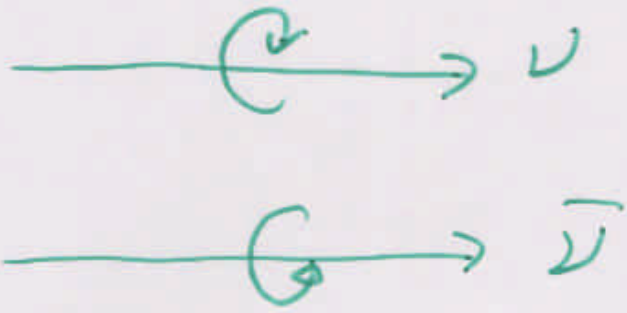
I WON'T BE PULLING ANY RABBITS OUT OF HATS TODAY ....

EXPERIMENT IS DEFINITELY AHEAD OF THEORY IN THIS AREA RIGHT NOW, PERHAPS EVEN MORE SO AFTER THIS MEETING

JUST REVIEW SOME IDEAS THAT ARE PROBABLY FAMILIAR ....

IN THE 1950's THE "TWO COMPONENT NEUTRINO" WAS ~~PRESUMED~~ [redacted] TO SHOW



THAT NEUTRINOS MUST BE MASSLESS.

A MASSIVE SPIN $\frac{1}{2}$ PARTICLE HAS TWO HELICITY STATES; THE NEUTRINO ONLY HAS ONE.

THERE IS A POTENTIAL FALLACY HERE, AS A RESULT OF WHICH BY THE 70's, THEORISTS CAME TO SUSPECT NEUTRINOS WERE MASSIVE AND TO GUESS ROUGHLY THE CORRECT MASS SCALE:

TO ARGUE THAT THE NEUTRINO SHOULD BE MASSLESS, ONE HAS TO ASSUME

LEPTON NUMBER SYMMETRY

IF LEPTON NUMBER IS NOT CONSERVED, WE CAN TREAT

ν_L

$\bar{\nu}_R$

AS TWO DIFFERENT SPIN STATES OF ONE PARTICLE, AND COMBINE THEM TO A SINGLE SPIN 1/2 MASSIVE PARTICLE.

(CALLED A MASSIVE MAJORANA FERMION - JUST MEANS IT IS ITS OWN ANTIPARTICLE)

IN FACT, KNOWN PARTICLE INTERACTIONS CONSERVE

B = BARYON NUMBER

AND THE THREE LEPTON NUMBERS

L_e

L_μ

L_τ

BUT IN THE '70's THEORISTS GENERALLY BECAME CONVINCED THAT NONE OF THESE WOULD BE TRUE SYMMETRIES, AND (HENCE) THAT NEUTRINOS WOULD BE MASSIVE

I'LL TRY TO LIST, IN THE ROUGH ORDER IN WHICH THEY HAD HISTORICAL IMPACT, ~~THE~~ PRINCIPAL ARGUMENTS THAT SUGGESTED THAT THE ~~BARYON~~ AND LEPTON SYMMETRIES WOULD BE VIOLATED.

(1) ALL ATTEMPTS TO UNIFY THE PARTICLES AND FORCES VIOLATED THE SYMMETRIES, BY PUTTING DIFFERENT FERMIONS IN THE SAME GAUGE MULTIPLET.

EXAMPLE:

SU(5) GRAND UNIFIED THEORY CONSERVES ONLY $B - L_e - L_\mu - L_\tau$

SO(10)
E_6
⋮
} VIOLATE ALL THE GLOBAL SYMMETRIES

(62)

Ex.

SU(5)

(2) AT FIRST, IT MIGHT SEEM THAT IF B AND L (i.e. L_e, L_μ, L_τ) ARE NOT FUNDAMENTAL SYMMETRIES OF NATURE, THERE IS A MYSTERY TO EXPLAIN: WHY THEN DOES THE STANDARD MODEL CONSERVE THESE SYMMETRIES?

IT TURNS OUT THAT THIS QUESTION HAS A COMPLETELY NATURAL ANSWER:

USING THE FIELDS OF THE STANDARD MODEL, IT IS IMPOSSIBLE TO VIOLATE B OR L BY RENORMALIZABLE INTERACTIONS

RENORMALIZABLE INTERACTIONS HAVE DIMENSIONLESS COUPLING CONSTANTS THAT ARE PURE NUMBERS.

UNRENORMALIZABLE INTERACTIONS ARE EXPECTED TO BE SUPPRESSED BY POWERS OF $1/M$, WHERE M IS A MASS SCALE AT WHICH THE STANDARD MODEL BREAKS DOWN

i.e. MAYBE

$M \sim 10^{15}$ GeV - GEORGI-QUINN-WEINBERG GUTS

10^{19} GeV GRAVITY

IN THE STANDARD MODEL THE LOWEST DIMENSION OPERATOR THAT VIOLATES BARYON NUMBER IS

$$\frac{1}{M^2} QQQL$$

AND THE LOWEST DIMENSION OPERATOR THAT VIOLATES LEPTON NUMBER IS

$$\frac{1}{M} HHLL$$

$L = \begin{pmatrix} \nu \\ e \end{pmatrix}$

Q = QUARK

$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

= HIGGS

IF WE GUESS

$$10^{15}\ \text{Gev} \lesssim M \lesssim 10^{19}\ \text{Gev}$$

WE GET

$$10^{30}\ \text{years} \lesssim \tau_{\text{proton}} \lesssim 10^{45}\ \text{years}$$

AND

$$.1\ \text{ev} \gtrsim m_\nu \gtrsim 10^{-5}\ \text{ev}$$

THIS IS A SOMEWHAT ABSTRACT WAY TO ESTIMATE THE NEUTRINO MASS. AN ELEGANT MECHANISM THAT FITS THE GENERAL SCHEME (AND ENABLES ONE TO SEE HOW TO MAKE THE NEUTRINO MASS BIGGER OR SMALLER, IF DESIRED) IS THE

"SEE-SAW MECHANISM"

WHERE ONE ASSUMES THAT A ν_R EXISTS BUT IS AN ELECTROWEAK SINGLET (AS THE V-A THEORY OF WEAK INTERACTIONS SUGGESTS)

ONE CAN THEN HAVE AN ORDINARY DIRAC NEUTRINO MASS THAT NEEDN'T BE SMALL

$$m \bar{\nu}_R \nu_L + \text{c.c.}$$

(FROM $H \bar{\nu}_R \begin{pmatrix} \nu \\ e \end{pmatrix}_L$)

BUT ν_R CAN HAVE A VERY LARGE "MAJORANA" MASS

$$M \nu_R \nu_R + \text{c.c.}$$

(WHICH VIOLATES LEPTON NUMBER CONSERVATION)

THIS LEADS TO A 2×2

MASS MATRIX

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \quad \text{FOR} \quad \begin{pmatrix} \nu_L \\ \overline{\nu_R} \end{pmatrix}$$

AND (FOR $m \ll M$) THE

RESULT AFTER "INTEGRATING OUT" ν_R

IS

$$\frac{m^2}{M} \nu_L \nu_L$$

i.e. THE ORDINARY NEUTRINO

GETS AN L-VIOLATING MASS

$$\frac{m^2}{M}$$

(see Arkani-Hamed et.al.
for models w/ m, M both small
from big extra dimensions)

THIS VERSION SUGGESTS

A WIDER RANGE OF PLAUSIBLE

m_ν's SINCE

$$m_\nu \sim \frac{m^2}{M}$$

WE MIGHT THINK m SHOULD

BE COMPARABLE TO A LEPTON OR QUARK

MASS - AND THESE SPAN MANY

ORDERS OF MAGNITUTE FROM

m_e TO m_τ TO m_{top}

AND WE CAN MAKE M LESS

THAN M_{GUT} IF WE WANT.

WHETHER WE TAKE THE ABSTRACT APPROACH OR RELY ON THE SEESAW MECHANISM, WE'D EXPECT NEUTRINO OSCILLATIONS SINCE IT IS HARD TO SEE WHY THE NEUTRINO MASS MATRIX WOULD BE DIAGONAL IN THE BASIS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

HOWEVER, IT COMES AS A SURPRISE, AT LEAST TO ME, THAT THE NEUTRINO MIXING ANGLES WOULD BE LARGE....

SO FAR I'VE REVIEWED ARGUMENTS THAT SUGGEST THAT LEPTON NUMBER VIOLATION, AND HENCE NEUTRINO MASSES, ARE NATURAL; NOW LET'S CONSIDER ARGUMENTS THAT TEND TO SHOW THAT THEY ARE INEVITABLE.

(1') ELECTROWEAK INSTANTONS

't HOOFT SHOWED (1976) THAT VIA INSTANTONS OF THE SU(2)×U(1) GAUGE GROUP OF WEAK INTERACTIONS THE STANDARD MODEL HAS A MECHANISM THAT VIOLATES MOST OF THE GLOBAL SYMMETRIES

B, L_e, L_μ, L_τ

IN FACT, UNBROKEN IS ONLY

$$B-L$$

i.e.

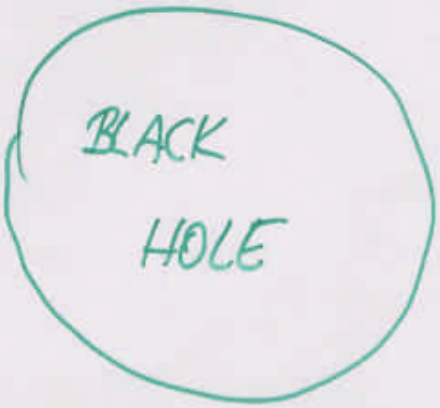
$$B - L_e - L_\mu - L_\tau$$

THIS SHOWS THAT MOST OF THE GLOBAL SYMMETRIES AREN'T EXACT; BUT $B-L$ CONSERVATION WOULD BE ENOUGH TO PREVENT NEUTRINO MASSES.

(21) BLACK HOLES AND QUANTUM GRAVITY

CLASSICALLY A BLACK HOLE

ABSORBS AND DOESN'T EMIT

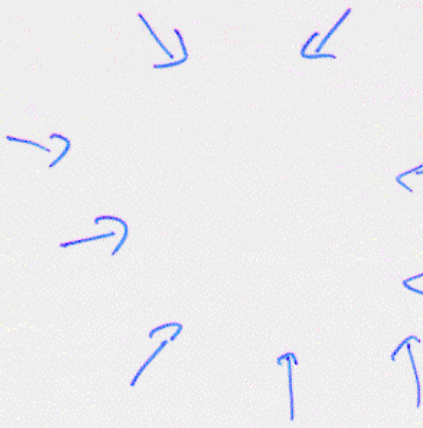


QUANTUM MECHANICALLY, THAT IS IMPOSSIBLE AS IT VIOLATES HERMITICITY OF THE HAMILTONIAN

$$\langle f|H|i\rangle = \overline{\langle i|H|f\rangle}$$

IN FACT, HAWKING SHOWED (1974) THAT BLACK HOLES DO RADIATE, APPROXIMATELY THERMALLY.

NOW MAKE A BLACK HOLE FROM A COLLAPSING STAR



OR INFALLING TABLES AND CHAIRS - WITH BIG BARYON NUMBER.

ONE DOESN'T GET BACK THE BARYONS IN THE OUTGOING HAWKING RADIATION!

SO BARYON NUMBER - AND SIMILARLY

$$L_e, L_\mu, L_\tau$$

CANNOT BE AN EXACTLY CONSERVED QUANTITY IN NATURE.

THIS ARGUMENT SHOULD WORK IN ANY CONSISTENT QUANTUM GRAVITY THEORY — WHETHER IT REALLY DESCRIBES NATURE OR NOT — AND WE CAN TEST IT OUT IN STRING THEORY, WHICH IS OUR ONLY REAL CANDIDATE FOR A QUANTUM GRAVITY THEORY.

WE INDEED FIND THAT

IN STRING THEORY WE NEVER

GET AN ADDITIVE GLOBAL

CONSERVATION LAW.

IN ANY STRING VACUUM ONE LOOKS AT,

THE APPARENT ADDITIVE GLOBAL

SYMMETRIES TURN OUT - SOMETIMES

IN A TRICKY FASHION - TO BE EITHER

* GAUGED

OR

** BROKEN

THE SYMMETRIES

B, L_e, L_μ, L_τ

ARE NOT GAUGED, SO SINCE

GRAVITY EXISTS, THESE CONSIDERATIONS

SUGGEST THAT THESE SYMMETRIES

ARE BROKEN.

THAT IS CERTAINLY A STRONG

HINT OF NEUTRINO MASSES, BUT

THERE IS A LOOPHOLE

ALTHOUGH L_e, FOR INSTANCE, CANNOT BE EXACTLY CONSERVED, IT MIGHT BE CONSERVED MOD 7 - OR MOD n FOR SOME $n > 2$ - AND THIS WOULD FORCE $m_{\nu_e} = 0$

THAT IS A BIT ELABORATE THOUGH, AND I THINK IT IS FAIR TO SAY, FOR EXAMPLE, THAT IN MODELS OF PARTICLE PHYSICS DERIVED

FROM STRING THEORY THAT HAVE QUARK AND LEPTON MASSES, THERE WILL GENERALLY BE NEUTRINO MASSES.

(GLOBAL MOD n SYMMETRIES ARE POSSIBLE IN STRING THEORY, BUT IF ONE ARRANGES SO THAT SUCH SYMMETRIES PREVENT NEUTRINO MASSES, THEY MIGHT WELL PREVENT QUARK AND LEPTON MASSES.)

(3') FINALLY, THE LAST HINT THAT B AND L ARE NOT EXACT SYMMETRIES IS SIMPLY THAT THE REAL UNIVERSE HAS A SMALL BUT NONZERO NET B AND L DENSITY RELATIVE TO THE ENTROPY DENSITY...

IF B AND L ARE NOT EXACT SYMMETRIES, IT IS NATURAL TO SPONTANEOUSLY GENERATE THE OBSERVED B AND L DENSITIES IN THE EXPANDING (AND CP VIOLATING) UNIVERSE.

OTHERWISE, THEY MUST BE POSTULATED AS INITIAL CONDITIONS.