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# Mirror Fermions, Universality and the Beam Dump Experiment

K. Enqvist[1], K. Mursula[2] and M. Roos[2,3]

1 Research Institute for Theoretical Physics, University of Helsinki, SF-00170 Helsinki, Finland

2 Department of High Energy Physics, University of Helsinki, SF-00170 Helsinki, Finland

3 Institut für Theoretische Physik der Universität Wien, A-1090 Wien, Austria

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**Abstract.** The electron deficiency observed in beam dump experiments is discussed within the mirror fermion model. We make a general study of the leptonic weak universality and show that only a 4% change in the $e/\mu$-ratio due to non-universal vector/axial vector charged couplings is allowed. In the mirror fermion model this corresponds to the possibility that the electron-like mirror neutrino $N_e$ is very heavy. If $N_e$ is light enough to be produced, oscillation of $\nu_e$ into sterile $N_e$ is possible. If $N_e$ is lighter than about 1 MeV, only a 6.5% decrease in the $e/\mu$ ratio is allowed, due to the constraints from reactor neutrino experiments. However, if $m_{N_e}$ is between a couple of MeV's and 45 MeV, only one loose bound exists, allowing the $e/\mu$ ratio to decrease by 11%.

## 1. Introduction

During the last few years many beam-dump (BD) experiments [1–2] have studied the interactions of prompt (anti) neutrinos coming from the weak decay of short-lived particles. The results of these experiments indicate an unequal production of electrons and muons, which is in apparent conflict with lepton universality of the standard electroweak theory.

Various suggestions have been made to explain this $e$–$\mu$ asymmetry. If the electron neutrino oscillates to a neutrino of another flavour, say $\nu_\tau$ [3], the amount of produced electrons would decrease correspondingly. Also speculations on charged Higgses with non-universal couplings [4] or an enhanced purely leptonic branching ratio of the charmed particles [5] have been proposed. None of these alternatives, however, has reached the observed level of asymmetry without introducing other undesirable features.

In this paper we discuss the BD experiment and the associated question of lepton universality in the light of the recently presented mirror fermion model [6–10]. The possible mixing of mirror and ordinary fermions naturally leads to a modified non-universal $V$, $A$ structure of weak currents, which might be the cause of the leptonic asymmetry.

We first consider the status of $e$–$\mu$ universality in the charged weak currents (CC) and its implications for the BD experiments using a (factorizable) one-boson exchange formalism with general, non-universal $V$, $A$ couplings. We then study a specific model of this kind, the mirror fermion model. We distinguish between heavy and light mirror neutrinos, which have a different effect on the BD experiments. Light mirror neutrinos can induce asymmetry in BD experiments due to neutrino-mirror neutrino oscillations, whereas the effects of heavy mirror neutrinos appear only as violation of lepton interaction universality.

## 2. Lepton Universality and the BD Experiment

Let us modify the conventional $V$–$A$ structure of $CC$ to a general mixture of (real) vector and axial vector couplings [6, 10]:

$$\mathcal{J}_l^\alpha = \bar{l}\gamma^\alpha(V_l - A_l\gamma_5)\nu_l$$
$$\mathcal{J}_q^\alpha = \bar{q}\gamma^\alpha(V_q - A_q\gamma_5)q' \qquad (1)$$

Assuming that, effectively, there is only one gauge boson we arrive at a factorizable, non-universal parametrization for charged weak interactions.

We have analyzed all the relevant leptonic $CC$ processes in terms of the parameters $\lambda_i$ and $\kappa$ defined [6, 8] by

$$\lambda_i = \frac{A_i}{V_i}(i = e, \mu); \quad \kappa = \frac{V_\mu}{V_e} \qquad (2)$$

We find the following best fit values (and limits; we will work at the 68% confidence level) for them:

**Table 1.** The theoretical formulas and experimental values of the leptonic $CC$ constraints. For a more detailed discussion, see [9]. Here we take into account the new result on $R_p$[15]

| Constraint | Theoretical formula | Experimental values and errors |
|---|---|---|
| $\rho$ | $\frac{3}{8}+\frac{3}{2}\frac{\lambda_e\lambda_\mu}{(1+\lambda_e^2)(1+\lambda_\mu^2)}$ | $0.7517 \pm 0.0026$ |
| $\delta$ | $\frac{3}{8}\frac{\lambda_e(1+\lambda_\mu^2)+\lambda_\mu(1+\lambda_e^2)}{2\lambda_e(1+\lambda_\mu^2)-\lambda_\mu(1+\lambda_e^2)}$ | $0.7551 \pm 0.0085$ |
| $\xi p_\mu$ | $\frac{4\lambda_\mu}{1+\lambda_\mu^2}\left\{\frac{2\lambda_e}{1+\lambda_e^2}-\frac{\lambda_\mu}{1+\lambda_\mu^2}\right\}$ | $0.9722 \pm 0.0140$ |
| $P_{e^-}$ | $\frac{2\lambda_e}{1+\lambda_e^2}$ | $1.001 \pm 0.008$ |
| $P_{\mu^-}$ | $\frac{2\lambda_\mu}{1+\lambda_\mu^2}$ | $0.99 \pm 0.16$ |
| $S$ | $\frac{1}{4}\left\{1+\frac{4\lambda_e\lambda_\mu}{(1+\lambda_e^2)(1+\lambda_\mu^2)}-2P_{\nu_\mu}\times\left(\frac{\lambda_\mu}{1+\lambda_\mu^2}+\frac{\lambda_e}{1+\lambda_e^2}\right)+0.375\times\left(1-\frac{4\lambda_e\lambda_\mu}{(1+\lambda_e^2)(1+\lambda_\mu^2)}-2P_{\nu_\mu}\times\left(\frac{\lambda_\mu}{1+\lambda_\mu^2}-\frac{\lambda_e}{1+\lambda_e^2}\right)\right)\right\}$ | $0.98 \pm 0.12$ |
| $R_p$ | $\frac{1}{\kappa^2}\frac{1+\lambda_e^2}{1+\lambda_\mu^2}$ | $0.993 \pm 0.010$ |

$$\begin{aligned} &\lambda_e = 1.085 \quad (<1.15) \\ &\lambda_\mu = 1.00 \quad (<1.115) \\ &(0.905<)\kappa = 1.047 \quad (<1.115) \end{aligned} \tag{3}$$

All the constraints used and their experimental values are given in Table 1. One can see that these constraints (except $R_p$) depend only on $\lambda_e$ and $\lambda_\mu$ and are symmetrical with respect to the replacements $\lambda_i \to 1/\lambda_i$. (In (3) we have given only the upper bounds and best fit values for $\lambda_i \geqq 1$. The lower bounds and the other optima are thus obtained by taking inverse values of these.) The parameter $\kappa$, which directly measures $e$–$\mu$ universality is constrained only by the remarkably accurate pseudoscalar ratio $R_p$.

We can thus conclude that both the $V$, $A$ structure and the universality of the charged currents of the first two generations are known within an error of 10–15%.

Let us now turn to the ratio $R_1 = (e^+ + e^-)/(\mu^+ + \mu^-)$ which is observed directly in bubble chamber BD experiments [1] and indirectly in electronic counter BD experiments [2]. The present experimental average of this ratio is $0.52 \pm 0.15$.

The total $CC$ cross sections for $\nu_l N$-scattering (where $N$ is any nuclear target) can be expressed compactly in this formalism as follows [10]:

$$\begin{aligned} &\sigma_{CC}(\nu_l N) \sim Q_-[C_1^l + P_{\nu_l} C_4^l + \xi(C_2^l + P_{\nu_l} C_3^l)] \\ &\sigma_{CC}(\bar{\nu}_l N) \sim Q_+[C_2^l + P_{\nu_l} C_3^l + \xi(C_1^l + P_{\nu_l} C_4^l)] \end{aligned} \tag{4}$$

where $Q_\pm$ denotes the integrated distributions of quarks and antiquarks with charges of the respective sign; $\xi$ is the ratio of $y$-distributions $(1-y)^2$ and 1, integrated over $y$ and the neutrino energy spectrum. The constants $C_i^l$ are given by

$$\begin{aligned} &C_{1(2)}^l = (V_l^2 + A_l^2)(V_q^2 + A_q^2) \underset{(-)}{+} 4 V_l A_l V_q A_q \\ &C_{3(4)}^l = \underset{(-)}{+} 2 V_q A_q (V_l^2 + A_l^2) - 2 V_l A_l (V_q^2 + A_q^2) \end{aligned} \tag{5}$$

The fact that the neutrino beam has now a non-trivial longitudinal polarization $P_{\nu_l} = -2V_l A_l/(V_l^2 + A_l^2)$ is explicitly taken into account in (4). The relative amount of electron and muon type neutrinos coming from the various decays of short-lived particles is given by the ratio $R_p$ (see Table 1).

Thus, using the above equations one easily derives the following expression for $R_1$ (for simplicity, we take an equal production of $\nu$'s and $\bar{\nu}$'s):

$$R_1 = \frac{1}{\kappa^4}\frac{1+6\lambda_e^2+\lambda_e^4+4c_1\lambda_e(1+\lambda_e^2)}{1+6\lambda_\mu^2+\lambda_\mu^4+4c_1\lambda_\mu(1+\lambda_\mu^2)} \tag{6}$$

Here we have assumed that the $V$, $A$ structure is equal (or trivial) for all the relevant quark currents. This is no real restriction, since the cross section is clearly dominated by the $\bar{u}d$-current, other currents bringing in negligible corrections only. We have introduced in (6) the constant $c_1 = P_q(1-Q)/(1+Q)$ where $P_q = 2\lambda_q/(1+\lambda_q^2)$ and $Q = (1+\xi r)/(\xi + r)$. It was shown in Ref. 10 that $\lambda_q$ must be fairly close to 1 $(0.87 \leqq \lambda_q \leqq 1.15)$ and therefore $P_q$ is within one percent of 1. The ratio $r = Q_-/Q_+$ is equal to 1 for an isoscalar target. It follows that for such a target $Q$ is also equal to 1, independently of $\xi$, and $c_1$ vanishes. Furthermore, expanding (6) with respect to $\lambda_i$'s around 1 one finds that $c_1$ appears only in the fourth order corrections and therefore one can safely set $c_1$ equal to zero there.

Concluding the above discussion one can say that $R_1$ depends only on the leptonic coupling constants since the effect of all other factors is negligible. Although the leptonic constants $\lambda_i$ and $\kappa$ still allow for rather large deviations from their conventional values a careful analysis shows that the minimum of $R_1$ is $R_1^{\min} = 0.96$. We thus conclude that deviation from universality of the leptonic charged currents cannot explain the BD experiments in this general formalism.

## 3. The BD Experiment and Mirror Fermions

We now turn to study the recently discussed [6–10] mirror fermion model and its implications for the BD experiment. This model produces the above presented non-universal one-boson exchange scheme for weak interactions of ordinary leptons. It also includes mirror fermions with opposite chirality and the possible mixing of ordinary and mirror fermions, parametrized in terms of the mixing angles $\theta_l$ and $\phi_l$ for charged and nautral leptons, respectively. In our analysis [8, 9] we considered various sub-models corresponding to different assumptions on the unknown masses of the mirror neutrinos. We first review our formulas for the charged and neutral current (NC) cross sections in the two possible cases of light and heavy mirror neutrino. Then we discuss the BD experiment for these two alternatives.

If the mirror neutrinos $N_l$ are heavy enough not to be produced in weak decays of either light or heavy particles, the only observable effect of mirror particles at present is the modification of weak currents of corresponding ordinary fermions due to possible mixing. In this case the above treatment ((4) and (5)) of the $CC$ cross sections and the results for the $e/\mu$ ratio are directly applicable once we make the identification:

$$V_l = \cos(\theta_l - \phi_l); \quad A_l = \cos(\theta_l + \phi_l)$$
$$V_q = \cos(\theta_d - \theta_u); \quad A_q = \cos(\theta_d + \theta_u) \tag{7}$$

(we have taken the $\bar{u}d$-current dominance into account).

Since the NC are also affected by the mixing one may also consider the ratio

$$R_2 = \frac{\#\text{ events with muons}}{\#\text{ events with no muons}} = \frac{\sigma_{CC}(\overset{(-)}{\nu}_\mu N)}{\sigma_{NC}(\overset{(-)}{\nu}_\mu N) + R_P(\sigma_{CC}(\overset{(-)}{\nu}_e N) + \sigma_{NC}(\overset{(-)}{\nu}_e N))} \tag{8}$$

which is directly measured in the counter BD experiments. For a heavy mirror neutrino case the total NC cross section is (normalized to the same constant as (4)):

$$\sigma_{NC}(\overset{(-)}{\nu}_l N) = \sigma_{NC}(\nu_l N) + \sigma_{NC}(\bar{\nu}_l N)$$
$$\sim 2[Q_u(u_V^2 + u_A^2) + Q_d(d_V^2 + d_A^2)]$$
$$\cdot(1 + \cos^2 2\phi_l)(1 - P_{\nu_l}\gamma_l)(1 + \xi) \tag{9}$$

where $Q_u(Q_d)$ denotes the total contribution of all up (down) quarks and antiquarks with the following modified NC couplings [9]:

$$u_V = \tfrac{1}{2} - \tfrac{4}{3}\sin^2\theta_W; \quad u_A = -\tfrac{1}{2}\cos 2\theta_u$$
$$d_V = -\tfrac{1}{2} + \tfrac{2}{3}\sin^2\theta_W; \quad d_A = \tfrac{1}{2}\cos 2\theta_d \tag{10}$$

The constant $\gamma_l$ is given by $\gamma_l = 2\cos 2\phi_l/(1 + \cos^2 2\phi_l)$.

It is also possible that mirror neutrinos are light enough to be emitted in weak decays. Then the neutrino and the corresponding mirror neutrino are produced coherently and, in analogy to the normal flavour oscillations, there appears an oscillating pattern in the cross sections due to neutrino-mirror neutrino oscillations. In particular, the $CC$ cross sections are modified (see [8–10] for details) to the form given in (4) with

$$C_1^l + P_{\nu_l} C_4^l = 4P_{\nu\nu}^l(x)[(V_q^2 + A_q^2)(\cos^4\theta_l + \sin^4\theta_l) + 2V_q A_q(\cos^4\theta_l - \sin^4\theta_l)]$$

$$C_2^l + P_{\nu_l} C_3^l = 4P_{\nu\nu}^l(x)[(V_q^2 + A_q^2)(\cos^4\theta_l + \sin^4\theta_l) - 2V_q A_q(\cos^4\theta_l - \sin^4\theta_l)] \tag{11}$$

where the oscillation factor at the distance $x$ is [10]

$$P_{\nu\nu}^l(x) = 1 - \tfrac{1}{2}\sin^2 2\phi_l\left(1 - \cos\frac{2\pi x}{L}\right) \tag{12}$$

The oscillation length is, as usual, $L = 4\pi E_\nu/\Delta m_l^2$, where $\Delta m_l^2 = |m_{N_l}^2 - m_{\nu_l}^2|$. Similarly, the NC cross section is

$$\sigma_{NC}(\bar{\nu}_l N) \sim 8P_{\nu\nu}^l(x)[Q_u(u_V^2 + u_A^2) + Q_d(d_V^2 + d_A^2)](1 + \xi) \tag{13}$$

We wish to point out two extreme cases for the oscillation factor $P_{\nu\nu}^l(x)$. If the mass term $\Delta m_l^2$ is very small, no oscillation has yet started and $P_{\nu\nu}^l(x) = 1$ trivially. We call this the "coherent" case and no limits to the corresponding neutrino mixing angle $\phi_l$ are obtained. In the opposite case, for large enough masses, $P_{\nu\nu}^l(x)$ is averaged to

$$\bar{P}_{\nu\nu}^l = 1 - 1/2\sin^2 2\phi_l \tag{14}$$

and an effectively incoherent scattering follows. In most BD experiments [1, 2a, b] the incoherent beam approximation is allowed for the main part of the electron like neutrino beam if $\Delta m_e^2 \geqq 20\,\text{eV}^2$. Such a value is reasonable in the light of the Moscow neutrino mass experiment [11].

Furthermore, if $N_e$ is light enough ($\leqq 0(1\,\text{MeV})$) to be emitted in nuclear beta decays, the above bound on $\Delta m_e^2$ also justifies the incoherent beam approximation for reactor neutrino experiments. The antineutrino beam flux would then be depleted by the same factor $\bar{P}_{\nu\nu}^e$, (14). However, the observed and theoretical intensities in reactor experiments are known to be in good agreement. Using the recent results [12], a strict lower bound is obtained for the oscillation factor $\bar{P}_{\nu\nu}^e$:

$$\bar{P}_{\nu\nu}^e \geqq 0.935$$

which turns to the following limit for the mixing angle $\phi_e$:

$$\phi_e \leqq 10.6°$$

Accordingly, the BD asymmetry cannot be decreased in this case lower than 6.5% from unity.

On the other hand, if the mass of $N_e$ is of the order of 10 MeV, then $N_e$ cannot be produced in nuclear beta decays and the above reactor experiment constraint is thus evaded. Stringent limits [13] exist on the mixing of extra neutrinos with masses between 45 and 74 MeV (corresp. 74 and 139 MeV), restricting the relative proportion of additional neutrinos to be less than 0.4% (3–6%). However, for $m_{N_e}$ below 45 MeV (and above, say, a couple of MeV's), there is only one loose bound coming from an electron neutrino stability experiment [14], using neutrinos from $K_{e3}^+$ decay. Their result for the averaged probability (corresponding to the incoherent approximation) is:

$$\bar{P}^e_{\nu\nu} = 1.04 \pm 0.15$$

giving the following bound on the mixing angle

$$\phi_e \leqq 14°.$$

Since this is the only measurement in this mass range, it is possible to have a decrease of the BD ratio $R_1$ by 11%. Therefore we regard it as important to re-examine this mass range by measuring, e.g., the electron spectrum at the corresponding energies in $\pi \to e$ decay [13].

Contrary to flavour oscillations, there are no sum rules for the averaged oscillation probabilities in the above model with light mirror neutrinos. Furthermore, the $NC/CC$-ratio does not depend on the oscillation factor. The neutrino-mirror neutrino oscillation is basically oscillation between an interacting and inert state. The reason for the sterility of the mirror neutrinos is, however, only kinematic and due to the large masses of charged mirror leptons. Ultimately at high energies the BD ratio will also approach the value 1. This may, actually, already happen at the highest present neutrino energies. It is therefore very important to study [2c] the neutrino energy dependence of the $e/\mu$ ratio.

## 4. Conclusions

Let us now present our conclusions. We first studied the level of leptonic universality of charged weak currents in a general non-universal one-boson exchange formalism, realized e.g. in the mirror fermion model with very heavy mirror neutrinos. We found that the parameters $\lambda_i$ and $\kappa$ measuring the $V$, $A$ structure and the $e$–$\mu$ universality were only known within an error of 10–15% (3). In spite of these large errors, the minimum (within 68% C.L.) of the electron to muon ratio in the BD experiment was not lower than 0.96. This was shown to be independent of many inaccuracies (due, e.g., to the poorly known neutrino energy spectrum).

We pointed out that if the electron-like mirror neutrino is light enough to be produce in weak decays, the ensuing neutrino-mirror neutrino oscillation may further decrease the $e/\mu$-ratio. Since the incoherent approximation for this oscillation seems appropriate, the electron like neutrino beam will be decreased by the factor $\bar{P}^e_{\nu\nu}$, (14). If $m_{N_e}$ is less than a few MeV, the reactor antineutrino experiments only allow for the decrease of the $e/\mu$-ratio by 6.5%. However, if $N_e$ is heavier than that (but lighter than 45 MeV) as small a value as 0.89 for the $e/\mu$-ratio is possible. We emphasize the importance of obtaining improved upper bounds on the mixing of neutrinos in this mass range. Furthermore, as the $e/\mu$-ratio should ultimately get close to the value 1 in the mirror fermion model this stresses the urgent need to measure the neutrino energy dependence of the $e/\mu$-ratio.

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