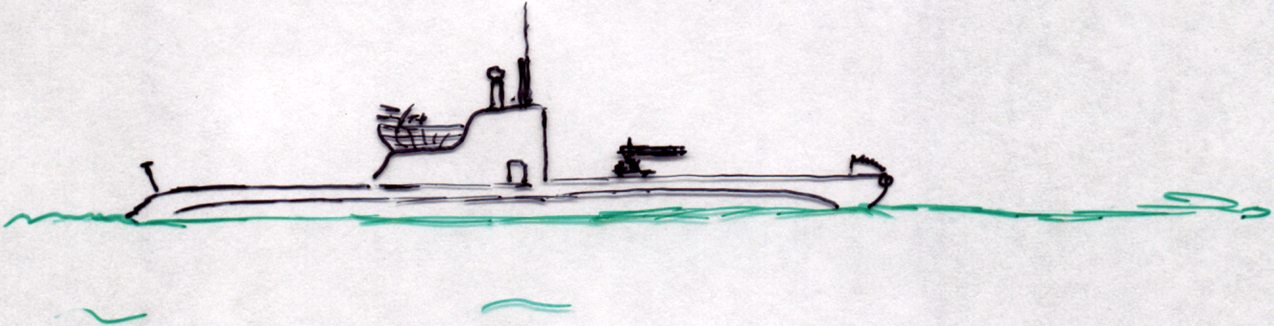
Neutrino beam for submarine detection

K2K

NEXT GENERATION

NEUTRINO DETECTOR



# NEUTRINO MASSES :

# WHAT DOES IT ALL MEAN ?

$\nu$-fact '00

P. Ramond

May 22, 2000

FermiLab and Univ. of Florida

- Some History
- Standard Model Neutrinos
- Experimental Outlook
- Theories
- Future Directions

# NEUTRINO HISTORY

- neutrinos have been around since the earliest moments of our universe, but their existence was noticed by humans only in the XXth century.

- POSTULATED BY W. PAULI , DEC 1930

"Dear Radioactive Ladies and Gentlemen ..."

"desperate remedy..." to explain

- exclusion principle for the nuclear wavefunction (N14, Li6)
- continuous β-spectrum

"I don't feel secure enough to publish anything about this idea..."

"Only those who wager can win..."

"However, I cannot appear in Tübingen since I am indispensable here on account of a ball ..."

- written 5 days after divorcing his first wife, actress Kate Deppner

- a year or so later, Pauli started seeing Carl Jung

- THERE IS A SPIN 1/2 NEUTRAL PARTICLE THAT LIVES INSIDE THE NUCLEUS

  THIS TAKES CARE OF THE SYMMETRY OF THE NUCLEAR WAVEFUNCTION

- IT IS EMITTED IN $\beta$-RADIOACTIVITY

  THIS TAKES CARE OF THE CONTINUOUS ELECTRON SPECTRUM

CALL IT NEUTRON ( lives inside nucleus by magnetic interactions ? )

MASS $\lesssim$ .01 PROTON MASS

1932

- CHADWICK DISCOVERS HEAVY NEUTRAL NUCLEON : NEUTRON

1933

- FERMI : PAULI'S PARTICLE IS NOT BOUND INSIDE NUCLEON BUT IS EMITTED IN $\beta$-PROCESS

  IT IS LIGHT : NEUTRINO is born!

- DETECTION OF $\bar{\nu}_e$ Cowan, Reines 1956

$$\bar{\nu}_e + p \rightarrow n + e^+$$

$e^+$ → annihilates

back to back $\gamma$'s .5 MeV

detected by pmt's

$n$ → slowed by Cadmium

$\gamma\gamma\gamma$ produced later

look for coincidences.

- 1962 DETECTION OF $\bar{\nu}_\mu$

- 1968 DETECTION OF SOLAR $\nu_e$ R. Davis

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

inert, radioactive (Pontecorvo, 1945)

find half as many as predicted by Solar models.

- 1987 SUPERNOVA NEUTRINO BURST DETECTED IN PROTON DECAY MONITORING DEVICES ! IMB, KAMIOKA.

- 1990-95 SOLAR $\nu_e$ SPECTRUM EXPLORED SAGE, GALLEX

  DEFICIT CONFIRMED !

- WEAKLY INTERACTING NEUTRINOS $\lessapprox 3$ SLAC, CERN.

- 1998 SUPERK EFFECT OF OSCILLATIONS OBSERVED IN NEUTRINOS PRODUCED BY COSMIC RAYS.

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

$$\nu_{\mu,e} + N \rightarrow \mu, e + X$$

$\nu_\mu / \nu_e \sim .6$ OF THEORY

# $\nu_\mu$ IS ZENITH-ANGLE DEPENDENT !

EVIDENCE FOR $\nu_\mu \rightarrow ?$ OSCILLATIONS !

NEUTRINO MASSES ARE A REALITY !

# NEUTRINOS IN THE STANDARD MODEL

$\nu_{Li}$ $\quad i = 1, 2, 3$ $\quad$ PART OF ISODOUBLET

$i = e, \mu, \tau$

$$I_W = \tfrac{1}{2} \qquad (I_W)_3 = \tfrac{1}{2} \qquad L_i = 1$$

ONLY POSSIBLE MASS TERM : MAJORANA MASS

$$\nu_i^T \nu_j \qquad I_W = 1 \quad \text{ISOTRIPLET}$$

$$(I_W)_3 = +1$$

$$L_i + L_j = 2$$

- NO TREE-LEVEL NEUTRINO MASS

  ( no HIGGS ISOTRIPLET WITH $\Delta L = -2$ )

AT QUANTUM LEVEL , CAN GENERATE

$$\nu_i^T \vec{\tau} \nu_j \; H \vec{\tau} H$$

INVARIANT UNDER $SU_2 \times U(1)$

HAS $L_i + L_j = 2$

STANDARD MODEL NEUTRINO MASS FORBIDDEN

ONLY BY

CHIRAL GLOBAL SYMMETRIES : LEPTON NUMBERS

- total lepton number $L \equiv L_e + L_\mu + L_\tau$

  $\rightarrow$ ( B-L by anomalies )

- relative lepton numbers $L_e - L_\mu$ , $L_\mu - L_\tau$

$m_\nu \neq 0 \Longrightarrow$ PHYSICS BEYOND STANDARD MODEL

WHAT KIND OF PHYSICS ?

CAN NEUTRINO MASSES AND MIXING

GIVE US A HINT ?

## WHAT DO EXPERIMENTS TELL US (SO FAR)?

- NEUTRINO MASSES ARE SMALL

$m_{\nu_e} \lesssim$ few eV

$m_{\nu_\mu} \lesssim 160$ keV WHY SO SMALL?

$m_{\nu_\tau} \lesssim 18$ MeV

WHAT KIND OF MASS?

$\nu_e$ MASS LIMITS : • $^3H \to {}^3He + e^- + \bar{\nu}_e$

direct kinematic search

• Absence of $\cancel{\nu}\beta^2$

violates $L_e$ by two units

tests $\Delta L \neq 0$ mass

MAJORANA MASS

# • OSCILLATION EXPERIMENTS

## SUPER K :

- **Atmospheric Neutrinos** produced when cosmic rays hit atmosphere

deficit in # $\nu_\mu + \bar{\nu}_\mu$ as a function of direction

SOME $\nu_\mu$ DISAPPEAR INTO $\nu_x$

- interpreted as oscillation with

$$| m^2_{\nu_\mu} - m^2_{\nu_\tau} |^2 \simeq 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{\nu_\mu - \nu_\tau} \gtrsim .86$$

- $\nu_x = \nu_\tau$

  - data favors $\nu_{active}$ with neutral current interactions (matter effects through the earth)

  - CHOOZ rules out $\nu_x = \nu_e$
  - PALO VERDE

so it seems that $\nu_\mu$ oscillates into $\nu_\tau$ .

## Solar neutrinos

MANY EXPERIMENTS HAVE REPORTED A SOLAR NEUTRINO <u>DEFICIT</u>

(solar theory in good shape)

- $^8B$ , PP , Be , ... Chlorine Davis ...

  Gallium SAGE , GALLEX

DEFICIT CAN BE PARAMETRIZED IN TERMS OF OSCILLATIONS IN SEVERAL WAYS :

- VACUUM OSCILLATIONS : $\nu_e \to \nu_?$

  Glashow-Krauss

$$|m^2_{\nu_e} - m^2_{\nu_?}| \sim 10^{-10} - 10^{-11} \text{ eV}^2$$

(VO)

$$\sin^2 2\theta \gtrsim .7$$

- MSW OSCILLATIONS : $\nu_e \to \nu_?$

  - non-adiabatic level crossing :

    Parke, Rosen-Gelb, ...

$$|m^2_{\nu_e} - m^2_{\nu_?}| \sim 5 \times 10^{-6} \text{ eV}^2$$

(SMA)

$$\sin^2 2\theta \gtrsim 2 \times 10^{-3}$$

(these numbers change slightly if $\nu_?$ has no weak interactions : sterile)

- adiabatic level crossing :

MSW

$$|m^2_{\nu_e} - m^2_{\nu_?}| \sim 10^{-4} - 10^{-5}\ eV^2$$

(LMA)

$$\sin^2 2\theta \gtrsim 0.65$$

## HOW DO WE DISTINGUISH ?

- MEASURE ENERGY SPECTRUM OF NEUTRINOS COMING FROM $^8B$

EACH SOLUTION VO, SMA, LMA ENTAILS DIFFERENT DISTORTIONS FROM LABORATORY MEASUREMENTS

SUPERK : measure electron (recoil) spectrum in $\nu_e e^- \to \nu_e e^-$

high end data ??

SNO : measure recoil electron energy but in $\nu D \to e + p + p$ reaction : much better accuracy

but : SNO is JUST STARTING

RESULTS SO FAR : INCONCLUSIVE

theoretical uncertainty : "hep" neutrinos

$$p + {}^3He \to {}^4He + e^+ + \nu_e$$

at high end of spectrum

- DAY-NIGHT ASYMMETRY

OBSERVATION WOULD FAVOR LMA

SUPER K : $2\sigma$ effect

but <u>nothing</u> fits very well

- <u>REACTOR OSCILLATIONS</u>

- LSND HAS REPORTED EVIDENCE

$$\bar{\nu}_\mu \to \bar{\nu}_e$$

$$|m^2_{\nu_\mu} - m^2_{\nu_e}| \sim \mathcal{O}(1)\,eV \quad \& \text{ LARGE MIXING}$$

- KARMEN 2 : NO EVIDENCE BUT AN "ANOMALY"

$$\pi \to \mu + X \quad 33\,MeV. \;!!$$
$$\hookrightarrow e^+e^-\nu$$

- TO BE STUDIED AT FERMILAB <u>IN THE FUTURE</u>

(BooNE)

- 

# BURNING QUESTIONS IN NEUTRINO PHYSICS

- ORIGIN OF SOLAR NEUTRINO DEFICIT

SUPERK : shape of $^8B$ spectrum

day-night asymmetry

seasonal variation

SNO : shape of $^8B$ spectrum

Charged Current better accuracy (recoil off deuterium)

day-night and seasonal variations ?

absorption vs superK elastic scattering

NEUTRAL CURRENT : neutron detectors (yet to be installed)

MEASURE FLUX OF ACTIVE NEUTRINOS

& COMPARE WITH $\nu_e$ FLUX

BOREXINO

MEASURE $^7Be$ CAPTURE NEUTRINOS

(seem suppressed from SAGE, GALLEX + K, SUPERK)

crucial for MSW

- ATMOSPHERIC NEUTRINOS

LONG BASELINE EXPTS (to corroborate superk)

K2K : on-line

MINOS : monitor $\nu$- beam at near and far site (Soudan)

KAMLAND

CERN : monitor $\nu$- beam at far site (Gran Sasso)

is it really $\nu_\mu \to \nu_\tau$ ?

$\nu_\tau$ appearance experiments ?

- IS THERE A LIGHT NEUTRINO WITH NO WEAK INTERACTIONS?

MINI BOONE : investigate LSND region.

- DIRECT MEASUREMENT OF NEUTRINO MASSES ?

neutrinoless $\beta^2$ decay ? kinematics of Tritium decay.

$\Omega_\nu$ ?

# THEORETICAL ROAD MAP

SMALL MASS

| | |
|---|---|
| $\nu_\tau$ | 5 ceV |
| $\nu_\mu$ | 1 meV |
| $\nu_e$ | .1 μeV |


?

GRAVITY AT LOW ENERGY

Arkani-Hamed et al
Dienes et al
Neubert + Grossman
Barbieri et al
⋮

DEEP ULTRAVIOLET PHYSICS

GUT ?

Proton decay ?

Babu, Albright, Shafi
⋮

GRAVITY ? again

Vacuum Osc

Halprin

SO-SO

SEE-SAW

JUST SO

# THEORIES OF NEUTRINO MASSES

ALL INTRODUCE NEW FUNDAMENTAL PARTICLES

- LEPTONIC HIGGS

ADD HIGGS FIELD WITH LEPTON NUMBER

BREAK LEPTON NUMBER EXPLICITLY OR SPONTANEOUSLY

FROM THEIR INTERACTIONS $\Delta L \neq 0$ THEORIES

- $\Delta L = 0$ THEORY

INTRODUCE DIRAC PARTNER FOR EACH NEUTRINO

$\bar{N}_e, \; \bar{N}_\mu \; \bar{N}_\tau$ ALL WEAK ISOSINGLETS

WITH COUPLINGS

$$y \begin{pmatrix} \nu_e \\ e \end{pmatrix} \bar{N}_e H \Rightarrow \underbrace{y G_F^{-1/2}}_{m_D^{\nu_e}} \nu_e \bar{N}_e$$

$m_D^{\nu_e}$ : DIRAC MASS

$$y \ll 1 \sim \frac{m_{\nu_e}}{m_e}$$

IS THAT NATURAL ?

# WELCOME TO BRANEWORLD!

$\bar{N}_e$ is electroweak singlet


ONLY FIELDS WITH STANDARD MODEL QUANTUM NUMBERS LIVE EXCLUSIVELY IN FOUR DIMENSIONS (OUR BRANE)

OTHERS, SUCH AS GRAVITONS, $\bar{N}$'s LIVE BOTH ON BRANE AND OUTSIDE (BULK)

SMALL DIRAC MASS : GEOMETRICAL FACTOR ....

THIS ALLOWS FOR BRANE DESCRIPTION UP TO ~ TeV's.

but

- NO THEORY FOR 3-2-1 BRANE
- NO GOOD REASON $\bar{N}$'s SHOULD BE MASSLESS

" ONE NEUTRINO ON THE BRANE IS WORTH TWO IN THE BULK "

but see later

• $\Delta L \neq 0$ THEORY

ADD MAJORANA MASS TERMS FOR $\bar{N}_e, \bar{N}_\mu, \bar{N}_\tau$.

$$M_{ij} \, \bar{N}_i \cdot \bar{N}_j \qquad \text{SCALE OF } \cancel{L}.$$

AFTER $\cancel{EW}$ OBTAIN 6x6 MATRIX

$$\begin{pmatrix} 0 & y\, G_F^{-1/2} \\ y\, G_F^{-1/2} & M \end{pmatrix} \sim \left(\begin{array}{c|c} \Delta I_W = 1 & \Delta I_W = \frac{1}{2} \\ \hline \Delta I_W = \frac{1}{2} & \Delta I_W = 0 \end{array}\right)$$

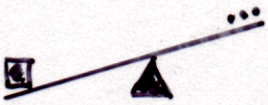
$$\text{if} \qquad \frac{\Delta I_W = 1/2}{\Delta I_W = 0} \ll 1 \sim \epsilon$$

THREE SMALL EIGENVALUES $\sim y\, G_F^{-1/2} \cdot \varepsilon$

can be of order 1

$$m_\nu \sim \frac{1}{M} v_{EW}^2$$

THREE LARGE EIGENVALUES $\sim M_{ij}$



CHARGED LEPTONIC CURRENT :

$$J_\mu = J_\mu^{quarks} + \nu_i^\dagger (\mathcal{U}_\nu^\dagger \, \mathcal{U}_\ell)^{ij} e_j$$

$\mathcal{U}_\nu$ : (almost) unitary matrix that diagonalizes the neutrino mass matrix

$$\mathcal{U}_\nu^\dagger \mathcal{U}_\nu = 1 + \mathcal{O}(\varepsilon^2)$$

$$\begin{pmatrix} m_{\nu_e} & 0 & 0 \\ 0 & m_{\nu_\mu} & 0 \\ 0 & 0 & m_{\nu_\tau} \end{pmatrix} = \mathcal{U}_\nu \left( M_{1/2} \frac{1}{M_0} M_{1/2}^T \right) \mathcal{U}_\nu^\dagger$$

right-handed neutrino mass

$\mathcal{U}_\ell$ : unitary matrix that diagonalizes the charge $-1$ lepton matrix.

$\mathcal{U}_\nu \mathcal{U}_\ell \equiv \mathcal{U}_{MNS}$ lepton mixing matrix : MNS (1962)

contains :
3 ROTATION ANGLES
1 $\cancel{CP}$ PHASE WITH $\Delta L = 0$
2 $\cancel{CP}$ PHASES WITH $\Delta L \neq 0$

# SOME THEORIES WITH 

- DO THE $\bar{N}_i$ ( ELECTROWEAK SINGLETS )

  HAVE ANY QUANTUM NUMBERS

  BEYOND THE STANDARD MODEL?

- MUCH DATA ON QUARK MASSES AND MIXING ANGLES

- QUARKS AND LEPTON ARE RELATED BY

  GAUGE ANOMALY CANCELLATION

  $\rightarrow$ GRAND UNIFIED GROUPS ?

- MYSTERIES OF MASS AND MIXING ANGLE HIERARCHIES

  $\rightarrow$ FAMILY SYMMETRIES ?

  extra symmetries of the Standard Model

- GRAND UNIFIED THEORIES

  M ~ GUT SCALE ~ Gauge Coupling Unification

  gives correct order of magnitude for $m_\nu$

# GRAND UNIFIED APPROACH TO $\nu$- MASSES

naturally appears with SO(10), $E_6$, ...

STANDARD MODEL : $SU(2) \times SU(3)^c \times U(1)$

3 families

$$\underbrace{\underbrace{\underbrace{\begin{pmatrix}\nu \\ e\end{pmatrix}}_{(2,1^c)_{-1}} \quad \underbrace{\bar{d}}_{(1,1^c)_{2/3}}}_{\bar{5}} \quad \underbrace{\underbrace{\bar{u}}_{(1,1^c)_{-4/3}} \quad \underbrace{\begin{pmatrix}u \\ d\end{pmatrix}}_{(2,3^c)_{1/3}} \quad \underbrace{\bar{e}}_{(1,1^c)_{2}}}_{10} \quad \underbrace{\underbrace{\bar{N}}_{(1,1^c)_0}}_{1}}_{16}$$

SU(5): $\bar{5}$ 10 1

SO(10) 16

DEFINITE IMPLICATIONS FOR MASSES AND MIXING ANGLES.

RELATES QUARK TO LEPTON MIXINGS

$\bar{5} \times 10$ contains charge $-1/3$ and $-1$ masses

$10 \times 10$ contains charge $2/3$ masses

SU(5) MASS RELATIONS : ( Georgi- Jarlskog )

$$(\bar{5}_1 \ \bar{5}_2 \ \bar{5}_3)\begin{pmatrix} 0 & 5_H & 0 \\ 5_H & 45_H & 0 \\ 0 & 0 & 5_H \end{pmatrix}\begin{pmatrix} 10_1 \\ 10_2 \\ 10_3 \end{pmatrix}$$

Higgs particle.

C.G.-coefficient.

$$\begin{pmatrix} 0 & R & 0 \\ R & S & 0 \\ 0 & 0 & T \end{pmatrix} \qquad \begin{pmatrix} 0 & R & 0 \\ R & -3S & 0 \\ 0 & 0 & T \end{pmatrix}$$

CHARGE $-1/3$ CHARGE $-1$

$$m_b = m_\tau$$

$$\left.\begin{aligned} m_d m_s &= m_e m_\mu \\ m_d - m_s &= 3(m_e - m_\mu) \end{aligned}\right\} \quad \frac{m_e}{m_\mu} = \frac{1}{9}\,\frac{m_d}{m_s}$$

also implies that $U_e \sim \begin{pmatrix} c & s & 0 \\ -s & c & 0 \\ 0 & 0 & 1 \end{pmatrix}$ $\tan\theta_{e\mu} \sim \sqrt{\frac{m_e}{m_\mu}}$

# SO(10) GENERALIZATIONS

L MASSES RESIDE IN

$$16 \times 16 = \underbrace{10}_{\underline{\underline{5}}+\underline{\underline{\bar{5}}}} + 120 + \underbrace{126}_{1+\underline{\underline{\bar{5}}}+10+\overline{15}+\underline{\underline{45}}+\overline{50}}$$

SU(5)

MAJORANA $\Delta I_W = 0$ MATRIX $M_0$

SO(10) CAN RELATE

- CHARGE $2/3$ TO CHARGE 0 DIRAC MASS MATRICES
- CHARGE $-1/2$ TO CHARGE $-1$ DIRAC MASS MATRICES
- MAJORANA $\Delta I_W = 0$ MASS MATRIX TO THE OTHERS

NEED 126 HIGGS REPRENTATION !!

confronting the main problem of GUT theoris : UGLY HIGGS !

- early approach (1982 ; Harvey, Reiss, P.R.)

"DAMN THE HIGGS TORPEDOES"

three results (with $M_{top} \sim 20$ GeV! )

- long-lived b-quark $V_{cb} = \sqrt{\frac{m_c}{m_t}}$ (not quite right) ~
- maximal $\nu_\mu - \nu_\tau$ mixing (decreases with $m_t\nearrow$) ~
- $\nu_e - \nu_\mu$ mixing $\sim \sqrt{\frac{m_e}{m_\mu}}$ (too large for SMA) ~

SO(10) WANTS TO WORK

EXAMPLE OF A MORE RECENT APPROACH (Babu, Barr)

$16_i \cdot 16_j \; \overline{126}_H$ comes from $(16_i \, \overline{16})_{45} (16_j \, \overline{16})_{45}$

EXPLAIN THE NEUTRINO SPECTRUM BY C.G. COEFFICIENTS:

$$\begin{pmatrix} 0 & C & 0 \\ C & B & 0 \\ 0 & 0 & A \end{pmatrix} \qquad \begin{pmatrix} 0 & \frac{3}{8}C & 0 \\ \frac{3}{8}C & -3B & 0 \\ 0 & 0 & \frac{3}{8}A \end{pmatrix} \qquad \begin{pmatrix} 0 & C & 0 \\ C & 0 & 0 \\ 0 & 0 & A \end{pmatrix} M$$

charge 2/3 matrix

charge 0 DIRAC $\Delta I_w = 1/2$ $M$

$\Delta I_w = 0$ MAJORANA MASS $M_0$

 : $M^T \dfrac{1}{M_0} M$

find

$$\frac{m_{\nu_\mu}}{m_{\nu_\tau}} = 16 \frac{m_c}{m_t} \qquad \frac{m_{\nu_e}}{m_{\nu_\mu}} = \frac{1}{256} \frac{m_u}{m_c}$$

$\nu_e - \nu_\mu$ mixing small consistent with SMA

no mixing between $\nu_\mu$ and $\nu_\tau$

need to rely on charge $-1$ matrix!

ANOTHER APPROACH :

EXTRA U(1) SYMMETRY(IES) . IN THE STANDARD MODEL

TO EXPLAIN MASS AND MIXING HIERARCHIES

inspired by some string theories.

THROUGH FROGGATT-NIELSEN LEADS TO A

THEORY OF <u>CABIBBO SUPPRESSION</u>

Ross + Ibañez
Irges, Lavignac
Binétruy, . . . .

GENERIC CONCLUSIONS :

NO CABIBBO SUPPRESSION OF $\nu_\mu \leftrightarrow \nu_\tau$

CABIBBO SUPPRESSION OF $\nu_e \leftrightarrow \nu_\mu$ $\qquad \mathcal{O}(\lambda_c^3)$

$\nu_e \leftrightarrow \nu_\tau$

NO SOLID PREDICTIONS FOR EIGENVALUES , BUT

$$m_{\nu_e} \ll m_{\nu_\mu} < m_{\nu_\tau}$$

# FERMION MASS HIERARCHIES

| | | |
|---|---|---|
| u | d | e |
| c | s | $\mu$ |
| t | b | $\tau$ |

INTER FAMILY

INTRA FAMILY

INTRA-FAMILY

$$\frac{b}{t} \sim \lambda^3 \qquad \frac{b}{\tau} \sim 1 = \lambda^0$$

AT $10^{16}$ GeV

WITH SUSY.

$\lambda$ = Cabibbo angle $\sim .22$

(pretty bad expansion parameters)

INTER-FAMILY ORDERS OF MAGNITUDE

at $M_{GUT} \sim 10^{16}$ GeV

$$\frac{u}{t} \sim \lambda^{8} \qquad \frac{c}{t} \sim \lambda^{4}$$

$$\frac{d}{b} \sim \lambda^{4} \qquad \frac{s}{b} \sim \lambda^{2}$$

$$\frac{e}{\tau} \sim \lambda^{6} \qquad \frac{\mu}{\tau} \sim \lambda^{2}$$

CKM matrix

$$\mathcal{U}_{CKM} \qquad \begin{pmatrix} 1 & \lambda & \lambda^{3} \\ \lambda & 1 & \lambda^{2} \\ \lambda^{3} & \lambda^{2} & 1 \end{pmatrix}$$

off-diagonal coefficients of order 1.

MODEST AIM:

LOOK FOR THEORY OF EXPONENTS ONLY

full theory would include prefactors, etc...

T-27

$Q_i$ $\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$ left-handed

$\bar{u}_i$ $\bar{u}$ $\bar{c}$ $\bar{t}$

right handed

$\bar{d}_i$ $\bar{d}$ $\bar{s}$ $\bar{b}$

$L_i$ $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$ left-handed

$\bar{e}_i$ $\bar{e}$ $\bar{\mu}$ $\bar{\tau}$ right-handed.

[ $\bar{N}_i$ $\bar{N}_e$ $\bar{N}_\mu$ $\bar{N}_\tau$ ] right-handed sterile neutrinos.

STANDARD MODEL INVARIANTS

$Q_i \, \bar{u}_j \, H_u$ $\longrightarrow$ CHARGE 2/3 MASS MATRIX

$Q_i \, \bar{d}_j \, H_d$ $\longrightarrow$ CHARGE −1/3 MASS MATRIX

$L_i \, \bar{e}_j \, H_d$ $\longrightarrow$ CHARGE −1 MASS MATRIX

$L_i \, \bar{N}_j \, H_u$ $\longrightarrow$ CHARGE 0 "DIRAC" MASS MATRIX

$\bar{N}_i \, \bar{N}_j$ $\longrightarrow$ "MAJORANA" MASS MATRIX

FROGGATT-NIELSEN APPROACH TO SMALL YUKAWA COUPLINGS:

EXTRA U(1) PHASE SYMMETRIES IN STANDARD MODEL

ELEMENTARY PARTICLES HAVE FLAVOR CHARGES:

example:

large top quark mass $\rightarrow$ $Q_3 \bar{u}_3 H_u \Rightarrow t\bar{t}\, m_{top}$

has zero FN charge(s)

"small" bottom quark mass $\rightarrow$ $m_b b\bar{b}$ comes from $Q_3 \bar{d}_3 H_d$

has non-zero FN charge.

Suppose the charge of $Q_3 \bar{d}_3 H_d$ is N

then invent an electroweak singlet field $\Theta$ with charge -1

$$Q_3 \bar{d}_3 H_d \left(\frac{\Theta}{M}\right)^N \quad \text{has zero charge}$$

mass to get right dimensions

if $\frac{\Theta}{M} \sim \lambda$ (Cabibbo angle, say), then

$$\frac{m_b}{m_t} \sim \lambda^N$$

EXPONENTS TRACK CHARGES OF OPERATORS!

# RECONSTRUCTING YUKAWA COUPLINGS

CKM

QUARK MIXING MATRIX

$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

CHARGE $-1/3$

$$\frac{d}{b} \sim \lambda^4 \qquad \frac{s}{b} \sim \lambda^2$$

$$Q \quad \underset{\bar{d}}{\begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^1 & \lambda^0 & 1 \end{pmatrix}}$$

CHARGE 2/3

$$\frac{u}{t} \sim \lambda^8 \qquad \frac{c}{t} \sim \lambda^4$$

$$\begin{array}{cc} \uparrow & \\ Q & \begin{pmatrix} \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^7 & \lambda^4 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix} \\ \downarrow & \\ & \longleftarrow \bar{u} \longrightarrow \end{array}$$

FAMILY
CHARGES

$$Q = (3, 2, 0) = \left(\tfrac{4}{3}, \tfrac{1}{3}, -\tfrac{5}{3}\right) - \tfrac{5}{3}(1, 1, 1)$$

$$\bar{u} = (5, 2, 0) = \left(\tfrac{8}{3}, -\tfrac{1}{3}, -\tfrac{7}{3}\right) - \tfrac{7}{3}(1, 1, 1)$$

$$\bar{d} = (1, 0, 0) = \left(\tfrac{2}{3}, -\tfrac{1}{3}, -\tfrac{1}{3}\right) - \tfrac{1}{3}(1, 1, 1)$$

TRACE

TRACE DOES NOT CONTRIBUTE TO INTERFAMILY HIERARCHY

UNIFORM DESCRIPTION OF TRACELESS PART

$\bar{d}$ : $-B\,(2,-1,-1)$

$Q$ : $-B\,(2,-1,-1) \quad + \quad 2\,(1,0,-1)$

$\bar{u}$ : $-B\,(2,-1,-1) \quad + \quad 2\,(1,0,-1)$

B = BARYON NUMBER

$$X_{Q,\bar{u},\bar{d}} = -B(2,-1,-1) + \eta(1,0,-1)$$

$$\eta = \begin{cases} 0 & \text{for } \bar{d} \\ 2 & \text{for } Q, \bar{u} \end{cases}$$

$\boxed{\eta \quad \text{SAME FOR} \quad Q, \bar{u}}$

$\boxed{X_{\bar{d}} \quad \text{SAME FOR } 2^{nd} \text{ AND } 3^{rd} \text{ FAMILY}}$

# GENERALIZE CHARGES TO LEPTONS

- STANDARD MODEL HAS SU(5) - CHARGES

  CONSEQUENCE OF ANOMALY CANCELLATION

$\bar{5}$ : $\bar{d}$ $L$ ← lepton doublet

$10$ : $Q$ $\bar{u}$ $\bar{e}$ ← lepton isosinglet

- BARYON NUMBER ⟶ B - L

POSTULATE CHARGES

$$X_{Q,\bar{u},\bar{d},L,\bar{e}} = (B-L)(2,-1,-1) + \eta\,(1,0,-1)$$

$$\eta = \begin{cases} 0 & \bar{d} \quad L \\ 2 & Q \quad \bar{u} \quad \bar{e} \end{cases}$$

$L$ : $(-2,\ 1,\ 1)$ LEPTON DOUBLET

↑ SAME CHARGE FOR 2nd & 3rd FAMILY!

# NEUTRINO MASSES AND MIXINGS

RIGHT-HANDED NEUTRINO MASS (MAJORANA):

$\bar{N}_i \bar{N}_j$ : $\qquad \bar{N}$ : $(A, B, 0)$ $\qquad$ U(1) charge

$$\bar{N}\bar{N} \quad \begin{pmatrix} \lambda^{2A} & \lambda^{A+B} & \lambda^{A} \\ \lambda^{A+B} & \lambda^{2B} & \lambda^{B} \\ \lambda^{A} & \lambda^{B} & \lambda^{0} \end{pmatrix} =$$

$$= \begin{pmatrix} \lambda^{A} & 0 & 0 \\ 0 & \lambda^{B} & 0 \\ 0 & 0 & \lambda^{0} \end{pmatrix} \hat{M}^{(0)} \begin{pmatrix} \lambda^{A} & 0 & 0 \\ 0 & \lambda^{B} & 0 \\ 0 & 0 & \lambda^{0} \end{pmatrix}$$

not Cabibbo-suppresed

$\hat{M}^{(0)}$ = RIGHT-HANDED NEUTRINO MASS WITHOUT CABIBBO SUPPRESSIONS.

DIRAC MASS:

$$L\bar{N}H_u : \begin{pmatrix} \lambda^{2P} & 0 & 0 \\ 0 & \lambda^{-P} & 0 \\ 0 & 0 & \lambda^{-P} \end{pmatrix} \left( \ \hat{} \ \right) \begin{pmatrix} \lambda^{A} & 0 & 0 \\ 0 & \lambda^{B} & 0 \\ 0 & 0 & \lambda^{0} \end{pmatrix}$$

not Cabibbo-suppresed

$5\cancel{8}\ \frac{1}{\cancel{8}\cancel{8}}\ \cancel{8}5 = 55$

LIGHT NEUTRINO MASS :

$$(L\bar{N})\ \frac{1}{\bar{N}\bar{N}}\ (\bar{N}L) = M_\nu$$

CABIBBO SUPPRESSION

$$\begin{pmatrix} \lambda^{2p} & & \\ & \lambda^{-p} & \\ & & \lambda^{-p} \end{pmatrix} (\hat{L\bar{N}}) \begin{pmatrix} \lambda^{A} & & \\ & \lambda^{B} & \\ & & \lambda^{0} \end{pmatrix} \frac{1}{\begin{pmatrix} \lambda^{A} & & \\ & \lambda^{B} & \\ & & \lambda^{0} \end{pmatrix} (\hat{\bar{N}\bar{N}}) \begin{pmatrix} \lambda^{A} & & \\ & \lambda^{B} & \\ & & \lambda^{0} \end{pmatrix}} \begin{pmatrix} \lambda^{A} & & \\ & \lambda^{B} & \\ & & \lambda^{0} \end{pmatrix} (\hat{\bar{N}L}) \begin{pmatrix} \lambda^{2p} & & \\ & \lambda^{-p} & \\ & & \lambda^{-p} \end{pmatrix}$$

$$= \begin{pmatrix} \lambda^{2p} & & \\ & \lambda^{-p} & \\ & & \lambda^{-p} \end{pmatrix} \hat{M}_\nu \begin{pmatrix} \lambda^{2p} & & \\ & \lambda^{-p} & \\ & & \lambda^{-p} \end{pmatrix}$$

$$= \begin{pmatrix} \lambda^{4p} & \lambda^{p} & \lambda^{p} \\ \lambda^{p} & \lambda^{-2p} & \lambda^{-2p} \\ \lambda^{p} & \lambda^{-2p} & \lambda^{-2p} \end{pmatrix} \sim \begin{pmatrix} \lambda^{6p} & \lambda^{3p} & \lambda^{3p} \\ \lambda^{3p} & 1 & 1 \\ \lambda^{3p} & 1 & 1 \end{pmatrix}$$

**HENCE :**

FAMILY STRUCTURE OF $M_\nu$ DETERMINED

BY LEPTON DOUBLET CHARGES !!

NO CABIBBO SUPPRESSION $\nu_\mu - \nu_\tau$

$$\left.\begin{array}{l} \nu_e \to \nu_\mu \\ \nu_e \to \nu_\tau \end{array}\right\} \lambda^3 \text{ SUPPRESSION}$$

$\nu_e \to \nu_\mu \quad \mathcal{O}(\lambda^3)$

$$\mathcal{U}_{MNS} = \mathcal{U}_{\nu}^{\dagger}\, \mathcal{U}_{\ell}$$

determined by Lepton doublet charges

determined <u>also</u> by lepton doublet charges

$$\mathcal{U}_{MNS} \sim \begin{pmatrix} 1 & \lambda^3 & \lambda^3 \\ \lambda^3 & 1 & 1 \\ \lambda^3 & 1 & 1 \end{pmatrix}$$

Alt-F : $\det\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \sim \mathcal{O}(\lambda^2)$

Neutrino masses : $\lambda^6 : 1 : 1$ $\qquad m \sim \dfrac{v^2}{M}$

- FLAVOR STRUCTURE OF NEUTRINO SECTOR

  DETERMINED BY FAMILY CHARGES OF LEPTON DOUBLETS!

- SCALE OF NEUTRINO MASSES SET

  BY CUT-OFF OF THEORY

# IMMEDIATE FUTURE

ORIGIN OF SOLAR NEUTRINO DEFICIT

OSCILLATIONS ? SNO

SMALL ANGLE ? $U_{\nu_e - \nu_\mu}$

SNO , BOREXINO, ..

$U_{\nu_e - \nu_\tau}$ KAMLAND.

generic : small angle : suppression

if no suppression nor hierarchy , then ...

perhaps origin of neutrino masses and mixings is truly out of this world.

on the other hand :

both couplings (of gauge) & neutrino masses suggest $10^{15 \pm \text{few}}$ GeV

need not get off the brane yet !

## WHAT ABOUT STERILE NEUTRINOS?

MOST THEORIES CONTAIN ELECTROWEAK SINGLET LEPTONS

**BUT**

CAN THEY BE $\boxed{\text{LIGHT}}$ AND $\boxed{\text{COUPLE WITH SM } \nu\text{'s}}$ ?

WHEN IS A FERMION LIGHT?

- WHEN ITS MASS IS PROTECTED BY SOME QUANTUM NUMBERS

  example: quark and charged lepton masses = 0 if SM symmetries are not broken.

WHAT ARE THE SYMMETRIES THAT KEEP STERILE NEUTRINO LIGHT?

not Standard Model Symmetries, (by definition)

then what? new symmetries ( → new interactions )

geometrical symmetries → branes? .. )

EITHER WAY: DEEP THEORETICAL IMPLICATIONS

# INDICATOR FOR NEW PHYSICS

SCALE OF $\Delta m^2$ $\longrightarrow$ $M \sim 10^{14-16}$ GeV

ANOTHER GLIMPSE INTO VERY SHORT DISTANCES!

OTHER IS GAUGE COUPLING UNIFICATION

BOTH MAKE SENSE ONLY WITH

- LOW-ENERGY SUPERSYMMETRY

- SETS THE SCALE FOR PROTON DECAY

# KARMEN ANOMALY

$\pi^+$ pulses $0.5\ \mu s$ at $50\ Hz$

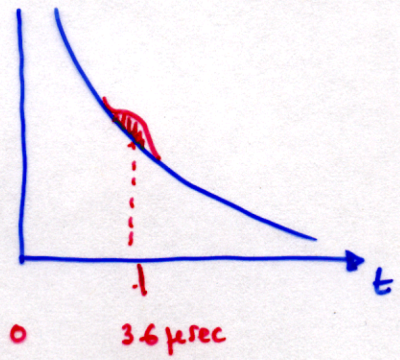
normal event: $\pi^+ \to \mu^+ + \nu_\mu$ $\qquad \tau \sim 26$ nsec

$\hookrightarrow e^+ \ \nu_e + \bar{\nu}_\mu$ $\qquad \tau_\mu \sim 2.2\ \mu$sec

after $.6 - 10\ \mu$sec, expect pulse of $\nu_e + \nu_\mu + \bar{\nu}_\mu$.

expect

(detector time res ~ 2 nsec)




$$A e^{-t/\tau_\mu} + B$$

excess at $3.6\ \mu$sec appear in both data sets.

if it is not an experimental problem, ... we have

Possible explanation: particle produced $\pi^+ \to \mu^+ + X$

time of flight $\beta \sim .016$ slowly moving

not much phase space

$$m_X \approx m_{\pi^+} - m_{\mu^+} \approx 33.9\ \text{MeV}$$

very fine tuned!
(1 part in $10^{-4}$)

- $X \to e^+ e^- \nu_e$
- lifetime long enough to have survived for $3.6\ \mu$sec.

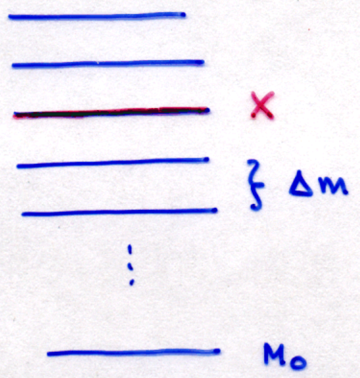
## WHAT IS IT?

- single sterile neutrino (Barger et al 1996)

  cooling rate of SN 1987A (Raffelt et al 1999)
  affects length of $\nu$-pulse.
  ruled out.

- PARTICLE (STERILE NEUTRINO) IN A KALUZA-KLEIN TOWER.

  (Lukas, Romanino, 2000)




- IF THERE IS A KK TOWER TO WHICH $\nu_\mu$ COUPLES THERE ARE STATES EVERYWHERE. IF $\Delta m / M_X$ is small, FINE TUNING ALLEVIATED.

- STATES ABOVE X CUT-OFF BY $M_\pi - M_\mu$ - MOVE SLOWER

- STATES LIGHTER THAN X ARE PRODUCED AT KARMEN, WITH MORE PHASE SPACE : MOVE FASTER : GET SOONER

IN DETECTOR, BUT SPEND LESS TIME IN DETECTOR.

SUCH STATES ARE NOT SEEN, HENCE $\Delta m \sim .9$ MeV
($1/R \sim 15$ MeV)

while $\Delta m \sim 6$ KeV $\rightarrow$ $\frac{1}{R} \sim 1.6$ MeV for 2 extra d's.
for no fine-tuning.

- ALLEVIATES FINE-TUNING
- PREDICTS PRESENCE OF OTHER STATES AT KARMEN (SOONERS)

SPECIFIC MODEL IN 6 DIMENSIONS.

# GENERIC KK TOWER.

~~circle~~ compactification.
torus