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# A new airborne detector for atmospheric muons

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**Abstract.** The University of Oxford has started the design and development of the new experiment ADLER (Airborne Detector for Low Energy Rays). This apparatus will measure the cosmic-ray muon flux at an altitude of 10 – 13 km. The detector should be flown by aircrafts on transatlantic routes crossing the magnetic equator to investigate the flux at different geomagnetic latitudes. The goal of the experiment is to obtain better constraints on the low energy atmospheric neutrino flux and the results will be of importance to the atmospheric neutrino anomaly.

## 1 Introduction

One of the most exciting results to emerge in particle physics in the last decade is the apparent deficit of atmospheric muon neutrinos reported by underground experiments (Fukuda et al., 1998; Ambrosio et al., 1998; Allison et al., 1998). The latest results from the Japanese Super-Kamiokande experiment provide strong evidence for a flavour oscillation of muon neutrinos into tau neutrinos, but the precision is limited by uncertainties in the predicted flux of atmospheric neutrinos with energies less than 1 GeV. The neutrinos are end product of a cascade of particles in the atmosphere: Incident cosmic rays (CR) produce light mesons in nuclear collisions with air molecules. Charged pions decay to muons and neutrinos; below 2.5 GeV the majority of muons will themselves decay to electrons or positrons and neutrinos. Charged kaons show a similar decay chain:

$$\begin{aligned} A_{\text{CR}} + A_{\text{Air}} &\rightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, \text{other hadrons} \\ \pi^{\pm}, K^{\pm} &\rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu} \\ \mu^{\pm} &\rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu} \end{aligned}$$

The uncertainties of present Monte Carlo calculations performed by the Bartol group (Barr et al., 1989; Agrawal et al., 1996) and by Honda, Kajita, Kasahara and Midorikawa (Honda et al., 1990) can be reduced by measuring the flux of low-energy muons. Those muons are strongly correlated to neutrinos but much easier to detect. While muon measurements at ground level are widely reported in the literature, there have been very few attempts to measure the muon flux as a function of altitude and latitude. An early experiment performed by Conversi (1950) gave the first information about muons at aircraft altitudes. The deployment of balloon-borne detectors since 1989 allowed more accurate measurements during their ascent in the atmosphere, but the main difficulty in such experiments remains the fixed location and the altitude of the detectors is continuously varying. A compilation of reported muon flux results on balloon measurements can be found in Ambriola et al., 2000.

This paper reports on the design of a compact and mobile apparatus to be flown by an aircraft. The method employed for distinguishing muons from other ionising particles is the observation of delayed coincidences in an active absorber together with anti-coincidences in surrounding veto-counters. The detector concept is similar to Conversi's, although scintillators are used in place of Geiger-Müller tubes.

## 2 Instrument description

The challenge is to construct a detector which is sufficiently rugged, light and low powered to be carried on an aircraft. Individual detector parts will be mounted in an steel frame and will be supported by strong wings in the four corners. The height of the frame will be 60 cm and its cross-section 85 $\times$ 85 cm$^2$. The total weight including the inactive absorbers is about 350 kg.

Fig. 1 presents a schematic cross-sectional view of the main components. The detector will consist of three similar scintillator hodoscopes. Each hodoscope is composed of two planes of plastic scintillator bars. For the first one (S1) there are 16 strips of length 56 cm in each layer, while 8 strips of length 28 cm make up the second (S2) and third

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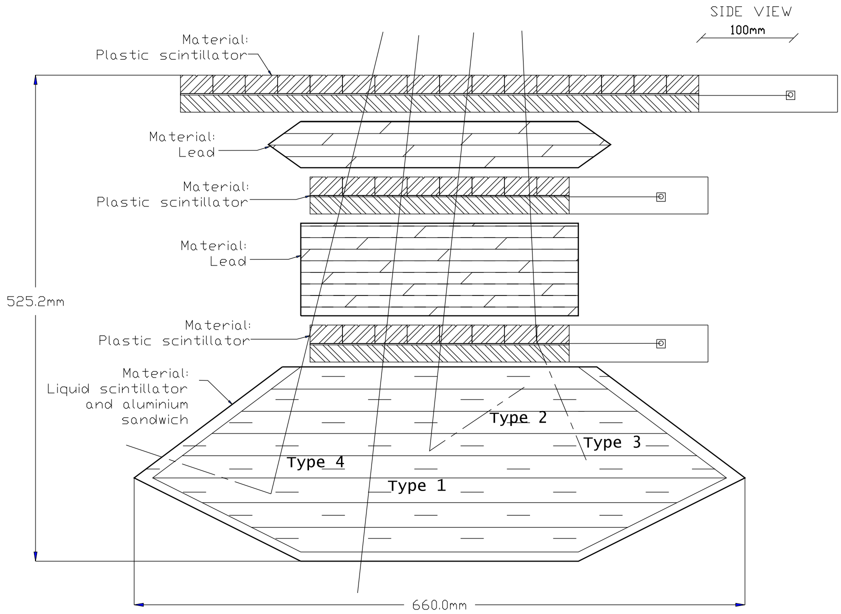


**Fig. 1.** Schematic drawing of the ADLER detector with a trapezoidal active absorber. Different types of particle tracks are distinguished by the timing of the detector response. Tracks of type 1 originate from high energy muons, type 2 tracks originate from low energy muons which have stopped in the active absorber, type 3 tracks originate from muons which have stopped in the third trigger hodoscope and the decay electrons of type 4 tracks produce additional signals in one of the veto-counters and leave the active volume.

(S3). All strips are 3.5 cm wide by 2 cm thick. The maximum detectable zenith angle is defined by the hodoscopes S1 and S3 and amounts to 53.6°. The opening angle and the active areas define the geometrical acceptance but muons with larger angles can scatter into the acceptance region.

Two blocks of lead (30 cm length and width) are stacked between the scintillators. The bottom part of the detector consists of an active absorber. The shape of the active absorber is a double trapezoid with a cross-section of $30 \times 30\,\mathrm{cm}^2$ at top and bottom and a cross-section of $62 \times 62\,\mathrm{cm}^2$ in the middle. Also different shapes like double cones or rectangular pyramids have been investigated. The use of liquid scintillator as the active detector element, in conjunction with wavelength-shifting fibres for light collection and transmission, is well suited for such an experiment. The anticipated commercial liquid scintillator[1] BC-517 L contains about 30% pseudocumene, has a light yield of 39% anthracene and a flash point of 102° Celsius. A volume of 60 litres will be contained in a single aluminium container segmented by optical separators. Furthermore it is chemically compatible with the blue to green wavelength-shifting fibre[1] BC-91 A (Young et al., 1993). Fibres of 1.2 mm diameter will be used in the shape of Archimedes' spirals inside the tank with an equal distance of 4 cm between adjacent turns.

The signals of the scintillators will be read out by the optical fibres to five small (3 × 3 cm) Hamamatsu multi-anode M16 (R5900) photomultiplier tubes operated at voltages of about 1000 V. The total number of analogue channels is 96. The signal processing will be done by simple, low-powered electronics and a data acquisition system based on laptop-PC. The trigger mode will be a coincidence of signals from the three scintillator hodoscopes which can be interpreted as a charged track, together with an anti-coincidence of the veto-counters. The timing of subsequent hits in the active elements is recorded in a 16 × 16 × 16 FIFO using a 40 MHz clock to keep the rate of false coincidences low. The time difference between trigger signal and delayed signal in measures the decay time of the muon. The background to the decay curve can be restricted by requiring an anti-coincidence of the veto-counters with the delayed signal if the reconstructed track is of type 2, see Fig. 1. The power consumption is about 30 W for the electronics and 20 – 30 W for the laptop. At the present stage of the experiment the design of the electronics is not yet finished. The position and altitude of the aircraft at any time could be obtained from mobile Global Positioning System (GPS) equipment or the aircraft log.

[1]Bicron, Newbury, OH, USA.

## 3 Muon charge ratio considerations

The flux ratio $r = N_{\mu^+}/N_{\mu^-}$ of positive to negative muons provides important information on the interactions of the primary cosmic rays with nuclei in the atmosphere. The positive excess is approximately 1.25 in the low energy range. Most of the previous measurements have been carried out using magnetic deflection to determine the muon charge with simultaneous determination of the energy.

The principle of the ADLER measurement is based on the capture of negative muons according to the reaction $\mu^- + p \rightarrow n + \nu_\mu$. Practically the entire energy liberated in this process is carried off by the neutrino and no signal will be produced in the detector. As a result the mean negative muon lifetime becomes $1/\tau = \Lambda_c + 1/\tau_0$ where $\Lambda_c$ is the capture probability and $\tau_0$ the decay lifetime for a free muon. At $Z = 11 - 12$ the capture probability is almost equal to the decay probability, for iron ($Z$ = 26) it is 90% of the total disappearance probability. For that reason the active absorber is designed flexible, making measurements with dif-

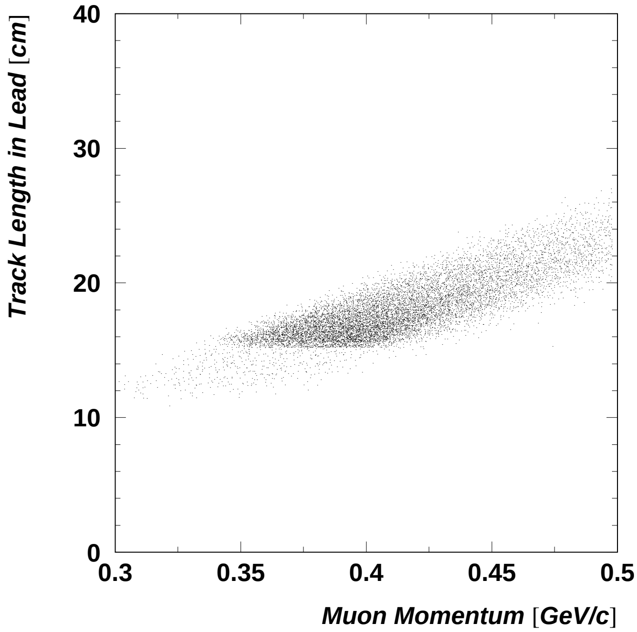


**Fig. 2.** Histogram of muon track lengths in lead versus muon momentum. Vertical muons travel through 15 cm of lead, equivalent to 26 radiation lengths.

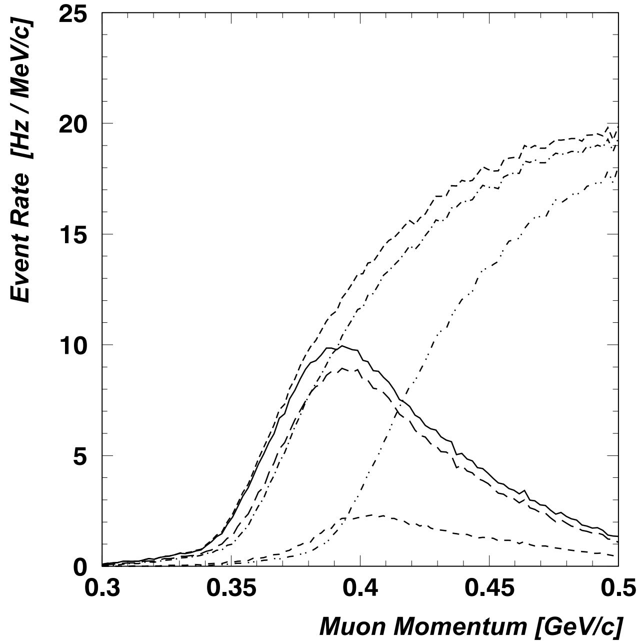


**Fig. 3.** Acceptance curves of the ADLER detector. The event rates are encoded as follows: dashed = trigger ($S_1S_2S_3$); dot-dashed = muon signals ($S_1S_2S_3A$); dot-dot-dashed = signals in veto-counters ($S_1S_2S_3V$); solid = stopped muons; long dashes = muon decay signals in absorber ($S_1S_2S_3A\overline{V}D_A$); short dashes = muon decay signals in veto-counters ($S_1S_2S_3\overline{V}AD_V$).

ferent absorbers (aluminium, steel, scintillator) possible. It could consist of horizontal partitions with half of the mass made of thin (1 mm) plates and the other half made of liquid scintillator cells. In the case of steel plates the total fraction of decaying muons will be 55%. Thus, the determination of the muon charge ratio will be achievable from a comparison of total count rates. Alternatively it can be extracted from the measured decay curve, which is a superposition of the different lifetimes of negative muons in liquid scintillator and the absorber material and of positive muons.

## 4 Muon flux considerations

The mixed radiation field induced by cosmic rays consists of a broad spectrum of different charged particles with varying momentum. The expected composition at 14 km height (atmospheric depth $\approx$ 200 g/cm$^2$) is 60% soft electrons, 30% protons, 10% penetrating muons, 1% penetrating electrons and 0.1% pions. The momentum acceptance and detection efficiencies have been studied carefully using the GEANT 3.21 Monte Carlo code. The geometrical set-up used was based on the construction drawings. The total amount of material above the active absorber amounts to 26 radiation lengths corresponding to about one nuclear interaction length. This will provide a considerable shielding of the lower scintillators from soft electrons and gamma-rays. Fig. 4 shows a histogram of simulated muon track lengths in the lead blocks of ADLER versus muon momentum.

The most interesting muons are those created with energies around $E_\mu \approx 2E_\nu$ and the most important range of neutrino energy is $E_\nu \approx 0.1 - 10$ GeV. The mean energy loss of vertical minimal ionising muons will be about 40 MeV in the scintillators and 187 MeV in the lead blocks. In Fig. 2 the acceptance curves are plotted versus muon momentum. Different detector signals have been calculated: Muons with momentum above 300 MeV/c will trigger the data acquisition (dashed line). The veto-counters will give a signal (dot-dot-dashed line) for penetrating muons. The rate of muons with identified decays is given by the coincidence requirements and is shown by the long dashed curve. This rate has to be compared with the total rate of stopped muons in the simulation (solid line). The FWHM of the acceptance curve for identified muons is 61 MeV/c corresponding to an effective momentum width of 28 MeV/c for the nominal geometrical factor of 2088 cm$^2$ sr. This factor has been calculated by means of two independent codes and allows to estimate the expected flux of muons of one charge for a given geomagnetic latitude. Assuming a flux of 0.01 $\mu$/(cm$^2$ sr s GeV/c) at a geomagnetic cut-off of 4.5 GV gives a count rate of 0.6 Hz or 2,200 counts per hour. A measurement with 3% statistical error can be performed in about 1/2 h. During this time a south-going flight covers a geomagnetic latitude difference of 4°. Those numbers lead to the expected count rates listed in Table 1.

Fig. 3 shows the corresponding efficiency curves, where the upper plot refers to count rates normalized to the trigger rate and the lower plot refers to count rates normalized to the rate of stopped muons. The efficiency of detecting a stopped muon is about 90%. In addition, 20% of the decay electrons

**Table 1.** Expected count rates in the detector components. The first line of each component presents the correlated background rate, every other line presents the uncorrelated background rate.

| Counter | Acceptance [cm$^2$ sr] | Flux $\times$ $10^{-2}$ [(cm$^2$ s sr)$^{-1}$] | Rate [Hz] |
|---|---|---|---|
| Scintillator S1 | 2000 | 30 | 2 $\times$ 600 |
| | 8000 | 30 | 2 $\times$ 2400 |
| Scintillator S2 | 2000 | 10 | 2 $\times$ 200 |
| | 400 | 30 | 2 $\times$ 120 |
| Scintillator S3 | 2000 | 8 | 2 $\times$ 160 |
| | 400 | 30 | 2 $\times$ 120 |
| Active absorber | 2000 | 8 | 8 $\times$ 160 |
| (one cell) | 10000 | 30 | 8 $\times$ 3000 |
| Veto-counters | 2000 | 8 | 160 |
| | 10000 | 30 | 3000 |
| $(S_1 S_2 S_3)$ | | | **120** |
| ($S_1$ or $S_2$ or $S_3$) | | | **7200** |

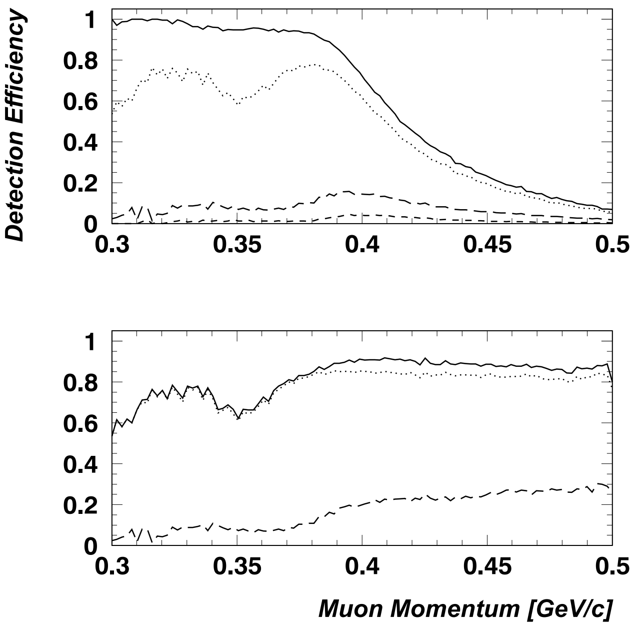


**Fig. 4.** Efficiency curves of the ADLER detector. The efficiencies are encoded as follows in the upper plot: solid = stopped muons per trigger; dots = muon decay signals in absorber per trigger ($S_1 S_2 S_3 A \overline{V} D_A$); long dashes = muon decay signals in veto-counters per trigger ($S_1 S_2 S_3 \overline{V} A D_V$); short dashes = muon decay signals in veto-counters only per trigger ($S_1 S_2 S_3 \overline{V} A \overline{D}_A D_V$); in the lower plot: solid = muon decay signals per stopped muon ($S_1 S_2 S_3 A \overline{V} D$); dots = muon decay signals in absorber per stopped muon ($S_1 S_2 S_3 A \overline{V} D_A$); long dashes = muon decay signals in veto-counters per stopped muon ($S_1 S_2 S_3 A \overline{V} D_V$).

are detected in the veto-counters providing a redundancy in the data analysis which can be used to reduce backgrounds.

## 5 Aircraft considerations

The effect of the geomagnetic field is recognized as very important in atmospheric neutrino flux calculations. At present, the confidence in the IGRF (International Geomagnetic Reference Field) models is strong. However, a measurement of the muon flux at different geomagnetic latitudes $\lambda$ is desirable. It is supposed that the relative muon flux $I/I_0$ can be parameterized by $I/I_0 = (1 + \alpha|\lambda|)R$, where $\alpha$ is a constant in (degree)$^{-1}$ and $R = \lambda/\lambda_0$ is the latitude ratio. The flight paths investigated involve transatlantic routes. The possible latitude band extends from $\sim 55°$ N to $\sim 35°$S. The majority of commercial flights have cruising altitudes from 11 to 13 km.

The whole structure of the detector must tolerate acceleration in each direction to meet the regulations of the aircraft. In the vertical and horizontal directions perpendicular to the aircraft axis the limits of maximum acceleration are at $3g$. Along the aircraft axis the limit is at $9g$. Finite element analysis has been performed during the design of the detector to meet those demands.

## 6 Conclusions

The ADLER detector is a small and compact apparatus for measuring the flux of atmospheric muons as a function of the geomagnetic coordinates. The momentum acceptance was chosen to be relevant to the atmospheric neutrino anomaly. The muon charge ratio will be determined by a comparison of the $\mu^-$ lifetimes in different absorbers. The results will lead to a better understanding of present and future atmospheric neutrino experiments. Furthermore, the measurements will provide an important check of the new 3-dimensional atmospheric neutrino flux calculations being performed at Oxford.

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