Multiplicity and Entropy Scaling of Medium-energy Protons Emitted in Relativistic Heavy-ion Collisions

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The behavior and the properties of medium-energy protons with kinetic energies in the range 26 – 400 MeV is derived from measurements of the particle yields and spectra in the final state of relativistic heavy-ion collisions (16O-AgBr interactions at 60 A and 200 A GeV and 32S-AgBr interactions at 3.7 A and 200 A GeV) and their interpretation in terms of the higher order moments. The multiplicity distributions have been fitted well with the Gaussian distribution function. The data are also compared with the predictions of the modified FRITIOF model, showing that the FRITIOF model does not reproduce the trend and the magnitude of the data. Measurements of the ratio of the variance to the mean show that the production of target fragments at high energies cannot be considered as a statistically independent process. However, the deviation of each multiplicity distribution from a Poisson law provides evidence for correlations. The KNO scaling behavior of two types of scaling (Koba–Nielsen–Olesen (KNO) scaling and Hegyi scaling) functions in terms of the multiplicity distribution is investigated. A simplified universal function has been used in each scaling to display the experimental data. An examination of the relationship between the entropy, the average multiplicity, and the KNO function is performed. Entropy production and subsequent scaling in nucleus-nucleus collisions are carried out by analyzing the experimental data over a wide energy range (Dubna and SPS). Interestingly, the data points corresponding to various energies overlap and fall on a single curve, indicating the presence of a kind of entropy scaling.

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1. INTRODUCTION

Multiparticle production (MP) is an important experimental phenomenon in high-energy nucleus-nucleus (AA) collisions [1, 2]. The history MP investigation is very interesting. It is connected on the one hand with the developing theory and on the other hand with the increasing energy of accelerators. In this regard, most features of MP, such as the average charged particle multiplicity and the particle densities, are of fundamental interest as their variations with the collision energy, impact parameter and the collision geometry are very sensitive to the underlying mechanism involved in the nuclear collisions. The energy-independent KNO (Koba-Nielsen-Olesen) scaling function [3] is a good measure for the study of the MP mechanism. In the recent past, the hypothesis of KNO scaling became the dominant frame-work for studying experimentally [4] and theoretically [5] the behavior of the multiplicity distribution of secondary hadrons produced in hadron-hadron and hadron-nucleus collisions at high energy.

The scaling represents independence of a scaling function from the collision energy, the types of the inclusive hadrons, and their production angles and includes spectra for various selection criteria with different charged multiplicities [6]. The general principles can be applied to the AA interactions as well. Various analyses have been carried out on the produced pions. Although very little work has been done with fast target recoil protons, which are also supposed to carry information about the interaction dynamics because the time scale of emission of these particles is the same (∼10⁻²² s) as that of the produced particles. These target fragments, which are known as grey-track particles in nuclear emulsion, are the low-energy part of the intranuclear cascade formed in high-energy interactions.

The main goal of the present investigation is to study...
the distributions of medium-energy protons emitted in the interactions of \(^{16}\text{O}-\text{AgBr}\) at 60 A and 200 A GeV and \(^{32}\text{S}-\text{AgBr}\) at 3.7 A and 200 A GeV. We have compared our experimental results with the results obtained from the analysis of the data generated by using the modified FRITIOF model [7]. The validity of two types of scaling laws (KNO scaling [3] and Hegyi scaling [8]) for the experimental data is examined as well. In our earlier publication [9], we also performed similar investigations in the case of black multiplicity for these interactions. Finally, we study of the entropy production and the subsequent scaling in AA collisions by analyzing the experimental data over a wide range of incident energies.

II. KNO-SCALING FORMULAE

In 1969, Feynman [10] concluded that the mean total number of particles increases logarithmically with increasing the collision energy \(\sqrt{s}\). He argued that the probability of finding a particle of type \(i\), mass \(m\), transverse momentum \(p_t\), and longitudinal momentum \(p_z\) had the form

\[
P_{i}(p_T, p_z, m) = f_i(p_T, p_z/W) \frac{dP_i d^2p_T}{E}, \tag{1}
\]

where the energy of the particle \(E\) and the parameter \(W\) is given by

\[
E = \sqrt{m^2 + p_T^2 + p_z^2} = \sqrt{m^2 + p_T^2} \quad \text{and} \quad W = \frac{\sqrt{s}}{2}. \tag{2}
\]

The function \(f_i(p_T, p_z/W)\) is a structure function and is known as the Feynman function. Feynman’s assumption was that \(f_i\) was independent of \(W\), which is called Feynman scaling.

If the invariant cross section, \(\sigma\), is used, the integration of Eq. (1) under the assumption Feynman made (\(W\) is large) can give the mean multiplicity in the form

\[
<n> \propto \ln(W) \propto \ln \sqrt{s}. \tag{3}
\]

The concept of Feynman scaling was the main assumption when Koba, Nielsen, and Olesen suggested a similar scaling in 1972 [3]. This scaling is now called KNO scaling.

One of the most influential contributions to the analysis of multiplicity distributions was made by KNO. They put forward the hypothesis that at very high energies, the probability distributions \(P(n)\) for detecting \(n\) final state particles exhibit a scaling law of the form

\[
P(n) = \frac{1}{<n>} \psi(z) = \frac{\sigma_n}{\sigma_{inel}}, \tag{4}
\]

where \(\psi(z)\) is the average number of charged secondary particles, \(\sigma_n\) is a partial cross-section for producing \(n\) charged particles and \(\sigma_{inel}\) is the total inelastic cross-section. That is to say, the \(<n>\) measured at different energies (i.e., \(<n>\) scales to the universal curve \(\psi\) when plotted against the multiplicity \(n\) rescaled by the average multiplicity \(<n>\). The scaling function \(\psi(z)\) must satisfy the normalization conditions

\[
\int_0^\infty \psi(z)dz = \int_0^\infty z\psi(z)dz = 1, \quad (i.e., <z> = 1). \tag{5}
\]

As the multiplicity increases, the fluctuations increase accordingly. To normalize the fluctuations from naively increasing in multiplicity, we define the normalized standard moments \(M_q\) as

\[
M_q = \frac{<n^q>}{<n>^q}, \tag{6}
\]

where \(q = 2, 3, 4 \cdots\). Obviously, the standard moments \(M_q\) of \(\psi(z)\) are independent of the collision energy if Eq. (4) is satisfied.

Besides \(\psi(z)\), a second properly-normalized scaling function is obeyed by \(P(n)\). Hegyi [8] demonstrated that in addition to \(<n>\) \(P(n)\), the more simple combination \(nP(n)\) also scaled to a universal curve in the variable \(n/\langle n\rangle\) if KNO scaling is valid. This yields the scaling law for the multiplicity distributions (MDs) in the form

\[
\varphi(z) = nP(n). \tag{7}
\]

The obvious advantages of this new scaling are as follows:

(i) \(nP(n)\) is not influenced by statistical and systematic uncertainties in \(<n>\); hence, \(\varphi(z)\) provides more selective power than the original KNO-scaling function \(\psi(z)\).

(ii) The new scaling function generates a scale parameter \(\sigma = 1\) because it depends only on the combination of \(z\) and the scale parameter of \(\psi(z)\).

III. EXPERIMENTAL DETAILS

Two stacks of nuclear emulsions were horizontally exposed to \(^{32}\text{S}\) beams at two widely differing energies. The first stack of Br-2 emulsion pellicles was irradiated at 3.7 A GeV at the Dubna Synchrophasatron, and the second one of FUJI films was exposed to 200 A GeV at the CERN-SPS (Exp. no. EMU03). Additionally, two stacks of nuclear emulsions were horizontally exposed to \(^{16}\text{O}\) ion beams at the CERN SPS. The first stack of the FUJI films was irradiated at 60 A GeV and the second one of the ILFORD—G5 was exposed to 200 A GeV. The chemical compositions of the used emulsion types are shown in Table 1.

The pellicles were scanned under 100x magnifications with an “along-the-track” scanning technique. Each beam track was carefully followed up to a distance of 5 cm or until it interacted with an emulsion nucleus. Other details of the irradiations and the scanning are given in...