On inconsistency of experimental data on primary nuclei spectra with sea level muon intensity measurements

A A Lagutin, A G Tyumentsev and A V Yushkov
Theoretical Physics Department, Altai State University, Lenin Avenue 61, Barnaul 656049, Russia
E-mail: yushkov@theory.dcn-asu.ru

Abstract. For the first time a complete set of the most recent direct data on primary cosmic ray spectra is used as input into calculations of muon flux at sea level in wide energy range $E_\mu = 1 - 3 \cdot 10^5$ GeV. Computations have been performed with the CORSIKA/QGSJET and CORSIKA/VENUS codes. The comparison of the obtained muon intensity with the data of muon experiments shows, that measurements of primary nuclei spectra conform to sea level muon data only up to several tens of GeV and result in essential deficit of muons at higher energies. As it follows from our examination, uncertainties in muon flux measurements and in the description of nuclear cascades development are not suitable to explain this contradiction, and the only remaining factor, leading to this situation, is underestimation of primary light nuclei fluxes. We have considered systematic effects, that may distort the results of the primary cosmic ray measurements with the application of the emulsion chambers. We suggest, that re-examination of these measurements is required with the employment of different hadronic interaction models. Also, in our point of view, it is necessary to perform estimates of possible influence of the fact, that sizable fraction of events, identified as protons, actually are antiprotons. Study of these cosmic ray component begins to attract much attention, but today nothing definite is known for the energies $> 40$ GeV. In any case, to realize whether the mentioned, or some other reasons are the sources of disagreement of the data on primaries with the data on muons, the indicated effects should be thoroughly analyzed.

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1. Introduction

A muon component of cosmic rays plays an important role in many fields of astroparticle physics. It provides a basis for verification of our knowledge on primary cosmic ray (PCR) spectrum behaviour, high-energy hadronic interactions and for solution of neutrino physics problems. In view of this, a question of interconsistency of information, gained in the last two decades on primary and muon fluxes, and on high-energy hadronic interactions presents great importance. In well known works of Volkova et al. (1979) [1], Dar (1983) [2], Butkevich et al. (1989) [3], Lipari (1993) [4], Honda et al. (1995) [5], Agrawal et al. (1996) [6] and Bugaev et al. (1998) [7] this problem was outside of the consideration, since the principal aim lied in the estimation of the secondary lepton fluxes. Authors relied on the information on primaries and nuclear interactions, that was available at the papers writing time. Certainly, these data were incomplete and ambiguous, as the consequence the inputs in the calculations also vary rather significantly. Nevertheless, the outputs, i.e. muon fluxes, satisfactory agree with each other (see comparisons in [5–7]) and muon experimental data. The given circumstance with necessity shows, that discrepancies in the used PCR spectra in the large part were compensated by different approaches to the treatment of nuclear cascades. This, in turn, may possibly relate to the fact, that muon flux in most of these works served only for normalization of neutrino fluxes and it was fitted to the muon experimental data via adjustment of not precisely known parameters of hadronic interactions. From these short remarks it is clear, that all these calculations lack some standardization, as it was recently proposed by Gaisser and Honda [8] in respect to the PCR spectra.

The current situation provides significantly better capabilities for adequate choice of PCR model and for simulation of nuclear cascades, and in this paper we have tried to take the maximum advantage of this. But, as our analysis has shown, unfortunately the information on all components of calculations is still very uncertain to provide a firm ground for accurate derivation of muon flux at sea level and, today, it is following ‘from top to bottom’. Direct measurements of primary cosmic ray spectra span up to the energy of \( \sim 1 \text{ PeV} \) for protons and up to few hundred TeV/n for other groups of nuclei. Most abundant data are collected for \( E_{\text{PCR}} < 1 \text{ TeV/n} \). Here proton spectrum is studied in series of recent satellite and balloon experiments with approximately 20% accuracy. Higher energy data of SOKOL [9], MUBEE [10], JACEE [11] and RUNJOB [12] although have relatively large statistic and systematic errors, also satisfactory agree with each other. At the same time, the measurements of the helium spectrum are much less concordant and still differ by almost a factor of 2 for all energies, and this uncertainty is especially crucial for evaluation of \( \mu^+ / \mu^- \) and \( \bar{\nu} / \nu \) ratios. As it is widely known, protons and helium nuclei contribute \( \sim 90\% \) to the nucleon flux at the top of the atmosphere, which is relevant for derivation of the muon spectrum at sea level, thus the particular emphasis should be given to the accurate description of these spectra.

To avoid simplification, for the simulation of nuclear cascades we have applied widely approved and thoroughly tested Monte-Carlo code CORSIKA [13], that allows
to treat hadronic interactions with the use of any of the up-to-date interaction models: QGSJET [14], VENUS [15], HDPM [13], NeXuS [16] or DPMJET [17]. Overall uncertainty, brought in computations of muon flux by the use of these models, is not very significant and considerably decreased in the last decade. So, the difference in $p - \text{air}$ inelastic cross-sections ‘between the models have shrunk from 80 mb to today 20 mb in the region of few PeV’ [18]. Average numbers of muons in cascades from primary protons, obtained with the use of these models, differ not more than by 20% [19] for all energies of interest. This means, that integral and differential muon fluxes at sea level will also differ by a close value, and this discrepancy is the smallest, in comparison with the uncertainties of PCR chemical composition and energy spectra for $E_{\text{PCR}} \gtrsim 1$ TeV/n, and the sea level muon data. The latter, for $E_{\mu} \lesssim 100$ GeV, are both numerous and, on the whole, quite ambiguous (see extensive summary in [20]), but the most recent ones of BESS [21] and CAPRICE [22] are very precise and closely agree with each other. They give a basis for checking information on primary light nuclei spectra up to the energies $\sim 10^4$ GeV/n. The interval of higher muon energies $10^2 - 10^4$ GeV, where the spread of the data on muon intensity is still small and amounts to some 20%, allows to examine with nearly the same accuracy behaviour of primary proton and helium spectra for the energies, extending to the upper bound of balloon and satellite measurements $\sim 1$ PeV/n. Evidently, that beyond the PCR data, it is not feasible to perform reliable calculations of the muon spectrum. What is more, the inverse problem, i.e. reconstruction of PCR fluxes from the data on muon spectrum, can not be also solved, because for $E_{\mu} > 10$ TeV there are only indirect data, in which muon flux at sea level is derived from results of underground measurements. These data are quite contradictory and have large systematic errors, mainly caused by incomplete information on rock properties and vagueness in question of prompt muon generation mechanisms (see, for example, [7, 23]). As a consequence of all this, now there is no possibility to make conclusions neither on the preferability of any model of charm generation, nor on behaviour of PCR spectra for $E_{\text{PCR}} > 1$ PeV/n.

As it is stated above, this paper is devoted to the investigation of compatibility of the present sea level muon flux measurements in energy interval $E_{\mu} = 1 - 10^5$ GeV with the experimental data on PCR spectra for corresponding primary energies $10 - 10^8$ GeV/n. In section 2 we briefly review the present data on primaries of H, He, CNO, Ne-Si and Fe groups and discuss PCR models, applied in this paper and in the papers of the other authors. Basic characteristics of computations are presented in section 3. Section 4 is devoted to consideration of consistency of our vertical muon flux, derived from the data of direct PCR measurements, with sea level muon experiments in the energy range $E_{\mu} = 1 - 10^5$ GeV. Since in this section we have revealed a sizable shortage of muons with energies, corresponding to that of primaries, studied with the emulsion chambers, in section 5 we examine possible effects, that may lead to a distortion of the information, obtained in the space and balloon experiments, employing this technique. Our conclusions are given in section 6.
2. Primary cosmic ray spectra

The extensive compilation of the modern data of space and balloon measurements plotted vs kinetic energy $T$, GeV/n is shown in figures 1-3. The most of the data are gathered for relatively low energies $<1$ TeV/n. But even here some 15 years ago the spread in experimental results was at least 100% for all groups of nuclei. In spite of series of experiments, performed since then, significant improvement was achieved only in the study of the proton spectrum. So, for energies from $\sim10$ GeV, where effects of geomagnetic cutoff and solar modulations become negligible, to some hundred GeV, data of recent experiments LEAP [24], CAPRICE [25], IMAX [26], BESS [27] and AMS [28] are consistent within 20% (see figure 1). Better mutually consistent, within 5–10%, data of AMS and BESS, now are considered as the most precise. From $\sim200$ GeV to $\sim2$ TeV there is a gap between magnet spectrometer and emulsion chamber experimental data, with the only ionization calorimeter measurements of Ryan et al. [29]. Since at the energies, overlapping with AMS and BESS, the given data overestimate proton intensity (but not for helium), probably they should be lowered by 25%, as proposed in [30]. In any case, more accurate information on behaviour of the proton spectrum in this energy interval is required for reliable evaluation of the muon and neutrino fluxes for the energies below 300 GeV. From approximately 2 TeV to 100 TeV SOKOL, MUBEE, JACEE and RUNJOB measurements provide rather consistent information on proton flux, though with the nearly 20% uncertainty. For understanding of the proton spectrum behaviour beyond the ‘knee’, valuable information is provided by the pioneer measurements of the Tibet hybrid experiment [31], carried out at the mountain altitude. These first results point at the steepening of the proton spectrum for $E_p \gtrsim 200$ TeV and this is an essential guideline for the extrapolation of the direct measurements. Spread in the data for all heavier nuclei practically for all energies of interest is much larger than that for hydrogen, and equals to 100% and more. The difference between the helium spectra of SOKOL, JACEE and RUNJOB is of major importance for accurate evaluation of secondary lepton fluxes.

From the aforesaid it becomes evident, that today no unique fit of all data on primary spectra can be given and considerable arbitrariness in the choice of them still remains. In such events one may use, for example, upper and lower estimates of all primary fluxes, or the flux, giving some average of the experimental data. The principal model of the PCR spectrum, employed in our calculations, may be regarded just as the latter case. It was obtained in frameworks of anomalous diffusion of cosmic rays in fractal interstellar medium [32–35], but here it is considered irrespectively to its validity for description of cosmic ray propagation. Altogether in our computations we have accounted for 5 groups of primaries: H, He, CNO, Ne-Si and Fe. Mass composition of the applied model is fitted to the direct and EAS experimental data on the all-particle primary spectrum (figure 4). As it is seen from figures 1-3 our model as well satisfactory corresponds to the available experimental information on elemental spectra and for high energies really gives some average of the data on nuclei, except that for hydrogen it
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Figure 1. Primary proton differential spectrum. Experimental data: [36] Chicago, [29] Ryan et al., [37] MASS, [9] SOKOL, [26] IMAX, [25] CAPRICE, [12] RUNJOB, [27] BESS, [11] JACEE and JACEE fit, [24] LEAP, [10] MUBEE, [28] AMS, [31] Tibet (HD) and Tibet (PD). Dashed line is the spectrum, proposed by Gaisser and Honda [8]. Solid line is the spectrum, used in this paper.

presents rather an upper estimate. For calculation of muon flux it also matters, that the data on the proton component become insufficiently statistically provided from
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Figure 2. Primary helium differential spectrum. Experimental data: [38] Ichimura et al. Two lines for the Gaisser and Honda spectrum correspond to their ‘low’ and ‘high’ helium fits. Other designations are the same as in figure 1.

∼ 10^5 GeV, and that sizeable uncertainty gives ±50% spread of the data on helium of JACEE and RUNJOB around the values, adopted in our model. So, though on the whole the situation looks quite well-defined for calculations of vertical muon intensity
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Figure 3. Primary nuclei differential spectra. Experimental data: [39] HEAO-3, [40] Lezniak and Webber, [41] Juliusson, [42] Simon et al., [43] CRN, [44] Minagawa. Other designations are the same as in figure 1.
up to the energies of several TeV, for the greater energies the existing PCR data are very ambiguous. In order to estimate the influence of these data spread on the resulting muon flux, we have additionally performed calculations with the use of another two PCR models, shown in figures 1-3: first of them presents the JACEE fit of their hydrogen and helium measurements [11], and the second is the model, suggested by Gaisser and Honda [8].

To compute sea level muon flux we have converted primary nuclei spectra to a spectrum in nucleons in standard manner:

\[ J_N(E) = J_p(E) + \sum_A J_A(E \cdot A) \cdot A^2, \]

here \( J_A(E) \) is the differential energy spectrum of the nuclei with atomic number \( A \), \( A = 4, 14, 28, 56 \). In figure 5 it is presented, along with our primary nucleon flux (solid line), fluxes, applied in calculations of muon intensity in works [1, 4–7]. These PCR spectra vary both in shapes and values and here it is useful to discuss all of them in order to realize, how they correspond to the modern experimental data. First of all, one can see that a sizable discrepancy between our, ‘Gaisser and Honda’ and ‘JACEE fit + 10%’ (here we add 10% to account a contribution of heavier, than H and He, nuclei) prevails, and this is a good illustration of the difficulties in the attaining of the unique description of the current experimental data. Behaviour of our model requires some more comments. Enhancement by \( \sim 20\% \) of intensity of the proton component in the energy range \( 10^3 - 10^5 \) GeV is dictated by the fact, that our first test calculations of muon flux with the ‘average’, close to JACEE fit, proton flux resulted in a very large shortage of muons at sea level (see section 4). In order to smooth this contradiction...
we have tested several variants of PCR spectra and eventually adopted the presented version. It gives the maximal increase of the nucleon flux, provided the elemental and all-particle spectra stay consistent with the experiment. Note, that if the muon data did not force us to enlarge the hydrogen flux, then it would reasonably agree with the new data of the Tibet ASγ collaboration [31]. Dip of our nucleon and elemental fluxes for $E_{\text{PCR}} \gtrsim 10^5$ GeV/n is an intrinsic feature of the anomalous diffusion propagation model, and, on the other hand, it corresponds to the numerous indications about the change of the PCR spectral index in the ‘knee’ region.

From the earlier works, the most appropriate PCR models were employed by Lipari [4] and Agrawal et al. [6]. The nucleon spectrum from the latter paper almost coincides with our one, deviating only from the energy of about $10^4$ GeV. Mainly, this discrepancy is caused by the use of excessive, in comparison with today’s, flux of protons, obtained from the results of the first 8 JACEE flights [52]. In 1993 JACEE reported, that proton spectrum consists of two parts with different slopes and a spectral break at $E_p = 40$ TeV. In paper [6] this break was not accounted for and extrapolation of the data for $E_p < 40$ TeV was applied for the higher energies. In work of Lipari a simple power primary nucleon spectrum was picked, which is convenient to use in analytic calculations, and no collation with the experiment was presented. Nevertheless, this is
a rather appropriate model, closely agreeing with the ‘Gaisser and Honda’ fit.

The three remaining spectra, applied by Volkova et al. [1], Honda et al. [5] and Bugaev et al. [7] are quite excessive, compared to what is known today. In the oldest of the discussed work of Volkova et al. [1], it is applied very large all-nucleon spectrum

\[ J_N(E) = 1.9 \times 10^4 E^{-2.65} \text{(GeV} \cdot \text{m}^2 \cdot \text{sec} \cdot \text{sr})^{-1}, \]

obtained from EAS data, and no elemental composition had been considered. Spectrum, used by Bugaev et al. [7], is taken from the work of Nikolsky [53], where it was derived from the analysis of fluctuations of muon and electron numbers in EAS. For \( E_p > 10^4 \) GeV proton intensity in this model is essentially overestimated (as a consequence, nucleon spectrum too), in comparison with the experimental data, and precisely such behaviour provides a good agreement of the resulting muon flux in [7] with the most of experimental data on sea level muon intensity. In the paper of Honda et al. [5] the proton flux for all energies is also rather high for the following reasons. In the low energy region the given spectrum relies on the compilation of Webber and Lezniak [54], i.e. mostly on the Ryan et al. [29] data. But they are referred in [54] incorrectly and do not match the original values, overstating them by \( \sim 20\% \). Extrapolation of this spectrum to the higher energies reasonably agree with the JACEE 1 – 8 flights results, but, as it was already said, to some extent overvalues the present data. From the analysis of these three last models a simple deduction follows: their renormalization down to the experimental values should cause a sizable deficit of calculated sea level muons. We shall return to this statement again in section 4.

3. Basic characteristics of calculations

Simulation of cascade processes in the atmosphere has been performed with the use of CORSIKA (v6.00, v6.018). In most of calculations as the model describing hadron-nucleus interaction for energies \( E_{\text{lab}} > 80 \) GeV QGSJET model is applied. This model is in a good agreement with accelerator and EAS experimental data (see e.g. [19, 55]) and provides comparatively high calculation speed. Hadronic interactions with energies \( E_{\text{lab}} < 80 \) GeV were simulated with GHEISHA [56].

In order to save machine time and accounting, that contribution of all nuclei, heavier than He to muon spectrum at sea level does not exceed 7–10\%, we have used a superposition model, considering nucleus with energy \( E_A \) as \( A \) nucleons with energies \( E_A/A \). Validity of such approach for calculation of number of secondaries in EAS at sea level is widely known (see, e.g., [57]), however, for verification, we have made our own computations of muon numbers in cascades, initiated by primary protons, carbon and iron nuclei, for energies \( 10^{13} \) and \( 10^{16} \) eV/n with the QGSJET model. Results are presented in figure 6. As it is seen, the agreement between numbers of muons in cascades, simulated with realistic nuclei fragmentation and those, obtained in the frameworks of superposition models is excellent. This, as well, allows not to make a distinction between showers, initiated by protons and neutrons, and further by nucleons we mean protons. In figure 7 the relative contribution of all nuclei groups, according to our PCR mass composition, to the integral muon flux at sea level is shown. Since the contribution of
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Figure 6. Numbers of muons at sea level in cascades, initiated by primary carbon and iron nuclei. Proton × 12 and Proton × 56 denote the calculation for carbon and iron nuclei in superposition model, i.e. the average number of muons in proton initiated shower, multiplied by 12 and 56 correspondingly. Statistical errors are not shown, since they are less than the symbol size.

Figure 7. Relative contribution of different groups of nuclei to the integral flux of muons at sea level.

He nuclei amounts to $\sim 20\%$ throughout the entire energy range, thus mentioned in the previous section $\pm 50\%$ spread of experimental results on helium flux around values, taken in our model, brings approximately $\pm 10\%$ uncertainty to muon flux at sea level. From this point of view, the uncertainty due to ambiguity of the experimental situation for heavier nuclei is insignificant.

To obtain easily the muon spectrum for any model of the primary spectrum, it is appropriate to perform calculations of integral muon flux in the following way:

\[
I_\mu(> E_{th}) = \int_{E_{th}}^{E_{max}} N_\mu(E_N, > E_{th}) J_N(E_N) dE_N.
\]
Table 1. Average number of muons with energy above threshold in shower from primary proton.

| Threshold energy $E_{th}$ | 1 GeV | 10 GeV | $10^2$ GeV | $10^3$ GeV |
|---------------------------|-------|--------|-------------|-------------|
| Primary energy $E_p = 10^5$ GeV |
| This paper                | 1011  | 318    | 21.0        | 0.605       |
| QGSJET [19]               | 1085  | 316    | 20.5        | 0.588       |
| [58]                      | 1008  | 310    | 20.9        | 0.696       |
| VENUS                     | 1079  | 347    | 23.5        | 0.679       |
| This paper                | 1150  | 349    | 24.0        | 0.604       |
| [19]                      |       |        |             |             |

Primary energy $E_p = 10^6$ GeV

| Threshold energy $E_{th}$ | 1 GeV | 10 GeV | $10^2$ GeV | $10^3$ GeV |
|---------------------------|-------|--------|-------------|-------------|
| This paper                | 8307  | 2292   | 132.3       | 3.612       |
| QGSJET [19]               | 8298  | 2207   | 124.9       | 3.240       |
| [58]                      | 8059  | 2257   | 129.8       | 3.332       |
| VENUS                     | 9629  | 2590   | 153.5       | 3.932       |
| [19]                      | 9706  | 2653   | 155.0       | 4.156       |

Here $N_\mu(E_N, > E_{th})$ is an average number of muons with energy $> E_{th}$ in shower from primary nucleon with energy $E_N$, $J_N(E_N)$ — differential primary spectrum converted to spectrum in nucleons, $E_{max}$ — energy, which provides the calculation accuracy $I_\mu(> E_{th}) \sim 0.1\%$. Most of results, presented below, obtained at $E_{max}/E_{th} = 3 \cdot 10^4$.

For each threshold energy average muon numbers were computed for 20–25 different primary energies (see figures 8, 9) with accuracy, generally better than 5% . Vertical lines in these figures show the areas of primary energies, giving 10%, 50% and 95% contributions to the integral muon flux in case of power primary spectrum $J_N(E) = 1.9 \cdot 10^4 E^{-2.65} \ (\text{GeV} \cdot \text{m}^2 \cdot \text{sec} \cdot \text{sr})^{-1}$. It is seen, that primaries with energies within $E_{th} - 300E_{th}$ on 95% determine muon intensity at sea level. Totally, with the use of the QGSJET it was simulated about $3 \cdot 10^7$ showers. Besides, for examination of sensitivity of muon spectrum to hadron-nucleus interaction model, series of calculations with the VENUS model have been carried out.

For the verification of our results, we have performed a comparison of numbers of muons in showers from primary protons, obtained by us, with those from papers of CORSIKA authors [19, 58] for two primary energies $E_p = 10^5$, $10^6$ GeV (table 1). On the whole, we see good agreement between the data, presented in this table. Some difference in muon numbers for $E_{th} = 10^3$ GeV may be explained by a statistical error, since simulation of 500 showers, made in the above mentioned papers for each primary energy, provides approximately 8% and 4% mean square deviation for energies $E_p = 10^5$ and $10^6$ GeV correspondingly.
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Figure 8. Number of muons $N_\mu(E_p > E_{th})$ with energy above threshold, generated in shower from primary proton with energy $E_p$. Vertical lines show the areas of primary energies, giving 10%, 50% and 95% contributions to the integral muon flux in case of power primary spectrum $J_N(E) = 1.9 \cdot 10^4 E^{-2.65}$ $(\text{GeV} \cdot \text{m}^2 \cdot \text{sec} \cdot \text{sr})^{-1}$.

4. Results and discussion

Obtained integral and differential muon spectra for our model of primary spectrum are presented in figures 10, 11. It is appropriate to split the consideration of the situation into three energy intervals.

$E_p \in [1 - 10^2] \text{ GeV}$. In this region our calculation of differential muon spectrum is in a good agreement with the most recent and accurate data, obtained by BESS 1995,97-99 [21] and CAPRICE 1994, 1997 [22]. This, along with the availability of unambiguous
Figure 9. Relative contribution of primary energy region from \( E_{th} \) to \( E_p \) to the muon integral flux at sea level \( I_\mu(>E_{th}) \) versus \( E_p/E_{th} \). Vertical lines have the same meaning as in figure 8.

data on primary spectrum and on behaviour of hadronic cross sections, once again evidences in favour of correctness of the applied calculation procedure. Selection of BESS and CAPRICE experiments is motivated by the fact, that measured there muon spectra have small statistic and systematic errors and excellently correlate with each other. In these experiments measurements were made with superconducting magnet spectrometers. Earlier data, obtained with iron magnet spectrometers differ from each other not only in values, but also in shapes of measured spectra, that may be due to the influence of some improperly accounted systematic errors. More detailed discussion
of this question may be found, for example, in [20,21,59,60].

Approaching to 100 GeV, the calculated muon flux becomes deficient, conforming only to the CAPRICE data. Two circumstances in this connection are worth noting. The first is that already from these energies information on muon intensity is not definite enough. The second is that muons with $E_\mu \gtrsim 100$ GeV are most effectively produced by the interactions of primaries with $E_{PCR} > 1$ TeV/n, measured in space and balloon emulsion chamber experiments. To this moment we shall pay more attention in section 5.

$E_\mu \in [10^2 - 10^4]$ GeV. Experimental data on differential proton spectrum for corresponding primary energies $10^3 - 10^6$ GeV of SOKOL, MUBEE, JACEE and RUNJOB show good interconsistency, but from $10^5$ GeV they become less definite for technical and natural (low flux) reasons. Experimental data on muon component have smaller errors and agree within $\sim 20\%$. In this region along with direct measurements on the surface (MARS [61], Nottingham [60,62], L3 [63,64]) there are results obtained at underground installations, in which the sea level muon spectrum is reconstructed from the ‘depth-intensity’ curve and in other ways. The latter are the data of the Baksan neutrino observatory (BNO) [65,66], Artymovsk scintillation detector [67], MSU [68], Frejus [69], LVD [70], MACRO [71], KGF [72,73] and CosmoALEPH [74]. Most of them are grouped within fit limits, given by MACRO, and comprise a well correlated data set. Comparison of the obtained differential and integral muon spectra with these data does not support reasonable expectation ‘PCR data fit $\rightarrow$ nuclear cascades $\rightarrow$ muon data fit’. The deviation of our results from the data of ‘MACRO zone’ is about 30–40%. This fact requires revising all steps of our calculation in order to realize how real the problem is and what may be done to overcome it. First of all, one should analyze an adequacy of nucleon cascades description. As it is shown in the previous section, our computations do not contain methodical errors, and total statistical + interpolation + integration error is less, than 5%. From figure 11 it is also seen, that the maximal difference $< 10\%$ in predictions of the QGSJET and VENUS hadronic interaction models is also practically out of significance in this situation. Since the VENUS model was initially chosen by us as the model, providing one of the largest muon numbers in shower (see [19]), hence 10\% should be regarded as the utmost possible increase of muon intensity for any interaction model in comparison with the QGSJET.

In this connection the results of the earlier works, not indicating any problems with the description of the muon data, deserve some closer consideration. We analyze here five works [1,4–7]. The collation of the PCR spectra with the experimental data, performed in section 2, allows to split these papers into 2 groups: papers with excessive [1,5,7] and appropriate [4,6] fluxes. In order to reveal differences in hadronic interactions and calculation technique, we have made computations of muon fluxes for the same PCR spectra, as used in the discussed works. Results are presented in figure 12. From this comparison it becomes evident, why no muon deficit was discovered earlier. In addition to overvalued nucleon fluxes, in the papers from the first group the muon yield is larger or, at least, comparable with that of QGSJET and VENUS. Muon production in the papers with appropriate primary fluxes is 20% – 30% higher, than obtained by us,
Figure 10. Differential muon spectrum at sea level. Experimental data: [61] MARS 1975, [62] Nottingham 1968, [60] Rastin 1984, [75] MASS 1989, [22] CAPRICE 1994, [59] OKAYAMA 2001, [76] Bateman 1971, [21] BESS 1995, 97, 99, [63] L3 1993, [64] L3 2003, [74] CosmoALEPH, [70] LVD 1998, [66] Baksan 1992, [67] ASD 1985, [68] MSU 1994, [69] Frejus 1994, [71] MACRO fit 1995. QGSJET and VENUS are the present work calculations with the corresponding interaction models. Prompt muons spectra: [77] — RQPM (recombination quark-parton model), QGSM (quark-gluon string model); [78] — VFGS (Volkova, Fulgione, Galeotti and Saavedra model).
Figure 11. Integral muon spectrum at sea level. Experimental data: [60] Rastin 1984, [62] Nottingham 1968, [75] MASS 1989, [61] MARS 1975, [72, 73] KGF 1990, [65, 66] Baksan 1990, 1992. QGSJET and VENUS are the present work calculations with the corresponding interaction models. Prompt muon spectra: [77] — RQPM, QGSM; [78] — VFGS.
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and this difference is sufficient to mask the muon shortage. Besides, PCR flux from the work [6] becomes excessive from $\sim 10$ TeV, as we have already pointed in section 2. The data in respect of muon production of the latter two papers closely agree, apparently because in both of these works essentially the same authors participated. In [6] also an explanation of relatively large muon yield may be found. In this calculations, for simulation of hadronic interactions TARGET code had been applied, but with the enhancement of pion and kaon production. This resulted in increase of contribution of kaon decays to muon flux with $E_\mu > 1$ TeV up to a very large value of 50%. Of course, uncertainties in description of hadronic interaction prevail, but, as our calculations show, discrepancies in muon yield at sea level between the widely recognized and extensively tested models, included in CORSIKA, are at the level of $\pm 10\%$. These models are evidently free from many drawbacks, peculiar to the models from the discussed works, and more thoroughly developed. Hence, likely the largest part of the discrepancy should be attributed to underestimation of primary nucleon flux, but not to the incorrectness of the simulation of the nuclear cascades in the atmosphere.

There is no need to repeat arguments from section 2 in favour of adequacy our PCR model, since it may be regarded just as a valid representation of the current experimental situation. We should only repeat, that our proton spectrum does not present a fit of the experimental data for $E_p = 10^4 - 10^5$ GeV, but even on $\sim 20\%$ overestimates them. This was done to smooth the discussed problem. If directly input in calculations fits of primary H and He spectra, obtained by JACEE, with addition of 10% contribution of heavier nuclei, or 'standard' spectrum, proposed by Gaisser and Honda, then resulting integral muon flux will be even lower, than ours (see table 2).

There is a possibility to compensate some of the muon deficit by increase of intensity of heavier nuclei in our model. But to get 10% addition to muon flux it is necessary to rise helium flux 50% or to double aggregate flux of CNO, Ne-Si and Fe groups. This mechanism is rather ineffective, because limitations, set by the data on all-particle spectrum thus would require to lower fluxes of other, lighter species. Summarizing, we see, that today for this energy region the situation is determined rather rigidly and the stated problem of muon deficit can not be resolved without some extraordinary assumptions. Necessity in rise of all PCR spectra as high, as possible to diminish the muon shortage, indicates, that measurements with emulsion chambers systematically understate fluxes of the primaries. A large spread in the data on PCR nuclei with $A \geq 4$ provides some more ground for such speculations and demonstrates necessity in further improvement of experimental technique. This question is closely related to the appropriate description of the characteristics of nuclear interactions and in more details is considered in section 5.

$E_\mu \in [10^4 - 3 \cdot 10^5]$ GeV. Analysis of this interval in the present situation looks vain for the following reasons:

i. Obviously, muon deficit takes place for these energies too, and its nature and quantity are unclear;

ii. There is no experimental data on chemical composition of PCR spectrum for
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Figure 12. Ratio of integral (a) and differential (b) muon fluxes, obtained with CORSIKA, to the muon fluxes calculated in papers [1] (Volkova et al.), [7] (Bugaev et al.), [6] Agrawal et al., [5] Honda et al., [4] Lipari. The CORSIKA results are for the same PCR spectra as used in these papers.

Table 2. Ratio of the integral muon intensity, calculated with the use of the present paper PCR model, to the intensities, obtained with the JACEE PCR fit [11] and the model, proposed by Gaisser and Honda [8].

| Muon threshold energies, GeV | Ratio I_{\mu}[present]/I_{\mu}[11] | 10 | 30 | 3 \cdot 10^2 | 3 \cdot 10^3 | 3 \cdot 10^4 | 3 \cdot 10^5 |
|-----------------------------|-----------------------------------|----|----|---------------|---------------|---------------|---------------|
|                             | I_{\mu}[present]/I_{\mu}[8]       | 1.02 | 1.08 | 1.12         | 1.13          | 1.10          | 1.03          | 0.89          | 0.75          | 0.58          |

energies higher than $10^6$ GeV, that is why, as in our case, one has to use only theoretical guidelines, describing the origin and transport of cosmic rays in interstellar medium.

iii. Behavior of hadron-nucleus cross-sections for $E_{\text{lab}} > 10^5$ GeV, despite the decrease of divergence between predictions of different models, remains also not enough studied, that results in additional uncertainty in calculations of the muon spectrum.

iv. All muon component measurements for the given energies are obtained from results of underground experiments and contain quite large systematic errors, that causes their poor mutual agreement. Dominant sources of the mentioned errors are such factors as incomplete information on chemical composition of overburden rock and necessity to input in calculation a ratio $X$ of prompt muons to $\pi, K$-muons as a function of energy, which is not only unknown, but should be determined from the experimental data.

Taking aforesaid into account, it seems impossible to make any definite conclusions on behaviour of PCR spectrum and on prompt muon contribution on the basis of sea level data in this energy region. Though from the comparison with the experimental data the VFGS (Volkova, Fulgione, Galeotti and Saavedra) model [78] of charm generation looks as the most preferable, however, here it is needless to stress all unreliability of this deduction.
5. Possible reasons of systematic PCR flux underestimation

In this section we intend to discuss some problems, that are inherent to the study of high-energy cosmic rays spectra with the application of the emulsion chambers (EC). In addition to all factors, listed below, one can easily add some more, that experimenters encounter during processing of the EC data, including, for example, not negligible experimental bias. We are mostly concentrated at the factors, depending on the description of nuclear interactions, and in this aspect the situation may eventually turn out similar to that with the calculations of sea level muons. The necessity of further improvements in the experimental technique is clearly recognized in connection with the serious disagreements between the current data on different groups of nuclei, and short history of space and balloon EC experiments gives many examples of how the reported data changed with the gain of experience and statistics. Further investigations will inevitably provide information, that improves our knowledge, and, possibly, will differ from it.

The most detailed description of the experimental technique is presented by the RUNJOB collaboration [12] and we shall mostly rely on their data, bearing in mind that the procedure is generally the same in all EC experiments (MUBE, JACEE and RUNJOB). The key moment lies in the determination of the energy, transferred to the electromagnetic component \( \sum E_\gamma \) in the cascades, initiated by the interaction of a primary particle within EC. This energy is related to the initial energy \( E_0 \) via partial inelasticity coefficient \( k \) (we shall denote so \( k_\gamma \) to avoid further confusion with the spectral index \( \gamma \)). The spectrum of primaries is obtained from the spectrum of electromagnetic cascades (EMC) with a simple shift in the energy scale by the value

\[
C^{-1}(k, \gamma) = \left[ \int_0^1 k^{\gamma} f(k) dk \right]^{-1/\gamma},
\]

here \( f(k) \) is a distribution function of \( k \) and \( \gamma \) is the spectral index of primary spectrum \( J(E) \sim E^{-(\gamma+1)} \). The given statement, at the least dating back to as early as 1962 [79], holds true, provided \( f(k) \) does not depend on \( E_0 \) in a wide energy range. Usually independence of \( C(k, \gamma) \) on energy is argued from the evidence, that total and partial \( < k > \) inelasticities are constant. But this may prove to be incorrect (see, e.g [80]), since \( < k^\gamma > \) essentially depends on the contribution of the large values of \( k \) to the distribution \( f(k) \), and even though \( < k > \) is constant, ‘tail’ of \( f(k) \) may change with \( E_0 \). Besides, large body of information on behaviour of the total inelasticity, presented in the literature, points at its slow growth with energy. Another important moment, is the difference in \( < k > \) between predictions of various interaction models. In comparison with FRITIOF, applied by RUNJOB, VENUS gives \( \sim 10\% \) lower value of partial inelasticity \( < k > \) in a single p-A, He-A collisions [12] (other experiments do not provide information neither on the code used, nor on the single interaction characteristics).

Note, that 10\% correction to the energy conversion from \( \sum E_\gamma \) to \( E_0 \) for power PCR flux \( J(E) \sim E^{-2.8} \) is equivalent to \( \sim 30\% \) correction to the intensity. Thus, at first
sight, the use of the VENUS provides not only the largest number of muons at sea level, but, as well may lead to an increase of the measured proton and helium fluxes. In fact, the estimation of the influence of the discussed effect on the results of EC measurements is much more complicated. Firstly, one needs to evaluate total energy, transferred to EMC in successive interactions of secondary particles, i.e. from the whole shower, not from single interaction, and to obtain distribution function $f(k)$ for this fraction $k$ of the initial energy. Secondly, this distribution for $k$ is rather broad, so the conversion to $E_0$ for individual shower is impossible and it is necessary to derive effective value of $C(k, \gamma)$, allowing to get PCR spectrum from the EMC one. So, simple knowledge of differences in $<k>$ in the first interaction does not allow to make straightforward qualitative estimate of changes in the final energy shift value. The analysis becomes even more complicated, if to account, that the choice of the interaction model strongly influences the previous steps of the experimental data processing. Namely, it affects the determination of $\sum E_\gamma$ and detection efficiency. For evaluation of both of these values a complete simulation of nuclear cascades in EC is required. For example, in the RUNJOB experiment the ‘actual’ EMC energy $\sum E_{\gamma,\text{true}}$ is obtained from the estimated with the $\gamma$-ray core method one $\sum E_{\gamma,\text{esti}}$ via direct Monte-Carlo simulation of showers with the FRITIOF code. In the JACEE experiment [11, 81] determination of cascade energies also involves complete Monte-Carlo calculations of the transition curves, used for calibration of the $\sum E_\gamma$, derived from the direct electron counting or from the X-ray film densitometry. Analogous calculations are required for evaluation of the detection efficiency (see detailed description in [12]).

Thus, deviations between the interaction models in hadron-nucleus cross-sections, energy spectra, multiplicities and phase space distributions (this is important for estimation of the most energetic in the lab system and back-scattered in CMS numbers of gamma-quanta. VENUS predicts the largest quantity of the latter, compared to the other models [19]) of secondary particles, in fluctuations of the energy, transferred to EMC, etc., may significantly influence the interpretation of the EC measurements results. The mentioned arguments give enough ground for performing of thorough analysis of sensitivity of the EC data to the use of various interaction models, which is still missing. This as well would allow to make fully consistent estimations of the cosmic ray fluxes, i.e. with the application of the single model, both at the top of the atmosphere and at the sea level.

Besides, it is possible that some data distortion may come from changes or anomalies in characteristics of hadronic interactions at very high-energies. At present, these questions are widely discussed in connection with the data of EAS experiments, also employing EC technique.

Another hypothetical reason, which may cause systematic errors in processing of the EC experiments data, could be the presence of sizable fraction of unusual component in PCR. This may be regarded equivalent to the ‘change’ in hadronic interactions and all aforesaid about that effect holds true in the given case. In this connection, rising interest to the primary antiproton component deserves closer attention.
As it is appropriately supposed, antiprotons present natural compound of PCR, produced mostly in interactions of nuclei (dominantly protons) with interstellar medium. Other, exotic $\bar{p}$ generation mechanisms, result in softer spectra and they are out of interest for the energies, we are dealing with (for more information, see references in caption to figure 13 and e.g. [94]). The experimental study of $\bar{p}$ component began in 1970’s from the first balloon measurements (Golden et al. [89] and Bogomolov et al. [87]), and today the direct data cover region from few MeV to approximately 40 GeV (figure 13). Higher energy region is scarcely studied and is marked by few indirect upper estimates of $\bar{p}/p$ ratio. One of them by Stephens (1985) [90] is derived from the analysis of sea level muon charge ratio. Soon we shall present elsewhere such calculations with the employment of improved since then knowledge on PCR fluxes, hadronic interactions and muon charge ratio. Other three $\bar{p}/p$ estimates by Tibet [91], L3+C [92] and MACRO [93] collaborations are made with the use of the Moon and the Sun shadow effects. The idea of this approach is the following: positively and negatively charged particles are deflected by the Earth’s magnetic field to the opposite sides, and when the Sun or the Moon, during their transit over detector, block particles, deficit of secondary particles should be observed, if antimatter presents in PCR along with the matter, at the both opposite sides of the real Sun/Moon positions. Since these experiments failed to detect ‘antimatter shadow’, they could report only upper limits of $\bar{p}/p$ ratio to be equal 22% at 10 TeV [91], 27.5% at 20 TeV [93] and 15% for muon sample with $E_\mu > 65$ GeV (primary energy $\sim 1$ TeV) [92]. Theoretical predictions are not able to clarify the situation, since there is no generally recognized propagation theory, reproducing satisfactory even low energy data on $\bar{p}/p$ ratio together with all totality of the data on elemental nuclei.

**Figure 13.** The primary antiproton to proton fluxes experimental data. Direct measurements: [82] CAPRICE98, [83] CAPRICE94, [84] BESS95,97, [85] IMAX92, [86] MASS91, [87] Bogomolov et al., [88] Buffington et al., [89] Golden et al. Upper estimates of the $\bar{p}/p$ ratio from the ground-based experiments: [90] — solid arrows; dashed arrows: [91] Tibet, [92] L3+C, [93] MACRO.
On inconsistency of experimental data on primary nuclei abundances, secondary to primary nuclei ratios, and fluxes of positrons and gammas. Standard diffusion/reacceleration models fail to do this, requiring introduction of specific assumptions, generally working for description of some kind of observations, but leading to contradictions in other cases. Among such assumptions one may readily call necessity in ‘artificial breaks in diffusion coefficients and in the primary injection spectrum’ [94] to match both $\bar{p}/p$ and secondary to primary nuclei ratios, suggestion about harder interstellar proton and/or electron spectra to explain well known ‘GeV excess’ in diffuse gamma ray flux, etc. (for more information see, e.g. [94–97] and references therein).

The detailed discussion of these problems is beyond the scope of our paper and we shall return to it elsewhere.

In any case, it is clear, that there is no firm ground to state neither the presence of significant fraction of $\bar{p}$’s for high energies, nor the reverse and that actual $\bar{p}/p$ ratio is still to be determined via direct and various kinds of indirect observations. Thus, one can not completely exclude probability, that among events, identified in EC as protons, sizable fraction of antiprotons presents. As it is already said above, it is difficult to estimate the influence of the differences between $p$-$A$ and $\bar{p}$-$A$ interaction characteristics on the results of PCR measurements with EC. It is known that antiprotons deposit more energy into $\gamma$’s, than $p$ in a single interaction [19], but, we should repeat, the complete analysis of changes, produced in the measured $p+\bar{p}(?)$ flux requires to perform evaluation of many parameters, that is possible to do only via direct Monte-Carlo simulations with respect to the specific experimental conditions.

We have made similar estimates for the total muon flux at sea level. As we have elucidated, actually all primary nucleons in our calculations are protons. Replacing them by antiprotons, we have computed integral muon flux for $E_{th} = 10^2, 10^3, 10^4$ GeV and have not found any noticeable changes, in comparison with the calculations for protons. In other words, total vertical sea level muon flux turned out to be insensitive to the fraction of antiprotons in PCR and, possibly, the same may happen with the EC results. Of course, this is not true for $\mu^+$ and $\mu^-$ spectra, and $\mu^+ / \mu^-$ ratio, their calculations may help to determine presence of $\bar{p}$’s in PCR.

In conclusion, we would like to present an estimation of the changes in nucleon flux, required to match the muon experimental data. In figure 14 we show, along with initially applied spectrum, its part for $E > 2$ TeV 8% shifted toward the higher energies. From the magnet spectrometers region to the EC energies we use an interpolation. So, muon spectra, given in figures 15, 16, are calculated with the use of the combined nucleon flux, shown in figure 14 with open circles. These spectra still present rather a lower estimate of the muon data and may be approximated via the following formula (energy is in GeV, $E_1 = 10$ GeV)

$$S_{\mu}(E) = AE^{(B+C \ln(E/E_1)+D \ln^2(E/E_1)+F \ln^3(E/E_1))},$$

with parameters, given in table 3.

The used nucleon spectrum is just a model spectrum, since in practice, correction to the PCR flux hardly may be constant and should depend both on the energy and
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Figure 14. Initially applied nucleon spectrum (solid line) and its part for the region, relevant to the EC measurements, 8% shifted in the energy (dashed line). Circles show the spectrum, used to get the lower estimate of the sea level muon flux, presented in figures 15, 16.

Table 3. Parameters of approximation (2) of muon spectra at sea level.

| Integral spectrum \((\text{cm}^2 \cdot \text{sec} \cdot \text{sr})^{-1}\) |
|---|---|---|---|---|---|
| \(E, \text{GeV}\) | \(A\) | \(B\) | \(C\) | \(D\) | \(F\) |
| \(\leq 100\) | \(5.8392 \cdot 10^{-3}\) | \(-8.4964 \cdot 10^{-1}\) | \(-2.5331 \cdot 10^{-1}\) | \(6.7652 \cdot 10^{-3}\) | \(3.3739 \cdot 10^{-3}\) |
| \(> 100\) | \(6.5584 \cdot 10^{-3}\) | \(-9.1783 \cdot 10^{-1}\) | \(-2.3051 \cdot 10^{-1}\) | \(1.3452 \cdot 10^{-2}\) | \(-3.3109 \cdot 10^{-4}\) |

| Differential spectrum \((\text{GeV} \cdot \text{cm}^2 \cdot \text{sec} \cdot \text{sr})^{-1}\) |
|---|---|---|---|---|---|
| \(E, \text{GeV}\) | \(A\) | \(B\) | \(C\) | \(D\) | \(F\) |
| \(\leq 100\) | \(1.7146 \cdot 10^{-3}\) | \(-1.1620\) | \(-4.1126 \cdot 10^{-1}\) | \(3.6839 \cdot 10^{-2}\) | \(-8.0472 \cdot 10^{-4}\) |
| \(> 100\) | \(3.7984 \cdot 10^{-3}\) | \(-1.5376\) | \(-2.7868 \cdot 10^{-1}\) | \(1.6661 \cdot 10^{-2}\) | \(-4.1802 \cdot 10^{-4}\) |

atomic mass of the projectile. But it is easy to note, that required 8% shift is significantly smaller, than the quoted accuracy of the energy determination in the EC experiments and, on the other hand, to some part it may be attributed to the effects, discussed in this section.

6. Conclusions

For the first time a complete set of the most recent experimental data on PCR nuclei spectra has been used in calculations of muon flux at sea level in a wide energy range from 1 to \(3 \cdot 10^5\) GeV. The adequate description of cascade processes in the atmosphere has been provided by the application of widely approved code CORSIKA along with
Figure 15. Differential muon spectrum at sea level. QGSJET and VENUS — present work calculations with the corresponding interaction models for the primary nucleon spectrum, shown in figure 14 with open circles. Other designations are the same as in figure 10.
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Figure 16. Integral muon spectrum at sea level. QGSJET and VENUS — present work calculations with the corresponding interaction models for the primary nucleon spectrum, shown in figure 14 with open circles. Other designations are the same as in figure 10.
QGSJET and VENUS models. This makes our results free of the possible errors, caused by a simplified approach to description of hadronic interactions.

The main and a rather unexpected conclusion, which our investigation has led to, is that the data on primaries conform to the muon data only for rather low energies up to several tens of GeV. From these energies a deficit of muons becomes evident, corresponding to a deficit of primary nucleons with $E_{\text{PCR}} \gtrsim 1$ TeV. In the earlier works of the other authors this problem was masked by the uncertainties of the data on PCR fluxes and hadronic interactions, existed those days. In a surprising way, refinement and gain of the information have not approached us to the possibility of the more accurate muon flux derivation, but, on the contrary, have revealed that our today’s, improved notions are in some part erroneous. This, by the way, makes obsolete attempts to standardize the lepton fluxes calculations in respect to the primary spectra, since, as our consideration shows, in the large part the problem lies in underestimation of PCR intensity. In our point of view, to remedy the situation with the least consequences, the re-examination of the EC experimental results with the application of different interaction codes is required. As we have noted, in this connection VENUS possesses with two positive features. In comparison with the other models it predicts a larger number of muons at sea level, and in the single hadronic interaction, less fraction of the energy is deposited into electromagnetic component, but the influence of the latter effect on the measurements results is not so simply to analyze, since it may be compensated at the different stages of the EC data processing. Another fact, that must be taken into account, is the possible presence in PCR of sizable fraction of antiprotons. If the emulsion chambers data would prove to be insensitive to the given effects, only then the problem should be attributed to some uncertainties or anomalies in the high-energy hadronic interactions. In any case, our calculations have demonstrated, that today the fit of the sea level muon data can not be derived directly from the PCR data, and the reasons, leading to this puzzle, look unclear.

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