EPJ Web of Conferences **145**, 14004 (2017) DOI: 10.1051/epjconf/201714514004
ISVHECRI 2016

The study of initial conditions in collisions of light, intermediate and heavy nuclei

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Abstract. The system size dependence for multiparticle processes has been recognized in both cosmic ray ("Stratosphere" collaboration) and at accelerator ("EMU" collaboration) experiments. The strong enhancement in multiplicity fluctuations for the most central light-light – (C, O, Ne) + (C/N/O) – collisions has been revealed at JINR-AGS-SPS energies. The sharp difference of light nuclear interactions are interpreted as the sign of intrinsic alpha-clustering in light nuclei.

1. Introduction

Understanding the initial stages of high energy nuclear interactions is one of the key problems for heavy ion physics. The importance of the new insight on the problems were pointed out in the discussions [1,2] just after QM 2014. To understand the problems of particle production in cosmic ray interactions the ever-increasing forward physics programs are considered at the LHC and RHIC colliders [3]. At accelerators the broad system size studies are being performed in the modern NA 61/SHINE experiments at the SPS as part of the program of a systematic search for the onset of deconfinement [4]. The new and far-reaching results have recently been obtained by ALICE in the comparative analysis of freeze-out radii in p-p, p-Pb and Pb-Pb interactions [5]. A better understanding of the initial state characteristics can be obtained from small system interactions. These problems were considered at QM 2014 [6], and at WWND 2016 [7] and more detailed at QM 2015 [8]. The new perspective fixed target experiment BM@N, as the 1-st stage in the heavy ion program at the NICA project [9], will be launched next year. In this work the system size dependence for multiparticle processes is considered at cosmic ray and accelerator experiments.

2. The difference of multiparticle processes generated by cosmic ray protons and light nuclei

The system size dependence for multiparticle processes generated by CR protons and light nuclei has been investigated on the data of the cosmic ray collaboration "Stratosphere" [10]. For this goal dynamical fluctuations of multiplicity and the transverse momentum spectra for γ-quanta were studied. In the well-known intermittency approach [11] the "genuine" dynamical fluctuations over the background of statistical fluctuations were revealed on the basis of the filtering properties of the scaled factorial moments. To overcome the "empty bin" effect we used the third averaging over the start point of the location of the original region D, where N_{step} is the number of small steps ($step/D \ll 1$) of the start position of the original region ,D, in the area of pionization.

$$\langle F_q \rangle = \frac{1}{M} \sum_m \frac{1}{N_{step}} \sum_{step} \frac{1}{N_{evt}} \sum_{evt} \frac{\langle n_m^{[q]} \rangle}{\langle n_m \rangle^q}$$

Three times F_q averaging has increased the value of the q-interval by at least two units in the comparison with the standard approach, i.e. up to rank q = 8. Quantitatively the patterns of the intermittency exponents $\phi(q)$, obtained on the high rank tails, clearly indicate two distinct regions of the q-behaviour for events produced by protons and light nuclei (Fig. 1). The additional

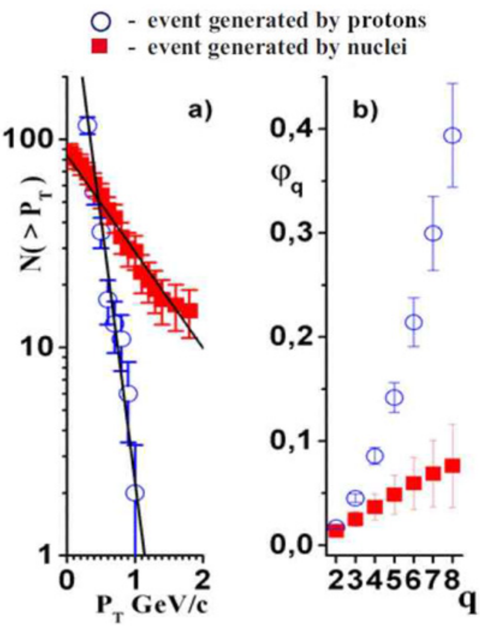

Figure 1. The distribution of transverse momentum and the intermittency exponent ϕ(q) behaviour for events produced by protons and nuclei.

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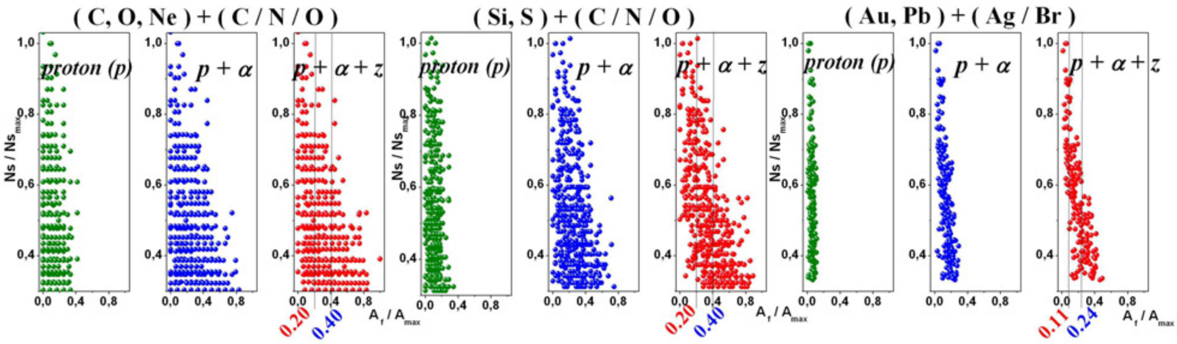

Figure 2. Three variants of the correlation plots $N_s/(N_s)_{max} - A_f/A_{max}$ for collisions of light-light, intermediate-light and heavy-heavy nuclei. In these figures different spectators take into account consecutively in the left (proton-spectators), middle (proton + alpha-particle-spectators) and right frame (proton + alpha + heavy mass fragment-spectators). All correlation panels show centrality intervals for the most central collisions in the top-left, whereas for the most peripheral ones in the bottom-right.

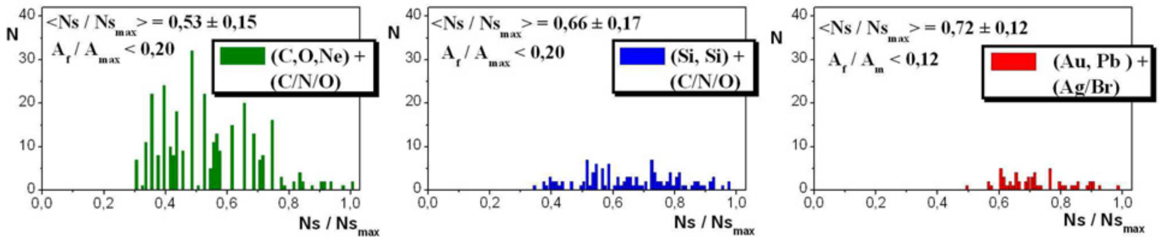

Figure 3. Multiplicity distributions for "central" interactions in light-light – (C, O, Ne) + (C/N/O), intermediate-light – (Si, S) + (C/N/O) and heavy-heavy – (Au, Pb) + (Ag/Br) collisions.

analyses of the transverse momentum spectra of all secondary γ-quanta in the soft region (up to 2 GeV/c) again demonstrated the two component patterns with large differences between proton/nuclei events: the inverse slope of the distribution $T_p \sim 0.2$ GeV/c, is essentially smaller than $T_A \sim 0.8$ GeV/c, (Fig. 1).

It is very important to compare our cosmic ray data with current collider experiments. However, there are some serious problems [12] to perform this analysis.

3. The system size dependence in nuclear collisions at accelerator energies

At accelerator energies the system size dependence for the initial stages of interactions has been investigated in the centrality selected collisions of light and heavy nuclei using the data of JINR-AGS-SPS fixed target emulsion experiments. The basic variables of the analyses are: the normalized multiplicity of the produced charged particles – $N_s/(N_s)_{max}$, and the normalized sum of the mass of all charged, – light and heavy, – fragment-spectators: proton-spectators, alpha-particle-spectators and heavy mass fragment-spectators – A_f/A_{max}. A_{max} corresponds to the mass of the projectile nucleus. $(N_s)_{max}$ corresponds to the maximal multiplicity in the experiment. The transfer from Z to A was performed on the basis of data for high energy cosmic ray nuclei. In order to research the multiparticle processes only events with high multiplicities $N_s > 1/3(N_s)_{max}$ were accepted.

The new solution for centrality determination has been proposed and realized for this goal [13], using correlations between the multiplicity and sum of all fast charged, light and heavy, – fragment-spectators A_f. In this approach the number of participant nucleons for projectile nucleus $N_{part}(projectile) = A_{max}\ \ A_f$. The model of quantitative Glauber nuclear geometry for the description of (near) right spherical nucleus collisions was not used.

From considering the light-light – (C, O, Ne) + (C/N/O), intermediate-light – (Si, S) + (C/N/O) and heavy-heavy – (Au, Pb) + (Ag/Br) nuclear collisions one can conclude that:

1. nonlinearity becomes stronger with the impact parameter increasing in both the multiparticle production processes and in the processes of projectile fragmentation,
2. there is a clear trend to the fluctuation enhancement with system size decreasing [13], (Fig. 2).

For more detailed comparative analyses of the "genuine production processes" we have to remove or, at least, minimize the uncontrolled fluctuations of the volume of the interaction. The projectile participants are adequately determined with our centrality estimator. In order to get rid of fluctuations in the target we have to consider the most central nuclear interactions [14]. With this goal we compare the multiplicity distributions for the "most central" interactions in light-light, intermediate-light and heavy-heavy collisions. The results have shown (Fig. 3) that the width of the normalized multiplicity $N_s/(N_s)_{max}$ distributions is inversely proportional to the volume of interacting systems. For:

- light-light interactions $\langle N_s/(N_s)_{max}\rangle = 0.53 \pm 0.15$,
- intermediate-light interactions $\langle N_s/(N_s)_{max}\rangle = 0.66 \pm 0.17$ and
- heavy-heavy interactions $\langle N_s/(N_s)_{max}\rangle = 0.72 \pm 0.12$.

It is a very significant trend with the connection of the system size behaviour for different measures of fluctuations [15]. On the other hand, it can provide a new insight into collision geometry for light nuclei, as the fluctuation increasing with system size decreasing can reflect the failure of the spherical nuclear pattern at the transition from heavy-heavy to light-light interactions. The obtained results can be interpreted as a clear sign of intrinsic alpha-clustering in the multiparticle processes for light nuclei.

It should be pointed out in this context, that interesting patterns, reflecting the alpha-cluster nature in the exited fireballs, have recently been computed and discussed for high energy asymmetrical light-heavy nuclear interactions [16].

4. Summary

The studies of proton and nucleus interactions at cosmic ray and accelerator energies have shown a clear system size dependence in the transverse momentum spectra for γ-quanta and multiplicity distributions for charged particles. The sharp difference in the multiplicity spectra for light nuclear interactions is interpreted as a sign of intrinsic alpha-clustering in light nuclei.

The work was supported by the project 0228/PCF-15 of Ministry of Education and Science of Kazakhstan Republic.

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