# The Proton, Helium and CNO Fluxes at $E_o \approx$ 100 TeV from the EAS-TOP (Cherenkov) and MACRO (TeV Muon) Data at the Gran Sasso Laboratories

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## Abstract

The cosmic ray primary proton, helium and CNO fluxes in the energy range 80-300 TeV are studied by means of the EAS-TOP and MACRO detectors at the National Gran Sasso Laboratories. As direct results of the measurement, the "p+He" flux, at $E_o = 80$ TeV, and the "p+He+CNO" one, at $E_o = 250$ TeV, are obtained: $J_{p+He}(80\ \text{TeV}) = (1.8{\pm}0.4){\cdot}10^{-6}\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{TeV}^{-1}$, and $J_{p+He+CNO}(250\ \text{TeV}) = (1.1 \pm 0.3) \cdot 10^{-7}\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{TeV}^{-1}$. By using the existing measurements of the proton spectrum we obtain for the relative weights of the three components at 250 TeV: $J_p : J_{He} : J_{CNO} = (0.20 \pm 0.08) : (0.58 \pm 0.19) : (0.22 \pm 0.17)$.

## 1. Introduction and method

The study of the proton, helium and CNO fluxes in the energy range 80 - 300 TeV has been faced, through a ground based experiment, at the National Gran Sasso Laboratories by means of EAS-TOP [1] (at mountain altitude, 2005 m a.s.l.) and MACRO [3] (deep underground, the surface energy threshold for a muon reaching the detector being $E_\mu^{th} \approx 1.3$ TeV). Due to their locations the two arrays allow the simultaneous detections of the high energy muons, and of the electromagnetic and Cherenkov light (C.l.) components of Extensive Air Showers [6], [7].

MACRO, in the underground Gran Sasso Laboratory at 963 m a.s.l., 3100 m w.e. of minimum rock overburden, is a large area multi-purpose apparatus designed to detect penetrating cosmic radiation. The lower part of the MACRO detector has dimensions $76.6 \times 12 \times 4.8$ m$^3$. In this work muon tracks, having at least 4 aligned hits in both views of the horizontal streamer tube planes over the 10 layers composing the lower part of the detector, are considered.

As Cherenkov light array of EAS-TOP, 5 telescopes 60-80 m apart from each other, with their optical axis aligned to the MACRO direction (i.e. zenith angle $\theta \approx 35^o$ and azimuth $\phi \approx 170^o$) have been used. Each telescope loads two wide angle detectors equipped with 7 photomultipliers each with photocathode

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diameters d = 6.8 cm positioned on a circular pattern on the focal plane of a parabolic mirror (0.5 $m^2$ effective collecting area, 40 cm focal length) for a total field-of-view (f.o.v.) of 0.16 sr, the f.o.v. of each individual pmt being $2.3 \times 10^{-2}$ sr. The total number of photoelectrons provides the C.l. flux; the data reduction and systematic uncertainties ($\sigma \approx 20$ %) are discussed in [7].
EAS-TOP and MACRO have run in coincidence in clear moonless nights between September 1998 and May 2000 for a live time of $\Delta T = 208$ hours. 3830 events have been found in coincidence with Cherenkov data in a time window $\Delta t = 7\mu$s, the expected accidental contamination being 3.0 events. The combined geometric factors and live times of the two detectors provide a total acceptance $A_c \approx 20{,}000$ hours·$m^2$·sr.
The technique is based on: a) the selection of air shower events through the TeV muon recorded by MACRO (therefore selecting the primaries on the basis of their energy/nucleon by means of the TeV muon information, which further provides the EAS core geometry: core location inside 20 meters, and arrival direction inside 1 degree), and b) the measurement of the Cherenkov light signal (which is related to the total primary energy) at the surface by means of the C.l. detectors of the EAS-TOP array at EAS core distance $r \approx 130$ m (operating at energy threshold $E_o^{th} \approx 40$ TeV).
The principle of operation is shown in fig. 1 (all simulations are performed through CORSIKA/QGSJET [9], [10]). The figure shows that the selection of primaries can be made on the basis of their energy/nucleon: only primary protons contribute at primary energy $E_o < 40$ TeV, protons and helium contribute for $40 < E_o < 100$ TeV, CNO primaries for $E_o > 100$ TeV. The present analysis relies on such selection criterion, since it allows to study the proton plus helium, "p+He", flux at $E_o \approx 80$ TeV and the "p+He+CNO" one at $E_o \approx 250$ TeV.

## 2. Results

The primary "p+He" flux can be obtained in the energy range 70-100 TeV, where the muon production efficiencies for p and He primaries, and the C.l. photons yields (for equal primary energies) are quite similar. The corresponding experimental event rate is inside the photon density range $(3.5 \div 5.6)\cdot 10^3$ ph/$m^2$, obtained from the C.l. photon density spectra (see fig. 2). Events from proton and helium primaries have been simulated, with extreme power law indexes 2.6 and 2.8 and the expected C.l. spectra have been obtained. The normalization to the experimental event number in the quoted photon density range ($N_{ev} = 268$) gives the fluxes for both power law indexes and the cases of all protons or all helium primaries. The differences in the flux at 80 TeV following the four different assumptions is inside 9% and is accounted for in the systematic error together with the calibration uncertainties. The resulting "p+He" flux at 80 TeV is: $J_{p+He}(80\ \mathrm{TeV}) = (1.80 \pm 0.14^{stat} \pm 0.40^{sys}) \cdot 10^{-6} \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{TeV}^{-1}$.

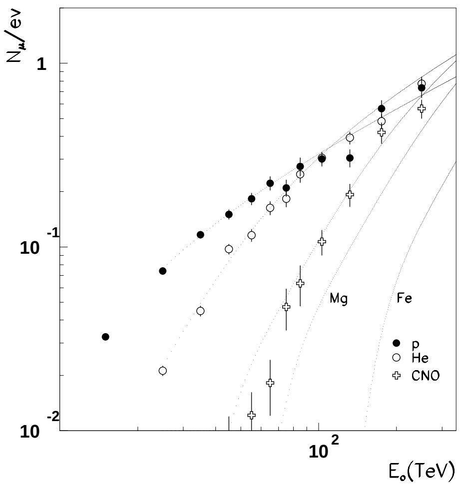


**Fig. 1.** Number of muons per event reaching the MACRO depth vs primary energy. Dots from [8] and $\mu$ energy threshold $E_\mu^{th} = 1.6$ TeV.

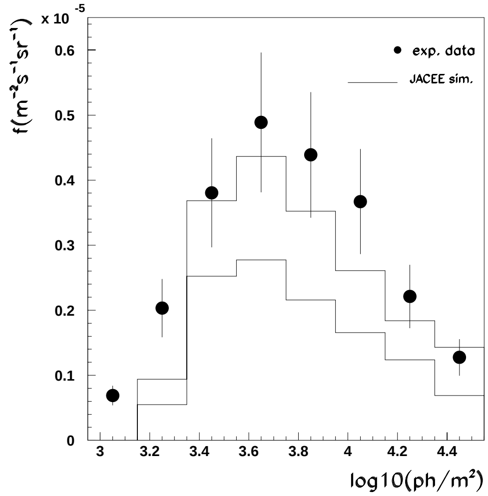


**Fig. 2.** Measured C.l. photon density spectra at distances 125 < r < 145 m from the shower core in coincidence with $\mu$ in MACRO. The $\pm 1\sigma$ band expected following JACEE [5] data is also given.

An analogous situation (similar muon numbers and C.l. yields) holds in the energy range $E_o$ = 220 - 300 TeV for proton, helium and CNO primaries. Therefore the same procedure described above to measure the "p+He" flux has been applied in the photon density range $(1.4 \div 2.2) \cdot 10^4$ ph/m$^2$ to infer the "p+He+CNO" flux. Proton, helium, and CNO primaries have been simulated with extreme power law indexes of primary spectra 2.8 and 2.6. The normalization to the experimental event rate (125 events) is done for the average of the six possible cases. The largest uncertainties due to different spectra and different primaries (6%) are included in the systematic uncertainties. The obtained "p+He+CNO" flux is: $J_{p+He+CNO}(250 \text{ TeV}) = (1.07 \pm 0.13^{stat} \pm 0.22^{sys}) \cdot 10^{-7}\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{TeV}^{-1}$.
Since the calibration errors affect in the same way the measurements of both "p+He" and "p+He+CNO" fluxes, their ratio is affected by a smaller systematic uncertainty. Shifting the "p+He" flux to 250 TeV with a 2.7 (± 0.1) index of the spectrum (and taking into account the additional 12% uncertainty due to the index indetermination), we obtain: $\frac{J_{p+He}}{J_{p+He+CNO}}(\approx 250 \text{ TeV}) = 0.78 \pm 0.17$.

## 3. Discussion and conclusions

The direct experiments as JACEE (J) and RUNJOB (R) [4] report quite similar proton fluxes in the $10 \div 100$ TeV range (the ratio of the differential spectra being R/J = 0.97 at 10 TeV and R/J = 1.02 at 100 TeV), also compatible with the

**Table 1.** Comparison of the present results alone (a), and combined with the direct p-flux measurements (b) with the JACEE and RUNJOB data (some data and/or errors are interpreted by ourselves from plots, and are therefore our responsibility). (*) Intensity units are $10^{-7}$ m$^{-2}$s$^{-1}$sr$^{-1}$TeV$^{-1}$.

| $Information(*)$ | $EAS-TOP\&MACRO$ | $JACEE$ | $RUNJOB$ |
|---|---|---|---|
| $(a)J_{p+He}$(80 TeV) | $18 \pm 4$ | $12 \pm 3$ | $8 \pm 2$ |
| $(a)J_{p+He+CNO}$(250 TeV) | $1.1 \pm 0.3$ | $0.7 \pm 0.2$ | $0.5 \pm 0.1$ |
| $(b)\frac{J_p}{J_{p+He}}$(80 TeV) | $0.29 \pm 0.09$ | $0.45 \pm 0.12$ | $0.63 \pm 0.20$ |
| $(a)\frac{J_{p+He}}{J_{p+He+CNO}}$(250 TeV) | $0.78 \pm 0.17$ | $0.70 \pm 0.20$ | $0.76 \pm 0.25$ |
| $(b)J_{He}$(80 TeV) | $12.7 \pm 4.4$ | $6.4 \pm 1.4$ | $3.1 \pm 0.7$ |

flux deduced from the hadron measurements at ground level [2]. We can therefore infer the helium flux needed to be compatible with the present data by subtracting the quoted proton flux: $J_p(80 \text{ TeV}) = (5.3 \pm 1.1) \cdot 10^{-7}$ m$^{-2}$s$^{-1}$sr$^{-1}$TeV$^{-1}$. We obtain: $J_{He}(80 \text{ TeV}) = (12.7 \pm 4.4) \cdot 10^{-7}$ m$^{-2}$s$^{-1}$sr$^{-1}$TeV$^{-1}$ and $\frac{J_p}{J_{p+He}}(80 \text{ TeV}) = 0.29 \pm 0.09$. A comparison with the existing (or extrapolated) measurements from JACEE and RUNJOB is given in tab. 1. While concerning the ratio $\frac{J_{p+He}}{J_{p+He+CNO}}(\approx 250 \text{ TeV})$ the three measurements are quite consistent, concerning the He flux a better agreement is found with the JACEE data, with respect to which the present data are slightly higher, but consistent inside the experimental (mainly systematic) uncertainties. The obtained ratio $\frac{J_p}{J_{p+He}}(80 \text{ TeV}) = 0.29 \pm 0.09$ implies that around 100 TeV the helium flux dominates over the proton one. From the ratio $\frac{J_{p+He}}{J_{p+He+CNO}}(250 \text{ TeV}) = 0.78 \pm 0.17$, it results for CNO a non negligible contribution to the flux in the 100-1000 TeV energy region. Such results can be described through the ratios of the three components at 250 TeV, that can be expressed as: $J_p : J_{He} : J_{CNO} = (0.20 \pm 0.08) : (0.58 \pm 0.19) : (0.22 \pm 0.17)$.

## 4. References


1. Aglietta M. et al. (EAS-TOP Coll.) 1986, Il Nuovo Cimento 9C 2, 262
2. Aglietta M. et al. (EAS-TOP Coll.) 2003, Astrop. Phys. 19/3, 329
3. Ahlen S.P. et al. (MACRO Coll.) 1993, Nucl. Instr. & Meth. A 324, 337
4. Apanasenko A.V. et al. (RUNJOB Coll.) 2001, Astrop. Phys. 16, 13
5. Asakimori K. et al. (JACEE Coll.) 1998, The Astrop. J. 502, 278
6. Bellotti R. et al. (MACRO Coll.) 1990, Phys. Rev. D 42, 1396
7. Bertaina M. et al. (EAS-TOP & MACRO) 2001, Proc. 27th ICRC Vol. 1, 14
8. Forti C. et al. 1990, Phys. Rev. D 42 3668
9. Kalmykov N.N., Ostapchenko S.S. 1993, Yad. Fiz. 56, 105
10. Knapp J., Heck D. 1998, Extensive Air Shower Simul. with CORSIKA (5.61)