Cross section for inverse β decay and polarization of electron antineutrinos

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Limitations on the polarization of the electron antineutrino are found from data on the cross sections for inverse β decay. Limitations on the parameters of the right-hand charged currents are derived in a model with a left-right symmetry $SU(2)_L \times SU(2)_R \times U(1)$. These limitations complement the corresponding limitations which have been found from the decay of polarized muons.

1. In the standard theory of electroweak interactions, only left-hand particles participate in processes induced by charged currents. Consequently, the neutrinos emitted in β decay must have a complete longitudinal polarization, while the electrons and the positrons of the decay would have a polarization $\mp v/c$. One of the most

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popular generalizations of the standard theory is a model with a spontaneously broken left-right symmetry[1-3] $SU(2)_L \times SU(2)_R \times U(1)$, which furnishes an attractive explanation for parity violation at low energies. In this model, the ordinary charged bosons $W_L^{\pm}$ are accompanied by some auxiliary bosons $W_R^{\pm}$, which mediate the interaction with right-hand charged currents.

In a theory with right-hand currents, the longitudinal polarization of the neutrinos emitted in β decay may not amount to 100%. In the present letter we find limitations on the helicity $\tilde{\nu}_e$ from data on the cross sections found for inverse β decay in experiments with reactor antineutrinos. It thus becomes possible to extract information on the parameters of right-hand charged currents, to complement the limitations found from other processes.

2. The most general form for the effective Lagrangian describing weak semileptonic processes at low energies is

$$L_{\text{eff}} = [a J_L j_L + b J_R j_R + c J_L j_R + d J_R j_L]. \tag{1}$$

Here $J_{L,R}$ are the hadron currents, $j_{L,R}$ are the lepton weak currents, and a, b, c, and d are phenomenological constants. In the simplest ("explicitly symmetric") version of the $SU(2)_L \times SU(2)_R \times U(1)$ theory we have

$$a = \frac{g^2}{8}\left(\frac{\cos^2\xi}{m_1^2} + \frac{\sin^2\xi}{m_2^2}\right), \quad b = \frac{g^2}{8}\left(\frac{\sin^2\xi}{m_1^2} + \frac{\cos^2\xi}{m_2^2}\right),$$
$$c = d = \frac{g^2}{8}\sin\xi\cos\xi\left(\frac{1}{m_2^2} - \frac{1}{m_1^2}\right). \tag{2}$$

Here ξ is the angle of the mixing of W_L with W_R; m_1 and m_2 are masses of the eigenstates of the mass matrix, W_1 and W_2 (W_L and W_R are linear combinations of W_1 and W_2); and g is the coupling constant.

The cross section for the inverse β decay $\tilde{\nu}_e p \rightarrow n e^+$ at low energies ($E_\nu \ll m_1, m_2$) can be written

$$\sigma = \frac{1}{2}\sigma_0 (1 + H_{\tilde{\nu}} H'_{\tilde{\nu}}). \tag{3}$$

Here $\sigma_0 = (G_F^2 \cos^2\Theta_C/\pi)(1 + 3\lambda^2) p_e E_e$ is the standard cross section in the V-A theory (in the absence of right-hand currents), E_e and p_e are the energy and momentum of the positron, $\lambda = G_A/G_V \simeq 1.26$, $H_{\tilde{\nu}}$ is the helicity of the captured $\tilde{\nu}_e$, and $H'_{\tilde{\nu}}$ is given by

$$H'_{\tilde{\nu}} \equiv \frac{|a|^2 + |d|^2 - |b|^2 - |c|^2 + 2\mathrm{Re}(a^* d - b^* c)\kappa}{|a|^2 + |d|^2 + |b|^2 + |c|^2 + 2\mathrm{Re}(a^* d + b^* c)\kappa}, \quad \kappa \equiv \frac{1 - 3\lambda^2}{1 + 3\lambda^2}. \tag{4}$$

Expressions (3) and (4) were derived under the assumption that the mass of the right-hand neutrino is negligible in comparison with the neutrino energy.

The quantity $H'_{\tilde{\nu}}$ is the same as the helicity of the $\tilde{\nu}_e$ emitted in the direct process:

in the β decay of the neutron. However, reactor antineutrinos are produced not in the decay of neutrons but in the β decay of fission products. Most of the neutrino flux comes from allowed β transitions, which may be Fermi transitions, Gamow-Teller transitions, or mixed transitions. The helicities of the $\tilde{\nu}_e$ emitted in these transitions can be found from the right side of Eq. (4) by replacing the parameter κ by 1, -1, or $(|M_{\rm F}|^2 - |M_{\rm GT}|^2)/(|M_{\rm F}|^2 + |M_{\rm GT}|^2)$, respectively. It is important to note that all these expressions become the same as $H'_{\tilde{\nu}}$ in the limit $\xi \to 0$. For the cross section for the inverse β decay we find the simple expression

$$\sigma = (\sigma_0/2)(1 + H^2_{\tilde{\nu}}), \tag{5}$$

from which it can be seen that σ is noticeably sensitive to the helicity of $\tilde{\nu}_e$.

3. Simple expression (5) holds if the mixing of W_L with W_R is slight: $|\xi| \ll (m_1/m_2)^2$. In general, we would have to use expression (3), and the helicity of the reactor neutrinos $\tilde{\nu}_e$ would have to be calculated from the expression $\overline{H}_{\tilde{\nu}}(E_\nu) = \Sigma_i w_i(E_\nu) H_{\tilde{\nu}i}$, where the sum is over all types of β transitions, and $w_i(E_\nu)$ are the weights of the transitions of each type. It is a rather complicated problem to calculate $\overline{H}_{\tilde{\nu}}(E_\nu)$, but there is no need to do so, as we will now show.

A reactor antineutrino spectrum is dominated by Gamow-Teller and mixed transitions; the Fermi β transitions of the nuclei, which are the fission fragments, are isospin-suppressed. Since the Fermi matrix elements are small ($|M_{\rm F}|^2/|M_{\rm GT}|^2 \lesssim 10^{-4}$; Ref. 4), the helicity of the $\tilde{\nu}_e$ emitted in mixed transitions is essentially the same as $(H_{\tilde{\nu}})_{\rm GT}$. For this reason, we can set $H_{\tilde{\nu}} = (H_{\tilde{\nu}})_{\rm GT}$ in Eq. (3). In the limit $3\lambda^2 \gg 1$ the quantity $H'_{\tilde{\nu}}$ would be the same as $(H_{\tilde{\nu}})_{\rm GT}$ (numerically, we have $3\lambda^2 \approx 4.76$). The quantity $H'_{\tilde{\nu}}$ is the same as $(H_{\tilde{\nu}})_{\rm GT}$ in the case $\xi = 0$ also. From the theoretical restriction[5] on ξ, $|\xi| \leqslant \eta \equiv (m_1/m_2)^2$, we conclude that the replacement of $H'_{\tilde{\nu}}$ by $(H_{\tilde{\nu}})_{\rm GT}$ could introduce an error no greater than 20% in the value of $1 - H_{\tilde{\nu}}$. Using (5), we find

$$H_{\tilde{\nu}} \approx \sqrt{2\frac{\sigma}{\sigma_0} - 1} \simeq \frac{\sigma}{\sigma_0} = \frac{\sigma_{\rm expt}}{\sigma_{\rm theo}}. \tag{6}$$

An averaging of the experimental data[6,7] yields the following value for $\sigma_{\rm expt}$: $({}^5\sigma_f)_{\rm expt} = 6.20 \times 10^{-43}$ cm^2/fission $\pm 5\%$ (${}^5\sigma_f$) is the cross section per ^{235}U fission event). As the theoretical value of the cross section we take the average value from Refs. 8–11, which are the values cited most frequently: $({}^5\sigma_f)_{\rm theo} = 6.2 \times 10^{-43}$ cm^2/fission $\pm 4\%$. The error in the theoretical values of ${}^5\sigma_f$ is due primarily to the uncertainties in the calculations of the spectra of the reactor $\tilde{\nu}_e$. It is rather difficult to evaluate that error; we take it to be equal to the maximum deviation from the mean value. We then find $\sigma/\sigma_0 = 1.0 \pm 0.065$, which in turn leads to $H_{\tilde{\nu}} > 0.935$ at a 68% confidence level. We can use expression (3) to find limitations on the parameters of right-hand currents. Since $\eta \ll 1$ and $|\xi| \leqslant \eta$, we find

$$2\xi^2 + 3.30\,\xi\eta + 2\eta^2 < 0.065. \tag{7}$$

In the limit of zero mixing we then find $m_1/m_2 = \sqrt{\eta} < 0.425$ or (with $m_1 \approx 83$ GeV) $m_2 > 195$ GeV. In the limit $m_2 \to \infty$ we find a limitation on the mixing angle: $|\xi| < 0.18$.

If we make no further assumptions regarding η and ξ, we find the following from (7): $(m_1/m_2) < 0.565$ for arbitrary ξ; $-0.32 < \xi < 0.18$ for arbitrary m_1/m_2.

4. The limitation $H_{\tilde{\nu}} > 0.935$ found here is essentially the first experimental value of the $\tilde{\nu}_e$ helicity. The only previous measurements have been of the helicity of the ν_e emitted in K captured by the ^{152}Eu nucleus. The recent value of this quantity is[12] $H_\nu = -0.93 \pm 0.10$; i.e., the error is 1.5 times the error in the value which we found for H_ν. Information on $H_{\tilde{\nu}}$ and H_ν is also contained implicitly in data on the helicities $H_{e^\pm}$ of electrons and positrons emitted in nuclear β decay (Ref. 13, for example).

The limitations found on the parameters of right-hand charged currents η and ξ are less stringent (by a factor of two or three) than the limitations found from the decay of polarized μ^+ particles.[14–16] However, the decay of a muon and inverse β decay are processes of different types: The former is a purely leptonic process, while the latter is semileptonic. For this reason, a study of such processes to extract information on right-hand currents would be a matter of independent interest. Furthermore, the combination of parameters in (7), on which we have found limitations, differs from that determined in the decay of μ^+ $(2\xi^2 + 4\xi\eta + 4\eta^2)$ and also from the combination $\xi\eta$, for which a limitation was recently found[17] from the ratios of the longitudinal polarizations of the e^+ particles emitted in Fermi and Gamow-Teller β transitions. A distinctive feature of the reaction which we are considering (inverse β decay in the flux of reactor antineutrinos) is that the helicity of the emitted $\tilde{\nu}_e$ is essentially equal to $(H_{\tilde{\nu}})_{\rm GT}$, while these particles are absorbed in a β transition of a mixed type.

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