EVIDENCE FOR A DIRECTIONAL DEPENDENCE OF BOSE-EINSTEIN CORRELATIONS

AT THE CERN INTERSECTING STORAGE RINGS

The Axial Field Spectrometer Collaboration

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ABSTRACT

In pp and p $\bar{p}$ collisions at the CERN Intersecting Storage Rings, a directional dependence of the size of the pion-emitting region is observed using Bose-Einstein interference between identical charged pions. The data reveal a substantially larger dimension in the direction parallel to the beam axis than in the transverse direction, indicating a prolate shape of the emission region. For $\alpha\alpha$ interactions, the data are consistent with a spherical shape.

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Bose-Einstein correlations manifest themselves as an enhanced probability for identical bosons to be emitted with small relative momenta, as compared to an uncorrelated case. The origin of this effect is the requirement imposed by quantum mechanics that the wave function of a system of bosons must be symmetric. The interference pattern for this system measures the extension of the emission region.

In astronomy, the effect has been observed for photons as the well-known Hanbury-Brown - Twiss effect, used to measure the size of stellar objects [1].

In high-energy physics, the correlations are also well established and have been studied for pions [2-4] as well as for kaons [5, 6], and a determination of the dimensions of the π - and K-emitting regions has been possible in several types of reactions. The decisive quantity for such a determination is the momentum difference $\Delta \vec{p}$ for the boson pairs, and in fact it is the dimension parallel to $\Delta \vec{p}$ that is probed by the correlations, as pointed out, for example, in ref. [7]. In the present study we make use of this fact to investigate a possible directional dependence of the spatial extension of the interaction region.

The data used in this analysis were obtained with the Axial Field Spectrometer (AFS) [8] at the CERN Intersecting Storage Rings (ISR). A cylindrical drift chamber surrounded the intersection point and was used to extract vertex and track information for the produced charged particles. The chamber is divided azimuthally into sectors of 4° , each containing 42 sense wires radially distributed at distances between 0.2 m and 0.8 m from the centre. Position coordinates in the plane transverse to the sense wires are determined from the drift time and have a resolution of $\approx 230 \mu\text{m}$. Along the wires, parallel to the beams, positions are measured from the relative pulse heights at both ends of each wire. The corresponding resolution is $\approx 1.5 \text{ cm}$. The pulse-height measurements also provide dE/dx information, used for particle identification. The detector covers the rapidity interval $|y| \lesssim 1.0$.

This analysis is based upon pp, $p\bar{p}$, and $\alpha\alpha$ collisions. One part of the data was obtained using a charged-particle high-multiplicity trigger, which gave 20,000 $\alpha\alpha$ events at $\sqrt{s} = 126$ GeV and 23,000 pp events at $\sqrt{s} = 63$ GeV. The remainder of the data was obtained with a minimum-bias trigger and consists of 40,000 $\alpha\alpha$ events at $\sqrt{s} = 126$ GeV, 115,000 pp and 90,000 $p\bar{p}$ events at $\sqrt{s} = 53$ GeV, and finally 117,000 pp events at $\sqrt{s} = 63$ GeV. After having been processed through standard track-finding, vertex reconstruction, and momentum determination programs, the data were subjected to several quality restrictions. Cuts identical to those described in ref. [3] were applied. Particle identification was based upon dE/dx measurements as in ref. [3]: all particles except clearly identified K, p, and $\bar{p}$ were treated as pions. The contamination of the pion sample thereby imposed is of negligible importance. Only events with at least two identified pions in the central detector were accepted. The total number of such events was 217,609.

The correlation function R, defined as the probability for emission of real boson pairs relative to uncorrelated pairs, is presented as a ratio between the actual distribution of particle pairs and a corresponding uncorrelated distribution. In theories with pion sources uniformly distributed over the surface of a sphere (see, for example, ref. [9]) this ratio is parametrized in terms of a Bessel function, and can be written:

$$R = 1 + \lambda [2J_1(q_T r)/q_T r]^2 \frac{1}{1 + (q_0 \tau)^2} \quad (1)$$

Here J_1 is the first-order Bessel function; q_T is the component of $\vec{p}_1 - \vec{p}_2$ transverse to $\vec{p}_1 + \vec{p}_2$, and $q_0 = |E_1 - E_2|$; r is the radius of the sphere; τ in some models represents the lifetime of the sources, in others it is ascribed to the depth of the emission layer; λ takes into account that the interference, for various reasons, is not complete. The parameter q_L , defined as the component of $\vec{p}_1 - \vec{p}_2$ parallel to $\vec{p}_1 + \vec{p}_2$, is a good approximation to q_0

in the case of relativistic pions with small opening angles. In this analysis q_0 has been replaced by q_L . The estimated resolution in q_T is roughly 15 MeV/c.

For a non-spherical emission region, formula (1) cannot be valid; however if it is used the resulting values of r should represent an average of the spatial extensions in the directions probed. To study this directional dependence of r , use has been made of the fact that r is the dimension parallel to $\Delta\vec{p}$. Consequently, the correlations were studied in terms of $\theta(\Delta\vec{p})$, i.e. the angle (in the centre-of-mass system) between the beam axis and the momentum difference of the pion pair. This variable is illustrated in fig. 1. In this analysis, the two-particle combinations are divided into angular intervals, the sizes of which are governed by statistics limitations.

The uncorrelated background is formed by combining particles from one event with those from a track bank consisting of four different events in the series of data. The distribution of different event combinations (D) and the one composed of pion pairs from the same event (S) were studied in terms of q_T and q_L , and the ratio of the two (S/D) versus (q_T, q_L) was formed. To take into account the limited two-track resolution of the drift chamber, a minimum opening angle $|\Delta\phi_{lab}| = 2.5^\circ$ was required for pairs from the same as well as from different events. The results presented in the next paragraph are not sensitive to moderate variations of the size of this cut. In particular, it is found not to be necessary to require the particles to be in different sectors of the drift chamber, i.e. $|\Delta\phi_{lab}| > 4^\circ$. For the uncorrelated distribution, in order to avoid combining particles from events with very different multiplicities, the low and high tails of the charged-particle multiplicity distributions were excluded. For consistency, the correlated distribution was extracted from events belonging to the same multiplicity interval. Values of the mean charged multiplicity $\langle n_{ch} \rangle$ quoted below refer to these truncated distributions. The truncations were performed for each data set, characterized by trigger and incident particle types.

In order to improve statistics, positively and negatively charged combinations were added, as no significant charge dependence was found in ref. [3]. Also, in the case of minimum-bias pp and $p\bar{p}$, data from different samples were added, assuming no dependence on incident particle type, as indicated in ref. [3]. From the results of direct comparisons between pp and $p\bar{p}$ collisions, e.g. ref. [10], we have no reason to expect such dependence

The following ratio was formed:

$$R = [(++)^S + (--)^S] / [(++)^D + (--)^D] \quad , \quad (2)$$

where S refers to the number of 'same-event' combinations in some particular bin of (q_T, q_L) , and D to the corresponding number of 'different-event' combinations. The signs indicate the electric charges of the pions. The Bessel parametrization was fitted to the correlation function so obtained. For reasons of limited statistics, we did not perform an independent determination of r , r_c , and λ by fitting to eq (1). Instead, the fit was done for a fixed bin of q_L ($q_L \leq 0.2$ GeV/c) using the following parametrization of the correlation function:

$$R = N \left\{ 1 + \lambda \left[\frac{2J_1(q_T r)}{q_T r} \right]^2 \right\} \quad , \quad (3)$$

as in ref. [6]; N is a normalization factor, introduced to take into account that the total numbers of S and D combinations are different. An example of the data, R versus q_T , as obtained from eq. (2), appears in fig. 2 for the high-multiplicity pp data. In the figure, T refers to data probing the transverse dimension of the pion source, as determined from pairs with $|\cos \theta(\Delta\vec{p})| < 0.60$, [$\langle |\cos \theta(\Delta\vec{p})| \rangle \approx 0.30$], whereas L corresponds to the longitudinal data, namely combinations from the angular interval $|\cos \theta(\Delta\vec{p})| \geq 0.60$, [$\langle |\cos \theta(\Delta\vec{p})| \rangle \approx 0.76$]. The data and the fitted functions are shown with $N = 1$. Already from this, it is clear that the correlations depend on the direction being probed. The values of the fitted parameters

[fit to eq. (3)], for various angular intervals and the different data sets, are quoted in table 1. In fig. 3a, r is shown as a function of $\langle |\cos \theta(\Delta\vec{p})| \rangle$ for pp and $p\bar{p}$ collisions. The corresponding quantities for $\alpha\alpha$ collisions appear in fig. 3b. We estimate the systematic error due to misidentified particles (if any) to be negligible. The error due to the method of normalization is contained within the statistical errors. Systematic errors due to the method of constructing the uncorrelated background should have little effect on r , but can have a large effect on the incoherence parameter λ' . The resulting values of λ' can therefore only be regarded as lower limits on λ , and cannot be taken to imply that part of the pion production is coherent. The following results are inferred:

$pp, p\bar{p}$:

- i) The radial parameter r increases with increasing $|\cos \theta(\Delta\vec{p})|$, i.e. the extension of the pion-emitting region parallel to the beam axis is longer than the one transverse to it, indicating a prolate shape of the region. Between the bins with the maximal angular separation that we are able to detect in this way, the lengths differ by about a factor of 2.
- ii) The overall multiplicity dependence found in ref. [3] is mainly due to an increase of the longitudinal dimension with multiplicity.

$\alpha\alpha$:

- iii) No significant dependence of r on $|\cos \theta(\Delta\vec{p})|$ is found for $\alpha\alpha$, the results being consistent with a spherical shape.

Conclusion (i) encourages us to try to determine the extreme extensions both parallel and transverse to the beam axis. We assume an ellipsoidal density distribution of the pion sources. For a three-dimensional Gaussian with widths $\sigma_x, \sigma_y, \sigma_z$, and rotational symmetry around the collision axis, i.e. $\sigma_x = \sigma_y = \sigma_{xy}$, one is led to a parametrization of the correlation function:

$$R = 1 + \lambda'' (\exp [-(\sigma_{xy} q_{xy})^2] [\exp -(\sigma_z q_z)^2]) \quad , \quad (4)$$

where $q_{xy} = (q_x^2 + q_y^2)^{1/2}$, and $\vec{q} = (q_x, q_y, q_z) = \Delta \vec{p}$. The result of a two-dimensional fit of the correlation data versus (q_{xy}, q_z) , for pp minimum-bias collisions at $\sqrt{s} = 63$ GeV, is: $\sigma_{xy} = (0.72 \pm 0.04)$ fm, $\sigma_z = (1.29 \pm 0.12)$ fm, and $\lambda'' = 0.30 \pm 0.02$. Since the function $2J_1(q_T r)/q_T r$ in eq. (3) can be well approximated by a Gaussian with $\sigma = r/2$, these parameters are in good agreement with the numbers presented in table 1.

In ref. [11] it is claimed that the charged particle multiplicity increases with the transverse dimension of the overlapping region of the two colliding particles, and that this region is related to r . Our results (ii) show that also the longitudinal extension of the source increases with the multiplicity of the event.

Comparisons with other investigations on the same topic should be made cautiously, because of differences in the types of reactions considered, the energy range, etc. We mention, however, the results of ref. [12], where for p ($\bar{p}$) incident on hydrogen and heavier nuclei at 200 GeV, an oblately to spherically shaped pion-emission region is observed. This is found using a different set of variables than the set used in our investigation (see ref. [12] for their definition). Repeating the analysis with our pp ($p\bar{p}$) data and these alternative variables, we get results consistent with a spherical shape. The same variables are used in the low-energy $p\bar{p}$ annihilation experiment of ref. [13], which reports indications for prolateness but, owing to limited statistics, does not exclude a spherical shape. The advantage of the present analysis is that we get a cleaner separation of the longitudinal and transverse directions. The directional dependence has also been studied for e^+e^- reactions, e.g. ref. [4], where an angular variable analogous to ours is used, and a spherical-to-prolate shape is arrived at.

In summary, Bose-Einstein correlations between pions of like charge are used to probe the extension, in different directions, of the pion-

emitting region. For pp and $p\bar{p}$ data, the length of this region transverse to the beam axis is shorter than the length parallel to it. For $\alpha\alpha$ data, no such difference is found, and the results are consistent with a spherical emission region.

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Table 1

Fit of the Bessel parametrization, eq. (3),
to the correlation data ($q_L \leq 0.2$ GeV/c)

Data	$ \cos \theta(\Delta\vec{p}) $	$\langle \cos \theta(\Delta\vec{p}) \rangle$	r (fm)	λ'
Minimum-bias pp + p $\bar{p}$ $\langle n_{ch} \rangle = 3.1$	0.00-0.25	0.125	1.2 ± 0.1	0.43 ± 0.02
	0.25-0.40	0.325	$1.3^{+0.2}_{-0.1}$	0.39 ± 0.03
	0.40-0.60	0.499	1.2 ± 0.1	0.40 ± 0.04
	0.60-0.75	0.672	1.9 ± 0.1	0.54 ± 0.04
	0.75-1.00	0.857	2.2 ± 0.2	0.57 ± 0.04
High-mult. pp $\langle n_{ch} \rangle = 7.2$	0.00-0.25	0.125	1.7 ± 0.2	0.37 ± 0.05
	0.25-0.60	0.424	1.8 ± 0.2	$0.30^{+0.05}_{-0.04}$
	0.60-1.00	0.761	3.2 ± 0.3	0.47 ± 0.07
Minimum-bias $\alpha\alpha$ $\langle n_{ch} \rangle = 5.5$	0.00-0.25	0.126	1.4 ± 0.1	0.26 ± 0.04
	0.25-0.60	0.426	1.7 ± 0.2	0.22 ± 0.04
	0.60-1.00	0.764	1.6 ± 0.1	0.34 ± 0.03
High-mult. $\alpha\alpha$ $\langle n_{ch} \rangle = 13.5$	0.00-0.25	0.125	$2.7^{+0.5}_{-0.4}$	0.20 ± 0.03
	0.25-0.60	0.426	2.0 ± 0.3	0.15 ± 0.02
	0.60-1.00	0.762	2.7 ± 0.3	0.20 ± 0.03

Figure captions

Fig. 1 Illustration of the variable $\theta(\Delta\vec{p})$ used to study the directional dependence of Bose-Einstein correlations. All momenta are measured in the c.m. system.

Fig. 2 The ratio $R(q_T)$, ($q_L \leq 0.2$ GeV/c), as given by eq. (2) for high-multiplicity pp data and two bins of $|\cos \theta(\Delta\vec{p})|$. The quantities transverse to the beam axis (T) are related to data with $|\cos \theta(\Delta\vec{p})| < 0.60$, whereas $|\cos \theta(\Delta\vec{p})| \geq 0.60$ correspond to the longitudinal properties (L). Also shown are the fitted Bessel functions, eq. (3) with $N = 1$:

$$r_T = (1.8 \pm 0.1) \text{ fm}, \lambda_T' = 0.33 \pm 0.03; r_L = (3.2 \pm 0.3) \text{ fm}, \\ \lambda_L' = 0.47 \pm 0.07.$$

Fig. 3 The radial parameter r , from the fitted Bessel functions [eq. (3)], for the various intervals of $|\cos \theta(\Delta\vec{p})|$ quoted in table 1:
a) minimum-bias pp + $p\bar{p}$ and high-multiplicity pp data, and
b) minimum-bias and high-multiplicity $\alpha\alpha$ data.

Fig. 1

Fig. 2

Fig. 3