Coherent particle production in collisions of relativistic nuclei *

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Here we give the results of our study of features of dense groups, or spikes, of particles produced in Mg-Mg and C-Cu collisions at, respectively, 4.3 and 4.5 GeV/c/nucleon aimed to search for a coherent, Čerenkov-like, mechanism of hadroproduction. We investigate the distributions of spike centers and, for Mg-Mg interactions, the energy spectra of negatively charged particles in spikes. The spike-center distributions are obtained to exhibit the structure expected from coherent gluon-jet emission dynamics. This structure is similar in both cases considered, namely for all charged and negatively charged particles, and is also similar to that observed recently for all-charged-particle spikes in hadronic interactions. The energy distribution within spikes is found to have a significant peak over the inclusive background, while the inclusive spectrum shows exponential decrease with two characteristic values of average kinetic energy. The value of the peak energy and its width are in a good agreement with those expected for pions produced in a nuclear medium in the framework of the Čerenkov quantum approach. The peak energy obtained is consistent with the value of the cross-section maximum observed in coincidence nucleon-nucleus interaction experiments.

1. Introduction

A coherent component of particle production mechanism, Čerenkov-like radiation, in high energy particle collisions has been introduced a long time ago. The idea of mesonic [1] and scalar (pionic) [2] radiation has recently been a subject of the systematic analysis of production of mesons in high-energy pion-nucleon scattering in nuclear medium in terms of classical quantum mechanics [3]. Characteristic signatures of the Čerenkov mechanism, such as the differential cross-sections and angle-energy correlations of produced particles, have been predicted.

Another approach of the Čerenkov-like radiation in strong interactions was suggested within the QCD based coherent gluon-jet emission model [4]. In this model the pseudorapidity distributions of centers of particle dense groups, called spikes, are proposed to be investigated. The distributions of spike centers are predicted to have two peaks due to destructive interference for quarks of the same colour (pp collisions) or to be singly peaked due to constructive interference for quarks of different colour (e.g. $p\bar{p}$ interactions). Recent observations in hadronic [5] interactions are found to be in agreement with these predictions.

The aim of this report is to present our recent results on investigations of spikes in relativistic nucleus-nucleus collisions [6–8]. We search for a coherent component of hadroproduction mechanism studying two types of distributions assigned to the two above descibed scenarios. Respectively, on the one hand, we analyse the distributions of centers of spikes in the frame of the gluon-jet emission model and, on the other hand, we investigate energy distribution within spikes to find the features predicted by the nuclear pionic Čerenkov-like radiation (NPICR) approach.

To note is that spikes have been extensively investigated last years using a stochastic picture of particle production, namely an intermittency

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phenomenon has been searched for and obtained in all types of collisions [9]. In our studies [10], we also found the intermittency effect leading to multifractality and, then, to a suggestion of a possible non-thermal phase transition during the cascading. The latter observation have been confirmed in different reactions [11].

2. Experimental details

The results presented here are based on the experimental data obtained after processing the pictures from the 2m Streamer Chamber SKM-200 [12] installed in a 0.8 T magnetic field. The chamber was irradiated at the Dubna JINR Synchrophasotron. A beam of magnesium nuclei with momentum 4.3 A GeV/c was used to collide with a magnesium target, while a 4.5 A GeV/c carbon beam interacted with a copper target. A central collision trigger was used to start the Chamber if there were no charged or neutral projectile fragments (momentum per nucleon required to be greater than 3 GeV/c) emitted in a forward cone of 2.4°. A more detailed description of the set-up design and data reduction procedure are given elsewhere [12–14]. Systematic errors related to the trigger effects, low-energy pion and proton detection, the admixture of electrons, secondary interactions in the target nucleus etc. have been considered in detail earlier and the total contribution is estimated to not exceed 3% [13,15].

A total of 14218 Mg-Mg events and 663 ones of C-Cu collisions were found to meet the above centrality criterion. In the utilized Mg-Mg sample only negative charged particles (mainly π^- mesons with a portion of some 1% kaons) have been studied, while in the C-Cu sample all charged aprticles have been considered.

In the Mg-Mg events the average measurement error in momentum $\langle \varepsilon_p/p \rangle$ was about 1.5% and that in the production angle determination was $\langle \varepsilon_\vartheta \rangle \simeq 0.1°$. The particles were selected in the pseudorapidity ($\eta = -\ln \tan \frac{1}{2}\vartheta$) window of $\Delta\eta = 0.4-2.4$ (in the laboratory frame), in which the angular measurement accuracy does not exceed 0.01 in η units. The mean multiplicity of the selected pions in the Mg-Mg sample is 6.70 ± 0.02.

In the C-Cu sample the average measurement error in momentum $\langle \varepsilon_p/p \rangle$ was about 12%, the error in the polar angle was $\langle \varepsilon_\vartheta \rangle \simeq 2°$, and the angular measurement accuracy does not exceed 0.1 in η-units in the pseudorapidity range of $\Delta\eta = 0.2-2.6$. In addition, particles with $p_{\rm T} > 1$ 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

To overcome an influence of the shape of the pseudorapidity distribution on the results, we use the "cumulative variable",

$$\widetilde{\eta}\,(\eta) \;=\; \int_{\eta_{\min}}^{\eta} \rho(\eta')\,{\rm d}\eta' \Bigg/ \int_{\eta_{\min}}^{\eta_{\max}} \rho(\eta')\,{\rm d}\eta'\;, \qquad (1)$$

with the uniform spectrum $\rho(\widetilde{\eta})$ within the interval [0,1], as advocated in Ref. [16]. This transformation makes it possible to compare results from different experiments.

The spikes are extracted in each event from the ordered pseudorapidities scanned with a fixed pseudorapidity window (bin) of size $\delta\widetilde{\eta}$. Spikes with a definite number of particles δn, hit in the bin, are determined and, for each δn, the distribution of centers of spikes, averaged over all events, is obtained. The center of spike is defined by $\widetilde{\eta}_0 = (1/\delta n)\sum_{j=1}^{\delta n} \widetilde{\eta}_j$.

To reveal dynamical correlations, the $\widetilde{\eta}_0$-distribution is compared with analogous distributions obtained from the simulated pseudorapidity single-particle spectrum $\rho(\widetilde{\eta})$ without any input information about particle correlations. The simulation procedure was as follows. The number of particles was randomly generated according to the multiplicity distribution of the data sample. Then, the pseudorapidities were distributed in accordance with the experimental $\widetilde{\eta}$-spectrum corresponding to the generated multiplicity. In each case of the reactions considered here, the total number of the simulated events exceeded the experimental statistics by a factor of 100. It is clear that the statistical properties of this set are completely analogous to those of an ensemble resulting from arbitrary mixing of tracks from different

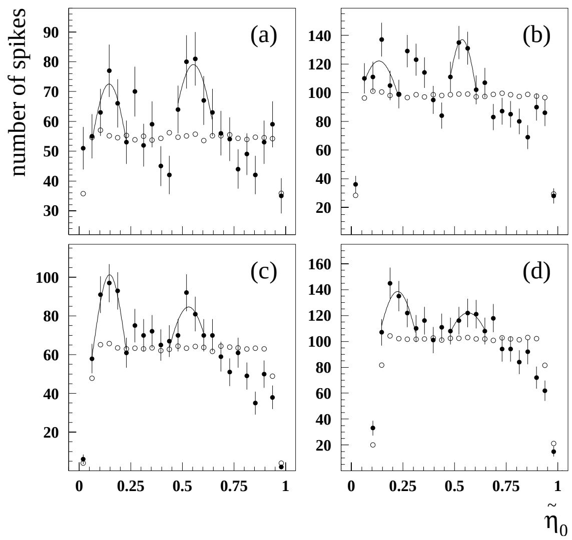

Figure 1. Experimental (•) and simulated (◦) spike-center distributions in C-Cu collisions for different $\delta\tilde{\eta}$-bins and multiplicities δn: (a) $\delta\tilde{\eta} = 0.04$, $\delta n = 4$, (b) $\delta\tilde{\eta} = 0.08$, $\delta n = 5$, (c) $\delta\tilde{\eta} = 0.12$, $\delta n = 7$, (d) $\delta\tilde{\eta} = 0.2$, $\delta n = 9$. The curves represent Gaussian fits.

events, subject to the condition of retention of the $\rho(\tilde{\eta})$-distribution. So, the obtained sample represents independent particle emission.

3. The results

3.1. Spike-center distributions

The pseudorapidity spike-center $\tilde{\eta}_0$-distributions for four different-size $\delta\tilde{\eta}$-bins and for spikes of various multiplicities δn are shown in Figs. 1 and 2 for C-Cu and Mg-Mg collisions, respectively.

For each reaction type, a two-peak structure of the measured distributions (solid circles) is seen with the peaks in the neighbourhood of the same $\tilde{\eta}_0$, independent of the width and multiplicity of spike. The shape of the distributions is in agreement with the structure predicted by the coherent gluon-jet emission model [4] and is similar to that observed in hadronic interactions [5].

In order to estimate the position of the peaks and the distance between them, we fit these bumps with Gaussians and average over different spikes. The peaks are found to be placed at $\tilde{\eta}_0 \approx 0.17$ and 0.57 corresponding to $\eta_0 = 0.60 \pm 0.05(\text{stat}) \pm 0.12(\text{syst})$ and $1.30 \pm 0.03(\text{stat}) \pm 0.10(\text{syst})$ in C-Cu collisions, and in $\tilde{\eta}_0 \approx 0.19$ and 0.63 corresponding to $\eta_0 = 0.89 \pm 0.03(\text{stat}) \pm 0.08(\text{syst})$ and $1.63 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})$ in Mg-Mg interactions.

They are separated by the following d_0 interval,

$$d_0 = 0.68 \pm 0.06(\text{stat}) \pm 0.16(\text{syst}) \quad \text{(C-Cu)}$$

$$d_0 = 0.75 \pm 0.06(\text{stat}) \pm 0.13(\text{syst}) \quad \text{(Mg-Mg)} \quad (2)$$

in η units. These values are close to those from the above mentioned hadronic interactions.

The dynamical origin of the structure obtained is seen from a comparison of the experimental $\tilde{\eta}_0$-distributions with those based on the above described simulated events (open circles in Figs. 1 and 2). No peaks are seen in the simulated distributions, levelling off at the background, far below the measured peaks. This points to a dynamical

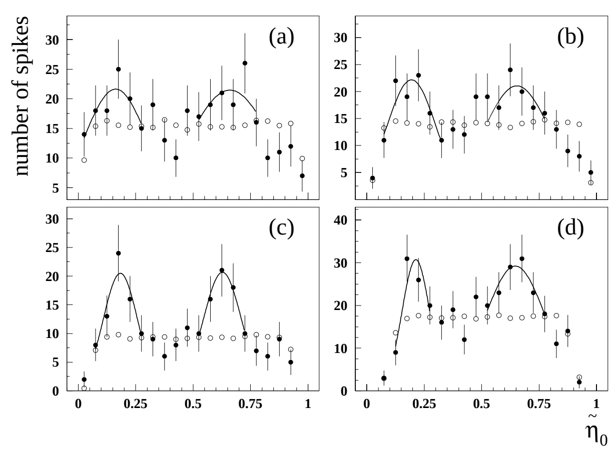

Figure 2. Experimental (•) and simulated (◦) spike-center distributions in Mg-Mg collisions for different $\delta\tilde{\eta}$-bins and multiplicities δn: (a) $\delta\tilde{\eta} = 0.05$, $\delta n = 4$, (b) $\delta\tilde{\eta} = 0.1$, $\delta n = 5$, (c) $\delta\tilde{\eta} = 0.15$, $\delta n = 6$, (d) $\delta\tilde{\eta} = 0.25$, $\delta n = 7$. The curves represent Gaussian fits.

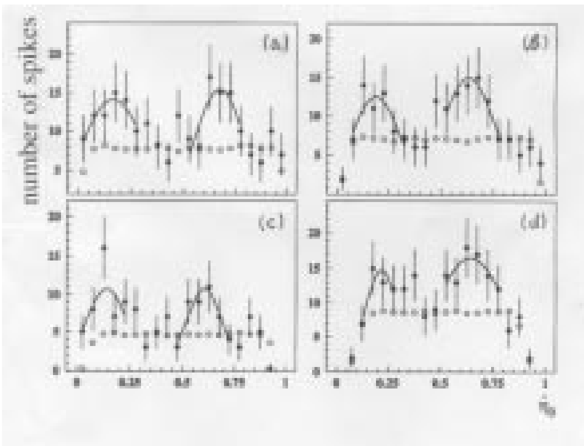

Figure 3. The same as in Fig. 2 but for azimuthally isotropic events (see text and Eq. (3)).

effect in the formation of spikes in agreement with the coherent gluon radiation picture.

In order to reveal a possible contribution of hadronic jets to the effect observed, for negative pions from Mg-Mg collisions we carried out additional analysis taking into account azimuthal collinearity. To this end, the alignment coefficients,

$$\beta = \frac{\sum_{i \neq j}^{n} \cos 2(\Phi_i - \Phi_j)}{\sqrt{n(n-1)}}\,, \tag{3}$$

for an individual event with multiplicity n were used with Φ_i being the ith particle azimuthal angle [17].

A $\beta < 0$ criterion were applied to minimize a contribution of the jet-structural events. This reduced statistics twice. The resulted $\widetilde{\eta}_0$-distributions are shown in Fig. 3 at the same $\delta\widetilde{\eta}$ and δn as in Fig. 2 without the β-criterion. One can see that the structure of the $\widetilde{\eta}_0$-distributions for such azimuthally isotropic events does not change compared to that of Fig. 2 and the distributions demonstrate two peaks. The Gaussian fits of the peaks give the peaks positions to be $\widetilde{\eta}_0 \approx$ 0.88 and 1.63 with the distance between them $d_0 = 0.75 \pm 0.06(\mathrm{stat}) \pm 0.15(\mathrm{syst})$. The obtained values are almost the same as those found from Fig. 2.

The nearness of the positions of the peaks with and without β-criterion points at the azimuthal isotropy of events with spikes.

In order to assess the reliability of the results obtained, we studied the influence of the $\Delta\eta$-range used and the experimental error $\langle \varepsilon_\vartheta \rangle$ in the measurements of the polar angle ϑ. Varying the $\Delta\eta$ range and the error $\langle \varepsilon_\vartheta \rangle$ we found the structure of the distributions unchanged and the positions of the two peaks and the distance d_0 to be within the above shown systematic errors, in support of the conclusions made.

3.2. In-spike energy spectra

The strong signal of the coherent emission dynamics obtained allows further search for its manifestation in the energy distribution, as predicted in the NPICR approach [3]. In this model, the energy spectrum of pions, emitted through the coherent Čerenkov-like mechanism when a few-GeV proton passes the nuclear medium, is predicted to have a peak. This peak is expected to appear at 260 MeV when an absorption effect is neglected and at 244 MeV otherwise.

In Fig. 4 we compare the c.m.s. inclusive kinetic energy distribution, $F(K^*) = (1/E^*p^*)\,\mathrm{d}N/\mathrm{d}K^*$, with analogous spectra calculated for pions from spikes in Mg-Mg interactions. Here, E^* and p^* denote, respectively, the particle energy and momentum in the c.m.s. frame.

Using the temperature description, utilized to characterize a system of excited hadrons [14, 18–20], we parametrize the inclusive spectrum (Fig. 4a) by a sum of two exponents,

$$F(K^*) = A_1 \exp(-K^*/T_1) + A_2 \exp(-K^*/T_2)\,, \tag{4}$$

where the temperatures $T_1 < T_2$ characterize [18] the two possible mechanisms of pion production, via Δ-resonance decay and directly, and are related to the pion average kinetic energies. The range of the parametrization shown is limited from below and from above due to detector effects and corresponding requirements on the momenta of pions. The fit gives $T_1 = 65 \pm 1$ MeV and $T_2 = 127 \pm 1$ MeV. These values are, in general, consistent with those obtained from the earlier analysis of the reaction under study [14] and from other experiments [18, 19]. Some difference in the values could be explained if one takes into account

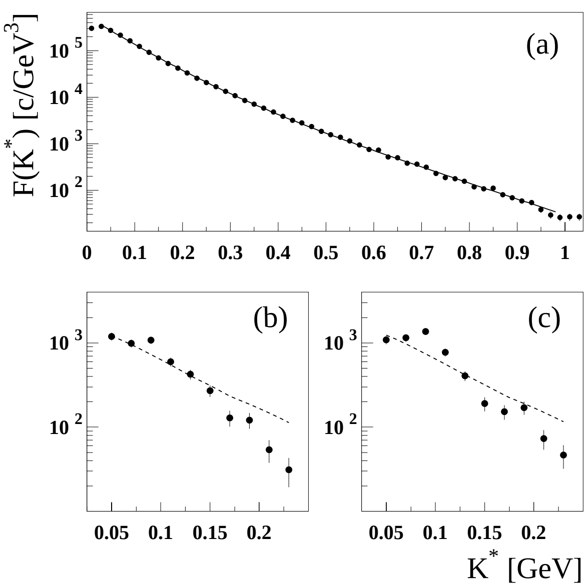

Figure 4. Inclusive kinetic energy distribution (a) and analogous distributions for spikes of negative pions in Mg-Mg interactions, (b) $\delta\widetilde{\eta} = 0.1$, $\delta n = 6$ and (c) $\delta\widetilde{\eta} = 0.15$, $\delta n = 7$. The solid line represents the exponential fit with Eq. (4), the dashed lines show the inclusive background.

the difference in the sizes of the (pseudo)rapidity regions used [20].

The shape of the $F(K^*)$ distribution changes when the analysis is extended to spikes, Figs. 4b and 4c. The energy spectrum of particles belonging to a spike differs significantly from the exponential law (4) and has a peaked shape. To extract the NPICR-signal we compare the in-spike energy spectra with the renormalized inclusive distribution, or inclusive background, depicted by the dashed lines. The first peak is seen to be above background with a statistical significance of 2.7 and 4.1 standard deviations in Figs. 4b and 4c, respectively. This peak is located at the kinetic energy $K^* \approx 100$ MeV, or the total energy $E^* \approx 240$ MeV, in accordance with the NPICR prediction.

To estimate the position of the peak and its width and to make the results more comparable with the NPICR expectations, the E^*-distributions of particles in spikes of various size $\delta\widetilde{\eta}$-bins and different δn-multiplicities are studied. Fig. 5 represents examples for these distributions. The following specific peculiarities are found.

All these E^*-distributions possess a non-exponential behaviour with a pronounced maximum in the vicinity of the value $E^*_{\rm m} = 240$ MeV regardless of bin size and multiplicity of spikes. The higher the multiplicity of spike is (at fixed $\delta\widetilde{\eta}$ size), the more peaks appear. A multi-peak structure is observed for bins with the multiplicities $\delta n > 3$, while at $\delta n \leq 3$ only one peak occurs (not shown).

To reveal the dynamical signal we compare the in-spike energy distributions with the inclusive background (dashed-line). As for the above kinetic-energy distributions, the value of E^* of about 240 MeV is obtained to be the position of the most prominently and statistical-significantly peak over background. To estimate the background and to parametrize the signal, we use a fifth-order polynomial for the background and a Gaussian for the peak. The solid curve shows the result of this fit. After averaging over various spikes, the position of the peak and its width are

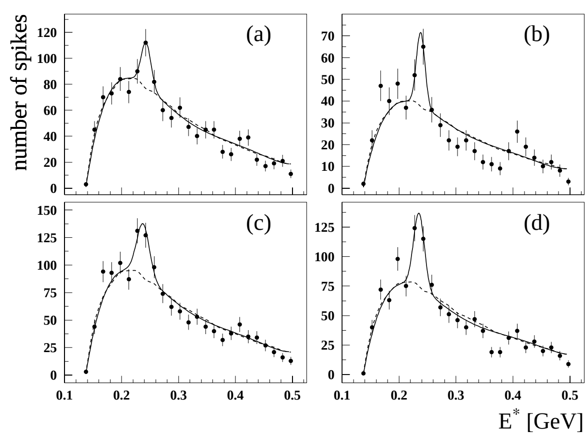

Figure 5. Total energy spectra for negative particles spikes of different $\delta\widetilde{\eta}$-bins and multiplicities δn in Mg-Mg collisions: (a) $\delta\widetilde{\eta} = 0.05$, $\delta n = 4$, (b) $\delta\widetilde{\eta} = 0.08$, $\delta n = 5$, (c) $\delta\widetilde{\eta} = 0.1$, $\delta n = 5$, (d) $\delta\widetilde{\eta} = 0.15$, $\delta n = 6$. The solid lines represent the fit (see text), the dashed lines show the inclusive background.

found to have the values,

$$E^*_{\rm m} = 238 \pm 3({\rm stat}) \pm 8({\rm syst})\ {\rm MeV},$$
$$\Gamma_{\rm m} = 10 \pm 3({\rm stat}) \pm 5({\rm syst})\ {\rm MeV}, \quad (5)$$

respectively.

The location of the obtained centre of the Gaussian lies within the interval of energies expected for pions from the Čerenkov-like mechanism for incident protons of a few GeV, $224 \leq E_{\rm m} \leq 244$ MeV [3]. The value of $E^*_{\rm m}$ (5) is similar to the position of the peak observed in the π^+p invariant mass distribution in the analysis of coincidence measurements of (p,n) reactions on carbon at 1.5 GeV/c in the Δ-resonance excitation region [21], the effect connected with the NPICR mechanism [3]. Also, the width $\Gamma_{\rm m}$ confirms an observation of the Čerenkov radiation signal expected to be $\Gamma \leq 25$ MeV.

4. Conclusions

In summary, in order to search for a coherent, Čerenkov-like emission mechanism of particle production, a study of spikes in relativistic nuclear collisions is carried out with charged particles from central C-Cu collisions at a momentum of 4.5 A Gev/c and with negative pions from central Mg-Mg collisions at a momentum of 4.3 GeV/c per incident nucleon. The spike-center distributions and the energy spectra of particles within a spike are investigated for various narrow pseudorapidity bins and different spike multiplicities.

The spike-center distributions are found to possess a double-peak shape that is in agreement with the structure expected from the coherent gluon radiation model. The obtained distance between the peaks as well as the shape of the distributions are similar to those observed recently in analogous studies of charged-particle spikes in hadronic interactions. The dynamical effect in the spike-center distributions is revealed in a comparison with an independent particle-emission model, where no peaks are seen.

The coherent character of the particle-production mechanism is confirmed by studying energy distributions in Mg-Mg interactions. The inclusive energy spectra show monotonic exponential decrease with two specific temperatures, while the in-spike energy distributions are obtained to exhibit a peak at a position and of a width both consistent with the values expected from the theoretical calculations based on the hypothesis of nuclear pionic Čerenkov radiation. The value of the peak energy is close to the recently observed maximum in the differential cross-sections studied in the coincidence experiments of a few GeV nucleon-nucleus interactions.

The results of the presented analysis signalize coherent emission as a complementary mechanism to the stochastic scenario of hadroproduction. Furthermore, the similarity of the spike-center distributions obtained for like-charged particles in the presented paper with those for all-charged-particle spikes in the earlier studies indicates important contributions of the coherent mechanism to the formation of Bose-Einstein correlations [22]. It is worth to mention that, in comparison to stochastic (intermittency) dynamics, the origin of which remains still unclear [9], the coherent emission has definite underlying dynamics. All this gives evidence for the necessity of further efforts in studying existing experimental data.

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