COHERENCY VS. STOCHASTICITY IN SPIKE PRODUCTION
IN NUCLEAR COLLISIONS AT INTERMEDIATE ENERGIES

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Multiparticle spike-production process is investigated in central C-Cu collisions at 4.5 A Gev/c per nucleon. The study is based on two different hypotheses - stochastic vs. coherent - of the formation of spikes. To observe manifestations of the stochastic dynamics, the non-regularities in the multiplicity distributions are analyzed using intermittency approach to a possible phase transition as well as the one-dimensional intermittency model. The entropy indices are calculated based on the erraticity approach. Coherency is studied in the framework of the coherent gluon-jet radiation model. To this end, the spike-center pseudorapidity distributions are analyzed. Coexistence of the two mechanisms of spike formation process is discussed.

1 Introduction

The aim of this talk is to compare the results of the studies of local fluctuations, or spikes, based on two different approaches to multiparticle production, namely on stochastic and coherent hypotheses. In the framework of the stochastic approach, the dynamical origin of the fluctuations is ascribed to the intermittency phenomena, extensively studied in all types of high-energy collisions and shown to exist. However, despite such an activity, an origin of the intermittency remains still unclear. Another possible mechanism of appearance of spikes could be the coherent particle emission. Recently such a model, based on a coherent gluon radiation picture, has been applied for hadronic collisions. The observations have been found to be in agreement with the theoretical predictions. A study of local fluctuations in coherent vs. chaotic terms has a specific interest in particle production in nuclear collisions due to an expectation of quark-gluon plasma formation and its possible manifestation in stochastic scenario. Note that coherent emission could be a reason of the intermittency effect suppression in nuclear collisions as observed.

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2 Data Sample

The study is based on a sample of hadrons produced in the interactions of 4.5 A GeV/c carbon $^{12}$C, nuclei with a copper target inside the 2m Streamer Chamber SKM-200 at the JINR Synchrophasotron (Dubna). A central collision trigger was used: absence of charged particles with momenta $p > 3$ GeV/$c$ in a forward cone of 2.4° was required. The systematic errors due to the detector effects were estimated do not exceed 3%.

The scanning and the handling of the film data were carried out on special scanning tables of the Lebedev Physical Institute (Moscow). The average measurement error in the momentum was $\langle \varepsilon_p/p \rangle \approx 12\%$, and that in the polar angle was $\langle \varepsilon_\theta \rangle \approx 2°$. The spikes are studied for charged particles in the pseudorapidity window $\Delta \eta = 0.2 - 2.8$ ($\eta = -\ln \tan(\theta/2)$) with the accuracy $\langle \varepsilon_\eta \rangle \approx 0.1$. In addition, particles with $p_T > 1$ GeV/$c$ are excluded from the investigation as far as no negative charged particles were observed with such a transverse momentum. Under the assumption of an equal number of positive and negative pions, this cut was applied to eliminate the contribution of protons. A total of 663 events has been analyzed with the average multiplicity of $23.0 \pm 0.4$.

To overcome the effect of the pseudorapidity spectrum shape and to make the results comparable with other experiments, the “cumulative” variable

$$\tilde{\eta}(\eta) = \frac{\int_{\eta_{\text{min}}}^{\eta} \rho(\eta') d\eta'}{\int_{\eta_{\text{min}}}^{\eta_{\text{max}}} \rho(\eta') d\eta'},$$

with the uniform spectrum $\rho(\tilde{\eta})$ within the interval $[0,1]$ is used.

3 Results

3.1 Stochasticity Search

To study stochasticity of the spike-production, we use the intermittency approach, based on the method of normalized factorial moments and one-dimensional intermittency model. The intermittency study is extended to search for the fluctuations in the distributions of the factorial moments that leads to another chaoticity characteristic such as erraticity.

The factorial moments, $F_q$, extracting the $q$-particle local fluctuations, are predicted to have a power-law increase, $F_q \propto M^{\varphi_q}$, if the spikes are of a non-statistical nature. Here, $M$ is number of equal bins into which the pseudorapidity subspace is divided. Such a behavior is called intermittency and reflects the underlying self-similar dynamics. The exponents $\varphi_q$, is pointed out to reflect an occurrence of possible phase transition via the fractal structure of the spike patterns. Monofractality characterizes a second-order phase transition,
while formation of multifractals is assigned\(^b\) to a self-similar cascading with
a possible “non-thermal” (non-equilibrium) phase transition. Multifractality
is found in all types of collisions\(^5\) as well as in those studied here.

As a signal of the transition, the existence of a minimum of the function

\[
\lambda_q = \frac{\varphi_q + 1}{q}
\]

at a certain “critical” value of \(q=q_c\) is expected\(^6\). However, the minimum of
Eq. 1 may also be a manifestation of a coexistence of many small (liquid-type)
fluctuations and a few high-density ones.\(^8\)

Fig. 1 shows the \(\lambda_q\)-function, confirming that at least two regimes of
particle production exist: one with the phase transition at \(4 < q_c < 5\), and another
one for which no critical behavior is reached. The \(q_c\)-value and the “critical”
\(M\)-intervals, which exhibit the minimum of \(\lambda_q\), \(11 \leq M \leq 17\), \(11 \leq M \leq 24\), are
found to be about the same as in our preceding analyses\(^2\) as well as in recent
similar studies in heavy-ion collisions at ultra-high energies\(^17\).

Taking into account the multifractality, the critical \(q_c\) indicates a “non-
thermal” phase transition rather during the cascade than within one phase.
Although the interpretation may be a matter of debate, it must be noted that
the minimum was found earlier also in hadronic interactions\(^5\) at small \(p_T\) and
has been indicated in high-energy nuclear interactions\(^18\).

\(^b\) To note is that the thermal phase transition can also lead to multifractality as described
in the framework of the Ginzburg-Landau theory\(^9\).
The quantities used in the intermittency approach represent the averages, for which changes of the density fluctuations from event to event are not taken into account. This leads to the loss of information about more structure, namely, about degree of chaoticity in multiparticle production. Recently, erraticity approach has been proposed to take into account the event-space ("spatial") fluctuations.\[15\] The method considers the $p$th moment, $C_{p,q}$, of the distributions of the "horizontal" normalised factorial moments which have a specific scaling behavior, $C_{p,q} \propto M^{\psi_{p,q}}$ in the case of self-similarity. The erraticity indices $\psi_{p,q}$ give a strength of the "spatial" fluctuations.

As a measure of chaoticity in multiparticle production, the entropy indexes, $\mu_q = \frac{d}{dp} \psi_{p,q} \big|_{p=1}$, are considered: the larger $\mu_q$ is the more chaotic the system is.

Fig. 2 shows the $\mu_q$ calculated\[3\] for different $M$-intervals and $q = 2\ldots5$. The intervals in $M$ are those from Fig. 1, for which different behavior of the function $\lambda_q$ is observed. The large values found for each interval indicate very chaotic dynamics of particle production, confirming its cascading nature. It is worthwhile to mention increase of the entropy index with approaching to the "critical" region. However, we must emphasize effect of empty bins at high $q$’s.

To search for dynamical correlations, we have also used\[1,4\] one-dimensional intermittency model\[14\] that suggests to analyse maximum density spikes. The key feature of the model is an existence of two regimes in particle production process - turbulent and laminar, - leading to two maxima in the maximum density distributions. Note that the model considers the spikes selected at given multiplicity $n$ to make an analysis energy and reaction-type independent and to allow compiling different experiments results.

Increased statistics, we have updated\[4\] our earlier results\[1\], carrying out analysis for different narrow $n$-intervals as shown in Fig. 3 for two of them along with the distributions for all $n$. Here, maximum density spike $\rho_{\text{max}}$ is defined as $\delta n_{\text{max}}/\delta \tilde{n}$, where $\delta n_{\text{max}}$ is the maximum number of particles in each event hit in the bin $\delta \tilde{n}$. One can see that for the fixed-$n$ intervals the shape of the distributions develops tails at $\rho_{\text{max}} > \langle \rho_{\text{max}} \rangle$, as expected from the model and has indeed been observed in hadronic interactions.\[19\] The non-poissonian character of the distributions, expressed as inequality between the dispersion and the mean values $\langle \rho_{\text{max}} \rangle$ (see\[4\]), points at a significant contribution of the multi-particle correlations, non-reduceable to the two-particle ones.\[20\]

To reveal the dynamical correlation effect, the obtained distributions are compared to those based on the sample of randomly simulated events. The
Figure 3: Normalized experimental (solid symbols) and simulated (open symbols) $\rho_{\text{max}}$ distributions for four $\hat{\delta} \eta$ and three multiplicity patterns (all $n$, $14 < n < 20$ and $24 < n < 30$, respectively): (a) $\delta \eta = 0.04$, $\chi^2/\text{DOF} \simeq 1.3, 0.5, 0.7$, (b) $\delta \eta = 0.12$, $\chi^2/\text{DOF} \simeq 1.2, 1.3, 2.0$, (c) $\delta \eta = 0.2$, $\chi^2/\text{DOF} \simeq 1.1, 1.0, 1.7$, (d) $\delta \eta = 0.4$, $\chi^2/\text{DOF} \simeq 0.9, 0.7, 0.9$. A total of 66300 events were generated, representing independent particle emission. The resulting distributions are shown as open symbols in Fig. 3. The values of $\chi^2/\text{DOF}$ tell us that the dynamical correlations are too suppressed by statistical “noise” in these distributions.

A study of the influence of the error $\langle \varepsilon_\theta \rangle$ in the measurement of the polar angle $\theta$ of the produced charged particles demonstrated stability of the obtained distributions and, therefore, the reliability of the conclusions done.

3.2 Coherency Search

In the coherency approach it is suggested to study the pseudorapidity spike-center distributions. According to the model of coherent gluon-jet emission,
these distributions must have two peaks in quark-quark radiation (pp collisions) vs. a single peak in quark-antiquark case (p$\bar{p}$, $\pi$Kp interactions). These structures has recently been observed in hadronic collisions. The center of spike, $\tilde{\eta}_0$, is determined as $\tilde{\eta}_0 = (1/\delta n) \sum_{j=1}^{\delta n} \tilde{\eta}_j$, where $\delta n$ is number of tracks in spike in each event. Fig. 4 represents the pseudorapidity $\tilde{\eta}_0$-distributions for different size $\delta \tilde{\eta}$ and for spikes of different density. Although multi-peak structure can be seen for small $\delta \tilde{\eta}$, two peaks are well pronounced for larger bins. Fitting these two bumps with Gaussians and averaging over the different spikes, the peaks are found to be placed at 0.17 and 0.57. Recounted to the $\eta$-variable, the positions of the peaks are centered at $0.60 \pm 0.05$ (stat) $\pm 0.12$ (syst) and $1.30 \pm 0.03$ (stat) $\pm 0.10$ (syst) with the distance,

$$d_0 = 0.68 \pm 0.06 \text{(stat)} \pm 0.16 \text{(syst)}$$
between them. This value is similar to that found for pp collisions\textsuperscript{3}, while the double-peak shape is in agreement with the predictions of the coherent gluon emission model. Note that $d_0$ is higher than that in pp-interactions due to intranuclear processes.

To isolate dynamical correlation effects in these distributions, analogous distributions have been obtained from the above described statistical sample of generated events. The $\tilde{\eta}_0$-distributions of the simulated events are shown in Fig. 4 by open circles. One can observe a remarkable difference between these distributions and those obtained from data. No any peaks are seen in the latter case, following the background level and consequently manifesting the double-peak structure in the data to be a significant one.

Similarly to the above studies of $\rho_{\text{max}}$-spectra, the result was checked by varying the $\Delta\eta$-range and the polar angle $\vartheta$. The character of the distributions remains unchanged.

To note is that a similar structure is observed now in large sample of Mg-Mg interactions at 4.2 A GeV/c, but for negative pions only.\textsuperscript{3}

4 Conclusions

In summary, a study of spike production in central C-Cu collisions at 4.5 GeV/c per nucleon is presented. The analysis considers two different approaches - stochastic vs. coherent - to the mechanism of spike formation. Stochasticity search is carried out based on the scaling properties of the normalised factorial moments and their distributions as well as using the one-dimensional intermittency model and its prediction for maximum density distributions. Coherency is searched as it is described by the model of Čerenkov radiation of gluons at finite length, predicting specific shapes of spike-center distributions.

In the stochasticity study, multifractality of spike-production is observed, indicating a possible non-thermal phase transition and two regimes during the cascading. The erraticity approach is used to calculate the entropy indexes, which points at a chaotic nature of particle emission process, particularly in a case of the phase transition. Analysis of maximum density fluctuations show their non-poisonsonian character, indicating a contribution of multiparticle correlations to the spikes.

In studying the spike-center distributions, a double-peak shape is observed in agreement with the expectation of the coherent gluon emission model. The distance between the peaks is with that found in pp-collisions.

To conclude, a direct study of coherency and stochasticity in spike appearance in central nuclear collisions at intermediate energy is performed. Coexistence of these two mechanisms is shown to exist.
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References

1. E.K. Sarkisyan and G.G. Taran, Phys. Lett. B 279, 177 (1992).
2. E.K. Sarkisyan et al., Phys. Lett. B 347, 439 (1995), and 7th Int. Workshop on Multiparticle Production, “Correlations and Fluctuations” (Nijmegen, 1996), eds. R.C. Hwa et al. (World Scientific, 1997), p. 271.
3. L.K. Gelovani et al., European Conference on “Advances in Nuclear Physics and Related Areas” (Thessaloniki, 1997), hep-ph/9803240.
4. G.L. Gogiberidze et al., Phys. Lett. B 430, 368 (1998).
5. P. Božek, et al. Phys. Reports 252, 101 (1995); E.A. De Wolf et al., ibid. 270, 1 (1996).
6. For review see: I.M. Dremin, Sov. J. Part. Nucl. 18, 31 (1987).
7. N.M. Agababyan et al., EHS/NA22 Collaboration, Phys. Lett. B 389, 397 (1996); Shoushun Wang et al., Phys. Lett. B 427, 385 (1998).
8. A. Bialas, Nucl. Phys. A 525, 345c (1991); ibid. 545, 285c (1992).
9. R.C. Hwa, Phys. Rev. D 47, 2773 (1993); A.K. Mohanty and S.K. Kataria, Phys. Rev. C 53, 887 (1996); C.B. Yang and X. Cai, Phys. Rev. C 58, 1183 (1998); R.C. Hwa, C.B. Yang, talks at this Workshop.
10. M. Anikina et al., Phys. Rev. C 33, 895 (1986).
11. G.G. Taran et al., FIAN preprint No.20 (Moscow, 1987).
12. A. Bialas and M. Gazdzicki, Phys. Lett. B 252, 483 (1990); W. Ochs, Z. Phys. C 50, 339 (1991).
13. A. Bialas and R. Peschanski, Nucl. Phys. B 273, 703 (1986); ibid. 308, 857 (1988).
14. J. Dias de Deus, Phys. Lett. B 194, 297 (1987).
15. Z. Cao and R.C. Hwa, Phys. Rev. Lett. 75, 1268 (1995); R.C. Hwa, 7th Int. Workshop on Multiparticle Production, “Correlations and Fluctuations” (Nijmegen, 1996), eds. R.C. Hwa et al. (World Scientific, 1997), p. 303, and talk at this Workshop.
16. R. Peschanski, Int. J. Mod. Phys. A 6, 3681 (1991).
17. D. Ghosh et al., Z. Phys. C 71, 243 (1996); ibid. 73, 269 (1997).
18. P.L. Jain and G. Singh, Phys. Rev. C 44, 854 (1991).
19. I.V. Ajinenko et al., EHS/NA22 Collab., Phys. Lett. B 222, 306 (1989).
20. I.M. Dremin, Sov. Phys. Usp. 33, 647 (1990).
21. G.L. Gogiberidze et al., Int. Nuclear Physics Conference (Paris, 1998).