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PION INTERFEROMETRY IN C+C AND C+TA COLLISIONS AT 4.2 A GEV/C

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Abstract. *Bose-Einstein correlations between negative pions emitted in C+C and C+Ta collisions at 4.2A GeV/c are presented. The experimental data are obtained using the 2m propane bubble chamber exposed on the JINR, Dubna, synchrophasotron. Data show a clear quantum interference effect as expected for identical bosons. A Gaussian parametrization is used to determine the size of the pion emission source.*

Key words: *pion interferometry, Bose-Einstein correlations, heavy-ion collisions*

1. INTRODUCTION

Identical pion interferometry has become a commonly recognised tool for studying the coherence and the dimensions of boson emitting source [1, 2]. In relativistic nucleus-nucleus collisions, the interferometry method has been used extensively in order to gain insight into the collision dynamics. There has been a considerable range of theoretical speculation on the nature of the pion emission processes, from a straightforward superposition of nucleon-nucleon interactions to chaotic pion source emitting from a thermalized pion fireball. Consequently, there are predictions for the BE correlation function for a variety of dynamical models.

The boson interferometry method is analogous to that proposed by Hanbury-Brown and Twiss in astronomy, to determine the angular size of stars from the second-order interference of light. Pion correlations appear as a consequence of pions obeying Bose-Einstein (BE) statistics: the wave function of identical bosons is symmetric with respect to particle exchange and this symmetrization requirement results in an interference term. Experimentally, this is reflected in an enhanced production of pion pairs of the same charge, closely emitted in the phase space, as compared to the pairs with opposite charge. Together with specific assumptions concerning the distribution of pion-point sources, the width of this enhancement is used to estimate the spatial and temporal dimensions of the

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pion emitting region. The height of the interference peak is believed to reflect the degree of coherence of the pion sources. This height is usually decreased by resonance production, Coulomb repulsion, strong final-state interactions, experimental acceptance etc. Some of these factors are difficult to account for quantitatively, and consequently the information about the coherence of pions obtained from interferometric measurements is less reliable than the extracted source size.

In order to study the probability for emission of the two identical bosons, it is useful to define a correlation function $C_2(Q)$

$$C_2(Q) = \frac{P_2(p_1, p_2)}{P_1(p_1) \cdot P_1(p_2)} \tag{1}$$

where $P_2(p_1, p_2)$ is the two-particle probability density with the Bose-Einstein (BE) effect included, and $P_1(p_1) \cdot P_1(p_2)$ is a reference density with BE effect excluded (here, p_1 and p_2 denote the four-momenta of the two pions). In practice, $P_1(p_1) \cdot P_1(p_2)$ is often replaced by $P_0(p_1, p_2)$, which ideally in all respects resembles $P_2(p_1, p_2)$, apart from its lack of BE effect. The major problem in this kind of study is to find an appropriate reference sample. The one-dimensional correlation analysis is usually made in terms of the kinematic variable Q defined by

$$Q^2 = -(p_1 - p_2)^2 = M^2 - (2m_\pi)^2 \tag{2}$$

where $M^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$ is the square of the invariant mass of pion pair. For particles with close energies, Q is approximately equal to $|\vec{p}_1 - \vec{p}_2|$.

There are several models which give the correlation function $C_2(Q)$ analytically; e.g. a Gaussian distribution of a source [2], a model by Kolehmainen and Gyulassy [3], and a model by Kopylov and Podgoretsky [4]. In this last case, sources distributed uniformly over the surface of a sphere of radius R are employed. If a Gaussian distribution of width R is used to approximate the space-time shape of the production volume

$$\rho(r) = 1/(4\pi^2 R^4) e^{-r^2/2R^2} \tag{3}$$

then the corresponding correlation function $C_2(Q)$ is

$$C_2(Q) = 1 + \lambda \exp(-R^2 Q^2) \tag{4}$$

The parameter λ $(0 \le \lambda \le 1)$, sometimes called chaoticity, represents the fraction of effectively interfering pion pairs and takes into account already mentioned physical and methodical causes for distortion of $C_2(Q)$. The parameter R, inversely proportional to the width of the correlation peak, characterises the space-time size of the pion radiation region. One should take into account that the root-mean square (r.m.s.) radius is $\langle r^2 \rangle^{1/2} = \sqrt{3} R$.

One-dimensional correlation analysis using the variable Q allows comparison with other experiments and it is useful in case of limited statistics. However, the extracted parameters are difficult to interpret physically. High-statistics data allow multi-dimensional correlation analysis [5]. This does not require the unrealistic assumption of a spherical source, is more sensitive to the collision dynamics, and less influenced by relativistic effects than the correlations analysed in the four-momentum difference Q.

The BE correlations between negative pions produced in inelastic C+C and C+Ta collisions at 4.2A GeV/c were investigated in [6, 7] using a data set with small statistics. To fit the correlation function, a variant of the Gaussian model, $C_2(|\vec{q}|, q_0) = 1 + \lambda \exp(-|\vec{q}|^2 R^2 - q_0^2 \tau^2)$, with $q \equiv (q_0, \vec{q}) = p_1 - p_2$ and τ denoting the lifetime of the source, was used for C+C collisions. Analogously, the Kopylov-Podgoretsky model was used for C+Ta collisions. Here, a similar analysis is made using much larger data set. The values of R and λ are obtained using the Gaussian parametrization and comparison is made with the other heavy-ion experiments.

2. EXPERIMENTAL DATA

The experimental data were obtained with the 2-m propane (C_3H_8) bubble chamber exposed at the JINR, Dubna synchrophasotron with carbon beam of 4.2A GeV/c. The ^{181}Ta target, consisting of three tantalum foils (1 mm thick and 93 mm apart), was placed inside the chamber working in the 1.5 T magnetic field. This allows the study of inelastic interactions with carbon (in propane) as well as with tantalum target. The chamber allows precise measurement of multiplicity and momenta of negative pions. Among the accepted π^- mesons remains an admixture of unidentified fast electrons ($p > 0.1$ GeV/c) from γ conversion in the target. The threshold for π^- meson registration is 0.07 GeV/c for C+C, and 0.08 GeV/c for C+Ta interactions. Below this threshold, the negative pions are erroneously detected as the protons stopped in the chamber, or absorbed in the tantalum plates. The π^- meson data are corrected to the loss of particles emitted at small angles relative to the optical axes of chamber and to the loss of particles absorbed by the tantalum plates. These two corrections amount to ≈7%. The aim of this two corrections is to obtain isotropic distribution in azimuthal angle φ, and smooth distribution in emission angle θ (both measured with respect to the direction of the incoming projectile). The accuracy of track measurements corresponds to an uncertainty in Q of less than 20 MeV/c.

The reference probability density $P_1(p_1)\cdot P_1(p_2)$, used in denominator of the correlation function (1), is obtained from mixed negative pion pairs. Each π^- is randomly chosen from different events with the close values of the total charge multiplicities $n_\pm$, and the same negative pion multiplicity. In this way we take into account the dependence of angular and momentum distributions, of negative pions, on the $n_\pm$ multiplicity. Additionally, in the background distribution we respect the "$n_\pm$ topology", meaning that the probability of pion combinations, from events with close values of $n_\pm$, is the same in the background and experimental distributions. The pairs in the background distribution are also weighted with a standard Gamov factor [8], $G(Q) = 2\pi\eta / (\exp^{2\pi\eta} - 1)$, where $\eta = \alpha m_\pi / Q$, and $\alpha = 1/137$, to account for the effect of the di-pion mutual Coulomb interaction. The effect of this correction, which is essential only at small Q (< 25 MeV), was found to be negligible as compared to the errors of the fit. Finally, the background distribution is normalised so that beyond certain Q value ($Q > 0.33$ GeV/c) the integrals of experimental and background distributions are equal.

This study is based on a sample of 7327 inelastic C+C, and 1989 inelastic C+Ta interactions. Only events with pion multiplicities ≥2 are considered: i.e. 2556 C+C interactions ($\sigma/\sigma_{in} \approx 34\%$) with 8407 π^- pairs, and 1183 C+Ta interactions ($\sigma/\sigma_{in} \approx 59\%$) with 16829 π^- pairs. The number of mixed pairs was chosen to be 10 times larger than that of real pairs.

3. RESULTS

Figure 1 shows the two-pion correlation functions $C_2(Q)$, for C+C and C+Ta collisions. Error bars are statistical only. The Bose-Einstein enhancement is clear in the low relative momentum region, while for $Q > 0.15$ GeV/c the distribution is consistent with unity. The solid curve represents the best fit to Gaussian model (4). The extracted fit parameters (chaoticity λ, source size R) are listed in the Table 1. The values of R are close for C+C and C+Ta interactions, while the λ parameter is larger in C+C interactions.

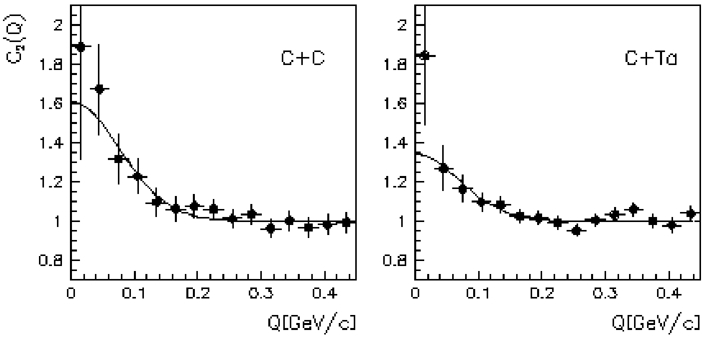

Fig. 1. The experimental $\pi^-\pi^-$ correlation function vs Q. The curve shows the best fit to equation (4).

Table 1. Source parameters extracted from the Gaussian fit.

A_p+A_t	λ	R[fm]	χ^2/NDF
$^{12}C+^{12}C$	0.6 ± 0.2	1.8 ± 0.4	5.0/13
$^{12}C+^{181}Ta$	0.3 ± 0.1	2.0 ± 0.4	11.0/13

Since in different experiments, various spatial distributions of the emission sources are used, the values of the "radius" cannot always be directly compared. To accomplish this, the radii are converted to the r.m.s. values. The conversion factor is $\sqrt{3}$ for the Gaussian distribution (4), and 1.0 for the Kopylov-Podgoretsky model. Our r.m.s. radii are (3.1 ± 0.7) fm for C+C collisions, and (3.4 ± 0.6) fm for C+Ta collisions. These values are comparable with the "effective nuclear radius" of the projectile nucleus obtained from $R_{eff} = 1.21 A_p^{1/3}$ ($R_{eff} \approx 2.8$ fm for carbon). This further suggests that the size of the interaction region is determined by the geometry of the projectile nucleus. Also, the r.m.s. radii are consistent with the values previously published in [6, 7] which were obtained with lower statistics. Fig. 2 compares our results with other heavy-ion data, at energies in the range 0.6-200 A GeV, for all inelastic and central collisions [9-15]. The r.m.s radii are plotted as a function of $A_p^{1/3}$. It is seen that, at energies of a few GeV per nucleon, the radius of the pion emission region increases with $A_p^{1/3}$, and is close to R_{eff}, shown in the figure with a straight line. To verify the scaling in projectile radius at 14.6A GeV and 200A GeV more data are needed.

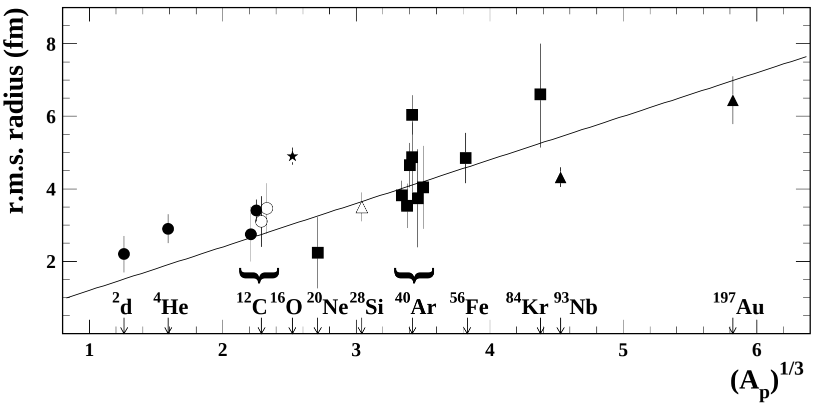

Fig. 2. Radii of the pion emission region in nucleus-nucleus collisions at 0.65A GeV [9] (▲), (1.2-2.1) A GeV [10-13] (■), 4.3A GeV [6,7, open circles are our points] (●,○), 14.6A GeV [14] (Δ), and 200A GeV [15] (★).

In conclusion, our data show that the size of the interaction region is determined by the magnitude of the projectile nucleus, and that there is little evidence for large expansion of the pion gas before the freeze out. This is also supported by the other heavy-ion data at energies of a few GeV per nucleon. Fine details of the shape of the correlation function will be available after careful investigation of the effects of resonances and analysis in terms of directional correlations rather than *Q*.

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PIONSKA INTERFEROMETRIJA U C+C I C+TA SUDARIMA NA 4.2A GEV/C

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Pretstavljene su Boze-Ajnštajnove korelacije između negativnih piona emitovanih u C+C i C+Ta sudarima na 4.2A GeV/c. Eksperimentalni podaci su dobijeni pomoću 2m mehuraste komore ozračene na sinhrofazotronu Objedinjenog instituta za nuklearna istraživanja u Dubni. Podaci jasno pokazuju efekt kvantne interferencije za identične bozone. Sa Gausovom parametrizacijom određena je veličina oblasti iz koje su emitovani pioni.

Ključne reči: *pionska interferometrija, Boze-Ajnštajnove korelacije, sudarih teških jona*