29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Primary proton spectrum in the energy range $5 - 10^3$ TeV from the sea level muon spectrum

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Primary proton spectrum in the energy range $5 - 10^3$ TeV is reconstructed from the sea level muon spectrum with the use of QGSJET01 and SYBILL2.1 interaction models. Heavier nuclei are taken in accordance with the direct measurements data, 100% uncertainty in helium flux is accounted for. The obtained proton intensity strongly contradicts to the available data of balloon experiments, exceeding them at the least by 100% for QGSJET01. This discrepancy is due to the combined effect of primary nucleon flux underestimation in the direct measurements and incorrect description of extensive air shower development. In the latter case it is required earlier shower development and harder spectra of secondary pions and kaons in comparison with QGSJET01. This conclusion is in agreement with the obtained by the KASCADE group on the basis of events rate study.

Primary proton spectrum from the different EAS observables

Recently it was shown [1, 2], that the use of direct data on primary cosmic rays (PCR) spectra and hadronic interaction models, included in CORSIKA, leads to significantly underrated, in comparison with the measurements, sea level muon flux for $E_\mu > 100$ GeV. The discrepancy takes place already for energies well below the "knee" ($E_{\text{PCR}} \lesssim 100$ TeV), where behavior of primary nucleon flux and hadronic interaction cross-sections seems to be rather reliably established. Attempts to explain the lack of high-energy muons by errors in EAS simulation [2,3] touch only one side of the problem, since direct data on PCR spectra are far from being considered as reference values. The emulsion chamber (EC) technique, applied in balloon experiments, is extremely labor consuming and sophisticated [4–6], and final results (PCR fluxes) are sensitive to many factors: from purely instrumental to the choice of hadronic generator. As a consequence, these experiments have limited energy resolution and disagree on the fluxes of nuclei with $Z \geq 2$.

The fact, that SIBYLL2.1 provides better, than QGSJET01, description of muon flux data up to several hundred GeVs [2] is not a basis to reduce all the problem to correct or incorrect choice of the EAS model. Our calculations show, that this model produces more positive, than negative, muons for small $E_{\text{primary}}/E_{\text{threshold}}$ ratio values both in showers from protons and neutrons, while for QGSJET01 and VENUS N_{μ^+}/N_{μ^-} is less, than unity, in showers from primary neutrons. We also found, that 20% difference between SIBYLL2.1 and QGSJET01 in total muon flux is almost entirely due to the difference in the flux of positive muons. This causes overestimation of muon charge ratio when one applies SIBYLL2.1 [2]. As one can see, none of the current EAS models reproduces the data on muons, problems with description of the data on other EAS observables are briefly discussed in [7]. By now, there remain large discrepancies between results on PCR energy spectra, extracted from the different EAS characteristics, indicating on disbalance in description of electromagnetic and hadronic components properties. It is necessary to add, that more definite conclusions on drawbacks of interaction models may be obtained if to apply them as well for processing of direct PCR spectra measurements [1].

Returning to the muon deficit problem one should not overlook existing uncertainties in the experimental data on muon intensity for $E_\mu > 100$ GeV. They do not allow to give more precise estimates of discrepancy between calculated and measured fluxes. Fortunately, underground experiments provide the needed information for higher energies $E_\mu = 1 - 10$ TeV. Reconstruction of muon spectrum at sea level from these data requires

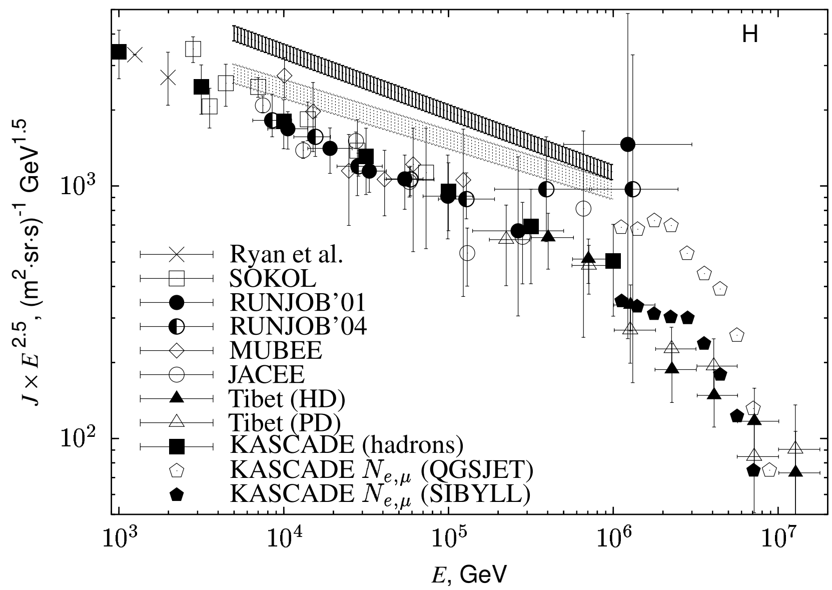

Figure 1. Primary proton spectrum (complete list of references may be found in [1, 8]). See explanation in text.

accurate description of muon transport in a dense medium. For this purpose we have applied a numerical method of adjoint equation solution and obtained muon intensities at large depths of rock and water with account of fluctuations in all muon interaction processes [9]. Our results are in good agreement with the results of Monte-Carlo codes MUM [10] and MUSIC [11]. It is important to note, that our calculations give upper estimate of muon fluxes at large depths in comparison with MUM and MUSIC. This happens for the fact, that we used 1% lower muon energy losses. From comparison of computed absorption curves with the data of underground installations we came to conclusion, that they are adequately described by the well-known muon spectrum [12]. It provides good agreement with the data of LVD, KGF, Frejus collaborations and even underestimates data of MACRO, Soudan and BNO for depths up to 8 km w.e., corresponding to $\sim$ 10 TeV median muon energy at sea level. Let us note, that muon intensity from [12] exceeds intensity, obtained from direct data on PCR spectra with QGSJET01 [1] by $\sim 45\%$ in the energy range 1–10 TeV. In order to reproduce behavior of the spectrum [12] for the given energies, we used interaction models SIBYLL2.1 and QGSJET01 with CORSIKA as EAS simulation code (for calculation procedure, see [1]). As input information we applied PCR spectra parameterizations, proposed in [13]. Since primary protons on $\sim$ 70% determine muon flux at sea level, we have tuned their spectrum to match behavior of muon spectrum from [12] within $\pm 5\%$ for $E_\mu = 1 - 10$ TeV (corresponding primary energies are $5 - 10^3$ GeV). Formulae for heavier nuclei [13] were taken without changes. The results, in comparison with available experimental data, are presented in Fig. 1. The upper shaded band is for QGSJET01: $J_p = (2.90 - 3.33) \times 10^4 E^{-2.74}$, and the lower one is for SIBYLL2.1: $J_p = (1.40 - 1.67) \times 10^4 E^{-2.70}$ (units are $(\mathrm{m}^2 \cdot \mathrm{sr} \cdot \mathrm{s} \cdot \mathrm{GeV})^{-1}$). Spread in proton intensity for particular model reflects the uncertainty in the helium flux data according to [13]. Before discussing reasons of the disagreement with the directly measured fluxes we should note, that obtained here proton spectra are not considered as the "final" versions: muon spectrum from [12] may be reproduced by proton spectra with slightly different set of coefficients and power indexes (including energy depending ones) and possible underestimation of heavier nuclei fluxes cannot be excluded. The relevant to this situation result was recently presented by EAS-TOP/MACRO [14]. In this experiment primary *p+He* flux was derived with QGSJET01 from Cherenkov light integral spectra and radial distributions. Subtraction of proton component from the total *p+He* intensity gave twice larger, than obtained by JACEE, helium flux at the energy of 80 TeV (note, however, rather large systematic errors). The given result and the muon deficit problem provide enough evidences in favor of hypothesis, that light nuclei fluxes are systematically underestimated in the direct experiments. Discussion of methodical errors, which can be responsible for this, may be found elsewhere [1,4,6]. Additional information on this subject gives recent paper [15], devoted to the galactic diffuse gamma-ray "GeV excess" problem. In this work it is shown, that account for Feynman scaling violation and diffractive interactions leads to 30–80% increase of π^0's, produced in $pp-$collisions, and the spectrum of incident protons is softer, than that of secondary $\gamma-$rays. Regarding the procedure, applied in the EC experiments, such effects would rather lead even to reduction of reconstructed PCR intensities (see, e.g. [1,6], for more details). To make correct deduction on this question, first, it is necessary to evaluate the given effects for proton-nucleus, nucleus-nucleus collisions and their influence on cascade development in EC. Second, it should be accounted, that the scaling violation does not allow any more to get PCR spectrum from the electromagnetic cascades one with simple constant energy shift: at the least, the shift coefficient becomes energy dependent. And the third, it is necessary to estimate size of systematic errors, inevitably introduced in EC data by the use of semi-empirical models, relying on the validity of scaling hypothesis in extrapolation of low-energy and incomplete accelerator data to high-energy region.

Though the modern EAS models incorporate scaling violation and diffractive interactions, none of them does it properly. This was demonstrated by KASCADE experiment on the basis of electromagnetic and hadronic events rate study [16]. In particular, it was shown, that in QGSJET01 the fraction of diffractive dissociation in the total *p-Air* inelastic cross-section must be diminished by 6.5% (i.e. halved). This is required to match the data on the observed hadronic events rate, which is 70% lower, than calculated with QGSJET01 [16]. Such model modification would influence on the other KASCADE result [17]: primary proton spectrum, reconstructed from flux of single hadrons, reaching the ground (full squares in Fig. 1). Qualitatively it is clear, that *larger* primary p flux would be needed to reproduce hadron spectrum, already not so perfectly conforming to the direct experiments data. The use for this purpose of SIBYLL2.1, where fraction of diffractive dissociation amounts to $\sim$ 5% at 10^4 GeV and rapidly decreases to 2% at 10^7 GeV [18], can possibly lead even to larger increase of primary p flux. Reduction of diffractive part of inelastic cross-section has another consequence for the muon deficit problem. It leads to the earlier shower development, hence, to higher probability of $\pi, K-$decays and to increase of muon number in EAS. For high-energy thresholds competitive process of muon decay can be neglected. Let us, however, note, that beside this factor, very important role in muon spectrum formation plays fraction of $\pi, K-$mesons, carrying the most part of primary particle energy. So, for high portion of diffractive events and high charged particle multiplicity, number of pions and kaons, falling into region $E_{\pi,K}/E_{\text{primary}} > 0.1$, is smaller in QGSJET01, than in SIBYLL2.1. As a consequence, the latter model gives larger muon flux. Basing on the same arguments from available information on QGSJETII [3] one may assume, that its use would bring to the intermediate, between SIBYLL2.1 and QGSJET01, values of muon flux. Finally, it can be concluded, that hardening of $\pi, K-$spectra and decrease of diffraction dissociation cross-section in QGSJET01 should result in better mutual agreement of primary proton spectra, reconstructed from hadron and muon fluxes. Notice also, that deduction on the need in harder, than in QGSJET01, spectra of secondary pions and kaons was also obtained in [16] on the basis of hadron multiplicities examination.

Another evidence of disbalance in description of hadronic and electromagnetic components also comes from KASCADE experiment [19]. In the given paper, PCR energy spectra were reconstructed from electron-vs-muon number distribution. Proton spectra, taken by us from figures in [19], are shown in Fig. 1 with pentagons (error bars are omitted). It can be stated, that if to take into account QGSJET01 modifications, proposed above, then all three spectra, derived from EAS observables (muons, hadrons, muons-vs-electrons) with this model, will be in satisfactory agreement. The use of SIBYLL2.1 leads to larger inconsistencies: it is evident, that application of p flux from [19] (full pentagons in Fig. 1) will enhance muon deficit. Let us note methodical aspect of this paper results: PCR energy spectra reconstruction procedure shows high sensitivity to the choice of hadronic generator, that is why it is required to perform such analysis in relation to the data, obtained in direct measurements.

Concluding remarks

Analysis of different kinds of EAS observations, performed in this paper, gave us evidences about possible underestimation of primary nucleon flux in direct experiments and information on drawbacks of QGSJET01 model (too soft $\pi, K-$spectra and high fraction of diffractive events). These conclusions hold rather qualitative character. We can not definitely say, that "true" primary proton spectrum lies between SIBYLL2.1 and QGSJET01 predictions, derived from the muon flux data. One cannot exclude, that significant part of primary nucleon flux underestimation is due to underestimation of nuclei fluxes with $Z \geq 2$, which are subject to large systematic uncertainties. Correct energy dependence of diffraction cross-section and specific shape of secondary $\pi, K-$spectra in reggeon models also can hardly be given. It cannot be pointed out, which portion of the model modification relates to simple parameters tuning, and which to conceptual changes. To settle this questions, consistency of the interaction models must be checked together against data of direct and indirect (EAS) measurements, that suggests investigation of EC data sensitivity to variations of hadron–nucleus interaction characteristics.

This work is supported in part by grants UR No. 02.01.001 and RFFI No. 04–02–16274.

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