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TITLE.

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ABSTRACT

Some consequences of a very light scalar boson coupled only to neutrinos are discussed. In particular, I argue that it is possible to sketch scenarios for the evolution of the Universe in which neutrinos cluster to a local density $\approx 10^{16}/cc$, that such clusters would be attracted to matter gravitationally, and that the existence of such a neutrino density in the solar system provides an alternative to $m_{\nu_e}^2 < 0$ in fitting tritium beta decay.

The question of neutrino masses, whether they are non-zero and, if so, what their values are, is a major open question in Electro-weak physics. In this conference we are hearing about experiments which study the end point of the beta ray spectrum of ^3H to extract information about m_{ν_e}. The actual quantity extracted in the usual analysis is m^2 and modern experiments,[1-5] while differing in experimental techniques, all report a best value of $m_\nu^2 < 0$, roughly by one to two standard deviations. Assuming that the result is not due to some shared systematic, like an error in the molecular final states, and setting aside the possibility that the free neutrino does have a space-like propagator,[6] what could this result mean?

The major assumption in the fitting is that the only difference from the standard, $m_\nu = 0$, description is in the evaluation of the neutrino momentum, $P_\nu = \sqrt{(E_o - E_\beta)^2 - m_\nu^2}$, where E_o is the energy available to the leptons and E_β is the electron energy. This corresponds to multiplying the usual spectrum (dn/dE_β) by $\left[1 - m_\nu^2/(E_o - E_\beta)^2\right]^{1/2}$. This is shown in Figure 1 with the spectrum displayed on 1a and the Kurie plot on 1b with the simplification of only one final state. Solid lines represent $m_\nu = 0$, dashed lines show the effect of a non-zero mass. The vertical bars show the effect of some mechanism that gives added counts near, but below, the end point. Should that be the case, forcing a fit with the standard formula will result in a best value of $m_\nu^2 < 0$. In presenting the Los Alamos result[5], we remarked on this effect and noted that we could obtain a statistically equivalent fit by setting $m_\nu^2 = 0$ and adding a spike of counts at the endpoint. The best fit correspondents to a branching ratio of 10^{-9} or a partial life-time of 10^{10} years.

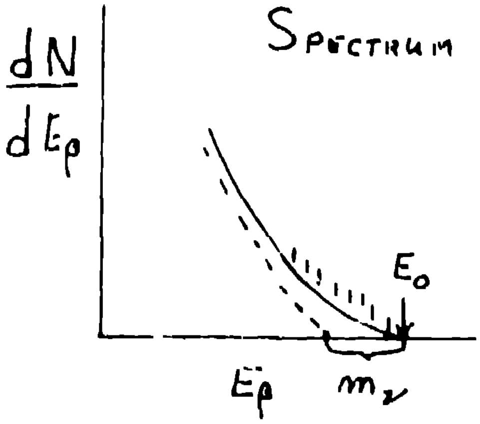

Fig. 1a Spectrum

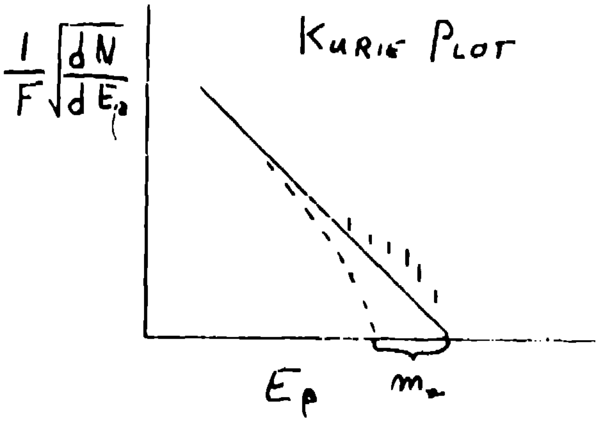

Fig. 1b Kurie Plot

A spike of some height is expected in standard model cosmology through the absorption of relic neutrinos, expected at a density of $\approx 50/cc$ for every flavor, through the mechanism of the usual Weak Interaction, in analogy with K-capture. This rate can be calculated[7] and, for $50/cc$, gives a partial life time of 10^{34} years. Therefore the data would require an increase in the density of relic neutrinos in the vicinity of the earth by some 14 orders of magnitude, which may not be as outrageous as it sounds.

Terry Goldman and I have been investigating the consequences of a light scalar boson which couples to neutrinos but no other light fermion.[8] While scalars coupled to neutrinos may arise in particular gauge theories, we have chosen to view this question phenomenologically, unhindered by other couplings such theories may require. We have concentrated on a scalar rather than a vector for several reasons. First, to avoid anomalies, in particular the coupling to one Z^0 and two new bosons, which cannot be cancelled in the neutrino sector alone. Second, to provide an attractive force between all neutrino species with no shielding. Third, to avoid serious conflict with primordial nucleosynthesis and supernova dynamics. Kolb, Turner, & Walker[9] have shown that this case is equivalent to 1/2 extra family of neutrino for nucleosynthesis, which is tolerable. For the previous statement to hold, there must be two states per light neutrino, i.e. the neutrino must be Majorana, and, hence, the chirality flip induced by the scalar does not produce sterile neutrinos within a supernova. In spite of the fact that, for Majorana neutrinos, there is no sense to the distinction neutrino and anti-neutrino, I shall use the former to denote the left handed state and the latter for the right handed state to facilitate comparisons with other work.

We write $\mathcal{L}_I = ig'\psi_\nu\psi_\nu\phi = ig(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)\phi$, where R and L refer to chiral projections and ϕ is a scalar field with mass m_ϕ. The region of parameter space of interest (for reasons given below) has m_{ν_e} of several eV and $m_\phi \ll m_{\nu_e}$. Then for $s \approx 4m_\nu^2 \ll m_\phi^2$, the total scattering cross section $\sigma' \approx \tilde{\alpha}^2/m_\phi^2$, where $\tilde{\alpha} = g^2/4\pi$. For s large compared to m_ϕ^2, $\sigma' \approx \tilde{\alpha}^2/s$, hence it is possible to arrange $\tilde{\alpha}$ and m_ϕ so that high energy neutrinos are not affected and low energy neutrinos undergo significant scattering. If $m_\phi \ll m_\nu$, two Majorana neutrinos will annihilate into two ϕ's with a rate given by $\omega \approx \frac{\pi\,\alpha^2}{16\,m_\nu^2}\rho c$. To sustain a density of 10^{15} ν/cc now requires that the associated rate be less than $10^{18}/s$, or $\tilde{\alpha}^2 < 4x10^{15}(m_\nu(eV))^2$. More detailed arguments are presented in ref (8).

Two other processes which can place limits on $\tilde{\alpha}$ directly are the Bremsstrahlung of ϕ's during a normal weak transition and the emission of a scalar in place of two neutrinos in nuclear double beta decay. Both processes have been studied. Barger, Keung and Pakvasa[11] use $K \to f2$ decays and Bernatowicz et al[12] compare the deduced $\beta\beta$-decay rates for $^{128,130}Te$. The limits, $\tilde{\alpha} < 10^{6}$, are well satisfied by the parameter set under discussion.

The general many-body problem of relativistic fermions interacting through a attractive scalar exchange and a reoulsive vector exchange (provided here by Z^{o} exchange, although the contribution to this problem is not significant) has been studied as a model of nuclear physics known as QHD[10]. While the parameters for that study are vastly different from the present case, all the necessary formulas are worked out to treat this problem of a self-bound gas of neutrinos. In particular, the effective mass is proportional to $\tilde{\alpha}/m_\phi^2$, so the potential can be scaled independently of the scattering cross-section. However, the scalar potential is scaled by m^*/e^*,[13] where the * refers to effective quantities in the medium. which leads to a transcendental equation for m* (see eq. 3.55, ref. 10),

$$m^* = m - \frac{g^2}{m_\phi^2(2\pi)^3}\int_0^{k_F} d^3k\,\frac{m^*}{(k^2+m^{*2})^{1/2}}$$

Examination of this equation shows that there is a minimum value of $m^* > 0$, which indicates that the average binding can't exceed m. For ρ of $10^{16}/cc$, k_F 16.8 eV/c, so the picture would appear to be in trouble for m_ν several eV.

There are, however, at least two distinct neutrinos and, most probably, three. Arguments using limits on the amount of dark matter would say that the sum of the three masses must be less than about 100 eV. The inclusion of the other two species, with at least one mass well in excess of 20 eV, circumvents the problem and makes it possible to sustain such a gas.

The evolutionary scenario is then something like this. between e^+e^- annihilation at about 1 MeV and recombination at about 20 eV. the neutrinos, as usual, expand with

$T_\nu = (4/11)^{1/3} T_\gamma$, internally thermalized by ϕ exchange and maintaining contact with the baryons only through gravity. As the Universe approaches the recombination epoch, some neutrinos begin to get cold (i.e., m>kT). On the one hand, given the relatively (to gravity) strong, finite range attraction, those neutrinos will tend to cluster, but, on the other hand, they are still coupled to hot, lighter neutrinos. Shortly after recombination, all the neutrinos are cold, the baryons are decoupled from the photons, so are very cold, and everything is coupled by gravity.

While this system may be rich enough to produce several scales, the most collective mode will be one in which all species condense together, hence, in general, the neutrinos will follow the matter (or vice versa). For a large fraction of the structures in the Universe, neutrinos should cluster where matter clusters. Whether this argument holds on solar system scales is an open question, but the existence of neutrinos clustered about the sun is a possibility. While the density increase from 50 to 10^{16} is nowhere near as large as that for baryons, space is still mainly devoid of neutrinos, allowing the propagation of neutrino signals from extra-Galactic sources. Note that $10^{16}/cc$ corresponds to the primordial density at a temperature of about 10eV; so as long as ϕ-exchange can sustain such a density, or a higher density, the uniform expansion of the early Universe will drive the density down to a value near this.

While these arguments do not prove the existence of neutrinos at a density about $10^{16}/cc$ around the earth, they do provide enough plausibility to examine further the effect on the endpoint of the ^3H beta spectrum. (Should they extend out to the earth's orbit? If neutrinos track the baryons exactly, so $m_\nu \sim 10^9 m_B$, the neutrino sphere would have a radius of about 0.033 lt. yr.) The existence of a Fermi momentum $k_F \sim 16.8\ eV/c$, and a corresponding $E_F \sim 16.8\ eV$ means that the previous analysis, done by putting a spike at the endpoint, is inadequate. Robertson, Wilkerson, Knapp and I have revisited that analysis to include the effects of the Fermi distribution,[14] and I shall report here on results using a subset of the data reported in ref. 5, one which gives a very similar $\langle m_\nu^2 \rangle$ to the full set.

Previous discussions[15] of the effect of a filled Fermi sea of neutrinos and antineutrinos have been based on the usual assumptions of cosmology and of the Weak Interaction.

a consequence of which is that the neutrinos and anti-neutrinos form completely non-interacting gases and that the particles obey the free dispersion relation. In contrast, the current picture has the neutrinos and anti-neutrinos occupying relatively isolated wells, with the Fermi distribution coming just to the top of the well. None of the other players in the process, the ${}^3He$, ${}^3H$ and electron, feel this well, so all of their variables are set by the conditions in a region of space where there is no neutrino background. A cartoon of this description is shown in Figure 2.

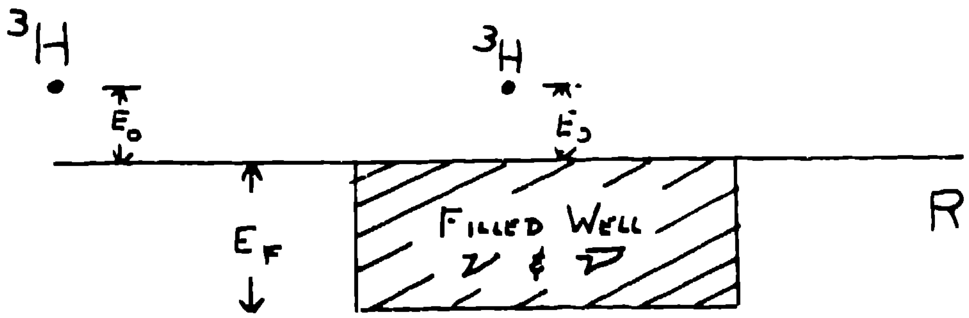

Fig. 2 Cartoon Showing Beta Decay With Neutrino Clusters

The effect of the usual argument is shown, again for only one final state and $m_\nu = 0$ in a Kurie plot on Figure 3a. The filled anti-neutrino sea blocks the emission of $\bar\nu$'s with energy less than $E_F = \sqrt{k_F^2+m_\nu^2}$, so the beta spectrum is cut off abruptly at $E_0 - E_F$. Neutrinos can be absorbed from the sea giving energies between 0 and E_F to the beta which gains the full E_0 from the hadronic system, so there is a non-zero counting rate for $E_0 \le E_\beta < E_0 + E_F$. A non-zero m_ν would not change the spectrum below E_0, but the additional counts would come for $E_0 + m_\nu \le E_\beta < E_0 + E_F$.

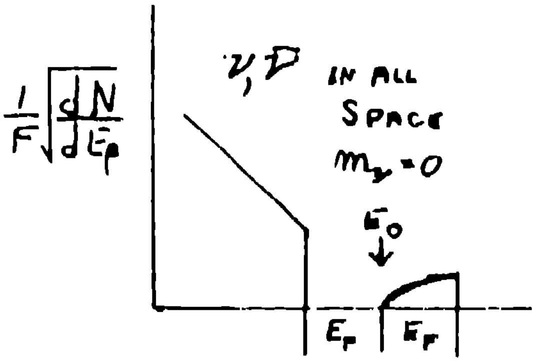

Fig. 3a Kurie Plot, No Clustering

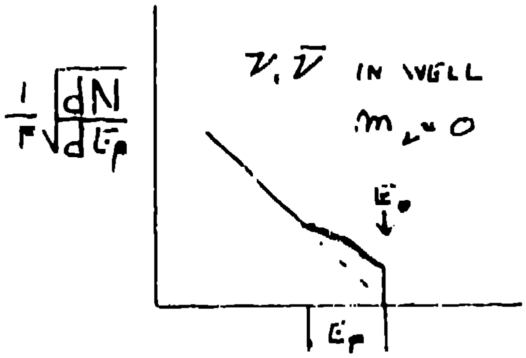

Fig. 3b Kurie Plot With Clustering

However, as I have shown above, that is not a consistent picture if $\rho > 50$, particularly 14 orders of magnitude greater. If the ^3T decays in a region of space where there is no neutrino background, the standard analysis will apply. If, however, the neutrino background is present, the analysis changes, but not as described in the previous paragraph. This is shown in Fig. 3b.

The anti-neutrino emission is not affected. The state into which the anti-neutrino is created has positive energy, is above the top of the well and is orthogonal to all the filled states, hence there is no Pauli suppression. Since, for the case at hand, the emission is s-wave, the change in k multiplied by the nuclear radius does not change j_o, therefore does not change the matrix element. In short, there is no modification.

The neutrinos will be absorbed and will provide extra counts, but, in the main, below E_o. Consider first $m_\nu = 0$ and a neutrino from the bottom of the well. To make that absorption go, E_F must go into the neutrino, so the contribution is at $E_o - E_F$. Since a neutrino at the top of the sea requires no additional energy, it will contribute at $E_\beta = E_o$. Therefore, the neutrino sea will contribute an essentially constant amount to the region $E_0 - E_f \geq E_\beta \leq E_o$. For fixed E_F, the existence of a neutrino mass, m_ν, will simply shift the interval upwards by m_ν, i. e. extra counts in $E_o - E_F + m_\nu < E_\beta < E_o + m_\nu$.

TABLE 1

$m_\nu^2(eV^2)$	N bins	E(ev)	ρ(#/cc)	Ξ^2
0	"spike"	0	$6x10^{15}$	547.1
0	4	9	$7.2x10^{15}$	547.6
0	6	15	$8.0x10^{15}$	547.2*
0	8	21	$8.6x10^{15}$	547.2
0	12	33	$9.2x10^{15}$	547.5
0	91	60	$14.2x10^{15}$	547.6
5	6	15	$8.2x10^{15}$	546.3
25	6	15	$9.0x10^{15}$	546.3
100	6	15	$11.8x10^{15}$	546.4
0	no relic absorption			549.4
-138.8	no relic absorption			547.2

To implement a fitting procedure, we wish to remain compatible with our earlier work(5), where the data are summed into fixed energy width bins. Therefore we fit to a amplitude distributed over a fixed number of bins, which corresponds to varying the density and the Fermi energy separately. This is done holding m^2 fixed at some value. The results are shown in Table 1. N is the number of bins affected and E is the total width of the added segment. This should correspond to the E_F appropriate to the density of relic neutrinos.

The * indicates the case where that energy and the fit density most nearly match, since $\rho = 8x10^{15}/cc$ implies $k_F = 15.4\ eV/c$. Ξ^2 is the measure of the fit, similar to χ^2, for a discussion, see ref. 16. The first line is the original spike. For comparison, the last two lines show cases where there is no relic neutrino absorption. $m_\nu^2 = 0$ is a forced fit, $m_\nu^2 = -138.8(eV)^2$ is the best fit with the simple function described at the beginning of the paper. For the forced fit there are 553 degrees of freedom, for all other cases there are 552 degrees of freedom.

These results, while preliminary, show certain features which we expect to persist. First, smearing the counts over a Fermi distribution does not destroy the general agreement with the data. Second, one can move the mass, energy width and density around in compensating ways, so there is not a clear preference from Ξ^2. However, ρ uniquely specifies $k_F = \sqrt{E_F^2 - m_\nu^2}$, and not all solutions satisfy this condition, so the result is more robust than is at first apparent.

I have presented a possible scenario for obtaining a high density of neutrinos and shown that such a picture can provide a fit to a subset of the Los Alamos tritium beta decay data. There does not appear to be any show stopper. There are many details to be filled in and the fit needs to be made to the full data set, but this appears to be a viable explanation of the data.

In addition to my colleagues named above, I want to thank the School of Physics, University of Melbourne, for its hospitality while this was being written, Bruce McKellar, Mark Thompson, Bill Spence and John Costella for illuminating conversations, and Prof.'s V. Lobashev and J. Bonn for long discussions during the workshop. This work was supported by the U. S. Department of Energy.

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