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A measurement of the proton, helium and CNO fluxes at $E_0 \sim 100$ TeV from the EAS-TOP (Cherenkov) and MACRO (TeV Muon) data at the Gran Sasso Laboratories

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The primary cosmic ray proton, helium and CNO fluxes in the energy range 80-300 TeV are studied at the National Gran Sasso Laboratories by means of EAS-TOP and MACRO detectors. Proton and helium ('p+He') and proton, helium and CNO ('p+He+CNO') primaries are selected at $E_0 \sim 80$ TeV, and at $E_0 \sim 250$ TeV respectively. Results of this measurement have been interpreted using two different interaction models (QGSJET and SYBILL) inside the CORSIKA framework. Results using both interaction models show a dominance of the helium component in the 80-300 TeV region.

1. Introduction and method

The knowledge of the energy spectrum of the different elements of the primary cosmic rays is a main tool for understanding the acceleration processes and the cosmic ray sources. Up to 10 TeV the results from direct measurements are quite reliable, but at higher energies the statistics becomes poor and the energy determination, being non calorimetric, depends on the interaction parameters and their fluctuations. As a consequence, recent data by direct experiment like JACEE [1], RUNJOB [2] and ATIC [3] (preliminary results at these energies) still do not completely match among each others in the abundances of the light components. JACEE and ATIC agree on a different slope between p and He spectra: $\gamma_p - \gamma_{He} = 0.12 \pm 0.06$ (JACEE) and $\gamma_p - \gamma_{He} = 0.104 \pm 0.009$ (ATIC), but the absolute flux of 'p+He' (J_{p+He}) at 80 TeV from ATIC (uncertainties currently based solely upon statistical errors) seems to be more consistent with RUNJOB results (see tab. 1).
At higher energies ($\sim 10^{15}$ eV) only Extensive Air Shower (EAS) arrays have operated so far. A common picture that comes out from different analysis performed by EAS-TOP [4], EAS-TOP/MACRO [5] and KASCADE [6] correlating N_e - N_μ, is the interpretation of the 'knee' at $E_0 \sim 3\times10^{15}$ eV as the steepening of the light component and the observation of a higher abundance of the helium component over the proton one. However, uncertainties still remain on the exact abundance of each component due to the difficulty of extracting such information as the interpretation of data relies on the comparison with simulations and consequently the interaction model in use. A sound starting point at "lower" energies would be therefore of great importance to interpret the data at "higher" energies.
A detailed description of our measurement has been extensively reported in [7]. We describe here only the key points of the analysis performed with EAS-TOP (at mountain altitude, 2005 m a.s.l.) and MACRO [8] deep underground (3100 m w.e., the surface energy threshold for a muon reaching the detector being $E_\mu^{th} \approx 1.3$ TeV) arrays at the National Gran Sasso Laboratories. Due to their locations the two arrays allowed the simultaneous detection of the high energy muons, and of the e.m. and Cherenkov light components of Extensive Air Showers. The technique is based on:
a) The selection of cosmic ray primaries on the basis of their energy/nucleon through the TeV muon recorded

by MACRO. The underground muons further provide the EAS geometry: core location and arrival direction, with precisions of about 20 m and 1°, respectively.
b) The measurement of the Cherenkov light intensity, which is related to the total primary energy by means of the C.l. detectors of the EAS-TOP array. The surface array operates at an energy threshold E_o^{th} of 40 TeV at an EAS core distance r of 130 m.
Due to the shower selection through the high energy muons ($E_\mu \gtrsim$ 1.3 TeV to reach the underground detector) at the total energy threshold (E_o^{th} ∼40 TeV) the selected primaries include only protons and helium nuclei. CNO primaries contribute significantly at energies $E_o > 100$ TeV (the contribution of each primary becoming significant for $A \cdot E_\mu / E_o^{th} \approx$ 0.1 to 0.2). The combined geometric factors and live times of the two detectors provided a total exposure A_c of 20,000 hours·m^2·sr.
The merits of this techniques are: a) a much higher statistics compared to direct measurements; b) a calorimetric measurement of the energy of the primary particle through the Cherenkov light produced in the shower development; c) lower ambiguity in the elemental composition in the 40÷300 TeV region due to the natural filter operated by the high energy muon required by MACRO.
As this technique is based on the measurement of EAS, the interpretation of data partly relies on the interaction model employed in the simulation. An extended simulation has been performed in the past using QGSJET version 5.61 inside the CORSIKA framework [9] and results have been reported in [7]. For a better understanding of the systematics of the measurement, in this work we investigate the dependence of such results on the interaction model used to interpret the data. Simulation has therefore been repeated with a limited statistics (500 events at low primary energies and 120 events at higher ones) using the new QGSJET (version 6.20) and SYBILL interaction models. A comparison with the recent ATIC data is also included.

2. Results

The primary "p+He" flux can be obtained in the energy 70-100 TeV, where the muon production efficencies for p and He primaries, and the Cherenkov light (C.l.) photon yields (for equal primary energies) are quite similar. The corresponding experimental event rate is inside the photon density range $10^{3.55-3.75}$ ph/m^2, obtained from the C.l. photon density spectra (see fig. 2). We have performed simulations of the pure proton and helium components, considering for each component the extreme values of the spectral index (from 2.6 to 2.8) for a total of 4 different cases. By imposing the normalization of the simulated number of events in that bin to the experimentally detected one (N_{ev} = 268) we obtain a set of values from the flux of 'p+He' at 80 TeV (J_{p+He}(80 TeV)). We include the dispersion of these results in the estimate of the systematic error of the measurement of J_{p+He}(80 TeV). The resulting flux is reported in tab. 1.
An analogous situation (similar muon numbers and C.l. yields) holds in the energy range E_0 220 - 300 TeV for p, He and CNO primaries. Therefore the same procedure described above to measure the "p+He" flux has been applied in the photon density range $10^{4.15-4.35}$ ph/m^2 to infer the 'p+He+CNO' flux. The normalization to the experimental event rate (125 events) is done for the average of the 6 possible cases with p, He and CNO spectra assuming extreme power law indices between 2.6 and 2.8. The largest uncertainties due to the different spectra and different primaries (11%) are included in the systematic uncertainties. Again the resulting flux ($J_{p+He+CNO}$(250 TeV)) is reported in tab. 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 results reported in tab. 1.

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

$Quantity(*)$	$ET-MACRO$ $QGSJET$	$ET-MACRO$ $SYBILL$	$JACEE$	$RUNJOB$	$ATIC$
$(a) J_{p+He}(80\ \mathrm{TeV})$	16 ± 4	14 ± 3	12 ± 3	8 ± 2	9 ± 1
$(b) J_{He}(80\ \mathrm{TeV})$	10.3 ± 4.2	8.7 ± 3.3	6.4 ± 1.4	3.1 ± 0.7	5.1 ± 0.6
$(b) \frac{J_p}{J_{p+He}}(80\ \mathrm{TeV})$	0.34 ± 0.11	0.38 ± 0.12	0.45 ± 0.12	0.63 ± 0.20	0.44 ± 0.06
$(a) J_{p+He+CNO}(250\ \mathrm{TeV})$	1.0 ± 0.3	0.9 ± 0.2	0.7 ± 0.2	0.5 ± 0.1	0.58 ± 0.08
$(a) \frac{J_{p+He}}{J_{p+He+CNO}}(250\ \mathrm{TeV})$	0.75 ± 0.19	0.71 ± 0.14	0.70 ± 0.20	0.76 ± 0.25	0.74 ± 0.14

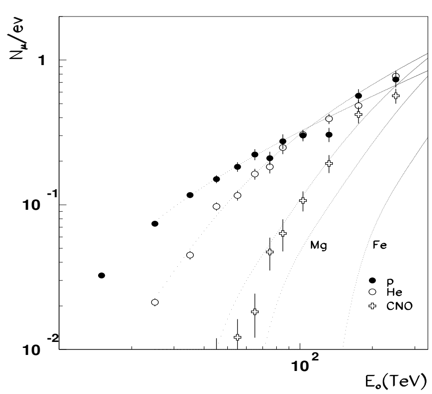

Figure 1. Number of muons per event (CORSIKA-QGSJET) reaching the MACRO depth vs primary energy. Dots from [10] and μ energy threshold E_μ^{th} = 1.6 TeV.

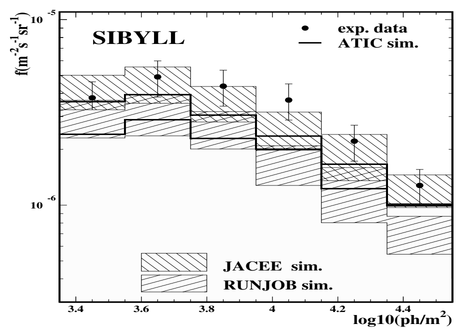

Figure 2. Measured C.l. photon density spectra (CORSIKA-SIBYLL) at distances 125 < r < 145 m from the shower core in coincidence with μ in MACRO. The $\pm 1\sigma$ band expected following JACEE, RUNJOB and ATIC data is also given.

3. Discussion and conclusions

Direct experiments such as RUNJOB (R) and JACEE (J) report quite similar proton fluxes in the 10 to 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 flux deduced from the hadron measurements at ground level [11]. We can therefore infer the helium flux needed to be compatible with the present data by subtracting the proton flux resulting from the weighted average of the quoted results: $J_p(80\ \mathrm{TeV}) = (5.3 \pm 1.1) \cdot 10^{-7}$ m^{-2}s^{-1}sr^{-1}TeV^{-1}. We obtain: $J_{He}(80\ \mathrm{TeV}) = (10.3 \pm 4.2) \cdot 10^{-7}$ m^{-2}s^{-1}sr^{-1}TeV^{-1} for QGSJET and $(8.7 \pm 3.3) \cdot 10^{-7}$ m^{-2}s^{-1}sr^{-1}TeV^{-1} for SIBYLL. The proton fraction is therefore $\frac{J_p}{J_{p+He}}(80\ \mathrm{TeV}) = 0.34 \pm 0.11$ for QGSJET and 0.38 ± 0.12 for SIBYLL. The quoted uncertainties are the combination of statistical and systematic contributions. A comparison with the existing (or extrapolated) measurements from JACEE, RUNJOB and ATIC is given in tab. 1 and fig. 3. While for the ratio $\frac{J_{p+He}}{J_{p+He+CNO}}(\approx 250\ \mathrm{TeV})$ all measurements are quite consistent, for the He flux a better agreement is found with JACEE, with respect to which the present data are slightly higher, but consistent within the experimental (mainly systematic) uncertainties. The obtained ratio $\frac{J_p}{J_{p+He}}(80\ \mathrm{TeV})$ implies that around 100 TeV the helium flux dominates over the proton one. From the ratio $\frac{J_{p+He}}{J_{p+He+CNO}}(250\ \mathrm{TeV}) = 0.75 \pm 0.19$ for

QGSJET and 0.71 ± 0.14 for SIBYLL, it results that CNO could provide a significant contribution to the flux in the 100-1000 TeV energy region. When combined with the direct p-flux measurements, the present data imply therefore a decreasing proton contribution to the primary flux well below the observed knee in the primary spectrum. Such considerations can be described through the ratios of the three components at 250 TeV, that can be expressed as: $J_p : J_{He} : J_{CNO} = (0.22 \pm 0.09) : (0.53 \pm 0.19) : (0.25 \pm 0.19)$ for QGSJET and $J_p : J_{He} : J_{CNO} = (0.23 \pm 0.08) : (0.48 \pm 0.16) : (0.29 \pm 0.17)$ for SIBYLL.

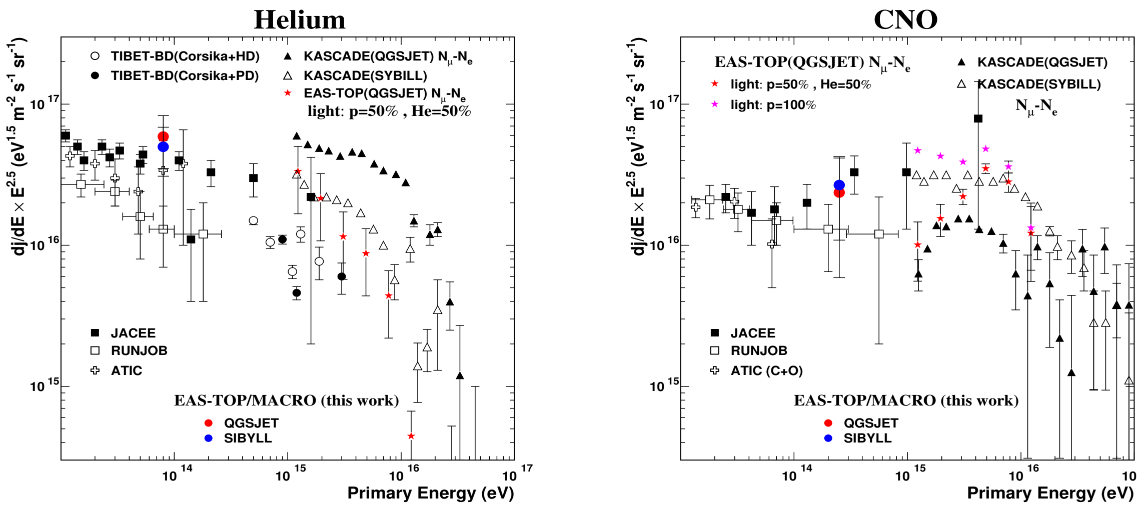

Figure 3. Results for the helium (left) and CNO (right) energy spectra for our analysis together with results from ATIC [3], JACEE [1], RUNJOB [2], TIBET [12], EAS-TOP [4] and KASCADE [6]. The error bars on the helium measurement of EAS-TOP N_μ-N_e indicate the 25% and 75% of the total light component. For ATIC, KASCADE and EAS-TOP N_μ-N_e only statistical errors are reported.

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