ANNOTATION

Ph.D. dissertation
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Fedosimova Anastasia Igorevna

Fluctuations in the distributions of secondary particles produced in interactions of relativistic nuclei

The dissertation is devoted to the study of fluctuations in the distributions of secondary particles produced in the interactions of relativistic nuclei of a wide energy range. Fluctuations are considered, both at the level of an elementary act and in cascade processes. A technique is proposed that allows one to significantly suppress the influence of huge fluctuations in the multiplicity of secondary particles during the development of the cascade process on the accuracy of determining the energy of primary cosmic particles based on direct measurements at primary energies above 10^{12} eV. A classification of correlations in the pseudorapidity distributions of secondary particles is proposed, which relates fluctuations of shower particles, the number of fragments of the projectile nucleus and the target nucleus to fluctuations of the initial interaction parameters. The analysis of anomalous fluctuations in the distributions of secondary particles detected in the events of the complete destruction of the projectile nucleus is presented.

Relevance of the topic

Accurate knowledge of the energy spectra and elemental composition of primary cosmic rays allows us to understand the features of the formation of cosmic rays in astrophysical sources, as well as details of the processes of propagation of cosmic rays in the Galaxy. Different cosmological models predict different spectra of elements and different elemental composition of cosmic rays. In this regard, the development of methods to increase accuracy in measuring the energy of high-energy space nuclei in a wide energy range is an urgent task.

To determine the parameters of the primary cosmic particle, it is necessary to solve a complex inverse problem, since a sufficiently large number of interactions take place up to the observation level. The most correct way to solve such a problem is to model a cascade. In this case, the characteristics of the elementary act (interaction cross section, inelasticity, multiplicity, etc.) are used from the data obtained at accelerators. Comparison of measurements of the characteristics of the cascade with the results of Monte Carlo simulations allows us to reconstruct the energy and estimate the mass of the primary particle.

The measurement of cosmic rays with energies $E>10^{14}$ eV takes place mainly at ground stations using the analysis of extensive air showers. These indirect measurements are based on a comparison of the results of measurements of the characteristics of secondary particles and simulation results, and thus depend on knowledge of the elementary act of nucleus-nucleus interaction. To restore the energy and mass of the primary cosmic particle, various approaches are used that interpret the signals in the detectors from the point of view of various models of hadron interactions.

Cosmic rays at E $<10^{14}$ eV are studied by direct measurements outside the Earth's atmosphere on high-altitude balloons and spacecraft.

The energies of cosmic particles are measured quite accurately for particles with an energy E $<10^{11}$ eV. Modern magnetic spectrometers can determine primary energy with an error of less than 10%. However, such devices have limitations at energies E$>10^{12}$ eV, and the task of determining the primary energy based on direct measurements of cosmic rays is complicated.

In the range 10^{12} - 10^{14} eV, there is a lack of measurement methods. The experimental data of various space and balloon experiments often contradict each other due to enormous errors in the measurement of primary energy. The development of approaches to increase the accuracy of measurements is a critical and urgent task for the development of cosmic ray physics in this energy field.

At the present stage of the development of space technologies, the only reliable device for determining primary energy in the range 10^{12} - 10^{14} eV is an ionization calorimeter.

The principle of operation of the ionization calorimeter (IC) is based on measuring the characteristics of the cascade of secondary particles during the passage of the dense substance of the calorimeter. To measure the number of particles in the cascade, the calorimeter is interlaced with special detectors. By measuring the number of particles *N* at each observation level, so-called, cascade curves – the dependence of log*N* on the penetration depth, *d*, to the observation level, are constructed. If the maximum of the cascade curve is measured, then the energy of the primary particle can be determined.

The higher the primary energy, the greater should be the thickness of the calorimeter. This complicates the use of IC on spacecraft.

In this regard, to solve the problem of huge weight, a thin calorimeter can be used. Only the beginning of the cascade of secondary particles is recorded in it. To determine the energy of the primary cosmic particle *E*, its dependence on the size of the cascade (the number of particles in the cascade) is used: $N = \alpha E^{\beta}$, where α, β are certain coefficients depending on the depth of the observation level (penetration depth) and the mass of the primary cosmic particle.

The main problem of the thin calorimeter is the huge fluctuations in the size of the cascade on the ascending branch of the cascade curve. For example, at the penetration depth d = 40 g/cm^2, the fluctuations are so great that some showers with an energy of 10^{14} eV have *N* higher than showers with an energy of 10^{15} eV.

Thus, a decrease in the size of the calorimeter leads to a significant decrease in the accuracy of measurements.

To solve this problem, the dissertation proposed an innovative technique for determining energy in an ultrathin ionization calorimeter, which can significantly reduce the size of the installation without losing the accuracy of energy determination. The essence of the technique is the transition from the analysis of cascade curves to the use of correlation curves, which are almost independent of fluctuations in the development of the cascade process.

In the dissertation, it is proposed to use the dependence of the cascade size (the number of particles in the cascade) on the rate of increase in the cascade size.

The energy of the primary cosmic particle is spent on ionization losses and the production of secondary particles. Moreover, at the beginning of the development of the cascade, the rate of increase in the number of particles in the shower is the highest. Then it gradually decreases to zero at the maximum of the cascade curve.

To determine the primary energy, it is necessary to measure the number of secondary particles N at two adjacent levels $Z1$ and $Z2$, separated by a layer of the absorber. Based on the measurements obtained, correlation curves are constructed – the dependence of the size of the cascade $\log N_{(Z1)}$ on the value of $\log N_{(Z1)}$ - $\log N_{(Z2)}$ corresponding to the cascade development rate.

Correlation curves corresponding to different primary energies are almost parallel to each other and practically independent of the depth of cascade development. This allows the use of a thin calorimeter. At the same time, the main problem of the thin calorimeter associated with huge fluctuations in the size of the cascade on the ascending branch of the cascade curve is solved.

It should be noted that the results of measuring the primary energy of high-energy cosmic rays are based on a comparison of the results of measurements of the characteristics of secondary particles and simulation results, and thus depend on knowledge of the elementary act of nucleus-nucleus interaction.

The study of correlations and fluctuations in the processes of multiparticle production in an elementary interaction act is critical for most theoretical models of multiparticle production. The analysis results allow a more detailed assessment of the predictions of the models used to describe nucleus-nucleus interactions, as well as the models used as particle generators for modeling cascade processes.

To reduce errors arising in the simulation, it is necessary to understand the features of the development of cascade processes, detailed information on fluctuations of multiplicity, pseudorapidity distributions of the products of the nucleus-nucleus interaction, features of the distribution of secondary particles in various types of nucleus-nucleus interactions is necessary.

In addition, the study of fluctuations in the processes of multiple particle production in relativistic nucleus-nucleus collisions is relevant for the analysis of the properties of nuclear matter at high densities and temperatures.

According to modern concepts, in hadron interactions at high energies, the hadron substance passes into the state of a quark-gluon plasma (QGP), in which quarks and gluons are in a quasi-free state, i.e., the process of deconfinement is observed.

The production of secondary particles from a bunch of excited nuclear matter is collective in nature, which should lead to significant fluctuations in the distributions of secondary particles.

The search for QGP is carried out in a wide energy range.

On the one hand, research is being conducted at the maximum available interaction energies. Studies at CERN (European Center for Nuclear Interactions) and at Brookhaven National Laboratory (USA) found a collective character in the distribution of secondary particles.

On the other hand, the energy region is actively studied near the critical point of the phase transition of hadron matter into a quark-gluon plasma. According to theoretical concepts, the critical point should be in the energy range from 4 to 11 GeV per nucleon. It is assumed that studies near the phase transition point will provide qualitatively new information on the properties of QGP and on the dynamics of the process. In addition, in this area they predict the existence of the so-called mixed phase of nuclear matter, which, in addition to free quarks, also includes protons and neutrons.

Several major international experiments, including the FAIR in Darmstadt and the NICA in Dubna, have been directed to study this particular problem.

The separation of fluctuations associated with the geometry of the collision from fluctuations associated with the manifestation of a phase transition near a critical point (phase transition point) is a critical moment for obtaining reasonable results. Moreover, about the initial state of interaction is usually not enough experimental information. Depending on the degree of centrality of the interaction, the distribution of secondary particles can vary significantly in individual interactions. In this regard, the most relevant for the search for dynamic fluctuations associated with the phase transition of nuclear matter to a quark-gluon plasma is event-by-event analysis of nuclear collisions at high energies. It is assumed that an analysis in detail of the characteristics of each individual event will directly observe the effects of a phase transition in events in which the most favorable conditions for the formation of a quark-gluon plasma were created. The rapid development of an event-by-event study in recent years is associated with the advent of complex experiments with large receiving detectors capable of measuring the characteristics of secondary particles with high accuracy.

The fundamental difference between the research presented in the dissertation is the use of, in addition to standard methods, additionally fragmentation characteristics of the target nucleus and the projectile nucleus to determine the initial interaction parameters. In experiments on colliding beams, fragments of the projectilel nucleus are usually not recorded. However, the study of their characteristics can provide significant information about the geometry of the initial state.

The study was primarily aimed at anomalous fluctuations in the distribution of secondary particles: events of complete destruction of the projectile nucleus, events with an anomalously high multiplicity of secondary particles, events with significant multi-particle correlations of shower particles, etc.

Such studies are relevant both for searching and analyzing the properties of quark-gluon plasma, and for improving models describing the processes of interaction of relativistic nuclei.

The purpose of the thesis

The study of fluctuations in the distributions of secondary particles produced in the interactions of relativistic nuclei to develop new methods for the analysis of highly fluctuating cascade processes.

Tasks

1 To develop a method for measuring the energy of primary cosmic particles based on direct measurements at primary energies above 10^{12} eV, which can significantly suppress the influence of huge fluctuations in the multiplicity of secondary particles during the development of a cascade process on the accuracy of energy determination.

2 To propose a classification of correlations in the pseudorapidity distributions of secondary particles, which relates fluctuations of shower particles, the number of fragments of the projectile nucleus and target nucleus with fluctuations of the initial interaction parameters.

3 To analyze the fluctuations in the distributions of secondary particles in the events of complete destruction of the projectile nucleus.

Objects of study: Fluctuations in the distributions of secondary particles produced in interactions of relativistic nuclei

Subject of research: Experimental studies of fluctuations in relativistic nucleus-nucleus collisions in the distributions of secondary particles in terms of multiplicity, pseudorapidity, correlations in the distributions of shower particles and fragments of the projectile nucleus and target nucleus, modeling of cascade processes, development of analysis methods.

Research methods: correlation curve method, Hurst method, event-by-event analysis

The main provisions to be defended:

1 Using the dependence of the number of secondary particles on the rate of cascade development in an ultrathin calorimeter significantly reduces the influence of fluctuations in the development of the cascade on the accuracy of determining the energy of primary particles with E > 1 TeV.

2 The dependence of the Hearst index on the width of the pseudo-fast interval in the distributions of secondary particles In collisions of ^{197}Au nuclei with an energy of 10.7 AGeV with photoemulsion nuclei obtained from the EMU01 collaboration experiment divides all events into four types of interaction depending on the initial conditions: explosive, jet, mixed and evaporative.

3 The total destruction of the impending ^{32}S sulfur core with an energy of 200 AGeV in interactions with the photoemulsion cores in the EMU01 collaboration experiment is characterized by an ultra-high multiplicity of rain particles and an abnormally narrow average pseudo-fast distribution with a shift towards lower values compared to other events.

Scientific novelty

1 A universal method has been developed for determining the energy of primary cosmic radiation for a wide energy range above 10^{12} eV based on an ultrathin calorimeter.

2 A classification of density fluctuations in the pseudorapidity distributions of secondary particles in the interactions of gold nuclei with emulsion nuclei based on the Hurst method is proposed, dividing all events into four types of interaction: explosive type, jet type, mixed type and evaporative type, depending on the initial conditions of interaction.

3 An anomalously high number of events of complete destruction of the projectile nucleus with a high multiplicity of shower particles and a narrow average pseudorapidity distribution shifted towards lower values of the average pseudorapidity was found.

Theoretical and practical significance of the research

1 The use of correlation curves to determine the energy of cosmic particles can significantly reduce the geometric dimensions of the calorimeter and increase the accuracy of the measurement of primary energy.

2 The proposed classification of correlations in the pseudorapidity distributions of secondary particles makes it possible to relate fluctuations in the multiplicity of shower particles and the number of fragments of the projectile and target nuclei with fluctuations of the initial interaction parameters (degree of centrality of interaction and degree of asymmetry of interacting nuclei).

3 Analysis of fluctuations in events of complete destruction of the projectile nucleus in S + Em interactions at 200 AGeV allowed us to find the distinctive features of these anomalous events.

The reliability and validity of the results

The results and conclusions obtained during the study reflect the content of all sections and are confirmed by the publication of the main scientific results in peer-reviewed international and domestic scientific publications. The reliability of the scientific conclusions of the work is confirmed by consistency with the results of independent research and conclusions obtained by other authors.

Sources of research are original scientific works listed in the list of used literature.

Personal contribution of the author

In the process of carrying out these studies, the author performed the bulk of numerical calculations, made a significant contribution to the development of analysis methods, and also took an active part in the formulation of the problem and the presentation of results at conferences.

Publications

Based on the materials of the dissertation, 22 scientific papers were published (12 articles, 1 patent, 9 abstracts), including 4 in journals indexed by Scopus and Web of Science, and 5 in publications recommended by Committee for Control of Education and Science RK.

Approbation of a dissertation

The results contained in the dissertation were discussed at international conferences: “Nuclear and Radiation Physics”, “Farabi Alemi”, “21st Int. Symposium on Heavy Ion Fusion ”,“ The 3rd international conference on particle physics and astrophysics ”,“ 19th International Symposium on Very High Energy Cosmic Ray Interactions ”, and were also discussed in Moscow at meetings of the

Department of Experimental Nuclear Physics of the National Research Nuclear University of Moscow Engineering Physical Institute.

The connection of the topic of the dissertation with the plans of scientific work.

The research carried out as part of the dissertation was carried out under the Target Financing Program No. BR05236730 “Investigation of the fundamental problems of plasma physics and plasma-like media”, under the grant project 4824GF4 “Search for experimental manifestations of deconfinement processes in the interactions of asymmetric nuclei”, under the grant project 1276GF2 “Development of scientific foundations technologies for measuring highly ionizing radiation based on a thin calorimeter ”, under the grant project 1563GF“ Studies of fragmentation and multiple processes in nuclear interactions ”.

Volume and structure of the dissertation.

The dissertation consists of introduction, three chapters, conclusion, list of sources used. The dissertation is 105 pages long, including 5 tables and 59 figures.