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A SEARCH FOR HEAVY NEUTRINO DECAYS IN A NEUTRINO BEAM

Experiment 734 Collaboration

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A SEARCH FOR HEAVY NEUTRINO DECAYS IN A NEUTRINO BEAM

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ABSTRACT

Decay of heavy neutrinos $\nu_H \rightarrow \nu_\ell \mu e$(ℓ =e, μ) has been searched for in the Brookhaven Alternating Gradient Synchrotron wide-band neutrino beam. Since no significant excess of such events was found, upper limits on the neutrino mixing matrix elements, $|U_{eH}|^2$ and $|U_{\mu H}|^2$ were obtained for the mass range of 180-500 MeV.

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INTRODUCTION

If neutrinos have mass, mass eigenstates of neutrinos may differ from the flavour eigenstates. In general the flavour eigenstates are related with the mass eigenstates through a unitary transformation, mixing matrix. In the case mass differences are large, heavy neutrinos could decay into lighter particles[1]. In this experiment heavy neutrino decays of the type $\nu_H \rightarrow \nu_\ell \mu e$(ℓ =e, μ) have been searched. Heavy neutrinos are assumed to be produced from the decays of kaons in a neutrino beam. Heavy neutrino production and sequential decay process through the mixing matrix is shown in Fig. 1.

The experiment was carried out in the Brookhaven Alternating Gradient Syncrotron(AGS) wide-band neutrino beam. The detector, which is 23m long, 170 ton fine grained calorimeter detector (E734 detector)[3], is located 110m downstream of the production target (Fig.2).

BEAM

The proton beam, an energy of 28 GeV from the Brookhaven AGS is transported to the target. The repetition rate is 1.4s and the beam intensity is 10^{13}/pulse. Secondary particles of selected sign which originated from collisions of protons in the target are focused by a horn system. The result is a nearly parallel beam in the decay region. In the decay region 30% of the pions decay and 90% of the kaions decay, then remaining pions, kaions and leptons are absorbed in the muon shield.

In the beam the neutrino fluxes were measured by qusielastic modes in the same detector used for this experiment. The mean energy of muon neutrinos is 1.4 GeV and integrated flux is $2\times10^{10}/m^2 10^{13}$POT.

DETECTOR

The detector consists of a main detector and a shower counter. The main detector has a area of 4m x 4m and a length of 21m. The main detector is made of the same 112 modules. A module is consists of a liquid scintillator wall (16 cells and 8 cm thick) and X and Y planes of proportional drift tubes (54 wires and 3.8 cm thick each). The fine segmentation (1792 scintillator cells and 12096 proportional drift tubes) and the pulse height and timing measurement of the elements provide a fine determination of electromagnetic showe,s and muon tracks.

EVENT SIGNATURE AND BACKGROUND

The signature of flight decay of heavy neutrinos is a long minimum ionizing track and an electromagnetic shower originating from the same vertex. For example a candidate observed in the detector is shown in Fig. 3.

Main background comes from a muon neutrino induced $\nu_\mu n \rightarrow \mu^- p \pi^0$ process, where proton recoil energy is small and one gamma ray from the pion passes through the detector without any interaction and the other gamma ray converts near the vertex.

The second background comes from an electron neutrino induced $\nu_e N \rightarrow e^- N \pi^+$(N=n, p) process, where the pion is missidentified as an electron. The electron neutrino flux is 1% level of the muon neutrino flux[4].

The third background is muon neutrino induced charmed barion production and its sequential decay,

$$\begin{aligned} \nu_\mu n \rightarrow \mu^- \Lambda_c^+ & \qquad m\Lambda_c^+ = 2.3\ \mathrm{GeV}/c^2 \\ \rightarrow n e^+ \nu_e & \qquad Br(\Lambda_c^+ \rightarrow e^+ + \mathrm{anything}) = 4.5\% \\ \rightarrow \Lambda^0 e^+ \nu_e & \\ \rightarrow p \pi^- & \\ \rightarrow n \pi^0 . & \end{aligned}$$

The muon flux more than threshold energy to make charmed barion (2.6GeV) is 10% and the branching ratio of charmed barion to e^++anything is 4.5%. The second and third backgrounds are small as compared with the first background.

DATA REDUCTION

For this analysis the data correponding to 534,000 AGS pulses (0.38×10^{19}POT) was processed. The data was passed through a software filter which requires that the visible energy is more than 1 GeV and the size of event in the beam direction is more than 15 modules. The filter reduced events produced by a low energy gamma ray from the interaction $\nu_\mu n \rightarrow \mu^- p \pi^0$ and selected events with a muon.

The resulting 61,000 events were scanned doubly by physicists to select events with a long minimum ionizing track, an electromagnetic shower comes from the same vertex and no other tracks around the vertex. Events with a electromagnetic shower pointing back to the muon vertex were also kept for the background subtraction. The energy of the electromagnetic shower had to be more than 1 GeV. In addition the muon track length was required to be more than 4 collision lengths(25 modules) to reduce pion contamination. The opening angle between the muon track and the electromagnetic shower was required to be more than 0.05 rad in order to make clear determination of the shower conversion point.

Finally 43 candidates remained.

The conversion distances were measured for the 43 candidates to subtract the background that a gamma ray converted near the muon track(Fig. 4). The coversion distance distribution except the first bin was fitted by the function $A*\exp(-x/x_0)$, using the design value of $x_0=5.94$ modules for the conversion length. The background from Dalitz decay of π^0 was calculated from the number of events induced by a gamma ray, using the detection efficiency for a gamma ray that is 60%. The single pion background produced by electron neutrinos was calculated to be 5.1 ± 1.8 events by the Monte Carlo simulation with the measured electron neutrino spectrum[4] and the well understood single pion cross section. The background from charmed barion production was also calculated to be 1.7 ± 0.8 events by the same way with the cross section based on a theoretical estimate[5]. All the backgrounds are tabulated in Table 1.

The final excess is $6.8\pm5.8\pm3.1$ after the background subtraction and correction of the software filtering efficiency 0.99 and the scanning efficiency 0.96.

There is no evidence for the decay $\nu_H \to \nu_\ell \mu e$. The upper limit at 90% C.L. is 15.2 events.

TABLE 1

Summary of Background Subtractions

Modes	Number of events
$\nu_\mu n \to \mu^- p \pi^0$	
$\to \gamma\gamma$	$12.\pm2.7$
$\to e^+e^-\gamma$	0.3 ± 0.2
$\nu_e p \to e^- p \pi^+$	2.0 ± 1.0
$\nu_e n \to e^- n \pi^+$	0.9 ± 0.4
$\nu_\mu n \to \mu^- \Lambda_c^+$	
$\to n e^+ \nu_e$	1.1 ± 0.7
$\to \Lambda^0 e^+ \nu_e$	
$\to p \pi^-$	---
$\to n \pi^0$	0.2 ± 0.1

HEAVY NEUTRINO MIXING MATRIX

The expected number of decays of heavy neutrinos with mass m in the detector is calculated by integral of product of the heavy neutrino flux, the decay probability and the detection efficiency.

$$N=\int \phi_H(E,m)Pdecay(E,m)\,\varepsilon(E,m)dE \qquad (1)$$

Heavy neutrinos can be produced from decays of $K^+\rightarrow e^+\nu_H$ or $K^+\rightarrow \mu^+\nu_H$. The heavy neutrino flux is given[6] by

$$\phi_H(E,m)=\Sigma\,\phi_{K.\nu\ell}(E,m)\,|U_{\ell H}|^2\rho_{K.\ell}(m), \qquad (2)$$

where $\phi_{K.\nu\ell}(E,m)$ is an energy spectrum of heavy neutrinos from a particular decay channel, $|U_{\ell H}|^2$ is a mixing matrix between the ordinary neutrinos and the heavy neutrino and $\rho_{K.\ell}$ is a helicity enhancement factor including the phase space effect.

The decay probability Pdecay(E,m) of $\nu_H\rightarrow\nu_\ell\mu e$ is given by

$$Pdecay(E,m)=\exp(\ -L/v_H*\tau_H*\gamma\ )\ \fallingdotseq\ L*m/E*\tau_H \qquad (3)$$

$$\tau_H=\tau_\mu(m/m_\mu)^{-5}f^{-1}(m_\mu/m)/\Sigma\,|U_{\ell H}|^2,$$

where L is the length of the decay fiducial and f is phase space factor.

The detector acceptance is calculated by the Monte Carlo simulation. In low energy region the acceptance is limited by the 1 GeV energy cut and in the high energy region by the requirement of 0.05 rad opening angle between the muon track and the electromagnetic shower. The opening angle cut reduces the acceptance of neutrino with lighter mass and sets a low mass limit of 180 MeV. By this reason the detector does not have any acceptance for heavy neutrino decays from pions.

As an example the energy spectrum of heavy neutrinos and the acceptance of the detector are shown in Fig. 5a, 5b in the case that heavy neutrino mass is 300 MeV.

RESULTS

The upper limit for decays of heavy neutrinos gives a constraint on the heavy neutrino mixing matrix through (1) by the form,

$$A(m)\,|U_{eH}|^4+(A(m)+B(m))\,|U_{eH}|^2\,|U\mu_H|^2$$
$$+B(m)\,|U\mu_H|^4 < 15.2 \text{ events} \qquad (4)$$

We obtained 90% C.L. limit for $|U_{eH}|^2$ and $|U\mu_H|^2$, which includes systematic errors of 15% for the spectrum shape and 30-40% for the acceptance. The results are shown as contours of the upper limits in the $|U_{eH}|^2$ vs. $|U\mu_H|^2$ space(Fig. 6).

To compare these results with other experiments which only determined the limit for a single mixing matrix elements, the upper limits are calculated for each mixing matrix element assuming that the other is zero. The calculated results are shown in Fig. 7a,7b together with previous experimental results[10].

CONCLUSION

There is no significant excess for the decay of heavy neutrinos with the mass range 180-500 MeV. Then contours of the upper limits are given in the $|U_{eH}|^2$ vs. $|U\mu_H|^2$ space in this mass region. The upper limit for $|U\mu_H|^2$ has been extended to 5×10^{-8} for the heavy neutrino mass around 400 MeV, assuming the $|U_{eH}|^2$ is zero.

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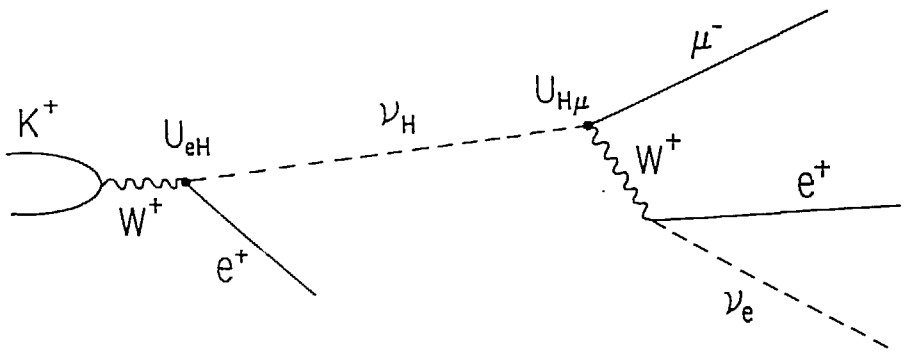

Fig. 1. Heavy neutrino production and sequential decay diagram

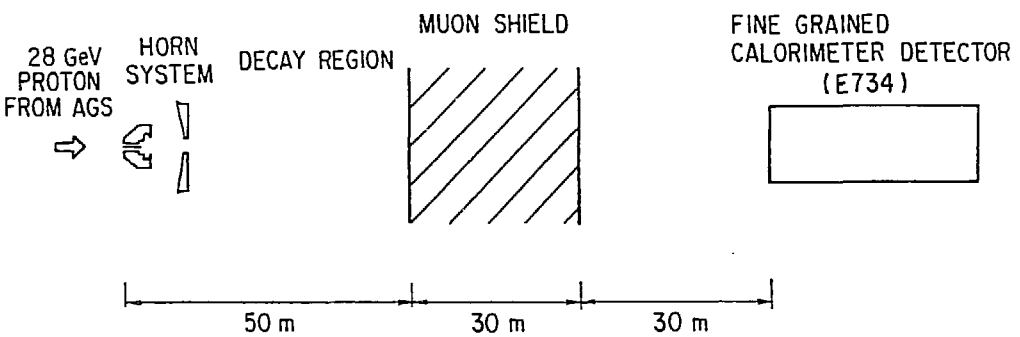

Fig. 2. The wide-band neutrino beam line and decay region are shown with the magnetic horns and the detector.

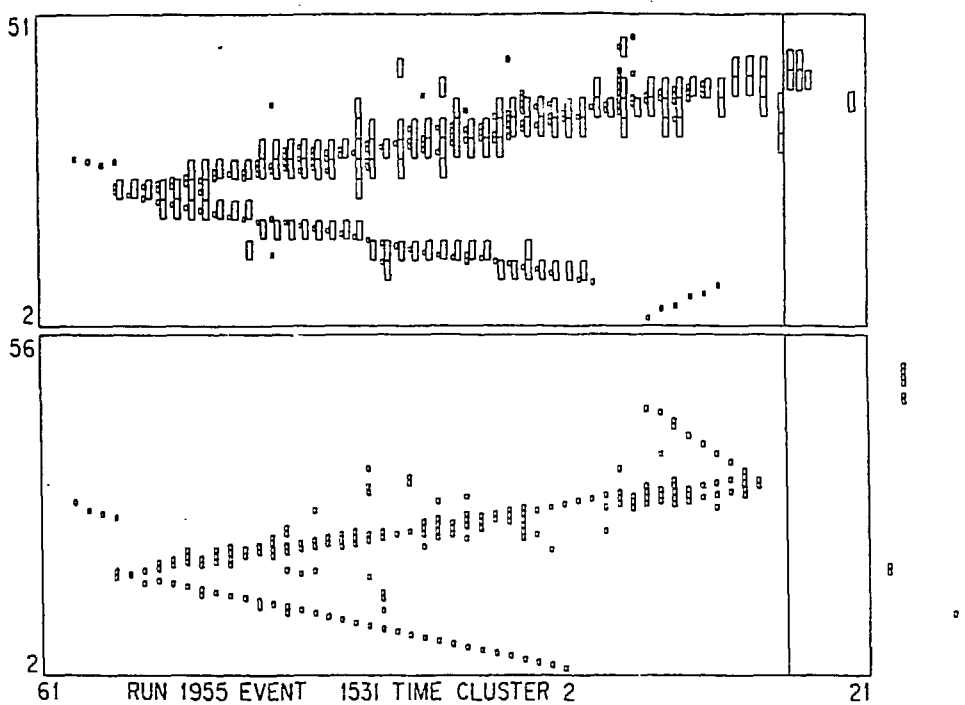

Fig. 3. A candidate of heavy neutrino decay in the detector, side view and top view. Larger box shows liquid scintillator cell hit and smaller box shows proportional drift tube hit.

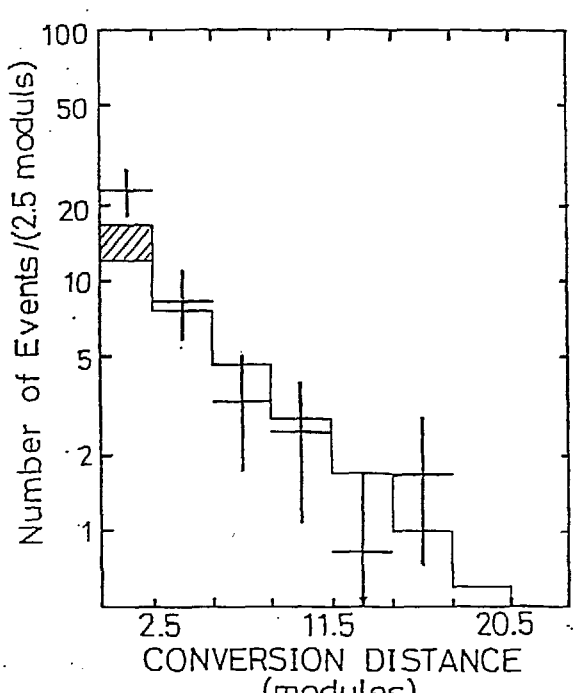

Fig. 4. Conversion distance distribution for the primary sample of 43 events. The lines are for the estimated π^0 background, $A \ast \exp(-x/x_0)$. The estimated conventional μe backgrounds are also shown in the first bin by the shaded area.

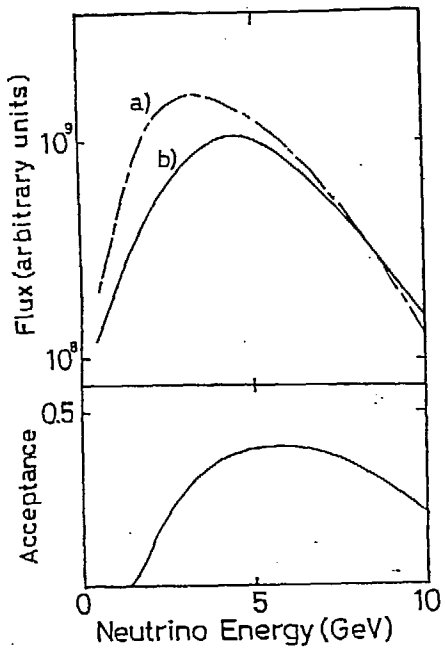

Fig. 5. An energy spectra and an acceptance of 300 MeV heavy neutrinos. Dashed line (a) in the upper figure shows the spectrum from the decay $K^+ \rightarrow \mu^+ \nu_H$ and solid line (b) from the decay $K^+ \rightarrow e^+ \nu_H$.

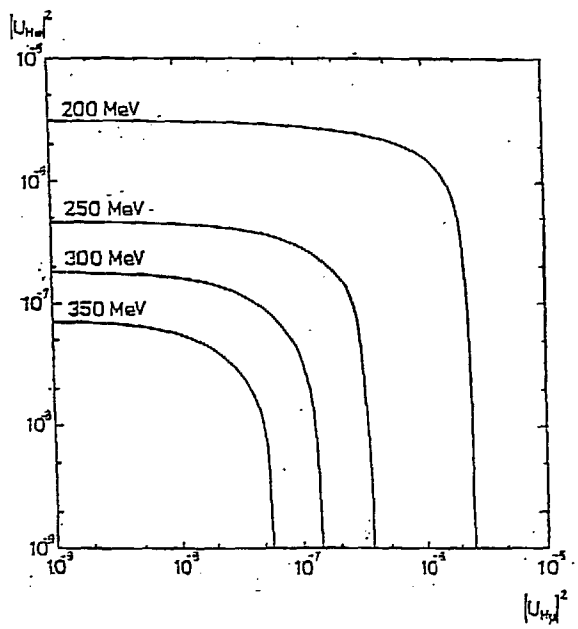

Fig. 6. 90% cofidence limits of the mixing matrix elements in $|U_{eH}|^2$ vs. $|U\mu_H|^2$ space.

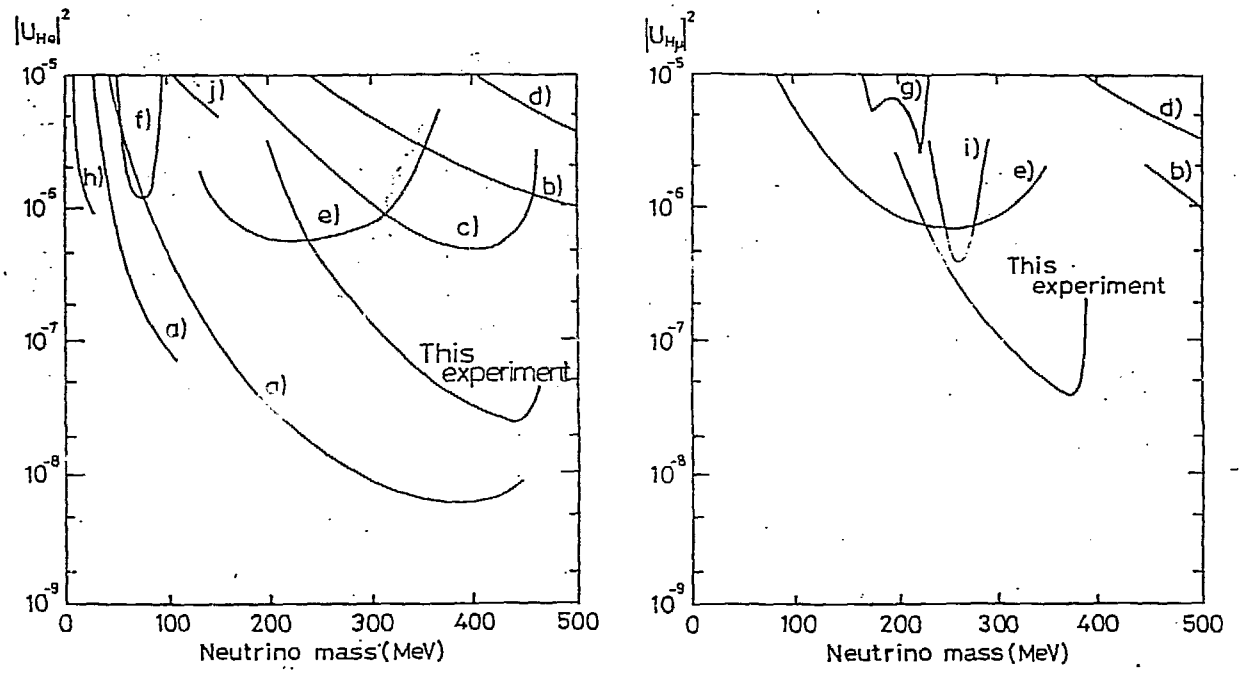

Fig. 7. (a) Limits on 90% C.L. of $|U_{\mu H}|^2$ and (b) $|U_{eH}|^2$ together with other experiments. See reference 7.