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PRESENT STATUS OF THE MONOLITH PROJECT

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MONOLITH is a proposed massive (34 kt) magnetized tracking calorimeter at the Gran Sasso laboratory in Italy, optimized for the detection of atmospheric muon neutrinos. The main goal is to establish (or reject) the neutrino oscillation hypothesis through an explicit observation of the full first oscillation swing. The Δm^2 sensitivity range for this measurement comfortably covers the complete Super-Kamiokande allowed region. Other measurements include studies of matter effects, the NC up/down ratio, the $\bar{\nu}/\nu$ ratio, the study of cosmic ray muons in the multi-TeV range, and auxiliary measurements from the CERN to Gran Sasso neutrino beam. Depending on approval, data taking with the part of the detector could start towards the end of 2004.

МОНОЛИТ — проект массивного (34 кт) трекового калориметра из намагниченной стали для лаборатории Гран-Сассо в Италии — оптимизирован для регистрации атмосферных мюонных нейтрино. Его основная цель — подтвердить (или опровергнуть) гипотезу нейтринных осцилляций путем прямого наблюдения первого осцилляционного минимума. Область чувствительности этих измерений по разности квадрата масс полностью перекрывает область, разрешенную экспериментом Супер-Камиоканде. Другие планируемые эксперименты включают: изучение эффектов влияния вещества, отношения вверх/вниз для нейтральных токов, отношения потоков антинейтрино/нейтрино, изучение мюонов космических лучей в мульти-ТэВ-ной области энергий, эксперименты с пучком нейтрино из ЦЕРНа. В случае одобрения проекта, набор данных может быть начат в конце 2004 года.

INTRODUCTION

The question whether neutrinos are massive, and hence the question of the existence of neutrino oscillations, is currently one of the main unsettled challenges in physics. All experiments measuring the flux of solar neutrinos observe a deficit compared to the prediction of solar models. The ratio of muon to electron events observed in atmospheric neutrino interactions is measured by most experiments to be less than expected from models of cosmic ray propagation through the atmosphere. The measurement of the up/down asymmetry of this ratio by the Super-Kamiokande collaboration is generally considered to be the strongest evidence for neutrino oscillations so far. Furthermore, possible oscillation signals in the $\bar{\nu}_\mu - \bar{\nu}_e$ and $\nu_\mu - \nu_e$ channels were observed by the LSND experiment. Finally, massive neutrinos could play an important role in the missing dark matter problem if at least one mass eigenstate lies in the eV range. All these observations make the study of neutrino oscillations a very worthwhile endeavor.

[1]For the list of the Collaboration see [2].

While the cumulative evidence for neutrino oscillations is very striking, a definitive proof that the observed anomalies are actually due to neutrino oscillations is still missing. The current observations of atmospheric neutrinos are consistent with the hypothesis of maximal ν_μ oscillations, but do not yet exclude some alternative unconventional explanations [1].

The main physics goal of the MONOLITH experiment [2, 3] is to establish the occurrence of neutrino oscillations in atmospheric neutrinos through the explicit observation of the full first oscillation swing in ν_μ disappearance, and to investigate and presumably exclude alternative explanations. This also yields a significantly improved measurement of the oscillation parameters with respect to previous measurements. The strong magnetic field, adopted in the detector design to extend the sensitivity to the full parameter range allowed by current experiments, is a novel feature among atmospheric neutrino detectors. The charge and momentum measurement of muons from charged current (CC) events also allows unique systematic studies of the atmospheric neutrino flux, and the search for potential matter effects in neutrino oscillations. The measurement of the oscillation pattern can be usefully supplemented by measurements in the CERN to Gran Sasso neutrino beam.

Provided that the neutrino oscillation hypothesis is confirmed, another goal of the experiment is to further investigate the nature of these oscillations. Depending on the oscillation parameters, oscillations into active (ν_τ) or sterile (ν_s) neutrinos can be distinguished through their different effects on the up/down ratio of neutral current (NC)-like events, and/or through the presence or absence of matter effects yielding a distortion of the observed oscillation pattern as a function of energy and/or muon charge. A particularly interesting option in the context of the standard 3-neutrino scenario would be the measurement of the sign of Δm^2 via an MSW resonance in $\nu_\mu - \nu_e$ oscillations, along the same line as currently studied for Neutrino Factory beams [4].

Due to its ability of in situ measurement of the energy of every muon in the multi-TeV range, MONOLITH will also be a unique facility for pioneer investigations of cosmic ray muons in the unexplored 100 TeV energy region. The results of these studies should give information which is relevant for the solution of the problem of the knee in the cosmic ray energy spectrum.

For this experiment we have designed a detector which has been optimized for the detection of atmospheric neutrinos (with additional substantial sensitivity to the neutrino beam from CERN) and can achieve these physics goals.

1. EXPERIMENTAL SET-UP

To explicitly detect an oscillation pattern in the *L*/*E* spectrum of atmospheric muon neutrinos, the energy *E* and direction θ of the incoming neutrino have to be measured in each event. The latter can be estimated, in the simplest experimental approach, from the direction of the muon produced from the ν_μ charged-current interaction. The neutrino energy *E* can be obtained by means of energy measurements of the muon and of the hadrons produced in the interaction. In order to make the oscillation pattern detectable, the ratio of the neutrino path-length to its energy *L*/*E* have to be measured with a FWHM error smaller than half of the modulation period. The energy and angular resolutions of the detector or, more generally, the experimental approach are constrained by this condition.

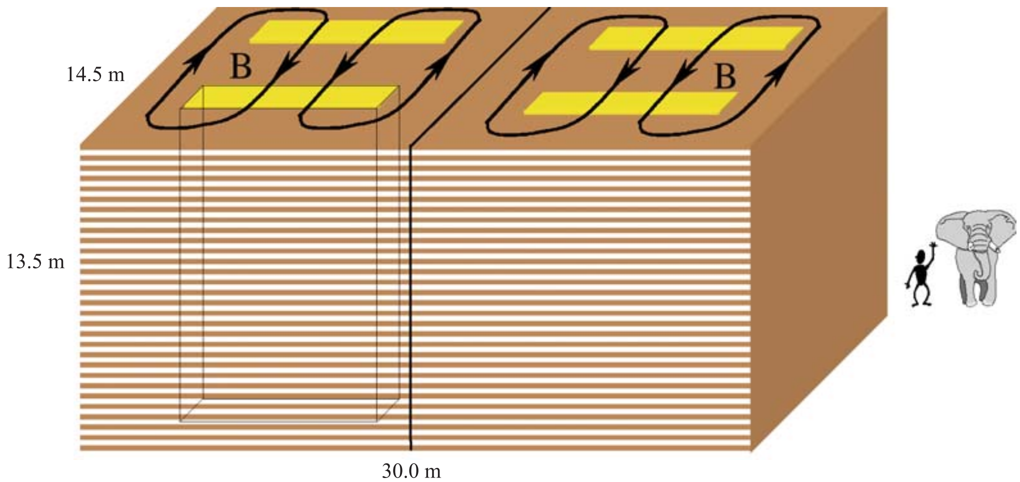

Fig. 1. Schematic view of the MONOLITH Detector. The arrangement of the magnetic field is also shown

In addition to these requirements on the *L*/*E* resolution, the experimental apparatus should guarantee the identification of the neutrino flight direction. In case the interaction vertex is not identified, this condition turns out to be very stringent and requires the identification of the muon flight direction with high efficiency. Different techniques based on the increase of curvature along the track in the magnetic field, on multiple scattering along the track or on time-of-flight measurements, can be used. The latter technique is more effective and allows almost perfect up/down discrimination of the relevant ν_μ-CC events for timing resolution of the order of 2 ns. A precise time-of-flight along the muon track will be also of utmost importance in the rejection of the cosmic muon background in the sample of partially contained ν_μ-CC events.

A large modular structure has been chosen for the detector (Fig. 1). One module consists of a stack of 125 horizontal 8 cm thick iron planes with a surface area of 15.0×14.5 m, interleaved with 2.2 cm gaps housing sensitive elements. The height of the detector is thus 13.1 m including antiseismic mechanical supports. The magnetic field configuration is also shown in Fig. 1; iron plates are magnetized at a magnetic induction of ≈ 1.3 T.

The detector consists of two modules. Optionally, the downstream module could be complemented by an end-cap of vertical planes to improve the performance for noncontained muons from the CNGS beam (see section 2.4). The total mass of the detector exceeds 34 kt. The sensitive elements provide two coordinates with a pitch of 2.8 cm, and a time resolution better than 2 ns.

The full detector is 30.0 m long, 14.5 m wide and 13.1 m high, which is consistent with construction and operation in the Gran Sasso Hall C. It is also possible to configure the detector for installation in Hall B. With the envisaged modular structure, we anticipate that the first module could be ready for operation 4 years after experiment approval.

1.1. Glass Spark Counters. Taking into account the overall dimensions of the apparatus (125 planes 30.0 m long and 14.5 m wide) the total active detector area is $\sim$ 54000 m^2. The large active area requires a low cost detector, suitable for a fast mass production.

For these reasons Glass Spark Counters (GSC) [5, 6] have been chosen as active elements. They are derived from resistive-plate chambers by substituting the bakelite by commercial float glass of high resistivity; for this reason they are sometimes called Glass RPC. Moreover they provide a timing of the order of 1–2 ns, and therefore excellent up-down discrimination of muons.

The GSC is a gaseous detector composed of two parallel electrodes made of glass with a volume resistivity of about 10^{12} Ωcm. The two electrodes, 2 mm thick, are kept 2 mm apart by means of suitable spacers. The gap between the two glass electrodes defines the gas volume where the particle detection occurs. Under particular gas mixture and electric field configurations (typically $\sim$ 48 % Argon + $\sim$ 4 % isobutane + $\sim$ 48 % R134A and $\sim 4 \div 5$ kV $\cdot$ mm^{-1}) the detector is operated in spark mode. Typical signal amplitudes of the order of $100 \div 200$ mV/50 Ω are observed, corresponding to a charge of about $100 \div 200$ pC (depending on the intensity of the applied electric field).

The GSCs will be equipped with X and Y pick-up strip electrodes, both with a pitch of $\sim$ 3 cm (2.8 cm), mounted on the opposite sides of the detector planes. The pulses are induced on the strips and then discriminated by the electronics directly connected to the strip ends. The electronics should also provide a fast discriminated signal for timing purposes.

This type of readout system will provide a three-dimensional tracking of particles inside the apparatus with a time resolution of $\sim$ 1 ns and a spatial accuracy of $\sim$ 1 cm on both views.

1.2. The Trigger System. The GSC signals are read out digitally. In addition, the signals of 16 or more channels are summed and sent to a TDC via a discriminator. These discriminator signals are also available for trigger purposes. As every spark provides both an X and Y coordinate, the processing of only one coordinate is sufficient for triggering. This leads to about 9000 trigger channels for the flat cable design. A VME trigger board processes groups of 120 of these trigger channels with a programmable local trigger logic. This results in 76 VME boards for all trigger channels.

The logic allows one to trigger on certain track patterns, such as 2 or 3 hit layers out of 5 consecutive layers. This results in a trigger efficiency near 100 % for the relevant atmospheric neutrino events (energy > 1.5 GeV). Through a combination of signals from different trigger boards on an additional logic level, a global multiplicity trigger is also possible. The signals of the veto counters are read out by TDC's and are also available for trigger purposes.

The expected trigger rate (mainly originating from cosmic ray muons and random coincidences of radioactive decays) is expected to be much less than 1 Hz. The trigger initiates the readout of the digital and TDC information, which is collected and further processed via VME CPU modules. The complete events are then fed into an online computer, which performs a preliminary event reconstruction. At this «2nd level trigger» stage, events can be filtered and/or distributed to several output streams.

1.3. The DAQ System. The MONOLITH DAQ system will be VME based. DAQ electronics will be located on the top of the detector, along the hall axis in 4 points (spaced $\sim$ 7.5 m), two for each detector module. Since VME crates and their read-out are the major DAQ cost, a big effort has to be done to minimize their number: STAS (control and readout) units serving 32 digital chains will be developed (the current commercial STASs serve 8 digital chains) and 64 chs/unit TDC modules will be used.

In this way every DAQ station will provide the readout of 16 digital chains and 32 TDC channels for all the 125 detector layers. The 60 STAS and TDC modules needed will be stored in 6 crates (3 9U and 3 6U). Every crate will serve 40 layers. In every DAQ point 2 VME crates devoted to trigger and slow control systems are foreseen.

Front-end data read-out will be performed using Motorola MVME CPUs. To minimize soft-ware cost, the Linux option, as operating system of VME embedded CPUs, will be investigated. Diskless CPU booting, event building and monitoring will be performed using a Linux PC for each DAQ station.

2. NEUTRINO OSCILLATIONS

2.1. Why Atmospheric Neutrinos? Atmospheric neutrino experiments offer several advantages over currently operational or planned long baseline neutrino beam programs.

- A very large L/E range (from about 1 to 10^5 km $\cdot$ GeV^{-1}; a typical long baseline beam covers only one or two orders of magnitude). Therefore, a very large range of oscillation parameters can be studied simultaneously.

- Two identical sources for a single detector: a near (downgoing neutrinos) and a far (upgoing neutrinos) one.

- For some of the measurements, e. g., the confirmation of the oscillation pattern, there is currently no alternative to atmospheric neutrino detectors if the atmospheric Δm^2 is low. The pattern measurement is competitive even at high Δm^2.

- During the next decade large matter effects with high energy neutrinos can only be observed in atmospheric neutrino experiments, since the current long baseline distances of 250 and 730 km are too short for a significant effect. Matter effects already yield discrimination between the pure 2-flavour ν_μ–ν_τ and ν_μ–$\nu_{\rm sterile}$ oscillation scenarios in Super-Kamiokande and MACRO. Adding muon charge discrimination in future large mass detectors allows the search for MSW-like resonances in subdominant contributions to 3 or more flavour oscillations. In particular, some sensitivity to the determination of the sign of the atmospheric Δm^2 and to complicated hybrid oscillation scenarios can be obtained.

Future new atmospheric neutrino experiments are therefore an important complement to current and future long baseline neutrino programs.

However, none of the experiments which have yielded indications for neutrino oscillations have so far succeeded to measure an actual sinusoidal oscillation pattern. Figure 2 shows the L/E distribution published by Super-Kamiokande [7] compared to the expectation for neutrino oscillations and to a functional form suggested by a recent neutrino decay model [8]. Once the detector resolution is taken into account, the two hypotheses are essentially indistinguishable [8]. Even though the current evidence is very suggestive of neutrino oscillations, a more precise measurement of the oscillation pattern is the only way to actually prove the oscillation hypothesis for atmospheric neutrinos. The crucial issue here is to prove that muon neutrinos do not only disappear, but actually reappear at some larger L/E.

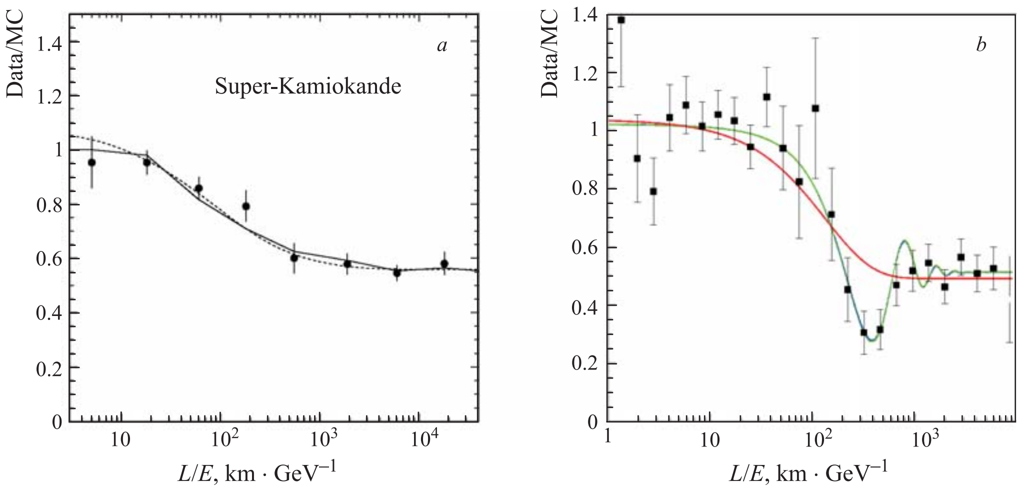

Fig. 2. *a*) L/E distribution from Super-Kamiokande [7] compared to the best fit oscillation hypothesis (continous line), and to a parametrization corresponding to the neutrino decay model of Ref. 8 (dashed line). The oscillations are smoothed out by detector resolution. *b*) L/E distribution to be expected from MONOLITH for $\Delta m^2 = 3 \cdot 10^3$ eV^2 compared to the best fit oscillation hypothesis (oscillating line) and to the corresponding best fit of the neutrino decay model of Ref.8 (smooth threshold effect)

2.2. Distinction of $\nu_\mu \to \nu_\tau$ vs. $\nu_\mu \to \nu_s$. If the current indications for three independent Δm^2 are confirmed, the only way out is the introduction of at least a fourth neutrino. Taking into account the LEP results [9] on the number of neutrinos, any extra neutrinos must be either very massive ($m_\nu > M_Z/2$) or sterile with respect to weak interactions (e. g., a right-handed neutrino or left-handed antineutrino). Present experiments are only now starting to distinguish oscillations with sterile neutrinos from standard flavour oscillations for either atmospheric or solar neutrinos. Significant ν_μ–ν_s oscillation contributions are therefore allowed in both cases.

Since the existence of one or more light sterile neutrinos would be evidence for new physics, proving or disproving the ν_μ–ν_τ oscillation hypothesis for atmospheric neutrinos is a crucial issue. Furthermore, it would exclude or confirm a large class of neutrino oscillation models (see, e. g., [10] and references therein). The observation of τ appearance in long baseline beams would be the most direct evidence for $\nu\mu$–ν_τ oscillations, but potentially leaves some loopholes for the interpretation of the atmospheric neutrino results. These loopholes would be closed by a direct $\nu_\mu \to \nu_\tau$ vs. $\nu_\mu \to \nu_s$ distinction in atmospheric neutrino experiments.

The MONOLITH experiment can exploit the spirit of both approaches to improve on these measurements. The first technique, based on τ appearance, consists in measuring the up/down asymmetry of «NC-like» events (muon-less events) as a function of the visible energy. For $\Delta m^2 \leq 10^{-2}$ eV^2, oscillations of ν_μ into ν_τ would in fact result in an excess of muon-less events produced by upward neutrinos with respect to muon-less downward, since charged-current ν_τ interactions would contribute to the muon-less event sample, due to the large τ branching ratio into muon-less channels. Moreover, due to threshold effect on τ production, this excess would be important at high energy. Oscillations into a sterile neutrino would instead result in a depletion of upward muon-less events. Discrimination between $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$ is thus obtained from a study of the asymmetry of upward to downward muon-less events.

2.3. Three Flavour Oscillations. Even in the absence of sterile neutrinos, matter effects are present in the case of a small contribution from $\nu_\mu - \nu_e$ oscillations at the «atmospheric» Δm^2. The CHOOZ limit [11] constrains the size of this contribution, and the expected effects are mostly small. However, if the $\nu_\mu - \nu_e$ mixing angle would be close to the CHOOZ limit, the corresponding MSW resonance might be observable as a localized ν_μ rate suppression either in ν_μ or in $\bar{\nu_\mu}$, yielding a measurement of the sign of Δm^2. This possibility is currently being investigated further. Another possible exception could be the observation of a large neutrino/antineutrino asymmetry predicted by tri-maximal mixing models [12], which are currently not yet completely excluded. Furthermore, fits of the solar neutrino results leaving out Homestake allow the solar Δm^2 to be as high as a few 10^{-4} eV^2. If the mixing is nonmaximal, differences in the ν and $\bar{\nu}$ rates could again be observed.

2.4. Physics with CNGS Neutrino Beam. In addition to atmospheric neutrinos, for which it has been optimized, MONOLITH will also detect more than 100000 events (CC + NC) per year from the CERN to Gran Sasso (CNGS) neutrino beam, which is scheduled to start operations in 2005.

Beam neutrinos arrive at an angle of 4° (upward) from the horizontal direction, almost parallel to the «long» axis of the MONOLITH detector. Despite its optimized design for atmospheric neutrinos, the MONOLITH detector in its uniformly horizontal option can reconstruct $\approx$ 46 % of the CC events with optimal energy resolution. In terms of events, this result makes MONOLITH the detector which will monitor the CNGS beam with the highest statistical precision and good energy resolution ($\approx$ 41000 events/year expected to be reconstructed with energy resolution $\leq$ 22 %). This huge sample can complement the MONOLITH atmospheric neutrino analysis of the L/E distribution in the region 20–200 km $\cdot$ GeV^{-1}. The remaining part of the data is reconstructed with less precision, but can still be used for flux monitoring purposes.

3. COSMIC RAY MUON STUDIES

MONOLITH is also well suited for the study of very high energy cosmic ray muons. Using a so-called «pair meter» technique [13], the energy of each muon in the multi-TeV range can be directly measured. The resulting measurement of the cosmic ray muon spectrum yields the opportunity to test potential extensions of the standard model which would affect the shape of this spectrum.

3.1. Muon Energy Spectrum. The spectrum of primary cosmic ray particles measured by means of extensive air shower (EAS) observations is well described by a power law over many decades in energy. However, it exhibits a well-known change in slope (the so-called «knee») between 10^{15}–10^{16} eV (1–10 PeV). In nucleon–nucleon collisions, PeV energies in the laboratory frame correspond to centre-of-mass energies in the TeV region, where new physics and new (heavy) particles are predicted by various theoretical models. Above 2 TeV, these energies are out of reach of the existing accelerators.

There are two main possibilities for the explanation of the knee: a change of the primary spectrum (and/or composition), or the appearance of new processes in very high energy interactions. Currently, most investigators support the first point of view. However, the second option remains possible. To explain the knee in this way, one should assume that the primary spectrum is not changed, but the part of the primary energy (above the knee) is carried away by the particles which are not or incompletely detected by EAS arrays. This missing energy ΔE may be estimated as [14]:

$$\frac{\Delta E}{E_1} = 1 - \left(\frac{E_0}{E_1}\right)^{\Delta\gamma/\gamma_2}, \tag{1}$$

where γ_1 and γ_2 are the power indices of the primary spectrum and of EAS spectrum above the knee; E_1 and E_2 are primary particle energy and detected EAS energy; $\Delta\gamma = \gamma_2 - \gamma_1$, and E_0 is the knee position. Among the known particles only neutrinos and very high energy muons can carry this missing energy. Neutrinos remain undetected, and usual EAS set-ups do not measure the muon energy but only estimate their number. In turn, these leptons could originate from the decay of new particles in the several TeV mass region or from a new state of matter (supersymmetry, compositeness, technicolor, quark-gluon plasma, superstrings, etc.). To have the necessary impact, such particles or states should be produced with a large cross section (of the order of tens of mb). As was pointed out recently [14], a good possibility to find such new particles in cosmic rays is to perform a direct measurement of the muon energy spectrum in the region of 100 TeV and higher.

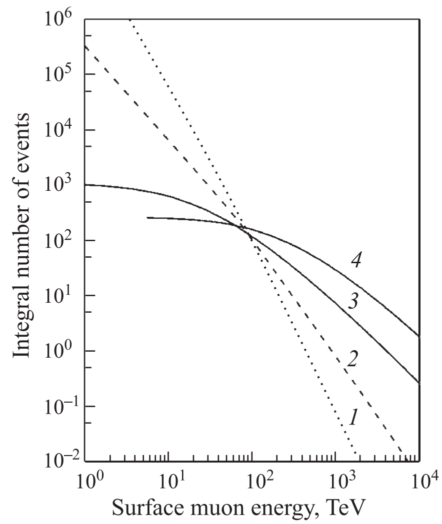

Fig. 3. Expected integral spectra of muons from various processes crossing MONOLITH in 3 years: *1* — muons from π, K decays; *2* — «prompt» muons for a ratio $R_{\mu/\pi} = 10^3$; *3, 4* — lower and upper estimates for muons from new VHE sources to explain the «knee» (see text)

The expected fluxes of very high energy muons which are needed for the explanation of the knee within the frame of the above model are shown in Fig. 3 together with the rate of standard cosmic ray muons (originated from π, K decays). In 3 years the MONOLITH detector will allow to register about 100 events with surface muon energies exceeding 100 TeV for conventional muon production mechanisms, whereas about 2–3 times higher statistics may be expected in the case of the appearance of the «new» muons. At 1 PeV, the expected rate could be increased by more than an order of magnitude. This drastic change of the muon energy spectrum around 100 TeV would be an excellent signature of new processes. In the case of a positive result, muon energy spectrum studies with MONOLITH may lead to the discovery of new physical processes of muon generation in the TeV (centre-of-mass) energy region. On the other hand, the absence of an excessive muon flux in this energy range would reinforce the evidence in favour of a cosmophysical origin of the knee.

3.2. The Pair-Meter Technique for TeV Muons. The size and the structure of the MONOLITH detector allow one to utilize a new method of muon spectrometry in the TeV energy range. The technique is based on the energy dependence of the cross section of direct electron-positron pair production by muons. In passing through a thick layer of matter, high-energy muons produce secondary cascade showers, mainly via electron-positron pair production process. Measurements of the number and energies of these cascades allow one to evaluate the muon energy.

The most important advantage of the technique in comparison with other existing methods of muon spectrometry is the absence of upper limitation on measurable muon energy: the energy resolution is not deteriorated with increasing of particle energy. The relative energy measurement error is determined mainly by the total target thickness T expressed in radiation lengths:

$$\delta_E = \sqrt{\frac{9\pi}{28\alpha T}} \approx \sqrt{\frac{137}{T}}, \qquad (2)$$

where α = 1/137 is the fine structure constant. The most informative region of energy transfers from the view-point of muon energy reconstruction is ε = (10^{-3}–10^{-2}) E_μ; thus, to perform measurements in the energy range E_μ $\sim$ 10 TeV and higher, it is sufficient to detect secondary electromagnetic cascades with energies ε $\sim$ 10 GeV. Due to the fact that the technique is based on the observation of multiple interactions of muon in the set-up material, it is rather tolerant with respect to individual cascade energy measurement errors, and may be implemented with a detector of a relatively simple structure.

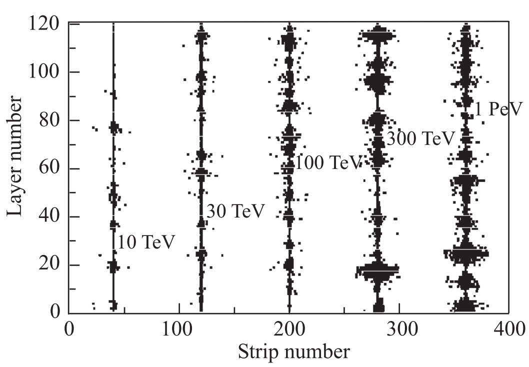

Fig. 4. Muons with different energies in the MONOLITH digital calorimeter. 120 layers of 8 cm steel and 3 cm wide strips have been assumed in the simulation of the detector response

The thickness of the target in MONOLITH (over 500 X_0) provides the possibility to measure individual muon energies, and hence to obtain direct measurements of the energy and angular distributions of the detected particles. Examples of simulated events for several muon energies are given in Fig. 4. On the average, a 10 TeV muon will generate (via electron pair production) 5 cascades with energies greater than 10 GeV and about 20 cascades above 1 GeV. For a 100 TeV muon, the typical number of cascades will already be 5, 20, and 50 for cascade energy thresholds 100, 10, and 1 GeV respectively, which will allow one to estimate the muon energy with about 50 % accuracy (and approximately log-Gaussian distribution of errors). Such accuracy is quite sufficient for muon energy spectrum studies.

The MONOLITH detector operated as a pair meter will have several thousand (!) times larger effective acceptance than the biggest magnetic spectrometers [15, 16], the results of which are still used as a standard of high energy muon spectrum measurements.

CONCLUSION

We showed the feasibility of a 34 kt magnetized iron detector which is able to

- measure the neutrino oscillation pattern in atmospheric neutrinos, therefore proving the oscillation hypothesis. Auxiliary beam measurements are being studied;
- significantly improve the measurement of Δm^2 and $\sin^2\theta$, covering the full allowed range independent of how it might evolve in the future;
- improve the discrimination between the $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_s$ oscillation hypotheses. Depending on the oscillation parameters, this could be achieved through the measurement of the up/down ratio of NC-like events, through the presence or absence of a distortion of the oscillation pattern as a function of energy by matter effects, or through the (non)observation of an asymmetry in the oscillation patterns for neutrinos and antineutrinos;
- with some luck, measure charge-dependent matter effects in $\nu_\mu - \nu_e$ oscillations, and therefore the sign of Δm^2, i. e., the hierarchy of the mass pattern.
- obtain the first measurement of the cosmic ray muon energy spectrum and angular distribution around 100 TeV, and significantly improve the knowledge of muon production mechanisms and the primary spectrum and composition in the 100 TeV–10 PeV region.

Many of these measurements are unique to this detector, and therefore complementary to other planned neutrino physics programmes. They can be achieved on a relatively short timescale, at a cost which is dominated by the required detector mass. Furthermore, a detector of this kind fits into even more ambitious long-term programmes for neutrino factories.

REFERENCES

1. See e.g. *Pakvasa S.* // Invited talk at the 8th Intern. Workshop on Neutrino Telescopes, Venice, Italy, Feb. 23–26, 1999; hep-ph/9905426, and references therein.
2. MONOLITH Proposal, LNGS P26/2000, CERN/SPSC 2000-031, SPSC/M657. August 15, 2000. http://castore.mi.infn.it/ /sim monolith/proposal/
3. *Picci P., Pietropaolo F.* Atmospheric Neutrino Oscillations Experiments. ICGF RAP. INT. 344/1997. Torino, 1997; CERN preprint SCAN-9710037.
4. *Bueno A., Campanelli M., Rubbia A.* hep-ph/0005007. May 2000.
5. *Bencivenni G. et al.* // Nucl. Instr. Meth. A. 1994. V. 345. P. 456.
6. *Gustavino C. et al.* INFN/TC-99/14; Nucl. Instr. Meth. (accepted).
7. *Fukuda Y. et al. (Super-Kamiokande Collaboration)* // Phys. Rev. Lett. 1998. V. 81. P. 1562.
8. *Barger V. et al.* // Phys. Rev. Lett. 1999. V. 82. P. 2640.
9. *Particle Data Group* // Eur. Phys. Journ. C. 1998. V. 3. P. 1.

10. *Bilenky S. M. et al.* hep-ph/9906251.

11. *Apollonio M. et al. (CHOOZ Collaboration)* // Phys. Lett. B. 1999. V. 466. P. 415.

12. *Harrison P. F., Perkins D. H., Scott W. G.* // Phys. Lett. B. 1999. V. 458. P. 79.

13. *Kokoulin R. P., Petrukhin A. A.* // Nucl. Instr. Meth. A. 1988. V. 263. P. 468; Sov. J. Part. Nucl. 1990. V. 21. P. 332.

14. *Petrukhin A.A.* // Talk at the XIth Rencontres de Blois «Frontiers of Matter», Blois, France, June 28–July 3, 1999; preprint MEPhI, No. 006-99. 1999.

15. *Allkofer O.C. et al.* // Nucl. Phys. B. 1985. V. 259. P. 1.

16. *Matsuno S. et al.* // Phys. Rev. D. 1984. V. 29. P. 1.