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A. G. Tyumentsev, A. A. Lagutin, A. V. Yushkov

Shape of primary proton spectrum in multi-TeV region from data on vertical muon flux

It is shown, that primary proton spectrum, reconstructed from sea-level and underground data on muon spectrum with the use of QGSJET 01, QGSJET II, NEXUS 3.97 and SIBYLL 2.1 interaction models, demonstrates not only model-dependent intensity, but also model-dependent form. For correct reproduction of muon spectrum shape primary proton flux should have non-constant power index for all considered models, except SIBYLL 2.1, with break at energies around 10–15 TeV and value of exponent before break close to that obtained in ATIC-2 experiment.

1. Introduction

The recent preliminary data of ATIC-2 experiment [1] on primary light nuclei fluxes has rendered more uncertain the situation in the energy range above magnetic spectrometers data. Besides the fact, that for energies below 10 TeV ATIC-2 proton spectrum power index $\gamma_p = 2.63$ [2] is in disagreement with emulsion chamber experiments values $\gamma_p = 2.74$ (RUNJOB [3]) and $\gamma_p = 2.80$ (JACEE [4]), there are also indications on proton spectrum steepening at ≈ 10 TeV, which may imply presence of new type of primary cosmic ray (PCR) sources, accelerating protons up to the energies of only few tens of TeV [2, 5]. Below we present results of reconstruction of primary proton spectrum behavior from data on muon vertical flux in this disputable energy range and show, that not only intensity, but also shape of primary proton flux is sensitive to the parameters of hadronic interaction models, allowing presence of break just above 10 TeV.

2. Sea-level muon spectrum

Depth-intensity relation, needed for reconstruction of sea-level muon spectrum, was obtained via numerical solution of one-dimensional adjoint transport equation [6] with account of fluctuations in all muon interaction processes. To describe the data on muon intensity underground and at sea-level, and to estimate influence of uncertainty in muon flux data on reconstruction of primary proton flux, we used two parameterizations in the simple form, proposed in [7]. Original fit for the vertical from [7] in $(\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{GeV})^{-1}$

$$S_\mu(E) = 18/(E + 145)/(E + 2.7)^{2.7} \qquad (1)$$

provides good agreement with the data at sea-level, but leads to underestimation of the muon flux for the depths below 6 km w.e.

To match better underground data for the depths 2–6 km w.e. we shall also apply modified fit with slightly $< 10\%$ increased intensity in multi-TeV region

$$S_\mu(E) = 20.8/(E + 194.3)/E^{2.71}. \qquad (2)$$

This parametrization for depths from 4 km w.e. up to 8 km w.e., corresponding to $\sim 2.5 - 10$ TeV median muon energies at sea level, provides good agreement with the data of LVD, BNO and Frejus collaborations and leads to some underestimation of data of MACRO and Soudan experiments (for more details and complete list of references see [8]).

3. Proton spectrum from muon data

Average numbers of muons $N_\mu(E_N, > E_{th})$ and hadrons $N_h(E_N, > E_{th})$ with energies above E_{th} in EAS from primary nucleon of energy E_N were obtained with the help of one-dimensional hybrid code CONEX [9] in regime of cascade equations solution for interaction models QGSJET 01, SIBYLL 2.1, NEXUS 3.97 and QGSJET-II-03. The procedure of differential spectrum calculation is simple and is described in [8].

As a basic model of PCR nuclei spectra the parameterizations from [10] were chosen. Nuclei with $A \geq 4$ were treated in the framework of the superposition model, high accuracy of this approach is well known and was checked by our calculations with the use of CONEX both for muons and hadrons once again. The reconstruction of primary proton flux was performed simply by picking up of its normalization constant and power index, minimizing the deviation of the calculated muon fluxes from the parameterizations (1) and (2).

First, we attempted to fit muon spectra (1), (2) for $E_\mu = 40$ GeV–10 TeV with single power law primary proton spectrum $J_p = AE^{-\gamma_p}$ in the entire primary energy range 100 GeV–500 TeV. It turned out, that it is possible to achieve agreement
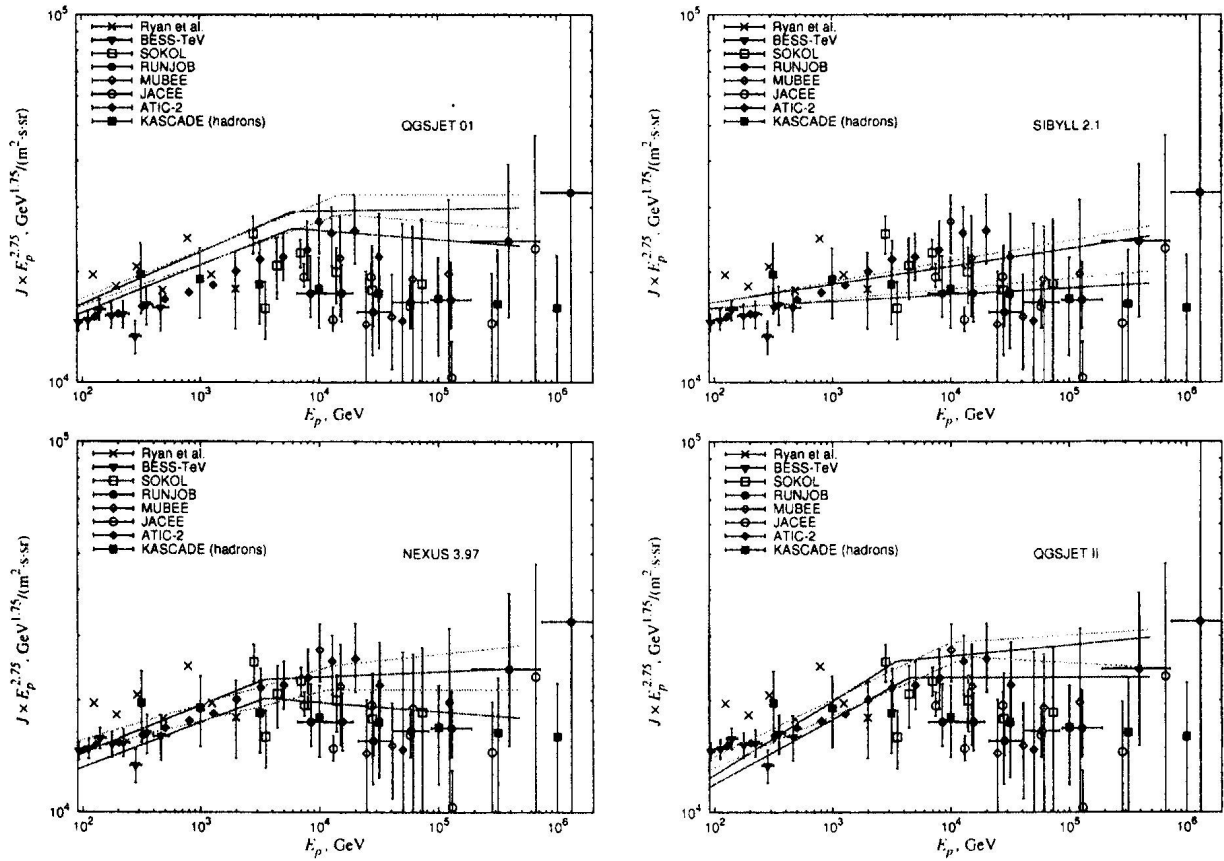
Figure 1. (color online). Primary proton spectrum. Complete list of references to experimental data can be found in [8]. Solid lines and dashed lines show primary proton spectra for muon flux parametrizations (1) and (2) correspondingly. Upper and lower lines reflect uncertainty in helium flux according to [10].

with the parameterizations (1), (2) only within 10% and only SIBYLL 2.1 reproduces their shapes correctly, with other models it is not possible to get right muon spectrum slope variation (see [8]). If to try to achieve correct reproduction of muon spectrum shape only in low energy range, i.e. up to 1 TeV, then resulting proton spectrum would be so flat that would bring to 25-30% overestimation of muon flux (for QGSJET models) already at 10 TeV. There are three possible explanations or solutions of this problem. First, the discrepancy can be completely removed by choice of appropriate interaction parameters, e.g. similar to those in SIBYLL 2.1. Another argument, which can be given is that the data on muon flux for energies above 1 TeV are not so definite to claim their inconsistency with the calculations, but it does not look well supported by underground data (see [6, 8, 11]). And the last possibility is to assume, that primary proton spectrum is not monotonous and either has sharp break or slowly changing exponent γ_p. Let us consider the latter assumption, which finds experimental [1] and theoretical [2, 5] justifications, in more detail. The results for the simple case with break (Fig. 1),

which allows to achieve correct description of muon spectrum shape with right asymptotic and deviation in flux value < 3%, show, that small difference between spectra (1) and (2) results not only in different proton intensities, but also in break positions. The latter lies for parametrization (2) in the primary energy range 10–15 TeV, the change in power index reaches appreciable values up to $\Delta\gamma_p \approx 0.15$ for QGSJET 01 and QGSJET II models. Proton spectra, obtained from muon flux (2), with QGSJET II and NEXUS 3.97 models are in the best agreement with ATIC-2 data, while SIBYLL 2.1 provides intermediate between ATIC-2 and emulsion chambers experiments slope value. Spectra, reconstructed from parametrization (1), have breaks at 3–6 TeV and in case of QGSJET II proton flux poorly agrees with experiments at primary energies around 100 GeV. Evidently, the latter problems are explained by too low, in comparison with underground data, muon flux and this parametrization is considered here mostly for estimation of sensitivity of primary spectrum features to the choice of reference muon flux. Finally it is necessary to note, that due to low sensitivity of dif-

ferential muon flux to helium and heavier groups of primary nuclei it is impossible to derive any conclusions on presence of the break in these PCR components [8].

Summarizing we can say, that primary proton spectrum shape turns out to be sensitive to the choice of interaction model and allows presence of break at 10–15 TeV with $\Delta\gamma_p$ up to 0.15, which can be slightly softened though, if to allow presence of the same break in other PCR components spectra.

To arrive to more definite conclusion about presence of the break one should analyze interaction models reliability and one of the plausible tests is to check their self-consistency, i.e. their ability to give correct estimates of several CR components at once. Provided we know behavior of primary proton spectra for every model from the muon data, we may check how these proton spectra agree with the data on hadrons. In Fig. 2 we give hadron intensities, calculated for primary proton spectra from Fig. 1, corresponding to muon spectrum parametrization (2). It is seen, that the best agreement with EAS-TOP measurements provide NEXUS 3.97 and SIBYLL 2.1. It is interesting to note that two models with different philosophies and inclusive spectra give the most self-consistent results on muons and hadrons, but, of course, this conclusion must be taken with much care, since it is based on the single set of data and we have only indirect indications on the accuracy of this set, e.g. such as agreement of primary proton fluxes, obtained by EAS-TOP and KASCADE teams (the latter is derived from flux of unaccompanied hadrons [12]). If to try to perform the same analysis with the variety of the data, obtained at different atmospheric altitudes and zenith angles, no consistent notions of such kind will be obtained
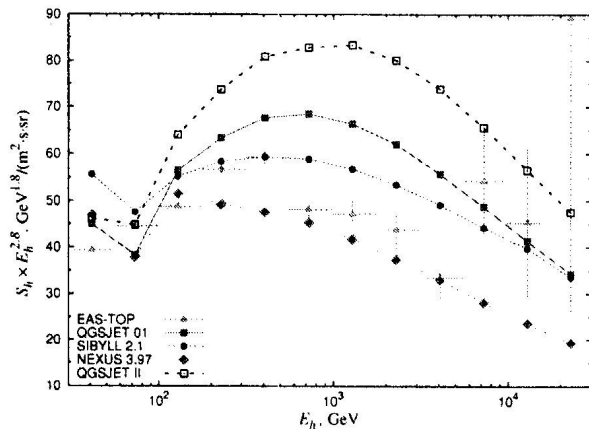
as can be easily seen from calculations, presented in [13].

4. Conclusions

The progress in CR and high-energy physics, achieved during last 10–15 years allowed to turn from statements about satisfactory (qualitative) concordance between different kinds of data to investigation of more fine effects. As an example, we managed to show that reconstructed from the data on vertical muon flux primary proton spectra have not only expected interaction model dependent intensities, but also model-dependent shapes. It is demonstrated, that application of QGSJET 01, QGSJET II and NEXUS 3.97 models brings to proton spectrum with break at 10–15 TeV and power index γ_p before break close to that, measured in ATIC-2 experiment. Nevertheless one can see, that absolute proton flux for QGSJET 01 is hardly compatible with any data of direct experiments, and the break for all these three models is more moderate, compared to what can be inferred from ATIC-2 data, which though become less definite right in the break region. On the other hand SIBYLL 2.1 allows to reproduce shape of the muon spectrum with single power law proton spectrum, which is in reasonable agreement with both emulsion chamber and ATIC-2 data within experimental errors. Further improvement of our understanding of the situation, which is of primary astrophysical interest, can be achieved via experimental study as of muon CR component characteristics with water and ice neutrino telescopes and so of inclusive spectra $p + A \rightarrow \pi^{\pm}, K^{\pm}$ in fragmentation region. Reduction of uncertainties in the latter component with the use of the data on primary spectra, hadron and muon components, does not look possible, because of 1) poor correlation between muon and hadron production mechanisms, 2) ambiguity of existing CR experimental data and 3) possibility to realize self-consistent description of the data on muons and hadrons with the models, having remarkably differing inclusive spectra and underlying philosophies.

Figure 2. (color online). Hadron spectra at the EAS-TOP depth $t = 820$ g/cm^2 for proton spectra from Fig. 1 (muon flux (2)).

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