Atmospheric and Accelerator Neutrino Physics with RPC's in the Soudan 2 Cavern.

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1 Introduction

Resistive plate chambers have certain properties which could make them useful as detectors for atmospheric and accelerator neutrino physics. In this paper we outline how RPC's might be used in the Soudan 2 cavern to upgrade the present 980 ton Soudan 2 detector [1] and how they might be used to provide the detecting medium for an 8 kton detector, in the same cavern, for neutrinos produced from the Main Injector under construction at Fermilab, 750 km away. The Soudan 2 cavern is located 2090 mwe (713 m) beneath Soudan, Minnesota, USA.

2 Physics - neutrino oscillations or proton decay ?

Atmospheric neutrinos are produced as a result of cosmic ray particles interacting with nuclei in the upper atmosphere, ~10 km from the earth's surface. These interactions produce pions which subsequently decay as follows :

$$\pi \longrightarrow \mu \overline{\nu_\mu} \tag{1}$$

$$\mu \longrightarrow e \overline{\nu_e} \nu_\mu \tag{2}$$

Thus two muon neutrinos are produced for every electron neutrino. The neutrino energy spectrum peaks at 300 - 400 MeV and tails of by ~1500 MeV.

About 100 - 150 atmospheric neutrino interactions are detected per kiloton year in the large underground water Cerenkov detectors and in the large ionisation detectors built initially to search for proton decay. The type of neutrino which interacts in the detector can be asertained by examining the Cerenkov ring profile in the water Cerenkov detectors or by looking at the event topology in the ionisation detectors. Fig. 1 shows a characteristic electron shower produced from a ν_e interaction in the Soudan 2 detector. In contrast a ν_μ interaction would have produced a muon track which is easily distinquished from an electron shower in the Soudan 2 detector for momenta above 300 MeV/c.

The 2:1 ratio for the number of ν_μ and ν_e produced by pion decay implies that twice as many contained muon tracks should be seen in the underground detectors as electron showers, after correcting for detector acceptance. In fact the observed ratio of contained μ and e events is about 0.6 of the value expected as measured by two water Cerenkov detectors [2] [3]. The results from two ionisation detectors [4] [5] and from Soudan 2 [6] are consistent with this finding, although these results have larger statistical errors (see Table 1) [7]. One possible explanation for the discrepancy is in terms of neutrino oscillations, $\nu_\mu \rightarrow \nu_\tau$. Thus the ν_μ interaction rate in the detectors will be diminished. This provides a possible explanation for the observed shortage of muons.

Fig 2 shows the momentum distribution for electrons and muons seen in the Kamiokande detector [2]. The heavy line shows the Monte Carlo expectation of Barr, Gaisser and Stanev (BGS) [8] for electrons and muons for the case of no oscillations. The muon data are clearly well below the Monte Carlo expectations. The narrow line shows the best fit using the BGS Monte Carlo with neutrino oscillations.

The probabilty of oscillation between two neutrinos of different mass is given by

$$P_{\nu_1 \rightarrow \nu_2} = sin^2(2\theta) sin^2(1.27 \cdot \Delta m^2 \frac{L}{E_\nu}) \qquad (3)$$

where θ is a mixing angle, Δm^2 (in eV^2) is the difference of the squared masses of the two neutrinos, L (in km) is the distance travelled from production and E_ν (in GeV) is the energy of the neutrino.

This probability can be tested by examing the rates for neutrino interactions in underground detectors where L is the same but E_ν is different. Such a test has been carried out by the IMB collaboration [9]. The group studied upward going muon tracks produced by ν_μ interactions in the rock surrounding their detector. Some of these muon tracks stopped in their detector, others passed through. The stopping muons come from ν_μ with an median energy of ~6 GeV whereas the through going muons come from ν_μ with a median energy of ~100 GeV. Each neutrino set is produced over the same region of the upper atmosphere and therefore has the same average distance, from production, to the rock surrounding the detector (in some cases the distance from production can be up to 13,000 km, i.e. for neutrinos traversing the diameter of the earth).

The IMB group found that the stopping fraction of upward going muons in their detector was 0.16±0.019. Various Monte Carlo models predicted this fraction to be between 0.154 and 0.163 for the case of no oscillations. Thus the IMB group find no evidence for oscillations with this analysis.

The conflicting evidence for neutrino oscillations has led part of the Soudan 2 group to question whether the contained event data comes entirely from atmospheric neutrino interactions or whether there is evidence for proton decay [10]. They argue that if they use the Monte Carlo flux generated by Bugaev and Naumov (BN) [11], instead of the BGS flux, then the flux for muon tracks seen in the Kamiokande detector, from ν_μ interactions, is described quite well. This is shown in fig. 3 in the top box, where the dashed line shows the Monte Carlo expectation (the dotted line indicates the detector efficiency) [12].

If the atmospheric neutrino flux rates are normalised to the contained muon data in Kamiokande, as the BN Monte Carlo suggests they should be, then the expected electron flux in their detector is given by the open triangles in the middle box of fig. 3. The filled circles indicate the data for the observed electron showers in Kamiokande. The observed electron flux is clearly in excess of the expected rate. The Tufts group [10] interpret this excess as evidence for proton decay. The bottom box in fig 3 shows the residual data after the expected electron spectrum has been subtracted from the observed electron spectrum. Shown on the plot is a dotted line for the expected shape of the spectrum for positrons from proton→ $e^+\nu\nu$. The lifetime over branching ratio thus implied for proton decay is $(\tau/B) = 3.7^{+1.7}_{-1.0} \cdot 10^{31}$ years.

3 Proposed Experiments

In order to investigate the neutrino oscillation question proposals have been made to Fermilab [13] to provide a neutrino beam from the Main Injector which is currently under construction. One of these proposals [14] requests that a neutrino beam be aimed at the Soudan 2 cavern 750 km away. Neutrino physics on a long baseline could then be carried out by the existing Soudan 2 detector. In order to extend the physics reach a new 8 kton detector could be built in the same cavern, adjacent to Soudan 2. This detector would provide higher statistics and thus greater physics coverage than Soudan 2 could provide alone. The average neutrino energy from this beam would be ~10 GeV. About 430 neutral current and charged current events would be expected per year per kiloton, for a detector in the Soudan 2 cavern, for 2.10^{20} 120 GeV protons on target at Fermilab per year.

In the near term a measurement could be made on upward going stopping and throughgoing muons in the Soudan 2 detector in order to check the IMB result discussed above. This would require detectors with fast timing to ascertain the muon direction for the through going muons. Unfortunately the long drift times in the Soudan 2 detector (of up to 80 μsec) preclude it from determining the muon direction for through going muons.

4 The possible roles for Resistive Plate Chambers

In order to construct an 8 kiloton detector in the Soudan 2 cavern the space occupied by chambers must be kept to a minimum. One proposal is for the detector to be made up of consecutive walls of 2 cm thick steel each followed by a plane of chambers occupying a space of about 1 cm as shown in fig. 4. This is the optimum granularity, obtained from Monte Carlo simulations, for studying neutrino oscillations with the Fermilab beam. Resistive plate chambers fit conveniently into this scheme. The basic structure of the chamber is only 6 mm thick. Monte Carlo simulations suggest a read-out strip width of 2 cm from these chambers would be sufficient in order to distinquish tracks from neutral current and charged current interactions. The strips might be ganged together to provide 8 m and 6 m long X and Y strips read out from each plane.

Each 2 cm thick steel wall would be 6 m high and 8 m across and would weigh 8 tons. Thus 1000 walls of steel and 1000 planes of chambers would be required to achieve an instrumented detector mass of 8 kilotons. Each plane of chambers would be made up from 24 2 m^2 resistive plate chambers. Thus 24,000 RPC's would be needed in total. About 400,000 X and Y strips would be read out. Although the good timing resolution of the RPC's has not been required it may be useful for the trigger. The trigger will be required to work locally over 3 or 4 successive walls anywhere within the 1000 wall detector. The timing resolution of the chambers could be used to reduce the accidental trigger rate.

Such a project, involving so many RPC's, would be a major undertaking. However, in the near term, RPC's could be used in order to measure the upward going muon rates discussed in the two previous sections. It has been proposed that two arrays, each consisting of 60 RPC's, be built initially [15]. These arrays would be placed above and below the existing Soudan 2 detector as shown in fig. 5. The direction of muons passing through the two arrays would be determined by time of flight, using the fast timing resolution of the RPC's. The arrays would be 6 m or more apart, vertically.

Downgoing muons would trigger the top array first. Upward going muons would trigger the bottom array first. By using only one of the arrays for a start time, then at least 40 nsec will exist between the recorded stop times for the two muon sets. The 2 nsec timing resolution of an RPC is easily adequate to correctly assign the through going muon direction with this arrangement. Stopping muons are seen directly by the Soudan 2 detector. The acceptance for upward going muons could be increased eventually by covering all sides of the Soudan 2 detector with RPC's, as is also illustrated in fig. 5.

5 Research needed on RPC's

The prime area of research needed for RPC's is that of finding a non flammable gas mixture with which to operate the chambers in the Soudan 2 cavern. The results presented at this RPC workshop, obtained from chambers operating with a pure freon gas, may be of considerable importance for employing RPC's in the Soudan 2 cavern.

We require that the singles counting rates from the RPC's be as low as possible in order to reduce background hits and accidental triggers. We would like to investigate the sources of background counting rates such as the dischage problems around the RPC spacers. Other sources of background counting rates are known and have been measured in the Soudan 2 cavern. One of these is due to gamma rays emitted from the rock in the Soudan 2 cavern. These gammas can create Compton electrons in the detectors which have enough energy to enter the chamber gas gap. In the Soudan 2 cavern these electrons contribute a counting rate of 80 Hz per m^2 of exposed detector area to the gas gap.

6 Conclusions

Resistive plate chambers have properties which make them attractive as possible detectors for atmospheric and accelerator neutrino physics. The need for a new generation of neutrino detectors is amply demonstrated by the controversy over whether neutrinos oscillate or whether protons decay or whether both or neither of these phenomena occur. We would like to thank Professor Santonico for providing an RPC for the Rutherford Appleton Laboratory in the UK, in order to enable research and developement to be carried out in preparation for possible future applications in the Soudan 2 cavern.

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Table 1: Contained event μ to e ratios

Experiment	Kton yr	$(\mu/e)_{\text{obs}}/(\mu/e)_{\text{calc}}$
Kamioka(2)	6.1	0.60 ± .07
IMB(3)	7.7	0.54 ± .07
Frejus(4)	1.56	0.87 ± 0.21
Nusex(5)	0.40	0.99 ± 0.40
Soudan 2(6)	0.50	0.55 ± 0.27

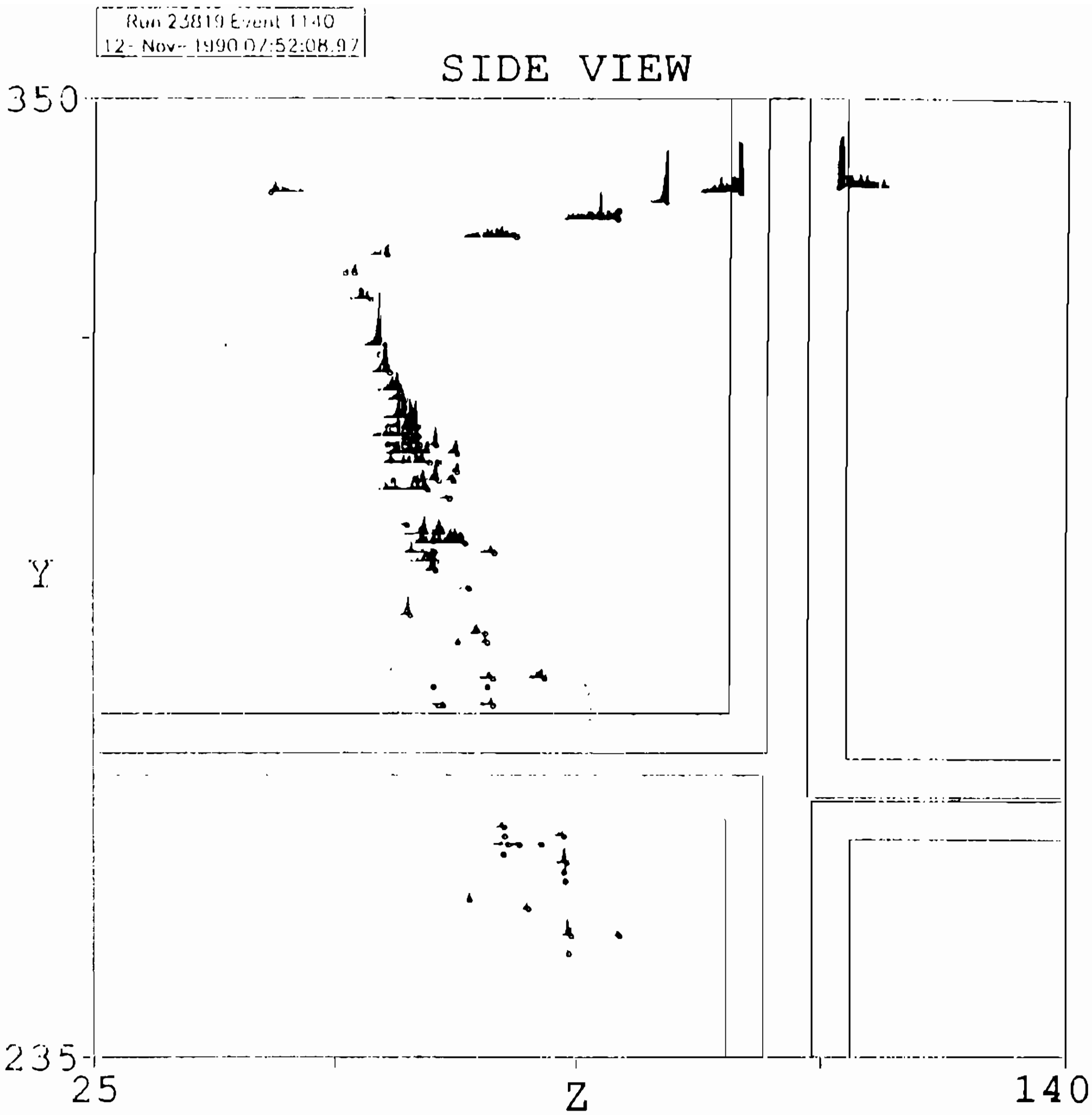

Fig. 1. A characteristic electron shower from a contained event in the Soudan 2 detector. The shower (coming from the top down) has an energy of 1635 MeV. A recoil track can also be seen going from top left to right.

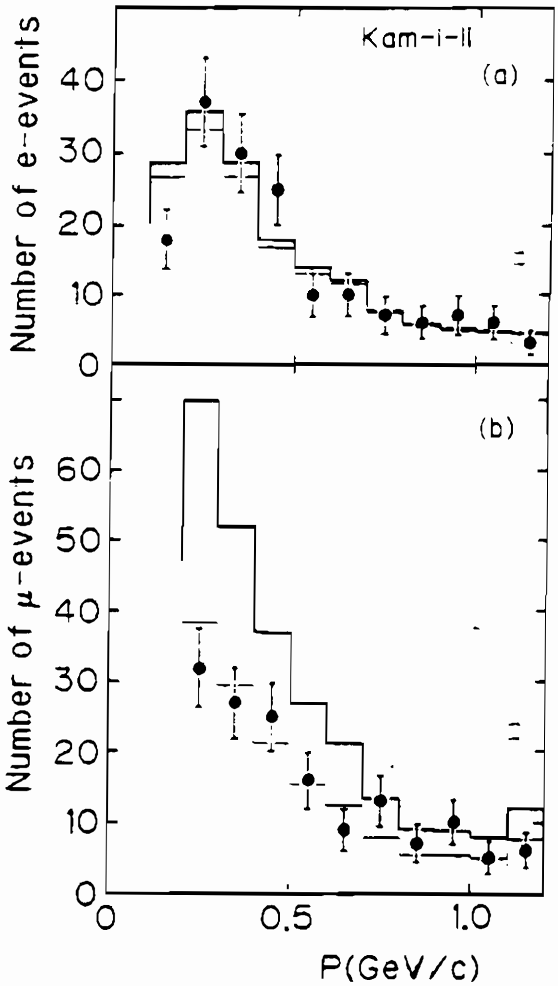

Fig. 2. The momentum spectra of e- and μ-events in the Kamiokande water Cerenkov detector together with the BGS Monte Carlo predictions.

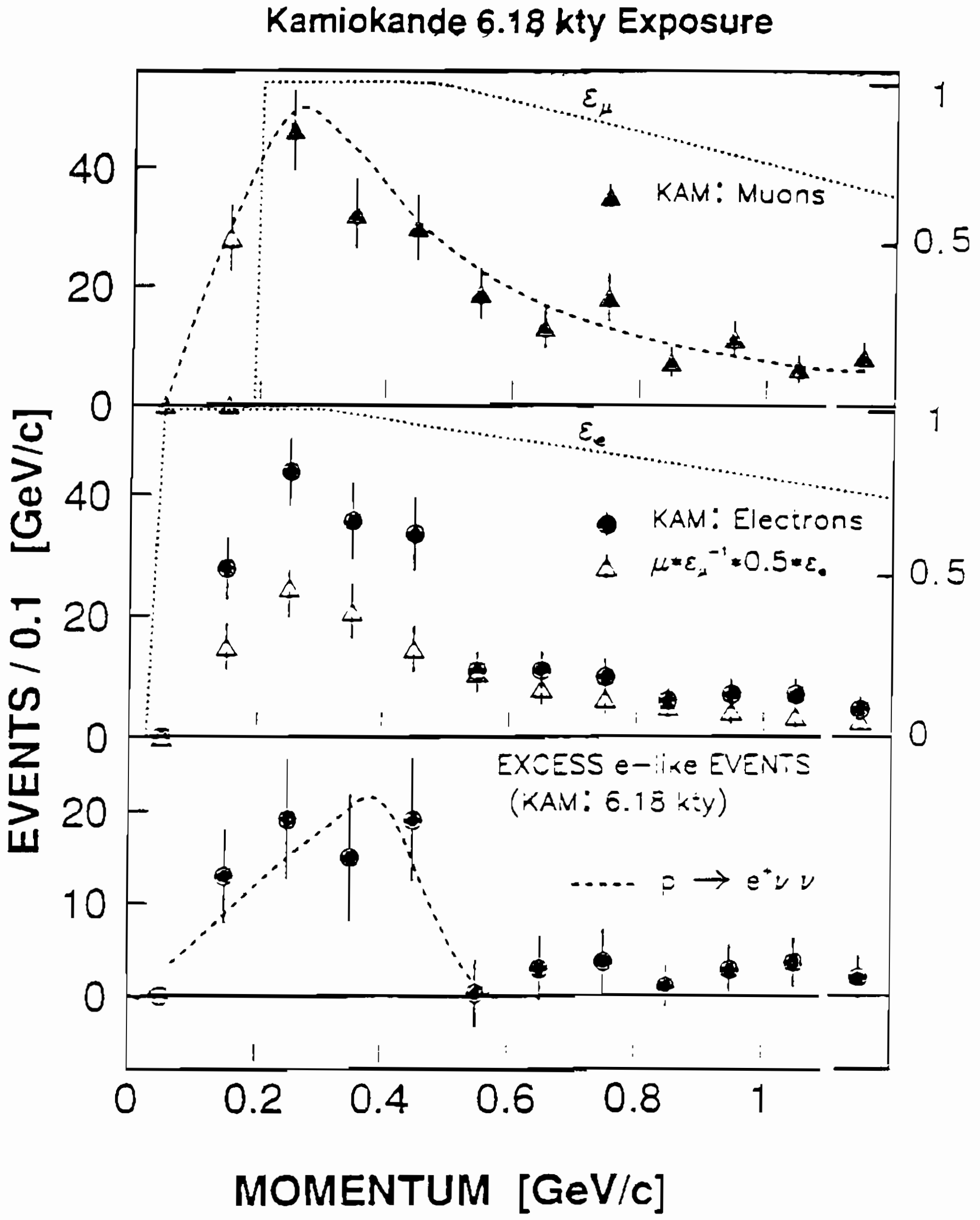

Fig. 3. Momentum distributions for muons and electrons in the Kamiokande detector together with the prediction of the BN Monte Carlo (top dashed curve) for the muon flux. The excess of electron events, which could be interpreted as coming from proton decay, is shown in the bottom box.

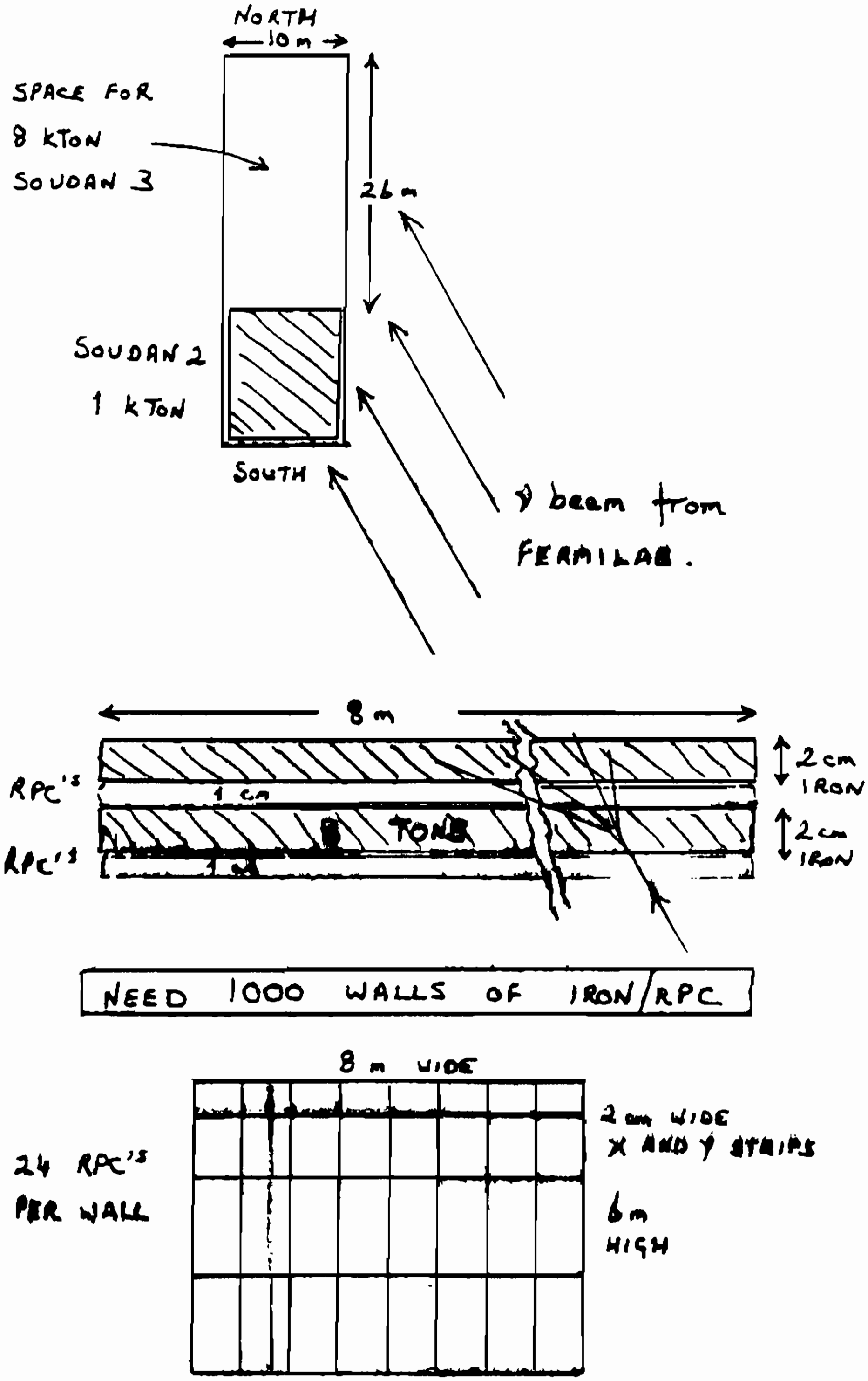

Fig. 4. The arrangement for an 8 kiloton neutrino detector in the Soudan 2 cavern using RPC's.

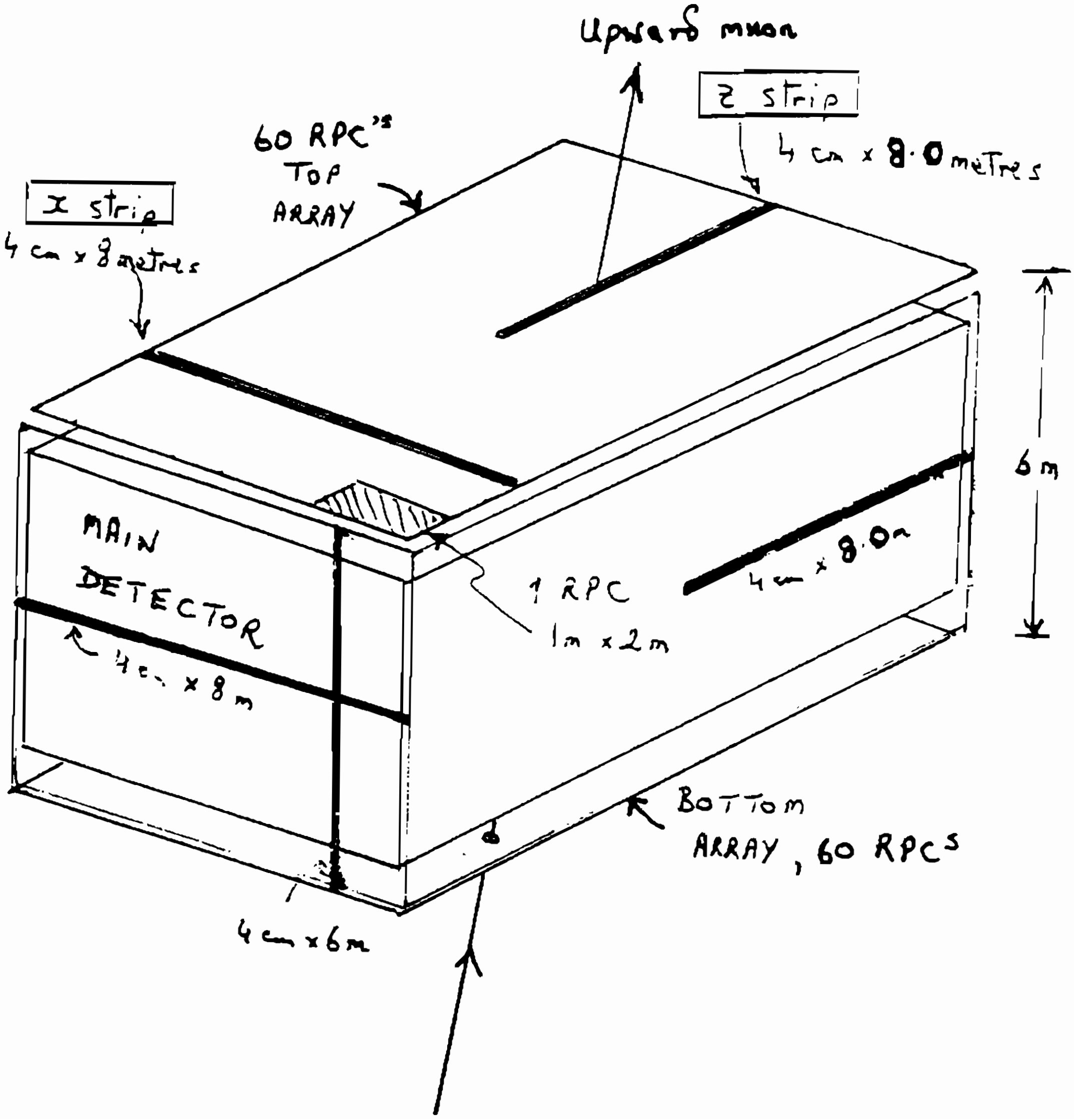

Fig. 5. The arrangment for two arrays of RPC's above and below the Soudan 2 detector in order to detect upward through going muons.