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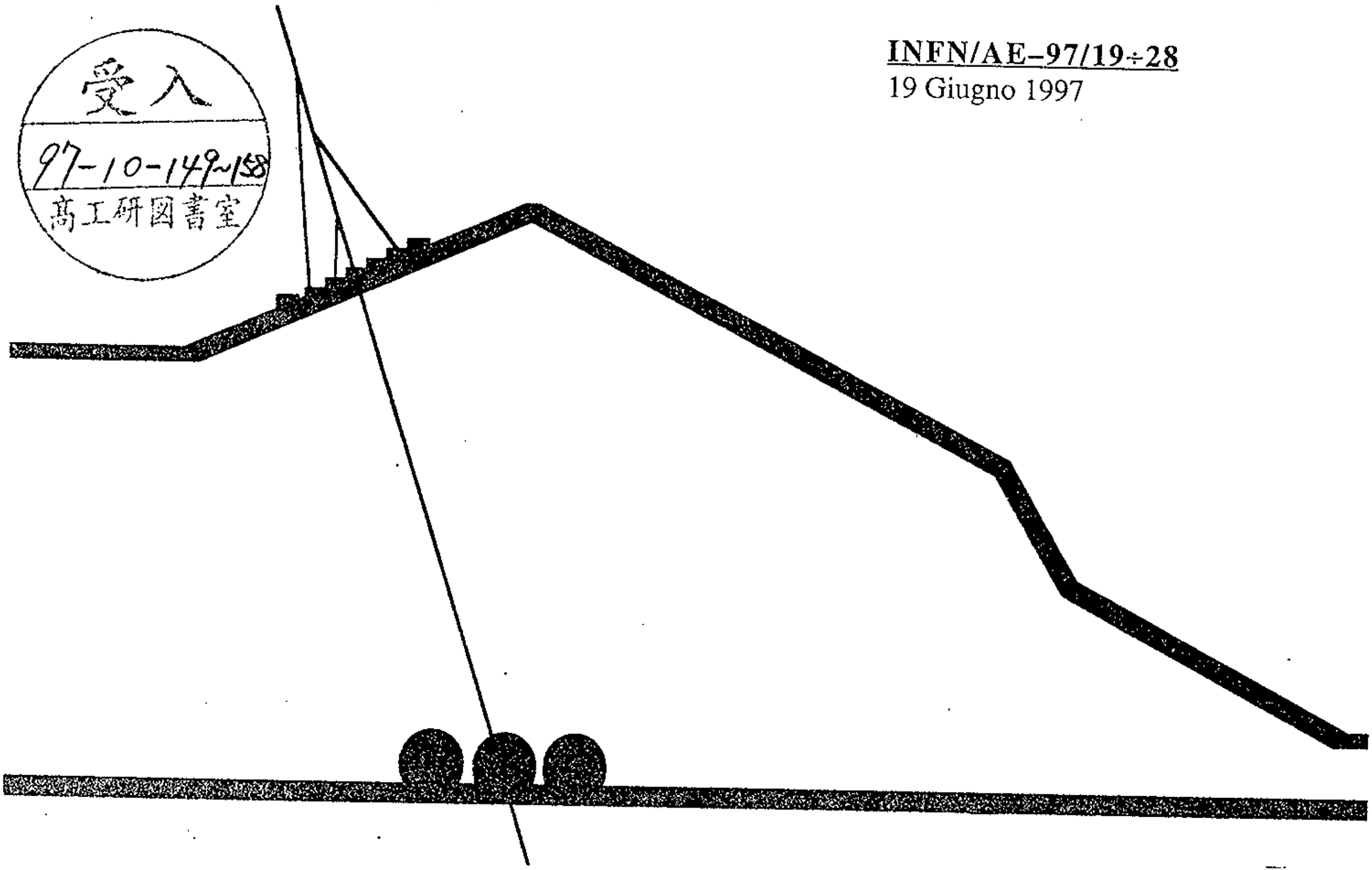

Contributions of the MACRO Collaboration to the 1997 Summer Conferences

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The MACRO Collaboration

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MEASUREMENT OF UNDERGROUND MUON ENERGIES USING A TRD IN MACRO

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19 Giugno 1997

ABSTRACT

The MACRO detector is located in the Gran Sasso Laboratory. MACRO's overburden varies from 3150–7000 hg/cm^2. A transition radiation detector (TRD) has been added to the MACRO detector in order to measure the energy of muons entering MACRO. At the top of the Gran Sasso, cosmic ray muons must have a threshold energy of 1.4 TeV to reach the MACRO detector. We measure the residual energy of cosmic ray muons, the energy they have after passing through the Gran Sasso and reaching the MACRO detector. Our transition radiation detector consists of three identical modules with a total horizontal area of 36 m^2. The results presented here were obtained with the first module collecting data for almost one year. The average residual energy of downgoing single muons, cut to retain muons below 930 GeV (our TRD saturation energy), is about 200 GeV.

INTRODUCTION

The muon energy spectrum deep underground can be derived from the surface muon spectrum and from calculations of energy losses, using assumptions on the interaction cross sections of high energy muons in the rock. A direct measurement of this spectrum therefore can give information on the interaction mechanisms of muons in the rock, and can be used to confirm the surface muon spectrum and the "all-nucleon" primary cosmic ray spectrum.

In order to increase the MACRO detector capabilities with a device able to measure the residual muon energy we designed and built a large area TRD. The TRD measures the energy of each muon up to the TeV region, although with modest resolution. This measurement may open a wide range of experimental opportunities for cosmic ray physics in underground laboratories. With this technique, the residual energy of downgoing and (neutrino induced) upgoing muons is directly measured.

THE MACRO TRD

Transition radiation (TR) is emitted in the X-ray region whenever an ultrarelativistic charged particle crosses the boundary of two materials with different dielectric properties. For each interface the emission probability for an X-ray photon is of the order of $\alpha = 1/137$ (fine structure constant). Radiators consisting of some hundreds of foils regularly spaced are used to enhance X-ray production; a few photons are produced allowing a reliable tagging of the fast particle. Due to the characteristic dependence (in a limited energy range) of transition radiation on the Lorentz factor γ of the incident particle, it is possible to evaluate its energy $E = m_o \gamma c^2$ in this range if the rest mass m_o is known, or if the particle has been identified, as is the case of muons reaching an underground laboratory. The multilayer radiator introduces physical constraints for the radiation yield, due to the so called "interference effects". The radiation emission practically starts at a Lorentz factor $\gamma_{th} = 2.5\omega_p d_1$, where ω_p is the plasma frequency (in eV units) of the foil material, and d_1 is its thickness in microns. At higher γ the radiation energy increases up to a saturation value $\gamma_{sat} \sim 0.6\gamma_{th}(d_2/d_1)^{1/2}$, where d_2 is the distance of the gap between the foils. Similar behaviours have been observed for irregular radiators such as carbon compound foam layers or fiber mats, where the role of the thin foil is played by the cell wall and by the fiber element, and the gap by the cell pore and by the fiber spacing. A detailed description of TR can be found in (Artru et al., 1975).

The MACRO TRD consists of three modules of 36 m^2 total aerea. Each module has an active volume of $6 \times 1.92 \times 1.7$ m^3 and contains 10 planes of 32 proportional tubes, 6 meters long and with a square cross section of 6×6 cm^2. These counters are laid close together between 11 Ethafoam radiator layers of 10 cm of height to form a large multiple layer TRD with reduced inefficient zones. A detailed description of the MACRO TRD is given in (Barbarito et al., 1995). In Figure 1 we show the TRD response, namely the average number of hits at various γ and various beam crossing angles, as measured in a test beam at CERN P.S.

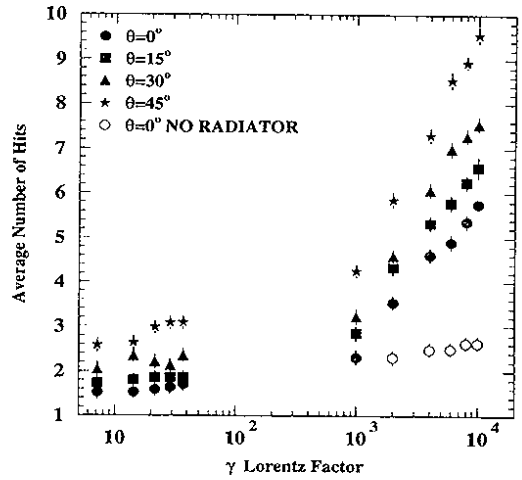

Fig. 1: Average total number of hits for various values of the γ factor : dots: 0^o incident beam angle; open circles: 0^o beam angle without radiator; squares: 15^o beam angle; triangle: 30^o beam angle; stars: 45^o beam angle.

The MACRO detector is located in Hall B of the Gran Sasso Underground Laboratory. The lab is located at an average depth of 3700 hg/cm^2, with a minimum depth of 3150 hg/cm^2. At these depths the residual energy differential distribution of the downgoing muon is estimated to be nearly flat up to 100 GeV and it falls rapidly in the TeV region; the mean value is a few hundred GeV. The TRD has been designed to explore the muon energy range of 100 GeV–1 TeV. Below 100 GeV there is no TR emission; from 100 GeV to 1 TeV the detector has a smoothly increasing response versus γ. For energies greater than 1 TeV, where the muon flux is estimated to be approximately 5% of the total, the TR signal is saturated.

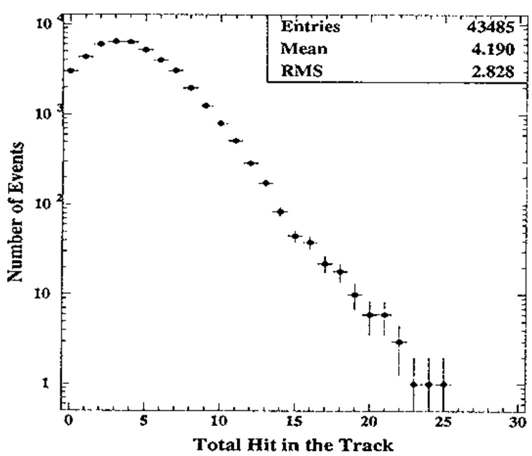

Fig. 2: Hit distribution for single muon tracks crossing the TRD. Only statistical errors are shown.

DATA SELECTION

In this analysis we have considered the data collected from April 1995 to March 1997 by the first TRD module. Since the TRD calibration was performed for particles crossing the ten layers and at zenith angles below 45°, in the analysis only single muons fulfilling these constraints have been included; the analysis method is described in detail in (Ambrosio et al., 1996a). The total number of hits in the track is evaluated by counting the number of TRD hits (in the view perpendicular to the anode wires) along the straight line fitted to the track reconstructed by the MACRO detector. In Figure 2 we report the distribution of the number of hits in the track for these muons.

MUON ENERGY SPECTRUM

In order to evaluate the local muon energy spectrum, we must take into account the TRD response function, which induces some distortions of the "true" muon spectrum distribution. The "true" distribution can be extracted from the measured one by an unfolding procedure that yields good results only if the response of the detector is correctly understood.

We have adopted an unfolding technique, developed according to Bayes' theorem, following the prescriptions of (D'Agostini, 1995) and (Mazziotta, 1995). Usually the unfolding methods require that the independent variable (the energy) is limited inside a finite interval. When it is practically boundless, as for the cosmic ray energy spectrum, the method cannot be automatically applied. However, in our case this problem can be overcome since the detector response is flat outside the 100 GeV–1 TeV energy interval; thus the number of hits related to the energy is effectively "bounded".

Detector simulation

The distributions of the hits collected along a muon track by the TRD at a given zenith and azimuthal angle, $N(k, \vartheta, \varphi)$, can be related to the residual energy distribution of muons, $N(E, \vartheta, \varphi)$, by:

$$N(k, \vartheta, \varphi) = \sum_{j=1}^{n_E} p(k \mid E_j, \vartheta, \varphi) N(E_j, \vartheta, \varphi) \qquad (1)$$

where the detector response function, $p(k \mid E_j, \vartheta, \varphi)$, represents the probability to observe k hits for a track of a given energy E_j and at a given angle ϑ and φ. The response function must contain both the detector acceptance and the event reconstruction efficiency. We have derived the response function simulating the MACRO behaviour using GEANT (Brun et al., 1992), including the trigger efficiency simulation. The simulation of the TRD was based on the test beam calibration data (Figure 1), taking also into account the inefficiency of the proportional tubes. A check of the response function of the TRD is obtained using low energy muons, namely stopping muons and muons with large scattering angle in MACRO, which have energies of about of 1–2 GeV.

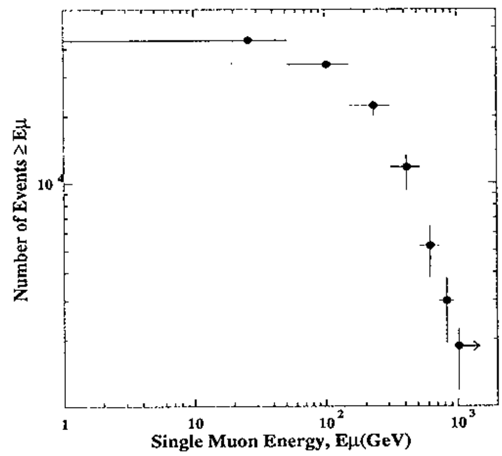

Fig. 3: Integral energy distribution of single muons in the TRD. The last bin to the right is relative to energies larger than saturation (930 GeV). Horizontal bars are the bin width, while vertical bars are the total error (statistical and systematic).

Experimental data distributions

The unfolding procedure described above was applied to the TRD experimental data, starting with a trial spectrum assigned to the unfolded distribution (D' Agostini, 1995; Mazziotta, 1995), according to a local energy spectrum of muons at 4000 hg/cm^2 with a spectral index fixed at 3.7 given by (Lipari and Stanev, 1991):

$$N_o(E, \vartheta, \varphi) \sim e^{-\beta h(\alpha-1)}(E + \epsilon(1 - e^{-\beta h}))^{-\alpha} \qquad (2)$$

The parameters are: $h = 4\ km\ w.\ e.$, $\alpha = 3.7$, $\beta = 0.383\ (km\ w.\ e.)^{-1}$ and $\epsilon = 0.618\ TeV$.

Because the TRD behaviour shows a saturated region (for $E_\mu \geq 930$ GeV), then in that range only the number of events can be evaluated, while below 930 GeV we can reconstruct the energy distribution and we can compute the average value cut to 930 GeV. Figure 3 shows the muon integral spectrum. Figure 4 shows the average muon energy cut to 930 GeV, as a function of the rock depth. The error bars include statistical and systematic uncertainties. The systematic errors have been evaluated by the search of low energy events in the TRD.

DISCUSSION AND CONCLUSION

The muon spectrum deep undergound is determined by the spectrum at the surface and the energy losses in the rock. The muon spectrum at surface is sensitive to the "all-nucleon" spectrum of primary cosmic rays. We have compared our results to the predictions from two extreme hypotheses on the primary spectra (Ambrosio et al., 1996b), namely the "Light" (Fitchel and Linsley, 1986) and the "Heavy" (Goodman, 1982) compositions. However, the mean primary energy that gives a single muon underground is rather similar in the two models (Forti et al., 1990). So the average muon energy underground for single muons is still equivalent for both models.

The interaction of the cosmic rays in the atmosphere was simulated with the HEMAS code (Forti et al., 1990). The produced muons at the surface were then propagated through the rock, with the muon energy loss in the rock evaluated according to the prescriptions of (Lipari and Stanev, 1991). The rock thickness was calculated at each ϑ and φ from the Gran Sasso map (MACRO, 1995). We used the correction procedure described in (Wright et al, 1973) for the conversion to standard rock.

Figure 4 shows the average single muon energies relative to the two predictions taking into account the saturated region of the TRD, together with experimental data (lower part of the figure). Due to the saturation of the TRD, the average energy computed in this way underestimates the real measurement, as is shown in the upper part of the same figure. The average muon energies (cut to retain energies below 930 GeV) for the above models have been evaluated using 6 bins as for the real data; while for the uncut case no binning procedure has been used.

We have measured directly the residual energy of cosmic ray muons crossing the MACRO detector at the Gran Sasso underground laboratory, using a TRD which took data since April 1994. The average single muon energy, removing energies above 930 GeV, is found to be $216 \pm 5 \pm 18$ GeV in the depth range 3150–7000 hg/cm^2. In this way we can estimate that the average single muon energy is about 300–330 GeV at the MACRO depth.

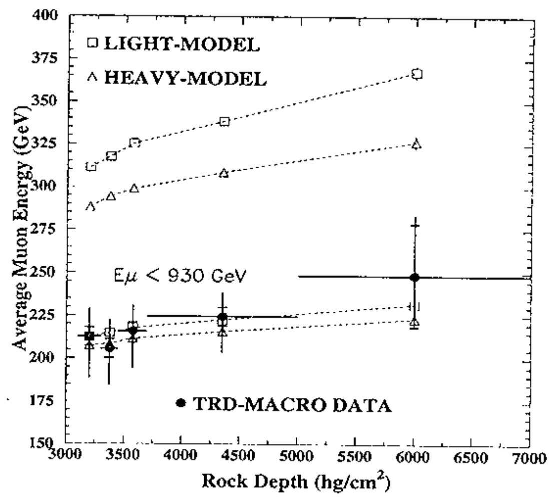

Fig. 4: The lower part of the picture shows the average single muon energy, cut to 930 GeV, versus the standard rock depth. The experimental data are shown together with the predictions of two primary composition models. In the upper part of the figure, the same distributions, with the same symbols, for the uncut case are shown. The extentions of the statistical error bars represent the estimates of systematic uncertainties. The dotted lines are drawn to guide the eye.

Our experimental data, after corrections for the propagation of the muons through the Gran Sasso rock, are consistent, within the errors, with the above predictions. The present precisions do not allow us to distinguish between the above models.

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