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INVESTIGATION OF THE DIMENSIONS OF SECONDARY PARTICLE EMISSION REGION IN π^- N-INTERACTIONS AT 40 GeV/c

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1. INTRODUCTION

Study of characteristics of multiple production processes at high energies is of great importance for clarifying the genuine nature of strong interactions due to the dominant role these processes play in the total act of collision.

Plenty of data revealing the main features of high energy hadronic processes have come up in the last years[1].

But some new experimental and theoretical research points out the existence of still unknown properties of these processes[2]. In particular, to understand the multiparticle production dynamics, it is essential to know the space-time structure of secondary particle emission source.

One of possible directions to determine the parameters of the space-time development of hadronic processes is a method of studying the second-order interference effects between pairs of identical particles emitted in a given collision. Utilisation of this method for deducing the radius (R) of the region, from which particles are emitted, and the "life-time" (τ) of the excited system was proposed and developed in detail in ref.[3-8].

Since then this method was thoroughly tested upon various hadron-hadron reactions in a wide range of energies. The results of the studies have unambiguously confirmed the efficiency of the method, and the space-time dimensions of the identical boson emission source have been measured. Namely, for hadron-hadron interactions the radius of secondary pion emission region appeared to be $R \approx 1.5$ fm, while the life-time of the excited state was $\tau \approx 10^{-23}$ sec.[1]. The method of using second-order interference phenomena for deducing the space-time structure of interactions has naturally advanced in finding its way into the field of hadron-nucleus[9] and of relativistic nuclear collisions[10]. Along with pions, other particles were also proved to be suitable for such an analysis[11].

2. THE EFFECT OF SECOND-ORDER INTERFERENCE BETWEEN IDENTICAL PARTICLES AND METHOD OF EXPERIMENTAL DATA ANALYSIS

The interference phenomenon is a consequence of the Bose-Einstein symmetrization requirements for produced pions of equal charge. Experimentally this effect was first encountered in 1960/12/ when an excess of like pion pairs over unlike ones was observed in $\bar{p}p$ annihilation. A description of this phenomenon in accordance with ref./3-7/, looks as follows. Let us consider a pair of identical pions ($\pi^\pm\pi^\pm$) with energies (momenta) $E_1(\vec{P}_1)$ and $E_2(\vec{P}_2)$, respectively, emitted from the surface of an excited spheric source of radius R and with life-time τ. Introducting the variables $q_0 = E_1 - E_2$ and $\vec{q}_\perp = \vec{q} - \vec{n}(\vec{q}\cdot\vec{n})$, where $\vec{q} = \vec{P}_1 - \vec{P}_2$ and $n = (\vec{P}_1 + \vec{P}_2)/|\vec{P}_1 + \vec{P}_2|$, for the probability to observe such a pair of pions, one can write

$$W(q_0,q_\perp^2) = \{1 + \frac{[2J_1(q_\perp,R)/q_\perp R]^2}{(1+q_0\tau)^2}\}\,W_\phi(q_0,q_\perp^2), \qquad (1)$$

where $J_1(q_\perp,R)$ is the first order Bessel function, while $W_\phi(q_0,q_\perp^2)$ is a "background" distribution, i.e., when the interference is absent. As can be seen from (1), the probability to observe a pair of like pions in comparison with that for a pair of unlike pions, is greater for smaller energy differences of the two pions and for smaller opening angles between them. It is obvious that the experimental accuracy of measuring the interference effect strongly depends on the correct choice of the "background" W_ϕ*. The reliability of treatment of the effect and the precision in determination of particle source parameters R and τ is also much dependent on the accuracy of both momentum and angular measurements for those particles, which are expected to contribute most significantly to the probability modulation region.

The experimental study of the interference (i.e., measurement of the R and τ parameters) reduces to the analysis of the two-dimensional distribution

$$D(q_0,q_\perp^2) = \frac{N_\phi}{N}\cdot\frac{dN(q_0,q_\perp^2)}{dN_\phi(q_0,q_\perp^2)}, \qquad (2)$$

where $N(q_0,q_\perp^2)$ is the number of like pion pairs with the given values of q_0 and q^2, while $N_\phi(q_0,q_\perp^2)$ is the number of background pairs. The values of R and τ parameters are obtained by means of fitting (2) to the function

$$D(q_0,q_\perp^2) = A\{1 + [\frac{(2J_1(q_\perp,R)/q_\perp R)^2}{1+(q_0\tau)^2}]\}, \qquad (3)$$

using the least-squares method. Here A is a normalization parameter which is equal to $D(q_0,q_\perp^2)$ outside the interference region. But probing by formula (3) has shown that it should be modified: before the second term another parameter λ is necessary *. This coefficient accouns for possible procedural ambiguities**, specific dynamical correlations/14/*** and for some other circumstances/13/.

Formula (1) was mostly applied to the analysis of pion-pion correlations: π^+ or π^- produced in various hadron-hadron interactions/1/. In these experiments the very existence of the interference effect and its two-dimensional structure were established. Thus, the obtained values of R and τ should not be treated as final ones for at least two reasons. The first reason is that the determined values of R and τ represent only the average or effective radius of poin emission source, as there exist different mechanisms of their production. For instance, the experimentally established copious resonance production in hadronic reactions/1/ seems to play an important role in forming an actual space-time structure of pion emission region. The second reason is associated with inevitable uncertainty in the background choice, which should be somehow accounted for while determining the R and τ parameters.

Later the study of the interference correlations of identical particle pairs was spread over the field of hadron-nucleus and of nucleus-nucleus collisions.

In fact, the first estimates of R were made in ^{40}Ar + Pb$_3$O$_4$, BaI$_2$ interactions at 1.8 GeV/c per nucleon and in ^{12}C Ta interactions at 4.2 GeV/c per nucleon/10/. The result was $R \approx 3.0$ fm. In a later work/16/ the interference was studied in ^{40}Ar+KCl collisions at 1.8 GeV/c per nucleon with corrections for Coulomb and nuclear interactions of identical pions. For this case R and τ values were found to be equal to $1.96^{+0.51}_{-0.64}$ fm and $2.70^{+0.64}_{-0.79}$ fm/c, respectively.

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* In the literature/1/ W_ϕ is often defined either as the distribution of unlike pion pairs from the same interactions, which are not the products of a resonance decay, or as the distribution of pairs of like pions, taken from different events, accounted for the phase-space limitations.

* As was shown in/13/ sometimes λ is close to 1, but usually $\lambda < 1$.

** Procedural ambiguities may arise from the impossibility of any reliable identification of high momentum particles, from limited accuracy of measurements, etc.

*** In some cases dynamical correlations may result in almost complete suppression of the interference maximum ($\lambda \approx 0$) (ref./15/).

Results of studying the interference in hadron-nucleus interactions are presented in ref./9/. In these papers the existence of the effect under investigation was demonstrated and it was also shown that the values of R and τ parameters agree within the errors with those obtained in hadron-hadron and nucleus-nucleus collisions.

3. NEW EXPERIMENTAL RESULTS

In this section we discuss new experimental data on space-time characteristics in the c.m.s. of pion emission region in the reaction

$$\pi^- + p \to \pi_1^- + \pi_2^- + X^{++} \qquad (4)$$

at 40 GeV/c obtained by the 2-m propane bubble-chamber group in the LHE, JINR/19/.

The analysed sample comprised ~18000 events representing reaction (4). The experimental details, data processing procedure and general characteristics of reaction (4) were described and discussed elsewhere/17/.

The two-dimensional distribution of the type (2) was fitted by the least squares method to a modification of function (1):

$$D(q_0,q_\perp^2) = A\{1+\lambda[\frac{(2J_1(q_\perp,R)/q_\perp R)^2}{1+(q_0\tau)^2}]\}, \qquad (5)$$

where A is a normalization parameter, which is equal to $D(q_0,q_\perp^2)$ outside the interference region.

The background distribution was built up of pairs composed of negative pions taken from different events. In more detail the problem of background is discussed in ref./18/.

Results of approximation of the distribution (2) by function (5) are given in Table I.

Table I

Kinematic region used:		A	λ	R (fm)	$c\tau$ (fm)	χ^2/NDF
q_0, GeV	$q_\perp^2$(GeV/c^2)					
0.2	0.04	0.88±0.03	1.1±0.3	3.5±0.5	4.0±1.3	1.1
0.3	0.06	0.90±0.02	1.0±0.2	3.4±0.5	3.4±0.9	0.9
0.4	0.08	0.89±0.04	0.8±0.3	2.4±0.8	2.3±0.9	1.0
0.5	0.1	0.65±0.11	0.9±0.3	1.1±0.2	0.6±0.1	1.1
0.5	0.2	0.72±0.04	0.7±0.1	1.0±0.1	0.7±0.1	1.1

It is seen that the values of A are always less than 1. This is probably due to the normalization of the experimental distributions to the total number of pion pairs with q_0,q_t^2 in the kinematic region considered. The values of λ do not differ from 1 within statistical errors/13/, except for the last kinematic region of approximation. But the space-time characteristics of the emission region appreciably vary with the extending approximation region. In fact, the value of R decreases from 3.5 to 1 fm, while the value of $c\tau$ changes from 4.0 to 0.7 fm. This indicates that formula (5) with fixed parameters R and τ does not describe the experimental data in the kinetic region of q_0,q_t^2 discussed.

Thus, the obtained results show that the space-time dimensions of the negative pion emission region in the reaction (4) in c.m.s. cannot be characterised by a unique set of R and τ parameters. Hence it is a plausible assumption that there exist several pion emission sources with different space-time structures.

In order to test this assumption, two possibilities were analyzed: i) a single source exists but with different longitudinal ($R_\perp$) and transverse ($R_\parallel$) dimensions relative to the collision axis in the c.m.s.; ii) two spherical sources exist with their own R_i and $c\tau_i$ parameters.

In case of a single nonspherical source it is necessary to extract from total sample of pairs those emitted at $\theta_\pi \approx 0°$ or at $\theta_\pi \approx 90°$ relative to the collision axis. Then at $\theta_\pi \approx 0°$ we obtain "transverse" $R_\perp$ and $c\tau_\parallel$ characteristics of the source in the c.m.s.; while at $\theta_\pi \approx 90°$ longitudinal $R_\parallel$ and $c\tau_\perp$ characteristics. Unfortunately, the available statistics allowed us to measure these values only in rather broad angular intervals: θ_π =0-30° and 60-120°. The following one-dimensional distributions were examined:

$$R(q_\perp^2) = \frac{N_\phi}{N}\frac{dN(q_\perp^2)}{dN_\phi(q_\perp^2)} \qquad (6)$$

and

$$T(q_0) = \frac{N_\phi}{N}\frac{dN(q_0)}{dN_\phi(q_\perp^2)} \qquad (7)$$

at various limitations on q_0 and $q_\perp^2$, respectively. Of course, in this case the interference effect is less pronounced in comparison with the two-dimensional distribution case. However, in so doing we have increased the statistics of pion pairs in the interference region thus improving the statistical accuracy of the determination of the R and $c\tau$ parameters/19/.

Table II ($0° \leq \theta_\pi \leq 30°$)

$q_\perp^2 \leqslant 0.2$ GeV/c^2 restrictions on q_o (GeV)	a	λ_1	$R_\perp$ (fm)	χ^2/NDF
0.1	0.87±0.04	1.2±0.4	3.3±0.7	1.7
0.2	0.91±0.03	0.6±0.2	2.8±0.6	1.2
0.3	0.92±0.03	0.5±0.2	2.6±0.6	1.1
0.4	0.94±0.03	0.4±0.1	2.7±0.6	1.1
0.5	0.94±0.02	0.4±0.1	2.7±0.6	0.9

Tables II-V present the values of the parameters obtained as a result of approximation of the distributions (6) and (7) for different angular intervals in θ_π by functions

$$R(q_\perp^2) = a[1 + \lambda_1 \frac{4J_1^2(q_\perp, R)}{(q_\perp R)^2}], \tag{8}$$

and

$$T(q_0) = b[1 + \lambda_2 \frac{1}{1+(q_0 r)^2}]. \tag{9}$$

Formulae (8) and (9) are obtained by integrating of (5) over q_0 and $q_\perp^2$, respectively.

As can be seen in the above tables, for pion pairs emitted at $\theta_\pi \leq 30°$ the values of the parameters $R_\perp$ and $cr_\parallel \approx (2.5 \div 3.0)$ fm and weakly vary with q_0. For pion pairs emitted at $\theta_\pi \geq 60°$ the values of $R_\parallel$ and $cr_\perp \approx (1.2 \div 2.0)$ fm. Hence, our results are consistent with the assumption of existence of a single pion source. But in this case its "transverse" dimensions in the c.m.s. are slightly greater than "longitudinal" ones.

Under the assumption about the existence of two sources, the experimental distributions (6) and (7) were approximated by function

$$\vec{R}(\vec{q}^{\,2}) = \alpha_1 \{ 1 + [\mu_1 \exp(-\vec{q}^{\,2} < R_1^2 >/6) + \mu_2 \exp(-\vec{q}^{\,2} < R_2^2 >/6)]^2 \} \tag{10}$$

according to refs.[13]*.

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*In this case it is assumed that both sources are present in each act interaction.

Table III ($0° \leq \theta_\pi \leq 30°$)

$q_0 \leq 0.3$ GeV restrictions on $q_\perp^2$, (GeV^2/c^2)	b	λ_2	$cr_\parallel$ (fm)	χ^2/NDF
0.020	0.83±0.08	0.8±0.3	2.3±1.3	1.3
0.040	0.88±0.06	0.6±0.2	2.6±0.9	1.4
0.060	0.88±0.06	0.5±0.2	2.0±1.1	0.9
0.080	0.89±0.05	0.5±0.1	1.9±0.9	0.9
0.100	0.89±0.04	0.5±0.1	2.2±1.1	0.7

Table IV ($60° \leq \theta_\pi \leq 120°$)

$q_\perp^2 \leqslant 0.2$(GeV/c)^2 restrictions on q_0 (GeV)	a	λ_1	$R_\parallel$ (fm)	χ^2/NDF
0.1	0.89±0.04	0.5±0.1	2.1±0.4	1.2
0.2	0.86±0.05	0.4±0.1	1.6±0.3	1.1
0.3	0.87±0.04	0.4±0.1	1.6±0.3	1.2
0.4	0.83±0.06	0.4±0.1	1.3±0.4	1.0
0.5	0.87±0.05	0.3±0.1	1.4±0.3	1.1

Table V ($60° \leq \theta_\pi \leq 120°$)

$q_o \leqslant 0.3$(GeV) restrictions on $q_\perp^2$ (GeV/c)^2	b	λ_2	$cr_\perp$ (fm)	χ^2/NDF
0.020	0.88±0.05	0.4±0.1	2.3±1.3	1.1
0.040	0.90±0.04	0.3±0.1	2.4±1.1	1.3
0.060	0.86±0.06	0.3±0.1	1.2±0.6	0.9
0.080	0.84±0.07	0.3±0.1	1.0±0.5	1.2
0.100	0.87±0.06	0.3±0.1	1.1±0.5	1.0

Table VI

restrictions on q_0, (GeV)	α_1	μ_1	μ_2	$\langle R_1^2\rangle^{1/2}$	$\langle R_2^2\rangle^{1/2}$	χ^2/NDF
0.100	0.89 ± 0.03	0.57 ± 0.09	0.8 ± 0.3	1.1 ± 0.5	5.5 ± 2.0	0.7
0.200	0.90 ± 0.03	0.58 ± 0.06	1.0 ± 0.6	1.1 ± 0.3	6.9 ± 2.8	0.9
0.300	0.91 ± 0.02	0.61 ± 0.05	1.3 ± 0.8	1.2 ± 0.2	8.0 ± 3.6	0.9
0.400	0.92 ± 0.02	0.63 ± 0.06	1.6 ± 4.6	1.2 ± 0.2	8.7 ± 9.6	0.9
0.500	0.92 ± 0.02	0.63 ± 0.05	1.6 ± 0.9	1.2 ± 0.2	8.7 ± 9.3	0.8

The results of the approximation are presented in Table VI. One can see that the existence of two sources is distinctly manifested: one, with $\langle R_1^2\rangle^{1/2} \approx (1.2\pm0.2)$ fm; and another, with $\langle R_2^2\rangle^{1/2} \approx (5.5\pm 2.0)$ fm for small values of q_0.

4. CONCLUSIONS

The analysis of new results on the interference effect of secondary negative pions obtained in $\pi^- p$ interactions at 40 GeV/c by the 2-m propane bubble chamber group at LHE, JINR shows that for a space-time description of pion source it is necessary to introduce at least two characteristic dimensions of such sources: $R_1 \approx c\tau_1 \approx 3$ fm and $R_2 \approx c\tau_2 \approx 1$ fm. This conclusion is supported by the analysis of both two-dimensional and one-dimensional distributions of pion pairs using different models for the emission source structure.

The existence of two sizes of emission source may be associated with the dynamics of multiple pion production processes. As was shown in ref./1/, mesonic resonances are copiously produced at this energy. Therefore the large size $R_1 \approx c\tau_f \approx 3$ fm is probably attributed to the interference of pions coming from the decay of resonances (ρ, f - mesons), while $R_2 \approx c\tau_2 \approx 1$ fm may be associated with direct pion production (see also refs./20/). However, the final approval of such interpretation of experimental results requires further research based on data of much higher statistical value.

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