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ANOMALOUS ELECTRON PRODUCTION OBSERVED IN THE CERN PS NEUTRINO BEAM

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ABSTRACT

Neutrino interactions in a fine-grain calorimeter have been analysed with emphasis on events with associated electromagnetic showers. The good granularity of the detector allows to separate photon from electron showers. The number of events with an electron was found to be about three times larger than expected on the basis of the beam composition. This may be interpreted as due to $\nu_{\mu} \rightarrow \nu_e$ oscillations.

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The experiment PS191 at CERN searched for decays of heavy neutrinos using a decay detector followed by a fine-grain electromagnetic calorimeter. The trigger conditions were set by a scintillator hodoscope at a depth of 1.7 radiation lengths inside the calorimeter. The purpose of the hodoscope was to select events where one or more showers traversed the hodoscope plane. The threshold for the acceptance of the scintillator signals was set to twice the minimum-ionization value in the scintillator (as measured in a calibration run). If more than one scintillator slab ($30 \times 300 \times 1 \text{ cm}^3$) out of the available twenty gave a signal, then the event was accepted even if the amplitudes corresponded to the minimum-ionizing level. These conditions were such that, as a by-product, about a thousand neutrino interactions were recorded in the calorimeter modules preceding the hodoscope. Clearly, shower-associated interactions were favoured in this sample. An analysis of these events shows an abnormal abundance of electrons stemming directly from the vertex of the interaction which cannot be explained on the basis of the neutrino beam composition except as an improbable statistical fluctuation.

Details of the beam and a general description of the apparatus are given elsewhere together with the results on neutrino decays [1]. The beam consisted of ν_μ with an energy spectrum peaking at $\sim 600 \text{ MeV}$ and a small admixture, $(0.7 \pm 0.2)\%$, of ν_e at somewhat higher energies. Fig. 1 shows the energy spectrum of the neutrino fluxes calculated using two independent and consistent simulation programs [2-3]. The part of the apparatus that we are concerned with is the calorimeter, made of flash-tube chambers separated by 3 mm thick iron plates. The granularity of the detector is 17% of a radiation length and the transversal dimensions of the tubes are $5 \times 5 \text{ mm}^2$. The "target" region for the interactions under study consisted of 10 layers of "flash-tube/iron-plate" sandwiches weighing a total of $\sim 5 \text{ t}$. The surface covered by the detector across the beam was $6 \times 3 \text{ m}^2$. The same target structure was repeated beyond the hodoscope for a total of 30 identical sandwiches, i.e. an additional 5.1 radiation lengths. The fine granularity of the detector allows the identification of the electromagnetic showers and the measurement of their energy with a resolution $dE/E \sim 12\%/\sqrt{E}$ (E is in GeV). It should be pointed out that a 1 GeV shower turns on about 110 cells; its appearance is spectacular and unlikely to be either missed or mistaken for something else.

The analysis is based on a double scan (in the vertical view) of events with a well defined vertex within the target region and inside a fiducial volume defined so as to insure the maximum containment of the showers. Fig. 2(a) shows an example of an event with three minimum-ionising tracks originating from the same vertex. A track was defined as a succession of at least three consecutive cells. A total of 408 two-track and 200 three-track interactions were found. We interpret these events as ν_μ interactions, although it should be understood that we have no way to tell if one of the tracks - or which - is a muon. The absolute and relative numbers of these events are in good agreement with the results of a simulation program [4] based on known neutrino cross sections and a flux of 2×10^{16} neutrinos through the detector generated during a run of 8.6×10^{18} protons on target. This program predicted (at the 20% level) 438 and 270 two- and three-track interactions, respectively. The search for events with only minimum ionizing tracks had the purpose of providing a convenient internal normalization and a check on the following analysis.

In addition to the above, we have searched for events with electromagnetic showers. The granularity of the detector is best exploited when the energy of the shower is larger than ~ 400 MeV, corresponding to more than 50 tubes hit. This selection has also the effect of rejecting most of the π^0 whose spectrum peaks at ~ 200 MeV. A total of 57 events with one shower plus one or two associated tracks was found. The same topology for the case of two showers (where the energy cut applies now to the sum of the shower energies) gave a total of 23 events.

We try now to interpret these "shower events" so as to understand their nature. Showers can have different origins. Firstly, they can be made by photons, either directly produced or from π^0 generated by a charged or neutral-current ν_μ interaction. Secondly, they can be made by electrons. Thirdly, they can be made by hadrons which - by bremsstrahlung or secondary interaction - simulate an electromagnetic shower. In principle, the experiment simulation [4] provides the expected number of these "shower events" for our exposure and the required topology: we expect 24 ± 6 events due to ν_μ interactions producing a π^0 and 12 ± 3 events due to ν_e charged-current interactions producing an electron. The hadron bremsstrahlung is negligible after the energy cut. As for the more

general hadronic background, the ambiguity in the e/π separation has been measured by the Frejus "proton-lifetime" group [5]. On the basis of an exposure of a detector of identical configuration and material as our calorimeter (in fact our calorimeter is really theirs) they reached the conclusion that the probability of misidentifying a pion with an electron of the same energy is less than 1%. This would then contribute to our sample (after the energy cut) with at most one event.

If we take the above evaluations at face value we are then confronted with a total of 80 events found against 36 expected. The discrepancy, however, is much more disquieting if we inspect the subsample of events where the shower starts developing immediately at the vertex, thus strongly suggesting that the parent particle was an electron and not a photon. Here we find a total of 53 events whereas, as mentioned above, the expected number is 12 ± 3 . Some of the discrepancy is certainly due to the presence of π^0 decays; the point is how to estimate reliably how many of them start showering directly at the vertex.

In order to circumvent the possible shortcomings of a Monte-Carlo simulation, we have resorted to an unbiased and calculation-free procedure to evaluate the actual number of showers due to electrons in our sample. The photon contribution (which is the dominant background in all these considerations) can be evaluated from the data themselves by comparing the distribution of the vertex-to-shower distance for events having one associated shower with that of events having two. This comparison yields the number of directly connected electrons because it tells us how many photons from π^0 start showering right at the emission point. This is possible only because the good granularity of the detector allows a clear discrimination between the photons showering some distance away from the vertex and the electrons which must appear (showering or not) right at production. As an example, fig. 2(b) shows an event where the shower develops directly from the vertex. The event in fig. 2(c), instead, shows a shower which starts developing at some distance from the vertex.

Considering first the events with two showers, the most likely interpretation is that they represent interactions where a π^0 was generated and immediately decayed into two photons which then showered.

For each of these events we have measured the distance between the vertex and the beginning of the closest shower by counting the number of chamber planes separating these points. The distribution of this distance (shown in fig. 3(a)) is consistent with that expected from the above hypothesis and the material of our detector (one radiation length is about six detector planes). The dashed curve in this figure is the distribution expected on the basis of a Monte-Carlo simulation of the shower process [6] calculated using the known π^0 energy spectrum. This curve has been specifically normalised^(*) to the observed events beyond the first bin because this is contaminated by electrons emerging directly from ν_e interactions where a π^0 was also produced.

Turning now to the events where only one shower is visible, fig. 3(b) gives the distribution of the distance between the vertex and the beginning of the shower. A peak of 42 events appears in the first bin, well above the level of the exponential dependence expected if the showers were due to one of the photons from a π^0 , the other having been lost. These events, where the shower is directly connected to the vertex, cannot be ascribed to anything else but a mixture of direct single electron emission and π^0 decays where one of the two photons had too low an energy to be seen or the two photons were superimposed or one of them escaped the detector. An estimate of these processes can be obtained by using a shower simulation [6]. The dashed line in fig. 3(b) is the result of the calculation; the normalisation has been made (as above) to the number of observed events outside the first bin. The number of background events thus calculated turns out to be 7 ± 3 . The subtraction of the background leaves a total of 35 ± 7 events where the shower cannot be accounted for by a π^0 decay.

The remaining hypothesis is that these events contain an electron directly emitted at the vertex. These can only arise from ν_e interactions. As mentioned above, the number of such interactions had been calculated to be 12 ± 3 . Notice that all errors are only statistical.

(*) The number of events of this type expected on the basis of the simulation of the neutrino interactions [4] is somewhat smaller than the number observed but not in serious conflict.

The conclusion is that we have an excess of 23 ± 8 events, i.e. a three-standard deviation effect from zero. If the above result were attributed to the presence in the beam of more ν_e than predicted by the standard and well established programs [2] and [3], we would find $(2.0 \pm 0.5)\%$ instead of $(0.7 \pm 0.2)\%$ for the ν_e/ν_μ ratio^(*).

It is tempting to interpret this excess of electrons as a possible manifestation of neutrino oscillations of the type $\nu_\mu \rightarrow \nu_e$. In the usual terminology the probability for a ν_μ turning into a ν_e is $P = \sin^2(2\theta) \times \sin^2(\pi R/L)$ where R is the distance to the detector and L is the oscillation distance given by $L(\text{Km}) = 2.5 E(\text{GeV})/\Delta M^2(\text{eV}^2)$. Our detector being 130 m away from the production target, the parameters of our solution would then be $\sin^2(2\theta) \sim (2 - 4)\%$ and $\Delta M^2 \sim (5 - 10) \text{ eV}^2$, assuming that we probe the first oscillation (i.e. $\sin^2(\pi R/L) = 1$). This result is not in disagreement with the most sensitive of the recent limits on the $\nu_\mu \rightarrow \nu_e$ oscillation [7] but disagrees (at the 90% confidence level) with an experiment which studied the ν_e elastic scattering [8] and found no evidence for anomalies in the ν_e flux. As for a previous indication [9] of neutrino oscillations by looking at $\bar{\nu}_e$ disappearance, our result is different but, since it applies to a different channel, the two experiments are not directly comparable. Being potentially of fundamental importance, we do not dwell further on other possible interpretations of this effect and prefer to wait until we increase the statistics with an improved detector in a coming run at BNL [10].

(*) The above ratio depends on the energy spectrum of the ν_e ; we have assumed that this was identical to that of the calculated ν_e . If this spectrum were softer (as in the case of ν_μ) then the ratio would become even larger.

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FIGURE CAPTIONS

- Fig. 1 Neutrino flux from the CERN PS beam on our detector, calculated using refs. [2] and [3]. The upper curve gives the ν_μ , the lower the ν_e flux.
- Fig. 2 (a) Neutrino interaction resulting in three tracks, as observed in the detector. The neutrino beam comes from the left. The display shows the vertical projection across the beam. The empty space between the two parts of the apparatus contains the hodoscope and separates the "target" (before the hodoscope) from the "calorimeter" region.
- (b) Neutrino interaction resulting in one shower stemming from the vertex.
- (c) Neutrino interaction with one shower unconnected to the vertex.
- Fig. 3 (a) Distribution of the distance between vertex and beginning of the closest shower for the two-shower events. Each bin represents one chamber, i.e. two planes.
- (b) Distribution of the distance between vertex and beginning of the shower for the one-shower events.

Fig. 1

Fig. 2

Fig. 3