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PECULIARITIES IN PRODUCED PARTICLES EMISSION
IN ^{208}Pb + Ag(Br) INTERACTIONS AT 158 A GeV/c

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Особенности эмиссии частиц, рожденных
в ^{208}Pb + Ag(Br)-взаимодействиях при 158 A ГэВ/c

Исследована угловая структура частиц, рожденных во взаимодействиях ядер ^{208}Pb с импульсом 158 A ГэВ/c с ядрами Ag(Br) фотоэмульсии. Найдены нестатистические кольцевые стуктуры в азимутальной плоскости взаимодействия и определены их параметры. Получены указания, что кольцевые структуры формируются из двух конусов испускания частиц, один из которых вылетает вперед, а другой назад в системе центра масс взаимодействия. Экспериментальные результаты находятся в согласии с идеей, высказанной И. М. Дреминым, о том, что в ядро-ядерных взаимодействиях возможен механизм рождения частиц, аналогичный черенковскому электромагнитному излучению.

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Peculiarities in Produced Particles Emission
in ^{208}Pb + Ag(Br) Interactions at 158 A GeV/c

The angular structures of particles produced in ^{208}Pb induced collisions with Ag(Br) nuclei in an emulsion detector at 158 A GeV/c have been investigated. Nonstatistical ring-like substructures in azimuthal plane of the collision have been found and their parameters have been determined. The indication on the formation of the ring-like substructures from two symmetrical emission cones — one in the forward and the other in the backward direction in the center-of-mass system have been obtained. The ring-like substructure parameters have been determined. The experimental results are in agreement with I. M. Dremin's idea that mechanism of the ring-like substructure formation in nucleus–nucleus collisions is similar to that of Cherenkov electromagnetic radiation.

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

INTRODUCTION

During the last two decades different nuclei have been accelerated to relativistic energies and brought to collisions with a great variety of target nuclei. An important aim of investigating nucleus–nucleus collisions is to search for a phenomena connecting with large densities obtained in such nuclear collisions.

One of the proposed signals for collective phenomena in relativistic nuclear interactions is large fluctuation in the number of produced particles in local regions of phase space [1]. As an example, the transition from the QGP (quark–gluon plasma) back to the normal hadronic phase is predicted to give rise to such fluctuations [2].

Whenever it is analyzed, the observed effects are dominated by statistical fluctuations. Significant deviations from them are only observed after painstaking efforts to remove the statistical part of the fluctuations [3]. Several such attempts have been made in the past.

In analyses of azimuthal distributions of produced particles two different classes of substructures were revealed, which could be referred to as jet-like and ring-like structures. The ring-like structures are occurrences where 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 substructure 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 substructure were observed in the accelerator experiments at high energy [3, 6–8].

A new mechanism of multiparticle production at high energies was proposed in [9–11]. 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 [12, 13]. The idea about possible Cherenkov gluons is relying [9] 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 [10] noticed that for such thin targets as nuclei the similar effect can appear due to small

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confinement length thus giving us a new tool for its estimate. If the number of emitted gluons is large enough and each of them generates a mini-jet, the ring-like substructure 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 substructures of charged produced particles from ^{208}Pb + Ag(Br) interactions in emulsion detector at 158 A GeV/c have been analyzed.

1. EXPERIMENT

The stacks of NIKFI BR-2 nuclear photoemulsions have been irradiated horizontally by ^{208}Pb beam at 158 A GeV/c (the CERN SPS accelerator — experiment EMU12) [14]. The photoemulsion method allows one to measure:
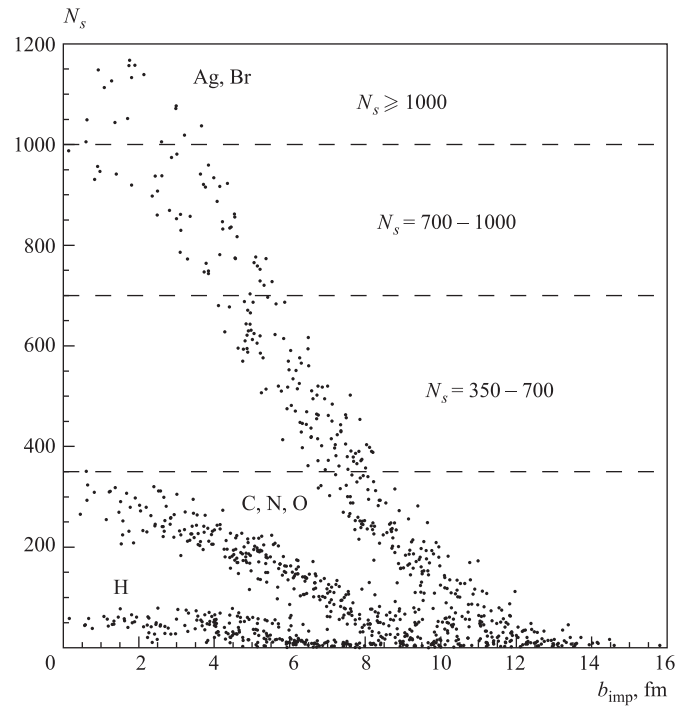

Fig. 1. N_s dependence on b_{imp} for Pb + Em collisions at 158 A GeV/c for different mass of photoemulsion components

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— multiplicities of any charged particles: produced particles (N_s) with $\beta > 0.7$, projectile fragments (N_F) with $\beta \approx 0.99$ and target fragments (N_h) with $\beta < 0.7$;

— angles of particles with the resolution of $\Delta\eta = 0.010 - 0.015$ rapidity units in the central region, pseudo-rapidity 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.

In this work we have analyzed 628 ^{208}Pb + Em collisions found by the along — the track scanning. From the collisions we have selected three centrality groups determined by the multiplicity of the shower particles: $350 \leq N_s < 700$, $700 \leq N_s < 1000$ and $N_s \geq 1000$.

The dependence of the number of produced particles N_s on the impact parameter b_{imp} calculated by the FRITIOF model [15] for our experiment is shown in Fig. 1 for different mass of photoemulsion components A_t.

One can see that the criterion $N_s \geq 350$ selects the interactions of lead nuclei with the heavy emulsion targets Ag and Br with $b_{\text{imp}} < 8$ fm only. Moreover the group with $N_s \geq 1000$ comprises the central Pb + Ag(Br) interactions with impact parameter $b_{\text{imp}} \approx (0-2)$ fm. The mean values of the shower particles multiplicity and pseudorapidity in the sample are $\langle N_s \rangle_{\text{exp}} = 623 \pm 30$ ($\langle N_s \rangle_{\text{fritiof}} = 649$) and $\langle \eta \rangle_{\text{exp}} = 3.7 \pm 0.2$ ($\langle \eta \rangle_{\text{fritiof}} = 3.6$).

2. METHOD

A method we use to search for a ring-like substructure and to determine parameters they have was devised in our paper [3]. The multiplicity N_d of 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) a size

$$\Delta\eta_d = \eta_{\text{max}} - \eta_{\text{min}}, \tag{1}$$

where η_{min} and η_{max} are the pseudorapidity values of the first and last particles in the subgroup;

b) a density

$$\rho_d = \frac{N_d}{\Delta\eta_d}, \tag{2}$$

c) an average pseudorapidity (or a subgroup position)

$$\eta_m = \frac{\sum \eta_i}{N_d}. \tag{3}$$

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To parameterize the azimuthal structure of the subgroup in a suitable way a parameter of the azimuthal structure

$$S_2 = \sum \left(\Delta\Phi_i\right)^2 \qquad (4)$$

have been suggested, where $\Delta\Phi$ is the difference between azimuthal angles of two neighboring particles in the investigated group (starting from the first and second and ending from 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

$$\langle S_2 \rangle = \frac{2}{N_d + 1}. \qquad (5)$$

This expectation value can be derived from the distribution of gaps between neighbors.
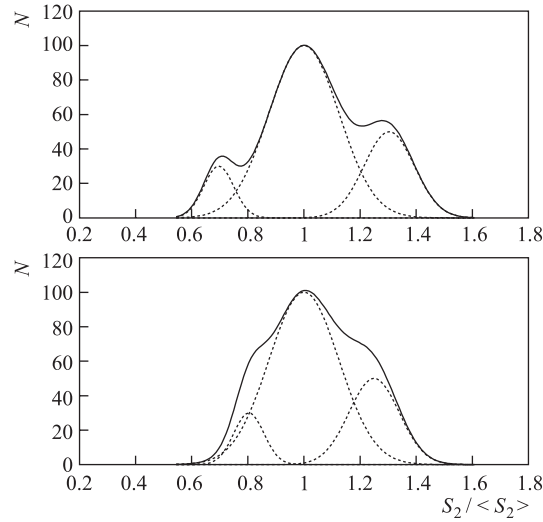

Fig. 2. The examples of summary $S_2/\langle S_2 \rangle$ distribution from three effects: stochastic distribution + ring-like effect distribution + jet-like effect distribution

What can one expect to see in the experimental $S_2/\langle S_2 \rangle$ distributions in different scenarios? It is illustrated schematically in Fig. 2 using for example Gauss distributions. In case of a pure stochastic scenario the distribution would

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have a peak position at 1. The existence of the jet-like substructures in collisions results to appearance of additional S_2 distribution from this effect, but shifted to the right side in comparison with stochastic distribution. Analogously, the existence of the ring-like substructures results to appearance of additions to S_2 distribution from this effect but shifted to the left side. As a result, the summary S_2 distribution from these three effects may have different form and depends on mutual order and sizes.

3. RESULTS

The first detailed study of the average values of the parameter S_2 was performed in [3]. The azimuthal substructures 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 HBT effects. It was conclude that jet-like and ring-like events do not exhibit significant deviations from what can be expected from stochastic emission. But average value studies do not give a full information about an effect.

The detailed study of ring-like substructures of the particles produced in 11.6 A GeV/c ^{197}Au interactions with Ag(Br) targets in emulsion detector has been done in [16]. Nonstatistical ring-like substructures have been found and cone emission angles as well as other parameters have been determined.

Figure 3 shows the S_2 distributions for ^{208}Pb + Ag(Br) collisions at 158 A GeV/c with $N_s \geq 1000$ and two different subgroups with $N_d = 60$ and $N_d = 90$. The experimental S_2 distributions are at the top of the figure and the corresponding ones given by the FRITIOF model are at the bottom.

In case of a pure stochastic scenario S_2 distribution would have a peak position around $S_2 = 0.033$ for $N_d = 60$ and around $S_2 = 0.022$ for $N_d = 90$ (see Eq. (5)). As was illustrated in Fig. 2 the existence of the jet-like substructures in collisions results to lengthening of the right part of the S_2 distribution and to appearance of additional peaks there. The existence of the ring-like substructures results to deformations and/or to appearance of additional peaks at the left part of the S_2 distribution, where $S_2 < \langle S_2 \rangle$.

One can see that the experimental distributions are shifted to the right and have tails in the right part and are broader than the spectra calculated by the FRITIOF. The left parts of both 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 experimental normalized $S_2/\langle S_2 \rangle$ distributions compared with the distributions calculated by the FRITIOF model are presented at the top of Fig. 4. The model distributions were aligned according to the position of the peak with
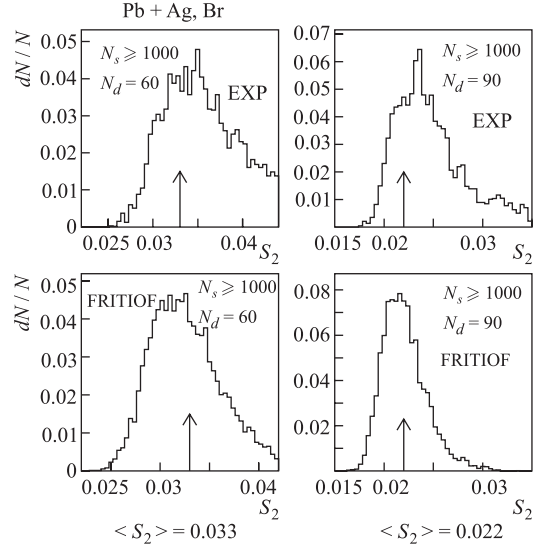
Fig. 3. The experimental (top) and calculated by the FRITIOF (bottom) S_2 distributions for $^{208}\text{Pb} + \text{Ag(Br)}$ collisions with $N_s \geq 1000$ at 158 A GeV/c and two different multiplicities in the subgroup $N_d = 60$ and $N_d = 90$
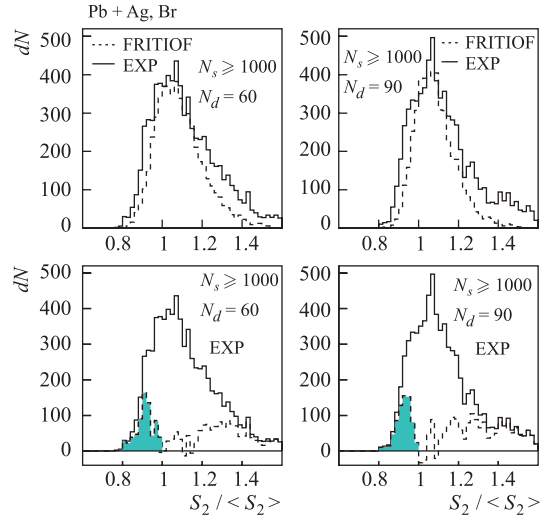

Fig. 4. The $S_2/\langle S_2 \rangle$ distributions — experimental and the FRITIOF (top) and the experimental $S_2/\langle S_2 \rangle$ distributions after the subtraction of the FRITIOF ones (bottom) for $N_d = 60$ (left) and $N_d = 90$ (right)

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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.

Below in Fig. 4 there are the results obtained from the experimental data after the subtraction of the statistical background. 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 ring-like substructures can be estimated as a rate of the surface of the ring-like part to the full surface of the experimental distribution.

The estimation of the contribution of the ring-like effect to the experimental data as a function of the number N_d for three groups of N_s is presented in Fig. 5. These dependences for every N_s group have a several maxima situated nearly at the same value of N_d. In the group with $N_s \geq 1000$ this dependence slowly increases as a full, in the two other groups the dependences are decreasing.

The shape of these distributions can be explained as follows. The observed ring-like substructures seem to be a sum result of independent formation of the rings from several individual gluons, a number of which may be different. Each hill in dependences in Fig. 5 corresponds to ring-like substructures with different multiplicity of the number of formatting gluons. The average multiplicity of the gluons $\langle N_g \rangle$, participated in the ring-like process formation is proportional to the overlap of the collided nuclei, i.e. it has to be bigger for more central interaction. So, the average multiplicity $\langle N_d \rangle$ of particles in the ring-like substructure is not fixed, but it is proportional to the number of the gluons participated in the formation of the ring-like substructures.
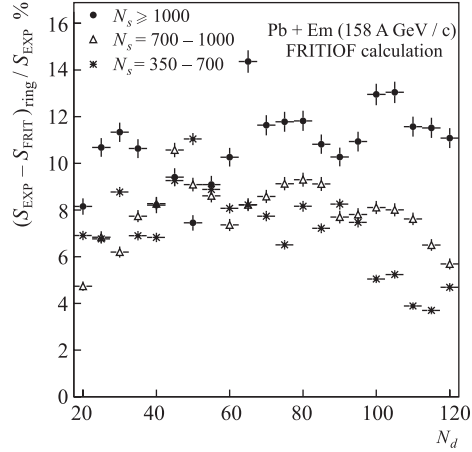

Fig. 5. The dependence of the contribution of the ring-like effect (%) to the experimental data as a function of the number N_d of the particles in a subgroup for three groups of N_s

The next step was to investigate the ring-like subgroups size $\Delta \eta$. Figure 6 shows the $\Delta \eta$ distribution for the most central interactions and the number of particles in the subgroup $N_d = 90$. This distribution is calculated for two classes: $S_2/\langle S_2 \rangle < 1$ — the region of the ring-like effects and $S_2/\langle S_2 \rangle > 1$ — the region of the jet-like effects. The experimental data are compared with those calculated using the FRITIOF model. One can see that there are some distinctions in the
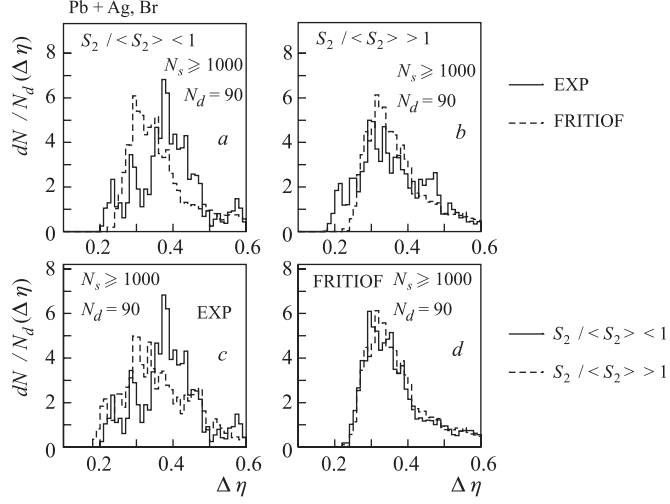
Fig. 6. Comparison of the experimental and FRITIOF model $\Delta\eta$ distributions for collisions with $N_s \geq 1000$ and subgroups with $N_d = 90$ for two regions: $S_2/\langle S_2 \rangle < 1$ and $S_2/\langle S_2 \rangle > 1$

shapes of the experimental and model distributions from one side (Fig. 6, a, b) and in the shapes of the experimental distributions for the regions $S_2/\langle S_2 \rangle < 1$ and $S_2/\langle S_2 \rangle > 1$ from the other side (Fig. 6, c). There are no differences in the distributions calculated by the model for both classes (Fig. 6, d). There appeared three or four peaks in the experimental $\Delta\eta$ distribution in the ring-like effect region $S_2/\langle S_2 \rangle < 1$, which we do not see in the other cases. This fact means that these peaks correspond to sizes of ring-like substructures.

To analyze the ring-like subgroup position η_m on the pseudorapidity axis, the η_m distributions for $N_s \geq 1000$ and $N_d = 90$ are given for experimental data and the FRITIOF model in Fig. 7. For comparison these distributions are divided into three classes:

$S_2/\langle S_2 \rangle < 0.95$ — the region of the ring-like effects,

$S_2/\langle S_2 \rangle = 0.95 - 1.10$ — statistical background,

$S_2/\langle S_2 \rangle > 1.10$ — the region of the jet-like effects.

The difference to the FRITIOF model calculations in the η_m distributions in ring-like region $S_2/\langle S_2 \rangle < 0.95$ indicates to existence of two η_m regions of preferred emission of ring-like substructures — one in the forward and the other in the back directions in the center-of-mass system.

If the ring-like substructures have been appeared due to an effect analogous to Cherenkov light there may be in a collision two ring-like subgroups forming
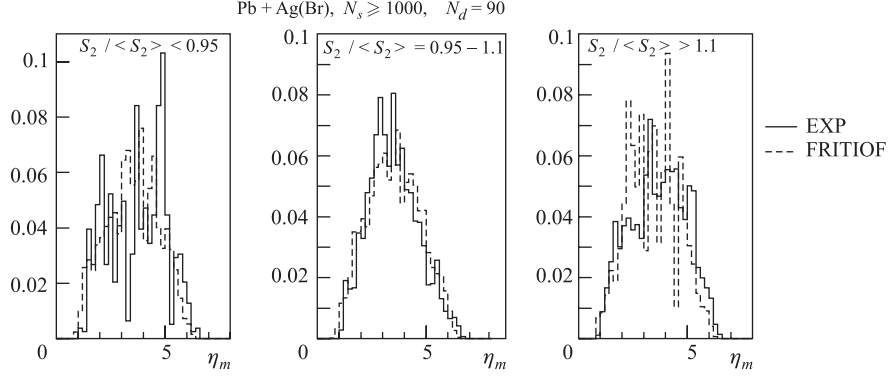
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Pb + Ag(Br), $N_s \geqslant 1000$, $N_d = 90$

Fig. 7. The ring-like subgroup position η_m for $N_s \geq 1000$, $N_d = 90$ and different $S_2/\langle S_2 \rangle$ classes is given for experimental data and the FRITIOF model

two cones with the equal emission angles — one in the forward and the other in the backward direction in the center-of-mass system. As well known the cone emission angle of the Cherenkov light is directly connected with the refractive index of matter, in our case of nuclear matter, and it is a way to measure it. It is interesting to note that the refractive index of nuclear matter may be changed in the case of changes 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 substructures of produced particles from collisions induced by the 158 A GeV/c ^{208}Pb beam in the emulsion detector have been investigated.

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

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

- The difference with the FRITIOF model calculations in the η_m distributions in ring-like region $(S_2/\langle S_2 \rangle < 0.95)$ indicates to existence of two η_m regions of preferred emission of ring-like substructures − one in the forward and the other in the back directions in the center-of-mass system.

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Our results are in good agreement with mechanism of the ring-like substructure production similar to that of Cherenkov electromagnetic radiation.

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