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An Unmixed 17 keV Neutrino

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ABSTRACT

We argue that the observation of the kink in the electron energy spectrum in β decay does not necessarily imply mixing amongst the neutrinos. We have constructed a model in which the kink occurs because the neutron can also β decay into an isosinglet neutrino (with a Dirac mass of 17 keV) via a new interaction mediated by spin zero, $Q=-1/3$ leptoquarks with a mass of $100 \div 1000$ GeV. Our model can be tested by modest improvements in the measurement of the longitudinal polarisation of electrons in β decay and in the branching fraction of the pion decay to electron. Astrophysical and cosmological implications of this new interaction of neutrinos are also discussed.

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Experiments using solid state detectors continue to confirm Simpson's original observation [1] of a kink in the electron energy spectrum from several β-emitters (^{3}H, ^{14}C, ^{35}S, ^{63}Ni, ^{55}Fe and ^{71}Ge) around 17 keV below the Q-value [2] although this result has not been confirmed [3] by any experiment using a magnetic spectrometer [4]. The observation of the kink implies that the electron spectrum consists of two components. The data are most simply accounted for by assuming that two varieties of neutrinos with masses m_1($<$9.4 eV [5]) and m_2 ($\simeq$ 17 keV) are emitted in β-decays, with probabilities p ($\simeq$ 99%) and $1-p$, respectively. We may thus write the energy spectrum as,

$$\frac{dN}{dE}(E) = p\frac{dN}{dE}(E,m_1) + (1-p)\frac{dN}{dE}(E,m_2) \tag{1}$$

where $dN/dE(E,m)$ is the usual β-decay spectrum for the emission of a massive neutrino. In order to account for the kink, it is usually assumed that ν_e is a coherent superposition of the mass eigenstates ν_1 and ν_2 with a mixing angle given by $\sin^2(\theta) \simeq 0.008$.

The purpose of this Letter is to explore alternative possibilities that can account for this observation. Our main result is that by introducing new interactions which allow for the decay $d \to u + e + \nu_2$, with a 1% branching fraction, the experimental results on the 17 keV neutrino can be accounted for without any neutrino mixing. Such new interactions are already present in well-studied extensions of the Standard Model. Several considerations will lead us to conclude that ν_2 should be a new SU(2) singlet neutrino and, as we will see, the required interactions have important implications both for laboratory experiments as well as for cosmology and astrophysics.

Before turning to the details of our proposal, we want to mention a variety of possibilities to account for the observation of the kink that do not entail mixing between the neutrinos and briefly comment on why we believe they are unlikely to be viable:

(a) a 1% branching ratio into an excited state 17 keV above the ground state.

(b) emission of an undetected 17 keV scalar companion [6] of the neutrino with a branching fraction of 1%,

(c) emission of a Majoron from the decay of a (virtual) ν_e into a 17 keV neutrino and a Majoron,

(d) the decay of a virtual ν_e into a 17 keV neutrino and a pair of massless neutrinos via a new four-neutrino interaction [7].

Alternative (a) would require a 17 keV excited level for the daughters of all six nuclei in which the 17 keV neutrino has been observed. Furthermore, the delayed gamma ray from the deexcitation of the daughter nucleus, even if not separately identified, should deposit electromagnetic energy in the calorimeter, leading to an excess of events for an "electron energy" of 17 keV. Possibilities (b)-(d) involve four or five particles in the final state. The resulting electron spectrum would, therefore, be considerably different [6] from the standard β-decay spectrum, although only for 1% of the decays. Further, known bounds [8] on Majoron couplings already exclude a branching ratio at the observed level of 1%.

For these reasons, we will henceforth assume that the 17 keV neutrino is emitted via the usual three body decay. Assuming that ν_2 is chiral, we introduce new effective interactions,

$$\mathcal{L}_{eff} = \sum_i \frac{F_i}{\sqrt{2}} \bar{u} O_i d \; \bar{e} O_i \nu_2 + h.c., \tag{2}$$

that can result in the required decay $d \to u + e + \bar{\nu}_2$, with a branching ratio of $O((F/G_F)^2)$ that should be around 1% (F is the generic value of the coupling constant in eq. (2)). In order to narrow the space-time structure of the operators O in Eq. (2), we note that for all the nuclei except for Tritium and ^{35}S in which the 17 keV neutrino is observed, the β-decay proceeds via a Gamow- Teller transition, so that only $O = P$, A and T can contribute [9]. Thus, at least one of these operators must be non-vanishing. Furthermore, since the pseudoscalar only results in forbidden transitions, in the case $O = P$ the corresponding value of F would have to be rather large to account for the observed 1% branching ratio. The same interaction would lead to chirally unsuppressed $\pi \to e\nu$ decays, and hence, is excluded. Note also that the data do not yield much information on S and V interactions of ν_2. These can best be searched for by studying the decays of nuclei where only Fermi transitions are possible. If the new interaction is purely a combination of A and T, there will be no kink in the decays of such nuclei. In nuclei such as ^{3}H, where both Fermi and Gamow-Teller transitions are possible, the observed effect should be smaller by 25%. We have searched for nuclei which decay by pure Fermi transitions. For the two possible candidates that we found, ^{66}Ga $\to^{66}$Zn and ^{156}Eu $\to^{156}$Gd, the lifetimes are, unfortunately, fairly short –9.4 hr and 15 days, respectively– while the corresponding Q values (5.2 MeV and 2.45 MeV) are rather large. In a gauge theory, it is possible to get tensor interactions via Fierz transformations of V and A interactions, but then, they are always accompanied by P (and S) interactions, which as we have seen lead to unsuppressed $\pi \to e$ decays. Hence, we will assume for definiteness that the new effect is due to an A type operator, appearing in (2) as $O = V \pm A$.

What are the possible candidates for ν_2? The simplest (and safest from the point of view of astrophysics) alternative is not to introduce new interacting neutrinos and consider the possibility that it is the left-handed muon or tau neutrino. It is simple to see that electroweak symmetry then implies that the charged member of the lepton doublet must also participate in this new interaction and that at least one of the other particles interacting via (2) must be part of a doublet. For $O = V \pm A$ it is not possible to form an SU(2) singlet state just from the two ordinary lepton doublets. In the remaining case in which the extra doublet is a quark, there will be a lepton flavour violating coupling involving the two charged leptons which will contradict observations since the strength of this coupling, F, is fixed to be about $0.1G_F$. For instance, if we identify ν_2 with ν_τ, the observed branching fraction [10] of 23% for the decay $\tau \to \rho\nu_\tau$ then implies a branching fraction of 2×10^{-3} for the decay $\tau \to \rho e$, in conflict with the experimental upper limit of 4×10^{-5}. Identification of ν_2 with the muon neutrino similarly leads to conflict with the experimental upper bounds [10] on $\mu + N \to e + N$ scattering cross sections, which would be expected to be about 1% of their flavour conserving counterparts. Also, the induced $\mu \to e\gamma$ decay (at one loop) would conflict with experimental upper bounds [10]. From this discussion and from the LEP results on the number of light neutrino doublets, we thus conclude that ν_2 must be a singlet neutrino.

We now argue that a singlet ν_2 cannot enter into (2) via a $V - A$ interaction. If ν_2 is indeed left-handed, so is the electron field in eq.(2) so that the electron participating in this interaction is part of an SU(2) doublet. In order that (2) is SU(2) invariant, one of the two quarks must an SU(2) singlet while the other one must be part of a quark doublet. This interaction is, therefore, impossible within the standard model framework since singlet and doublet quarks have opposite chiralities. We therefore conclude that ν_2 must be right handed.

Turning now to consider a $V + A$ type of leptonic current, let us examine whether existing data allow the possibility of such a "β decay" of quarks to left-handed anti-neutrinos. The most stringent constraint comes from the measurement [11] of the longitudinal polarisation $P = -1.001 \pm 0.008$ of the electron in Gamow-Teller type β decays (for Fermi transitions, this is very poorly determined), which suggests that the electron is dominantly left handed. Assuming that there is a new four Fermi interaction of right handed neutrinos with a strength ϵG_F, the expected longitudinal polarisation is, $[-1+\epsilon^2]/[1+\epsilon^2] \simeq [-1+2\epsilon^2]$, so that incorporating the experimental constraint requires [12] $\epsilon < 0.09$ (allowing a 2σ error), or p (in Eq. (1)) exceeding 99.2%. The required admixture in (1) is possible if we allow for a two standard deviation from the central value of the measured longitudinal polarisation.

The data on the y distributions in deep inelastic neutrino scattering also potentially constrain the $V + A$ type of interactions. Note, however, that ν_2 is produced only in interactions involving electrons, so that the ν_2 content of a neutrino beam is about 1% its ν_e content, and further, it interacts with just 1% of the standard strength. The CDHS data [13] which bound wrong helicity interactions in a (dominantly) muon neutrino beam at the 1% level, therefore do not lead to significant constraints on ν_2, as long as it does not couple to muons. The new interaction leads to an additional contribution of 1% to $\pi \to e$ decays (relative to $\pi \to \mu$ decays) which is within the error quoted in the PDG compilation [10]. Lepton universality would be similarly violated in K decays.

Another important constraint is that, in order to accomodate the non-observation of neutrinoless double β-decay [14], the mass term for the singlet neutrino should not be Majorana. We can then either introduce a mass term between ν_2 and another singlet neutrino (not participating in interactions like (2)), or a usual Dirac mass term with one of the ordinary neutrinos, ν_μ or ν_τ.

The simplest way to realise the new interaction of ν_2 is to take it to be a right handed neutrino in a left-right model (not necessarily left-right symmetric), in which the interaction (2) arises via W_R exchange, with $g_R^2/M_{W_R}^2 \simeq 0.1 g^2/M_W^2$. The measurement of muon polarisation in π decays implies that the decay to "wrong helicity" muons is restricted to be $< 0.4\%$ at 90%CL [10], so that the charged current involving muons cannot have a $V + A$ part coupling with a strength $\sim 0.1 G_F$, i.e. even the particle assignments cannot be left-right symmetric (unless the $\nu_{\mu R}$ is very heavy). Ignoring $W_L - W_R$ mixing, all the data can be accounted for by couplings of the form, $[\bar{d}_L \gamma_\mu u_L + \bar{e}_L \gamma_\mu \nu_{1L}] W_L^\mu$ and $[\bar{d}_R \gamma_\mu u_R + \bar{e}_R \gamma_\mu \nu_{2R}] W_R^\mu$. The recent CDF lower bound [15], $M > 520$ GeV (obtained assuming $g_R = g$) on the mass of any extra W boson then implies $g_R^2/4\pi > 0.14$; the actual bound will be somewhat larger because the increased value of the coupling leads to a larger cross section for W_R production.

The large value of the coupling constant required for the new gauge interactions considered above, led us to look for other possibilities for the new interaction. One alternative is the scalar mediated interaction given by the Lagrangian,

$$\mathcal{L} = f_1 \; \bar{e}_R u_R^c \phi + f_2 \; \overline{d_R^c} \nu_{2R} \phi^*, \tag{3a}$$

which, on Fierz rearrangement, leads to an effective four fermion interaction of the form

$$\mathcal{L} = \frac{f_1 f_2}{2 m_\phi^2} \; \bar{u}_R \gamma_\mu d_R \bar{e}_R \gamma^\mu \nu_{2R}, \tag{3b}$$

if the new scalar ϕ is very heavy. In order to reproduce the observations, we must have $f_1 f_2/(2 m_\phi^2) \simeq 0.1 G_F/\sqrt{2}$, or, $m_\phi \simeq \sqrt{f_1 f_2}$ TeV, which suggests that the scalar has a mass in the range 100 GeV$\div$1 TeV. [1] Present lower mass bounds on m_ϕ are about $M_Z/2$ from

[1] Low energy constraints on right-handed currents in the Lagrangian of (3b) have also

the LEP experiments [16], whereas the UA2 experiment [17], from ϕ pair production, finds the model-independent limit $m_\phi > 67$ GeV. It is also possible to produce the scalars singly with a cross section dependent on the unknown coupling constants f_1 and f_2 that appear in (3). We refer the reader to Ref. 18 for a discussion of these cross sections, and the mass range that can be probed via these processes. It is, of course, obvious that unless f_1 is very small, the existence of such a scalar lighter than about 200-250 GeV should lead to spectacular signatures at HERA [19].

It is interesting to note that a leptoquark scalar of the type we are discussing is already present in many known extensions of the SM. It could, for instance, be identified with the isosinglet leptoquark fields in the fundamental representation of E_6. Such scalar fields would automatically be present in supersymmetric E_6 models [20]. It is easy to see that if the interactions (3) arise from a superpotential, the scalar cannot be the partner of the ordinary quarks (for instance, a term $d_R \nu_R \phi_R$ in the superpotential would require the existence of a $Q = -1/3$ isosinglet colour antitriplet superfield ϕ_R, which does not exist in the supersymmetric version of the standard model).

Turning now to the cosmological implications of the new singlets, a potentially serious difficulty is that the same interactions leading to the new effect in the β-decay, Eq. (2), will keep the singlets in equilibrium until late times so that they will count at the time of nucleosynthesis (NS) as one extra ν species [21]. In the model with a W_R, the singlets are kept in equilibrium through the reaction $\nu_2\bar{\nu}_2 \leftrightarrow e\bar{e}$, whose rate $\Gamma \simeq F^2T^5$ becomes smaller than the expansion rate $H \simeq T^2/M_{Pl}$ for $T \simeq 5$ MeV, at which the singlets freeze out. For the case of singlets coupling only via the leptoquark mediated interactions the story is different because equilibrium is maintained only via their interactions with hadrons [22]; since these are heavy, their density is suppressed by a Boltzmann factor so that the decoupling may occur at a higher temperature. Even after including the suppression in the pion number density, $N_\pi \sim (m_\pi T)^{3/2}e^{-m_\pi/T}$, we find that reactions such as $\nu_2+\pi^0 \leftrightarrow e+\pi^+$, keep the singlets in equilibrium until $T \lesssim 25$ MeV [2] In both cases, the decoupling occurs well after the bulk of the pions and muons have disappeared, so that the singlet density will not be further diluted with respect to the density of radiation until

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been discussed in Ref. 13 where it is concluded that the strength of right handed interactions can be as large as 13% of the normal weak interaction. For us, the limit is even looser as those constraints involving muons are not applicable.

[2] Recently Babu et al. [23] proposed a mechanism to suppress the leptoquark mediated singlet coupling to mesons. Their trick cannot be used in our case, that involves charged current interactions.

the period of e^+e^- annihilation. Hence, they will count as almost one full extra neutrino for NS.

It is well known that $N_\nu = 4$ would imply a primordial ^{4}He abundance of at least 0.248, in contradiction with a recent detailed analysis [24] which yields an upper-limit of 0.243, unless the discrepancy can be attributed to a residual systematic error or to values of $\eta \equiv n_B/n_\gamma < 2.6 \times 10^{-10}$. If $N_\nu = 4$ is taken as conclusively ruled out, the scenario we have outlined can obtain only if there is some other entropy generating mechanism between the time of singlet decoupling and nucleosynthesis, that reheats the radiation but not the singlet, making its contribution to the energy density at the epoch of NS to effectively be less than that of an extra ν. This could be the case for instance in the presence of a new late decaying particle that contributes significantly to the energy density before decaying, as was discussed by Kamionkowski and Turner [25].[3]

Another cosmological problem is that, since the relic number density of the 17 keV neutrinos is of the order of that of an ordinary neutrino, their contribution would lead to a predicted lifetime of the universe that is much smaller than its present age. All 17 keV models have this problem and are usually made viable by assuming yet another interaction that leads to an invisible decay of ν_2 (e.g. $\nu_2 \to \nu_1 +$ majoron) with a rest frame lifetime shorter than O(10^{14} sec) [27]. Structure formation considerations further restrict this lifetime to $\tau \lesssim 10^8$ sec [28].

As regards the supernova, since the neutral singlets will be abundantly produced in the SN core by the new interactions and leave it much more easily than the ordinary neutrinos, one should worry about their contribution to the energy transport that may significantly reduce the duration of the ν burst observed at IMB and KII. This is similar to the situation for the usual case of a 17 keV ν with a Dirac mass, in which singlets are produced in helicity flipping interactions. However, in the present situation the singlets are not sterile, but interact with matter with cross section of strength 1% of a weak cross section, which is just right to allow their efficient trapping [22], so that the arguments of Burrows and Gandhi [29] and refinements thereof are not applicable.

In summary, we have argued that the observation of the kink in the electron spectrum of β decay does not necessarily imply a mixing between neutrinos. We have constructed a model in which the kink is due to the β decay of the neutron into an isosinglet neutrino (with a Dirac mass of 17 keV) that occurs via a new interaction mediated by spin zero

[3] There exists a model of baryogenesis where this happens at precisely the right time; see, e.g. Ref. 26, in which overabundant relic gravitinos (with $m_{3/2} \simeq 100$ TeV) decay just before NS.

leptoquarks, that may even be accessible at HERA. Our model is qualitatively different from mixing models and is a readily testable alternative: it may be conclusively ruled out by a small improvement in the measurement of the longitudinal polarisation of the electron in β decay or the ratio $(\pi \to e)/(\pi \to \mu)$. The new interaction also has several cosmological and astrophysical implications. It causes a late decoupling of the singlet neutrinos so that they would count as an additional neutrino species at the epoch of nucleosynthesis. Unless this is circumvented, the primordial ^{4}He abundance would be quite large. The same interaction is also responsible for trapping the singlet neutrinos in the core of a supernova, so that the usual constraints on Dirac neutrinos are no longer applicable. Solutions to the solar neutrino problem that involve mixing between ν_{eL} and $\nu_{\mu L}$ (be they the MSW, "just so" or the decay variety) [30] can be readily incorporated within our model of the 17 keV neutrino.

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