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A Novel Possibility for Neutrino Masses and Decay

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A Novel Possibility for Neutrino Masses and Decay

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Abstract

I consider the possibility that a sigma model is relevant for calculating the masses and mixings of Dirac neutrinos. New processes involving pairs of Goldstone bosons are predicted. Heavy neutrinos decay into lighter ones and a pair of Goldstone bosons, $\nu_2 \to \nu_1 + b + \bar{b}$. For a dark-matter mass of ν_2 of $\sim$ 15 eV, a lifetime $\lesssim 10^{21}$ sec is possible; for a mass of ν_2 of $\sim$ 17 KeV, a lifetime $\lesssim 10^6$ sec is possible.

After hearing this morning's talks, and anticipating those from tomorrow, it seems fair to say that basic physics issues underlying these wonderful experimental adventures are: (1) the possible "disappearance" of some of the Sun's (electron) neutrinos due to some mechanism involving finite neutrino mass; and (2) the possible discovery of distant, point-sources of very high-energy neutrinos, and gamma rays - or perhaps even exotic objects - via detection of interactions producing charged leptons, muons in particular.

I would like to make some remarks upon these matters, that is on neutrino masses and decay, and upon the role of hypothetical Goldstone bosons[1]. If neutrinos have mass, the heavier ones presumable decay. The question is: how? The answer presumably has something to do with the way neutrinos acquire mass.

Consider a neutral Dirac fermion, a "neutron", n. It acquires its mass m_n from the mechanism shown in Fig. 1.

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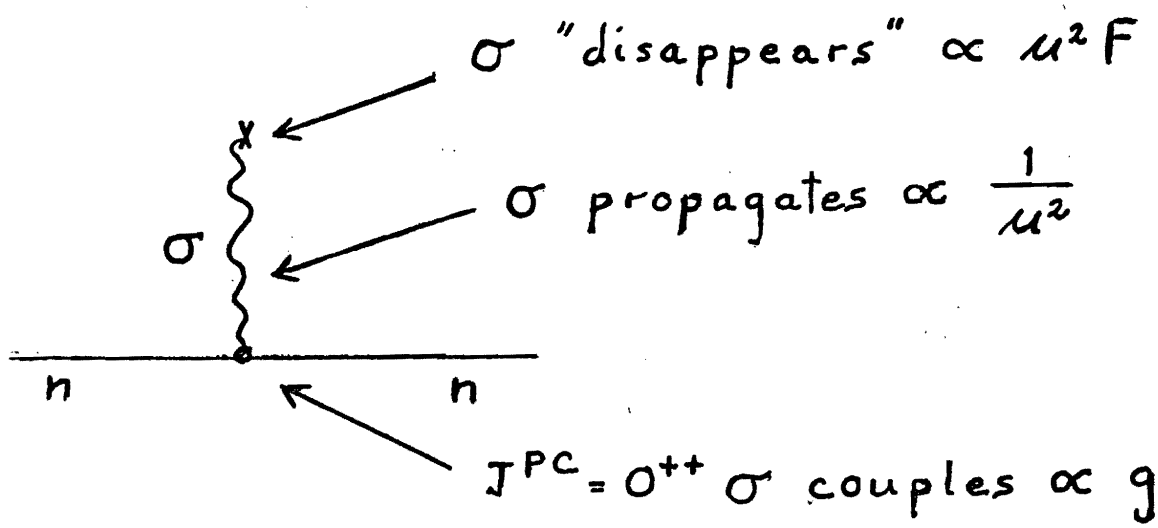

Fig. 1 Mechanism for the mass m_n

The result is clearly,

$$m_n = g\left(1/\mu^2\right)\left(\mu^2 F\right) = gF \quad \left(\Rightarrow g = m_n/F\right) \tag{1}$$

Consider a second, neutral Dirac fermion, a lighter "neutron", n'. For simplicity, take its mass as "initially" zero, <u>but</u> couple n' a little to n. Then n' acquires a mass $m_{n'}$, from the mechanism shown in Fig. 2.

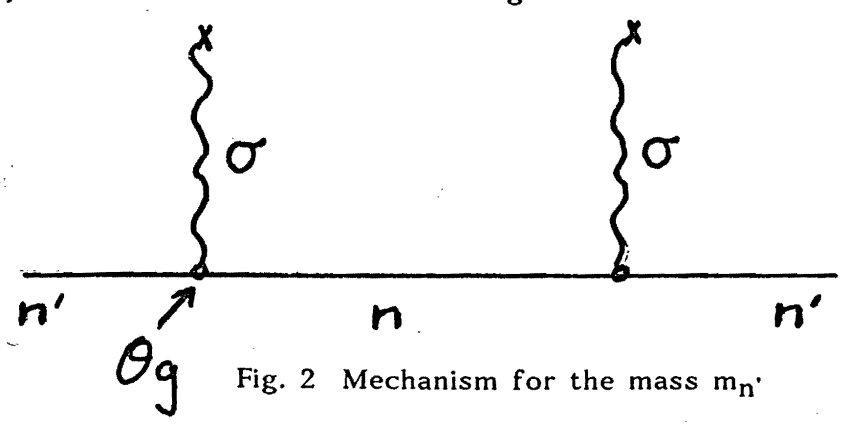

Fig. 2 Mechanism for the mass $m_{n'}$

The result is

$$\begin{aligned} m_{n'} &= \left(\Theta g\right)^2 \left(1/m_n\right)\left(\left(1/\mu^2\right)\cdot \mu^2 F\right)^2 \\ &= \left(\Theta m_n/F\right)^2 \left(1/m_n\right)\left(F\right)^2 \\ &= \Theta^2 m_n \end{aligned} \tag{2}$$

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Now n decays, because of the process shown in Fig. 3.

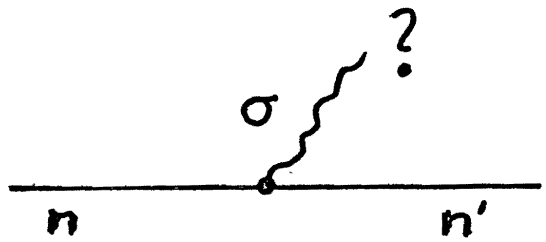

Fig. 3 Transition via a virtual σ

What does it decay into, n' and a σ? No, not generally, because the σ boson is heavy and not real. But, it is always present virtually. So, what does σ decay into? Answer: into <u>two</u> Goldstone bosons, b (assume b is approximately massless, i.e. $m_b \ll (m_n - m_{n'})$). Therefore, we have the decay[1],

$$n \rightarrow n' + b + \bar{b} \quad . \tag{3}$$

This is so, if the mass generation of m_n arises because of a spontaneously broken, global symmetry[2,3]. The decay mechanism is shown in Fig. 4.

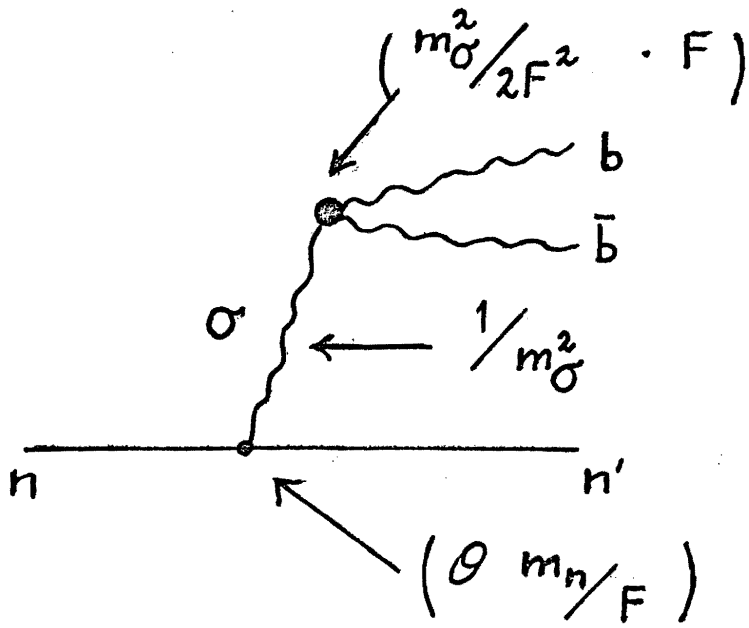

Fig. 4: The decay $n \rightarrow n' + b + \bar{b}$, via σ

This leads to the lifetime[F1],

$$\tau(n \rightarrow n' + b + b) = \left\{ \left(\Theta m_n/F \right)^2 \left(m_n/F \right)^2 \left(m_n/6144\pi^3 \right) \right\}^{-1}$$

To get a feeling for the consequences of these considerations, I put in some numbers. (1) For an assumed mass m_n = 15 eV, which would be relevant for dark-matter consideration[4], and using $\Theta^2 \gtrsim 10^{-3}$, which is an empirical upper limit[5] for $\nu_\tau - \nu_\mu$ mixing, one has

$$m_{n'} = \Theta^2 m_n \gtrsim 10^{-2}\ \text{eV} \tag{4a}$$

$$\tau_n \sim 8 \times 10^{20}\ \text{sec} \tag{4b}$$

This is for[F2] $F \cong 300$ MeV. So, $m_{n'}$ is a mass in the range relevant[6] to resolution of the solar neutrino anomaly. The lifetime means that decays are occuring in the present universe. (2) Assuming[7,8,9,10] a mass m_n = 17 KeV, and $|\Theta| \gtrsim 0.03$, one has

$$m_{n'} = \Theta^2 m_n \sim 17\ \text{eV} \qquad \text{(dark matter ?)} \tag{5a}$$

$$\tau_n \sim 8 \times 10^5\ \text{sec} \quad \text{(a factor[11] in the development of very large scale structure[12,13] in the universe?)} \tag{5b}$$

Again, this is for $F \cong 300$ MeV. Why this F? I don't know. (Do you know why $F_{el\text{-}wk} \cong 300$ GeV?) But, what has been sketched here is ~ the σ-model of pion-nucleon physics[2] ($F_\pi \cong 100$ MeV). The symbol ~, here means without the second "neutron", n'; and with only a neutral π^o as the pseudoscalar, Goldstone boson required[3] by a spontaneously broken, chiral symmetry[2], which breaking allows the nucleon to acquire mass. That is, a "primary" mass term ($\propto m_n^o \neq 0$) for n is forbidden in the Lagrangian $\mathcal{L}(\psi_n, \bar{\psi}_n)$, by invariance under the chiral transformation[2],

$$\begin{aligned} \psi_n &\Rightarrow \psi_n + \delta\psi_n = \psi_n - \frac{i\beta}{2}\gamma_5\psi_n \\ \bar{\psi}_n = \psi_n^\dagger\gamma_o &\Rightarrow \bar{\psi}_n + \delta\bar{\psi}_n = \bar{\psi}_n - \frac{i\beta}{2}\bar{\psi}_n\gamma_5 \end{aligned} \tag{6a}$$

(β is infinitesimal)

which gives,

$$\delta\left\{-m_n^o\bar{\psi}_n\psi_n\right\} = i\beta m_n^o\bar{\psi}_n\gamma_5\psi_n \neq 0 \tag{6b}$$

Rather, postulate[2] in $\mathcal{L}$, interaction terms

$$-\frac{g_n}{2}\bar{\psi}_n(\sigma + i\gamma_5 b)\psi_n - \frac{g_n}{2}\bar{\psi}_n(\sigma^\dagger + i\gamma_5 b^\dagger)\psi_n \tag{7}$$

Under the chiral transformation, now including

$$\begin{aligned} \sigma &\Rightarrow \sigma + \delta\sigma = \sigma - \beta b \\ b &\Rightarrow b + \delta b = b + \beta\sigma \end{aligned} \tag{8a}$$

one has, $$\delta \left\{ \bar{\psi}_n \, (\sigma + i \, \gamma_5 \, b) \, \psi_n \right\} = 0 \tag{8b}$$

Now, with $\sigma \to F + \tilde{\sigma}$, the vacuum expectation value $\langle\sigma\rangle = F \neq 0$ ($\langle\tilde{\sigma}\rangle = 0$); therefore $\mathcal{L}$ contains an n mass term,

$$g_n \, F \, \bar{\psi}_n \psi_n \, , \qquad g_n = m_n / F \tag{9}$$

The specifically new element here[1] is a term in $\mathcal{L}$ which explicitly breaks the chiral symmetry, linking n' to n via σ; giving mass to n'.

$$\tilde{\mathcal{L}} = \tilde{\mathcal{L}}^{\dagger} = -i \left(\Theta g_n \right) \bar{\psi}_n \, \gamma_5 \psi_{n'} \sigma - i \left(\Theta g_n \right) \bar{\psi}_{n'} \, \gamma_5 \, \psi_n \, \sigma^{\dagger} \tag{10}$$

The γ_5 in the interaction results[F3] in a positive mass shift from the mechanism shown in Fig. 2, i.e. $m_{n'} = 0 \Rightarrow m_{n'} > 0$.

The masses and interactions in the bosonic sector[F4] follow from part of $\mathcal{L}$,

$$\mathcal{L}_{\lambda} = -\frac{\mu^2}{2}(\sigma^{\dagger}\sigma + b^{\dagger}b) - \frac{\lambda^2}{4}(\sigma^{\dagger}\sigma + b^{\dagger}b)^2$$

$$\underset{\sigma \to F + \tilde{\sigma}}{\Longrightarrow} \quad -\frac{m_{\sigma}^2}{2} \tilde{\sigma}^{\dagger}\tilde{\sigma} - \frac{m_b^2}{2} b^{\dagger} b - \frac{\lambda^2}{2} F \, (\tilde{\sigma} + \tilde{\sigma}^{\dagger}) \, b^{\dagger} b$$

$$- \frac{m_b^2}{2} F \, (\tilde{\sigma} + \tilde{\sigma}^{\dagger}) \; + \; \ldots$$

with $$m_{\sigma}^2 = \mu^2 + 2\lambda^2 F^2 \, , \quad m_b^2 = \mu^2 + \lambda^2 F^2 \tag{11}$$

For $$F \neq 0, \text{ but } \langle\tilde{\sigma}\rangle = 0, \text{ we must have } m_b^2 = 0 \quad (\mu^2 < 0) \tag{12}$$

The Goldstone boson is b, massless but for explicit symmetry-breaking terms in $\mathcal{L}$. Also,

$$m_{\sigma}^2 = \lambda^2 F^2 \Longrightarrow \lambda^2 = m_{\sigma}^2 / F^2 \tag{13}$$

So the effective decay coupling in Fig. 5 is $\frac{\lambda^2}{2} F = m_{\sigma}^2 / 2F$.

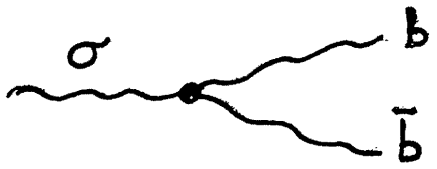

Fig. 5 The decay $\sigma \to b + \bar{b}$

Limiting[F5] $|\lambda| \lesssim 10$, gives $m_\sigma \lesssim 3$ GeV for $F \cong 300$ MeV. Then,

$$\Gamma_\sigma = \left(\frac{m_\sigma}{F}\right)^2 \frac{m_\sigma}{64\pi} \sim 0.5\, m_\sigma \sim 1.5 \text{ GeV} \tag{14}$$

In conclusion, it is worthwhile to keep some general issues before ones' eyes. What are the <u>physical</u> uses of neutrino masses?

(1) (a) $m_{\nu_\tau} \sim 15$ eV, dark-matter contributor[4]?

(b) $\Theta^2 \lesssim 10^{-3} \Rightarrow m_{\nu_\mu} \lesssim 10^{-2}$ eV , solar $\nu_e \to \nu_\mu$ transition[6] ?

(c) $\tau_{\nu_\tau}(\nu_\tau \to \nu_\mu + b + \bar{b}) < 10^{21}$ sec

($t_{universe} \sim 5 \times 10^{17}$ sec)

$\Rightarrow$ decays occuring now ?

(2) (a) $m_{\nu_\tau} \sim 17$ KeV, more very large-scale structure[12,13] in the universe, <u>because</u>[11], F7

$\tau_{\nu_\tau}(\nu_\tau \to \nu_\mu + b + \bar{b}) < 10^6$ sec.

(b) $\Theta^2 \lesssim 10^{-3} \Rightarrow m_{\nu_\mu} \gtrsim 15$ eV, a dark-matter mass follows "naturally".

What are the physical uses of (~ massless) Goldstone bosons b, coupled to neutrinos (via $\tilde{\sigma}$, largely unobservable directly)?

(1) Possibly sporadic, distant "point-sources" of Goldstone bosons in the sky, which bosons induce anomalous high-energy interactions[14] (probably rich in $\mu(\tau)$-pairs) here?

(2) A contribution to dark matter i.e. m_b not exactly zero?

It is 30 years since Goldstone's paper[3]. We have yet to observe a "real" Goldstone boson[F6]. Or a Higgs-like σ. Do they exist in Nature?

Footnotes

F1. Proportionality to m_n for a two-body phase space goes over to proportionality to $m_n^2 \cdot m_n$ for a three-body phase space.

F2. Note $g_n = \frac{m_n}{F} \cong 0.5 \times 10^{-7}$. For m_n = 17 KeV, $g_n \sim 0.5 \times 10^{-4}$.

F3. Note that an admixture of 1 here, brings in parity violation at the level of mass generation (not removable by a choice of relative phase between ψ_n and $\psi_{n'}$). For γ_5 only, a third n" interacting with n and with n', brings in parity violation not removable by a choice of phases.

F4. The fields $\tilde{\sigma}$ and b are not Hermitian.

F5. The relevant strength measure is $\lambda^2/8\pi^2$.

F6. The pion in Ref. 2 is the best-known "pseudo" Goldstone boson. However, the pion is also expected as a quark-antiquark bound state. As such, it does have a rather small mass.

F7. As of this date (April, 1992), the experimental case for a 17 KeV neutrino is weakened. See the brief review in "Pursuing the 17 KeV Neutrino", A. Hime, Los Alamos preprint, LA-UR-92-946. The argument (Ref. 6) for a neutrino mass $\lesssim 10^{-2}$ eV remains. Thus, it would be useful to consider possible consequences of a neutrino decaying, with emission of two Goldstone bosons, in the present universe.

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Added note (June, 1992). The specific hypothesis for the solar neutrino issue put forth in reference 6, has $m_{\nu_\mu} \gtrsim 10^{-3}$ eV, $\Theta^2 \gtrsim 10^{-2}$; therefore $m_{\nu_\tau} \sim m_{\nu_\mu}/\Theta^2 \lesssim 0.1$ eV is hardly relevant for dark matter. Here, I have argued that $m_{\nu_\mu} \sim 10^{-2}$ eV, $\Theta^2 \sim 10^{-3}$, such that $m_{\nu_\tau} \sim m_{\nu_\mu}/\Theta^2 \sim 10$ eV <u>is</u> relevant for dark matter. (Assumed, $\Theta^2_{\mu\tau} \gtrsim \Theta^2_{\mu e} = \Theta^2$.) Then few, (if any) of the main-cycle neutrinos from the Sun are effected (note Fig. 1 in H.A. Bethe and J.H. Bahcall, Phys. Rev. D44 (1991) 2964). This situation appears relevant today ($\sin^2\Theta_{\mu e} \sim 1/2 >>> \Theta^2_{\mu\tau}$ is also possible).

With the kind of dynamical mass generation discussed here, if one imposes a sum-rule for corresponding "mixing" angles in the quark and lepton sectors, one obtains $\theta_{ct} + \theta_{sb} = \theta_{\mu\tau} + \theta_{\nu_\mu\nu_\tau}$ which translates into a mass-ratio sum-rule: $(m_c/m_t)^{1/2} + (m_s/m_b)^{1/2} = (m_\mu/m_\tau)^{1/2} + (m_{\nu_\mu}/m_{\nu_\tau})^{1/2}$. The left-hand side reads $(0.095 + 0.184) = 0.28$ for $m_t = 150$ GeV ($m_c = 1.35$ GeV, $m_s = 0.180$ GeV, $m_b = 5.3$ GeV); the right-hand side reads $(0.244 + 0.032) = 0.276$ for $\theta^2_{\nu_\mu\nu_\tau} \sim 10^{-3}$. Similarly, $\theta_{uc} + \theta_{ds} = \theta_{e\mu} + \theta_{\nu_e\nu_\mu}$ translates into $(m_u/m_c)^{1/2} + (m_d/m_s)^{1/2} = (m_e/m_\mu)^{1/2} + (m_{\nu_e}/m_{\nu_\mu})^{1/2}$, which implies a relatively large ν_e-ν_μ mixing, i.e. $\theta_{\nu_e\nu_\mu} \sim 0.23$ (these sums are $=0.3$, close to the previous 0.28).