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SIZE OF THE PROTON EMISSION REGION IN PION-XENON INTERACTIONS AT 3.5 GeV/c FROM TWO-PARTICLE CORRELATIONS

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1. INTRODUCTION

Knowledge of the space-time development of high-energy nuclear collisions is essential for understanding the mechanism of these processes. Many theoretical models, based on different assumptions, pretend to describe particle production in high-energy collisions. An extensive investigation of inclusive spectra of secondary particles has not led to any discrimination between models as most of them describe single-particle spectra fairly well, and obviously a more sophisticated approach should be used. An investigation of two-particle small-angle correlations allows one to obtain information on the space-time dimensions of the region of their emission, by analogy with the Hanbury-Brown and Twiss method of intensity interferometry of photons, used in astronomy to determine the size of stars [1]. The relevant theoretical approach for the case of correlations between identical bosons has been developed in refs.[2-4] and for identical fermions in refs.[5,6]. As it is believed that different particles are emitted at different stages of the interaction[7], then studying small-angle correlations of various types of secondary particles can provide information on the space-time development of the collision process.

Two-particle small-angle correlations were extensively studied in hadron-hadron, hadron-nucleus and nucleus-nucleus interactions. In hadron-hadron interactions only two-pion correlations were investigated, while in collisions involving nuclei also two-proton correlations were studied.

The aim of this paper is to determine the size of the proton emission region in pion-xenon interactions at 3.5 GeV/c from two-proton correlations*. Refs. [8-10] contain results of similar studies for other hadron-hadron reactions.

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*Preliminary results of this work were presented at the Second International Conference on Nucleus-Nucleus Collisions, Visby, Sweden, June 10-14, 1985, Abstract D.21.

2. EXPERIMENTAL DATA

Experimental data come from an exposure of 180-litre xenon bubble chamber to a beam of negative pions from the ITEP synchrotron in Moscow. The beam momentum was 3.5 GeV/c.

The dimensions of the chamber were $103\times44\times40$ cm^3, interactions of beam particles were recorded in a central region of $40\times10\times10$ cm^3 (the first dimensions are along the beam direction). The chamber had no magnetic field. Protons emitted from the interactions of beam particles with xenon nuclei ($Z = 54$, $\langle A\rangle = 131.3$) were identified as tracks which stop in the chamber liquid. Tracks with a minimum length of 5 mm were accepted, which corresponds to a 22 MeV kinetic energy for protons. The admixture of heavier nuclear fragments (d, t, ^3He, ^4He) should not exceed a few per cent as most of them produce shorter tracks, and that of negative pions should not exceed 2%. Protons with momenta between 200 and 600 MeV/c are recorded with full efficiency, while some of faster protons leave the chamber volume without stopping. Extrapolation of the proton spectrum indicates that the corresponding loss should not exceed 4% of all protons, and this should not cause any serious distortions of the distributions.

All proton tracks were measured on digitized microscopes, and their momenta were determined from range-energy relation with an accuracy of $\langle p/p\rangle = 3\%$; emission angles were measured with an accuracy of $\langle\Delta\theta\rangle = 2°$. Other particles emitted from the interaction vertex were also recorded - these were charged pions, gamma-quanta and neutral strange particles.

From the sample of 6301 inelastic interactions, 3879 events with two or more sencondary protons were selected for the present analysis. They contain altogether 17233 protons.

3. THEORETICAL FORMALISM AND DATA ANALYSIS

According to ref. /6/, the two-proton correlation function can be written in the form

$$R(q,p) = A_c(k^*)\,[1 + B_0(q,p;r_0,\tau) + B_i(q,p;r_0,\tau)]\ ,$$

where $q = P_1 - P_2$, $p = P_1 + P_2$, $k^* = 0.5\sqrt{-q^2}$, $P_{1,2}$ are the four-momenta of protons. The functions $B_0(q,p;r_0,\tau)$, $A_c(k^*)$ and $B_i(q,p;r_0,\tau)$ describe effects of quantum statistics, Coulomb and final-state strong interactions, respectively. The parameters r_0 and τ which characterize the space-time size of the proton emission region, were introduced assuming a Gaussian-type distribution of emitting sources. The r.m.s. radius is then by $\sqrt{3}$ larger than r_0 /11/.

In earlier papers /8-10/ the value of r_0 was determined from the correlation function plotted as a function of $\vec{q}$, $\vec{q}_T$ ($\vec{q}_T = \vec{q} - \vec{n}(\vec{n}\cdot\vec{q})$, $\vec{n} = \vec{p}/|\vec{p}|$), or $q_0 = |E_1 - E_2|$. Now we decided to use k^* which seems to be a more appropriate variable as, under our experimental conditions, the correlation function depends mainly on k^*. The correlation function R plotted as a function of k^*, similarly to the previous case, shows a maximum, the height of which is related to the radius of the proton emission region, r_0 (see Fig. 1). The curves were calculated according to the formulae of ref. /6/ assuming $\tau = 1$ fm, $\vec{v} = |\vec{p}|/(E_1+E_2) = 0.4$ and $q_0 = 0$. These values of the model parameters seem adequate to our data.

Experimental values of the correlation function were obtained as ratios $R(k^*) = D(k^*)/D_{bg}(k^*)$, where $D(k^*)$ is the number of proton pairs recorded in a given interval of the variable k^*, and $D_{bg}(k^*)$ is the corresponding number of pairs when no correlations are present. The "background" distribution $D_{bg}(k^*)$ was obtained by "mixing" protons from different events showing the same number of protons. For a realistic comparison with the theoretical correlation function, the latter was transformed to the form of a histogram in the same intervals as the experi-

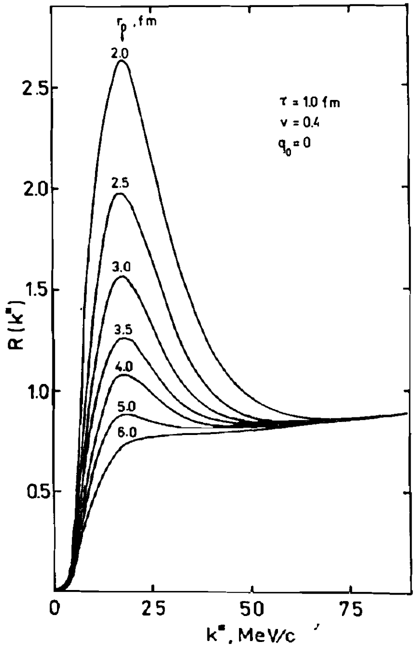


Fig. 1. Theoretical two-proton correlation function for different values of the radius of the proton emission region, r_0.

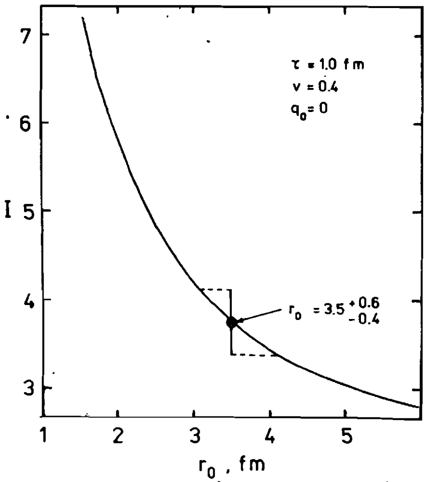


Fig. 2. Dependence of the "integrated correlation effect" on r_0.

mental distribution. When calculating the "average" values of the theoretical correlation function in the given interval of k^*, the experimental resolution and the nonuniform population of the experimental distribution across the interval (due to increasing D_{bg}) were taken into account. Details of this prosedure will be published elsewhere. The experimental distribution $R(k^*)$ was then normalised to the theoretical one for $100 < k^* < 240$ MeV/c, i.e., beyond the expected effect. In order to limit the influence of statistical fluctuations, the sum, I, of the values of the correlation function over the first four intervals of the histogram (i.e., for $0 < k^* < 60$ MeV/c) was taken as a measure of the correlation effect. Figure 2 shows the theoretical dependence of the value of I on the radius of the emission region, r_0, and the principle of determination of r_0 together with its error limits from the values of I.

4. RESULTS

Figure 3 shows the experimental correlation function for proton pairs with different momenta $p = \frac{1}{2}|\vec{p}_1 + \vec{p}_2|$. An interval of $0.2 < p < 0.7$ GeV/c (Fig. 3b) corresponds to the total sample, other distributions are for various momentum selections. Histograms represent theoretical distributions for the values of the radius of the emission region, r_0, determined as described above (see Fig. 2). These values are indicated in Fig. 3. It can be seen that with increasing momentum the correlation effect becomes stronger. This is shown quantitatively in Fig. 4a which gives the dependence of I, the sum of the values of the experimental correlation function over the first four intervals of k^* (i.e., for $0 < k^* < 60$ MeV/c), on the average momentum $\langle p \rangle$ of the proton pair. The values of I increase with increasing $\langle p \rangle$. This is in disagreement with the predictions of the intranuclear cascade model/12/ which are also shown in this figure. This version of the cascade model does not contain any dynamical correlations between secondary particles of the type discussed by us. In Figure 4b the values of I have been converted into the rms radii of the proton emission region, $\langle r^2 \rangle^{1/2} = \sqrt{3}\, r_0$. The radius of the proton emission region decreases with increasing the momentum of the proton pair, what has been already observed in refs. /8-10/ . The value of the rms radius of the xenon nucleus, $\langle r^2 \rangle^{1/2}_{Xe} = 4.87 \pm .03$ fm, obtained from the nuclear cross section data of ref./13/ is indicated in Fig. 4b for comparison with our results.

Figures 5a,b show the values of I and the corresponding rms radii of the proton emission region for events with different total numbers of secondary protons, N_p. It can be seen that in

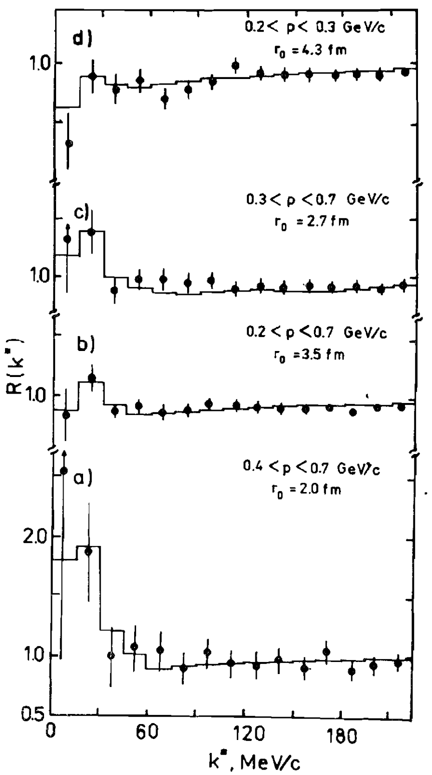


Fig. 3. Experimental two-proton k^* distribution for different intervals of proton momenta. Histigrams are theoretical expectations for the values of r_0 indicated in the figure.

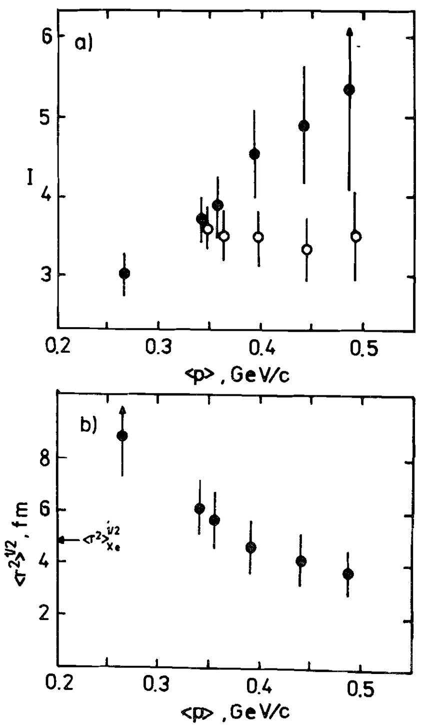


Fig. 4. "Integrated correlation effect" (a) and the corresponding rms radii of the proton emission region (b) for different momenta of the proton pair. Full points: experimental data; open points: calculation according to the cascade model.

events with a lower total number of protons (i.e. with smaller energy transfer to the nucleus), protons are emitted from larger distances. In Figure 6 two groups of events with $N_p \leq 5$ and $N_p > 5$ are studied separately. The radius of the proton emission region for the first group of events does not change with the momentum p of the proton pair, while the second group of events seem to be responsible for the entire momentum dependence of the size of the proton emission region.

The Table summarizes our results. The values of the "integrated correlation effect" I and the corresponding values of the rms of the proton emission region are given for different

Table

Selection criterion	I	$\langle r^2\rangle^{1/2}$, fm
p > 0.2 GeV/c (all events)	3.7 ± 0.3	$6.2\,^{+1.0}_{-0.7}$
p > 0.2 GeV/c N_π = 0, 1	3.9 ± 0.7	$5.7\,^{+1.8}_{-1.1}$
p < 0.3 GeV/c	3.0 ± 0.3	$8.8\,^{+5.0}_{-1.4}$
p ≥ 0.3 GeV/c	4.6 ± 0.6	$4.6\,^{+0.9}_{-0.7}$
p_T < 0.25 GeV/c	3.4 ± 0.4	$7.2\,^{+1.7}_{-1.2}$
p_T ≥ 0.25 GeV/c	4.4 ± 0.6	$4.8\,^{+1.1}_{-0.8}$
p ≥ 0.3 GeV/c $N_p \le 5$	2.9 ± 0.4	$9.7\,^{+5.0}_{-2.3}$
p ≥ 0.3 GeV/c $N_p > 5$	5.0 ± 0.7	$4.2\,^{+0.8}_{-0.7}$

$\langle r^2\rangle^{1/2}_{Xe} = 4.87 \pm 0.03$ fm

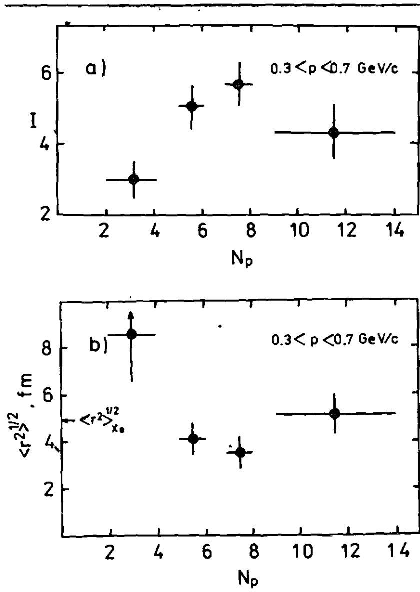
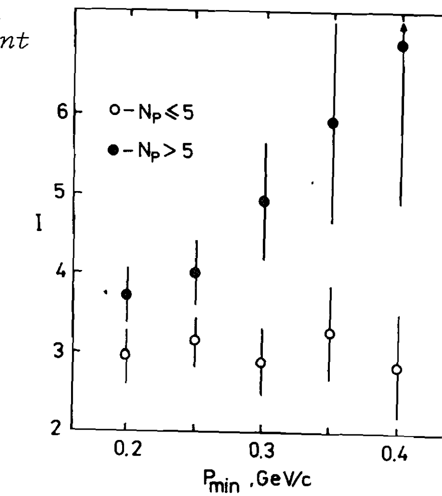


Fig. 5. "Integrated correlation effect" (a) and the corresponding rms radii of the proton emission region (b) for different proton multiplicities, N_p.

Fig. 6. "Integrated correlation effect" for events with different total multiplicity of protons, N_p, *as a function of the lower momentum cut,* p_{min}.



selection criteria. For the total sample (the first raw) our result is $\langle r^2\rangle^{1/2} = 6.2\,^{+1.0}_{-0.7}$ fm. The selection of events with no pion production (the second raw) does not change this value within error limits. The selection of proton pairs with small transverse momentum yields radii larger than the radius of the xenon nucleus, while proton pairs with larger p or p_T seem to be emitted from the region compatible in size with that of the xenon nucleus. Finally, protons in events with low total proton multiplicity seem to be emitted from larger distances.

5. CONCLUSIONS

Correlations between secondary protons with small relative momentum have been studied in pion-xenon interactions at a 3.5 GeV/c incident momentum with the aim to find the size of the proton emission region. The method for a realistic comparison of experimental two-particle distribution with the theoretical correlation function has been developed which takes into account various uncertainties in the experimental data. The rms radius of the proton emission region has been determined for different selections of events and different momenta of proton pairs. It has been found compatible with rms radius of the xenon nucleus for not very small momenta (or transverse momenta) of proton pairs, while for small momenta ($p \lesssim 300$ MeV/c or $p_T \lesssim 250$ MeV/c) the size of the emission region seems to be larger than that of the nucleus. A similar effect is observed when interactions with a small number of secondary protons are selected which means lower excitation energy transferred to the nucleus. A possible explanation of this might be the influence of the Δ(1232) and/or other nucleon isobars which should be copiously produced in interactions with the nucleus at these, relatively low, energies. One cannot, however, exclude other reasons related to the used theoretical approach which assumes uncorrelated emission by point-like, uniformly distributed sources. Nonfulfillment of these conditions, the emission time much larger than that assumed, a dynamical expansion of the emission region, its non-spherical shape, or intermediate clusters might modify the observed distributions. In particular, for an expanding fireball it has been shown that particles with lower momenta should yield larger radii [14]. In a model with intermediate clusters a similar effect might be expected [15].

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Размеры области испускания протонов во взаимодействиях π-Хе при 3,5 ГэВ/с, полученные методом двухчастичных корреляций

Проведен анализ корреляции вторичных протонов, испускаемых с малыми относительными импульсами во взаимодействиях π^--Хе при 3,5 ГэВ/с, с целью определения радиуса области испускания протонов. Из полного числа 6301 неупругих взаимодействий отобрано 3869 событий с числом протонов $N_p \geq 2$. Разработан метод реалистического сравнения двухчастичных распределений с теоретической корреляционной функцией, учитывающей конкретные условия эксперимента. Определены радиусы области испускания протонов в разных классах событий и для разных импульсов протонов. Получено согласие со среднеквадратичным радиусом ядра ксенона для быстрых протонов / $p \geq 0,3$ ГэВ/с/. Для медленных протонов / $0,2 \leq p < 0,3$ / ГэВ/с область испускания представляется больше размеров ядра.

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Size of the Proton Emission Region in Pion-Xenon Interactions at 3.5 GeV/c from Two-Particle Correlations

Correlations between secondary protons with small relative momenta have been studied in interactions of 3.5 GeV/c negative pions with xenon nuclei with the aim to find the radius of the proton emission region. From the total sample of 6301 inelastic interactions, 3879 events with two or more secondary protons were selected. The method for a realistic comparison of experimental two-particle distributions with the theoretical correlation function has been developed which takes into account various uncertainties in the experimental data. The rms radius of the proton emission region has been determined for different selections of events and different momenta of proton pairs. It has been found compatible with the rms radius of the xenon nucleus for fast protons / $p \geq 0.3$ GeV/c/. For slow protons / $0.2 \leq p < 0.3$ GeV/c/ the size of the emission region seems to be larger than that of the nucleus.

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

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