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CONFERENCE ON FUNDAMENTAL SYMMETRIES AND FUNDAMENTAL CONSTANTS

15 - 18 September 2004

MILLI-CHARGED PARTICLES

R.N. Mohapatra
U. Maryland. USA

MINI-

~~MILLI~~-CHARGED PARTICLES

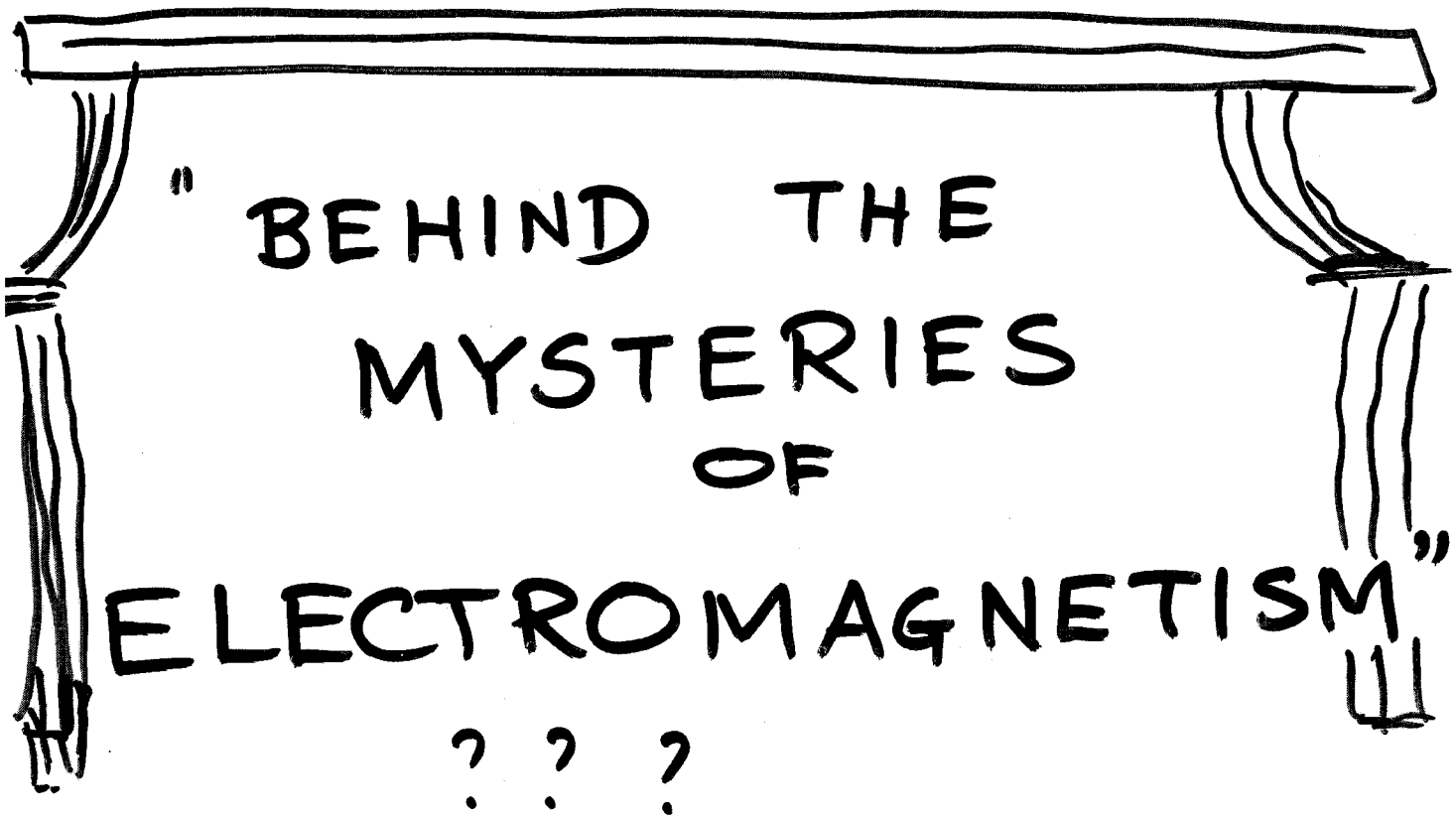
R. N. MOHAPATRA
TRIESTE, 2004.

- CONSTRAINTS
- THEORETICAL PLAUSIBILITY

WE ALL BELIEVE:

$$\begin{pmatrix} u\left(\frac{2}{3}\right) & u\left(\frac{2}{3}\right) & u\left(\frac{2}{3}\right) & \nu(0) \\ d\left(-\frac{1}{3}\right) & d\left(-\frac{1}{3}\right) & d\left(-\frac{1}{3}\right) & e(-1) \end{pmatrix}$$

HOW TRUE AND WHY?



MYSTERIES

*1. PARTICLES OF ARBITRARY CHARGES

2. $\partial_\mu J^\mu_{em} = 0$

3. $m_\gamma = 0$

4. P-CONSERVATION IN QED

(LOCAL, LORENTZ INV. FIELD THEORIES)

SOME FACTS:

1) IS ELECTRIC CHARGE CONSERVED?

$\Delta Q \neq 0 \Rightarrow$ $e \rightarrow \nu + \gamma$

$\rightarrow 3\nu$

$e^- \leftrightarrow e^+$

SPONTANEOUS X-RAY EMISSION FROM ATOMS

$\tau_e \geq 10^{25}$ yrs

$\Delta Q \neq 0 \Rightarrow \delta m_\gamma \neq 0$

$\delta m_\gamma \leq 10^{-22}$ MeV

(DAVIS, GOLDHABER, NIETO)

JUPITER MAGNETIC FIELD, GEOMAGNETIC FIELD OF EARTH, ...

WILL ASSUME:

"ELECTRIC CHARGE CONSERVED".

ii) EVIDENCE FOR QUANTIZATION:

(a) NEUTRALITY OF ATOMS:

$$N Q_n + Z(Q_p + Q_e) = Q_{ATOM}$$

- n-beam from REACTORS:

$$Q_n \leq 10^{-21} e$$

MAMPE et. al. 1989

- $Q(CO_2) \leq 2.2 \times 10^{-19} e$ PICCARD & KESSLER 1925

$$Q(N_2) \leq (6 \pm 6) \times 10^{-20} e$$
$$Q(Ar) \leq (4 \pm 4) \times 10^{-20} e$$
$$Q(He) \leq (4 \pm 2) \times 10^{-20} e$$
$$Q(H_2) \leq (-2.5 \pm 1.5) \times 10^{-20} e$$

$$Q(Cs) \leq 10^{-20} e$$ (HUGHES et. al.)

•, D_2, ...

$$Q_p + Q_n \leq 10^{-20} e$$

- ν - FROM SN 1987A

$$Q_\nu \leq 10^{-17} e$$ Cocconi & BARBIELLINI

- β-DECAY

$$Q_n - Q_p = Q_e - Q_\nu$$

b) SUPPOSE $Q_p \neq Q_e$. $Q_p + Q_e = Q_E$; P

EARTH WILL HAVE A NET CHARG

$$\frac{N_A Q_E}{R_\oplus^2} \simeq E_\oplus \leq 100 \frac{\text{Volts}}{\text{m}}$$

$$\Rightarrow \quad Q_E < 10^{-27}$$

(CANCELLATIONS , SCREENINGS ; ...)

COULOMB'S LAW: $F = k \frac{q_1 q_2}{r^2}$; $E = \frac{\text{Newtons}}{\text{Coulomb}}$

$k = 9 \times 10^9 \ N m^2/C^2$

$e = 1.6 \times 10^{-19} \ C$

$N_A \simeq 4 \times 10^{51}$ (NO. OF ATOMS IN EARTH).

c) STABILITY OF GALAXIES

SUPPOSE: $Q_p + Q_e = 0$

BUT $Q_n = -Q_{\bar{\nu}}$

$\Rightarrow$ GALAXIES BECOME UNSTABLE WHEN

$$V_{EM} \approx V_{GRAVITY}$$

OR $$Q_n^2 N_A^2 \approx G_N m_p^2 N_A^2$$

$$\Rightarrow \quad Q_n \leq \frac{1}{10} \left(G_N m_p^2 \right)^{1/2} \simeq 1$$

OF COURSE NEUTRINOS COULD SCREEN V_{EM} AND HELP SAVE TH SITUATION !!

HOWEVER, $L_{\nu,\,SCREEN} \approx \frac{1}{Q_\nu e T_\nu} \approx 10^{21}$ $\ll L_$

CHARGE CONSERVATION IN WEAK INT.

$$Q_p - Q_n = Q_u - Q_d = Q_\nu - Q_e$$

ALLOWS:

$$Q_u = \frac{2}{3} + \varepsilon_1$$

$$Q_d = -\frac{1}{3} + \varepsilon_2$$

$$Q_\nu = \varepsilon_1 + \delta$$

$$Q_e = -1 + \varepsilon_2 + \delta$$

$$\varepsilon_1, \varepsilon_2, \delta \lesssim 10^{-19} - 10^{-20}$$

SEVERE LIMITS FOR $p, n, \nu e$!

BUT WHAT ABOUT OTHER PARTICLES ?

MANIFESTATION OF MINI-CHARGED PARTICLES OF ARBITRARY MASS : (Q_ϵ, m_ϵ)

(i) NUCLEOSYNTHESIS

$$\delta N_\nu < .3$$

$$\Rightarrow \quad Q_\epsilon > 10^{-8}, \quad m_\epsilon < \text{MeV}$$

RULED OUT !!

DAVIDSON, PESKIN

$$R(e^+e^- \to \epsilon^+\epsilon^-) < \sqrt{g_*}\,\frac{T^2}{M_{Pl}}$$

$$+ \quad R(\epsilon^+\gamma \to \epsilon^+\gamma) < \sqrt{g_*}\,T^2/M_{Pl}$$

iv) CMB ANISOTROPY:

DUBOVSKY, GORBUNOV, RUBTSOV
hep-ph/0311189.

$$10^{-6} < Q_\epsilon < 1$$

$$\text{WMAP} \Rightarrow \Omega_\epsilon h_0^2 \leq 0.007$$

(95% CL)

v) RELIC ABUNDANCE

R. N. M., NUSSINOV '92

$$\sigma_{\epsilon^+\epsilon^-} \sim Q_\epsilon^2/m_\epsilon^2 \text{ OR } Q_\epsilon^4/m_\epsilon^2$$

$m_\epsilon < m_e$

$$\frac{m_\epsilon}{Q_\epsilon^2} \leq \text{TeV}$$

ALLOWED.

$m_\epsilon > m_e$

$$\frac{m_\epsilon}{Q_\epsilon} \leq \text{TeV}$$

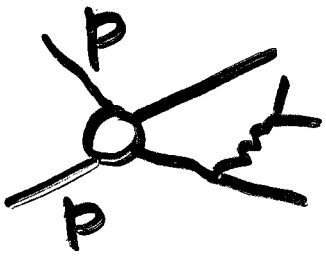
"

SN 1987A

(R.N.M., ROTHSTEIN '90)

$m_\epsilon < 100\ \text{MeV}$

$\Rightarrow$ NEW CHANNEL FOR ENERGY LOSS !!



$+ \cdots$

$$E_\epsilon < 20\%\ E_\nu$$

$\Rightarrow$ $m_\epsilon < 100\ \text{MeV}$ } RULED OUT !!

$$10^{-13} \lesssim Q_\epsilon \lesssim 10^{-7}$$

(iii) OTHER ASTROPHYSICAL BOUNDS:

(DAVIDSON, HANNESTAD, RAFFELT

HB STARS: $10^{-8} \leq Q_\epsilon \leq 2 \times 10^{-14}$

FOR $m_\epsilon <$ 10 keV.

STELLAR EVOLUTION AFFECTED BY LIGHT MIALI CHARGES:

$H^* \longrightarrow H_\epsilon^*$

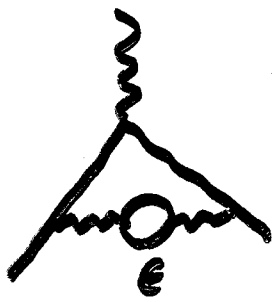
NEW CHANNELS $\Rightarrow$ FASTER EVOLUTION

LABORATORY

Z - WIDTH :

RULES OUT $m_\epsilon < \frac{M_Z}{2}$, $Q_\epsilon > \cdot 2$

g - 2



$Q_\epsilon > 10^{-2}$ **OUT.**

SLAC (98) EXPT.

(PRINZ et. al. PR

$e^+e^- \to \epsilon^+\epsilon^-$

$Q_\epsilon > 4 - 5 \times 10^{-5}$, $m \sim 1 - 10$ MeV

OUT.

INVISIBLE DECAYS OF ORTHO-POSITRONIUM: $(1^3S_1\ e^+e^-)$

$$(e^+e^-)_{1^3S_1} \longrightarrow \epsilon\bar{\epsilon}$$

FOR $m_\epsilon < m_e$:

MITSUI et. al. (92)

$$B_r(o\text{-}Ps \to \epsilon\bar{\epsilon}) < 2.8 \times 10^{-6}$$

$$\Gamma_\epsilon \approx \frac{\alpha^5 Q_\epsilon^2 m_e}{6} \; ; \; \Gamma_\gamma \sim \alpha^3$$

NEW PROPOSAL BY BADERTSCHER et. al. (hep-ex/0404037)

TO 10^{-8} LEVEL.

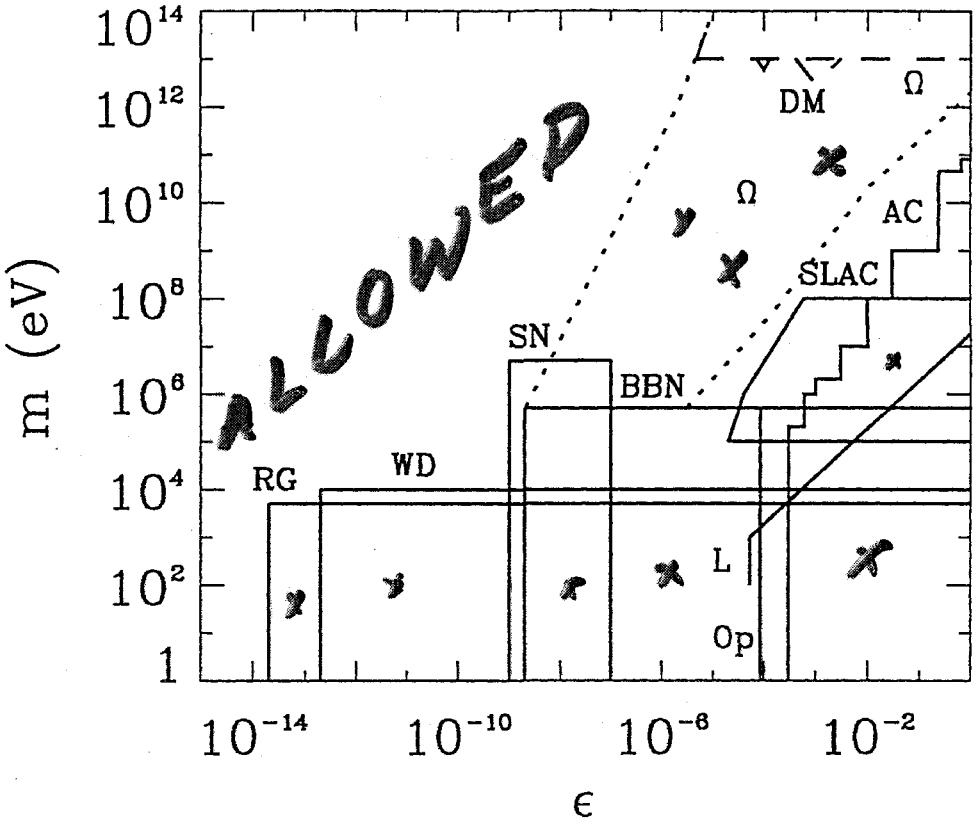


Figure 1: Regions of mass-charge space ruled out for milli-charged particles. The solid and dashed lines apply to the model with a paraphoton; solid and dotted lines apply in the absence of a paraphoton. The bounds arise from the following constraints: AC—accelerator experiments; Op—the Tokyo search for the invisible decay of ortho-positronium [26]; SLAC—the SLAC milli-charged particle search [27]; L—the Lamb shift; BBN—nucleosynthesis; Ω —$\Omega < 1$; RG—plasmon decay in red giants; WD—plasmon decay in white dwarfs; DM—dark matter searches; SN—Supernova 1987A.

HOW THEORETICALLY PLAUSIBLE ARE MINI-CHARGES ?

1. PHOTON - PARAPHOTON MIXING AND MINICHARGES : (HOLDOM &c)

- **MANY EXTENSIONS OF STD. MODEL WITH PARAPHOTONS :**

A. MIRROR UNIVERSE MODELS :

GLASHOW '85
FOOT, VOLKAS '95
BEREZHIANI, R.N.M's

B. STRING MODELS WITH BRANE - ANTI - BRANE MIXING.

ABEL, SCHOFIELD
hep-th/0311051

$$\Rightarrow -\frac{Q\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

$$e \to e(1+Q\epsilon)$$

MIRROR UNIVERSE MODEL

(MOTIVATED BY ν - PHYSICS (LSND) AND DARK MATTER).

$G_{STD} \otimes G'_{STD}$

$SU(3)_c \times SU(2)_L \times U(1)$ $\quad$ $SU(3)_c \times SU(2)_L \times U(1)$

Q $\quad$ Q'

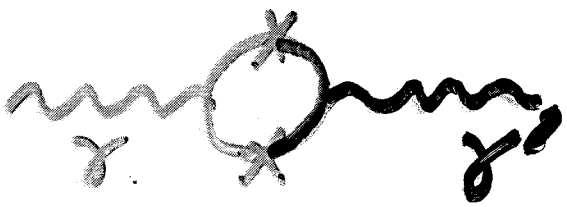
L $\quad$ L'

u_R, d_R, e_R $\quad$ u'_R, d'_R, e'_R

N_R $\quad$ N'_R

W, Z, γ $\quad$ W', Z', γ'

$\Rightarrow$



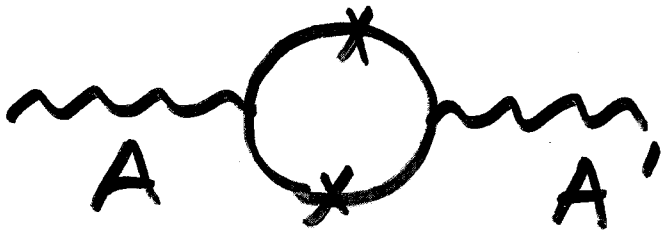
$\simeq \frac{\alpha}{4\pi} \cdot \left(\frac{\mu\mu'}{M^2}\right) \ldots$

TWO U(1)'s AND MILLI-CHARGE

$$\mathcal{L} = e\left(J_\mu A^\mu + J'_\mu A'^\mu\right)$$

$$-\frac{1}{4}\left(F^{\mu\nu}F_{\mu\nu} + F'^{\mu\nu}F'_{\mu\nu}\right)$$

$$-\frac{1}{2}\chi\, F^{\mu\nu}F'_{\mu\nu}$$



- MIRROR UNIVERSE MODEL

  + ...

DIAGONALIZE:

$$A_1'' = (1-\chi)^{1/2}(A + A')/\sqrt{2}$$
$$A_2'' = (1+\chi)^{1/2}(A' - A)/\sqrt{2}$$

$$\Rightarrow \mathcal{L}_{em} = \frac{e}{\sqrt{2}} J \left(\frac{1}{(1-\chi)^{1/2}} A_1'' - \frac{1}{(1+\chi)^{1/2}} A \right.$$

$$+ \frac{e}{\sqrt{2}} J' \left(\frac{1}{(1-\chi)^{1/2}} A_1'' + \frac{1}{(1+\chi)^{1/2}} A_2'' \right)$$

OUR PHOTON $= \frac{1}{\sqrt{2}} \left[\frac{A_1''}{(1-\chi)^{1/2}} - \frac{A_2''}{(1+\chi)^{1/2}} \right]$

$\equiv A_{PHYS.}$

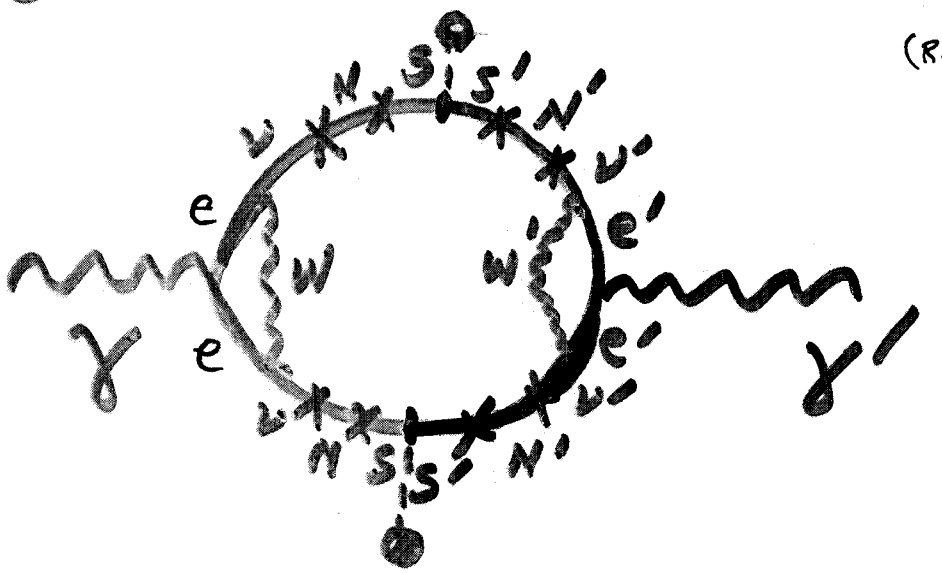
J' INTERACTION:

$$\mathcal{L}' = e J_\mu' \left[\tilde{A}_{PHYS} + \chi A_{PH} \right.$$

PRIME MATTER IS MILLI-CHARGED!

ESTIMATE OF χ (Q_e) IN A MIRROR MODEL THAT AVOIDS ALL COSMOLOGICAL PROBLEMS AND FITS LSND:

(R.N.M., NASRI '04)



$$\chi \simeq G_F G_F' \frac{\alpha}{4\pi} \cdot \frac{M_{\nu D}^2 M_{\nu D'}^2 \langle \phi \rangle^2}{M_N^2}$$

$$\simeq 10^{-23} - 10^{-24}$$

$$Q_e \simeq 10^{-23} ;$$

STUCKELBERG U(1) AND MILLI-CHARGES:

KÖRS & NATH '04

$U(1)_{ST.}$: (MASS WITHOUT HIGGS MECH.)

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} (\partial_\mu \sigma - A_\mu)^2$$

$$A \to A + \partial_\mu \Lambda$$
$$\sigma \to \sigma + \Lambda$$

MILLICHARGES:

GAUGE GROUP: $G_{STD} \times U(1)_{ST.}$

WITH $-\frac{1}{2} (\partial_\mu \sigma - c A_\mu - s B_\mu)^2$

SUPPOSE: $A_\mu J^\mu_{\text{HIDDEN MATTER}}$.

$\Rightarrow$ MILLICHARGED HIDDEN MATTER

STANDARD MODEL AND ELECTRIC CHARGES OF QUARKS AND LEPTONS:

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$Q_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L : \quad (2, Y_q)$$

$$u_R \qquad (1, Y_u)$$

$$d_R \qquad (1, Y_d)$$

$$e_R \qquad (1, Y_e)$$

$$L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad (2, Y_\ell)$$

$$H \qquad (2, -1)$$

5 Y's:

YUKAWA COUPLING (OR MASS) $\Rightarrow$

$$Y_u = Y_q + 1$$
$$Y_d = Y_q - 1$$
$$Y_e = Y_\ell - 1$$

(SAME HIGGS FOR EWSB AND FERMION MASSES)

$5 - 3 = 2$ Y's.

ANOMALY FREEDOM:

$$\Rightarrow \quad \mathrm{Tr}\, Y\,[SU(2)_L]^2 = 0 \quad \Rightarrow \quad 3Y_q + Y_\ell = 0$$

$$\mathrm{Tr}\, Y^3 = 0 \qquad\qquad Y_\ell = -1$$

ALL Y'S DETERMINED AND ELECTRIC CHARGE QUANTIZED!!

STD. MODEL $\Rightarrow$ $m_\nu = 0$.

$m_\nu \neq 0$ $\Rightarrow$ ADD ν_R. (Y_ν)

6 Y'S: $(Y_q, Y_\ell, Y_u, Y_d, Y_e, Y_\nu)$

BUT 5 CONSTRAINTS.

$\Rightarrow$ NO ECQ !!

FOOT, LEW, JOSHI, VOLK, DESHPANDE

REASON:

STD + ν_R

$$\mathrm{Tr}\,(B-L)^3 = 0.$$

$\Rightarrow$ B-L IS GAUGEABLE SYM.

IT DEQUANTIZES $Q_{e.l.}$:

$$Q = I_{3L} + \frac{Y}{2} + \epsilon(B-L)$$

(BABU, R.N.M '90)

TRUE FOR DIRAC ν.

IF ν = MAJORANA

$\Rightarrow$ $Y_\nu = 0$ AND QUANTISATION IS RESTORED!!

OTHERWISE

QUARKS AND LEPTONS WOULD HAVE APPRORRIATELY SHIFTED MILLICHARGES !!

EXAMINE THE ASSUMPTIONS THAT LEAD TO ECQ$_X$ IN SM:

i) ONE HIGGS DOUBLET: (Φ)

SUPPOSE Y_Φ IS ARBITRARY

$$Q = I_3 + \frac{1}{2}\frac{Y}{Y_\Phi}$$

REDEF. $g_Y \Rightarrow Y_\Phi = 1 \Rightarrow$ USUAL FORMULA.

i) ASSUME THE SAME HIGGS $\Rightarrow$ FERMION MASSES.

$$\Rightarrow \quad Y_u = 1 + Y_Q$$

$$Y_e = -1 + Y_\ell \quad \text{etc.}$$

$$\Rightarrow \quad Q_{e_L} = Q_{e_R}\,; \quad Q_{u_L} = Q_{u_R}$$

(OR QED VECTOR LIKE).

$$\Rightarrow \quad Q_\nu = 0. \quad (\text{VECTOR QED CONNECTED TO } Q)$$

SUMMARY :

i) ANOMALIES

+ VECTOR QED

$\Rightarrow$ CHARGE QUANTIZATION IN STANDARD MODEL (DESPITE $U(1)_Y$)

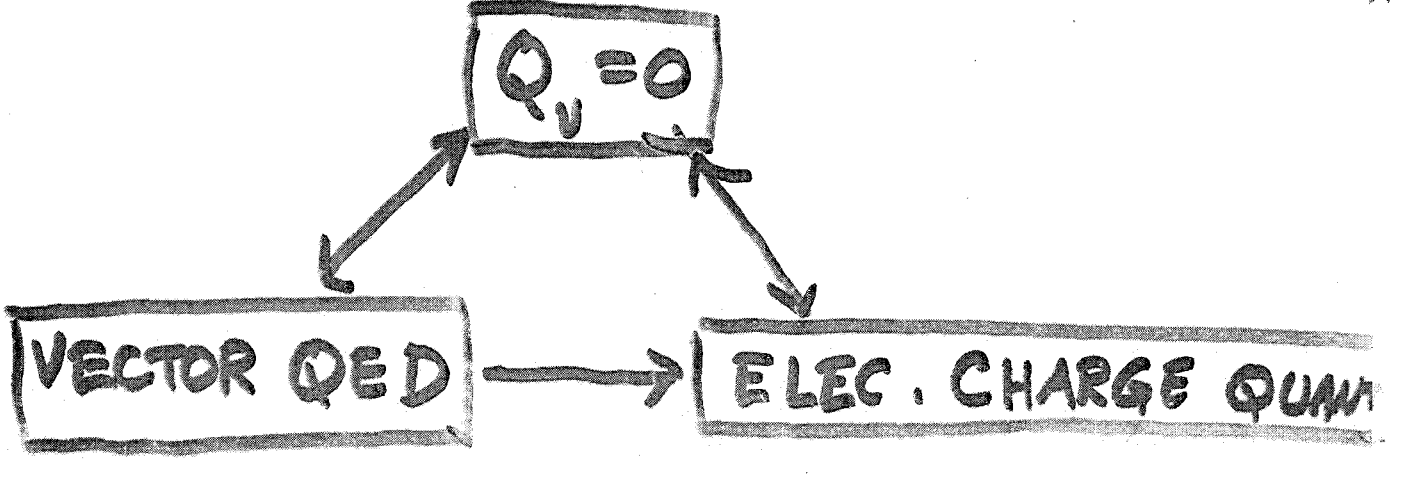
+ $Q_V = 0$

ii) ALTERNATIVELY.

ANOMALIES + $Q_V = 0$

$\Rightarrow$ a) VECTOR QED

+ b) CHARGE QUANTIZATION



SUPPOSE WE HAVE 2 HIGGS DOUBLETS : $(\phi_{1,2})$

$\{\phi_1$ BREAKS SYMMETRY
ϕ_2 GIVES FERMION MASSES$\}$

- $Y_{\phi_1} = 1$; BUT Y_{ϕ_2} ARBITRARY

$\langle\phi_1\rangle \neq 0 \Rightarrow Q = I_{3L} + \frac{Y}{2}$

$\langle\phi_2\rangle \neq 0 \Rightarrow \Delta Q \neq 0$ $\quad (Y_{\phi_2} = Q_e)$

ONE CAN HAVE $Q_\nu = \frac{1}{2} Q_e$

A NEW SOLN. TO THE ANOMALY EQN's.

$$Y_L = -1 + Q_e$$

$$Y_q = \frac{1}{3}(1 - Q_e)$$

$$Y_e = -2(1 - Q_e)$$

$$Y_{d_R} = -\frac{2}{3}(1 - Q_e); \quad Y_{u_R} = \frac{4}{3}(1 - Q_e)$$

$$Y_\nu = -1 + Q_e \Rightarrow Q_\nu = Q_e$$

STD MODEL' $\Rightarrow Q_\nu \neq 0$; $Q_e \neq Q_{em}$ ...

$\Delta Q \neq 0$

QED VIOLATES PARITY!!

$$\mathcal{L}^{(-)}_{QED} = \frac{i}{2} e Q_\epsilon \left[-\bar{e}\gamma_\mu\gamma_5 e + \bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d \right]$$

$$m_\gamma \simeq \frac{e}{\sqrt{2}} Q_\epsilon \tilde{v}_{wk} .$$

(BABU, R.N.M. '90)

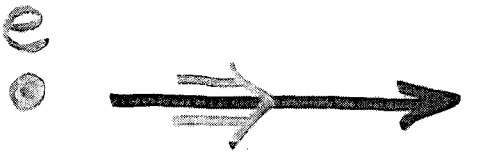
$$m_\gamma < 10^{-25}\ \text{GeV}$$

$$\Rightarrow Q_\epsilon < 10^{-27}$$

- CONNECTS Q^ν, $\Delta Q \neq 0$ AND P-VIOLATION IN QED

SEEING CHARGE VIOLATION INTUITIVELY

LAB

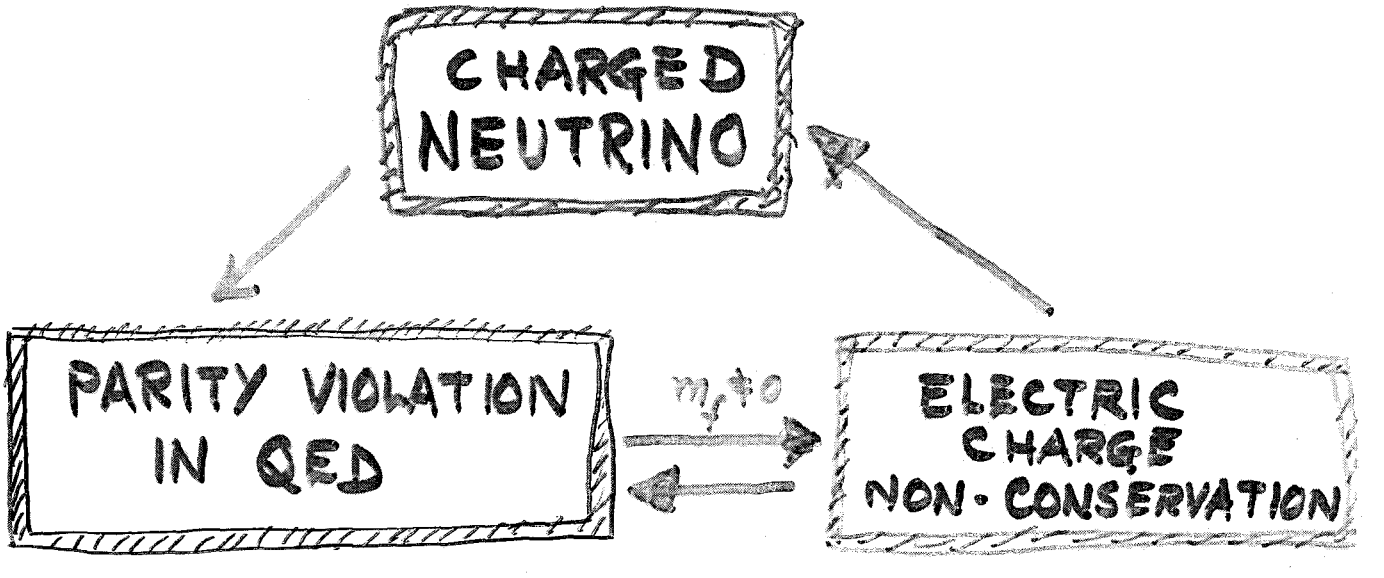


$Q_{e_R} = -1$

MOVING FRAME $(V_{OBS.} > V_e)$

$Q_{e_L} = -1 + \varepsilon$

POSSIBLE ONLY IF $m_e \neq 0$!! (OR $\langle \phi_2 \rangle \neq 0$)



P-VIOLATING QED ⇒

(i) SPIN DEPENDENT LONG RANGE FORCE

$$\approx \frac{Q_e^{\prime} N_n}{m_f} \frac{\vec{\sigma}\cdot\hat{r}}{r^2}$$

(ii) $$Q_p + Q_e = 0$$

$$Q_n = -Q_\nu \neq 0$$

$$E_{earth} \leq 100\ V/m$$

$$\Rightarrow |Q_\nu| \leq 10^{-21} e .$$

$E \neq 0$

EARTH

INTRIGUING CONNECTIONS:

- $m_\nu = 0$: $\gamma_5 \nu = \nu$ ⇒ V-A TH. OF WEAK INT.

- $Q_\nu = 0$: $e^{i\alpha Q_{em}} \nu = \nu$ ⇒ PURE V E&M

- $m_\nu \neq 0$ ⇒ V+A CURRENTS

(LEFT-RIGHT SYM. MODELS)

$$H_{wk}(V+A) \simeq \frac{m_\nu^2}{m_e^4} (V+A)(V+A)$$

- $Q_\nu \neq 0$ ⇒ SMALL PARITY VIOLATING EFFECTS IN E&M !!

CONCLUSION

- MILLI-CHARGED PARTICLES, THOUGH AT THE FRINGE OF OUR EXPECTATIONS, PROVIDE AN INTRIGUING POSSIBILITY THAT IS COMPLETELY PLAUSIBLE !!
- THEY ARE HOWEVER SEVERELY CONSTRAINED BY BOTH COSMOLOGY AND ASTROPHYSICS AS WELL AS TO SOME EXTENT BY LABORATORY !!
- NEED TO BE EXPLORED FURTHER !!
- AN INTRIGUING CONNECTION BETWEEN Q_ν, $\Delta Q \neq 0$ AND P-CONSV IN QED.