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# INTERFERENCE OF SECONDARY PIONS AND TIME-SPACE CHARACTERISTICS OF THEIR EMISSION VOLUME IN $\pi^-$p INTERACTIONS AT 40 GeV/c

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## I. INTRODUCTION

The like-pion interference, observed first by G.Goldhaber et al./1,2/, allows the time-space characteristics of pion emission volume (p.e.v.) to be determined. The method was proposed and developed by Kopylov and Podgoretsky/3,4/, and a large number of experimental results were published elsewhere (see, for example,/5–8/).

In this paper we present results obtained in $\pi^-p$ interactions at 40 GeV/c. Except the radius and the life-time of pion emission volume in C.M.S. the influence of resonance production on the time-space characteristics of p.e.v. is studied.

## II. FORMALISM

For like bosons the interference is constructive, and the density $dN/dP_1\,dP_2$ of like-pion pairs in phase space can be written as:

$$dN/dP_1\,dP_2 = [\,1 + \Delta(q,P)\,]\,dN^{backgr}/dP_1\,dP_2\,, \qquad (1)$$

where $P_{1,2}$ are four momenta of pions $q = P_1 - P_2$, $P = P_1 + P_2$; $dN^{backgr}/dP_1\,dP_2$ is pair density in the absence of interference; $\Delta(q,P) \to 1$ for $q \to 0$ and $\Delta(q,P) \to 0$ outside the interference region.

The analytical form of $\Delta(q,P)$ depends on the model describing particle emission sources. For independent point-like sources, with life-time $\tau$, distributed over the sphere with radius

$$\Lambda(q,P) = \frac{[\,2J_1(q_\perp R)/q_\perp R\,]^2}{1 + (q_0\tau)^2}\,, \qquad (2)$$

where

$$\vec{q}_\perp = \vec{q} - \vec{n}(\vec{q}\,\vec{n}), \qquad \vec{n} = \frac{\vec{P}_1 + \vec{P}_2}{|\vec{P}_1 + \vec{P}_2|}, \qquad q_0 = |\,E_1 - E_2|$$

$J_1(x)$ is the first order Bessel function. Because of possible methodical uncertainties and specific dynamic correlations it is useful to put parameter $\lambda$ before $\Delta$-function in formula (1)[9]. As statistics in bubble chamber experiments is insufficient, it is useful to study one-dimensional distributions $dN/dq_\perp^2$ or $dN/dq_0$ with different cut-offs on $q_0$ or $q_\perp^2$, except two-dimensional $dN/dq_\perp^2 dq_0$.

The ratios

$$R(q_\perp^2) = (dN/dq_\perp^2)\,/\,(dN^{backgr}/dq_\perp^2)\,|_{q_0 \leq const} \qquad (3)$$

and

$$T(q_0) = (dN/dq_0)\,/\,(dN^{backgr}/dq_0)\,|_{q_\perp^2 \leq const} \qquad (4)$$

can be approximated with functions:

$$R(q_\perp^2) = A[1 + \lambda(2J_1(q_\perp R)/q_\perp R)^2] \qquad (5)$$

$$T(q_0) = A[1 + \frac{\lambda}{1+(q_0 \tau)^2}] \qquad (6)$$

(A is a normalization factor).

## III. TIME-SPACE CHARACTERISTICS OF PION EMISSION VOLUME

In our investigation we studied the reactions

$$\pi^- p \to \pi_1^\mp \pi_2^\mp + x^{\pm\pm}$$

registered in 2 m JINR propane bubble chamber exposed to a 40 GeV/c $\pi^-$-beam at the Serpukhov accelerator. The experimental material contains about 12000 $\pi^- p$ interactions. The results obtained by approximating the experimental distributions (3) and (4) with functions (5) and (6) are presented in Tables 1-2 for $\pi^-\pi^-$ pairs, in Tables 3-4 for $\pi^+\pi^+$ pairs.

One can notice that the results obtained for negative pions differ from those obtained for positive ones. The radius of negative pion emission volume rapidly decreases for a $q_0$ cut-off equal to 0.2 GeV (see Fig.1 as well). The interference of positive pions gives only one size of p.e.v. $R \sim 1$ fm.

We conclude that it is necessary to introduce at least two types of negative pion sources, each with its own radius to describe our data. Lednitsky and Podgoretsky have shown [9] that assuming Gaussian-like space distribution of two type sources:

$$\rho(\vec r_1, \vec r_2) = \left[\frac{\mu_1 e^{-\vec r_1^{\,2}/2R_1^2}}{(2\pi R_1^2)^{3/2}} + \frac{\mu_2 e^{-\vec r_2^{\,2}/2R_2^2}}{(2\pi R_2^2)^{3/2}}\right]\left[\frac{\mu_1 e^{-\vec r_2^{\,2}/2R_1^2}}{(2\pi R_1^2)^{3/2}} + \frac{\mu_2 e^{-\vec r_1^{\,2}/2R_2^2}}{(2\pi R_2^2)^{3/2}}\right]. \qquad (7)$$



Table 1

Values of parameters of approximation of distribution (3) for $\pi^-\pi^-$ pairs with function (5)

| $q_0$ cut-off GeV | A | $\lambda$ | R fm | $\chi^2$/NDF |
|---|---|---|---|---|
| 0.050 | 0.89±0.02 | 0.85±0.16 | 3.3±0.4 | 50.8/36 |
| 0.100 | 0.92±0.02 | 0.69±0.12 | 3.4±0.4 | 60.3/36 |
| 0.150 | 0.94±0.02 | 0.49±0.08 | 3.1±0.4 | 53.5/36 |
| 0.200 | 0.88±0.02 | 0.32±0.04 | 1.6±0.3 | 64.2/36 |
| 0.250 | 0.90±0.02 | 0.32±0.05 | 1.7±0.3 | 65.4/36 |
| 0.300 | 0.88±0.03 | 0.31±0.05 | 1.5±0.3 | 61.5/36 |
| 0.350 | 0.89±0.04 | 0.30±0.05 | 1.4±0.3 | 67.6/36 |
| 0.400 | 0.89±0.03 | 0.27±0.04 | 1.4±0.3 | 64.4/36 |
| 0.450 | 0.92±0.02 | 0.25±0.03 | 1.7±0.3 | 63.7/36 |
| 0.500 | 0.95±0.01 | 0.30±0.04 | 1.9±0.3 | 64.7/36 |

Table 2

Values of parameters of approximation of distribution (4) for $\pi^-\pi^-$ pairs with function (6)

| $q_\perp^2$ cut-off (GeV/c)$^2$ | A | $\lambda$ | $c\tau$ fm | $\chi^2$/NDF |
|---|---|---|---|---|
| 0.010 | 0.86±0.04 | 0.76±0.16 | 3.9±1.2 | 14.5/16 |
| 0.020 | 0.87±0.03 | 0.50±0.09 | 2.4±0.8 | 7.6/16 |
| 0.030 | 0.94±0.02 | 0.44±0.08 | 3.3±1.0 | 9.3/16 |
| 0.040 | 0.88±0.03 | 0.37±0.06 | 1.8±0.7 | 10.0/16 |
| 0.050 | 0.86±0.04 | 0.37±0.06 | 1.5±0.8 | 8.3/16 |
| 0.060 | 0.84±0.05 | 0.37±0.06 | 1.1±0.4 | 8.4/16 |
| 0.070 | 0.84±0.05 | 0.36±0.07 | 1.0±0.3 | 7.5/16 |
| 0.080 | 0.82±0.05 | 0.37±0.08 | 0.9±0.2 | 8.6/16 |
| 0.090 | 0.81±0.05 | 0.40±0.08 | 0.9±0.3 | 13.6/16 |
| 0.100 | 0.83±0.05 | 0.36±0.07 | 1.0±0.3 | 12.0/16 |

Table 3

Values of parameters of approximation of distribution (3) for $\pi^+\pi^+$ pairs with function (5)

| $q_0$ cut-off GeV | A | $\lambda$ | R fm | $\chi^2$/NDF |
|---|---|---|---|---|
| 0.050 | 0.88±0.03 | 0.48±0.11 | 2.0±0.4 | 41.5/36 |
| 0.100 | 0.81±0.12 | 0.43±0.18 | 1.2±0.4 | 40.4/36 |
| 0.150 | 0.75±0.18 | 0.55±0.36 | 1.0±0.4 | 32.2/36 |
| 0.200 | 0.79±0.17 | 0.44±0.30 | 1.0±0.4 | 36.5/36 |
| 0.250 | 0.76±0.21 | 0.49±0.40 | 1.0±0.4 | 31.6/36 |
| 0.300 | 0.78±0.19 | 0.44±0.33 | 1.0±0.4 | 35.0/36 |
| 0.350 | 0.69±0.43 | 0.59±0.35 | 0.8±0.6 | 36.2/36 |
| 0.450 | 0.79±0.19 | 0.40±0.33 | 0.9±0.5 | 41.0/36 |
| 0.500 | 0.80±0.18 | 0.38±0.30 | 1.0±0.5 | 37.3/36 |

For $q_0$ cut-off equal to 0.4 GeV fit has not converged.

Table 4

Values of parameters of approximation of distribution (4) for $\pi^+\pi^+$ psirs with function (6)

| $q_\perp^2$ cut-off $(GeV/c)^2$ | A | $\lambda$ | $c\tau$ fm | $\chi^2$/NDF |
|---|---|---|---|---|
| 0.010 | 0.93±0.03 | 0.59±0.26 | 7.8±5.2 | 21.4/16 |
| 0.020 | 0.77±0.11 | 0.47±0.19 | 8.3±4.2 | 28.6/16 |
| 0.030 | 0.84±0.05 | 0.40±0.08 | 1.2±0.5 | 17.3/16 |
| 0.040 | 0.83±0.07 | 0.36±0.10 | 1.0±0.4 | 15.8/16 |
| 0.050 | 0.85±0.05 | 0.35±0.07 | 1.1±0.4 | 12.9/16 |
| 0.060 | 0.84±0.05 | 0.33±0.08 | 1.0±0.4 | 10.4/16 |
| 0.070 | 0.83±0.06 | 0.34±0.09 | 0.9±0.3 | 14.4/16 |
| 0.080 | 0.85±0.05 | 0.30±0.07 | 0.9±0.4 | 19.1/16 |
| 0.090 | 0.84±0.07 | 0.30±0.10 | 0.8±0.3 | 18.2/16 |
| 0.100 | 0.83±0.07 | 0.30±0.10 | 0.7±0.3 | 16.5/16 |



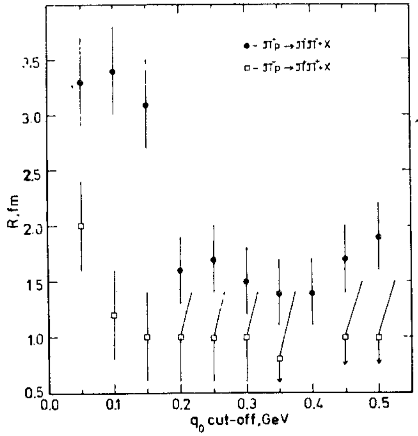


Fig.1. Values of radii of pion emission volume for $\pi^-$ and $\pi^+$ mesons for different $q_0$ cut-offs.

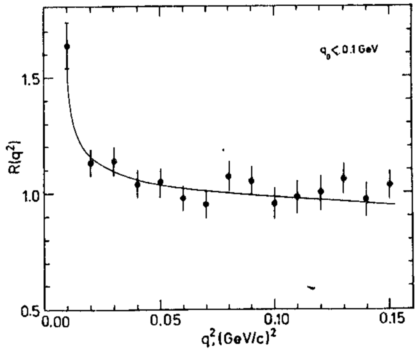


Fig.2. The $\vec{q}^{\,2}$ distribution for $\pi^-\pi^-$ pairs fitted with function (9) (straight line).

Table 5

Values of parameters of approximation of distribution (8) for $\pi^-\pi^-$ pairs with function (9)

| $q_0$ cut-off GeV | A | $\mu_1$ | $\mu_2$ | $R_1$ fm | $R_2$ fm | $\chi^2$/NDF |
|---|---|---|---|---|---|---|
| 0.100 | 0.89±0.03 | 0.57±0.09 | 0.8±0.3 | 1.1±0.5 | 5.5±2.0 | 30.2/35 |
| 0.200 | 0.90±0.03 | 0.58±0.06 | 1.0±0.6 | 1.1±0.3 | 6.9±2.8 | 31.1/35 |
| 0.300 | 0.91±0.02 | 0.61±0.05 | 1.3±0.8 | 1.2±0.2 | 8.0±3.6 | 33.0/35 |
| 0.400 | 0.92±0.02 | 0.63±0.06 | 1.6±0.6 | 1.2±0.2 | 8.7±9.6 | 29.8/35 |
| 0.500 | 0.92±0.02 | 0.63±0.05 | 1.6±0.9 | 1.2±0.2 | 8.7±9.3 | 32.1/35 |

the formula approximating the experimental distribution

$$R(\vec{q}^{\,2}) = (dN/d\vec{q}^{\,2}) \,/\, (dN^{backgr}/d\vec{q}^{\,2})\,|_{q_0 \le const} \qquad (8)$$

takes the form

$$R(\vec{q}^{\,2}) = A\,[\,1 + (\mu_1 e^{-R_1^2\vec{q}^{\,2}/2} + \mu_2 e^{-R_2^2\vec{q}^{\,2}/2})^2]. \qquad (9)$$

Here $\mu_1$ and $\mu_2$ are the "intensities" of the sources (see Fig.2 as well). The results obtained using function (9) are presented in Table 5. Note that for Gaussian distribution of sources, $R_{1,2}$ in formulae (7) and (9) have the sense of Gaussian $\sigma$, so one should use the mean square radius $<r_{1,2}^2>^{1/2} = \sqrt{3}R_{1,2}$ to compare results obtained by formula (9) with those presented in Tables 1 and 3.

We would like to pay attention to the fact that a similar analysis for life-time $\tau$ is impossible because of big errors connected with a bad experimental resolution in $q_0$ variable.

## IV. INFLUENCE OF RESONANCE PRODUCTION ON SIZE OF P.E.V.

The simplest explanation of the existence of two sizes of p.e.v. is to connect them with different pion production mechanism. One can say that a bigger radius is due to resonance production, while a smaller one can be connected with the direct emission of pions. As was shown/10/,at least 50% of all pions produced in $\pi^- p$ interactions at 40 GeV/c come from the decay of $\rho$, $\omega$ and f -mesons. The cross sections for the production of these resonances are $\sigma(\rho^\circ)$ = 8.1±0.7 mb, $\sigma(\omega)$ = 7.3±0.8 mb and $\sigma$(f) = 1.3±0.5 mb, respectively/10/*.

The influence of f -meson on like-pion interference is negligible because of small cross section for its production.

Our investigations have shown that the interference effect is observed in kinematical region $|Y_{CMS}^{\pi\pi pair}| \leq 1$. From data in paper/10/ one can deduce that the average pass-lengths of $\rho^\circ$ and $\omega$-mesons in this region are, respectively, ~3 fm and ~50 fm. The resolution in our experiment allows us to study the radii from ~1 fm to ~5 fm, so it is evident that we are able to observe only the influence of $\rho^\circ$ production. In order to study this, we have searched for the interference in the resonance region and outside it. As a pion from resonance region (i.e., from $\rho^\circ$ decay) we took $\pi^+$ (or $\pi^-$) which, with opposite charged another pion, had an invariant mass within an interval of 776±100 MeV ($M_\rho$ = 776 MeV, $\Gamma_\rho$ = 158 MeV). It has been found/10/ that about 55% of all $\rho^\circ$ lies in this interval, and the ratio of the resonance signal to the background is about 20%. The obtained results are presented in Tables 6-8. One can notice that negative pions in resonance region, unlike other ones, are emitted from larger distances. For positive pions the interference in resonance region is not observed, while outside it, it is present, and the obtained radius is about 1 fm. The reflection of this effect is visible in the pion pair rapidity distribution in the interference region. For

*In our experiment we are able to study only $\rho^\circ \to \pi^+\pi^-$ decay.



Table 6

Values of parameters of approximation of distribution (3) for $\pi^-\pi^-$ pairs in resonance region with function (5)

| $q_0$ cut-off GeV | A | $\lambda$ | R fm | $\chi^2$/NDF |
|---|---|---|---|---|
| 0.050 | 0.94±0.03 | 0.51±0.21 | 3.3±0.9 | 22.1/16 |
| 0.100 | 0.95±0.02 | 0.50±0.16 | 3.4±0.7 | 26.1/16 |
| 0.150 | 0.96±0.02 | 0.38±0.12 | 3.3±0.7 | 21.8/16 |
| 0.200 | 0.86±0.14 | 0.29±0.18 | 1.1±0.6 | 28.7/16 |
| 0.250 | 0.96±0.02 | 0.29±0.07 | 2.7±0.5 | 33.8/16 |
| 0.300 | 0.81±0.18 | 0.37±0.28 | 1.0±0.5 | 31.2/16 |
| 0.350 | 0.96±0.01 | 0.29±0.07 | 3.0±0.5 | 43.1/16 |
| 0.400 | 0.96±0.01 | 0.28±0.07 | 3.0±0.5 | 36.8/16 |
| 0.450 | 0.96±0.01 | 0.27±0.06 | 2.9±0.5 | 31.1/16 |
| 0.500 | 0.96±0.01 | 0.28±0.06 | 3.0±0.5 | 30.1/16 |

Table 7

Values of parameters of approximation of distribution (3) for $\pi^-\pi^-$ pairs outside resonance region with function (5)

| $q_0$ cut-off GeV | A | $\lambda$ | R fm | $\chi^2$/NDF |
|---|---|---|---|---|
| 0.050 | 0.67±0.06 | 1.42±0.23 | 1.9±0.3 | 26.1/16 |
| 0.100 | 0.82±0.03 | 1.23±0.23 | 2.9±0.3 | 34.1/16 |
| 0.150 | 0.84±0.03 | 0.78±0.14 | 2.3±0.3 | 25.5/16 |
| 0.200 | 0.85±0.03 | 0.64±0.11 | 2.2±0.3 | 24.6/16 |
| 0.250 | 0.85±0.03 | 0.60±0.10 | 2.0±0.3 | 29.5/16 |
| 0.300 | 0.87±0.03 | 0.54±0.09 | 2.1±0.3 | 27.9/16 |
| 0.350 | 0.86±0.03 | 0.54±0.09 | 2.0±0.3 | 29.7/16 |
| 0.400 | 0.88±0.03 | 0.50±0.08 | 2.1±0.3 | 29.1/16 |
| 0.450 | 0.88±0.03 | 0.49±0.08 | 2.1±0.3 | 30.7/16 |
| 0.500 | 0.89±0.03 | 0.51±0.09 | 2.3±0.3 | 30.7/16 |

Table 8

Values of parameters of approximation of distribution (3) for $\pi^+\pi^+$ pairs outside resonance region with function (5)

| $q_0$ cut-off GeV | A | $\lambda$ | R fm | $\chi^2$/NDF |
|---|---|---|---|---|
| 0.050 | 0.80±0.05 | 1.04±0.26 | 2.3±0.4 | 8.87/16 |
| 0.100 | 0.76±0.10 | 0.69±0.20 | 1.5±0.4 | 9.96/16 |
| 0.150 | 0.64±0.24 | 0.91±0.66 | 1.1±0.5 | 12.3/16 |
| 0.200 | 0.71±0.24 | 0.69±0.52 | 1.1±0.5 | 11.9/16 |

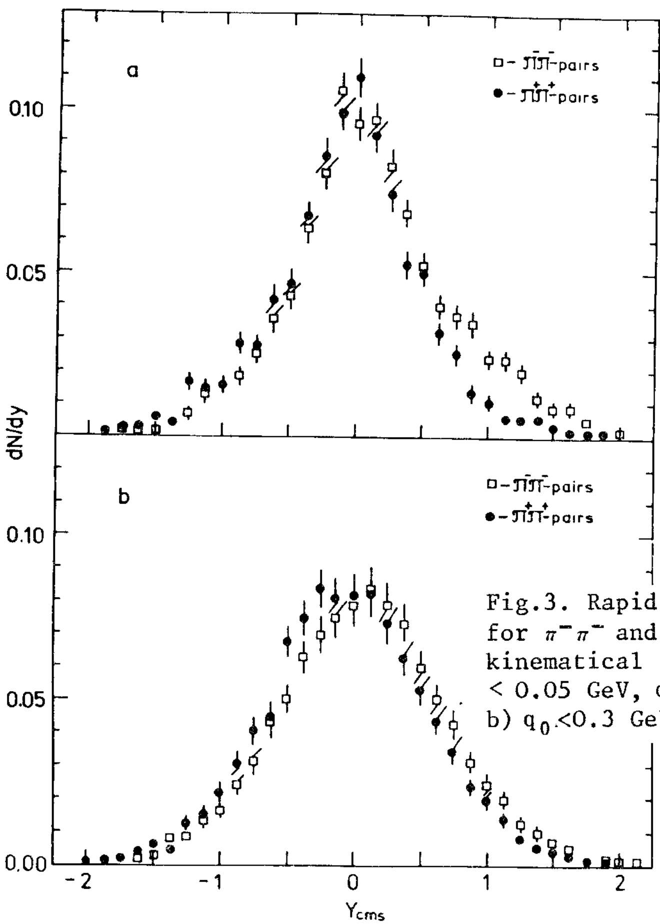


Fig.3. Rapidity distribution for $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs within kinematical limits: a) $q_0 <$ $< 0.05$ GeV, $q_\perp^2 < 0.2$ (GeV/c) ; b) $q_0 < 0.3$ GeV, $q_\perp^2 < 0.2$ (GeV/c).



Table 9

Values of radii of pion emission volume in central region

| $q_0$ cut-off, GeV | $R_{\pi^+\pi^+}$, fm | $R_{\pi^-\pi^-}$, fm |
|---|---|---|
| 0.100 | 1.49±0.65 | 1.32±0.63 |
| 0.200 | 1.13±0.87 | 1.08±0.74 |
| 0.300 | 1.10±0.66 | 1.08±0.78 |

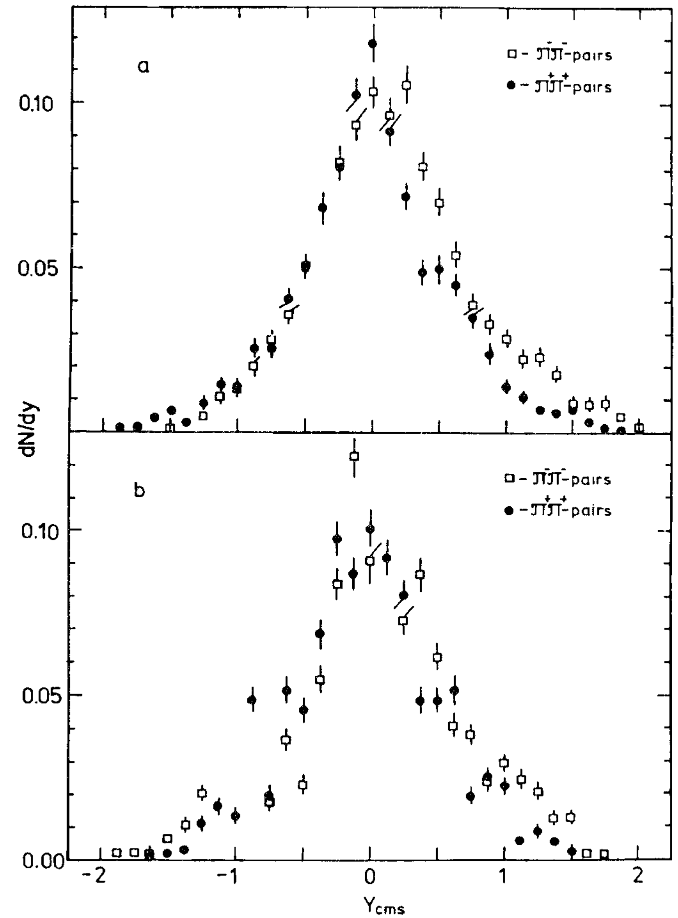


Fig.4. Rapidity distribution for $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs for $q_\perp^2 <$ $< 0.2$ (GeV/c)$^2$, $q_0 < 0.05$ GeV; a) in resonance region, b) outside resonance region.

"narrow" interference region ( $q_\perp^2<0.2$ $(GeV/c)^2$, $q_0<0.05$ GeV) the excess of fast $\pi^-\pi^-$ pairs is observed, while for "wider" one ( $q^2<0.2$ $(GeV/c)^2$, $q_0<0.3$ GeV) the rapidity distributions of $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs are similar (fig.3a,b). This excess of negative pion pairs is due to resonance production (fig.4a,b).

Our data show that the negative pions are emitted from large ($R\sim4-5$ fm) and small ($R\sim1$ fm) distances, while positive ones only from small ($R\sim1$ fm) distance. Probably it is due to the absence of positive pions and $\rho^+$ resonances in fragmentation region ($Y>0.5$). In the central region ($|Y|<0.5$), where the rapidity spectra of $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs are similar, see Fig.3a, the sizes of p.e.v. should be equal (Table 9). Such picture is consistent with predictions of an additive quark model.

## V. CONCLUSIONS

We have presented the results of studying the time-space characteristics of secondary pion emission volume in $\pi^-p$ interactions at 40 GeV/c. It has been shown that the sizes of p.e.v. obtained using the interference method are different for positive and negative pions. We connected this effect with resonance production and the different mechanisms of the emission of negative and positive pions in $\pi^-p$ interactions.

We have shown that it is necessary to introduce two radii of negative pion emission volume to describe the experimental data.


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Ахабабян Н. и др. E1-82-607

Интерференция вторичных пионов
и пространственно-временные характеристики
области их излучения в $\pi^-p$ -взаимодействиях при 40 ГэВ/с

Изучается интерференция положительных и отрицательных пионов, образованных в $\pi^-p$ -взаимодействиях при 40 ГэВ/с. Показано, что отрицательные пионы испускаются с больших расстояний, чем положительные. Наблюдается влияние рождения резонансов на размеры области излучения пионов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1982

Akhababian N. et al. E1-82-607

Interference of Secondary Pions
and Time-Space Characteristics
of Their Emission Volume in $\pi^-p$ Interactions at 40 GeV/c

The interference of positive and negative pions produced in $\pi^-p$ interactions at 40 GeV/c is studied. It is shown that negative pions are emitted from larger distance than positive ones. The influence of resonance state production on the size of pion emission volume is observed.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1982