Application of ASAS method to PAMELA calorimeter

A I Fedosimova 1*, I A Lebedev 1, A G Mayorov 2, E A Dmitriyeva 1, E A Bondar 1, P M Krassovitskiy 3, Kh K Olimov 4, I I Absalyamova 1, D O Murzalinov 1

1 Institute of Physics and Technology, Satbayev University, Almaty, Kazakhstan
2 National Research Nuclear University MEPhI, Moscow, Russia
3 Institute of Nuclear Physics, Almaty, Kazakhstan
4 Physical-Technical Institute of SPA “Physics-Sun” of Uzbek Academy of Sciences, Tashkent, Uzbekistan

*E-mail: ananastasia@list.ru

Abstract. In this paper, we propose a method that makes it possible to improve energy reconstruction for data obtained via thin heterogeneous calorimeters for direct measurements of cosmic rays with energies of TeV and higher. Despite the large number of modern experimental complexes, the primary energy of cosmic nuclei with energies above 1 TeV is determined with large errors associated with fluctuations in the development of the cascade. For heterogeneous calorimeters, transient effects give an additional negative effect. In this paper, we analyze the main causes of fluctuations and discuss a method for reducing the effect of fluctuations on the results of primary energy reconstruction. The method of accumulation of signal along the spectrum (ASAS) is used to reduce fluctuations associated with transient effects. The method was tested using the heterogeneous calorimeter of the PAMELA collaboration. It is shown that the proposed approach makes it possible to correctly determine the energy of slowly developing showers, the maxima of which are not measured.

1. Introduction

Measurements of the chemical composition and fluxes of cosmic rays play a decisive role in understanding the mechanisms of their acceleration and propagation. Different cosmological models predict different elemental composition of cosmic rays and different spectra of the elements [1-3].

Modern space and balloon experiments for determining the energy of cosmic particles in recent years have shown extremely high accuracy for energies less than 1 TeV due to a wide variety of instruments [4-5]. However, for energies above 1 TeV, most detectors (magnetic spectrometers, Cherenkov detectors, scintillation detectors, transient radiation detectors) have significant limitations [6-7]. Currently, the best device for measuring energy in the range from 1 TeV to 100 TeV is an ionization calorimeter [8-9].

The method of measuring energy using a calorimeter is following. As result of particle interactions with the substance of the calorimeter, a cascade of secondary particles is produced. For measurement of characteristics of the cascade the dense substance is sandwiched with special detectors. By measurement of signals from these detectors the cascade curve is formed. As soon as the cascade reaches its maximum, it is possible to determine the energy of the incident particle. However, the problem arises in the size of the installation, since the calorimeter must have sufficient depth to...
determine the value of the total energy release in the calorimeter. Moreover, the higher the primary energy, the thicker the calorimeter should be. The huge weight of the installation makes it much more difficult to use such a device in space experiments.

Therefore, thin calorimeters are used for space experiments, which do not measure the cascade as a whole, but only register its beginning. However, due to significant fluctuations in the development of the cascade, the energy resolution of thin calorimeters when measuring hadron cascades at the present stage is 30–70% [10-14].

To improve the accuracy of energy determination, either the size of the calorimeter needs to be increased or high-precision methods for energy determination must be developed. One of such methods is the lessening fluctuation method (LFM) [15-16]. This method is designed for a mixed calorimeter (target unit and measuring block). With this method, it is possible to suppress the influence of fluctuations on the results of primary energy reconstruction. However, to apply LFM to a heterogeneous calorimeter, it is necessary to reduce fluctuations from layer to layer.

In this paper, we discuss the application of LFM in the PAMELA heterogeneous calorimeter. To reduce fluctuations associated with transient effects, we used the method of accumulation of signal along the spectrum (ASAS) [17-18].

2. Determination of energy in a thin calorimeter

By their design, calorimeters are divided into homogeneous and heterogeneous. Heterogeneous calorimeters consist of layers of a substance with a high density (lead, tungsten), where particles lose their energy during passage, alternating with layers of detectors (silicon), where the energy released by the particles of the cascade is measured. Homogeneous calorimeters use substances (bismuth germanate crystal, lead tungstate, etc.), which simultaneously provide both the energy loss of the primary particle (i.e., the development of cascades) and the measurement of the amount of this lost energy [19-20].

The geometric dimensions of heterogeneous calorimeters are usually significantly lower than that of homogeneous ones. In addition, they have better spatial resolution as they are segmented in both the longitudinal and lateral directions.

A significant drawback of heterogeneous calorimeters is the transient effects due to the significant difference between the value of the critical energy in the material of an absorber and a detector. The main ionization in a calorimeter is generated by relativistic electrons from the developing cascade. The number of electrons in the maximum of the cascade depends on the ratio of the energy of primary particles and the critical energy in a substance. The critical energy in lead and in silicon varies significantly. It is 7.4 MeV in lead and 37.5 MeV in silicon. Thus, the number of particles in lead and in silicon differs approximately by 5 times. Thus, when moving from lead to silicon, particles are quickly absorbed and the balance is disturbed. In this regard, it is possible to observe fluctuations in the development of the cascade from layer to layer. The strongest fluctuations from layer to layer are at the beginning of the development of the cascade. This makes the analysis very difficult.

For example, consider several modern space experiments.

The PAMELA calorimeter is a heterogeneous calorimeter. It consists of 22 (x,y) silicon sensing planes alternating with tungsten absorber planes. The calorimeter thickness is 16.3 radiation lengths and 0.6 of nuclear interaction length. The particle energy is determined for energies above 1 TeV at the maximum of the cascade. If the shower maximum is located outside the calorimeter, then the energy released in the last layer of the calorimeter is used to estimate the energy. The energy resolution of the calorimeter for protons is ~ 40% [10].

NUCLEON apparatus includes the charge measurement system consisting of 4 pad silicon detectors layers, the KLEM energy measurement system consisting of the carbon target and the silicon microstrip detectors interleaved with thin tungsten layers, the trigger system consisting of the 6 scintillator layers and the calorimeter [8]. With an energy measurement system and a target, the NUCLEON calorimeter thickness is 15.3 radiation lengths. However, the applied energy determination methods give a low energy resolution (~ 70%) [12].
CALET consists of a charge detector, a finely segmented pre-shower imaging calorimeter and a total absorption calorimeter. The primary particle energy is calculated based on the total energy release in the calorimeter. The obtained energy resolution is close to 30% [13-14].

What is the reason for such major errors?

First of all, the number of particles in a cascade depends on fluctuations of the penetration depth before the first interaction. The earlier the primary particle interacts, the more secondary particles will be at the observation level.

In addition, fluctuations in the number of particles in a cascade depend on the features of the nucleus-nucleus interaction, such as the initial geometry of the collision, multiplicity of secondary particles, etc. Different approaches and methods are used to study the features in multiparticle production [21-26].

Depending on the point of the first interaction and the multiplicity of the first few interactions, the cascade can develop in different ways. Rapidly developing showers can reach their maximum in the calorimeter. Slow-developing showers of the same energy may not reach their maximum, and therefore the total energy release of both showers will be significantly different. In this regard, the accuracy of the determined energy remains quite low.

LFM has been tested on the PAMELA calorimeter. Simulation of the development of cascade processes formed by primary particles of various masses and energies was carried out using the GEANT4 software package [27].

As the analyzed value of the cascade size, we used the logarithm of the energy release, log $Q$, at the measuring layer. The measuring levels of the PAMELA calorimeter are equidistant. Therefore, as cascade curves, we analyzed the dependence of the cascade size on the layer number, $N_s$.

Figure 1a shows a fast and slowly developing cascade curves initiated by a 10 TeV proton.

As can be seen from Figure 1, the total energy release for these cascades is significantly different, despite the same energy of the primary particle. If the first interaction is central, then many particles are produced and the cascade develops rapidly. If the first interaction is peripheral, then the cascade develops slowly. For example, the proton that initiated the slow cascade interacted at the beginning of the calorimeter, but the rapid development of the cascade began only after layer 9. Due to the fact that
most experimental groups determine the energy of the primary particle by its energy release, the errors remain quite large. In addition, fluctuations from layer to layer have a significant effect.

To use the lessening fluctuation method, it is necessary to minimize the layer-by-layer fluctuations. Unfortunately, in some cases, the use of standard fitting procedure may be wrong. Figure 1a shows that the third-degree polynomial fit for a slowly developing cascade is significantly incorrect.

The signal accumulation method along the spectrum allows you to more gently minimize fluctuations from layer to layer, unlike fitting with a polynomial function.

In Figure 1b, smoothing was carried out by ASAS method on three points in accordance with the formula:

$$\log Q_j = \frac{1}{3} \sum_{i=j-1}^{j+1} \log q_i,$$

where \( \log q_i \) is the measured value of the shower size, and \( \log Q_j \) is the accumulated value of the shower size.

In Figure 1b, signal smoothing is performed more correctly, which makes it possible to determine energy in a heterogeneous calorimeter without loss of accuracy using the lessening fluctuation method.

3. The lessening fluctuation method

Most of the energy measurement methods used in modern experiments are based on the use of a cascade curve. If the cascade curve has reached its maximum in the calorimeter, then the primary energy is reconstructed quite accurately. But in order to measure the maximum of the cascade, the calorimeter must have a sufficiently large thickness. Moreover, the higher the primary energy, the larger thickness required for the calorimeter.

If the maximum of the cascade curve is not reached in the calorimeter, then the energy release at the last layer of the calorimeter or the total energy release in the calorimeter is used to determine the energy. Cascade curves fluctuate significantly. The cascade can begin to develop on the first measurement layer or, for example, on the 9th measurement layer. And accordingly, the total energy release in the calorimeter for these two cascades will differ significantly. And since total energy release is used to define primary energy, large fluctuations in total energy release lead to large errors in primary energy reconstruction.

The lessening fluctuation method is based on the use of so-called correlation curves - the dependence of the cascade size \((S=\log q)\) on the cascade development rate \((dN)\). The cascade development rate is understood as a value equal to the difference in the cascade size at two measurement levels, divided by the calorimeter thickness, during the passage of which this change in the cascade size occurred: \(R = (S_1 - S_2)/(d_1 - d_2)\), where \(d_1\) and \(d_2\) are the penetration depths to these two measurement layers.

As the correlation curves, the dependence of the cascade size \(S_i\) on the \(i\)-th measuring layer on the difference in the cascade size at two levels \(dN = S_i - S_{i+3}\) was chosen. In this dependence, \(dN\) characterizes the rate of shower development. When choosing the thickness of the unit absorber, we took into account two main factors. The first factor is fluctuations from layer to layer. The thinner the unit absorber, the higher the relative fluctuations of \(dN\) due to fluctuations from layer to layer. Therefore, it is preferable to choose a thicker unit absorber. The second factor is the calorimeter thickness. The thinner the unit absorber used in the LFM, the more points on the correlation curve can be obtained. Looking to the future, a thin unit absorber makes it possible to use an ultra-thin calorimeter to measure primary energy.

Figure 2 shows the correlation curves for the same cascades that were presented in Figure 1. As it can be seen from Figure 1b, in contrast to the cascade curves (Figure 1a), the correlation curves almost coincide for fast, medium, and slow cascades.
This greatly simplifies the task of determining the primary energy. Regardless of fluctuations in the development of a cascade, proton cascades of the same energy are located on the same curve. Therefore, the energy of these cascades will also be defined as the same.

4. Conclusion
The use of the signal accumulation method along the spectrum allows the use of the lessening fluctuation method for thin heterogeneous calorimeters. The size-rate curves practically do not fluctuate. They practically coincide for the cascade, which began to develop at the first measuring layer, and the cascade, which began to develop at the 9th measuring layer. Therefore, the energy resolution is better than using cascade curves. Moreover, using this method, the primary energy can be reconstructed near the beginning of the development of the cascade. Thus, with increasing energy, it is not necessary to increase the calorimeter thickness. Moreover, the calorimeter thickness can be reduced and an ultrathin calorimeter can be used. It becomes possible to significantly increase the amount of analyzed data in existing experiments and expand the measurement area to higher-energy areas.

Acknowledgements
This paper was supported by a grant from the Ministry of Education and Science of the Republic of Kazakhstan No. AP08855403.

References
[1] Ptuskin V, Zirakashvili V and Seo E S 2013 The Astrophysical Journal 763 47
[2] Boos E et al 2006 J. Phys. G: Nucl. Part. Phys. 32 2273
[3] Erlykin A D and Wolfendale A W 2015 J. Phys. G: Nucl. Part. Phys. 42 125201
[4] Lipari P and Vernetto S 2020 Astroparticle physics 120 102441
[5] Bogomolov E A et al 2019 82 704
[6] Borisov S V, Voronov S A and Karelkin A V 2011 Cosm. Res. 49 247
[7] Petrukhin A A 2020 Nuclear instruments and methods in physics research section A: accelerators, spectrometers, detectors and associated equipment 952 161585
[8] Yue C et al 2020 Nuclear instruments & methods in physics research section A-accelerators
spectrometers detectors and associated equipment 984 164645

[9] Adriani O et al 2019 Physical review letters 122 181102
[10] Menn W et al 2018 Astrophys. J 862 141
[11] Atkin E et al 2017 Journal of cosmology and astroparticle physics 2017 020
[12] Atkin E et al 2019 Bulletin of the Russian Academy of Sciences: Physics 83 977
[13] Asaoka Y et al 2017 Astroparticle physics 91 1
[14] Pacini L 2018 Il nuovo cimento C 41 64
[15] Dmitrieva E et al 2020 J. Phys. G: Nucl. Part. Phys. 47 035202
[16] Fedosimova A et al 2017 EPJ Web of Conferences. 145 10004
[17] Tompakova N M et al 2019 Materials Today: Proceedings 25 83
[18] Lebedev I et al Signal-to-Noise Ratio Enhancement by Accumulation of Signal and Noise along the Spectrum 2021 Fluctuation and Noise Letters https://doi.org/10.1142/S021947752250016X
[19] Casolino M and Picozza P 2008 Advances in space research 41(12) 2043
[20] Mayorov A G et al 2015 Fundamental Research in Particle Physics and Cosmophysics 74 314
[21] Fedosimova A et al 2017 EPJ Web of Conferences 145 19009
[22] Adamovich M I et al 2001 APH N.S. Heavy Ion Phys. 13 213
[23] Adamovich M I et al 2004 Physics of Atomic Nuclei 67(2) 273
[24] Fedosimova A I et al 2016 Journal of Physics: Conference Series 668 012067
[25] Kvochkina T N et al 2000 J. Phys. G: Nucl. Part. Phys. 26 35
[26] Olimov Kh K et al 2020 Modern Physics Letters A 35(14) 2050115
[27] Allison J et al 2016 Nuclear instruments and methods in physics research section A: accelerators, spectrometers, detectors and associated equipment 835 186