Algebras

Numerous applications and by-products of the Current Algebra scheme:

- The Adler-Weisberger relation
- Pion scattering lengths
- Many relations and Sum Rules
- Spontaneous breaking of the chiral symmetry and the pseudoscalar mesons as pseudo-Goldstone particles

  The most important legacy.

Current Algebras on the Light Cone

Around 1970, the SLAC Deep Inelastic electron-nucleon scattering data drew attention to the physics at the vicinity of the light cone, i.e. high energy and large momentum transfer with fixed ratio.

Light cone current algebra

Harald Fritzsch (Munich, Max Planck Inst.), Murray Gell-Mann (Caltech)

Jan 2003 - 45 pages

(1971)
Conference: C71-04-05, p.317-374
Proceedings
LMU-23-02
e-Print: hep-ph/0301127 | PDF

Explained scaling behaviour using free-field commutation relations

"On the light cone, Nature reads only free field theory books"

Quarks, or the missing triplet

Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark.
Finnegans Wake, James Joyce

A Schematic Model of Baryons and Mesons

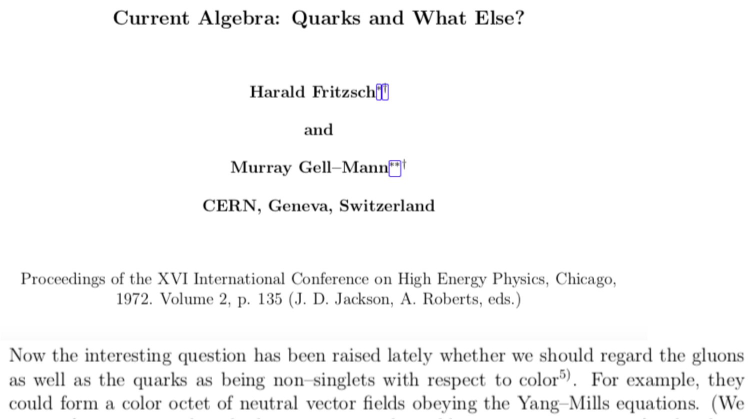
Murray Gell-Mann (Caltech)

1964 - 2 pages

Phys.Lett. 8 (1964) 214-215
Also in *Lichtenberg, D.B. (ed.), Rosen, S.P., (ed.), Developments In The Quark Theory Of Hadrons, Vol. 1*, 20-21
DOI: 10.1016/S0031-9163(64)92001-3

- Quarks as elementary constituents of hadronic matter (ind. G. Zweig)
- Quarks as mathematical entities
- QCD - Quarks as "physical" but confined particles

QCD-The first version


Current Algebra: Quarks and What Else?

Harald Fritzsch*†

and

Murray Gell–Mann†**

CERN, Geneva, Switzerland

Proceedings of the XVI International Conference on High Energy Physics, Chicago, 1972. Volume 2, p. 135 (J. D. Jackson, A. Roberts, eds.)

Now the interesting question has been raised lately whether we should regard the gluons as well as the quarks as being non–singlets with respect to color[5)]. For example, they could form a color octet of neutral vector fields obeying the Yang–Mills equations. (We

Sept 6-13 1972.

$\beta < 0$ *was found by 't Hooft in June 1972, but he did not mention any connection to strong interactions*

The Gross-Wilczeck and Politzer results date from 1973.

For almost twenty years he dominated the world of High Energy Physics providing ideas to both theorists and experimentalists.