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SEARCH FOR NEUTRINO OSCILLATIONS

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The present paper reports on preliminary results from the E 816 experiment at Brookhaven National Laboratory. E 816 is the continuation of a 1984 experiment (PS 191) which was devoted to a neutrino decay search in the CERN PS neutrino beam. No candidate was seen (ref 1), but a study of neutrino interactions in the calorimeter indicated an anomalous electron production (ref 2). The statistics was too low and the experiment has been rerun in spring 86 at BNL to look specifically, with an improved detector for ν_e arising from a low energy ν_μ beam.

The results presented here are preliminary for at least two reasons : first the collaboration is presently running a calibration test which results are not included here; second, only 1/3 of the neutrino data is used, and no mention will be made to antineutrino data for which the analysis is still going on.

The physics of neutrino oscillations has been extensively justified and described in previous talks (see e.g. Marciano's and Vannucci's contributions). This report will directly start with a description of our apparatus, followed by the data analysis. Few question marks are raised at the end concerning possible interpretations of our results.

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APPARATUS

Beam

The AGS (Alternate Gradient Synchrotron) produces every 1.2 s about 10^{13} protons at 28.3 Gev/c. For the neutrino facility they are dumped on a 45 cm titanium target. The outgoing charged particles, mainly pions and kaons, are focused by a pulsed magnetic horn operating at 285 KAmps. The 90 m decay tunnel ends with a 30 m iron-concrete shielding which stops the muons and remaining hadrons. As mainly pions are produced at the target, the beam is 99% ν_μ. The muon flux and profile in the shielding are used to monitor the neutrino beam. We also used the signal from a scintillator counter placed in this shielding as a time reference for the experiment. The short extraction time (2.5 μs) and the fine time structure (30 ns buckets separated by 224 ns, fig 1-a) allow good cosmics and noise rejection.

As the horn does not make a momentum selection on the mesons, the intensity is high, but the neutrino energy is not well defined as always in a Wide Band Beam (fig 3). The mean energy of the beam is around 1.5 Gev according to the beam line simulation described below. Our apparatus is located 175 m away from the target and 130 m from the middle of the decay tunnel: L/E, the relevant oscillation parameter† is therefore of the order of 0.1. That sets the δm^2 region we can explore around 10 ev^2 as in PS 191.

Detector

We use a fine grained calorimeter, made of sandwiches of 3mm thick iron plates and flash-tube chambers. The tubes are 5 by 5 mm^2 in cross section and 6 m long ; they only give the vertical coordinate. The 13% of a conversion length between 2 sensitive planes allow a good γ/e separation, as we will see further. The front dimension of the detector is 3*6 m^2, while it is only 3.3 m long, and thus has a large angular acceptance.

Placed downstream of a liquid scintillator veto counter, 22 out of the 49 sensitive planes constitute the fiducial volume (10 tons, 2.5 X_0, less than 1 interaction length), followed by 2 plastic scintillator

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† The standard oscillation formula connecting E, L, δm^2 is derived in ref 3 and discussed in many papers of these proceedings.

hodoscopes for trigger purposes. To get a good shower containment the remaining 27 planes have been sandwiched with lead plates (added to the iron) to achieve 15 radiation lengths from the middle of the "target" (fig 1).

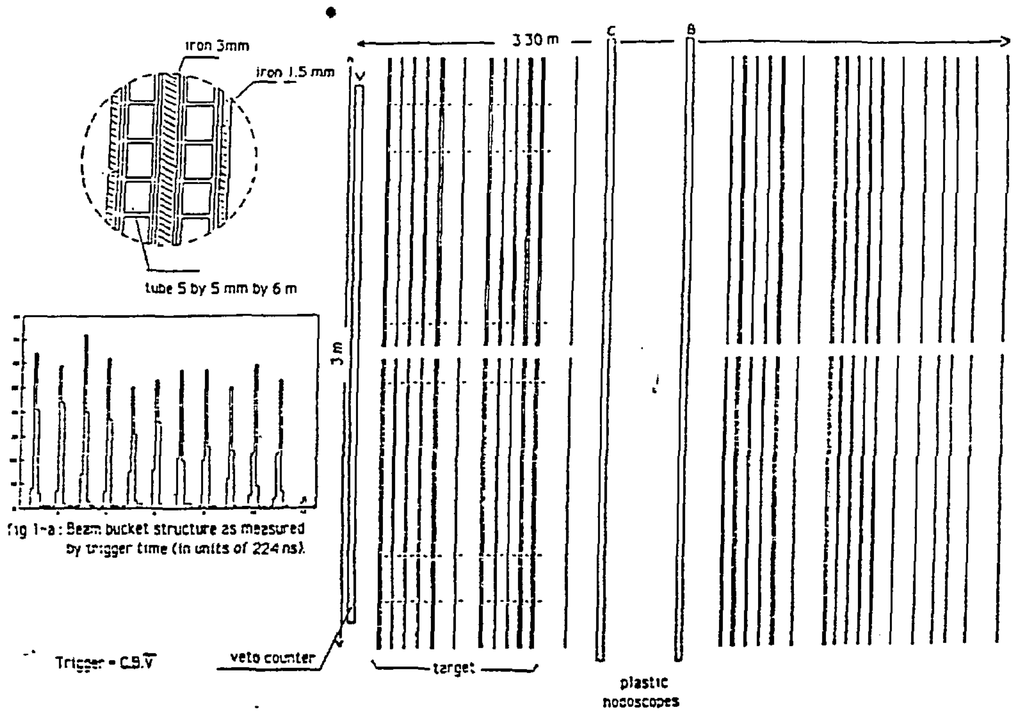

fig 1 : Detector side view.

The energy of a shower is estimated by simply counting the number of hit tubes. Altough the electron test is still in progress, we already have a preliminary calibration curve (fig 2) showing a rough linear relation between energy and number of hits.The actual energy resolution is presently being refined. We are also calibrating the detector with pion data, but since it has not been analysed so far, we only quote here PS 191 result (ref 2) : less than 1% of charged pions fake an electromagnetic shower.

We triggered within the beam gate on non-vetoed coincidences of the two hodoscopes, the veto being the liquid scintillator counter at the front of the detector. All scintillators threshold were set slightly below the minimum ionizing particle energy loss. As the two hodoscopes are divided

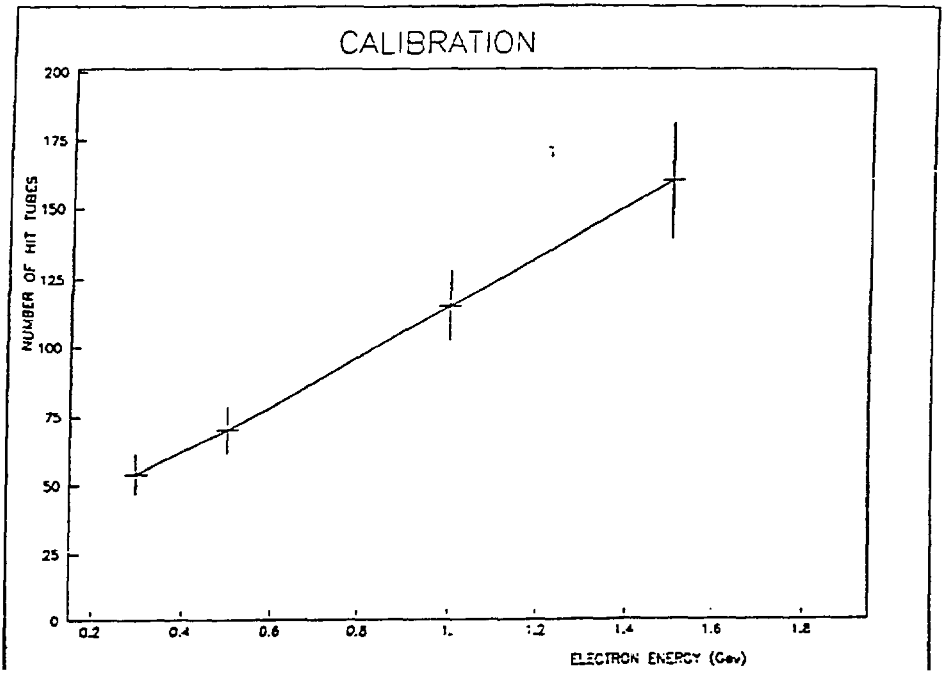

fig 2 : On this calibration curve, the error bars are plotted for the resolution and come from MC.

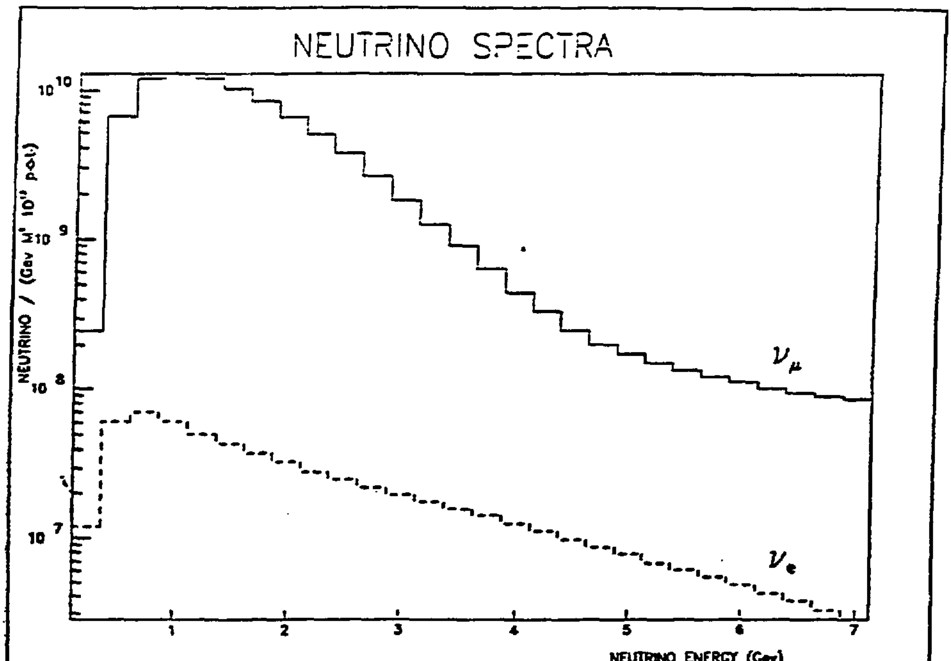

fig 3 – The ν_μ and ν_e spectra as computed by Nubeam for 10^{13} protons on target, in neutrino / Gev .m^2.

in 20 vertical slabs they give an indication on the horizontal position of the vertex. They especially allow to reject events due to particles coming from the side walls.

Besides the hit pattern, we record the time and height (measured by TDC's and ADC's) of the signals of one of the plastic hodoscopes, and the hit phototube pattern for the two other hodoscopes. Because of a flash chamber recovery time of 0.6 s we can only take one trigger per burst. We actually trigger once every 4 bursts when running neutrinos, loosing 1/8 of the beam. Adding the vetoed buckets the dead time amounts to 14%. Half of the triggers are due to neutrons and entering by side particles from neutrino interactions in the concrete walls and ceiling.

DATA ANALYSIS

Data sample

We have collected 1.1 10^{19} protons on the target (p.o.t.) and 500,000 triggers in neutrino beam, and 1.3 10^{19} p.o.t. and 120,000 triggers in antineutrino (i.e. with reversed horn polarity). After processing the tapes through a filter program, we are left with half of the triggers. This program was designed to remove the events with zero or one track, and worked with a negligible bias towards the selected ν interaction sample as defined below. The remaining events are then visually scanned by physicists, and part of them twice. The results presented here are based on 1/3 of the ν data (3.64 10^{18} p.o.t.).

Strategy

As an oscillation experiment of the appearance type we want to measure the ν_e/ν_μ ratio, and point out a possible enhancement with respect to its predicted value : if ν_μ oscillate into ν_e, even weakly, we would "see" more ν_e than expected. Assuming the same spectrum for both ν flavours we get $\nu_e/\nu_\mu = \#(\nu_e\ N \to e^-\ X)\ /\ \#(\nu_\mu\ N \to \mu^-\ X)$. In our detector the simplest X shows up as a single charged track. We thus look for 2 track events and events with one track and one electromagnetic shower (1T1S). We will then compare the ratio of these 2 classes to its expected value, according to real spectra, cross-sections and acceptances. This method relies on correct evaluations of both initial ν_e contamination and of all background contributions.

Thus, we can roughly estimate the π^0 background level as:

$$\underset{\text{cross section ratio}}{0.2} \ * \ \underset{\text{energy cut efficiency}}{0.2} \ * \ \underset{\text{connection probability for 2 showers}}{2*0.13} \ \sim 1\%$$

of quasi-elastic ν_μ interactions ; this is of the same order of what we expect from ν_e contamination.

Scanning rules

Since we look for CC reactions, we demand a lepton candidate, i.e.: either a non interacting track crossing more than 10 sensitive planes (3.3 cm of iron) as a muon candidate, or a shower firing more than 50 tubes and connected to the vertex as an electron candidate. Fig 4 displays an electron shower from the test beam run: the signature is quite striking and such a cluster of ~115 hits (for a 1 Gev electron) seems hard to miss or to misidentify.

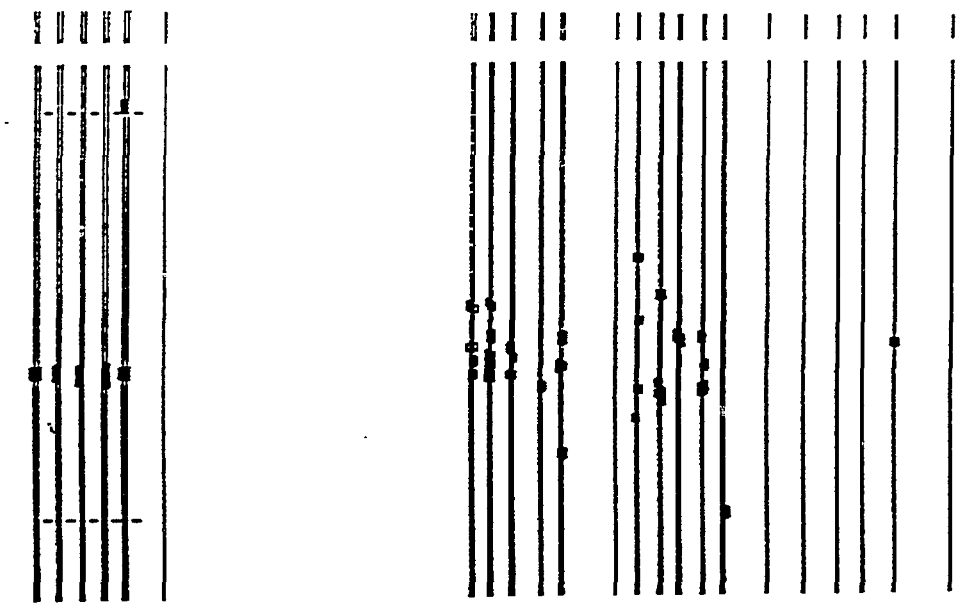

fig 4 - 1 Gev electron from test beam.

Neutrino spectra

The ν_μ and ν_e spectra are computed by a standard simulation program Nubeam (ref 5), using measured π and K production cross-sections, together with the horn and tunnel geometry. Secondary μ decays are also simulated. The main outputs are the neutrino energy spectra and integrated fluxes at a given distance for a given amount of protons (fig 3). We can check the integrated flux (assuming the spectrum shape) but we are not able with this apparatus to measure its energy dependence; this last measure was done by the E734 experiment (ref 4), which obtained a good agreement with Nubeam. These spectra, corrected for the slightly higher distance are used in our Monte Carlo†. According to them, the ν_e/ν_μ ratio is small :the ratio of integrated fluxes is below 1 %, a standard though somehow uncertain value.

Background

The big background we have to deal with is the ν_μ induced π^0 production : $\nu_\mu N \rightarrow X \pi^0$, $\pi^0 \rightarrow 2\gamma$, since the γ showers can fake an e^-. The cross section is approximately 20 % of the quasielastic one. But as the π^0 is mainly produced with a small energy (the mean value is 500 Mev) an energy cut is likely to get rid of many of them, whilst keeping most of the ν_e induced events. We actually do not consider showers of less than 50 tubes (i.e. 400 Mev according to the test beam), then cutting 80% of the π^0's and less than 10% of the ν_e events, according to our simulation.

Our search would however be hopeless if the remaining π^0 events did fake ν_e interactions. But most photons start showering some distance away from the vertex (i.e. at least one sensitive plane) and can therefore be rejected. Our background reduces to 1 track+1 π^0, the π^0 being seen as a single shower beginning right at the vertex, that is in the first 13% of a conversion length.

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† Our Monte Carlo uses a generator we got from BEBC collaboration. It simulates elastic, quasielastic, delta production, 2 and 3 pions, in charged and neutral currents. The reinteractions of hadrons on the way out of the nucleus are also included, as well as the Fermi motion. The detector simulation and shower generation are performed by the Geant package (ref 6). The events are then visually scanned with the same program as the data: this explains that we deal with about the same statistics in data and MC.

fig 5 a -
2 track event .

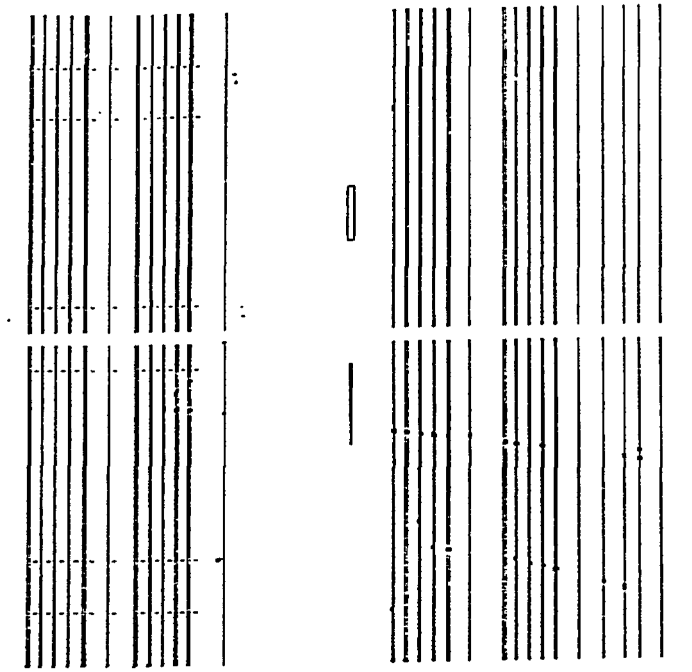


fig 5 b -
1 track +
1 connected shower .

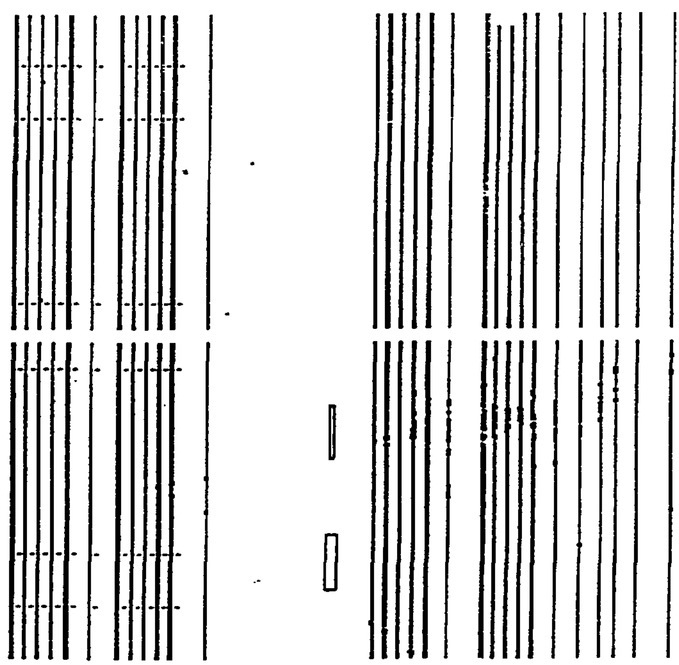


fig 5 c -
1 track +
1 disconnected
shower .

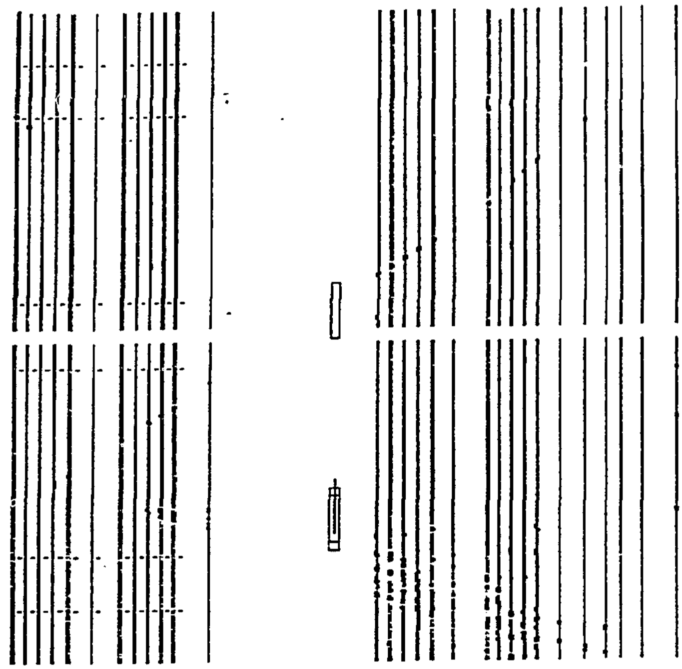
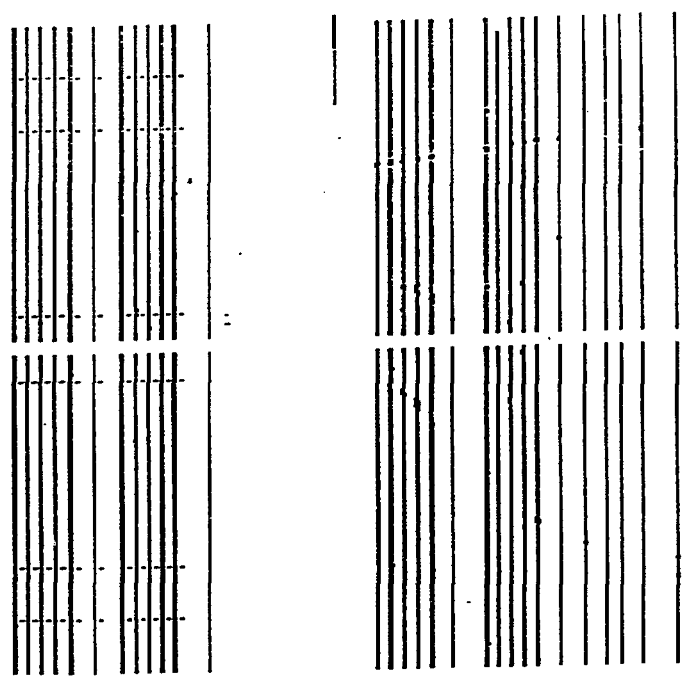


fig 5 d -
1 track +
2 showers .



We also require a track accompanying the lepton candidate, which is a hadron candidate. It has to cross at least 4 sensitive planes: this ensures a long enough lever arm and provides a minimum number of points both for scanning and fitting in pattern recognition. It also eliminates most of nuclear fragments from the intranuclear cascade. One such track has to emerge from the vertex on top of the lepton candidate, and is required to be at least 5 degrees away from it. This last cut is expected to have the same efficiency on ν_e and ν_μ, as charged current cross sections only differ by the outgoing lepton mass (which is negligible at our energy). If we remark now that the lepton requirements are not very stringent, we can expect a similar global acceptance for our two basic topologies : 2 tracks from ν_μ and 1 track + one shower from ν_e.

Events with one or two showers are kept even if those do not connect to the vertex (i.e. are not electron candidates) but arise from it: they provide a tool to monitor and substract the π^0 background.

At the end, the interaction is required to occur in the fiducial part and to trigger the apparatus. Events satisfying the cuts are shown on fig 5.

Results

The following table shows the observed and expected number of events for four different topologies, with the cuts applied.

		neutrino data	Monte Carlo scan (only ν_μ interactions)
2 tracks		3334	3226
3 tracks		707	693
1 tr + 1 sh	connected	93 ± 9	31 ± 6
1 tr + 1 sh	disconnected	64 ± 8	64 ± 9
1,2 tr + 2 showers		54 ± 7	55 ± 8

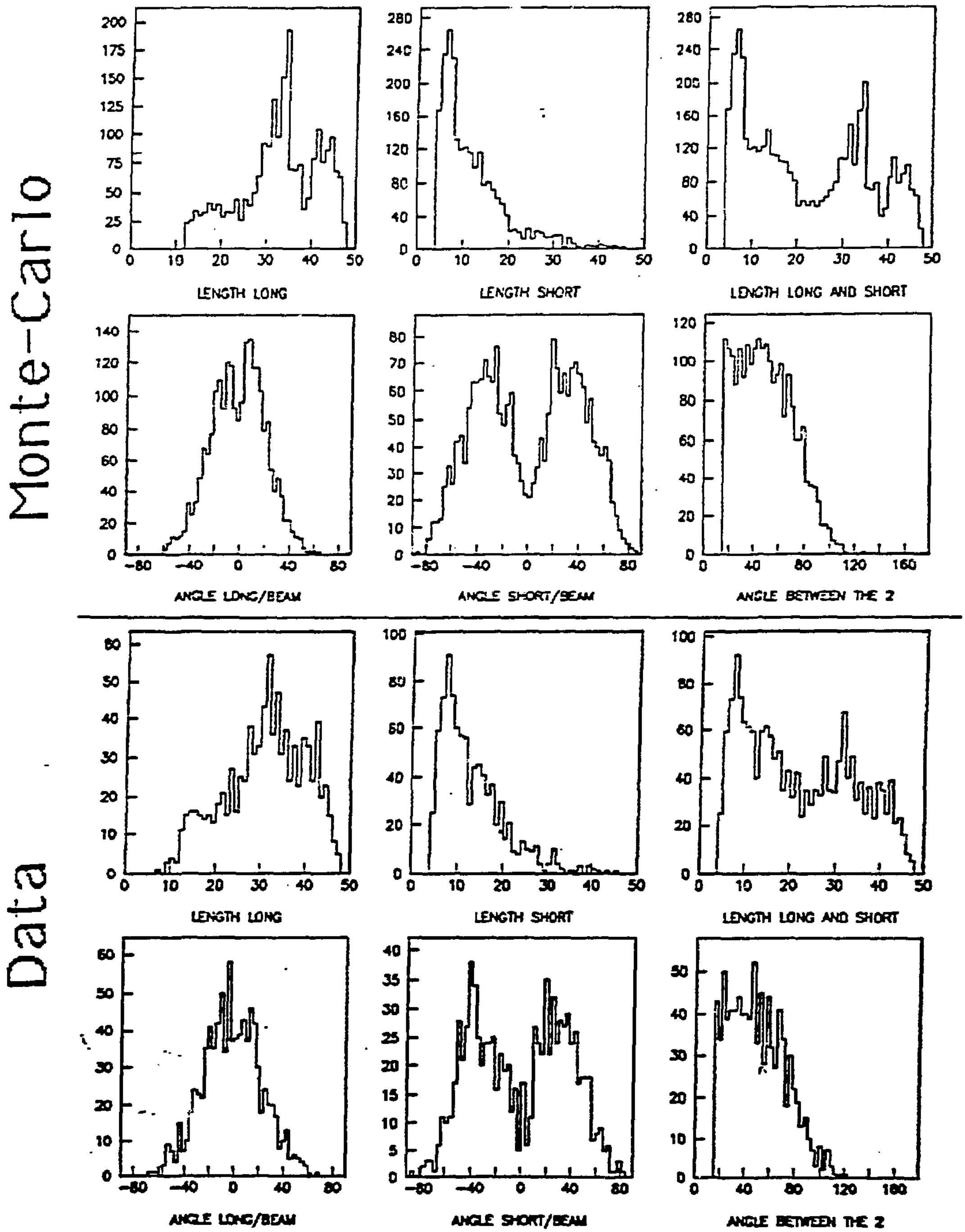


fig 6 - angle and track length distributions for 2 track events (data and MC)

The 2 and 3 track event sample is used for normalization and Monte Carlo checks. Absolute and relative number of events, angle and track length distributions agree with MC predictions (fig 6), the discrepancy being far below cross-section uncertainties. We should emphasise that MC and data are scanned in exactly the same way to take into account possible scanning systematics.

After a 3 pass scan the shower event sample has been separated into two classes : events with 2 showers and 1 or 2 tracks, and events with 1 track and 1 shower. To disentangle gamma and electron showers we are using our fine granularity by considering the vertex-to-shower distance distributions.

We study first the distributions obtained from the ν_μ Monte Carlo scan (fig 7). We observe on the 2-shower histograms that we get (with a poor statistics) the expected exponential decrease. The slopes of the 2 shower plots lie not so far from -1. and -2. as expected, while it turns to be -1.5 for the one track + 1 shower, in between the two other slopes. But the main feature is that no excess appears in the first bin: though our Monte Carlo simulates nuclear interactions and produces a substantial amount of short protons, our scanning does not suffer a bias from faked connections by short tracks.

If we now look at the same plots for the data (fig 7), we see that the fitted slopes are similar within the statistics, but the first bin of the 1T1S plot is 3 times higher than in the MC. That is not a real surprise as the ν_e induced events (not included in the MC) are expected there, on top of the π° contribution. This contribution can be evaluated by simply extrapolating the distribution without its first bin, as confirmed by the MC histogram. We get 31 ± 4 π° induced 1 track + 1 connected shower events, the uncertainty being derived from the fitting procedure. We will call the 93-31 = 62 remaining events 1 track +1 electron events. The next step is to evaluate the number of such events expected from ν_e contamination.

As we expect from our cuts and trigger conditions a similar acceptance for ν_μ and ν_e interactions, we induce

$$\frac{\#\ \text{1T1S from } \nu_e}{\#\ \text{2Tr}} = \frac{\int dE\ \phi_{\nu_e}(\sigma(ep) + \sigma(ep\pi))}{\int dE\ \phi_{\nu_\mu}(\sigma(\mu p) + \sigma(\mu p\pi))} = 0.8\ \%$$

DISCONNECTION

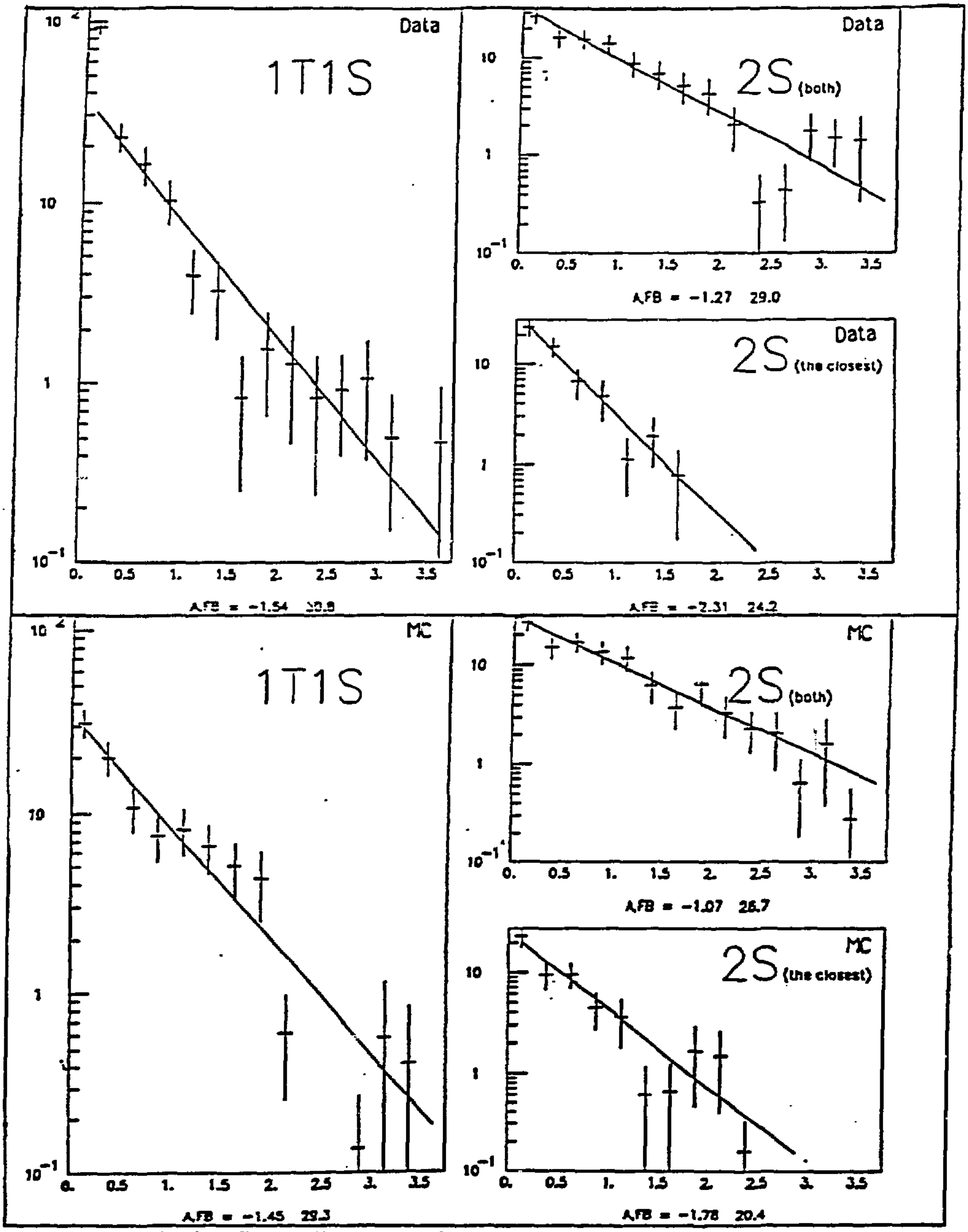


fig 7 – The disconnection is defined as the number of sensitive planes crossed when going from the vertex to the beginning of the shower. The disconnection is 7 for the event of fig 5-c. On these histograms, the disconnection is converted in radiation length. The numbers written below each histogram are the fitted slope and the extrapolated content of the first bin.

because 2 track events are mainly quasielastic and inelastic. This is simple and reliable. We however scanned ν_e MC events and found for this sample 24 ± 3 1T 1 connected shower events : this sets the above ratio to $0.7 \pm 0.1\%$. We attribute the difference between the 2 expectations to the shower energy cut and the presence of some neutral current events in the MC and experimental 2 track event sample. We will use the first conservative estimate and point out that the most uncertain factor is not the relative acceptances neither cross section shape but the fluxes ratio. Putting a 25% uncertainty on the estimate we expect

$3334 * 8 * 10^{-3} = 27 \pm 6.7$ 1T 1 connected shower from ν_e contamination.

To summarize,

$93 \pm 9.6 - 27 \pm 6.7 - 31 \pm 4 = 35 \pm 12.4$ events are in excess.

We should point out that we depend on a Monte Carlo (i.e. Nubeam) quantitative prediction only for the ν_e contamination calculation. Although the π^0 production rate inside our cuts is consistent with our absolute prediction, both for 1 track + 1 disconnected shower and 2 shower classes, we did not use these quantitative predictions in our π^0 background substraction.

If we extrapolate from now to the whole experiment we should have 100 "unexpected" 1 track + 1 electron events to explain. Oscillations are obviously a tempting interpretation but we will however be unable to strictly prove that we saw oscillations. Furthermore, most of our sensitivity region in the $\sin^2(2\theta)$ versus δm^2 plot is excluded by negative results from other experiments, see e.g. E 734 and BEBC in these proceedings. Apart from oscillations at least two features could explain the excess: first a wrong computation of ν_e contamination (by a factor of 2), second an unknown Z dependent effect: our target material is iron, one of the heaviest used for this kind of experiment.

References

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