Concrete Quarks

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- QCD - developed in two phases:
  - Discovery of quarks
  - Specification of their interactions
- Arose from two very different traditions
  - Rutherford-Bohr
  - Einstein
- Discovery of radioactivity: Henri Becquerel (1896)

Phosphorescence? Becquerel's photographic plate fogged by exposure to radiation from uranium salts. A metal Maltese Cross placed between the plate and the uranium salts is visible.

- Rutherford at Cambridge (1899): α and β

- Rutherford & Soddy at McGill (1903):
  "the spontaneous disintegration of [a] radio-element, whereby a part of the original atom was violently ejected as a radiant particle, and the remainder formed a totally new kind of atom with distinct chemical and physical character."

  Nobel prize in Chemistry (1908), Soddy (1921)

PROCEEDINGS OF

THE ROYAL SOCIETY.

Section A.—Mathematical and Physical Sciences.

On a Diffuse Reflection of the α-Particles.

By H. Geiger, Ph.D., John Harling Fellow, and E. Marsden, Hatfield Scholar, University of Manchester.

(Communicated by Prof. E. Rutherford, F.R.S. Received May 19,—Read June 17, 1909.)

In the following experiments, however, conclusive evidence was found of the existence of a diffuse reflection of the α-particles. A small fraction of the α-particles falling upon a metal plate have their directions changed to such an extent that they emerge again at the side of incidence. To form an

We are indebted to Prof. Rutherford for his kind interest and advice throughout this research.

- Interpretation (Rutherford 1911)
- Impossible!
- Marsden (1914): Nuclei contain protons!
- Bohr (1912, 1914-1916): Stationary states
  Charge separation & Quantization

Rutherford's group at Manchester University, 1912.

Rutherford is seated second row, center.

Back rows: (standing): C. G. Darwin, J. M. Nuttall, J. Chadwick,

2nd row: H. Geiger, E. Rutherford,

Front row: H. G. J. Moseley, E. Marsden.

· The nuclear force (1927)

LII. *The Scattering of α-particles by Helium.* *By* Prof. Sir E. RUTHERFORD, *O.M., P.R.S., Cavendish Professor of Experimental Physics, and* J. CHADWICK, *Ph.D., F.R.S., Fellow of Gonville and Caius College, Cambridge* *.

THE study of the collisions of α-particles with hydrogen nuclei has shown that the force between the α-particle and the H nucleus obeys Coulomb's law for large distances of collision, but that it diverges very markedly from this law at close distances. The experiments of Chadwick and Bieler † showed that for distances of collision less than about 4×10^{-13} cm. the force between the two particles increased much more rapidly with decrease of distance than could be accounted for on an inverse square law of force. For

SUMMARY.

into action. Possible explanations of the origin of these additional forces are discussed, and it is suggested tentatively that they may be due to magnetic fields in the nuclei.

Cavendish Laboratory, Cambridge.

· Heisenberg (1925 for atoms; 1943 & 1944 for the nucleus): Work only with observables!

Lone Ranger Atom Bomb Ring Spinthariscope (1947 - early 1950s)

This ring spinthariscope was known as the Lone Ranger Atom Bomb Ring and advertised as a "seething scientific creation." The Lone Ranger was more closely associated with silver bullets than atomic bombs but that's what it was called. When the red base (which served as a "secret message compartment") was taken off, and after a suitable period of time for dark adaptation, you could look through a small plastic lens at scintillations caused by polonium alpha particles striking a zinc sulfide screen.

Distributed by Kix Cereals (15 cents plus a boxtop), the instructions stated: "You'll see brilliant flashes of light in the inky darkness inside the atom chamber. These frenzied vivid flashes are caused by the released energy of atoms. PERFECTLY SAFE - We guarantee you can wear the KIX Atomic "Bomb" Ring with complete safety. The atomic materials inside the ring are harmless."

The following advertisement was appearing in newspapers in early 1947.

New nuclear particles (π, K) discovered in 1947

THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 76, NO. 12 DECEMBER 15, 1949

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

I. INTRODUCTION

IN recent years several new particles have been discovered which are currently assumed to be "elementary," that is, essentially, structureless. The probability that all such particles should be really elementary becomes less and less as their number increases.

It is by no means certain that nucleons, mesons, electrons, neutrinos are all elementary particles and it could be that at least some of the failures of the present theories may be due to disregarding the possibility that some of them may have a complex structure. Unfortunately, we have no clue to decide whether this is true, much less to find out what particles are simple and what particles are complex. In what follows we will try to work out in some detail a special example more as an illustration of a possible program of the theory of particles, than in the hope that what we suggest may actually correspond to reality.

We propose to discuss the hypothesis that the π-meson may not be elementary, but may be a composite particle formed by the association of a nucleon and an anti-nucleon. The first assumption will be, therefore, that both an anti-proton and an anti-neutron exist, having the same relationship to the proton and the neutron, as the electron to the positron. Although this is an assumption that goes beyond what is known experimentally, we do not view it as a very revolutionary one. We must assume, further, that between a nucleon and an anti-nucleon strong attractive forces exist, capable of binding the two particles together. We assume that the π-meson is a pair of nucleon and anti-nucleon bound in this way. Since the mass of the π-meson is much smaller than twice the mass of a nucleon, it is necessary to assume that the binding energy is so great that its mass equivalent is equal to the difference between twice the mass of the nucleon and the mass of the meson.

According to this view the positive meson would be the association of a proton and an anti-neutron and the negative meson would be the association of an anti-proton and a neutron. As a model of a neutral meson one could take either a pair of a neutron and an anti-neutron, or of a proton and an anti-proton.

It would be difficult to set up a not too complicated scheme of forces between a nucleon and an anti-nucleon, without about equally strong forces between two ordinary nucleons. These last forces, however, would be quite different from the ordinary nuclear forces, because they would have much greater energy and much shorter range. The reason why no experimental indication of them has been observed for ordinary nucleons may be explained by the assumption that the forces could be attractive between a nucleon and an anti-nucleon and repulsive between two ordinary nucleons. If this is the case, no bound system of two ordinary nucleons would result out of this particular type of interaction. Because of the short range very little would be noticed of such forces even in scattering phenomena.

Ordinary nuclear forces from the point of view of this theory will be discussed below.

Unfortunately we have not succeeded in working out a satisfactory relativistically invariant theory of nucleons among which such attractive forces act. For this reason all the conclusion that will be presented will be

* Now at the Institute for Advanced Study, Princeton, New Jersey.

- M. Gell-Mann & E.P. Rosenbaum, "Elementary Particles," *Scientific American*, July 1957, 72-86: 19 in number

  M. Gell-Mann & A.H. Rosenfeld, "Hyperons and Heavy Mesons," *Ann. Rev. Nucl. Sci*, 1957, 407-478:

  Two kinds of Elementary Particles:

Point particles

Spin 1/2 leptons	
Particle	Mass
e^-	1
μ^-	206.7
ν	0

Spin 1 photon	
Particle	Mass
γ	0

Extended particles (strongly interacting)

Spin 1/2 baryons		
Multiplet	Particle	Mass (m_e)
Ξ	Ξ^0	?
	Ξ^{-1}	2585
Σ	Σ^{-1}	2341
	Σ^+	2325
	Σ^0	2324
Λ	Λ	2182
N	n	1838.6
	p	1836.1

Spin 0 mesons		
Multiplet	Particle	Mass
π	π^+	273.2
	π^{-1}	273.2
	π^0	264.2
K	K^+	966.5
	K^-	966.5
	K_1^0	965
	K_2^0	965

– No resonances mentioned!

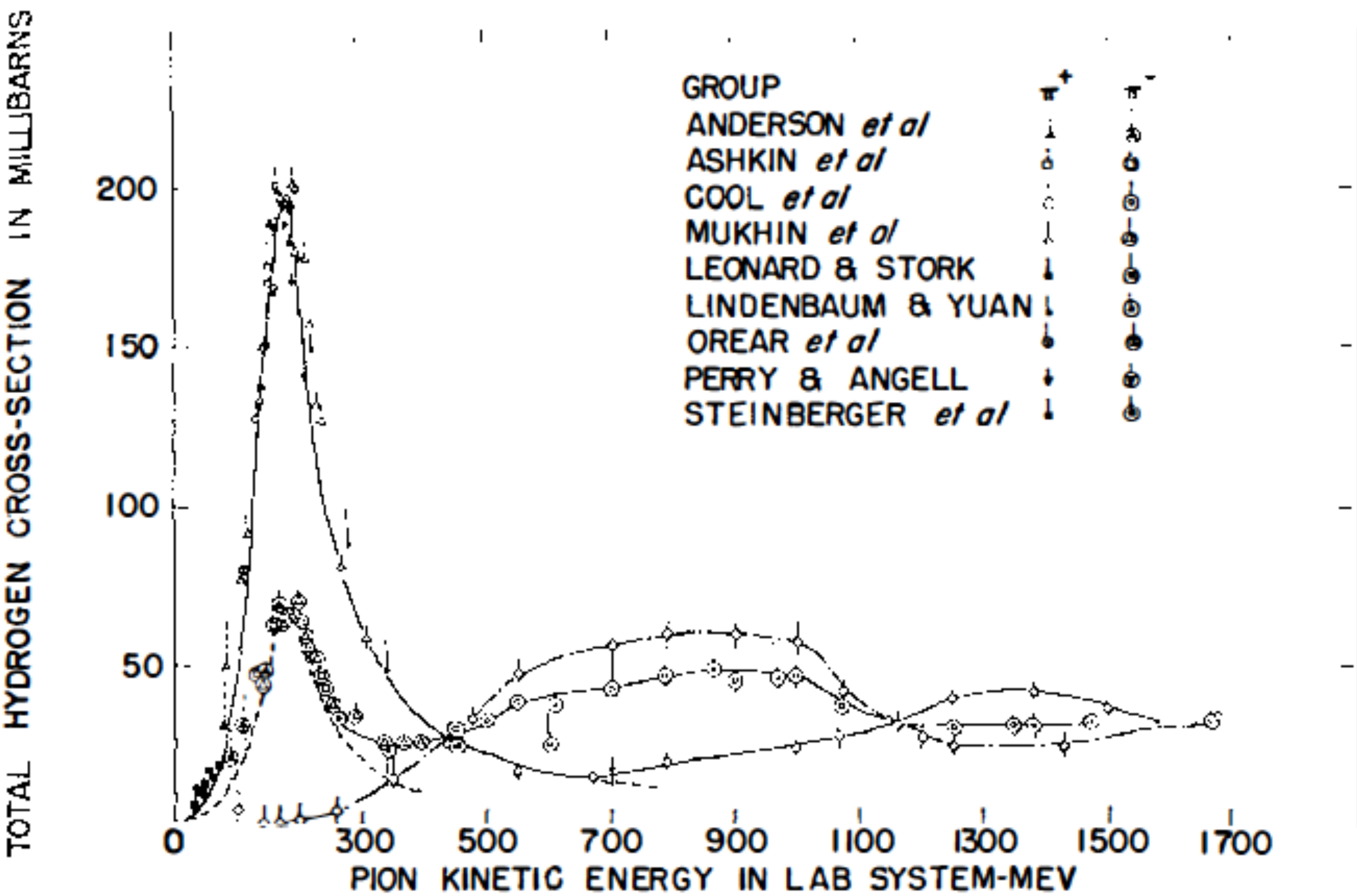


FIG. 3. A plot of $\pi^{\pm}+p$ total cross-sections as a function of energy, using in general

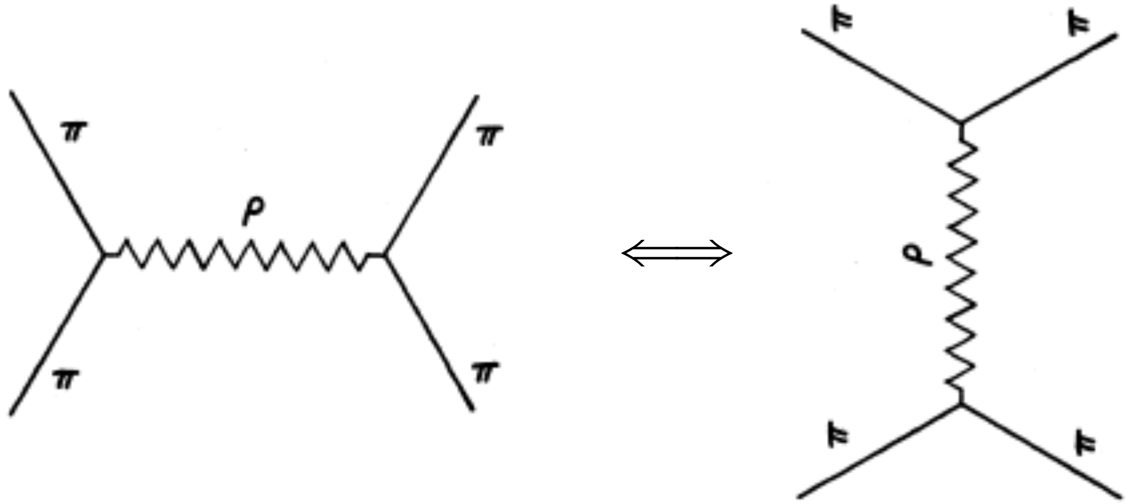
- Caltech:
  - Bob Christy ... Alvin Tollestrup
  - My thesis: A test of time reversal symmetry $K^+ \to \pi^0 + \mu^+ + \nu$.
  - Mexico!
  - Murray?
- Every Thursday at 1:30 PM during 1962-63
- Theoretical physics:
  - Axiomatic field theory (no physics)
  - Theory related to belief (Chew, June 1961):

    "I believe the conventional association of fields with strongly interacting particles to be empty. ... field theory..., like an old soldier, is destined not to die but just fade away."

  - Theory related to experiment:
    * Classification (no dynamics):
      - Sakata model: Wrong baryon spectrum
      - G(2) & SU(3) were in contention

* Dynamics (no classification): Bootstrap

  Fred Zacharisen (1961)



Exchanging a ρ binds two pions into a ρ.

But cannot bootstrap the π!

- Experimental physics:
  - More particles discovered since 1957:
    * Point particles: the 4th lepton (ν_μ)
    * Extended particles: the 8th spin 1/2 baryon (Ξ^0), and an 8th spin 0 meson (η)
    * Resonances: 26 meson resonances listed in the RMP, April 1963 (ρ, ω, K^*, ϕ, $\cdots$)

- One Thursday afternoon:

  P.L. Connolly, et al., "Existence and Properties of the ϕ Meson", *Phys. Rev. Lett.* **10**, 371 (1963):

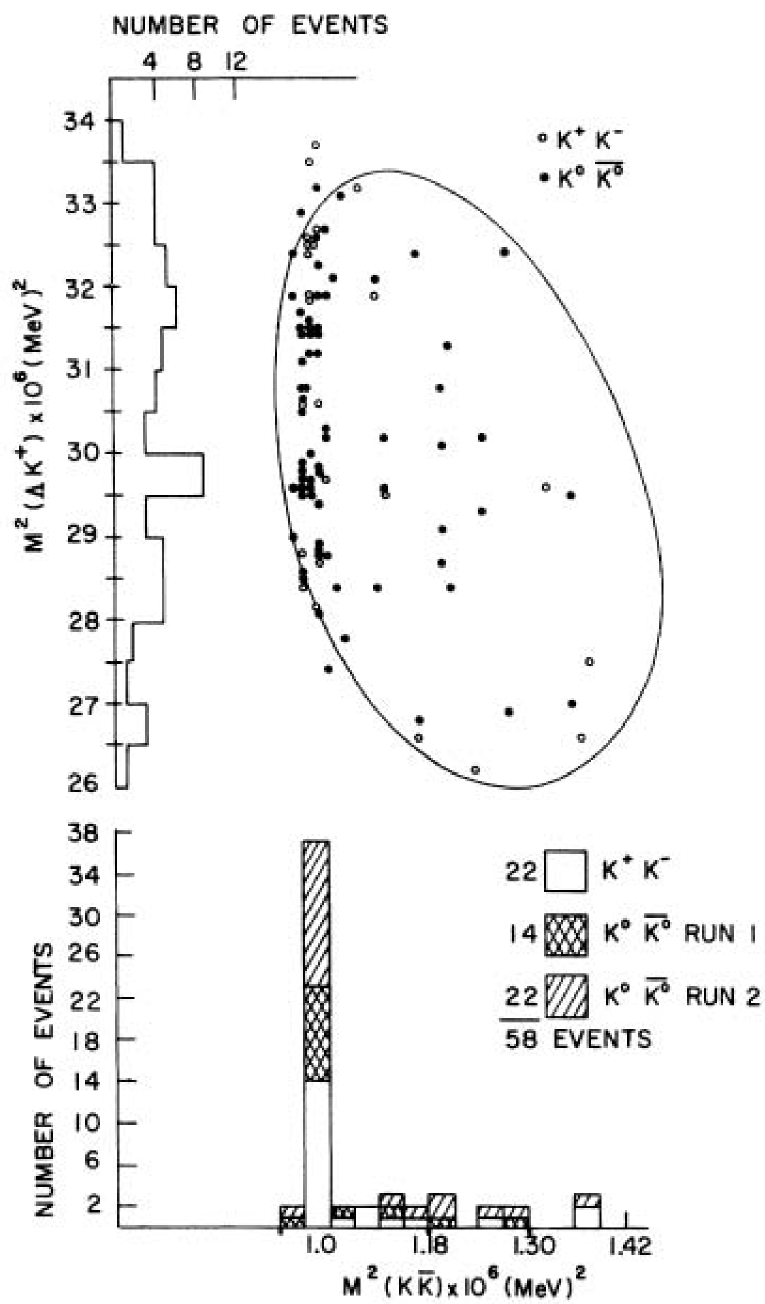


FIG. 1. Dalitz plot for the reaction $K^- + p \rightarrow \Lambda + K + \bar{K}$. The effective-mass distribution for $K\bar{K}$ and for ΛK^+ are projected on the abscissa and ordinate (see reference 7).

$$\phi \rightarrow K\bar{K}$$

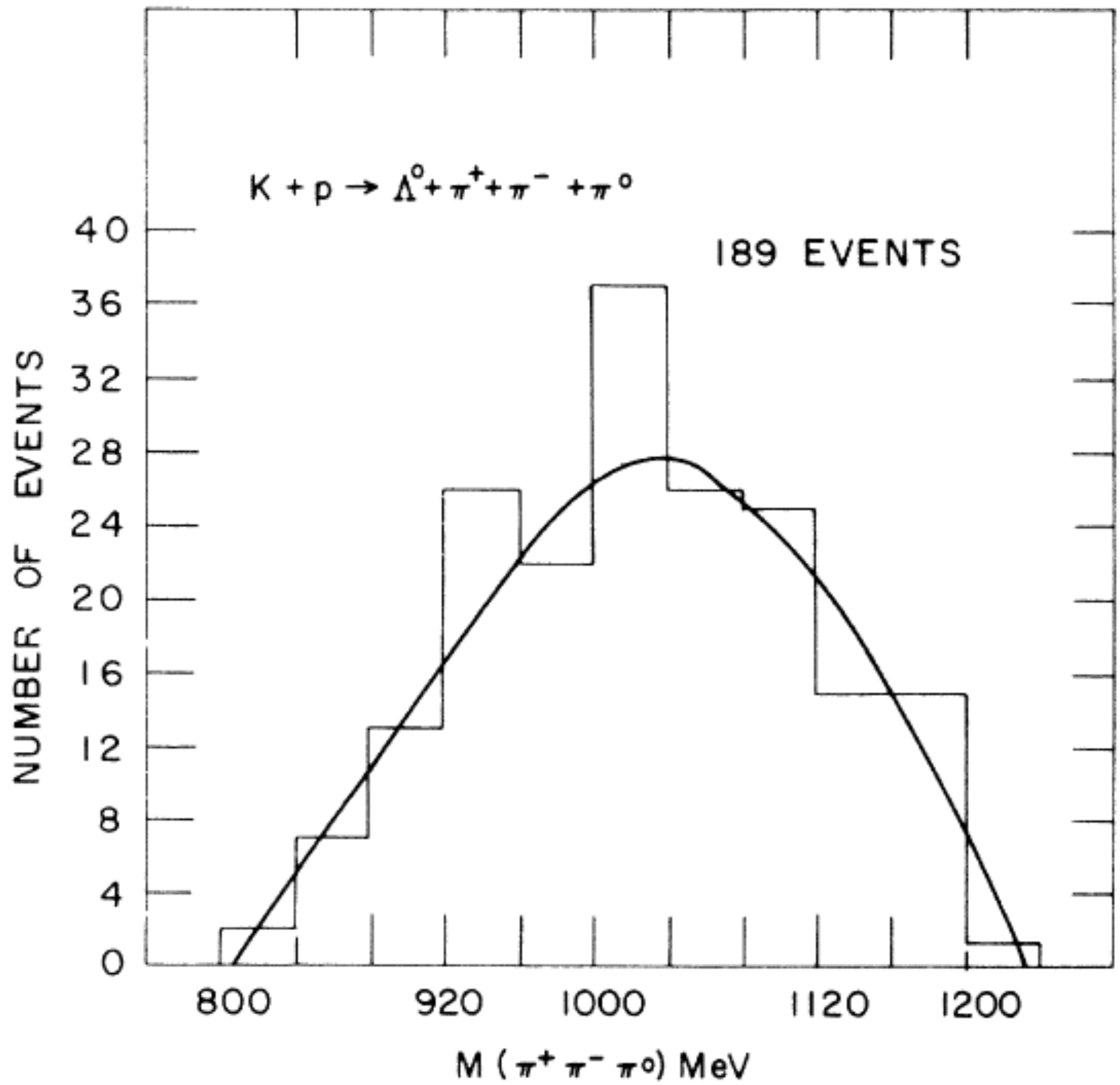


FIG. 4. The $M(\pi^+\pi^-\pi^0)$ distribution from the reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0$ after removing $Y_1{}^*$ production events (see text).

$$\phi \not\rightarrow \rho + \pi$$

"The observed rate [for $\phi \to \rho + \pi$] is lower than ... predicted values by one order of magnitude; however the above estimates are uncertain by at least this amount so that this discrepancy need not be disconcerting."

$$\frac{\Gamma_{K\bar{K}}}{\Gamma_{\rho\pi}} \sim \left(\frac{p_{K\bar{K}}}{p_{\rho\pi}}\right)^3,$$
$$= 1/4 \text{ (expected)},$$
$$\geqslant 35 \quad \text{(observed)}.$$

– Feynman:

– GZ:

- Assumed hadrons have constituents a called aces:

$$[\,N_0,\ \Lambda_0\,]\ \&\ [\,\bar{N}_0,\ \bar{\Lambda}_0\,]$$
$$[\,(p_0,\ n_0),\ \Lambda_0\,]\ \&\ [\,(\bar{p}_0,\ \bar{n}_0),\ \bar{\Lambda}_0\,]$$

Mesons $\equiv a\bar{a}$ with $\uparrow\downarrow$ (π, K and η) and
$\uparrow\uparrow$ (ρ, ω, K^* and ϕ).

Baryons $\equiv aaa$ with $\uparrow\uparrow\downarrow$ (p or n),
and $\uparrow\uparrow\uparrow$ ($\Delta \equiv \pi\, N$)

Nonet of vector mesons represented as "deuces"

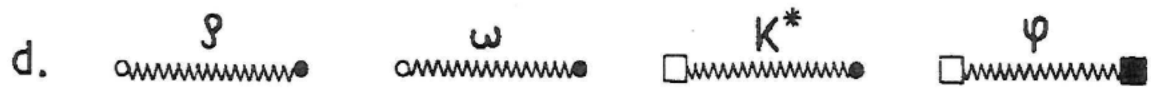
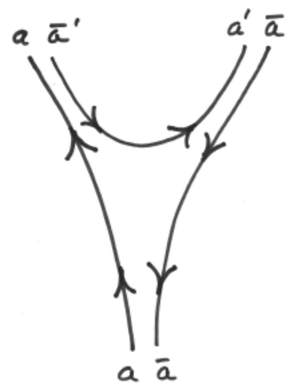


FIG. 2, CERN report TH-401, January 1964.

- A rule for *decay* ("Zweig's Rule") (in modern notation):



Meson decay: a is an ace, $\bar{a}$ an antiace.

– Implies $\phi \not\rightarrow \rho + \pi$

- A hierarchy of mass relations:

Mass $=$ Σ *constituent masses* $+$ *energies of interaction,* $|\Delta m| > |\Delta E|$.

– Identical binding energies:

$$m^2(\rho) \approx m^2(\omega) \; < \; m^2(K^*) \; < \; m^2(\phi).$$

750^2 $\quad$ 784^2 $\quad$ 888^2 $\quad$ 1018^2

– $E_{\Lambda_0}^{\bar{N}_0} = E_{N_0}^{\bar{\Lambda}_0} \approx \frac{1}{2}(E_{\Lambda_0}^{\bar{\Lambda}_0} + E_{N_0}^{\bar{N}_0}), \;\; N_0 = p_0, n_0 :$

$$m^2(\phi) \approx 2m^2(K^*) - m^2(\rho).$$

1018^2 $\quad$ 1007^2

Like the "constituent-quark model,"
but *no potential is assumed.*

- Since aaa is a baryon,

  $B = \frac{1}{3}$,

  $Q = e[I_z + \frac{B+S}{2}]$,

  $[\,(p_0,\; n_0),\; \Lambda_0\,] \rightarrow [\,(\frac{2}{3},\; -\frac{1}{3}),\; -\frac{1}{3}\,].$

  $3 \times 3 \times 3 = 1 + 8 + 8 + 10.$

Octet of baryons represented as "treys"

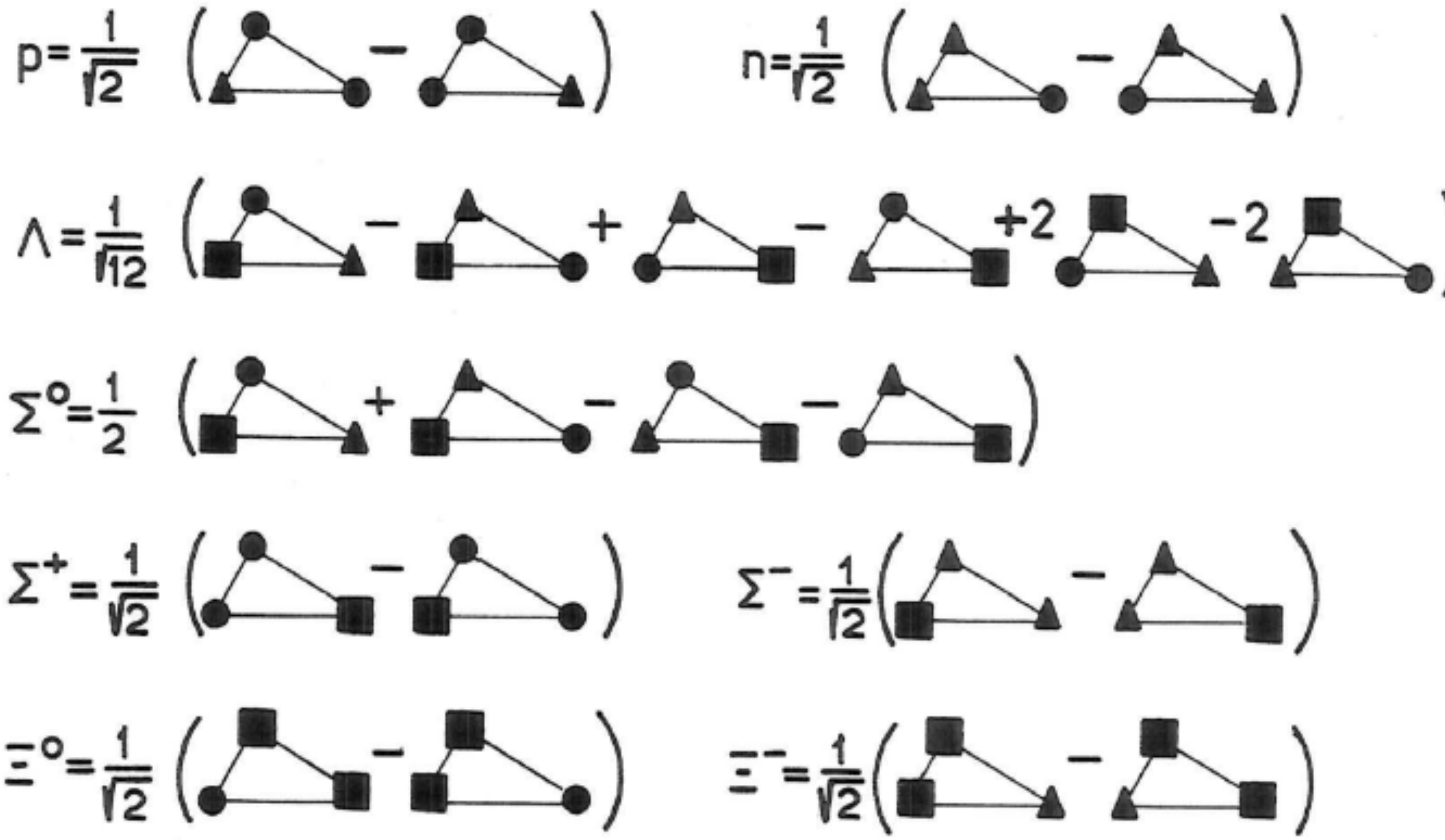


FIG. 3

CERN report TH-412, February 1964

- Mass differences break SU(3) & SU(2) symmetry
  - SU(3) symmetry: $m(p_0) = m(n_0) = m(\Lambda_0)$,
  - Broken SU(3): $m(p_0) = m(n_0) < m(\Lambda_0)$,
  - Broken SU(2): $m(p_0) < m(n_0)$.

- Interactions: *Aces, not hadrons, interact.*
  - Strong interaction couplings: "Zweig's rule"
  - Electromagnetic and weak couplings:

    $\gamma + a \to a$
    $a \to a' + e^- + \nu$ when $n \to p + e^- + \nu$,
    $n_0 \to p_0 + e^- + \nu$

    The "current-quark model"

- concrete-quarks $\equiv$
  current-quarks, constituent-quarks + Zweig's rule

Summary

- Hadrons have point constituents
- Leptons $\leftrightarrow$ Aces
- Origin of SU(3) symmetry
- Beyond SU(3) symmetry:
  - Restricted representations, quantum numbers:
    * Baryons only in 1, 8, 10,
      Mesons only in 1, 8, and 9.
    * There is an $\vec{L}$ and an $\vec{S}$, with $\vec{J} = \vec{L} + \vec{S}$.
    * $L = 0$ baryons: $(8, J^P = \frac{1}{2}^+)$ and $(10, \frac{3}{2}^+)$,
      $L = 0$ mesons: $(8, J^{PC} = 0^{-+})$ and $(9, 1^{--})$.
    * Higher L excitations.
    * $\vec{L} \cdot \vec{S}$ interactions.
    * 0^{--}; $0^{+-}, 1^{-+}, \cdots$ forbidden for any L.
- 80 pages
- Not as easy as it looks:
  - 26 =19+7, 19=12+7

- What did people think? Were aces real?
  - GZ: Aces had dynamics!
  - Murray Gell-Mann:
    - "Concrete-quark model"
    - Five years after the deep inelastic scattering experiments at SLAC (partons) "Quarks," *Acta Physica Austriaca, Suppl. IX*, 733-761 (1972)

> "In these lectures I want to speak about at least two interpretations of the concept of quarks for hadrons and, the possible relations between them.
>
> First I want to talk about quarks as 'constituent quarks'. *These were used especially by G. Zweig (1964)* [italics added] who referred to them as aces. ..."

More precise to say:

These were introduced by G. Zweig

> "The whole idea is that hadrons act as if they are made up of quarks, but the quarks do not have to be real. ..."

That's a mischaracterization.

"There is a second use of quarks, as so-called 'current quarks' which is quite different from their use as constituent quarks ...

If quarks are only fictitious there are certain defects and virtues. The main defect would be that we never experimentally discover real ones and thus will never have a quarkonics industry. The virtue is that then there are no basic constituents for hadrons – hadrons act as if they were made up of quarks but no quarks exist - and, therefore, *there is no reason for a distinction between the quark and bootstrap picture: they can be just two different descriptions of the same system, like wave mechanics and matrix mechanics."* [italica added]

This was Murray's vision. Concrete quarks?

– Heisenberg (early 1970s)

"Even if quarks should be found (and I do not believe that they will be), they will not be more elementary than other particles, since a quark could be considered as consisting of two quarks and one anti-quark, and so on. I think we have learned from experiments that by getting to smaller and smaller units, we do not come to fundamental units, or indivisible units, but we do come to a point where division has no meaning. This is a result of the experiments of the last twenty years, and I am afraid that some physicists simply ignore this experimental fact."

- Richard Feynman:
  - Current quarks/aces?
  - Constituent quarks/aces?
    - "The correct theory should not allow you to say which particles are elementary."
  - Zweig's rule?
    - " Everything that can possibly happen does $\cdots$" .
  - "Did I miss anything Zweig?"

Problems with acceptance

- Aces violated the spin-statistics theorem
  - Rutherford's atom & Bohr's orbits
  - Wegener's continental drift
- Aces violated current dogma:
  - Nuclear democracy
  - Work with observables.

(Copernicus's view of the solar system)

A way to judge new theories

Bayes Theorem:

$P(A|E) = \frac{1}{1+\lambda}$,

where $\lambda \geqslant 0$, and

$\lambda = \frac{P(E|\bar{A})}{P(E|A)}\frac{P(\bar{A})}{P(A)}$.

Since

$P(\bar{A}) \approx 1$ and $P(E|A) \approx 1$,

$\lambda \approx \frac{P(E|\bar{A})}{P(A)}$.

Accept A when $P(E|\overline{A}) << P(A)$.

– Einstein tradition: $P(E|\overline{A}) >> P(A)$:

– Rutherford-Bohr tradition: $P(E|\overline{A}) << P(A)$

When did acceptance come?

– Pauling

– Bogolubov

– Dalitz

– Feynman

– Deep inelastic scattering

– ψ/J

Invention or discovery?

Invention: “a product of the imagination.”

Discovery: “the act of finding or learning something for the first time.”

– Current quarks invented (Einstein)

– Constituent quarks discovered (Rutherford-Bohr)

– Aces contained a bit of each

google: zweig CERN interview

Conclusion of
CERN report TH-412, February 1964

There are, however, many unanswered questions. Are aces particles ? If so, what are their interactions ? Do aces bind to form only deuces and treys ? What is the particle (or particles) that is responsible for binding the aces ? Why must one work with masses for the baryons and mass squares for the mesons ? And more generally, why does so simple a model yield such a good approximation to nature ?

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there is also the outside chance that the model is a closer approximation to nature than we may think, and that fractionally charged aces abound within us.