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AZIMUTHAL STRUCTURES OF PARTICLES PRODUCED IN HEAVY-ION INTERACTIONS

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Вокал С., Легоцка С., Орлова Г. И. E1-2005-66
Азимутальные структуры частиц, рожденных во взаимодействиях тяжелых ионов

Проанализированы азимутальные структуры частиц, рожденных во взаимодействиях ядер ^{208}Pb с импульсом 158 A ГэВ/c и ^{197}Au с импульсом 11,6 A ГэВ/c с ядрами Ag(Br) фотоэмульсионного детектора. Найдены нестатистические кольцевые структуры рожденных частиц в азимутальной плоскости взаимодействия и определены их параметры.

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Vokál S., Lehocká S., Orlova G. I. E1-2005-66
Azimuthal Structures of Particles Produced in Heavy-Ion Interactions

The angular structures of particles produced in ^{208}Pb at 158 A GeV/c and ^{197}Au at 11.6 A GeV/c induced interactions with Ag(Br) nuclei in an emulsion detector have been investigated. Nonstatistical ring-like structures of produced particles in azimuthal plane of a collision have been found and their parameters have been determined.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energies, JINR.

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INTRODUCTION

An important aim of nuclear-collision investigation at high energies is to search for phenomena connected with large densities obtained in such collisions. As an example, the transition from the QGP (quark–gluon plasma) back to the normal hadronic phase is predicted to give large fluctuations in the number of produced particles in local regions of phase space [1, 2]. The observed effects of such a type are dominated by statistical fluctuations. Significant deviations from them are only observed after removing the statistical part of the fluctuations [3].

In case of azimuthal structures of produced-particle investigation, two different classes were revealed, which could be referred to as jet-like and ring-like structures.

The goal of our work was to study the ring-like structures of produced particles in azimuthal plane. They are occurrences if many particles are produced in a narrow region along the rapidity axis, which at the same time are diluted over the whole azimuth. The jet-like structures consist of cases where particles are focused in both dimensions [4].

For the first time, the individual nucleus–nucleus collisions with a ring-like structure of produced particles in the azimuthal plane have been observed more than 20 years ago in cosmic ray experiments [5]. Later, a lot of the nucleus–nucleus collisions with the ring-like structure were observed in the accelerator experiments at a high energy [3, 6–10].

To explain observed peculiar structures, a new mechanism of multiparticle production at high energies was proposed in [11–13]. This mechanism is similar to that of Cherenkov electromagnetic radiation. As a hadronic analogue, one may treat an impinging nucleus as a bunch of confined quarks, each of which can emit gluons when traversing a target nucleus [14, 15]. The idea about possible Cherenkov gluons [11] relies on experimental observation of the positive real part of the elastic forward scattering amplitude of all hadronic processes at high energies. This is a necessary condition for such a process because in the commonly used formula for the refractivity index its excess over 1 is proportional to this real part. Later, I. M. Dremin [12] noticed that for such thin targets as nuclei the similar effect can appear due to small confinement length thus giving us a new tool for its estimation. If the number of emitted gluons is large enough and each of them generates a minijet, the ring-like structure will be observed in the target (azimuthal) diagram. If the number of emitted gluons is not large, we will see several jets correlated in their polar but not in the azimuthal angles. Central collisions of nuclei are preferred for observation of such effects because of a large number of participating partons.

In the present study, the ring-like structures of charged produced particles from ^{208}Pb- and ^{197}Au-induced interactions with Ag(Br) target nuclei in emulsion detector at 158 and 11.6 A GeV/c, correspondently, have been analyzed. The comparison with the FRITIOF calculations [16] has been made. All used data have been obtained in the frames of EMU01 collaboration.

1. EXPERIMENT

The stacks of NIKFI BR-2 nuclear photoemulsion have been irradiated horizontally by ^{208}Pb beam at 158 A GeV/c (the CERN SPS accelerator — experiment EMU12) and by ^{197}Au beam at 11.6 A GeV/c (the BNL AGS accelerator — experiment E863).

The used photoemulsion method allows one to measure: *multiplicities of any charged particles*, which include produced particles (N_s) with $\beta > 0.7$, projectile fragments (N_F) with $\beta \approx 0.99$ and target fragments ($N_h = N_b + N_g$) with $\beta < 0.7$; *angles of particles* with the resolution of $\Delta\eta = 0.010 - 0.015$ rapidity units in the central region, pseudorapidity is given by $\eta = -\ln(\tan(\theta/2))$, and θ is the emission angle with respect to the beam direction; *charges of projectile fragments* (Z_F).

Further details on both the experiments, measurements and experimental criteria can be found in [17, 18].

In this work, we have analyzed:

- 628 Pb+Ag(Br) collisions found by along-the-track scanning. From the collisions, we have selected three centrality groups determined by the multiplicity of the produced particles: $350 \leq N_s < 700, 700 \leq N_s < 1000$ and $N_s \geq 1000$. As shown in our previous paper [19], the criterion $N_s \geq 350$ selects the interactions of lead nuclei at 158 A GeV/c with the heavy emulsion targets Ag and Br with impact parameter $b_{\text{imp}} < 8$ fm only. Moreover, the group with $N_s \geq 1000$ comprises the central Pb+Ag(Br) interactions with $b_{\text{imp}} \approx$ 0–2 fm.

- 1185 Au+Ag(Br) collisions found by along-the-track scanning. From the collisions, we have selected, correspondently, three centrality groups determined by the multiplicity of the produced particles: $100 \leq N_s < 200, 200 \leq N_s < 300$ and $N_s \geq 300$.

2. METHOD

A method we use to search for a ring-like structure and to determine their parameters has been devised in paper [3]. The produced-particle multiplicity N_d

of the analyzed subgroup from an individual event is kept fixed. Each N_d-tuple of consecutive particles along the η axis of individual event can then be considered as a subgroup characterized by *a size*: $\Delta\eta = \eta_{\max} - \eta_{\min}$, where $\eta_{\min}$ and $\eta_{\max}$ are the pseudorapidity values of the first and last particles in the subgroup; by *a density*: $\rho_d = N_d/\Delta\eta$; and by *an average pseudorapidity* (or a subgroup position): $\eta_m = \sum \eta_i/N_d$. Another way is to keep a fixed $\Delta\eta$ interval. This method has been used by G. L. Gogiberidze et al. in papers [9, 10].

To parameterize the azimuthal structure of the subgroup in a suitable way, a parameter of the azimuthal structure $S_2 = \sum(\Delta\Phi_i)^2$ has been suggested, where $\Delta\Phi$ is the difference between azimuthal angles of two neighboring particles in the investigated subgroup (starting from the first and second and ending with the last and first). For the sake of simplicity, it was counted $\Delta\Phi$ in units of full revolutions $\sum(\Delta\Phi_i) = 1$.

The parameter S_2 is large ($S_2 \to 1$) for the particle groups with the jet-like structure and is small ($S_2 \to 1/N_d$) for the particle groups with the ring-like structure. The expectation value for the parameter S_2, in the case of stochastic scenario with independent particles in the investigated group, can be analytically expressed as $\langle S_2 \rangle = 2/(N_d + 1)$. This expectation value can be derived from the distribution of gaps between neighbors.

What can one expect to see in the experimental S_2 distributions in different scenarios? As shown [19] in case of a pure stochastic scenario, the normalized $S_2/\langle S_2 \rangle$ distribution would have a peak position at $S_2/\langle S_2 \rangle = 1$. The existence of the jet-like structures in collisions results in appearance of additional $S_2/\langle S_2 \rangle$ distribution from this effect but shifted to the right in comparison with stochastic distribution. Analogously, the existence of the ring-like structures results in appearance of additional $S_2/\langle S_2 \rangle$ distribution from the effect but shifted to the left. As a result, the summary $S_2/\langle S_2 \rangle$ distribution from these three effects may have a different form depending on mutual order and sizes [19].

3. RESULTS

The first detailed study of the average values of the parameter S_2 was performed in [3]. The azimuthal structures of particles produced within dense and dilute groups along the rapidity axis in the central ^{16}O- and ^{32}S-induced collisions with Ag(Br) and Au targets at 200 A GeV/c (EMU01 data sets) were analyzed. The results were compared with different FRITIOF calculations including γ conversion and the HBT effects. It was concluded that jet-like and ring-like events do not exhibit significant deviations from what can be expected from stochastic emission.

The study of the S_2-parameter distributions for subgroups of the particles produced in ^{197}Au interactions at 11.6 A GeV/c with Ag(Br) targets in an emulsion detector has been done in [20]. Nonstatistical ring-like structures have been found and cone emission angles as well as other parameters have been determined.

In Fig. 1, a–c, the S_2 distributions for groups with $N_d = 90$ are shown for Pb+Ag(Br) collisions with multiplicities of the produced particles $N_s \geq$

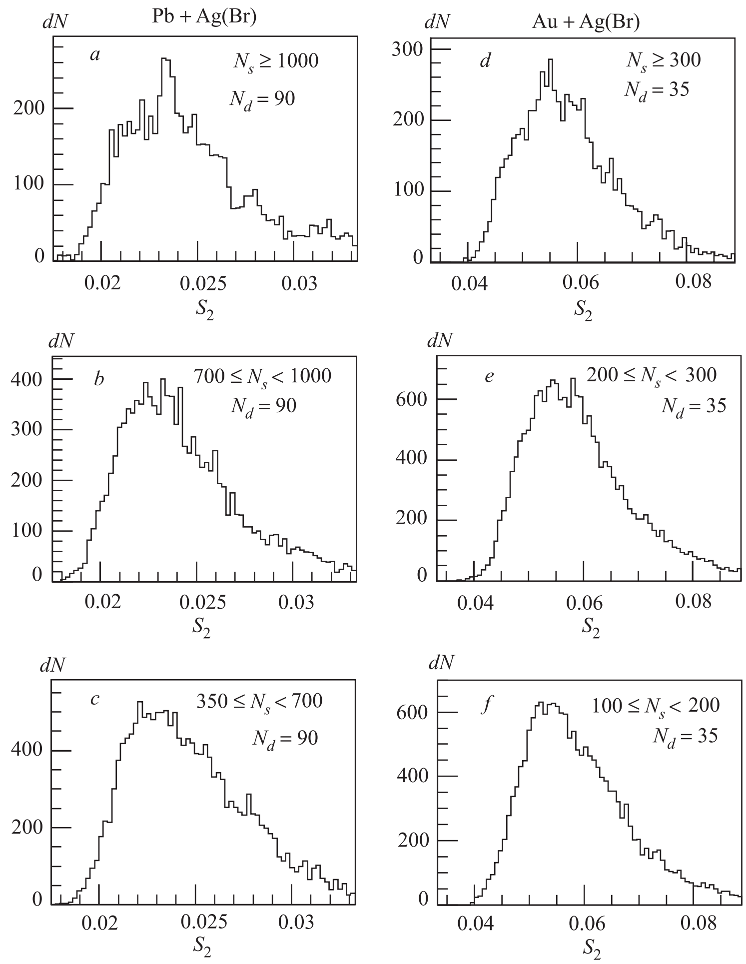

Fig. 1. The S_2 distributions for subgroups with $N_d = 90$ and different groups of shower-particle multiplicity N_s in Pb+Ag(Br) collisions at 158 A GeV/c (a, b, c); The S_2 distributions for subgroups with $N_d = 35$ and different groups of shower-particle multiplicity N_s in Au+Ag(Br) collisions at 11.6 A GeV/c (d, e, f)

1000 (a), $700 \leq N_s < 1000$ (b) and $350 \leq N_s < 700$ (c). The analogical S_2 spectra for subgroups with $N_d = 35$ obtained in Au+Ag(Br) collisions are shown in Fig. 1, d–f for different centrality groups with $N_s \geq 300$ (d), $200 \leq N_s < 300$ (e) and $100 \leq N_s < 200$ (f). As one can see at all three cases of different centralities, the S_2 distributions have the peak position around the value corresponding to the stochastic scenario ($\langle S_2 \rangle = 0.022$ for Pb and $\langle S_2 \rangle = 0.056$ for Au) and tails on the right side. In order to study the ring-like structures, only the left part of the S_2 distribution, where a signal of ring-like structure may be expected, is essential. As one can see, only the central collisions ($N_s \geq 1000$ in Pb- and $N_s \geq 300$ in Au-induced collisions with Ag(Br) targets) have a proved additional peak in the left part. This indicates that a certain ring-like structures are present at these two experiments.

The experimental normalized $S_2/\langle S_2 \rangle$ distributions compared with the calculated ones by the FRITIOF model for the most central groups of events measured in ^{208}Pb- and ^{197}Au-induced collisions with Ag(Br) nuclei at 158 and 11.6 A GeV/c are presented in Fig. 2. The model distributions were aligned according to

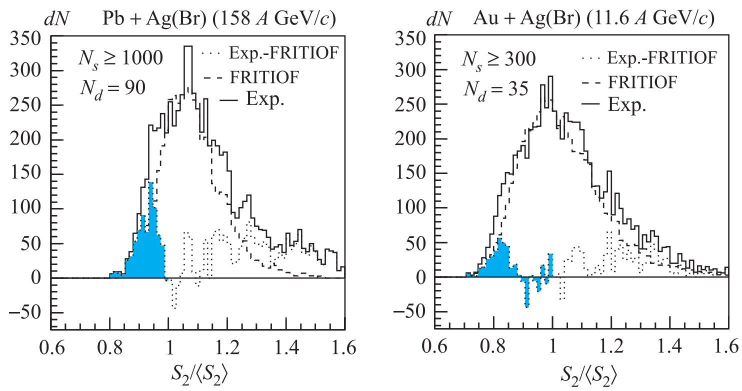

Fig. 2. The experimental and FRITIOF model normalized $S_2/\langle S_2 \rangle$ distributions for central ^{208}Pb- and ^{197}Au-induced collisions with Ag(Br) targets in the emulsion detector. Here, N_s is the number of produced particles, and N_d is the number of particles in the analyzed subgroup

the position of the peak with the experimental one. The FRITIOF model includes neither the ring-like nor the jet-like effects, so the model distributions are used like the statistical background.

One can see that both the experimental distributions are shifted to the right, have a tail in the right part and are broader than the spectra calculated by the FRITIOF. The left parts of both the experimental distributions are not as smooth as in the model and there are some shoulders that refer to the surplus of the events in this region.

The results obtained from the experimental data after the subtraction of the statistical background are also shown in this figure. The resultant distributions have two very good distinguishable hills: the first, in the region $S_2/\langle S_2 \rangle < 1$, where the ring-like effects are expected; and the second, in the jet-like region $S_2/\langle S_2\rangle > 1$. The probability of the formation of the nonstatistical ring-like structures can be estimated as a ratio of the surface of the ring-like part to the full surface of the experimental distribution.

Our preliminary results have shown that the estimated contribution of the events with nonstatistical ring-like structures in the emission of produced particles is about 10–12% for Pb+Ag(Br) collisions and about 5–7% for Au+Ag(Br) collisions in the most central group. This value slowly decreases for less central groups of collisions (or with decreasing of the multiplicity of produced particles N_s).

To analyze the ring-like subgroup position on the pseudorapidity axis, the η_m distributions for subgroups with $S_2/\langle S_2\rangle < 1$ from central collisions are presented for experimental data and FRITIOF model in Fig. 3. One can see that

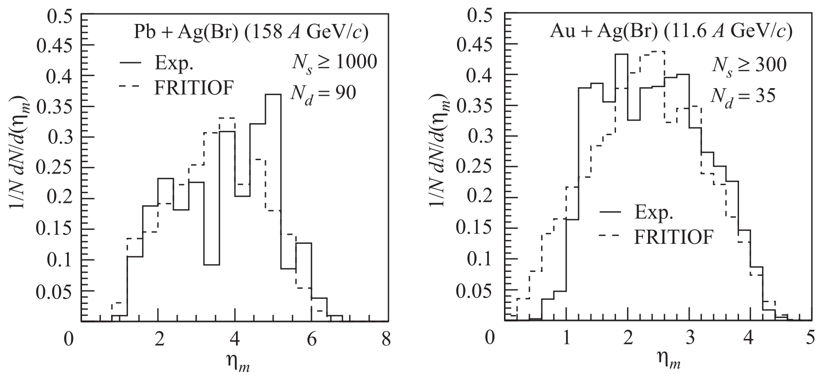

Fig. 3. The ring-like subgroup position (η_m) distributions for central experimental (solid histogram) and FRITIOF model (dashed histogram) for ^{208}Pb+Ag(Br) and ^{197}Au+Ag(Br) collisions

the experimental distributions have a downfall in the central region, where the FRITIOF distributions have maximum and two symmetrical hills from both sides of the center. For central ^{208}Pb+Ag(Br) collisions, η_m distribution has two hills: one, at η = 1.6–3.2, and the other, at η = 3.6–5.2; the center of the distribution for produced particle is at $\eta \approx 3.5$. For central ^{197}Au+Ag(Br) collisions η_m distribution has two hills: one, at η = 1.2–2.0, and the other, at η = 2.2–3.0, the center of the distribution is at $\eta \approx 2.2$. The downfall of the η_m distributions is more visible for ^{208}Pb+Ag(Br) interactions, which is probably connected with larger cross section of the effect for the collisions with a bigger multiplicity that is realized at a higher beam energy and for more central collisions.

To investigate the ring-like subgroup size, the $\Delta\eta$ distributions are shown in Fig. 4 in the region of the ring-like effects ($S_2/\langle S_2\rangle < 1$) for the most central ^{208}Pb ($N_s \geq 1000, N_d = 90$) and ^{197}Au ($N_s \geq 300, N_d = 35$) induced collisions

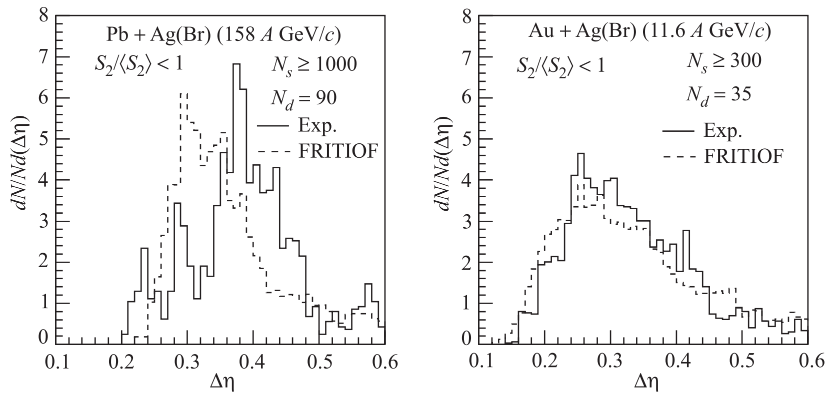

Fig. 4. Comparison of the experimental and the FRITIOF model $\Delta\eta$ distributions for central interactions of ^{208}Pb and ^{197}Au nuclei with Ag(Br) targets for the ring-like region ($S_2/\langle S_2\rangle < 1$)

with Ag(Br) targets compared with FRITIOF model. One can see that there are some distinctions in the shapes of the experimental and model distributions for Pb-induced collisions. There appeared three or four peaks in the experimental $\Delta\eta$ distributions in the ring-like effect region that we do not see in other cases. Moreover, in our previous paper [19] it was shown that on the one hand there are some distinctions in the shapes of the experimental distributions for the regions $S_2/\langle S_2\rangle < 1$ and $S_2/\langle S_2\rangle > 1$, but on the other hand there are no differences in the $\Delta\eta$ distributions calculated by the model for both classes of events ($S_2/\langle S_2\rangle < 1$ and $S_2/\langle S_2\rangle > 1$). The difference for ^{197}Au data is not so obvious.

If the ring-like structures have been appeared due to an effect analogous to Cherenkov light, in a collision there may be two such structures forming two produced particle cones: one, in the forward, and the other, in the backward direction in center-of-mass system. In such a case, the cones must have the equal emission angles, because, as well-known, the Cherenkov emission angel depends on the refractive index of matter only. In our case, in case of nuclear matter, it is a way to measure the refractive index of nuclear matter. It is interesting to note that the refractive index of nuclear matter has to be changed in the case of the changes of the nuclear matter properties, for example, in the case of phase transition from a normal hadronic matter to quark–qluon plasma.

CONCLUSION

The azimuthal ring-like structures of produced particles from collisions induced by the 158 A GeV/c ^{208}Pb and 11.6 A GeV/c ^{197}Au beams with Ag(Br) targets in the emulsion detector have been investigated.

- The additional subgroups of produced particles in the region of the ring-like structures ($S_2/\langle S_2\rangle < 1$) in comparison to the FRITIOF model calculations have been observed.

- The difference with the FRITIOF model calculations in the η_m distributions in the ring-like region $S_2/\langle S_2\rangle < 1$ indicates the existence of two symmetrical η_m regions of preferred emission of the ring-like structures: one, in the forward, and the other, in the backward direction in center-of-mass system.

- The $\Delta\eta$ distribution, which gives the information about a ring-like structure size in pseudorapidity scale, for the experimental data in ring-like region $S_2/\langle S_2\rangle < 1$ differs from the FRITIOF model calculations.

- The nonstatistical ring-like structure formation is more visible for central collisions and for bigger primary energies.

- The results are in good agreement with an idea that the ring-like structures appear due to an effect analogous to Cherenkov light.

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