IC/74/76
INTERNAL REPORT
(Limited distribution)

International Atomic Energy Agency

and

United Nations Educational Scientific and Cultural Organization

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

TOPICAL MEETING
ON THE PHYSICS OF COLLIDING BEAMS

20 - 22 June 1974

(SUMMARIES AND CONTRIBUTIONS)

MIRAMARE - TRIESTE

July 1974

LEPTON NUMBER AS FOURTH QUARK COLOUR

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and
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① Baryon - Lepton Symmetry ⇒ STRONG LEPTONIC INTERACTIONS ↓ PATI + S.

② Boson - Fermion Symmetry
WESS + ZUMINO, STRATHDEE + S.

Pati + Salam 1972

BARYON - LEPTON SYMMETRY

GAUGE THEORY OF STRONG WEAK E.M. Int: 1973

Motivation

(1) 3 Quarks (1964) $\rightarrow SU(3)$

p	$2/3$
n	$-1/3$
λ	$-1/3$

one triplet

(2) 4 Quarks (1964) $\rightarrow SU(4)$

Nuyts, Amati, Bruntki, Bjorken, Glashow, ... charm $\leftarrow$ χ

p	$2/3$
n	$-1/3$
λ	$-1/3$
χ	$2/3$

Importance recognised after work of GIM

Forbid $K^0 \rightarrow \mu^+ + \mu^-$

(3) Parallel Introduction of colour (1965)

$SU(3) \times SU'(3)$ Han - Nambu, Greenberg, Freund

Three triplets $\begin{vmatrix} p_a & p_b & p_c \\ n_a & n_b & n_c \\ \lambda_a & \lambda_b & \lambda_c \end{vmatrix}$

Two choices of charge Either $\begin{vmatrix} 0 & 1 & 1 \\ -1 & 0 & 0 \\ -1 & 0 & 0 \end{vmatrix}$ OR $\begin{vmatrix} 2/3 & 2/3 & 2/3 \\ -1/3 & -1/3 & -1/3 \\ -1/3 & -1/3 & -1/3 \end{vmatrix}$

WHY COLOUR ?

① Quark Statistics Quarks are $\overset{\text{ANTI COM:}}{\text{Fermions}}$ IF COLOURED

② SATURATION WHY ONLY $q\bar{q}$, qqq allowed & Not qq, $q\bar{q}q\bar{q}$

③ $\pi^0 \to 2\gamma \Rightarrow \langle Q_p^2\rangle - \langle Q_n^2\rangle$ Fits if quarks coloured

Lipkin's Parable of Deutron World

<u>Epoch of Physics</u>

low-lying nuclear states ⟺ made of deutrons

nucleons not discovered

Bright Theorist ([illegible]) postulates nucleon(N) model of deutron
GZ

"nucleon" Era ↓ double the number of nucleons $\boxed{p, n}$

charge assignment $N = \frac{1}{2}$ —

WRONG CHARGE ; WRONG STATISTICS

Bright Theorist (HN)

Postulates Colour (then called I-spin)

Two models → charge $(p, n) \Rightarrow \frac{1}{2}, \frac{1}{2}$

or $(p, n) \Rightarrow 1, 0$

nucleon spin-statistics problem resolved.

Brighter Theorist ([illegible]) notices colour (I-spin)

resolves saturation problem if colour is gauged

(ie ρ-mesonic potential attractive $I = 0$ $\left.\begin{matrix} NN \\ N\bar{N} \end{matrix}\right\}$

So only colour (I-spin) SINGLETS EXIST | Repulsive $I = 1$

Next Development combine **CHARM** + **COLOUR** ②

$$B = \begin{array}{c|ccc|} \uparrow & p_a & p_b & p_c \\ C,S,I.\text{spin} \;\; \text{valency} & n_a & n_b & n_c \\ & \lambda_a & \lambda_b & \lambda_c \\ \downarrow & \chi_a & \chi_b & \chi_c \end{array}$$

$\xleftarrow{\;}\ \underset{R}{3}$ colours $\xrightarrow[B]{}$ $\langle Q^2 \rangle = 6$

$SU(4) \times SU(3')$

strong Int:

Plus $L = \begin{vmatrix} \nu_e \\ e^- \\ \mu^- \\ \nu_\mu \end{vmatrix}$ Lepton Quartet.

Pati + Salam Is lepton Number the Fourth Colour?

$$F = \begin{array}{c|cccc|} \uparrow & p_a & p_b & p_c & \nu_e \\ \text{valency} & n_a & n_b & n_c & e^- \\ & \lambda_a & \lambda_b & \lambda_c & \mu^- \\ \downarrow & \chi_a & \chi_b & \chi_c & \nu_\mu \end{array}$$

$\longleftarrow$ 4 colours $\longrightarrow$

16 - Fold of $SU(4) \times SU(4')$

ALL MATTER IN ONE MULTIPLET

Define Fermion Number $F = B + L$

$B=1$ $L=0$ Quark

$B=0$ $L=1$ Lepton

Note $\left.\begin{array}{l} \mu^- \longrightarrow \text{strange Lepton} \\ \nu_\mu \longrightarrow \text{charmed lepton} \end{array}\right\}$ OR $\begin{array}{l} e^- \rightarrow \text{strange} \\ \nu_e \rightarrow \text{charmed} \end{array}$

④

Charge schemes

Symmetrical $\begin{vmatrix} 0 & 1 & 1 & 0 \\ -1 & 0 & 0 & -1 \\ -1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \end{vmatrix}$ OR Fractional $\begin{vmatrix} 2/3 & 2/3 & 2/3 & 0 \\ -1/3 & -1/3 & -1/3 & -1 \\ -1/3 & -1/3 & -1/3 & -1 \\ 2/3 & 2/3 & 2/3 & 0 \end{vmatrix}$

IMPORTANT. given quark charges + $SU(4)\times SU(4')$ group structure $\}$

Cannot have any charge except $\begin{pmatrix} 0 \\ -1 \\ -1 \\ 0 \end{pmatrix}$ for leptons

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IN PARTICULAR impossible to have $\begin{pmatrix} 0 \\ +1 \\ +1 \\ 0 \end{pmatrix}$

ie quarks + $\begin{pmatrix} \bar{\nu}_e \\ e^+ \\ \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}$ is IMPOSSIBLE TO COMBINE

ABSOLUTE MEANING TO WHAT IS A LEPTON IF WE DEFINE QUARK

So $\begin{pmatrix} p \\ n \\ \lambda \\ \chi \end{pmatrix}_{a,b,c}$ quarks go together with $\begin{pmatrix} \nu_e \\ e^- \\ \mu^- \\ \nu_\mu \end{pmatrix}$

to make up Fermions ; anti-quarks + $(\bar{\nu}_e, e^+, \mu^+, \bar{\nu}_\mu)$ make ANTI FERMIONS with $F = -1$

⑤

① First Prediction

Strong Weak Int: will pick $(V\text{-}A) = \frac{1-i\gamma_5}{2}$ projection for quarks $\begin{pmatrix} p \\ n \\ \lambda \\ \chi \end{pmatrix}_{abc}$ and $\begin{pmatrix} e^- \\ \mu^- \end{pmatrix}$ (NOT e^+, μ^+)

Feynman's Lament 1961
NO OTHER SUGGESTION

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② Second Prediction

If postulate **Fermion Number** is absolutely conserved, $F = B + L$ $|\Delta F| = 0$,

but B, L individually not conserved (gauge theory) spontaneously broken

then $\boxed{\begin{array}{l} \text{quark} \rightarrow \text{lepton transition possible} \\ \quad\ \rightarrow \text{anti-lepton} \quad \text{"} \quad \text{impossible.} \end{array}}$ $|\Delta F| \neq 0$

IN PARTICULAR $P = (p_b p_c n_a)$ 3 quark-composite $F = 3$

will decay INTO 3 leptons + pion

$$\underset{F=3}{P} \rightarrow \underset{F=3}{\nu + \nu + \nu} + \pi^+$$

Minimum No of Decay Product in Proton Decay is Four

TWO, THREE BODY decay OF PROTON FORBIDDEN

(3) <u>THIRD PREDICTION</u>

In a theory which gauges all degrees of freedom no distinction between quarks & leptons

Leptons must have strong Interactions at suitably high energies. WHAT ENERGY?

Group $SU(4) \times SU(4')$

Ideally gauge $SU(4)_L \times SU(4)_R \times SU(4')_L \times SU(4')_R$

IMPOSSIBLE unless double the number of Fermions (Heavy Leptons + More quarks PRODIGAL MODEL)

DOUBLE THE NUMBER

due to anomalies (SABJ)

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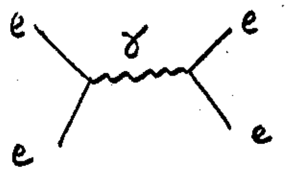
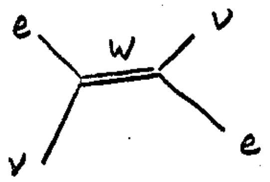
will gauge $\underbrace{SU(2)_L \times SU(2)_R}_{\text{Weak}} \times \underbrace{SU(4')}_{\text{COLOUR STRONG}}$

$SU(2)_L \downarrow$ V-A, $SU(2)_R \downarrow$ V+A

← E.M. →

⑩ Leptonic Interactions become as strong as hadronic — in the same sense as neutrino interactions become E.M. beyond a certain energy range





same group $\begin{pmatrix} \nu \\ e^- \end{pmatrix} \rightarrow SU(2) \times U(1)$

same coupling $\frac{e^2}{4\pi} = \alpha$

But at energies $< m_W$.

Effective potl: V_{ee} ~ strength $\alpha \sim 10^{-2}$

$V_{e\nu}$ ~ strength $\frac{\alpha}{m_W^2} \sim G_F \sim 10^{-5}$

Analogously suggest there exist superheavy gauge bosons, beyond whose energies

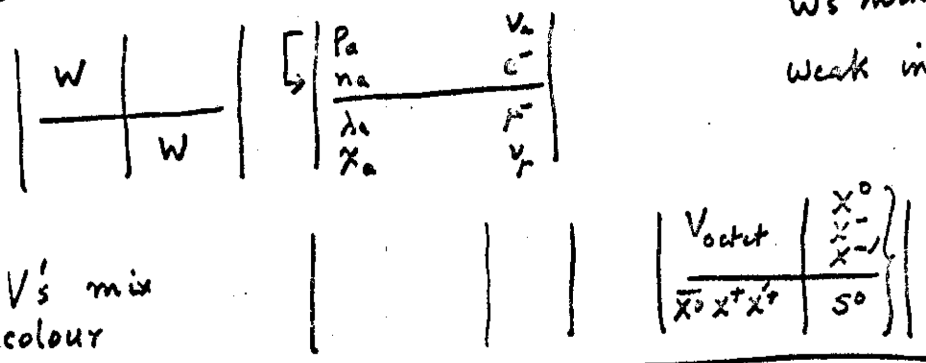
No distinction between Leptons & Hadrons dynamically.

$$\begin{array}{ccccc}
SU(2)_L & \times & SU(2)_R & \times & SU'(4) \\
\downarrow & & \downarrow & & \downarrow \\
W_L & & W_R & & V \\
\underset{\sim}{3} & & \underset{\sim}{3} & & \underset{\sim}{15} \\
 & & & & \text{strong} \\
V-A & & V+A & & \\
\frac{g_L^2}{4\pi} \sim \alpha & & \frac{g_R^2}{4\pi} \sim \alpha & & \frac{f^2}{4\pi} \sim 1 \\
\end{array}$$

$$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{\displaystyle\downarrow \atop \displaystyle E.M.}$$

(Non-Abelian → Asym: Free)

BASIC MODEL



W's mix valency
weak int.

V's mix
colour

Among the 15 V's are six Exotic Mesons

$X^0, X^-, X^{-\prime} + \overline{X^0}, X^+, X^{+\prime}$

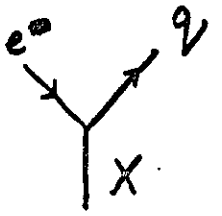
which mix L with R, W, B

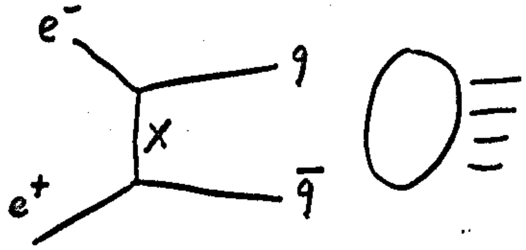
X's Carry $\left.\begin{array}{l} B=-1 \\ L=+1 \end{array}\right\}$

$\bar{X}$'s carry $\begin{array}{l} B=+1 \\ L=-1 \end{array}$

(~~[illegible]~~ quark atoms) F=0
(integercharge)

Exotics

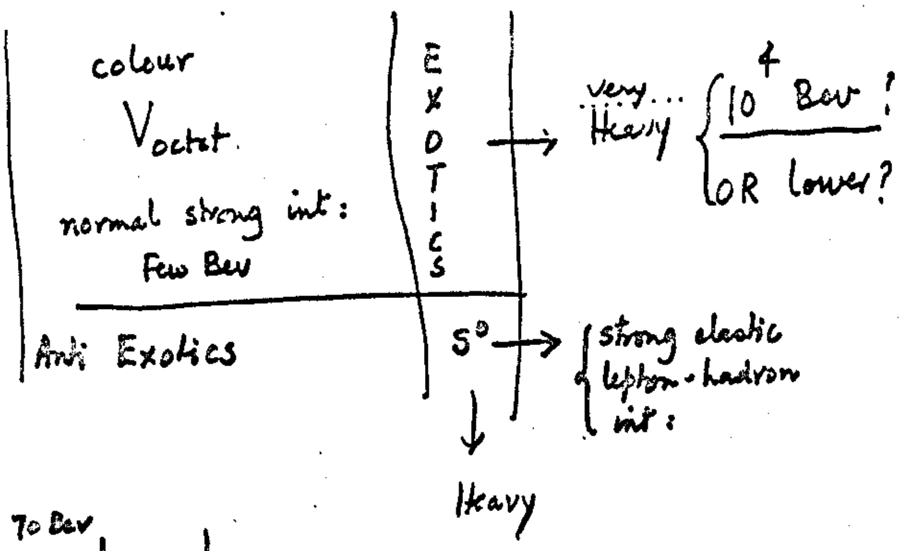




hadrons

Relevant to present expts.

$V(15) \approx$



$$W_L(3) \quad \left|\begin{array}{c|c} \overset{70\text{ Bev}}{\underset{\sim}{W}} & \\ \hline & \underset{\sim}{W} \end{array}\right|$$

$$W_R(3) \quad \left|\begin{array}{c|c} \underline{W} & \\ \hline & \underset{\sim}{W} \end{array}\right| \rightarrow 300\text{ Bev.}$$

⑭ Estimates of Masses of Gauge Particles to give observed Low-energy Phenomenology

① $W_L \to (V-A)$ weak $\quad \frac{g_L^2}{4\pi} \approx \alpha$ $\frac{e^2}{m_W^2} \sim G_F \sim 10^{-5}$	$m_{W_L} \sim 100$ Bev
② $W_R \to V+A$ weak assume $g_R \sim g_L$ Present expts: amplitude $< \frac{1}{10}(V-A)$ $\Rightarrow g_L = g_R \Rightarrow$ PARITY CONSERVATION AT HIGH ENERGIES	$\tan \theta_W \sim \frac{g_R}{g_L}$ if S^0 heavy $m_{W_R} > 300$ Bev
③ $V_{octet} \to$ strong colour quark Forces $\frac{f^2}{4\pi} \sim 1$ MUST BE PRODUCED IN PAIRS IN KNOWN PARTICLE COLLISIONS	$m_{V_8} \sim 3$-5 Bev
④ $V_{15} = S^0 \quad \begin{matrix} e+e \to e+e \\ e+p \to e+p \end{matrix} \quad \frac{f^2}{4\pi} \sim 1$ $\left\lvert\begin{array}{c\|c} V_8 & Ex: \\ \hline E_x & V_{15} \end{array}\right\rvert$ provides for strong elastic int: of leptons and hadrons for energies $\gg m_S$	$m_S \gtrsim 1000$ Bev.

Masses OF EXOTICS

2 Models ① Very Heavy Exotics $\gtrsim 10^4$ Bev

BASIC MODEL : IRRELEVANT FOR SLAC EXPT.

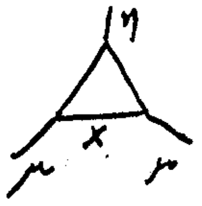
PRODIGAL MODEL ② Heavy Exotics $\sim 10^2$ BeV Relevant

Relevant — but then must add more fermions to the model. }

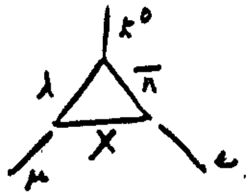
HOWEVER SPONT: SYM: BREAKING DIFFICULT TO ARRANGE. Find $m_X \geqslant m_S \geqslant 3$ BeV

Basic 1st model

4-colour model X- contributes to $\eta \to e^+e^-$
$\to \mu^+\mu^-$



and also to $K^0 \to e^- + \mu^+$
$\bar{K}^0 \to e^+ + \mu^-$



Since observed rate < that given by effective coupling $G_F\alpha^2$

so $\frac{f^2}{m_X^2} \ll G_F \alpha^2 \sim 10^{-9}$

ie $m_X \gtrsim 10^4$ BeV.

ENERGY NOT RELEVANT TO SLAC EXPT:

Variant $\boxed{\text{PRODIGAL}}$

Second Model separate electrons and muons ; two distinct colours

either Introduce 5 colours

or double the Fermions

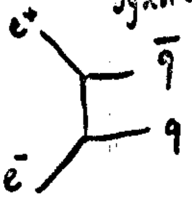
$$\begin{vmatrix} p_a & p_b & p_c & E^0 \\ n_a & n_b & n_c & E^- \\ \lambda_a & \lambda_b & \lambda_c & e^- \\ \chi_a & \chi_b & \chi_c & \nu_e \end{vmatrix} \quad \text{and} \quad \begin{vmatrix} p_a' & p_b' & p_c' & M^0 \\ n_a' & n_b' & n_c' & M^- \\ \lambda_a' & \lambda_b' & \lambda_c' & \mu^- \\ \chi_a' & \chi_b' & \chi_c' & \nu_\mu \end{vmatrix}$$

No problem with $K^0 \to e + \mu$

X-mass could be as low as 300 Bev

Still Not Relevant for SLAC; Semi-phenomological attitude ↓

Ignore Theoretical Difficulties since $m_X \sim 100$ Bev ; large ; for $\sqrt{s} \sim 5$ Bev



$$V_{\text{effective}} = \text{Four Fermi int}^{\text{n}} :$$

$$\approx (\bar{e}\, q)(\bar{q}\, e)$$

$$\text{Fierz Reshuffle} \approx (\bar{e}\, e)(\bar{q}\, q)$$

$$\text{arbitrary} \Leftarrow \boxed{V, A, P, S}$$

$$\quad C = -1 \quad C = +1, +1, +1$$

Note ν_e, ν_μ BOTH CHARMED in the variant above ; e, μ both strange

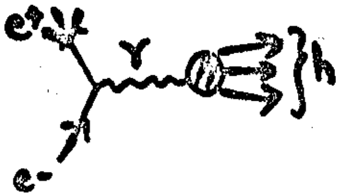
$$\mathcal{L}_x = f\,(\bar{e}\gamma_\mu q)\,X_\mu + \text{h.c.} \qquad (q = n \text{ or } \overset{1}{\lambda})$$

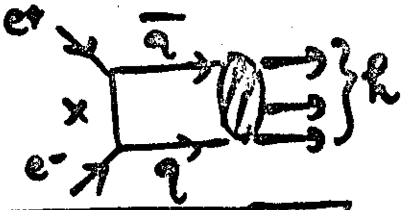
$$(f^2/4\pi) \equiv \frac{\alpha\,\epsilon}{(\text{Bev})^2}$$

$$\mathcal{L}_x^{\text{eff}} = \frac{f^2}{m_x^2}\cdot\frac{1}{4}\sum_{i=S,V,A,P}\{\bar{q}(x)\Gamma_i q(x)\}\{\bar{e}(x)\Gamma_i e(x)\}.$$

$$\Gamma_S = 4\times 1\!\!1,\ \Gamma_V = -2\gamma_\mu,\ \Gamma_A = +2\gamma_\mu\gamma_5,\ \Gamma_P = -4\gamma_5$$

<u>$e^-e^+ \to$ Hadrons</u>





$$\boxed{\sigma_h(s) = \frac{4\pi\alpha^2\rho_{\gamma\gamma}(s)}{3}\left[\frac{1}{s} + 2\overset{(1)}{\delta} + \delta^2 s\right] \quad \text{units: } (\text{Bev})^{-2}}$$

$$\delta = \epsilon\,\frac{\rho_{xx}(s)}{\rho_{\gamma\gamma}(s)}\ ;\ \overset{(1)}{\delta} = \epsilon\,\frac{\rho_{\gamma x}(s)}{\rho_{\gamma\gamma}(s)}$$

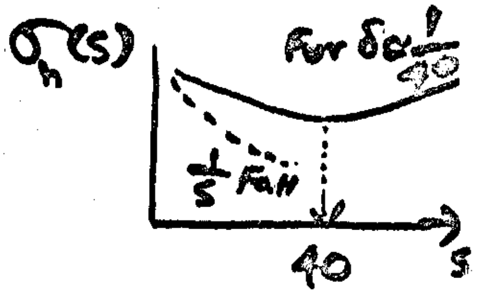
$$\langle 0|V_\mu^{em}\,V_\nu^{em}|0\rangle \to \rho_{\gamma\gamma} \xrightarrow[\text{L.C.}]{} \sum_{\text{quarks}} \text{Tr}\,Q_\gamma^2 + \left(\begin{matrix}\text{Color}\\ \text{Gluons}\\ \text{if photon}\\ \text{has Color}\end{matrix}\right)$$

$$\langle 0|V_\mu^{em}\,V_\nu^{X\dagger}|0\rangle \to \rho_{\gamma X}$$

$$\langle 0|V_\mu^{X}\,V_\nu^{X}|0\rangle \to \rho_{xx}.$$

A, S and P <u>add</u> Constructively To $\delta^2 s$ Term.

SPEAR DATA May be Explained for δ and $\delta' \approx \frac{1}{30} \sim \frac{1}{40}$ (specially For $\delta' > 0$)



Predict:

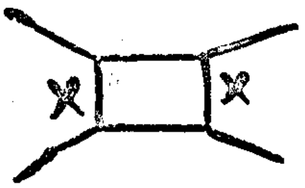
(1) $J^P = 1^+, 0^\pm$, C-even Final States at high s (much bigger than 2-photon Contrib.)

(2) $\sigma_h(s)$ should Fall slowly, then rise beyond $S \simeq 40$, or 50 $(\text{Bev})^2$ till when m_X is relevant

(3) Uniform Angular Distrib (Pt. Int:)

Other Effects

① $e^+e^- \to e^+e^-$, or $\mu^+\mu^-$ in 4th order



Should be important at much higher energies.

② $\eta \to (\mu^+\mu^-, e^+e^-)$; $\pi^0 \to e^+e^-$

$$\text{Amplitude} \sim \frac{f^2/4\pi}{m_X^2} \sim \frac{\alpha\epsilon}{(8m)^2} \approx \alpha^2$$

Consistent since $\epsilon \sim \frac{1}{50}$

③ ep & μp - Scattering - Low Energy

Axial Part in $\mathcal{L}_X^{eff}$ contributes to hfs. (Beg & Feinberg)

Contribution for hydrogen:

$\simeq 10\, g_q^A$ parts per million

for $\epsilon \simeq 1/50$

$$g_q^A \, \bar{u}_p \gamma_\mu \gamma_5 u_p \equiv (p|\bar{q}\gamma_\mu\gamma_5 q|p)$$

Same $\underset{\text{quark}}{q}$ as in $(\bar{\varepsilon}\gamma_\mu q)X_\mu$

$\boxed{q = n\cos\theta + \lambda\sin\theta}$

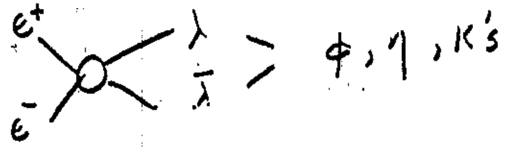
$$\therefore g_q^A = O(1) \to q = n \longleftarrow$$
$$= O(\sin^2\theta) \to q = \lambda \longleftarrow$$

Though expt. does not rule out the possibility $q = n$, uncomfortably close; better possibility

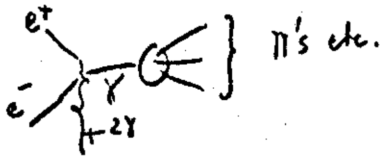
$\lambda_{\text{quark}} \longleftrightarrow e$ $\quad$ e-strange lepton?

If $e \longleftrightarrow \lambda_{\text{quark}}$

then



+ of course



Ⓑ Compare e^-p with e^+p ~ 1 if $q_{(e)} \sim n$
and μ^-p with μ^+p $\sim \sin^2\theta_c$ if $q_{(\mu)} \sim \lambda$
at high $q^2 \simeq 30$ to $50\ (\text{Bev})^2$

S, A & P Contrib. even $C \,|\, e^- \leftrightarrow e^+$

V " odd $C \,|\, e^- \leftrightarrow e^+$

LARGE V means $(e^+p)/(e^-p) \simeq$ ~~[illegible]~~ 1 & vice-versa

Difference is significant for high q^2. (much more important than 2-photon).

Ⓒ Compare $(e^\pm p)$ with $(\mu^\pm p)$

$$\frac{(e^+p)-(e^-p)}{(\mu^+p)-(\mu^-p)} \simeq O(\sin^2\theta) \quad (q_e = \lambda)$$

$$\text{or } O\left(\frac{1}{\sin\theta}\right) \quad (q_e = n)$$

$\simeq 1$ for $\left\{\begin{matrix}\text{Prodigal} \\ \text{Model}\end{matrix}\right.$ ~~[illegible]~~ Both strange ~~For~~ ~~[illegible]~~ Model.

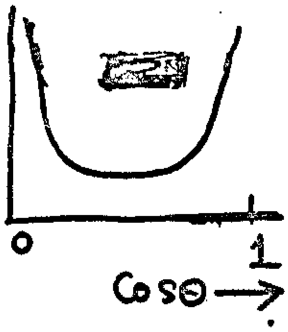
DIFFRACTIVE PICTURE (GREENBERG & Yodh / Nanopoulos & Vlassopoulos)

electron has a strong interaction radius ~ 10^{-16} cm.

① Small order α Correction to Bhabha Scattering

② one-particle Distribution in $e^-e^+ \to$ Hadrons

should have a sharp forward & backward peak



③ Reggeisation of Leptons

slope of Regge Trajectory governed by G_F

Different Picture P. Budini
P. Furlan }

SUMMARY

① X - mass $> 10^4$ Bev

Not Relevant SLAC Expt.

② X - mass ~ 300 Bev

still Not relevant SLAC Expt.

Gauge scheme = Basic
only 16 Fermions.

Gauge scheme = Prodigal
32 Fermions
new leptons
new quarks

③ *Phenomenological* X-mass 100 Bev

Relevant To SLAC

Question → Is e strange Then $\frac{e^+p}{e^-p} \approx 1$ always

But $e^+ + e^- \to$ expect $K, \bar{K}, \Lambda, \bar{\Lambda}, \phi$

If e not strange, then $\frac{e^+p}{e^-p} \approx 1 \pm (10\%)$

$\frac{e^+p}{e^-p} - 1$ = large if P, S, A interactions emphasised

= small if V emphasised.

Quark And proton - neutron Decays into Leptons

Is Baryon Number Experimentally Conserved ?

Stückelberg 1938
Wigner 1941
Oneda 1952
Proton life $> 10^{17}$ years
Universe $\sim 10^{10}$ years

Quark Decays

$q \quad B = 1 \;, L = 0 \qquad F = 1$

$\ell \quad B = 0 \;, L = 1 \qquad F = 1$

Assume $\mathcal{L}_{eff} = \frac{G_B}{\sqrt{2}} (\bar{q}\ell)(\bar{\ell}\ell) + h.c.$

Assume $G_B \, m_p^2 \leq 10^{-9} \quad (\approx G_F \alpha^2)$

then $\Gamma(q \to \ell + \ell + \bar{\ell}) = G_B^{\,2} \, m_q^5 / 24 (2\pi)^3$

$m_q \sim 10$ Bev $\qquad \Gamma \sim 3 \times 10^7 \text{ sec}^{-1}$

~ 50 Bev $\qquad \Gamma \sim 10^{10} \text{ sec}^{-1}$

quarks not seen because they decay into Leptons

Nucleon Decay

proton - neutron

so (p, n) decay into leptons

3 quark - composite

Triple B - decay $\quad |\Delta B| = 3$

21

(p, n) $B = 3$ $L = 0$ $F = 3$

$|\Delta B| = |\Delta L| = 3, \ \Delta F = 0$

$$n \longrightarrow \nu + \nu + \nu$$

$$p \rightarrow \begin{cases} \nu + \nu + \nu + \pi^+ \\ 4\nu + e^+ \\ 4\nu + \mu^+ \end{cases}$$

No Two Body Decay For neutrons

No Three Body Decay For Proton (charged leptons have negative charge)

If effective decay constt for $q \rightarrow \ell$ is $10^{-9} \mp G_B m_p^2$

the effective constt for nucleon decay is $(G_B m_p^2)^3 \approx 10^{-27}$

No surprise that for $p \rightarrow 3\nu + \pi$ straightforward phase space estimate give $\Gamma \sim 10^{-35}$ sec^{-1}.

iè life-time $\approx 10^{29} - 10^{30}$ years ;

Proton stability & long life } consequence of <u>Quark-Model</u>

Age of Universe 10^{10} years

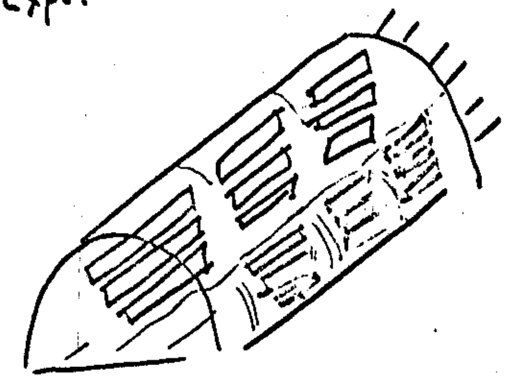
㉒ Expt:	Years	
Goldhaber (1954)	$>1.4\times10^{18}$	spontaneous fission of Th^{232}
Reines Cowan & Goldhaber (1954)	$>1\times10^{22}$	Toulene detector 30m below surface High Energy Decay Fragment.
Kropp & Reines [redacted] (1964)	$>6\times10^{27}$ $>4\times10^{28}$ 15 events; 2 events accepted	High Energy fragment Liquid Scintillation with anti-coincidence shield 585m below surface
Backenstoss, Frauenfelder, Hyams, Koester, Marin (1960)		
Gurr Kropp Reines Meyer (1967)	$>2\times10^{28}$ $>8\times10^{29}$ for special modes	3200 metres below surface
Reines & Crouch (1974)	$>2\times10^{30}$ for $p\to\mu^+$ decay mode 5 events	Same Expt.

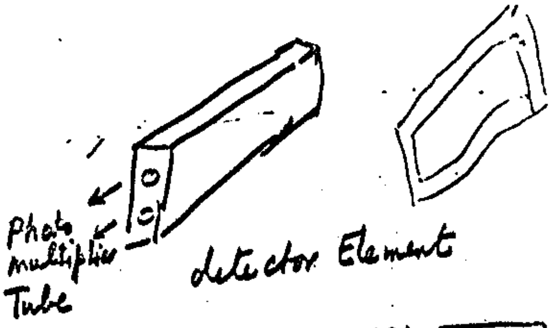
㉓

Impressive except when we realize Reines throughout stresses 2-body decays $p \to \mu^+ + \gamma$, $e^+ + \gamma$ etc

Which are Forbidden in our model

1967 Expt: 3200 m. undergrd.





Detector ~~[illegible]~~ Elements Line The Two Walls

20 Tons = 10^{31} nucleons
180 m^2 scintillator detector

Run length 2.7 years

5 Events of μ^+

stopping & decaying in the scintillator (distinctive delayed coincidence)

could be proton-decay candidates

㉔

Muons produced in atmosphere & penetrating 3.2 km of earth Are rare & energetic; acct for $< \frac{1}{10}$ of observed decay rate

Main backgrd. neutrino-produced muons originating in the rock or the detector.

"It seems prudent to interpret the signal so as to yield a lower lt. on nucleon lifetime."

$\Big\{$ observed Muon Range ~ 200 Mev

$p \rightarrow$ 5 body decay; $4\nu + \mu^{+}$ in our theory so 200 Mev muon rare

Two refinements proposed

(1) look for <u>lower energy</u> muons

(2) Use 100 tons instead of 20 ton material

$n \rightarrow 3\nu + \pi^{0} \rightarrow 3\nu + 2\gamma$ spark chamber

㉕

Cosmology

Proton decay → Early Universe different

→ Black Holes

If nucleon - lepton decay occurs, then only strict law → Charge conservation

⟹ zero mass gauge field, photon

No gauge field of zero mass → B-conservation

Eötvös limit on coupling (Yang & Lee) 10^{-8} times

weaker than gravity.

so if exact conservation ⟺ long-range massless gauge particle, then Baryon conservation does not qualify

Summary.

Matter of one variety ; lepton - Hadron distinction
SLAC ??
a low - energy phenomenon.

Lepton Number is 4th Colour ; quarks carry other three colours

quark Lepton transition possible

Proton decay a triple B-decay → long life of proton

Photon has colour pieces → photon comes completely from non-Abelian generators ; 't Hooft's theorem, monopoles of mass 137 M_W exist.

V+A amplitudes a few % of V-A exist

$\theta_W \sim \frac{g_R}{g_L} \sim$ attractive value ~ 45^0 $\sin^2\theta_W \sim \frac{1}{2}$

Georgi + Glashow 1974 SU(5) model
combines Leptons + Baryons ;
Baryon unstable

Fermion - Boson Super-Symmetry.

① Int: Sym: multiplets SU(2) $\begin{pmatrix} P \\ N \end{pmatrix}$, $\begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}$ ⇒ Particles of same spin

② 1964 → SU(6) / Wigner's SU(4) } attempt to include diff: spins in one multiplet

$$\begin{pmatrix} \pi \\ \rho \\ \omega \end{pmatrix} \begin{matrix} J=0 \\ J=1 \\ J=1 \end{matrix} \qquad \begin{pmatrix} N \\ \Delta \end{pmatrix} \begin{matrix} J=\frac{1}{2} \\ J=3/2 \end{matrix}$$

all Bosons　　　all Fermions

Attempt discredited ⟷ violation of unitarity

NO GO THEOREM

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③ Amazing Development

Not only IS IT POSSIBLE TO CIRCUMVENT THE NO-GO THEOREM; WE NEED TO BE THOROUGH-GOING

It is $\begin{pmatrix} \text{Fermi} \\ \text{Bose} \end{pmatrix}$ particles which make EXACT unitarity preserving multiplets
same mass

Amazing —:

① Bose C.R.
Fermi Anti C.R. $\Big] \Rightarrow$ assertion
Both emerge from the same
formalism

② As a rule Fermions $\begin{pmatrix}\text{leptons}\\ \text{Baryons}\end{pmatrix} \Rightarrow$ Source particles

prejudice in favour of Fermi Partons as basic building Blocks of other matter

<u>Bosons</u> $\longrightarrow$ Exchanged Quanta

① Gauge Particles $\rightarrow$ W, V
② Goldstone zero-mass Particles resulting from broken symmetry spontaneously broken

Now with Fermi - Bose symmetry. expect

Fermion Gauge Particles together with W, V's etc.

$$\downarrow \quad \begin{pmatrix} V \\ A_\mu \end{pmatrix} \quad \downarrow$$

same coupling

Fermion — Goldstone Multiplets

And Bose Partons As Basic Building BLOCKS OF matter specifically

$$\mathcal{M}_{\text{matter}} = \begin{pmatrix} 0^+ \\ 0^- \\ \frac{1}{2} M \end{pmatrix}$$ make a multiplet

one member of which transforms into another

His' extended space-time rotations

A second multiplet is

$$G = \begin{pmatrix} \frac{1}{2} M \\ 1 \end{pmatrix}$$ e.g. $\begin{pmatrix} \nu \\ A_\mu \end{pmatrix}$ neutrino photon

Representation of Super-symmetry

Ⓐ other multiplets obtained by (vectorially) adding spin J to M or G

e.g. $$M_J = \begin{pmatrix} J^+ \\ J^- \\ J+\frac{1}{2} \\ J-\frac{1}{2} \end{pmatrix} \qquad G_J = \begin{pmatrix} J+\frac{1}{2} \\ J-\frac{1}{2} \\ J+1 \\ J-1 \end{pmatrix}$$

Ⓑ OK include int: sym: e.g. $$M_{I=1} = \begin{pmatrix} 0^+ & I=1 \\ 0^- & I=1 \\ \frac{1}{2} & I=1 \end{pmatrix}$$

(C) Further generalisations SU(4) possible

③

Formally Consider
$$A \pm iB = A_\pm$$
$$F \pm iG = F_\pm$$
$$\tfrac{1}{2}(1 \pm i\gamma_5)\psi = \psi_\pm$$

Then Klein-Gordon + Dirac Lagrangian

$$\partial_\mu A_+ \, \partial_\mu A_- + \overline{\psi}_+ \gamma\partial\psi_+ + \overline{\psi}_- \gamma\partial\psi_- + F_+ F_-$$

is INVARIANT FOR
$$\begin{cases} A_\pm \to A_\pm + \overline{\epsilon}\,\psi_\pm \\ \psi_\pm \to \psi_\pm + \frac{1 \pm i\gamma_5}{2}(F_\pm - i\gamma\partial A_\pm)\epsilon \\ F_\pm \to F_\pm - \overline{\epsilon}\, i\gamma\partial\psi_\pm \end{cases}$$
WESS ZUMINO

$\left.\begin{matrix} A_+ \to 0^+, 0^- \\ \psi \to \tfrac{1}{2}M \end{matrix}\right\}$ F dummy Field

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Note transformation parameter is a spinor ϵ_α with the anti-commuting property
$$\epsilon_\alpha \epsilon_\beta + \epsilon_\beta \epsilon_\alpha = 0$$

What is the nature of this transformation and this supersymmetry ; What 'super' object has $\begin{pmatrix} A_\pm \\ \psi_\pm \\ F_\pm \end{pmatrix}$ as its components ?

STRTHDEE SALAM NUC PHYSICS B (1974)

④

Adjoin to space-time manifold $x, y, z, t = x_\mu$ also a 4-component anti-commuting angle θ_α

$$\theta_\alpha \theta_\beta + \theta_\beta \theta_\alpha = 0$$

Define Fields $\Phi(x, \theta)$ super field

Since $\theta_{\alpha_1} \theta_{\alpha_2} \theta_{\alpha_3} \cdots \theta_{\alpha_n}$ must be anti-sym:

it vanishes for $n > 4$.

Hence $\Phi(x, \theta)$ is a polynomial in θ which terminates at θ^4

$$\begin{aligned} \text{So} \quad \Phi(x, \theta) = \; & A(x) \\ & + \bar{\theta}\psi(x) \\ & + \bar{\theta}\theta F(x) + \bar{\theta}\gamma_5\theta G(x) + \bar{\theta} i\gamma_\mu\gamma_5\theta A_\mu \\ & + \bar{\theta}\theta\, \bar{\theta}\chi(x) \\ & + (\bar{\theta}\theta)^2 D(x) \end{aligned}$$

The superfield has 16 components ; 8 Fermions
8 Bosons

Now consider rotations of $\Phi(x,\theta)$ ⑤
through the anti-commuting angle ϵ

Rotation generator S_α,

$$\{S_\alpha, S_\beta\} = -(\gamma_\mu C)_{\alpha\beta} P_\mu$$

$$[S_\alpha, P_\mu] = 0$$

Then the transformations which left K-G + Dirac Lagrangian invariant – ie

$$A \to A + \bar\epsilon\psi$$
$$\psi \to \psi + F\epsilon + \cdots \qquad \text{etc.}$$

are simply the rotations of the *superfield* $\Phi(x,\theta)$ through anti-com: angle ϵ –:

$$e^{i\bar\epsilon S}\,\Phi(x,\theta)\,e^{-i\bar\epsilon S} = \Phi(x-\tfrac{1}{2}\bar\epsilon\gamma_\mu\theta,\ \theta+\epsilon)$$

The Dirac + K-G Lagrangian can be replaced by a Lagrangian for Φ

$$\mathcal{L} = (\bar{D}D)^2 \qquad \Phi\,(\bar{D}D - 2M)\,\Phi$$

where $D = \frac{\partial}{\partial\bar{\theta}} + \frac{i}{2}(\gamma_\mu\theta)\frac{\partial}{\partial x_\mu}$

$$M = \begin{pmatrix} 0^+ \\ 0^- \\ \frac{1}{2}M \end{pmatrix} \Rightarrow \begin{pmatrix} A \\ B \\ \psi \\ F \\ G \end{pmatrix}$$

$A_\pm = A \pm iB$

$F_\pm = F \pm iG$

$$G = \begin{pmatrix} \frac{1}{2}M \\ 1 \end{pmatrix} \Rightarrow \begin{pmatrix} \lambda \\ A_\mu \\ D \end{pmatrix}$$

$$\Phi = M + G$$

Both CR for A, B .. fields (Bosons)
ACR ψ fields (Fermions)

contained in $\boxed{\text{C.R.}}$ $[\Phi(x,\theta)\ \Phi(x',\theta')]$

$$\Rightarrow [A(x)\ A(x')] + \theta\bar{\theta}'\,\{\bar{\psi}(x)\ \psi(x')\} + \cdots\cdots$$

Renormalizable Lagrangians

⑦

Three Known Lagrangians

(Wess - Zumino)

(1) MMM $\Longrightarrow$ A, B, ψ

Form $g\,(\bar{\Psi} A \psi + \bar{\Psi} \gamma_5 B \psi)$

$+ g^2 (A^4 + B^4 + 2A^2 B^2)$

$+ gm\,(A^3 + B^2 A)$

usual Yukawa-like but __definite__ couplings

ILIOPOLOUS + Zumino only one infinite Z.

self-mass
self-charge finite.

(2) __Gauge Lagrangian__

– Wess Zumino
(Salam Strathdee
Wess Zumino)
Ferrara

⑧

$$G = \begin{pmatrix} \lambda \\ A_\mu \\ D \end{pmatrix} \to \begin{pmatrix} \frac{1}{2} \\ 1 \\ \end{pmatrix} \qquad \partial_\mu A_\mu = 0$$

Assume each field represents ⇒ an adjoint rep: of an internal sym: SU(n).

$$\mathcal{L} = GGG \Rightarrow \quad D^2 + \left| \partial_\mu A_\nu - \partial_\nu A_\mu + ig\,[A_\mu, A_\nu] \right|^2$$
$$+ \quad \bar{\lambda}\, \gamma_\mu (\partial_\mu + ig A_\mu) \lambda$$

New feature <u>gauge Fermion λ</u>

Dummy field D Eqn of motion $D = 0$

Third Lagrangian Matter Gauge interaction

MGM = usual Yang Mills int: of A_μ with matter

$$M = \begin{pmatrix} A_+ \\ \psi_+ \\ F_+ \end{pmatrix} \qquad G = \begin{pmatrix} \lambda \\ A_\mu \\ D \end{pmatrix}$$

Analogy + new Yukawa-like int:

$$\left.\begin{matrix}\text{Higgs} \\ \bar{\psi}\psi\phi\end{matrix}\right\} \qquad g\, \underset{\text{matter}}{\bar{\Psi}_+}\ \underset{\text{gauge}}{\lambda}\ \underset{\text{matter}}{A_+}$$

$$\left\{\begin{matrix}\text{Higgs} \\ \phi^4\end{matrix}\right. \to \quad + \; g\, \underset{\text{matter}}{A_+^+}\ \underset{\text{gauge}}{D}\ \underset{\text{matter}}{A_+} \qquad \text{Same constant } g$$

Peculiar Features of Supersymmetric Lagrangians ⑨

(1) Gauge Int: GGG

Besides gauge mesons in adjoint rep:

must have gauge Fermions in adjoint rep:

(2) To conserve Fermion number (B or L, or B+L)

must have both $\left.\begin{matrix} V+A \\ V-A \end{matrix}\right\}$ gauges → $\boxed{\begin{matrix}\text{EM} \\ \text{Monopole}\end{matrix}}$

(3) Matter gauge Int: If matter belongs to adjoint rep:, int: is automatically FREE of ANOMOLIES

(4) To conserve Fermion number, can not allow explicit supersym: mass term for ~~mat~~ matter

(can not allow mass term for gauge fields d local gauge invariance).

(3) $V+A \longrightarrow \begin{matrix}\text{Gauge } \lambda_R \\ \text{Matter } \psi_L\end{matrix}$ so No anomolies

⑪

If ν is gauge fermions its universal coupling to all matter will mean its mixing in - of Lepton + Baryon number thro'

$$g \; \overline{L}_+ \, \nu \; A_+$$
$$+ g \; \overline{Q}_+ \, \nu \; A'_+$$

when $\langle A_+ \rangle , \langle A'_+ \rangle \neq 0$

to give masses to L and Q