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Evidence for a bump in the primary cosmic ray energy spectrum at 3–200 PeV

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Abstract: We present the primary cosmic-ray energy spectrum obtained by a multi-parametric event-by- event evaluation of the primary energy. The results are obtained on the basis of the GAMMA EAS data set detected at the mountain level (700 g/cm^2). The energy evaluation method has been developed using the EAS simulation with the SIBYLL interaction model taking into account the response of detectors and reconstruction uncertainties of EAS parameters. The explicit irregularity ('bump') of the spectrum is observed at primary energies of 70 - 80 PeV.

Introduction

The study of the fine structure in the primary energy spectrum is one of the most important tasks in the very-high energy cosmic ray experiments [1]. Commonly accepted values of the all-particle energy spectrum indexes of -2.7 and -3.1 before and after the knee are an average and do not reflect the real behaviour of the spectrum particularly after the knee. It is necessary to pay a special attention to the energy region of 10-100 PeV, which was extremely poor with experimental results hitherto. Irregularities of the energy spectrum in this region were observed a long time ago. They can be seen from the energy spectrum obtained more than 20 years ago with AKENO experiment [2] as well as in the later work of the GAMMA [3] experiment. At last, the same irregularities can be seen in KASCADE [4] experiment results where an inverse approach for the primary spectral reconstruction has been used. It is necessary to underline that bumps observed in these experiments are seen at the same narrow regions of the spectrum: ~ 30 PeV and 70 — 80 PeV. At the same time the large statistical errors did not allow to discuss the reasons of these irregularities. On the other hand results of many experiments on the study of extensive air shower (EAS) size spectra, the behaviour of the age parameter and muon component characteristics point out that the primary mass composition beyond the knee becomes significantly heavier. Based on these indications, ad-ditional investigations of the fine structure of the primary energy spectrum at 10-100 PeV have an obvious interest.

There are two ways to obtain the primary energy spectra using detected EAS. The first one is a statistical method that using the detected EAS data set and the model of the EAS development in the atmosphere, the primary energy spectra are unfolded from the corresponding integral equation set [5,6]. The second one is an event-by-event method [2,7,8] that using the detected EAS parameters $q \equiv q(N_e,N_\mu,N_h,s,\theta)$ the evaluation of primary energy is obtained by the parametric $E = f(q)$ [2,7,8] or non-parametric [9] energy estimator previously determined on the basis of shower simulations in the framework of a given model of the EAS development. Here, applying the event-by-event parametric energy evaluation $E = f(q)$, the all-particle energy spectrum in the knee region is obtained on the basis of the data set, obtained with the GAMMA EAS array [6,8] and the simulated EAS database obtained using the SIBYLL [10] interaction model. Preliminary results have been presented in [7,8].

The GAMMA experiment

The GAMMA installation [6,8] is a ground based array of 33 surface detection stations and 150 underground muon detectors, located on the south side of Mount Aragats in Armenia. The elevation of the GAMMA facility is 3200 m above sea level, which corresponds to 700 g/cm^2 of atmospheric depth.

The surface stations of the EAS array are arranged in 5 concentric circles of ~20, 28, 50, 70 and 100 m radii, and each station contains 3 plastic scintillation detectors with the dimensions of 1 x 1 x 0.05 m^3. Each of the central 9 stations contains an additional (the 4th) small scintillator with dimensions of 0.3 x 0.3 x 0.05 m^3 (Fig. 1) for high particle density (> 10^2 particles/m^2) measurements.

A photomultiplier tube is placed on the top of the aluminum casing covering each scintillator. One of the three detectors of each station is viewed by two photomultipliers, one of which is designed for fast timing measurements. 150 underground muon detectors ('muon carpet') are compactly arranged in the underground hall under 2.3 Kg/cm^2 of concrete and rock. The scintillator dimensions, casings and photomultipliers are the same as in the EAS surface detectors.

The shower size thresholds of the 100% shower detection efficiency are equal to N_{ch} = 3 x 10^5 and N_{ch} = 5 x 10^5 at the EAS core location within *R* < 25 m and *R* < 50 m respectively [6,8].

The time delay is estimated by the pair-delay method [11] to give the time resolution of about 4-5 ns. The EAS detection efficiency (P_d) and corresponding shower parameter reconstruction accuracies are equal to: P_d = 100%, $\Delta\theta \sim 1.5°$, $\Delta N_{ch}/N_{ch} \sim 0.1$, $\Delta s \sim 0.05$, Δx and $\Delta y \sim 0.7$-1 m. The reconstruction accuracies of the truncated muon shower sizes for $R_\mu < 50$ m from the shower core are equal to $\Delta N\mu/N\mu \sim 0.2 - 0.35$ at $N\mu \sim 105 - 103$ respectively [6,8].

The event-by-event energy estimation

The 7-parametric energy estimator was obtained using the CORSIKA NKG mode [12] with the SIBYLL [10] interaction model:

$$\ln E_1 = a_1 x + a_2 s^{0.5}/c + a_3 + a_4 c + a_5/(x - a_6 y) + a_7 y \exp(s)$$

where $x = \ln N_{ch}$, $y = \ln N_\mu$ (R<50m), $c = \cos\theta$, s is the shower age and E_1 is in GeV.

The approximation parameters $a_1, \ldots, a_7$ are presented on Table 1. Detailed information on energy estimator evaluation has been presented in [8].

Table 1 :

a_1	a_2	a_3	a_3	a_5	a_6	a_7
1.030	3.641	-5.743	2.113	6.444	1.200	-0.045

The all-particle energy spectrum

The data set analysed in this paper has been obtained for 5.63 x 10^7 sec of the live run time of the GAMMA facility, from 2004 to 2006. Showers to be analysed were selected with the following criteria: $N_{ch} > 5 \times 10^5$, R < 50 m, $\theta < 45°$, $0.3 < s < 1.6$, $\chi^2(N_{ch})/m < 3$ and $\chi^2(N_\mu)/m < 3$ (where *m* is the number of scintillators with non-zero signal), yielding a total data set of ~ 7-10^5 selected showers.

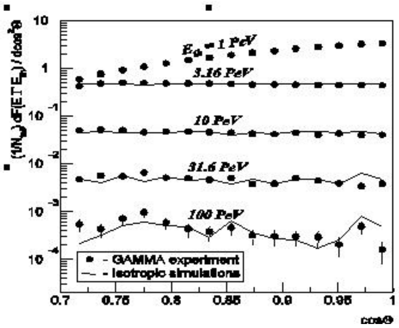

Figure 1: Detected zenith angular distributions for different energy thresholds (symbols). The lines are corresponding simulated isotropic distributions with the same statistics

The selected measurement range provided the 100% EAS detection efficiency and similar conditions for the reconstruction of showers produced by primary nuclei H, He,..., Fe with energies 3 < E < 200-300 PeV. The independent test of energy estimates can be done by the detected zenith angle distributions which have to be isotropic for different energy thresholds. In Fig. 1 the corresponding detected distributions (symbols) are compared with statistically equivalent simulated isotropic distributions (lines). The agreement of detected and simulated distributions at E > 3 PeV gives an additional support to the consistency of energy estimates in the whole measurement range. The anisotropic spectral behaviour at low energies (E ~ 1-3 PeV) is explained by the lack of heavy nuclei in the detected flux due to applied shower selection criteria. Using the unbiased (< 5%) event-by-event method of primary energy evaluation, we obtained the all-particle energy spectrum. Results are presented in Fig. 2 in comparison with the same spectra obtained by the EAS inverse approach from [4,6] and our preliminary results [8] obtained using the 7-parametric event-by-event method with the shower core selection criterion of $R < 50$m and $\theta < 30°$.

As follows from our preliminary data [7,8], the all-particle energy spectrum derived by event-by-event analysis with the multi-parametric energy estimator depends slightly on the interaction model (QGSJET01 [13] or SIBYLL2.1) and thereby, the accuracies of obtained spectra are mainly determined by the sum of statistical and methodical errors presented in Fig. 2 by the dark shaded area.

Shower detection threshold effects distort the all-particle spectrum in the range of E < 2-2.5 PeV depending on the interaction model and determine the lower limit E_{min} = 3 PeV of the energy spectrum in Fig. 2 whereas the upper limit of the spectrum E_{max} ~ 200-300 PeV is determined by the smallness of the saturation of our shower detectors which begins to be significant at E_p > 200 PeV and E_{Fe} > 400 PeV for primary proton and Fe nuclei. The range of minimal methodical errors and biases is 10-100 PeV, where about 13% and 10% accuracies were attained [8] for primary proton and Fe nuclei respectively.

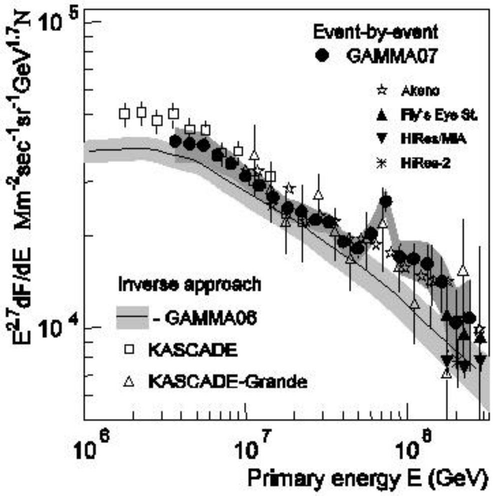

Figure 2: The all-particle energy spectrum in comparison with the results of EAS inverse approach [6,8,9]

The obtained energy spectrum agrees with KASCADE [4] and AKENO [2] data both in the slope and in the absolute intensity practically in the whole measurement range. However, our statistical and methodical errors are less than in these experiments. Looking at the experimental points we can unambiguity point out at the existence of the irregularity in the spectrum at the energy of 70-80 PeV. The energy estimator has minimal biases (~ 4-5%) and errors (~ 0.09-0.12) at this energy. With these errors the obtained bump has an apparently real nature. If we try to fit our spectrum in the 4-200 PeV energy range by the smooth power law then the probability P of such fit taking into account only statistical errors is $P \cong 5$ x 10-3. We did not use errors in this estimate since they are not independent in the nearby points but correlated: the possible overestimation of the energy in one point cannot be followed by an underestimation in the neighbouring point if their energies are relatively close to each other. errors can change slightly the general slope of the spectrum but cannot imitate the fine structure and the existence of the bump.

It is necessary to note that some indications of the mentioned bump are seen also in KASCADE-Grande [4] data (Fig. 2) but with larger statistical uncertainties. Moreover, the locations of the bump in different experiments agree well with each other and with an expected knee energy for Fe-like primary nuclei according to the rigidity-dependent knee hypothesis [6]. However, the observed width (< 10%) and height of the bump at the energy of 70-80 PeV, which exceeds by the factor of 1.5 (~ 5.6 standard deviations) the best fit straight line fitting all points above 4 PeV in Figure 2, are difficult to describe in the framework of the conventional model of cosmic ray origin [14]. Its origin needs a more detailed analysis and we are now preparing a special paper on this point. Notice, that detected EAS charged particle and muon size spectra [6] independently indicate the existence of this bump right for obtained energies.

Conclusion

The multi-parametric event-by-event method provides the high accuracy for the energy evaluation of primary cosmic ray nuclei σ(E) ~ 10-15% regardless of the nuclei mass (biases< 5%) in the 5-200 PeV energy region. Using this method the all-particle energy spectrum in the knee region and above has been obtained (Fig. 2) using the EAS database from the GAMMA facility. The results are obtained for the SIBYLL2.1 interaction model.

The all-particle energy spectrum in the range of statistical and methodical errors agrees with the same spectra obtained using the EAS inverse approach [4,6] in the 3-200 PeV energy range. However, the high accuracy of energy evaluations and small statistical errors point out at the existence of explicit irregularity ('bump') in the 70- 80 PeV primary energy region.

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