Results on high-energy cosmic rays by EAS-TOP at Gran Sasso

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Summary. — Very High-Energy cosmic rays have to be studied through the ground-based detectors of the Extensive Air Showers (EAS) that they produce in the atmosphere. The main measurements to be performed are of: primary energy spectra, composition, anisotropies, «neutral primary» astronomy, and interaction properties. This requires complete detectors of all the EAS components, and for this purpose the EAS-TOP array has been constructed at Campo Imperatore (2000 m a.s.l.) on top of the Gran Sasso underground laboratories. The array has been progressively going into operation since 1988. In this paper we present the status and performances of the different detectors, and the results obtained up to now on the different items under discussion.

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1. – Introduction

The EAS-TOP experiment at Gran Sasso [1] has been planned to study the cosmic radiation in the energy range 10^{12}–10^{17} eV, *i.e.* from the primary energies above the range of direct measurements, to the energies of the «giant» arrays.

The main measurements to be performed are of the primary

a) energy spectrum;

b) chemical composition;

c) anisotropies;

d) gamma-ray component (sources, diffuse, transients);

e) interactions (from the present collider energies to centre-of-mass energies 1-2 orders of magnitude greater).

For such studies it is of major importance to develop detectors of all the EAS components, that have to combine good resolutions with large collecting areas (to have good statistics both on the event rate at the highest energies and on the content of the individual components at the lowest energies). This is the main principle of the experiment, that moreover exploits the opportunity of operating at 2000 m a.s.l. (at the atmospheric depth $x_0 \approx 810$ g cm^{-2}), 1000 m above the underground Gran Sasso laboratory, and therefore of running in coincidence with the additional detectors of muons provided by the underground installations (the mean muon energy threshold at the surface, to reach the underground laboratories at the relative zenith angle $\vartheta \approx 30°$, is $E_\mu = 1.4$ TeV; for a first observation and interpretation of muon bundles underground, see ref. [2]).

The EAS-TOP array had therefore to be located in a pre-fixed site, with ambiental constraints both on the detectors and on the operation techniques and construction procedures.

Fig. 1. – The EAS-TOP array. ■ Scintillator modules, ● Cherenkov telescopes, ▲ radio antennas, □ muon-hadron detector.

The array (see fig. 1) includes detectors of:

a) the electromagnetic e.m. component [3],

b) the muons ($E_\mu >$ GeV) and hadrons [4],

c) the atmospheric-Cherenkov-light (C.l.) component [5],

d) the atmospheric radio emission [6].

Concerning the TeV muon underground detectors, EAS-TOP is operating in coincidence with LVD [7] and MACRO [8].

2. – Status and performances of the detectors

a) The e.m. array [3] consists of 35 modules of scintillator detectors (10 m^2 each) distributed over an area of $\approx 10^5$ m^2. Each of the 10 m^2 modules is split into 16 individual scintillators (NE102A, (80×80) cm^2 area, 4 cm thick) and each scintillator is viewed by two photomultipliers for timing and particle density measurements.

The array is in operation, in different configurations, since 1988. The event rate in the minimum trigger condition (4-fold coincidences) is $f \approx 30$ Hz. The EAS parameters are reconstructed for the so called «internal events», *i.e.* seven-fold coincidences with maximum density recorded by an inner module ($f \approx 1.5$ Hz).

The EAS parameters N_e, X_{core}, Y_{core}, s (slope of lateral distribution function within the Nishimura-Kamata-Greisen formalism) are reconstructed from particle density

Fig. 2. – Percentage integral deficit of events inside the opening angle θ from the centre of the Moon.

data, *i.e.* amplitude measurements. The resolutions, obtained from simulations based on the measured fluctuations and cross checks with EAS data are, for $N_e = 10^5$

$$\sigma_{N_e}/N_e \approx 0.1\,, \qquad \sigma_{\Delta X_{core}} = \sigma_{\Delta Y_{core}} \approx 5\ \text{m}\,, \qquad \sigma_s \approx 0.1\,.$$

The arrival directions are measured through the time-of-flight technique. The accuracy of this measurement is obtained by internal consistency of data and checked through the observation of the shadow of the moon on primary cosmic rays (see fig. 2). The so obtained resolution includes systematic errors. σ_θ results $\approx 2.5°$ for external events, $\approx 0.85°$ for all internal triggers, and $\approx 0.5°$ for internal events with $N_e > 10^5$.

An example of a fully reconstructed event is shown in fig. 3.

b) The muon-hadron detector consists of one module of (12×12) m^2, 3 m high, operating as a hadron calorimeter and as a muon tracking detector. It is made of nine active layers, each of them including two planes of Iarocci tubes operating in streamer mode for muon tracking, and one plane operating in quasi-proportional mode for hadron calorimetry; eight layers of iron 13 cm thick act as absorber (the total thickness is 7 nucleon interaction lengths, corresponding to a 95% energy containment up to

Fig. 3. – *a*) Full reconstruction of a UHE cosmic-ray event: the particles number detected by each module is shown, together with the core position (indicated as a $\times$), N_e, s, as reconstructed through the NKG fit, and the arrival direction as measured by the times of flight (see text) ($\log N_e = 6.31$, $s = 1.14$, $\vartheta = 40.1$, $\varphi = 46.9$). The modules used for the arrival direction determination are included within the dotted line: their relative firing times (adjusted in order to take into account the different detectors heights and referred to the first fired one) are shown in the box in the upper part of the figure: the arrow indicates the event direction. *b*) Experimental lateral distribution of the same event: the solid line shows the best fit to the NKG formula ($\log N_e = 6.31$, $s = 1.14$).

1 TeV hadrons). Below the 2nd layer of iron, a larger spacing (15 cm) allows the installation of plastic scintillators for timing measurements of individual hadrons (and a cross-check of amplitude measurements). Four similar scintillators are operating on top of the calorimeter.

*b*1) Muons [9] are tracked by the streamer tubes of the muon-hadron detector (resolution 3 cm both on the wires and the orthogonal strips). The measured accuracy in reconstructing the muon arrival direction is 0.9°, and in muon counting is $\Delta N_\mu / N_\mu < 5\%$ up to $N_\mu = 30$ (a muon track is defined by the alignment of 6 hits). The muon detector includes also a distributed array (for a total of 130 m^2) made of scintillators located below the e.m. detectors and covered by 25 cm of iron, providing information on the muon content of EAS not limited to a single core distance.

*b*2) Charges induced by hadronic cascades developing in the quasi-proportional chambers are detected through a matrix of 840 pads for each layer of tubes. The pad dimension chosen ((38×40) cm^2) matches the lateral spread of the hadronic shower (the confinement radius is approximately 20 cm), allowing to minimize the number of ADC channels (7560 in total).

The energy resolution for hadron calorimetry has been obtained through a Monte Carlo simulation assuming the charge resolution and dead space measured in laboratory tests and in operating *in situ* conditions [10]. The charge response and efficiency of each pad is checked during special runs, with a single muon trigger. From the simulation [11], a good linearity in energy response is expected up to 2 TeV, with an energy resolution $\leqslant 40\%$ beyond 50 GeV. At higher energies, due to the lack of containment, the energy resolution reaches $\approx 60\%$ at 50 TeV.

c) The atmospheric-Cherenkov-light detector [12] consists of 8 steerable telescopes (4 in operation and 4 under construction), each of them supporting three 0.6 m^2 parabolic mirrors, 70 cm focal length. Each atmospheric-Cherenkov-light telescope includes:

*c*1) two large-angle detectors ($\approx 18°$ full field of view) for operation in coincidence with the underground muon apparatuses, and in general with the detectors of the other EAS components. Beside the large opening angle, such configuration provides a good measurement of the amplitude of the C-light signal, and a large effective detection area.

*c*2) one high-resolution imaging device [13], based on multi-channel photomultipliers (Philips XP4702 and XP1702 and Hammamatsu H4140, with pixel dimension 2.5 mm corresponding, with the used optics, to $\Delta\theta = 0.2°$). Combined with technique *c*1), with the underground muon detectors, and the detectors of other EAS components, this provides a tool to study the EAS development in the atmosphere, besides gamma-rays from point sources.

d) The radio array [6] consists of three antennas 15 m high, located on different sides of the apparatus, at distances of 200 m, 400 m and 550 m from each other, operating in two wave bands: 350–500 KHz and 1.8–5 MHz. The antennas can operate both triggered by a multiple coincidence of the e.m. detector ($N_e > 5 \cdot 10^5$; corresponding to $E_0 \approx 10^{15}$ eV), and in self-trigger mode.

3. – Results

3·1. UHE γ-*ray astronomy*

3·1.1. Limits from candidate point sources. A search for excesses in the counting rate from candidate point sources has been performed through data collected in 1989 and 1990-1993, for a total of 5000–6000 h/source [14].

Thirteen candidate sources (*i.e.* Cygnus X-3, Hercules X-1, Cygnus X-1, 4U0115 + 6112, Crab Nebula, Geminga, PSR1953 + 29, PSR1937 + 214, PSR 0157 + 6112, LSI + 61, North Gal. Pole, M31, Markarian 421) have been studied in the different trigger configurations (corresponding to different primary energies), in the search for possible d.c., sporadic and periodic emissions: no evidence for significant excesses has been found and upper limits have been placed (for results obtained from other arrays, see, for example, ref. [15]).

In the case of *Cygnus X*-3, the limits (*e.g.* $\Phi_{\text{d.c.}}(>230\ \text{TeV}) < 2.0\cdot 10^{-14}\ \text{cm}^{-2}\ \text{s}^{-1}$, $\Phi_{4.8\text{h}}$ [16] $(>230\ \text{TeV}) < 3.2\cdot 10^{-15}\ \text{cm}^{-2}\text{s}^{-1}$, at 90% c.l.) are well below the fluxes reported in the early '80s [17] (of factors ≈ 80 and ≈ 300, respectively, for d.c. and periodic signals). Moreover, a long-term variation in the emission can be excluded, due to the yearly analysis, at least from 1989 to 1993.

The upper limit obtained from the *Crab Nebula* is $\Phi\ (>25\ \text{TeV}) < 4\cdot 10^{-13}$ $\text{cm}^{-2}\text{s}^{-1}$, *i.e.* a factor from ≈ 2 to ≈ 10 higher than the fluxes derived from the extrapolation of the measurements at lower energies [18].

The results obtained in the search for sporadic emission is negative at < 1.5 events/y with flux level $\Phi\ (>105\ \text{TeV}) < 2.7\cdot 10^{-12}\ \text{cm}^{-2}\text{s}^{-1}$ and duration < 5.5 h. The study of transient phenomena through contemporaneous observations by different arrays is thus most important. Of particular significance is the event recorded on 23rd February 1989 from the direction of the Crab Nebula by the Baksan [19], KGF [20] and EAS-TOP [21] arrays. The three experiments detected an excess of showers, at the transit of the Crab Nebula over them: a summary of the three observations is given in table I.

The overall confidence level of the event is 10^{-5} and the observed flux in ≈ 5.5 hours of observation is

$$\Phi(>105\ \text{TeV}) = 2 \pm 1\cdot 10^{-12}\ \text{cm}^{-2}\text{s}^{-1}\,.$$

This flux is about 60 times higher than the extrapolation at 100 TeV of the observed TeV flux.

The event duration is inferred from the fact that there were no reports about the effect at eastern (Akeno) or western (Hegra) air shower arrays: the total duration is

TABLE I. – *Summary of the observations of the Crab Nebula on the* 23rd *February* 1989, *by the Baksan,* KGF *and* EAS-TOP *arrays* (S_i = *internal events*, S_e = *external events*).

Array	observation time (h UT)	On	⟨Off⟩	(on-off)/σ
KGF	13-16	35	17.8	3.4
Baksan	15-18	55	34.1	3.1
EAS-TOP (S_i)	17-20	38	25.5	2.1
EAS-TOP (S_e)	17-20	403	378.3	1.2

thus ≈ 10 h. During this time interval, no installation having the source within its field of view contradicts the observation; this episode still stands as the most significant effect recorded at UHE energies.

3.1.2. The study of Geminga. After the detection of pulsed radiation ($P = 237$ ms) from Geminga in X-rays (ROSAT) [22] and 300 MeV γ-rays (EGRET) [23], the search for the same periodicity in the UHE energy range became possible.

This search has been performed in the EAS-TOP 1992 and 1993 data sets. The light curve [24] resulting from ≈ 1200 h of observation from December 1991 to January 1993 showed, on the lower energy trigger ($E_0 \approx 45$ TeV), a significant signal in the two bins expected from the EGRET ephemeris without any degree of freedom in the analysis (see fig. 4*a*)). The probability for the excesses in the two bins to be due to statistical fluctuations (shown to be Poissonian) is $\approx 2 \cdot 10^{-4}$, taking into account the four different classes of events analysed. The observation time has then been extended until December 1993 (≈ 2200 h) [14]: a slight d.c. excess at 1.7 s.d. is still present. The obtained light curve is shown in fig. 4*b*): the two arrows indicate the phases of EGRET peak 1 (P1) and peak 2 (P2). The light curve shows only one excess in the bin corresponding to peak 1: it contains 52 971 events against 52 190 expected from a uniform distribution of the background into the 20 bins, corresponding to an excess of 3.4 s.d.

Taking into account the total number of data sets analysed (4) and the number of peaks of the emission (2), the probability for the excess to be due to statistical fluctuations is $\approx 2 \cdot 10^{-3}$. Such probability is not low enough to allow a definite

Fig. 4. – Geminga Pulsar light curve: *a*) 1993, *b*) 1992-1993 data. Phases corresponding to peak 1 (P1) and 2 (P2) of «EGRET» emission are indicated. The typical error is shown.

conclusion; therefore we derive the limit to the pulsed emission in the two pulsar peaks

$$\Phi(>45\ \text{TeV}) < 1.2\cdot 10^{-13}\ \text{cm}^{-2}\,\text{s}^{-1}(90\%\ \text{c.l.})\,.$$

3·1.3. Study of the galactic disc. A search for UHE ($\geqslant 100$ TeV) diffuse γ-ray emission from the galactic disc [25] has been carried out, through the excess in the cosmic-ray counting rate. Measurements are performed from angular scales $|b^{\mathrm{II}}| \approx 2°$ (as in 100 MeV satellite experiments [26], and as expected from CR interactions with the ISM [27]) to $|b^{\mathrm{II}}| \approx 10°$.

The obtained upper limits (90% c.l.) to the γ-ray excess over the cosmic-ray flux from the galactic-disc region are $I_\gamma / I_{\mathrm{p}} < 0.2\%$ for $|b^{\mathrm{II}}| < 2°$, corresponding to upper limits to the flux of $I_\gamma < 3.2\cdot 10^{-13}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{rad}^{-1}$. This measurement, obtained inside the angular window corresponding to the distribution of the ISM, is still a factor ≈ 30 higher than the flux calculated from the CR interactions by Berezinsky and Kudryavtsev [27]. Other studies of the galactic disc are reported in ref. [28].

The lower limit that we obtain to the power law index of the differential energy spectrum of galactic γ-rays from 100 MeV to 100 TeV is $\gamma > 2.3$, thus setting a limit to the possibility of a hard extrapolation of the galactic γ-ray spectrum to the 100 TeV region.

3·1.4. The sky survey. A search for excesses in the cosmic-ray counting rates from regions of the sky not coincident with candidate γ-ray point-like sources (or not compatible with the detector angular point spread function) has been performed at primary energy $E_0 > 200$ TeV [29]. Upper limits to possible excesses in the c.r. counting rates from any sky cell of dimensions $\Omega_1 = 1.7\cdot 10^{-3}$ sr, $\Omega_2 = 1.0\cdot 10^{-2}$ sr, $\Omega_3 = 3.0\cdot 10^{-2}$ sr have been derived (using different classes of events with the appropriate angular resolution) and are, respectively

$$I_1(>200\ \text{TeV}) < 2.0\cdot 10^{-10}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,,$$

$$I_2(>200\ \text{TeV}) < 2.0\cdot 10^{-11}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,,$$

$$I_3(>200\ \text{TeV}) < 1.2\cdot 10^{-11}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,.$$

The resulting upper limit to point-like sources in any region of the sky (based on I_2 which provides the best significance) is

$$\Phi(>200\ \text{TeV}) < 2.0\cdot 10^{-13}\ \text{cm}^{-2}\,\text{s}^{-1}\,.$$

The results of a sky survey based on the EAS muon content can be found in ref. [30].

3·2. *The search for γ-ray bursts of* $E_\gamma \geqslant 10$ GeV *and* $E_\gamma \geqslant 100$ TeV. – Cosmic γ-ray bursts [31] are searched at primary energies $E_1 > 10$ GeV (by exploiting the total counting rate of the e.m. detector operating in single mode, and therefore without information on the arrival directions, time scale ≈ 1 s) and at $E_2 \geqslant 80$ TeV (from the EAS data, and therefore with the arrival direction measurements; time scale 0.1–10 s). For previous data from ground-based installations see, *e.g.*, ref. [32].

The present results [33] show one candidate event (with significances 20.1 and 10.6

s.d. in two independent channels) observed in the energy range E_1 (on July 15, 1992, 13:22:26 UT) in 4444 hours ON time.

No candidate event is observed in 2743 hours ON time at energies E_2.

During the operation 7 BATSE events have been detected over the horizon. No excess has been found on both triggers in the time interval corresponding to the BATSE excesses; the resulting upper limits are

$$\Phi(>10\ \text{GeV}) = 1.9\cdot 10^{-3}\ \text{photon cm}^{-2} \quad \text{and} \quad \Phi(>100\ \text{TeV}) = 1.7\cdot 10^{-8}\ \text{photon cm}^{-2};$$

This implies as lower limits to the differential index of energy spectrum for such bursts

$$\gamma > 1.8\ \text{between 100 KeV and 10 GeV and}\ \gamma > 2.0\ \text{between 100 KeV and 100 TeV}.$$

3·3. *The cosmic-ray anisotropy at* $E_0 \approx 100$ TeV. – The cosmic-ray sidereal anisotropy [34] has been studied [35] at median primary energies $E_1 = 60$ TeV (fourfold coincidences) and $E_2 = 170$ TeV (internal events).

At energies E_1 an anisotropy is observed with significance 7.2 s.d., with consistent results over two years of data taking (*i.e.* 1990 and 1992). The amplitude is $A = (6.5 \pm 0.9)\cdot 10^{-4}$, and the phase $\Phi = (2.6 \pm 0.5)$ h LST. This measurement, compared with the lower-energy data [33], shows that the c.r. anisotropy is constant in phase and amplitude over about three decades in primary energy ($\approx 10^{11}$–10^{14} eV), implying a similarity in the c.r. propagation over the whole energy range, and a constant structure of the local interstellar medium up to distances $\approx (3–5)\cdot 10^3$ AU.

Data analysed *vs.* declination show the «$\cos\delta$» behaviour expected for a vectorial anisotropy.

No significant second harmonic is observed; the obtained upper limit is $A_2 < 3\cdot 10^{-4}$.

At energies E_2 the upper limit to the observed anisotropy is $A < 8\cdot 10^{-4}$, thus excluding a sharp increase of the anisotropy itself above 100 TeV.

3·4. *Fractal behaviour of cosmic-ray time series.* – An analysis of the fractal and statistical behaviours of the recorded cosmic-ray time series has been performed [36]. Two time series of single-particle rates (essentially all muons, $E_1 \geqslant 10$ GeV) and two time series of fourfold coincidences (air showers, $E_2 \geqslant 80$ TeV) are considered. The aim is to investigate the nature of the physical processes encountered by the galactic cosmic rays during their propagation from the source to the detector.

The fractal analysis estimates the fractal dimension of the measured signal in four independent ways (namely the Grassberger-Procaccia correlation dimension algorithm, the scaling exponent method, the yardstick length method and the power spectrum dimension simulation), the reason for this multiple evaluation being that if the four estimates agree, then the system is most probably stochastic.

The analysis leads to the following results: 1) the single-muon time series, corresponding to $E_1 \geqslant 10$ GeV, have fractal dimensions $d = 2.2 \pm 0.2$; all the used tests agree in indicating that, in the frequency domain $4\cdot 10^{-6}$ Hz $< f < 8\cdot 10^{-4}$ Hz, the signal is stochastic, and in particular, is coloured random noise with spectral index $\alpha = 1.85 \pm 0.05$; 2) the EAS time series, corresponding to $E_2 \geqslant 80$ TeV, have fractal dimension $d = 4.7 \pm 0.6$; all results agree and indicate that, in the frequency domain 10^{-6} Hz $< f < 10^{-4}$ Hz, the signal is coloured random noise with spectral index $\alpha = 1.25 \pm 0.10$.

In conclusion, the finite value of the fractal dimension obtained for the EAS-TOP data does not support the presence of a strange attractor in the system dynamics. Moreover, the similarity of these results to those obtained with underground muons and neutron monitors suggests that stochasticity and dependence of the fractal dimensions of the detected particles on the primary energy may indeed be common features to all cosmic-ray time series detected on Earth.

3·5. *Phenomenology: lateral and temporal characteristics of* EAS. – Understanding the possibilities of obtaining information on the EAS longitudinal development from measurements of the e.m. component at the observation level is one of the experimental problems in UHE c.r. physics and γ-ray astronomy. By exploiting the good reconstruction capabilities of EAS-TOP on the EAS lateral distribution function (LDF), and the good timing accuracies, a study has been performed of the correlation between the slope of the LDF (represented by the «s» parameter of the NKG formalism), and the curvature of the EAS front [37] (represented by the delay τ of the particles at fixed core distance with respect to the plane tangent to the disk in the core).

Inside large fluctuations, an anticorrelation is found, the experimental relation being $\Delta\tau(\mathrm{ns}) \approx -6\Delta s$, for $r \approx 100$ m. In fact showers originated higher in the atmosphere have flatter lateral distributions (*i.e.* larger «s»), and larger radii of

Fig. 5. – The experimental EAS size spectrum and the expected one from the extrapolations of the lower energy data; the error band corresponding to 1 s.d. error of the measured helium spectrum is also shown (dotted line).

curvature (*i.e.* smaller τ). This proves that both parameters are correlated to the EAS stage of development.

The experimental results are in agreement with the calculations by Nakatsuka [38], where pure e.m. cascades were considered.

3·6. *The primary spectrum between* 10^{14} *and* 10^{16} eV. – The EAS primary spectrum (see, *e.g.*, ref. [39]) has been studied, through the shower size spectrum, at the depth of ≈ 810 g cm^{-2} in the size interval 10^5–10^7 particles [40]. The total intensity above 10^5 particles is $(1.18 \pm 0.02) \cdot 10^{-5}$ m^{-2} s^{-1} sr^{-1}; as can be seen in fig. 5, the change in slope («knee») is observed at $N_e \approx 10^6$ particles, with change in the index of the power law integral energy spectrum from 1.67 ± 0.01 (for $5.2 < \log N_e < 5.7$) to 2.09 ± 0.1 (for $6.2 < \log N_e < 6.7$).

TABLE II. – *Integral flux at* 100 TeV(m^{-2} sr^{-1} s^{-1}) *and spectral indices of the nuclear components of the* Σ*-model.*

Mass group	Integral flux	$\gamma - 1$
p	$(1.33 \pm 0.31) \cdot 10^{-5}$	1.86 ± 0.07
He	$(2.28 \pm 0.44) \cdot 10^{-5}$	1.72 ± 0.09
CNO	$(7.09 \pm 0.48) \cdot 10^{-6}$	1.67 ± 0.06
Mg-Si	$(2.48 \pm 0.15) \cdot 10^{-6}$	1.82 ± 0.11
Fe	$(6.94 \pm 0.63) \cdot 10^{-6}$	1.60 ± 0.11

Fig. 6. – Lateral distributions of muon for vertical showers at fixed EAS sizes. ▲ $\log N_e = 4.5$–4.8, ○ $\log N_e = 4.8$–5.0, △ $\log N_e = 5.0$–5.3, $\log N_e = 5.3$–6.0, ● $\log N_e > 6.0$.

As a first step, data are interpreted by means of

a) the conversion from primary energy to shower size obtained through the HEMAS code [41];

b) the extrapolation of the primary spectra directly measured at lower energies (JACEE [42] and CRN [43]).

It results that such extrapolation of the cosmic-ray primary beam (Σ-model, see table II) from ≈ 100 TeV to ≈ 1000 TeV (*i.e.* below the knee, maximum energy at which the extrapolation is meaningful) explains fairly well the measured size spectrum.

3·7. GeV *muon studies*. – The lateral distribution of muons ($E_\mu > 2$ GeV) and the dependence of N_μ on N_e in EAS is obtained through the analysis of $\approx 500\,000$ events triggered by the e.m. detector [9]. The muon density is measured by the μ *tracking detector* after correcting for its acceptance and subtracting the background accidental muons. The lateral muon distribution for vertical showers (*i.e.* EAS zenith angle $\vartheta < 17.7°$) for different N_e values is plotted in fig. 6, in which the results of least-square fits obtained by means of a Greisen parametrization are also shown:

$$\varrho_\mu(r) = kr^{-0.75}(1 + r/r_0)^{-2.5} .$$

From the fit the average value of r_0 is ≈ 530 m. Using these muon lateral distributions, the total number of muons N_μ in a shower is calculated and compared to the shower size N_e (see fig. 7). A relation $N_\mu = K\, N_e^\alpha$, with $\alpha = 0.73$ is found.

Fig. 7. – Number of muons (N_μ) *vs.* EAS size (N_e), for three intervals of zenith angles: ● $1.00 < \sec\vartheta^{\rm EAS} < 1.05$, $1.15 < \sec\vartheta^{\rm EAS} < 1.20$, ◇ $1.30 < \sec\vartheta^{\rm EAS} < 1.40$.

3·8. *Study of the* EAS *core structure*. – Presently the upper layer of proportional chambers of the *calorimeter* has not been shielded with the absorber and it is therefore used as a detector of the e.m. component of EAS with high spatial resolution, allowing a precise core mapping.

The study of the core structure of EAS is relevant when performing:

i) a detailed analysis of the EAS electrons lateral distribution function (LDF) in the core region ($r \approx 0$–10 m), also as a tool for the study of the primary composition [44];

ii) an investigation of the EAS core absorption characteristics, to measure the fraction of energy not yet transferred to the e.m. cascade;

iii) a search for events with anomalous LDF («multicore»). This study gives information on the transverse momenta [45] of secondary particles produced in interactions occurring at energies greater than the ones presently observed at accelerators.

In fig. 8*a*) we show the particle distribution observed at the top level of the calorimeter (without absorber and therefore dominated by the e.m. component) in an event with the core on the apparatus. The spatial resolution of the pad matrix allows,

Fig. 8. – Image of an EAS core (*a*)) as observed by the unshielded upper layer of the calorimeter, and number of particles detected by each module of the scintillator array (*b*)) for the same event.

Fig. 9. – *a*) Lateral distribution of the electrons in the event shown in fig. 8 (716573). The dashed and continuous lines show the fits (according to the NKG formula) for the scintillator and calorimeter data, respectively. *b*) Lateral distribution of the electrons in an event (24035) showing a different behaviour at small core distances. Both in *a*) and *b*) △ EMD data, ○ MHD data.

as expected, a very precise location of the core. The EAS parameters of such events are therefore obtained [46] using the core region data (fig. 8*a*)) and the distant-scintillator e.m. ones (fig. 8*b*)).

Figure 9*a*) shows the obtained LDF of the quoted event. The agreement between the calorimeter (open circles) and scintillator (triangles) data is in this case excellent. The fits of the two data give pratically the same results ($\log(N_e) = 5.93$ and 5.92, respectively). In some cases the two LDFs obtained at core distances of a few metres and tens/hundreds of metres are different. Figure 9*b*) shows an event with a clear flattening of the LDF near the core. This effect, which can be related to primary composition [43], has been already observed [47], but up to now without conclusive results.

The analysis of one year of data, with core located on the calorimeter, is in progress; it includes > 100 events with primary energy above the «knee» of the primary spectrum.

3˙9. *Primary composition and interactions*

3˙9.1. The coincidences of the e.m. array with the deep underground detectors (MACRO). The rate of coincidences between EAS-TOP and MACRO in the present detector and trigger configurations is ≈ 10 ev/h, while the rate of internal events (*i.e.* events for which the core can be located and the shower size can be measured) is ≈ 1 ev/h. Coincidences are based only on timing data ($\Delta t < 1$ μs), and good agreement between the reconstructed EAS parameters from the two detectors has been obtained (*i.e.* compatible with the resolutions of the two individual detectors) [8].

The analysis of the data collected in 1990 with two supermodules of MACRO in operation, and in 1992 with six supermodules of MACRO has been performed [8, 48]. This indicates, in the shower size range below the «knee» (*i.e.* $E_0 \approx 10^{14}$–$2.0 \cdot 10^{15}$ eV), a general agreement of the N_μ / N_e data with the expectations from the extrapolation of the lower-energy composition data (Σ-model, see table II), while pure proton or pure iron beams cannot fit the experimental data, with significances > 5 s.d. Above the «knee» of the primary spectrum, the quantitative conclusions are still limited by statistics to the constraint that pure «light» (proton) or «heavy« (Fe) compositions can be excluded with good confidence levels (> 2 s.d.). No dramatic change of composition is therefore required around the «knee» of the c.r. primary spectrum. Of course these results are still dependent on the interaction model; a check of the model will be partly possible through the contemporaneous observation of different EAS components (low-energy muons, atmospheric Cherenkov light, hadrons).

3·9.2. The coincidences of the e.m. and μ arrays with the deep underground detectors (LVD). Coincidences with the underground LVD installation have been reported on different items [7, 49]:

i) study of the c.r. composition and interactions from the correlated data on N_e / N_μ(TeV) (the highest-energy event recorded in coincidence by the two arrays has $N_\mu = 32$, and $N_e = 5 \cdot 10^7$, corresponding to $E_0 \approx 10^{17}$ eV), and N_e / N_μ(GeV)$/ N_\mu$(TeV);

ii) search for the neutral component produced in c.r. UHE interactions, and detected by the LVD scintillator (an interesting study of the background-induced deep underground by the high-energy cosmic rays can be performed);

iii) correlated studies with large energy losses deep underground, due to the muons with the highest energies (*i.e.* due to primaries with high energy / nucleon at the top of the atmosphere, or to secondaries produced in the tail of the fragmentation region).

The coincidence rate between EAS-TOP and the first tower of LVD is ≈ 2.4 events / hour; 10% of such showers have axis internal to the EAS-TOP boundaries.

3·9.3. The coincidences of the Cherenkov array with the deep underground detectors (LVD and MACRO). The main aim of such measurement (proposed and first realized by the EAS-TOP group) [12, 50] is to lower the primary energy threshold in the coincident surface-deep underground experiments. In fact, with such technique it is possible to operate at primary energies $E_0 < 10$ TeV, where only primary protons contribute to the muon flux observed deep underground, and therefore perform a measurement of the product «flux times cross-section» with a known primary beam. We remember that both the primary proton flux and the effective cross-section for secondary production are known with errors $> 10\%$ in this energy range. Moreover, following the recent satellite and balloon data, the p spectrum seems to steepen at these energies with respect to the spectrum of the heavier nuclei (including α) [51]. This would be of huge significance, and this technique could provide a significant contribution in the measurement of the ratio

Fig. 10. – Distribution in primary energy of the events giving at least one μ deep underground for p and α primaries. Part *a*) shows the result for a steepening p-spectrum (see ref. [50]); in part *b*) the same spectral index ($\gamma = 2.75$) for p and α primaries is used.

α/p, by exploiting the main feature of the high-energy muon component of being related to the energy/nucleon of the primary nucleus [52].

This can be deduced from fig. 10, where the distributions in primary energy of different primaries giving at least one muon at the depth of the underground laboratories (*i.e.* $E_\mu > 1.4$ TeV) are shown. Different spectra are used: in fig. 8*a*) the p spectrum with slope $\gamma_1 = 2.64$ and cut-off at 40 TeV with $\gamma_2 = 3.22$ (ref. [50]), and in fig. 10*b*) the same spectral index $\gamma = 2.75$ for both p and α spectra. At $E_0 \approx 10$ TeV, primary energies are measured in individual events through the Cherenkov-light (C.l.) signal with accuracy better than 30%. By neglecting the inaccuracies of the interaction model, the two relative compositions can be separated from the rate of coincidences $n(E_0 > 2.0 \cdot 10^4 \text{ GeV})/n(E_0 > 5.0 \cdot 10^3 \text{ GeV})$. Viceversa, if the uncertainties in the p spectrum could be neglected, as at $E_0 \approx 10^3$ GeV, the cross-section for production of secondaries could be measured in the fragmentation region ($x > 0.1$), of difficult access to the colliders.

First coincidences between the underground muons recorded by MACRO and atmospheric-Cherenkov-light flashes recorded by EAS-TOP have been observed in winter 1989-1990 [49]. Correlated measurements with LVD [7] have been performed in 1992: an efficiency $\varepsilon > 40\%$ in detecting the atmospheric counterpart of TeV muons reaching LVD has been obtained.

A complementary approach is provided by the measurement of the Cherenkov-light signal associated to high-energy hadrons triggering the EAS-TOP calorimeter (a first detection and interpretation of atmospheric EAS Cherenkov light associated with high-energy hadrons was reported in ref. [53]). In fig. 11 the distribution of $y = 1/x = E_0/E_\mathrm{r}$ (E_0 = primary energy, E_r = energy of the residual hadron) is shown. Again a measurement of $n(y > 5)/n(y > 0)$ provides a measurement of the primary ratio α/p in the energy range 5–50 TeV. Both these measurements are possible at a 10% statistical level in a few seasons of data taking, and are complementary to the direct meas-

Fig. 11. – Expected distribution of the ratio E_0/E_r (E_0 = primary energy, E_r = energy of the residual hadron) calculated for p and α primaries (f = event rate in a.u.).

urements (that at the highest energies suffer from statistics and systematics limitations). Moreover, concerning the interaction properties, the two methods (C.l. + TeV muons, and C.l. + hadrons) depend on different uncorrelated features; the former on the cross-section of secondary production: $(\mathrm{d}\sigma/\mathrm{d}x)_{x\approx 1}$ and the latter on the total cross-section and elasticity.

3·10. *Imaging of atmospheric Cherenkov light.* – Images of atmospheric-Cherenkov-light flashes have been obtained by using multi-channel photomultipliers (p.m.) Philips XP1702 (64 pixels), XP1704 (96 pixels) and Hammamatsu H4140 (256 pixels).

A shower as observed with p.m. Hammamatsu H4140 is shown in fig. 12, the pixel dimension being $\Delta\theta = 0.2°$, and the primary energy $E_0 \approx 5\cdot 10^{13}$ eV. We want to outline here two studies, concerning:

a) the comparison of the responses of two imaging detectors operating in coincidence on the same mounting, and

b) the first correlated analysis of the C.l. images and the e.m. detector data.

The obtained main results are the following:

a) after superimposing the two images, the comparison between the numbers of photoelectrons (p.e.) recorded on corresponding pixels on the two photocatodes

Fig. 12. – EAS Cherenkov-light image observed with photomultiplier. Hammamatsu H4140.

provides the error measurement of the number of p.e.:

$$\sigma/\langle n\rangle = (1.48^2/\langle n\rangle + 0.15^2)^{0.5} ,$$

i.e. a term with Poissonian behaviour plus a 15% constant value (mainly due to uncorrected differences of the pixel gains).

This [54] provides the experimental accuracy with which the EAS can be reconstructed in space. In particular, the direction of the maximum of the C.l. signal, defined as the barycentre of the four pixels with the largest p.e. counting, for a large number of p.e., is measured with accuracy $\delta\theta \approx 0.2°$.

b) the dependence of the parameters (width, length, azwidth [55], used by the Whipple group to select directional γ-ray primaries with respect to the uniformly distributed hadronic background) on the detection geometry has been studied [5]. As an example, the result for the width is shown in fig. 13, compared to the expectations from a simulation. The agreement is good, and, as expected, EAS propagating parallel to the axis of the detector are characterized by smaller values of the parameter. This dependence, previously obtained through simulations, has been successfully applied to the search of VHE γ-rays from the Crab Nebula [56].

3·11. *Detection of «horizontal air showers»*. – Showers recorded from directions near to the horizon provide a low-background channel for the detection of penetrating particles, as muons and neutrinos, at high energies.

For zenith angles $\vartheta > 70°$, an excess of EAS is observed with respect to the expectations from their attenuation length in the atmosphere (see fig. 14), which can be represented by an exponential absorption law: $I(\vartheta) = I(0°)\ \exp[-k \sec\vartheta]$, where

Fig. 13. – Plot of the parameter width *vs.* the tilt angle α between the optical axis of the Cherenkov detector and the EAS arrival direction (▲). The expectations from a simulation ($*$) of the detection geometry are also drawn.

$k = \gamma x_0 / \Lambda_{\mathrm{EAS}} \approx 6$ provides a value of the attenuation length of EAS $\Lambda_{\mathrm{EAS}} \approx 230\,\mathrm{g\,cm^{-2}}$ compatible with other measurements, being $\gamma = 1.7$ and $x_0 = 810\ \mathrm{g\ cm^{-2}}$.

The arrival direction of these events is confirmed by different approaches [57]:

i) the measured arrival direction accuracy for the very inclined events ($\sigma_\vartheta = 1.5°$ for $\vartheta > 60°$);

ii) the absence of events from the direction of the sky shaded by the top of the mountain on which the array is located;

iii) the agreement between the arrival directions as reconstructed by the electromagnetic and the muon detectors: $\sigma(\vartheta_{\mathrm{e.m.}} - \vartheta_\mu) = 4.7°$ for $\vartheta_{\mathrm{e.m.}} > 70°$.

Accurate measurements of the arrival directions allow to select these events only from the zenith angle selection ($\vartheta > 75°$); the contamination from events with lower zenith angle being $\approx 20\%$. In 326 observation days we recorded 36 events with $\theta > 75°$: 21, 15 and 7 of them with energy losses in the triggering modules (we use only internal events) larger than $\Delta E_{\min} = 8.2$, 16.4 and 32.8 MeV, respectively.

In the following we discuss the first results obtained on the muon flux and an upper limit to the extraterrestrial neutrino flux [58].

3·11.1. The muon flux at $E_\mu > 30$ TeV. If we assume that all observed events are produced by muon interactions (bremsstrahlung and photoproduction) then

Fig. 14. – The measured zenith angle distribution of the detected EAS. The solid line shows the exponential behavior of the angular distribution of primary cosmic rays.

comparing the experimental rate with the calculated one we can derive the UHE muon flux.

Using the events with $\Delta E_{min} = 8.2\,\text{MeV}$, we obtain

$$S_\mu(> 30\ \text{TeV}) = 1.1 \cdot 10^{-11}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,,$$

with statistical error 22% and systematic errors 10% and 6% due to the uncertainties in the calculations and in the index of the assumed muon energy spectrum ($\gamma = 3.70$).

This result is well consistent, within the experimental errors, with the extrapolation of the MUTRON spectrum [59], the underground measurements [60], and calculations [61].

3.11.2. Limit to the diffuse extraterrestrial neutrino flux. Since all events with threshold $\Delta E_{min} = 32.8$ MeV can be explained by muon interactions, we can derive upper limits to the flux of other penetrating particles as neutrinos.

The upper limit to the neutrino flux is obtained assuming the neutrino spectrum calculated by Szabo and Protheroe of the $\nu_\mu + \bar{\nu}_\mu$ fluxes from AGNs [62], and using the asymptotic flavour ratio [63] $I_{\nu_e + \bar{\nu}_e} = 0.45\, I_{\nu_\mu + \bar{\nu}_\mu}$. We obtain that the maximum contribution to the shower rate (about 80%) would come from the energy interval $E_\nu = 10^5$–10^6 GeV; the limit to the integral flux (90% confidence level) is

$$I_\nu(> 10^5\ \text{GeV}) < 1.5 \cdot 10^{-8}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,.$$

For the resonant process ($\bar{\nu}_e + e^- \Rightarrow W^- \Rightarrow$ hadrons) at $E_{\bar{\nu}_e} = 6.4 \cdot 10^6$ GeV the limit is

$$\frac{dI_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} (E_{\bar{\nu}_e}) < 7.6 \cdot 10^{-18}\ \mathrm{cm^{-2}\, s^{-1}\, sr^{-1}\, GeV^{-1}}\,.$$

These limits represent, in the energy range 10^4–10^7 GeV, new results on the extraterrestrial diffuse neutrino flux. Although they are more than one order of magnitude higher then the fluxes predicted from AGNs and other extraterrestrial sources [62], these results demonstrate the potential effectivity of the HAS technique for UHE neutrino astronomy.

4. – Conclusions

The development and completion of the array(without increasing the external installations) require:

a) The coverage of the central calorimeter with lead absorber (15 cm) to shield the detector from the e.m. component in the region of the EAS core. This is necessary to perform hadron calorimetry in the higher-energy region, and in particular above the «knee» of the primary spectrum.

b) The coverage of such lead absorber with a detector of the e.m. component based on the same technique (proportional tubes) and with the same resolution ($\approx 40 \times 40\ \mathrm{cm}^2$) as the hadronic one.

c) The completion of the muon-hadron detector with a simple module (three layers of iron absorbers of $12 \times 12\ \mathrm{m}^2$ interleaved with a total of six layers of streamer tubes, located in the experimental hall). This will increase the total area of the muon detector to a total of $\approx 400\ \mathrm{m}^2$.

EAS-TOP is the first Extensive Air Shower Array planned to operate as a multiparameter and multipurpose detector in the field of VHE-UHE cosmic-ray physics. The different combinations of the different detectors are organized to provide a full set of data in the whole energy range of interest. The different measurements are interconnected with each other with the aim of obtaining a consistent picture of the physics of cosmic radiation at the primary energies above the direct observations. Moreover, the combined observations with the deep underground detectors represent a unique way to integrate the deep underground muon measurements, and are therefore essential for their interpretation.

* * *

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