Contact interactions involving right-handed neutrinos and SN 1987A

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(Received 1 August 1997; published 30 December 1997)

We consider lepton-quark contact interactions in models with right-handed neutrinos, and find that observational data from SN 1987A restricts the scale of such interactions to be at least $\Lambda > 90$ TeV. [S0556-2821(98)02003-7]

PACS number(s): 14.60.St, 97.60.Bw

Nonstandard lepton-quark contact interactions may arise at low energies as a consequence of a common quark and lepton substructure or of heavy boson exchanges, when integrated out. There has recently been renewed interest [1] in contact interactions due to the fact that they are one of the potential explanations of the excess of events reported by H1 [2] and ZEUS [3], the DESY ep collider at HERA, when measuring deep-inelastic e^+p scattering at high-Q^2 and comparing with standard model predictions.

The four-fermion operators that could contribute to the HERA excess involve the electron and the u and d quarks. The corresponding Lagrangian is written as an effective electron-quark interaction

$$\mathcal{L}_{\rm eq} = \sum_{\substack{I,J=L,R\\ q=u,d}} \tilde{\eta}^q_{IJ} \frac{4\pi}{(\tilde{\Lambda}^q_{IJ})^2} \overline{e}_I \gamma^\mu e_I \overline{q}_J \gamma_\mu q_J . \qquad (1)$$

The factors $\tilde{\eta}$ can be $+1$ or -1, allowing for constructive or destructive interferences. In Eq. (1) the various high-energy scales $\tilde{\Lambda}$ could be quite different, so that one allows for the possibility that only a subset of terms in $\mathcal{L}_{\rm eq}$ is relevant. It is clear that if one of the scales is much lower than the rest of the scales, the corresponding term will be dominant at low energies. Of course, it may very well be that the dominant scales are two or more because they are of the same order of magnitude. Also it could happen that some energy scales $\tilde{\Lambda}$ are equal but with a combination of $\tilde{\eta}$ factors such that there are cancellations among them. Such cancellations, in order to be natural, should occur because of underlying symmetries.

Restrictions on the terms in Eq. (1) have been elaborated in the past [4] and now reexamined [1] at the light of the HERA results. The constraints come from high-energy accelerators and from precision experiments. If the HERA anomaly is going to persist and the explanation comes indeed from nonstandard contact interactions, it follows from those studies that some particular combinations of chiralities in Eq. (1) are preferred over others, and also that some cancellations should occur in order not to be in conflict with precision experiments as atomic parity violation observations [1]. The scale that fits the HERA data and is compatible with other experimental constraints turns out to be on the range $\tilde{\Lambda} \sim 3-4$ TeV.

It is worth to study all implications of contact interactions. With additional hypotheses, one is able to find further restrictions. For example, if such interactions come from exchanges of heavy bosons, and there are bosons with electric charge, one expects charged contact interactions [5]. Another aspect that has been worked out is the fact that gauge invariance implies the presence of other operators with the same strengths [6]. Also, the implications of universality have been studied [7].

Although HERA directly probes electron-quark contact interactions, it is clear that lepton-quark interactions need not be restricted to charged leptons (e.g., electrons) only. In the present paper we will consider lepton-quark contact interactions in models where a right-handed neutrino is present. The right-handed neutrino ν_R appears quite generally in any extension of the standard model (SM). It is natural that neutrinos participate in the contact lepton-quark interactions that would have then a structure similar to Eq. (1):

$$\mathcal{L}_{\nu q} = \sum_{\substack{I,J=L,R\\ q=u,d}} \eta^q_{IJ} \frac{4\pi}{(\Lambda^q_{IJ})^2} \overline{\nu_I} \gamma^\mu \nu_I \overline{q}_J \gamma_\mu q_J . \qquad (2)$$

We will focus our attention on the electronic ν, so that both Lagrangians Eqs. (1) and (2) refer to the fermions in the first generation. However, for the ease of notation we will not display the subscript e when writing ν. We assume that ν_R in Eq. (2) is a singlet of $SU(2)_L$ and, together with its left-handed partner constitutes the four-component electron neutrino with (Dirac) mass $m_{\nu_e} < 10-15$ eV [4].

A priori, one expects that the dominant scale Λ in the neutrino sector is of the same order of magnitude as the dominant scale $\tilde{\Lambda}$ in the electron sector. Should this be the case, then atomic parity violation (APV) experiments impose severe limits on the scale Λ. Indeed, APV *in cesium* [8] requires $\tilde{\Lambda} > 10$ TeV and, hence, $\Lambda > 10$ TeV for the dominant interaction in Eq. (2). To elude this bound (and, hence, to comply with the HERA requirement $\tilde{\Lambda} \sim 3-4$ TeV) one demands that the Lagrangian Eq. (1) is parity conserving (i.e., left and right couplings are equal). In case B below we consider a kind of scenario for our effective Lagrangian Eq. (2) where we assume that the underlying theory is vectorlike. However, the requirement $\Lambda \sim \tilde{\Lambda}$ can be obviously relaxed in a general phenomenological analysis, and this we do in case A below where no extra relationships arising from underlying left-right symmetries are being imposed. Note that this procedure does not conflict APV results since the interaction in Eq. (2) does not participate in APV effects.

The Lagrangian (2) allows for emission of the right-handed electron neutrinos (and left-handed antineutrinos) by the dense nuclear medium in the core of a collapsing star as long as these neutrinos are light, $m_\nu \ll T$, where $T \simeq 50$ MeV is the core temperature. The purpose of the present paper is to show that contact interactions involving right-handed neutrinos have potential effects in a supernova and to use the supernova 1987A observational data to restrict the such hypothetical interactions. It has become a standard procedure to use observational data to limit exotic effects affecting stellar energy losses [9]. These contact-interaction mediated processes constitute a new channel of energy drain in the nascent neutron star and therefore may alter its standard evolution. If a large amount of the gravitational energy released in the collapse escaped the star as a flux of right-handed neutrinos, the duration of the ordinary neutrino burst would be significantly affected. The observation of a neutrino burst in terrestrial underground detectors coming from SN 1987A in the large magellanic cloud sets constraints on the flux of ν_R produced in its core, and allows us to obtain bounds on the coupling constants in Eq. (2).

The part in Eq. (2) involving the right-handed neutrino can be written as

$$\mathcal{L}_R = \sum_{q=u,d} 2\pi\left(\frac{\eta^q_{RL}}{(\Lambda^q_{RL})^2}+\frac{\eta^q_{RR}}{(\Lambda^q_{RR})^2}\right)\overline{\nu_R}\gamma^\mu\nu_R\overline{q}\gamma_\mu q + \sum_{q=u,d} 2\pi\left(-\frac{\eta^q_{RL}}{(\Lambda^q_{RL})^2}+\frac{\eta^q_{RR}}{(\Lambda^q_{RR})^2}\right)\overline{\nu_R}\gamma^\mu\nu_R\overline{q}\gamma_\mu\gamma_5 q. \tag{3}$$

It is natural to suppose that the two scales Λ_{RL} and Λ_{RR} are roughly similar. However, the signs η_{RL} and η_{RR} can introduce cancellations arising from underlying symmetries of the theory. In order to obtain a bound on the energy scales Λ one has to distinguish two possible cases. For the first case, that we call A, we suppose there are no cancellations so that the vectorial and the axial coupling of quarks to right-handed neutrinos are both present, with roughly the same strength. In the second case, that we call B, we accept the following relationship to be true:

$$\frac{\eta^q_{RL}}{(\Lambda^q_{RL})^2}=\frac{\eta^q_{RR}}{(\Lambda^q_{RR})^2}; \tag{4}$$

hence, only the vectorial coupling to quarks is present. Let us examine each case separately.

Case A. When the vectorial and axial couplings of quarks to neutrinos are both present in the Lagrangian with similar weight, i.e., similar coupling constant, the problem is analogous to that of emission of ordinary neutrinos, which interact with the nuclear medium by means of the effective Fermi Lagrangian. The main production process is bremsstrahlung of neutrino pairs by the interacting nucleons of the medium. It can be shown that the axial coupling dominates over the vectorial one [10]. In the axial case the source of neutrinos is the time fluctuating nucleon spin density, while in the vectorial case the source of neutrinos would be the time fluctuations in the nucleon number density, which remains constant to a good approximation [9]. The total energy carried off by neutrinos per unit time and volume is calculated in [10]. These authors describe the nucleon interaction using the one pion exchange (OPE) approximation and perform the calculation in two different extreme cases for the nuclear medium: nondegenerated nucleons (ND's) and extremely degenerated nucleons (D). To adapt their results to our case we only have to make the replacement

$$\sqrt{2}C^N_A G_F \to \frac{4\pi}{\Lambda^2}, \tag{5}$$

with C^N_A the axial vector coupling between nucleons and ordinary neutrinos and G_F the Fermi constant. We have defined

$$\frac{4\pi}{\Lambda^2} \equiv 2\pi\left|-\frac{\eta^q_{RL}}{(\Lambda^q_{RL})^2}+\frac{\eta^q_{RR}}{(\Lambda^q_{RR})^2}\right|, \tag{6}$$

where we consider the dominant quark contribution and drop the upperindex q. In this fashion we obtain (neglecting the pion mass)

$$Q^{ND}_{\nu\nu} = \frac{16384}{385\pi^{3/2}}\frac{\alpha^2_\pi}{m^2_N}\frac{1}{\Lambda^4}\; n_n n_p\left(\frac{T}{m_N}\right)^{1/2} T^5, \tag{7}$$

$$Q^{D}_{\nu\bar\nu} = \frac{328\pi^3}{4725}\alpha^2_\pi\frac{1}{\Lambda^4}p_F T^8, \tag{8}$$

$\alpha_\pi \approx 30$ being the strong coupling constant for the vertex $np\pi$, $m_N \approx 939$ MeV the nucleon mass, n_n and n_p the neutron and proton number densities, respectively, T the core temperature, and p_F the Fermi momentum of the nucleons. The total energy carried off by ν_R and $\overline{\nu_L}$ per unit time is $Q_{\nu\bar\nu}V_c$, where V_c is the core volume of the collapsing star. It cannot exceed 10^{52} erg/s, the gravitational power released by SN 1987A in the form of standard neutrinos. This observational constraint renders the following bounds on Λ:

$$\Lambda > 170 \quad \text{TeV} \qquad \text{ND nucleons}, \tag{9}$$

$$\Lambda > 250 \quad \text{TeV} \qquad \text{D nucleons}. \tag{10}$$

We have used the standard supernova parameters $n_n = 7\times10^{38}$ cm^{-3}, $n_p = 3\times10^{38}$ cm^{-3}, $T = 50$ MeV, and $R_c = 10$ km. In the real situation the nuclear medium is neither nondegenerate nor degenerate but in between. The true bound on Λ falls then between these two limiting cases.[1]

Case B. Now the dominant axial vector coupling to nucleons is absent, since the relation (4) holds. Only the vectorial coupling is left. As discussed above, one expects that neutrino bremsstrahlung by nucleons is small. In the absence of the axial vecotr coupling another process should be considered: emission of neutrino pairs by the virtual pions ex-

[1]It is interesting to point out that, at least for axion bremsstrahlung, the nondegenerate calculation seems to be a better approximation when compared with numerical calculations [11].

changed by the nucleons. This sort of process has never been considered previously in the literature, and although one expects an emission rate smaller than that found in case A; it is now interesting to study its contribution to the energy drain.

The Lagrangian (3) induces the following structure:

$$\langle \pi | \mathcal{L}_R | \pi \rangle = \sum_{q=u,d} \frac{4\pi}{\Lambda^2} \overline{\nu_R} \gamma^\mu \nu_R \langle \pi | \overline{q} \gamma_\mu q | \pi \rangle, \tag{11}$$

where now

$$\frac{4\pi}{\Lambda^2} \equiv 2\pi \left| \frac{\eta^q_{RL}}{(\Lambda^q_{RL})^2} + \frac{\eta^q_{RR}}{(\Lambda^q_{RR})^2} \right|. \tag{12}$$

Using Lorentz invariance one can write the matrix element in Eq. (11) as

$$\langle \pi(p') | \overline{q} \gamma_\mu q | \pi(p) \rangle = A(p,p')(p+p')^\mu + B(p,p')(p-p')^\mu. \tag{13}$$

When contracted with the neutrino current the term proportional to B is negligible for $m_\nu \ll T$. The function A is, to lowest order, 1, -1, 0 (quark u) and -1, 1, 0 (quark d) for the pions π^+, π^-, π^0, respectively. Therefore, the only process that has to be considered is

$$n(p_1) p(p_2) \to n(p_4) \;\; p(p_3) \nu(q) \overline{\nu(q')}. \tag{14}$$

Using the OPE approximation, the squared amplitude summed over spins can be written, in the appropriate nonrelativistic limit for the nucleons, as

$$\sum_{\text{spin}} |\mathcal{M}(np \to np \nu \overline{\nu})|^2 = \frac{1}{\Lambda^4} M^{ij} N^{ij}, \tag{15}$$

where

$$M^{ij} = 4\alpha_\pi^2 \frac{p^4}{(p^2+m_\pi^2)^4} p^i p^j, \tag{16}$$

$$N^{ij} = 8[q^i q'^j + q^j q'^i + (qq')\delta^{ij}], \tag{17}$$

being $\vec{p}$ the three momentum exchanged by the nucleons and m_π the charged pion mass. This factorization is reminiscent of the factorization in a nuclear form factor and an emission term that appears when studying bremsstrahlung of neutrinos or axions by nucleons [9]. However, it is crucial to realize that the mentioned nuclear form factor does not coincide with the present ''nuclear form factor'' M^{ij}, since now we have an additional pion propagator stemming from the neutrino emission by the virtual pion. In the nonrelativistic limit one can write

$$Q_{\nu\overline{\nu}} = \frac{1}{20\pi^4} \frac{1}{\Lambda^4} \int_0^\infty d\omega \;\; \omega^6 q(\omega), \tag{18}$$

where

$$q(\omega) \equiv \frac{4\alpha_\pi^2}{3} (4\pi)^4 \int \prod_{i=1}^4 \frac{d\vec{p}_i}{2m_N(2\pi)^3} \times f_1 f_2 (1-f_3)(1-f_4) \delta^3(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4) \times \delta\left(\frac{p_1^2 + p_2^2 - p_3^2 - p_4^2}{2m_N} - \omega \right) \frac{p^6}{(p^2+m_\pi^2)^4}, \tag{19}$$

with $\vec{p} \equiv \vec{p}_1 - \vec{p}_3$ and f_i the equilibrium Fermi-Dirac distributions for the nucleons.

For the nondegenerate case, in order to solve these phase space integrals one follows the steps described, for example, in [9]. The key point is the change of the Fermi-Dirac distributions by Maxwell-Boltzmann distributions. Neglecting the pion mass we obtain the following expression:

$$Q^{ND}_{\nu\overline{\nu}} = \frac{65536}{1001\pi^{3/2}} \frac{\alpha_\pi^2}{m_N^2} \frac{1}{\Lambda^4} n_n n_p \left(\frac{T}{m_N} \right)^{3/2} T^5. \tag{20}$$

One should consider instead of m_N the effective nucleon mass in a dense medium m_N^* [9]. The error made neglecting this fact is small and opposed to the error made using a vanishing pion mass, so that the two errors nearly compensate each other.

In the extreme degenerate case we follow the technique described in [10]; only the contributions of nucleon momenta near the Fermi momentum p_F are considered in the phase space integrals in Eq. (19). We find

$$Q^D_{\nu\overline{\nu}} = \frac{31\pi^6}{2970} \;\; \alpha_\pi^2 \frac{1}{\Lambda^4} \;\; F(p_F/2m_\pi) \;\; \frac{T^{10}}{m_\pi}, \tag{21}$$

with

$$F(u) \equiv \frac{2}{\pi} \left(\arctan u - \frac{11}{5} \frac{u}{u^2+1} + \frac{26}{15} \frac{u}{(u^2+1)^2} - \frac{8}{15} \frac{u}{(u^2+1)^3} \right). \tag{22}$$

For $p_F \approx 480$ MeV and $m_\pi = 140$ MeV, $F(u) \approx 0.71$.

The observational constraint $Q_{\nu\overline{\nu}} V_c < 10^{52}$ erg/s gives the following bounds:

$$\Lambda > 90 \quad \text{TeV} \qquad \text{ND nucleons}, \tag{23}$$

$$\Lambda > 150 \quad \text{TeV} \qquad \text{D nucleons}. \tag{24}$$

As mentioned before the actual bound on Λ falls between these two values.

We have estimated that for scales of the order $\Lambda > 1$ TeV the ν_R are not trapped in the core by rescattering or pair absorption due to the contact interactions in Eq. (2). Since they do not participate in ordinary weak interactions, once they are produced they leave the star and do not contribute to the energy transport inside the core.

To sum up, we have considered contact interactions between quarks and right-handed neutrinos. We expect the scale Λ of such interactions to be of the same order of magnitude as the electron-quark interactions, reconsidered recently at the light of HERA data. We have shown that they may lead to potential effects in a supernova. We have restricted the scale of the contact interaction to be $\Lambda > 170$ TeV for nondegenerated nucleons and $\Lambda > 250$ TeV for degenerated nucleons, when quarks have both axial and vector couplings. In the case that quarks have only vector couplings, we have evaluated the production mechanism consisting in neutrino emission from virtual pions and found the bound $\Lambda > 90$ TeV for nondegenerate nucleons and $\Lambda > 150$ TeV for degenerate nucleons. We conclude that in models with right-handed (Dirac) neutrinos the scale of contact interactions should at least be $\Lambda > 90$ TeV.

We thank the Theoretical Astroparticle Network for support under the EEC Contract No. CHRX-CT93-0120 (Direction Generale 12 COMA). This work was partially supported by the CICYT Research Project Nos. AEN95-0815 and AEN95-0882. R.T. acknowledges the financial support of the Ministerio de Educación y Ciencia (Spain).

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