Comparison of hadron shower data in the PAMELA experiment with Geant 4 simulations

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Abstract. The sampling imaging electromagnetic calorimeter of ≈ 16.3 radiation lengths and ≈ 0.6 nuclear interaction length designed and constructed by the PAMELA collaboration as a part of the large magnetic spectrometer PAMELA. Calorimeter consists of 44 single-sided silicon sensor planes interleaved with 22 plates of tungsten absorber (thickness of each tungsten layer 0.26 cm). Silicon planes are composed of a 3 × 3 matrix of silicon detectors, each segmented into 32 read-out strips with a pitch of 2.4 mm. The orientation of the strips of two consecutive layers is orthogonal and therefore provides two-dimensional spatial information. Due to the high granularity, the development of hadronic showers can be study with a good precision.

In this work a Monte Carlo simulations (based on Geant4) performed using different available models, and including detector and physical effects, compared with the experimental data obtained on the near Earth orbit. Response of the PAMELA calorimeter to hadronic showers investigated including total energy release in calorimeter and transverse shower profile characteristics.

1. Introduction

The PAMELA instrument is installed on board of Russian satellite Resurs–DK1 and intended to study fluxes of charged particles in cosmic rays with particular focus on antiparticles. The PAMELA instrument consists of following detectors: a time-of-flight system, an anticoincidence system, a magnetic spectrometer, an electromagnetic calorimeter, a neutron detector, a shower tail catcher detector (S4) [1]. This set of detectors, except of calorimeter, gives us an information about a type and energy of the incoming particles.

The main task of the PAMELA calorimeter is to distinguish positrons/electrons from protons/antiprotons and to measure energy of stopped particles, electrons and positrons [2]. But with calorimeter, we also may compare different simulation models of hadronic interactions (in case of this work, the Geant4 physics), comparing energy releases, longitudinal and transverse shower profiles for experimental and simulation data.

In this work, simple shower data analysis provided for the following characteristics, which were calculated for each event:

- \( Q_{\text{tot}} \) — total energy release in the calorimeter;

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• $Q_{tr}$ — energy release in the cylinder with radius of 4 strips around the shower axis (see figure 1). This characteristic describes shower transverse profile.

![Figure 1. Shower initiated by proton.](image)

2. Simulation software and models
We simulate monoenergetic isotropic proton flux for the various models of the hadronic interaction and for the various energies from 0.75 GeV to 50 GeV with the following software suit:

| Program                        | Version  |
|-------------------------------|----------|
| Geant 4                       | 4.10.01  |
| CLHEP                         | 2.2.0.4  |
| Root                          | 5.34.23  |
| Virtual Geometry Model (VGM)  | 4.2      |
| Geant4 Virtual Monte Carlo (VMC) | 3.1     |

Geant4 models of hadronic interaction [3] used in simulation are presented in figure 2 with correspondent energy ranges.

![Figure 2. Available Geant4 models with correspondent energy ranges.](image)

3. Selection Criteria
Experimental and simulation proton events were filtered by the following selection criteria:

• no signals in anticoincidence systems;
• no more than one paddle triggered in each plane of the time-of-flight system;
• particle track reconstructed by 5 points in the deflecting projection (X), and by 4 points in other projection (Y), track satisfies a quality criterion \( \chi^2 \);
• no hits in strips out of track;
• the tracks reconstructed by the calorimeter and the tracker independently coincide;
• protons are selected by measurements of energy losses vs particle rigidity in tracker.

4. Two-sample Kolmogorov-Smirnov test
Let \( A \) and \( B \) be two real-valued samples of size \( m \) and \( n \), respectively. Empirical cumulative distribution function (CDF) is defined as

\[
F_A(x) = \frac{\text{number of elements in } A \text{ that are } \leq x}{m}
\]

Define

\[
D_{m,n} = \max_x |F_A(x) - F_B(x)|
\]

See illustration of these notions on figure 3.

![Figure 3](image)

**Figure 3.** There are two samples of the simulation and the experimental data. Both samples consist of proton events with rigidity \( \sim 2 \text{ GV} \). For each event, \( Q_{\text{tot}} \) parameter value was calculated. The figure shows empirical CDFs of \( Q_{\text{tot}} \) values for experimental (thick line) and simulation (thin line) samples. \( D \approx 0.0352 \) is the maximal difference between empirical CDFs defined by formula (2).

The null hypothesis is \( H_0 \): \( A \) and \( B \) come from the same distribution. We reject the null hypothesis if \( D_{m,n} > D_{m,n,\alpha} \) where \( D_{m,n,\alpha} \) is the critical value for the significance level \( \alpha \).

\[
D_{m,n,\alpha} = c(\alpha)\sqrt{\frac{m+n}{mn}},
\]

where values of \( c(\alpha) \) are known and tabulated for various \( \alpha \) [4].

For the significance level, the commonly used values are \( \alpha = 0.01 \), \( \alpha = 0.05 \), and \( \alpha = 0.1 \). In calculations, we used \( \alpha = 0.01 \), which corresponds to the “softer” treatment of the agreement notion.

5. Results
We performed comparison of experiment and simulation data \( Q_{\text{tot}} \) and \( Q_{\text{tr}} \) shower characteristics.
5.1. Total energy release

$Q_{\text{tot}}$ is the energy release by the primary and all of the secondary particles, which occurred due to hadronic interaction of the primary proton with the calorimeter material, i.e., the total energy measured in each of 96 strips of each of 44 silicon detector planes of the calorimeter.

![Figure 4](image)

**Figure 4.** Difference between empirical CDFs of simulation and experimental data for different models with fixed rigidity values. Distribution of $Q_{\text{tot}}$ parameter was compared. Hashed line corresponds to the threshold value $D_{m,n,\alpha}$ for Kolmogorov-Smirnov test with significance level $\alpha = 0.01$.

Results of the comparison of experimental and simulated data for $Q_{\text{tot}}$ parameter shown in figure 4. Described in section 4 method works only on hypothesis rejection or acceptance and does not presume the use of errors. By this reason, there are no error bars on that figure.

For protons energies below 20 GeV we consider FTFP\_BERT model as preferable for total energy release simulation. For higher energies, QGSP\_BERT model seems best.

5.2. Energy release around shower axis

Let’s consider $Q_{\text{tr}}$ parameter — the total energy release inside cylinder with radius of 4 strips around the shower axis. This characteristic describes the transversal profile of the particle shower.

Results of the comparison of experimental and simulated data for $Q_{\text{tr}}$ parameter shown in figure 5. As well as the previous case, for protons energies below 20 GeV we consider FTFP\_BERT model as preferable for $Q_{\text{tr}}$ simulation. For higher energies, no considered model passed the agreement test. If we consider $D_{m,n}$ statistic as a measure of distribution difference, the QGSP\_BERT and QGSP\_INCLXX models seem the best for this parameter.

6. Conclusion

In this work, a comparison of the interaction of protons with the calorimeter material was performed for simulation and experimental data for $Q_{\text{tot}}$ and $Q_{\text{tr}}$ parameters. Generation of the simulation dataset was performed with the software package based on Geant4.10, which is approved in the PAMELA collaboration. It was shown that the best coincidence of the simulation and the experimental data is achieved for the FTFP\_BERT model for protons with
Figure 5. Difference between empirical CDFs of simulation and experimental data for different models with fixed rigidity values. Distribution of $Q_{tr}$ parameter was compared. Hashed line corresponds to the threshold value $D_{m,n,\alpha}$ for Kolmogorov-Smirnov test with significance level $\alpha = 0.01$.

energy less than 20 GeV. For protons with energy in range 20...50 GeV, the best coincidence reached for the QGSP_BERT and the QGSP_INCLXX models.

In the future, more detailed analysis of the results will be performed. Also, the larger energy range will be considered.

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