FIRST RESULTS FROM THE CERN-HAMBURG-AMSTERDAM-ROME-MOSCOW NEUTRINO EXPERIMENT

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\section*{ABSTRACT}

Preliminary results of the neutrino counter experiment carried out by the CHARM collaboration are presented. They cover the following topics:

Study of the strength and the structure of the neutral current in inclusive reactions on an isoscalar target.

Neutrino scattering on electrons.

Measurement of the polarization of positive muons produced in high-energy antineutrino interactions\textsuperscript{**)}. 

We present preliminary results of three neutrino experiments which make use of the novel features of the new neutrino detector of the CHARM (CERN-Hamburg-Amsterdam-Rome-Moscow) Collaboration. The experiments were performed in the neutrino beams of the 400 GeV Super Proton Synchrotron (SPS) accelerator at CERN.

\section*{I. THE APPARATUS}

The CHARM neutrino detector\textsuperscript{1)} (see Fig. 1) consists of a fine-grained marble calorimeter which allows the measurement of the energy and the direction of the hadron or electromagnetic showers, and of a magnetized iron spectrometer which allows the measurement of the momentum of muons. The target calorimeter contains 78 submodules. Each of these submodules consists of:

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\end{itemize}
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i) a marble plate, 8 cm thick and of $300 \times 300 \, \text{cm}^2$ cross-sectional area, surrounded by a magnetized iron frame;

ii) a plane of 128 proportional drift tubes, each having dimensions of $3 \times 3 \, \text{cm}^2$ in cross-section and 400 cm in length;

iii) a plane of 20 plastic scintillators, each 3 cm thick and $15 \times 300 \, \text{cm}^2$ in cross-sectional area, oriented at $90^\circ$ with respect to the proportional drift tubes.

The total weight of the target calorimeter is 175 tons. The marble calorimeter is followed by the muon spectrometer, made of four toroidal magnetized iron modules.

2. INCLUSIVE NEUTRAL CURRENTS

Inclusive neutral-current (NC) reactions were studied in the 200 GeV narrow-band neutrino beam$^1$. The data sample obtained in the autumn of 1978 yielded 9200 neutrino and 2700 antineutrino events in a fiducial volume with a mass of 61 tons.

The special features of this experiment are:

i) the low hadron energy cut: $0.5 \, \text{GeV}$ trigger threshold and $2 \, \text{GeV}$ off-line cut, and good energy resolution: $\Delta E_h/E_h = \left[1 + 43/(E/\text{GeV})^2\right] %$;

ii) low muon momentum cut of $\sim 1.5 \, \text{GeV}/c$;

iii) automatic pattern recognition of muons;

iv) measurement of the hadron shower direction.

The dichromatic narrow-band beam provides a relation between the radial position of the event vertex and the energy of a neutrino from pion or kaon decay. The Lorentz structure of the neutral currents can be studied using the inelasticity ($\gamma = E_{\text{H}}^\text{M}/E_{\nu}$) distributions.

To resolve the pion-kaon neutrino energy ambiguity, a statistical method has been developed which makes essential use of neutrino flux information. After a few iterations, this method is independent of the initial assumptions on $\gamma$ distributions. It has been tested by comparing the $\gamma$ distribution of charged current (CC) events, which was determined using the measured muon momentum, with the statistical one obtained using hadron energy only. The detailed description of the method employed can be found in Ref. 2.

Preliminary $\gamma$ distributions obtained for neutrino and antineutrino data are shown in Figs. 2 and 3. In this analysis the CC events were treated in the same way as NC events. No corrections are applied to these distributions. The data show the dominance of $(V-A)$ coupling. The dots represent the Monte Carlo predictions with the weak mixing angle $\sin^2 \theta_w = 0.25$. The Monte Carlo predictions are in satisfactory agreement with the data. Another way to test the structure of the neutral currents is to determine the ratio of NC to CC cross-sections. These ratios are shown as a function of $\gamma$ in Fig. 4. The Monte Carlo predictions of the quark-parton model with $\sin^2 \theta_w = 0.25$ follow the data reasonably well. The ratios integrated over all $\gamma$ are:

$$R = 0.30 \pm 0.006 \pm 0.02$$
$$\bar{R} = 0.39 \pm 0.014 \pm 0.02$$

where the first error is statistical and the second is an estimate of systematic uncertainties. Figure 5 shows a comparison of this result with other experiments$^{1-7}$, and the
prediction of the quark-parton model\(^8\) and its modification by QCD effects\(^9\). Our data are in good agreement both with other experiments and with theoretical predictions.

The knowledge of the neutrino energy-radius correlation and the measurement of the hadron shower direction allow us to determine the scaling variable \(x = Q^2/(2Mv)\) and to study the structure functions of the nucleon with the neutral current. Preliminary results on the ratio of NC to CC cross-sections as a function of \(x\) are obtained in a way similar to that used for the \(y\) distributions, but with a cut of \(E_h > 20\) GeV (Fig. 6). They indicate the similarity of structure functions obtained with neutral and charged currents, as expected in the quark-parton model.

3. NEUTRINO SCATTERING ON ELECTRONS

Measurements of neutrino electron scattering, \(\nu_\mu + e^- \rightarrow \nu_\mu + e^-\), give information on the coupling constants of the weak leptonic neutral current. The extremely low cross-section \((\sim 10^{-4}\) of the neutrino nucleon cross-section\(^{10}\)) requires a detector comprising special features, which combines some of the advantages of bubble chambers in the event selection and of a massive calorimeter to obtain good event rates.

There are two main experimental problems that have to be solved in this experiment. The first one is the separation of hadronic showers from electromagnetic ones, which is achieved in the fine-grained CHARM calorimeter owing to the difference in their transversal profile.

Figure 7 shows the distribution of the width of electron and pion showers obtained in calibration runs. It can be seen that electron (solid lines) and pion (dotted lines) showers can be well separated using both scintillator counters and proportional tubes.

The narrow angular distribution of electrons recoiling in the reaction \(\nu_\mu e + \nu_\mu e\) \((\theta_e \sim (2m_e/E)^{\frac{1}{2}})\) allows this reaction to be separated from various backgrounds which have a wider angular distribution. Thus, the second experimental problem is to achieve good angular resolution for electron showers. Results of calibration measurements, performed in an electron beam at 6, 15, and 20 GeV, are well approximated by the expression

\[
\Delta \theta_{\text{proj}} = \frac{1}{(\ln \frac{E}{c} + 0.4)} \left[ 3 \times 10^{-1} + 4 \times 10^{-2} \frac{E}{E} \right] \text{ mrad ,}
\]

where the electron energy \(E\) is measured in GeV and \(c = 0.05\) GeV. This corresponds to an angular resolution of \(\Delta \theta = 11\) mrad at 20 GeV. As can be seen from this equation, the angular resolution is a function of the electron energy. If the measured angle is expressed in units of the angular resolution, the distribution of events as a function of \((\theta/\Delta \theta)^2\) becomes energy independent.

The experiment was performed during the summer of 1978 in the 350 GeV neutrino wideband beam with a partly equipped apparatus\(^{11}\). A data sample of 73,000 neutrino interactions with shower energy in the range \(5 \leq E_{sh} \leq 50\) GeV was collected in a fiducial target of 22 tons. Several cuts were applied to the data, rejecting events with single tracks longer than 180 g/cm\(^2\), large shower angles \((\theta^2/\Delta \theta^2 > 10)\), proportional tube multiplicity at the vertex > 2, or with energy deposition in the first scintillator plane after the vertex > 8 minimum-ionizing particles. Events with a transverse width of the shower in scintillators
and proportional tubes, as expected for electrons, were retained. Twenty-one events satisfied these criteria. Contributions from the following background processes must be subtracted from the data:

a) hadronic CC events with very low energy muons and a large electromagnetic component;
b) semileptonic neutral currents with a large electromagnetic component e.g. 
\[
\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + N;
\]
c) quasi-elastic CC events induced by the \( \nu^e \) component of the neutrino beam.

Backgrounds (a), (b), and (c) are expected to have wider angular distributions than \( \nu_\mu \) scattering. Figure 8a shows the distribution of 21 candidates as a function of \( \theta^2/\Delta \theta^2 \).

The dashed line shows the flat angular distribution of backgrounds (a) and (b) normalized to the observed number of events for \( \theta^2/\Delta \theta^2 > 3.0 \). The shaded area represents the angular distribution of events due to the background (c), which was obtained by multiplying the observed number of events of the reaction \( \nu_\mu + N \rightarrow \mu^- + (\text{invisible hadrons}) \) by the computed ratio\(^{12}\) of electron and muon neutrino fluxes \( (\nu_e + \nu^e)/\nu_\mu = 1.9\% \). We observe a peak containing 11 events with \( \theta^2/\Delta \theta^2 < 2.25 \) with a background of \( 4.5 \pm 1.4 \) events. The energy distribution of the 11 candidates is shown in Fig. 8b, together with the expected spectrum for \( \sin^2 \theta_W = 0.23 \). The overall efficiency for selecting \( \nu_\mu \) events by the criteria given above is \( e = (58 \pm 17)\% \). Normalizing the excess of 6.5 ± 2.6 events to the total number of NC and CC neutrino events using a cross-section of \( \sigma/E \nu = 0.85 \times 10^{-48} \text{ (cm}^2/\text{GeV)} \) and assuming a linear energy dependence of the \( \nu_\mu \) cross-section with energy, we find

\[
\frac{\sigma(\nu_\mu e)}{E} = \left( 2.5 \pm 1.4 \text{ statistical error} \right) \times 10^{-42} \text{ (cm}^2/\text{GeV)}.
\]

This result is consistent with earlier experiments\(^{16}\) and with the Weinberg-Salam model.

3. POLARIZATION OF POSITIVE MUONS PRODUCED IN ANтинEUTRINO INTERACTIONS

This experiment was performed using the massive CDHS (CERN-Dortmund-Heidelberg-Saclay) neutrino detector\(^{13}\) as a target for \( \bar{\nu}_\mu \) interactions and the fine-grained CHARM detector as a muon polarimeter. Positive muons produced in \( \bar{\nu}_\mu \) interactions are focused in the toroidal field of the CDHS detector, and \( \sim 5\% \) of them stop in the CHARM polarimeter (see Fig. 9).

The longitudinal polarization of positive muons can be determined by the forward-backward asymmetry of positrons emitted in \( \mu \) decay at rest. A magnetic field of 0.0058 T perpendicular to the beam direction is produced inside the polarimeter, causing the spin of the stopped \( \mu \) to precess with a period of 1.3 \( \mu \)s. Conventional V and A currents preserve the lepton helicity, whereas possible S, P, T interactions flip the helicity and produce muons with negative helicity. The helicity of muons emitted in pion and kaon decays has been measured\(^{14,15}\), but no corresponding measurements exist at higher centre-of-mass energies, confirming directly the V and A nature of the current.

The data sample was obtained in spring 1978 in an antineutrino wide-band beam exposure\(^{16}\). It consists of 13,000 muons produced in the target and stopping in the polarimeter; 3400 decay positrons were detected. The observed time dependence of the backward-forward asymmetry,
is shown in Fig. 10. The method of spin precession is insensitive to systematic forward-backward asymmetries of the apparatus. The data are well fitted by the oscillating curve, and the values of the polarimeter analysing power and positron detection efficiency are in good agreement with Monte Carlo predictions. The results are

i) the measured phase of the oscillations $\phi = -3.1 \pm 0.2$ (rad) is in perfect agreement with $-\pi$ predicted for muons of positive helicity;

ii) the absolute value of the polarization is $P = 1.09 \pm 0.22$. Within the experimental errors the helicity is +1, consistent with a pure $V$, $A$ structure of the interaction. One can put an upper limit $c_{S,P,T}^2 = 18\%$ at the 95\% confidence level on the $S$, $P$, $T$ helicity-flipping contribution to the charged-current interaction at an average four-momentum transfer of $\langle Q^2 \rangle = 3.2$ GeV$^2$.

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Fig. 1 Perspective view of part of the CHARM detector.

Fig. 2 Preliminary $y$ distribution for NC events induced by neutrinos. Dots represent the Monte Carlo predictions with $\sin^2 \theta_W = 0.25$.

Fig. 3 Preliminary $y$ distribution for NC events induced by antineutrinos.
Fig. 4 Preliminary results on the ratio of neutral to charged current cross-sections as a function of $y = v/E_{\nu}$.

Fig. 5 The comparison of the integrated ratios $R$ and $\bar{R}$ with other experiments. The lower curve is a quark-parton model prediction $^9$, the upper curve includes QCD corrections $^9$. 
Fig. 6 Preliminary results on the $x$ dependence of the NC/CC ratio for neutrinos and antineutrinos.

Fig. 7 a) Distributions for incident electrons and hadrons of 6, 15, and 50 GeV of the difference $\Delta W$ between the observed width of showers and that expected for a hadron shower, as measured by the scintillators. The arrow indicates the cut at $\Delta W = -6$ cm.

b) Distributions of the normalized r.m.s. width of the energy deposited in the proportional tubes by electrons and pions at 15 and 20 GeV. The arrow indicates the cut at $\sigma = 9$ cm.
Fig. 8  a) Distribution of $\nu_e e^- \rightarrow \nu_e e^-$ candidates as a function of $\theta^2/\Delta \theta^2$. The dashed line represents the background due to semileptonic NC events initiated by $\nu_\mu$'s. The shaded area is the computed contribution of elastic and quasi-elastic events induced by the $\nu_e$ contamination of the beam.

b) Energy distribution of the events with $\theta^2/\Delta \theta^2 \leq 2.25$. The line is the expected distribution for $\sin^2 2\theta_W = 0.23$.

Fig. 9  Layout of the $\mu^+$ polarization experiment
Fig. 10 Observed time dependence of relative backward-forward positron asymmetry. The sinusoidal function is the best fit to the experimental points for a phase $\phi = -3.1 \pm 0.2$ and a polarization $P = +(1.09 \pm 0.22)$, in agreement with helicity +1.