SEARCH FOR HEAVY NEUTRINO DECAYS IN THE BEBC BEAM DUMP EXPERIMENT

WA66 Collaboration

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ABSTRACT

New limits on lepton mixing parameters are derived from a search for decays of heavy neutrinos in a proton beam dump experiment. The limits $|U_{\mu i}|^2$, $|U_{e i}|^2 < 10^{-6}$ to 10^{-7} are obtained for neutrino mass eigenstates ν_i of mass between 0.5 and 1.75 GeV, which can be produced through mixing in charmed D meson decays. This is the first such limit on $|U_{\mu i}|^2$ for neutrino masses greater than 0.5 GeV. For the mass eigenstate ν_3 in particular, we obtain the limits $|U_{\mu 3}|^2 < 10^{-7}$ to 10^{-8} , $|U_{e 3}|^2 < 10^{-9}$ to 10^{-10} for the mass range 150 to 190 MeV, assuming ν_3 's to be produced directly in charmed F meson decays.

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1. INTRODUCTION

The standard $SU(2)_L \times U(1)$ model considers only massless neutrinos, however, a finite neutrino mass cannot be excluded experimentally [1]. Moreover, Majorana neutrino masses arise naturally in models with intrinsic left-right symmetry and lepton-hadron symmetry, such as $SO(10)$ and its subgroup $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, while extended $SO(10)$ models may admit massive Dirac neutrinos [2].

If neutrinos do have masses, the flavour eigenstates ($\nu_e, \nu_\mu, \nu_\tau, \dots$) need not coincide with the mass eigenstates ($\nu_1, \nu_2, \nu_3, \dots$), but would, in general, be related through a unitary transformation. Such a generalised Cabibbo-like mixing,

$$\nu_\ell = \sum_i U_{\ell i} \nu_i; \quad \ell = e, \mu, \tau, \dots, \quad i = 1, 2, 3, \dots \quad (1)$$

could result in neutrino oscillations when mass differences are small, and in decays of heavy neutrinos [3-5] when mass differences are large.

We consider neutrinos in the mass range $1 < m_{\nu i} < 1800$ MeV, decaying into the channels $\nu_i \rightarrow e^- e^+ \nu_e, \mu^- e^+ \nu_e, e^- \pi^+, \mu^- \mu^+ \nu_\mu, \mu^- \pi^+$, and also the corresponding $\bar{\nu}$ decays (ν_i should be taken to denote ν_i and $\bar{\nu}_i$ throughout the paper). The three-body decays proceed as illustrated in fig. 1 with a decay rate given by [3]

$$\tau_p^{-1} = \frac{G_F^2 m_{\nu i}^5}{192 \pi^3} |U_{\ell i}|^2 \Gamma_{\ell \ell'}, \quad (2)$$

where $\Gamma_{\ell \ell'}$ is the phase space factor; $\ell, \ell' = e, \mu$ appropriately. The two-body decay modes are described by the same diagram when the $SU(2)$ doublet is a bound $u\bar{d}$ quark-antiquark pair. Their decay rate is given by [3]

$$\tau_p^{-1} = \frac{G_F^2 m_{\nu i}^3}{16 \pi} f_\pi^2 |U_{\ell i}|^2 \Gamma_{\ell \pi}, \quad (3)$$

where $\Gamma_{\ell \pi}$ is the appropriate phase space factor.

Previous comparable work has considered only the decay $\nu_i \rightarrow e^- e^+ \nu_e$ [6,7]. In BEBC we can also detect decays into muons and hence we can constrain the mixings $|U_{\mu i}|^2$. Furthermore, we can detect the two-body decays $\nu_i \rightarrow \ell^- \pi^+$, which dominate over the three body decays for most of the mass range considered. We thus set limits on $|U_{ei}|^2$ comparable to those given by CHARM [6,7] despite the smaller decay volume of our detector.

2. HEAVY NEUTRINO FLUXES

As is evident from eq. (1), any source of " ν_e " or " ν_μ " neutrinos will create all kinematically accessible massive eigenstates according to the appropriate mixings. Thus a conventional neutrino beam, generated mostly by π and K decays, can contain neutrinos of mass up to $(m_\pi - m_e)$, $(m_K - m_e)$. In a beam dump experiment, however, a proton beam is dumped onto a high density target which absorbs nearly all the secondary π 's and K 's before they can decay, thus greatly suppressing the flux of "conventional" neutrinos. This enhances the fraction of neutrinos produced in the decays of heavy short-lived charmed particles (the "prompt" flux), and thus enables us to probe a larger kinematic range of neutrino mass, for example up to $(m_D - m_e)$. However, the results of oscillation experiments already imply that the mixings of heavy ($m_{\nu_i} > 1$ MeV) neutrinos are rather small. Thus it is still valid to adopt the usual assumption that such beams contain only "massless" neutrinos, and to derive the massless neutrino flux from the observed number of neutrino interactions.

The flux of heavy neutrinos, $\phi(\nu_i)$, can then be related to the prompt flux of massless neutrinos $\phi(\nu_\ell)$ as follows. We assume that these massless neutrinos are created in the decays $D \rightarrow \ell' \nu_\ell + X$ which have branching ratios of $\sim 19\%$ for $D^\pm$ and 5.3% for $(\bar{D})^0$ [8]. The two-body decays $D \rightarrow \ell' \nu_\ell$ are normally negligible because of helicity suppression. However this suppression disappears rapidly as the neutrino mass increases, and the branching ratio for $D \rightarrow \ell' \nu_i$ becomes significant [3];

$$\text{BR}(D \rightarrow \ell' \nu_i) = \text{BR}(D \rightarrow \ell' \nu_\ell) \cdot \tilde{\lambda}^{\frac{1}{2}}(x, y) \cdot \tilde{h}(x, y) \cdot |U_{\ell' i}|^2, \quad (4a)$$

where,

$$\begin{aligned}\tilde{\lambda}(x,y) &= \lambda(x,y)/\lambda(x,0), \\ \tilde{h}(x,y) &= h(x,y)/h(x,0), \\ \lambda(x,y) &= 1 + x^2 + y^2 - 2xy - 2x - 2y, \\ h(x,y) &= x + y - (x-y)^2, \\ x &= (m_{\ell'}/m_D)^2, \quad y = (m_{\nu_1}/m_D)^2.\end{aligned}\tag{4b}$$

For example, for $\tau_D = 9.2 \times 10^{-13}$ sec, $BR(D \rightarrow \mu \nu_\mu) \approx 6.5 \times 10^{-4}$, and $BR(D \rightarrow e \nu_e) \approx 1.5 \times 10^{-8}$ [9]. But for $m_{\nu_1} = 1$ GeV and $|U_{\ell'1}|^2 = 1$, $BR(D \rightarrow \mu \nu_1) \approx 2.85 \times 10^{-2}$, and $BR(D \rightarrow e \nu_1) \approx 2.6 \times 10^{-2}$. Thus we may calculate a lower limit to the heavy neutrino flux, $\phi(\nu_1)$, assuming that they are only produced in two-body decays, i.e.

$$\frac{\phi(\nu_1)}{\phi(\nu_{\ell'})} \approx \frac{\sigma(pN \rightarrow D^+ D^- + X) \cdot BR(D \rightarrow \ell' \nu_1)}{[\sigma(pN \rightarrow D^+ D^- + X) \cdot BR(D \rightarrow \ell' \nu_{\ell'} + X) + \sigma(pN \rightarrow D^0 \bar{D}^0 + X) \cdot BR(D^0 \rightarrow \ell' \nu_{\ell'} + X)]}\tag{5}$$

We assume $\sigma(D^+ D^-)/\sigma(D^0 \bar{D}^0) \sim \frac{1}{2}$ in agreement with EHS data [10]. Hence the heavy neutrino flux can be directly related to the observed prompt neutrino interaction rate through its relation to $\phi(\nu_{\ell'})$.

Another source of heavy neutrinos, for masses $m_{\nu_1} < 190$ MeV, is the decay of the charmed F meson, $F \rightarrow \tau \nu_\tau$, and the subsequent τ decay, $\tau \rightarrow \nu_\tau + X$. These decays yield the massive eigenstate ν_3 directly, since the mixing matrix is expected to be nearly diagonal, i.e. $|U_{\tau 3}|^2 \approx 1$. The flux of ν_3 , $\phi(\nu_3)$, is given in ratio to the massless prompt flux, $\phi(\nu_{\ell'})$, as follows,

$$\frac{\phi(\nu_3)}{\phi(\nu_{\ell'})} = \frac{\sigma(pN \rightarrow F + X) \cdot BR(F \rightarrow \tau \nu_\tau) \cdot 2}{\sigma(pN \rightarrow D + X) \cdot BR(D \rightarrow \ell' \nu_{\ell'} + X)} \cdot |U_{\tau 3}|^2 \cdot \tilde{\lambda}^{\frac{1}{2}}(x', y') \cdot \tilde{h}(x', y')\tag{6}$$

where, in this case, $x' = (m_\tau/m_F)^2$, $y' = (m_{\nu_3}/m_F)^2$. The branching ratio, $BR(F \rightarrow \tau \nu_\tau)$, has previously been assumed to be 3% [6], corresponding to an F mass, $m_F = 2.03$ GeV; however we use the value 1.7% [11] corresponding to $m_F = 1.97$ GeV [8]. Theoretical estimates of the ratio $\sigma(F)/\sigma(D)$ vary between

0.1 and m_D^2/m_F^2 [12]. We adopt the value 0.2 for comparability with previous work [6]. This value is consistent with recent data from EHS [10]. The limits on $|U_{\ell 3}|^2$ scale directly with this quantity and can easily be reevaluated when a reliable experimental measurement is obtained.

There are indications [13] that $\Lambda_c \rightarrow \ell' \nu_{\ell'} + X$ decays may also contribute to $\phi(\nu_{\ell'})$. This would introduce an extra term in the denominator of eqns. 5 and 6, which would degrade all beam dump limits.

3. SEARCH FOR NEUTRINO DECAYS

The bubble chamber BEBC was filled with a 74 mole% mixture of Ne/H₂, giving a fiducial mass of 11.5 t, and exposed to a neutrino flux produced by $1.9 \cdot 10^{18}$ protons on a solid copper target and $0.8 \cdot 10^{18}$ protons on a laminated copper target with effective density of $1/3$ that of solid copper. BEBC was equipped with an External Muon Identifier (EMI) [13]. A total of 3743 neutral induced events was recorded. Neutrino decay candidates were required to have an oppositely charged particle pair and no associated neutral hadron interactions or neutral strange particle decays. Associated γ pair conversions were allowed only if the γ was consistent with production by bremsstrahlung from either of the charged tracks. In order to obtain a reliable scan efficiency the total resultant momentum in the charged tracks was required to be greater than 1 GeV/c. This efficiency is then 97%. Only 83 events passed these search criteria and these were subjected to further cuts as detailed below.

(a) Transverse Mass cut: Since we assume that heavy neutrinos ν_1 are produced in two-body charmed particle decays, $C \rightarrow \ell' \nu_1$, we can obviously reduce the number of candidates further by imposing a cut on M_I , the invariant mass of the charged particle pair, such that $M_I < m_C - m_{\ell'}$. In practice, we imposed a stricter cut, $M_T < m_C - m_{\ell'}$, where, $M_T = \{(p_T^2 + M_I^2)^{1/2} + p_T\}$ is the transverse mass of the pair and p_T is the transverse component of their resultant momentum vector with respect to the neutrino beam direction. This cut includes the missing p_T , $\cancel{p}_T$, of the final state light neutrino in three-body heavy neutrino decay and embodies the obvious restriction that $\cancel{p}_T \equiv -p_T = 0$ for a two-body heavy neutrino decay. We required that, $(M_T - 2 \cdot \Delta M_T) < 0.19, 1.75, 1.85$ GeV, for neutrino decay candidates for which the source is considered to be the

decay $F \rightarrow \tau \nu_3$, $D \rightarrow \mu \nu_1$, $D \rightarrow e \nu_1$, respectively. No candidate passed the cut at 0.19 GeV, while 35 candidates passed both the cuts at 1.75 and 1.85 GeV. These candidates were individually examined and rejected if both tracks could be definitely identified as hadrons, or if the candidate could be identified as an interaction in a nucleus due to evidence of nuclear break-up. Only 12 candidates survived these visual checks.

- (b) Lepton identification: The electron detection efficiency for this experiment is 96% for tracks of momentum > 0.8 GeV/c, and the muon identification efficiency is 97% for tracks of momentum > 3 GeV/c, which fall within the acceptance of the EMI. We imposed these momentum cuts appropriately according to the decay channel under consideration, and required the corresponding lepton identification for events which survived the cuts. This left no candidates for the decay channels $\nu_1 \rightarrow e e \nu$, $e \mu \nu$, $\mu \mu \nu$, 2 candidates for the channel $\nu_1 \rightarrow e \pi$ and 6 candidates for the channel $\nu_1 \rightarrow \mu \pi$.

- (c) Kinematic Fitting: We now fit the remaining two-body decay candidates to the hypothesis that they result from the decays of heavy neutrinos of arbitrary mass, travelling along the beam direction. The two candidates for the $e \pi$ channel have fit confidence levels of $< 10^{-4}$, and are thus rejected. Of the 6 candidates for the $\mu \pi$ channel, 1 fits the decay $\bar{\nu}_1 \rightarrow \mu^+ \pi^-$, $m_{\nu_1} \sim 1$ GeV, with a fit confidence level of $\sim 1\%$, prompting us to examine possible backgrounds. Charged current neutrino interactions may yield a $\mu \pi$ final state when the outgoing baryon, and any accompanying neutral particles, are not detected. Such events can only fit the two-body decay hypothesis well when the incoming neutrino scatters coherently off a nucleus, e.g. $\bar{\nu} \text{Ne} \rightarrow \mu^+ \pi^- \text{Ne}$ [14], so that the nuclear recoil momentum is very small. To evaluate this background we have used data from the WA59 experiment, in which BEBC, filled with a Ne/H₂ mix similar to the present experiment, was exposed to a conventional wide band neutrino beam. The fraction of heavy neutrinos in the mass range of interest in such a beam is $< 1\%$ of that in our beam dump beam. We have applied the same search criteria to the WA59 events as to the present experiment, and performed two-body kinematic fits for those events which passed the search criteria. Normalising the background sample to the

present experiment, we find that the χ^2 distribution for these background events and our 6 candidate events are compatible. If we require a fit confidence level of $> 1\%$, we obtain a background of 0.6 ± 0.2 events for 1 candidate event. Hence we have no significant signal for neutrino decay.

4. CALCULATION OF LIMITS

For a given flux of heavy neutrinos, $\phi(\nu_i)$, the expected number of decays in a detector of length L at a distance $L'(>>L)$ from the source is given by

$$N_{\text{decay}} = \phi(\nu_i) \cdot \exp(-L'm_\nu/p_\nu \tau) \cdot [1 - \exp(Lm_\nu/p_\nu \tau)] \cdot (\tau/\tau_p) \cdot A \cdot \epsilon, \quad (7)$$

where p_ν is the neutrino momentum, τ_p is the partial lifetime for the decay mode under consideration and $\tau (= [\sum \tau_p^{-1}]^{-1})$ is the total lifetime. The acceptance A of the detector was calculated using a Monte Carlo programme to track neutrinos produced at the target through to the detector, taking all relevant momentum and angular distributions into account. The differential production spectra of F and D mesons were taken to be [15], $Ed^3\sigma/dp^3 \propto (1-x_F)^4 e^{-2p_T}$, where E , x_F , p_T are respectively the energy, Feynman x variable and transverse momentum of the produced charmed particle. The $D \rightarrow \ell' \nu_{\ell'}$, $F \rightarrow \tau \nu_\tau$ decays are isotropic; the branching ratios for $\tau \rightarrow \nu_\tau + X$ decays are taken from ref. [8] and the appropriate angular distributions from refs. [3,16,17], with the effects of non-zero neutrino mass taken into account. The detection efficiency ϵ was calculated for each decay mode taking into account lepton identification and scan efficiencies and the EMI acceptance, together with the probability that the final state lepton/s would pass the imposed momentum cuts.

Over most of the $|U_{\ell i}|^2 - m_{\nu i}$ plane, the neutrino lifetime is sufficiently long (see eqs. (2-3)) that $Lm_\nu/p_\nu \tau \ll L'm_\nu/p_\nu \tau \ll 1$. We may then write

$$\begin{aligned} N_{\text{decay}} &\approx \phi(\nu_i) \cdot (Lm_\nu/p_\nu \tau_p) \cdot A \cdot \epsilon \\ &\propto |U_{\ell' i}|^2 \cdot |U_{\ell i}|^2, \end{aligned} \quad (8)$$

where $|U_{\ell'1}|^2$ enters at production of ν_i in association with a lepton ℓ' and $|U_{\ell i}|^2$ enters at ν_i decay, $\nu_i \rightarrow \ell + X$. Thus for $\ell = \ell'$, a limit on N_{decay} translates into an upper limit on $|U_{\ell i}|^4$ as a function of $m_{\nu i}$. The limits thus derived are quite general in that they apply to the couplings of any neutral heavy lepton to the light flavour eigenstates. For the particular case of ν_3 production in F decay, $|U_{\ell'1}|^2 \equiv |U_{\tau 3}|^2 \approx 1$, so that a limit on N_{decay} translates directly into an upper limit on $|U_{\ell 3}|^2$.

When the neutrino lifetime is very short such that $L'm_\nu/p_\nu \tau \gtrsim 1$, the approximation of eqn. 8 is no longer valid. This region of the $|U_{\ell i}|^2 - m_{\nu i}$ plane corresponds to the case for which the ν_i flux in the beam is strongly attenuated. A lower limit to $|U_{\ell i}|^2$ is obtained by requiring that the attenuation is sufficient to restrict the number of heavy neutrinos which reach the detector before decaying. Thus, the region enclosed by curve A is excluded in figs. 2 and 3.

5. RESULTS

In fig. 2 we show our 90% confidence upper limit (curve A) on $|U_{\mu i}|^2$ for ν_i 's produced in $D \rightarrow \mu \nu$ and decaying through $\nu_i \rightarrow \mu \pi, \mu \mu \nu, \mu e \nu$. This is the only limit on $|U_{\mu i}|^2$ in this mass range. Fig. 3 shows our limit (curve A) on $|U_{e i}|^2$ for ν_i 's produced in $D \rightarrow e \nu$ and decaying through $\nu_i \rightarrow e \pi, e \mu \nu, e e \nu$. This limit is comparable to the preliminary result from CHARM [7] in the same mass range because we have examined more decay channels.

These figures also illustrate our limits (curves B) on $|U_{\mu 3}|^2$ and $|U_{e 3}|^2$ in the mass range $120 < m_{\nu 3} < 190$ MeV and $30 < m_{\nu 3} < 190$ MeV respectively, for ν_3 's produced in $F \rightarrow \tau \nu_3$ and decaying through $\nu_3 \rightarrow \mu \pi, \mu \mu \nu, \mu e \nu$ (fig. 2) and $\nu_3 \rightarrow e \pi, e \mu \nu, e e \nu$ (fig. 3). The latest limits on $|U_{\ell i}|^2$ obtained from peak search experiments on π and K decays [18-20] are shown for comparison. For $m_{\nu 3} > 140$ MeV, our limit on $|U_{\mu 3}|^2$ improves substantially on that obtained from K decay [20] and our limit on $|U_{e 3}|^2$ is comparable to that given by CHARM [6] if the latter is corrected for the new F mass (this would degrade the CHARM limit by a factor of ~ 2). However, we note that the limit on the " ν_τ " mass has recently been lowered to 125 MeV [21].

These limits constrain models of horizontal unification which predict inter-family mixings $|U_{e3}|^2, |U_{\mu 3}|^2 \sim 10^{-4} - 10^{-5}$ [22]. The limits on $|U_{\ell i}|^2$ apply to the mixings of right-handed heavy leptons which arise in many unification models [23]. Finally, these limits imply lower bounds on heavy neutrino lifetimes which are of interest in cosmology [24].

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FIGURE CAPTIONS

Fig. 1 Heavy neutrino decay through the weak charged current.

Fig. 2 Upper limits on the leptonic mixing parameter $|U_{\mu 1}|^2$ as a function of neutrino mass, derived from: Searches for the decays (A) $\nu_1 \rightarrow \mu e \nu$, $\mu \mu \nu$, $\mu \pi$; (B) $\nu_3 \rightarrow \mu e \nu$; searches for secondary peaks in (C) $K \rightarrow \mu \nu$ [20]; (D) $\pi \rightarrow \mu \nu$ [19]. The region enclosed by curve (A) is excluded.

Fig. 3 Upper limits on the leptonic mixing parameter $|U_{e 1}|^2$ as a function of neutrino mass $m_{\nu 1}$, derived from : Searches for the decays (A) $\nu_1 \rightarrow e e \nu$, $e \mu \nu$, $e \pi$; (B) $\nu_3 \rightarrow e e \nu$, $e \mu \nu$, $e \pi$; (C) $\nu_3 \rightarrow e e \nu$ [6] (uncorrected, see text); searches for secondary peaks in (D) $K \rightarrow e \nu$ [20]; (E) $\pi \rightarrow e \nu$ [18]. The region enclosed by curve (A) is excluded.

Fig. 1.

Fig.2.

Fig.3.