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A MEASUREMENT OF THE EXPANSION VELOCITY OF PION PRODUCTION VOLUME

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Измерение скорости расширения области генерации π^--мезонов

С помощью нового метода обработки экспериментальных данных при исследовании интерференционных корреляций тождественных частиц получено прямое доказательство нестационарности области генерации π^--мезонов в центральных Mg-Mg-взаимодействиях при импульсе $p_{лаб} = 4{,}4$ ГэВ/с на нуклон. В выражение, аппроксимирующее интерференционный пик, в качестве свободного параметра включена скорость источника пар коррелированных π^--мезонов. Эта скорость растет с ростом средней быстроты ансамбля пар π^--мезонов, выбранных для интерференционного анализа.

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A Measurement of the Expansion Velocity of Pion Production Volume

Using a new method of data processing in the investigation of interference correlations of identical particles, a direct proof of nonstationarity of the π^- production volume in central Mg-Mg collisions at a beam momentum of $p_{lab} = 4.4$ GeV/c per nucleon was obtained. The velocity of a source of correlated π^- meson pairs is introduced as a free parameter in the interference peak approximation formula. This velocity increases with increasing the mean rapidity of a sub-ensemble of π^- meson pairs which are chosen for the interference analysis.

The investigation has been performed at the Laboratory of High Energy, JINR.

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1. INTRODUCTION. It is known that identical pions, emitted from their production volume Δr_i in size, must be connected by quantum-mechanical interference correlations, that are significant for particles with close momenta $\Delta p_i \cdot \Delta r_i \sim \hbar/2$ [1]. Moreover, the correlation function, that is a distinction between the real two-particle spectrum and the spectrum in which the interference correlations are "off" somehow

$$C(q) \equiv \frac{d^4\sigma/d^4q}{(d^4\sigma/d^4q)^{off}}, \qquad (1)$$

contains information both on the size of the production volume and the duration of pion emission [2, 3]. Here $q = (q_0, \vec{q}) \equiv p_1 - p_2$ is the 4-momentum difference for two pions $(p = (E, \vec{p}))$.

If pions are independently emitted from the production volume of space-time shape $\rho(r)$, where $r = (t, \vec{r})$ is the 4-point of pion emission, then the correlation function is equal to [4, 5]:

$$C(q) = 1 + \left| \int \rho(r) exp(iq \cdot r) d^4r \right|^2. \qquad (2)$$

Here the 4-point of emission is the point where the pion had been produced or significantly rescattered last time before it left the production volume, when it can be considered as a free particle (see review [6]). In our case these points can be, e.g., space-time points of diverse nucleon-nucleon or pion-nucleon collisions and resonance decays.

Our conditions allow us to hope that π^- mesons in our experiment are emitted independently of one another. The mean multiplicity of π^- mesons is equal to ~0.6 for inelastic nucleon-nucleon interaction at our energy [7]. Therefore π^- mesons in our nucleus-nucleus interaction are not related genetically in an approximation of independent nucleon-nucleon interactions [7].

Equality (2) is correct only in that case if the pion momentum is not correlated with the 4-point of its production [8]. As will be shown later, in our experiment this condition is not fulfilled for the total ensemble of π^- mesons.

The Gaussian distribution was used to approximate the space-time shape of the production volume or its individual elements in their rest frames:

$$\rho(r) = \frac{1}{(2\pi)^2 R_\perp^2 R_\parallel T}\ exp\left(-\frac{r_\perp^2}{2R_\perp^2} - \frac{r_\parallel^2}{2R_\parallel^2} - \frac{t^2}{2T^2}\right), \qquad (3)$$

where $R_\perp$ and $R_\parallel$ are the perpendicular and parallel to the beam root-mean-square radii of the pion production volume and T is the root-mean-square dispersion of their emission times. Following eq. (2), one obtains:

$$C(q) = 1 + exp\left(-q_\perp^2 R_\perp^2 - q_\parallel^2 R_\parallel^2 - q_0^2 T^2\right). \tag{4}$$

If the production volume moves relative to the observation frame with velocity β along the reaction axis, then after Lorentz transformations of q_i correlation function (4) can be rewritten in the form:

$$C(q) = 1 + exp\left\{-q_\perp^2 R_\perp^2 - \gamma^2(q_\parallel - \beta q_0)^2 R_\parallel^2 - \gamma^2(q_0 - \beta q_\parallel)^2 T^2\right\} \tag{5}$$

where q_i are given in the observation frame while $R_\perp$, $R_\parallel$ and T are determined in the rest frame of production volume. The value of β, if unknown, can be obtained along with other free parameters by fitting experimental data using approximation (5) [9].

The parameters of the production volume can be determined using pions chosen from any bound part of phase space because correlation function (2) only depends on the *difference* of pion 4-momenta. For example, in case of two flying away fireballs which have strongly overlapping pion spectra, one can measure the size of either using pions chosen from a distant, nonoverlapping part of its rapidity spectrum if one knows the velocity β of this fireball [4]. This velocity can be also obtained as a free parameter approximating the experimental data for this kinematic interval of pions by function (5) [10].

2. *EXPERIMENTAL DATA AND THEIR FITTING.* The experimental film material was obtained on a 4.4·A GeV/c ^{24}Mg beam of the Dubna synchrophasotron using a 4π spectrometer SKM-200 — GIBS including a two-meter streamer chamber placed in a magnetic field of 0.9 T [11]. A 1.2 g/cm^2 Mg target was placed inside the chamber sensitive volume. The streamer chamber was only triggered in case of "central" [11] $MgMg$ interactions, i.e. if stripping neutrons, protons and other beam nuclear fragments do not hit a forward cone of ~2.4° (~4 msr) which corresponds to a stripping nucleon transverse momentum of ~180 MeV/c. The antistripping counters were placed at a distance of 6 m downstream the target beyound 2 m of the 0.9 T magnetic field, and so particles, that were

softer than stripping ones, scarcely hit them. These central interactions accounted for ~4·10^{-4} of all inelastic $MgMg$ interactions [12].

We used in the analysis 420 000 of the π^- pairs (100 000 pions from 13 000 events). The accuracy in measuring pion momenta was about 1% and angles 5 mrad. Approximately 10% of π^- were lost, mainly due to absorption in the target and bad measurability of vertical tracks. These losses are localized around a target rapidity value of -1.1 in the $MgMg$ rest frame, resulting in a shift of mean rapidity of detected π^- by +0.1 relative to the $MgMg$ c.m.s.

The pion emission independence of one another allows us to obtain the denominator of correlation function (1), i.e. the π^- two-particle spectrum with "off" correlations. Then it coincides with the mixed two-particle spectrum of π^- pairs where each π^- is randomly chosen from different events (but with the same π^- multiplicity) [3]. In our case a correction of mixed spectrum distortion due to two-particle interference correlations (see [13]) is negligible because only 2% π^- pairs fall within the interference peak region. We have chosen the number of mixed pairs 20 times larger than that of real pairs (much smaller than the number of all possible combinations) and then normalized.

The independence of π^- mesons allows one also not to introduce an extra free parameter λ often used in front of the interference term in (2). If this parameter was used in our analysis, it was found to be close to 1.

The method of maximum likelihood was used to obtain the parameters of pion source, like in [13]. 3-dimension histograms of $q_\perp$, $q_\parallel$ and q_0 were individually plotted for the number of real and mixed pion pairs with 10 MeV/c (MeV) bins inside an interval of -200÷200 MeV/c (MeV). The contents of each non-empty bin of the histogram of mixed pairs was multiplied by $C(q)$ for a given set of parameters $R_\perp^2$, $R_\parallel^2$, T^2 (as well as λ or β). Assuming this value as a Poisson distribution mean value, the probability of the number of pairs contained in the same bin of the real pair histogram was calculated. The product of probabilities for all bins was maximized relative to these parameters by the FUMILI program. Central bins of -10÷10 MeV/c (MeV) were not used because of possible measurement errors due to tracks interchange. χ^2 was calculated by the same method as χ^2_{PML} in equation (10) in [13].

3. RESULTS FOR THE TOTAL ENSEMBLE OF π^-. The results of fitting our data for the total ensemble of pions under different conditions are presented in Table 1. It should be noted that the sign of the parameter T^2 was obtained to be negative (opposite to the signs of $R_\perp^2$ and $R_\parallel^2$), that eliminates the possibility to interpret this parameter as the square of emission time for the total π^- sample. Then expressions (3)-(5) also lose their original physical meaning.

Table 1

The results of fitting for the total ensemble of π^- mesons. 1 - approximation with expression (4); 2 - the same but the extra free parameter λ before the exponent is added; 3 - the same as 1 but Gamov's correction is added; 4 - approximation with expression (5); 5 - approximation with expression (6).

	$R_\perp$ (fm)	$R_\parallel$ (fm)	$\sqrt{-1}\,T$ (fm/c)	Conditions	χ^2/NDF
1	3.4 ± 0.1	3.5 ± 0.2	2.1 ± 0.5	approximation (4)	1.19
2	3.1 ± 0.2	3.2 ± 0.2	2.1 ± 0.5	$\lambda = 0.8 \pm 0.1$	1.19
3	3.0 ± 0.1	3.1 ± 0.1	2.1 ± 0.5	Gamov's correction	1.20
4	3.4 ± 0.1	3.6 ± 0.2	2.2 ± 0.5	$\beta = -0.04 \pm 0.09$	1.26
5	R_{inv}=3.71±0.08			approximation (6)	3.45

In other nucleus-nucleus experiments (under different conditions) in various cases the parameter T^2 was found to be positive, equal to 0, it was not included in approximation, its values were restricted by positive one at fitting (see [13-19] and references there).

Our result: $R_\perp^2 \approx R_\parallel^2 \approx -T^2$, is found to be close to a one-parameter relativistic invariant approximation often used to describe elementary lepton and hadron interactions:

$$C(q) = 1 + exp(-R_{inv}^2 Q^2) \equiv 1 + exp\left[-R_{inv}^2(q_\perp^2 + q_\parallel^2 - q_0^2)\right], \qquad (6)$$

where the invariant variable Q depends only on the effective mass of a pair: $Q^2 \equiv q_\perp^2 + q_\parallel^2 - q_0^2 = M_{\pi\pi}^2 - 4m_\pi^2$. The physical meaning of the parameter R_{inv} is usually the *spatial* size of the production volume observed in the c.m.s. of each pair averaged over the pairs and directions. In this frame $q_0 = 0$, and emission time is out from the analysis.

4. RESULTS FOR RAPIDITY INTERVALS. The Fig.1 presents the sizes and the emission times of pion sources in their rest frames, as well as their rapidities in the mean rapidity frame of all detected π^- ($Y_{source} = \frac{1}{2}\,ln[(1+\beta)/(1-\beta)]$). Sources' parameters were obtained by fitting our data using approximation (5) for different intervals of pair mean rapidity $<y_{\pi\pi}> = (y_{\pi_1} + y_{\pi_2})/2$ where $y_\pi = \frac{1}{2}\,ln[(E+p_\parallel)/(E-p_\parallel)]$.

The rapidity of the source did not have to depend on the interval of pair mean rapidity and had to be equal to 0 in the $MgMg$ rest frame if the π^- momentum were independent of its emission point. One can see it is not the case. Our production volume consists of different "elements" moving relative to each other and emitting pions in different parts of the rapidity spectrum. Thus, equation (2) is not correct for the total sample of π^- in our experiment.

Certainly, the notion "element" is conventional here and means merely a part of the production volume inside which the difference of momentum spectra at its various points is substantially lower than over the whole volume. Each element of the production volume may not be quite stationary also. However, expression (2) must be "more correct" for an individual element than for the whole production volume. One can see that here the emission time becomes real ($T^2 > 0$), in contradistinction to the result for the total ensemble of π^-.

Table 2

The parameters of the elements of the production volume corresponding to different intervals of the mean rapidity of a π^- pair for central $MgMg$ interactions at 4.4 A GeV/c.

Interval	-1.5÷-1.0	-1.0÷-0.5	-0.5÷0.0	0.0÷0.5	0.5÷1.0	1.0÷1.5
N_{pair}	13 945	58 948	137 656	136 925	59 465	11 502
$<y_\pi>$	-1.22	-0.69	-0.23	0.23	0.69	1.19
Y_{source}	-1.16±0.43	-0.83±0.20	-0.35±0.14	0.03±0.13	0.75±0.20	0.68±0.25
$R_\perp$ (fm)	2.7±0.9	2.3±0.3	3.0±0.2	2.9±0.4	3.3±0.5	2.0±0.3
$R_\parallel$ (fm)	5.5±2.0	5.5±0.8	4.1±0.3	3.6±0.7	3.4±0.5	4.2±1.0
T (fm/c)	2.2±4.6	3.5±1.4	2.1±1.3	2.2±1.1	4.4±1.9	4.1±1.7
χ^2/NDF	0.59	0.99	1.13	1.16	1.08	0.80
R_{inv} (fm)	3.8±0.9	3.3±0.3	3.8±0.5	3.6±0.6	4.3±0.3	3.8±0.5
χ^2/NDF	1.89	1.42	0.89	1.76	1.11	0.99
	$<R_{inv}>$= 3.78±0.17					

The mean rapidity of the different sub-ensembles of analyzed π^- pairs $< y_\pi >$ almost coincides with their source rapidity. This can help to explain the result for the total spectrum — the negative sign of the parameter T^2. We have obtained that each pion pair from the reference frame close to its c.m.s. ($q_0 \approx 0$) "sees" only its element of the production volume almost resting in this frame ($\beta \approx 0$). Thus, in our case, approximations (5) and (6) practically coincide for each given element in the corresponding frame (if, in addition, $R_\parallel \approx R_\perp$). But approximation (6) does not depend on the reference frame in contradistinction to approximation (5). Therefore, the use of approximation (6) for the total π^- ensemble (see Table 1) must be equivalent to averaging over the results for different elements (see Table 2).

Thus, in our case the physical meaning of the parameter R_{inv} in (6) for the total ensemble of π^- is the averaged spatial size of *different* elements of the production volume moving, relative to each other and observed in the systems close to the rest frames of each of the elements.

Using the new method, it would be interesting to check experimentally whether *the effect of equal velocities* of the emitted pair and its source is valid in other nucleus-nucleus and elementary interactions. It would help to understand the physical meaning of used approximations and obtained parameters.

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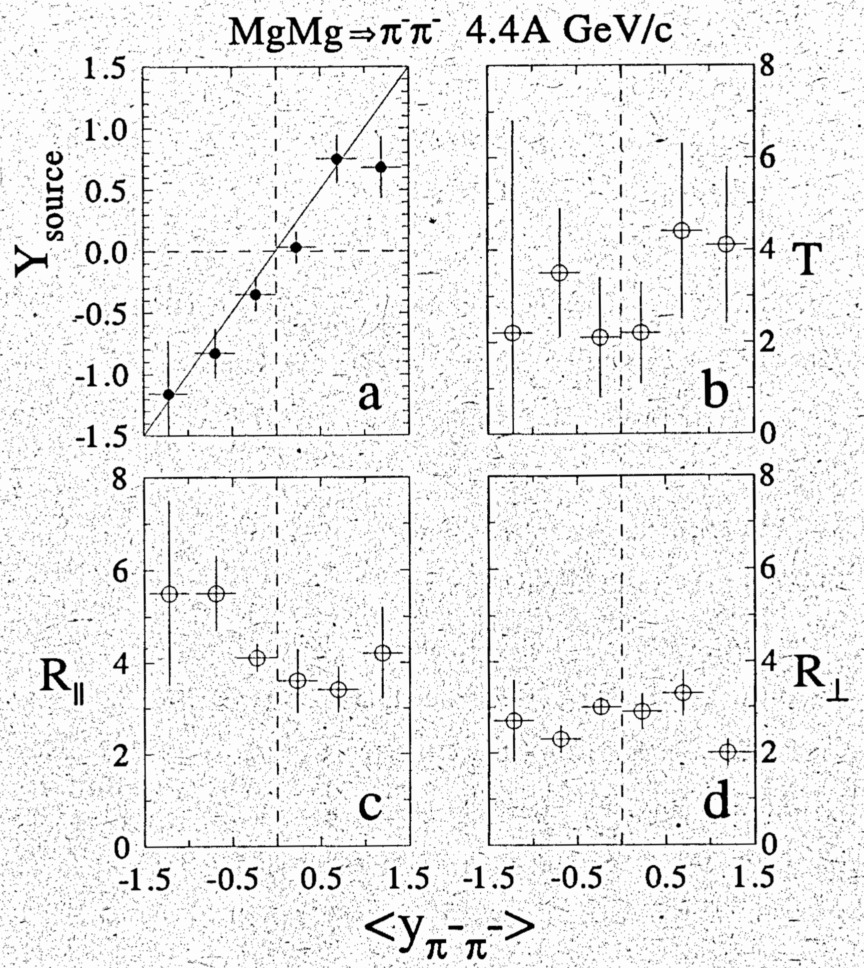

Fig.1 *a): The rapidities of different elements of the production volume emitting π^- pairs having different mean rapidities. Straight line is $Y_{source} =< y_{\pi^-\pi^-} >$. b),c),d): Root-mean-square dispersion of π^- emission times and root-mean-square radii of the production volume elements in their rest frames. The horizontal bars designate the bounds of pair mean rapidity intervals.*

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