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Proton-proton correlations in dp and ^{16}Op interactions

Research Article

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Abstract: Correlations between two protons emitted in dp and ^{16}Op collisions at momenta 3.3 GeV/c and 52.6 GeV/c, respectively, are presented. The experimental data have been obtained using the one metre hydrogen bubble chamber exposed to nuclear beams from the synchrophasotron, JINR, Dubna. Data show a clear interference effect as expected for identical fermions. A Gaussian parametrization is used to determine the size of the proton emission source. The root mean square radius of the proton source calculated from the correlation function has been found to be equal to $(2.10^{+0.43}_{-0.35})$ fm and $(2.67^{+0.54}_{-0.38})$ fm for d and ^{16}O respectively. It agrees with the known radii of these nuclei.

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Keywords: two-proton correlation • deuteron-proton collision • oxygen-proton collision • emission zone • proton source radius • root mean square radius

1. Introduction

Correlation studies of two identical particles at small relative momenta became an effective tool how to get information about the space-time characteristics of the emitting source. A central role in this study plays the correlation function which is defined as a ratio of the measured two-particle distribution divided by the reference spectrum obtained from the former ones by mixing particles from different events. The correlation between nucleons has been examined for various beam and target combinations and at different incident momenta [1]. For nucleon-nucleon pairs at small relative velocities one has to take into account the symmetry properties of the wave function, strong final state interaction and Coulomb repulsion in the case of two protons. Positive correlation may be caused by attractive S-wave interactions while the spatial antisymmetry of the proton-proton spin triplet state leads to anticorrelation.

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The Coulomb repulsion of two protons reduces the correlation at small relative momenta. The interplay between these effects leads to a characteristic shape of the correlation function. The final correlation picture also involves the space-time properties of the radiation source. Theoretical calculations of two nonrelativistic proton correlation functions, depending on the space-time parameters r_0 and t_0 of the particle emission region have been obtained numerically solving the Schrödinger equation [2] and later as an analytic expression [3]. In order to extract the spatial extent of the emitting system, we use the final state interaction model developed by [3].

In a previous paper of ours [4] proton-proton and deuteron-deuteron correlations have been investigated in ^{3}Hep and ^{4}Hep collisions. For the protons strong positive correlation has been found related mainly to the $^1S_0$ final state interaction. The proton source root mean square radii determined from the correlation functions agree with those of the studied nuclei. Similar results have been reported for the pp [5] and pn [6] systems in ^{4}Hep interaction at 5 GeV/c of the ^{4}He beam momenta. In the present paper proton-proton correlations from deuterium-proton and ^{16}O-proton collisions will be examined. The deuteron-proton collision predominantly proceeds via quasi nucleon-nucleon interaction with one participant nucleon from the deuteron, while the other is a passive spectator. This simple picture may be destroyed by the presence of more complicated reaction mechanisms [7]. So, it seems to us interesting to verify how the method of the determination of the interaction radii based on the intensity interferometry is sensitive in this case, when also the combinatorial background is minimal. One can also naively expect that the particles are emitted almost simultaneously. Our experimental data have been obtained in a full solid angle geometry with beams of light nuclei d, ^{3}He, ^{4}He and ^{16}O. The aim of the present paper is, thus to complete the obtained results on proton-proton correlations from He-p interactions with the first results from d-p and ^{16}O-p interactions.

2. Experiment

The experimental data have been taken by the 1 metre JINR hydrogen bubble chamber, irradiated in the beams of deuterium and ^{16}O nuclei at momenta 3.3 GeV/c and 52.6 GeV/c, respectively. The use of a nuclear beam impinging on a proton target makes all the fragments of the incoming nuclei fast in the laboratory frame what enables them to be detected, well measured and identified practically without losses. On the other hand almost all the losses due to the chamber threshold momenta are concentrated in the elastic channel. The description of the experimental set-up can be found in [8]. In the case of dp interactions the geometrical reconstruction and kinematical analysis have been carried out by using the CERN program package based on HYDRA library [9]. Reactions containing not more than one neutral particle can be studied in an exclusive approach. From the complete data summary tape containing 237 413 events of dp interaction a sample of 102 778 events fitting the dp → ppn reaction has been collected. These events can be divided into two channels:

- the charge retention channel - proton is the fastest secondary particle with respect to the deuteron rest frame (85 254 events)
- the charge exchange channel - neutron is the fastest secondary particle with respect to the deuteron rest frame (17 524 events).

The two protons in the latter case have small relative momenta as the fastest particle is the neutron, that is why correlation between them can be expected and this part will be subject to further analysis. Protons momentum distribution in the laboratory frame for the reaction dp → (pp)n is shown in Fig. 1. In the case of ^{16}Op interaction the experimental procedure is described in [10–14]. The data summary tape contains 11 019 events. Identified protons can be divided into two categories: protons unambiguously identified by ionization, with momenta less than 1 GeV/c in the laboratory frame. They are mainly recoiled target protons. Protons identified as fragments with charge $Z = 1$ are expected to have momenta in the range (1.75 — 4.75) GeV/c in the laboratory frame and the correlation only between these fragments will be examined, i.e. 16 873 proton pairs.

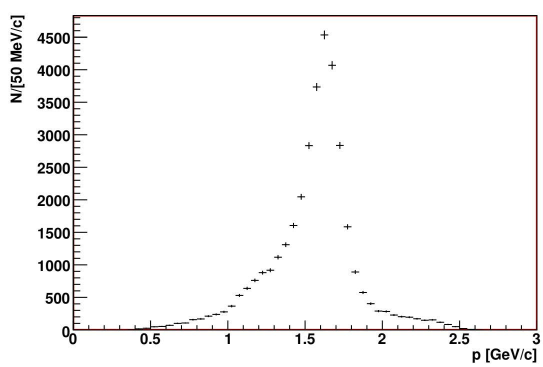

Figure 1. Protons momentum distribution from charge exchange dp → (pp)n reaction at 3.3 GeV/c deuteron beam momentum.

Table 1. Proton multiplicity in ^{16}O-p interactions

N_p	1	2	3	4	5	6	7-9
N_e	2866	2136	1303	691	322	140	59

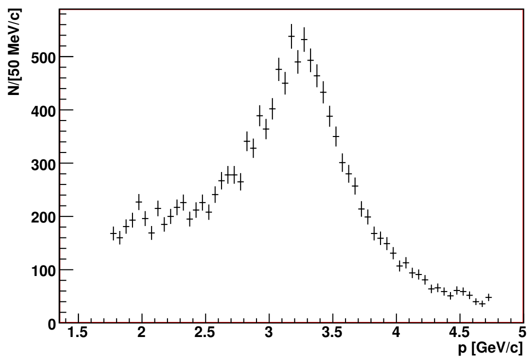

Figure 2. Fragment proton momentum distribution in ^{16}Op interactions at 52.6 GeV/c ^{16}O beam momentum.

The numbers of events (N_e) with various number of protons (N_p) are listed in Table 1. Momentum distribution of these protons in the laboratory frame is presented in Fig. 2. The average relative error of the proton momenta does not exceed 3.4% for tracks with length $L > 35$ cm. In this case with additional momentum cuts also fragments with $Z \leq 4$ can be well separated by mass number [10–14].

3. Results and discussion

The correlation function $R(\vec{p}_1, \vec{p}_2)$ of two protons is defined [1–3]:

$$R(\vec{p}_1, \vec{p}_2) = \frac{\frac{d^2\sigma}{d\vec{p}_1 d\vec{p}_2}}{\frac{d\sigma}{d\vec{p}_1}\frac{d\sigma}{d\vec{p}_2}}, \quad (1)$$

where $\frac{d\sigma}{d\vec{p}_1}$, $\frac{d\sigma}{d\vec{p}_2}$ are inclusive single differential cross sections and $\frac{d^2\sigma}{d\vec{p}_1 d\vec{p}_2}$ is the two-particle differential cross section of the studied particles.The denominator has been obtained by event mixing technique from different events of the same class, e.g. with the same number of protons. The correlation function $R(\vec{p}_1, \vec{p}_2)$ was plotted as a function of the four-momentum difference squared k of the two protons:

$$k = \frac{\sqrt{(\vec{p}_1 - \vec{p}_2)^2 - (E_1 - E_2)^2}}{2}. \quad (2)$$

The theoretical correlation functions have been calculated according to the model [3], where independent emission of protons from a Gaussian shaped source is assumed. The protons final state interaction includes Coulomb force as well as short-range S-wave nuclear one. The space-time distribution of the protons has been generated from two spherically symmetric Gauss shaped independent sources – expressions (15) and (16) in [3]. For this case the correlation function R depends on three free parameters: the source radius r_0, lifetime t_0 and velocity v, i.e. the proton pair velocity w.r.t. source frame.

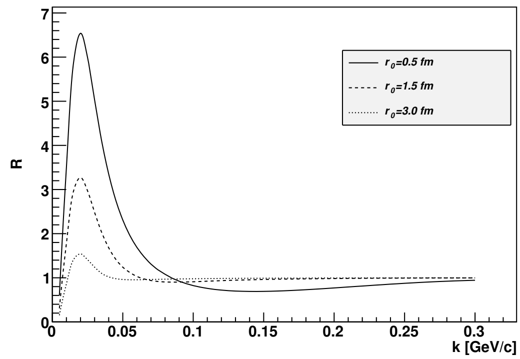

Figure 3. The pp correlation function for different values of r_0.

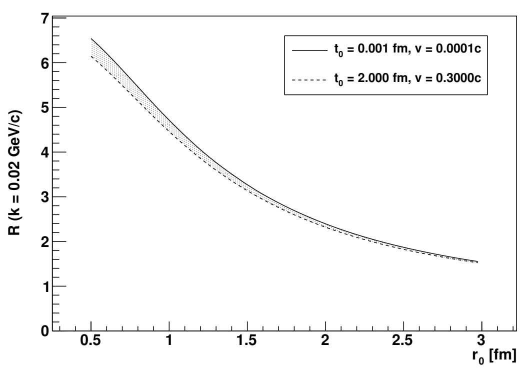

Figure 4. The pp correlation function value at k = 20 MeV/c dependence on r_0 for different lifetime t_0 and velocity v of the emitting source.

Figure 3 shows the two-proton correlation function for different values of the source radius r_0 and fixed source lifetime $t_0 = 0.01$ fm and pair velocity $v = 0.001$c. For the chosen set of parameters the correlation function reaches maximum around $k = 20$ MeV/c. As one can see in Fig. 3

with increasing size of the source the maximal value is decreasing and the correlation function becomes narrower.
Figure 4 displays the dependence of the maximum value of the correlation function $R(k{=}20$ MeV/c) on the source radius r_0 for different values of t_0 and v. As it can be seen for $t_0 \in (0.001,\ 2.0)$ fm and $v \in (0.0001c, 0.3c)$ the $R(k{=}20$ MeV/c) dependences on r_0 are similar. And for the region of interest r_0 $(1.2 < r_0 < 1.6$ fm) the dependences are week. The maximum of the correlation function for $r_0 = 1.2$ fm and $r_0 = 1.6$ fm decreases by about 5% and 4%, respectively when the model parameters change from $t_0 = 0.001$ fm and $v = 0.0001c$ to $t_0 = 2.0$ fm and $v = 0.3c$. These results will be used to evaluate the systematic errors.
Since in different experiments, various spatial distributions of the emission sources are used, the obtained values of the "radius" cannot always be directly compared. To accomplish this the radii are converted to the root mean square values. The root mean square radius of the generation region for the Gaussian distribution is $\sqrt{3}$ times larger than r_0 parameter.

3.1. Two-proton correlations in the ^{16}Op $\rightarrow$ pp + X reaction at 52.6 GeV/c

The correlation function for two fragment protons from ^{16}Op interactions is depicted in Fig. 5. Full dots stand for experimental quantities, the bars include only statistical errors, the curves will be explained later. The enhancement is clear in the low relative momentum region while for $k > 0.15$ GeV/c the distribution is consistent with unity.

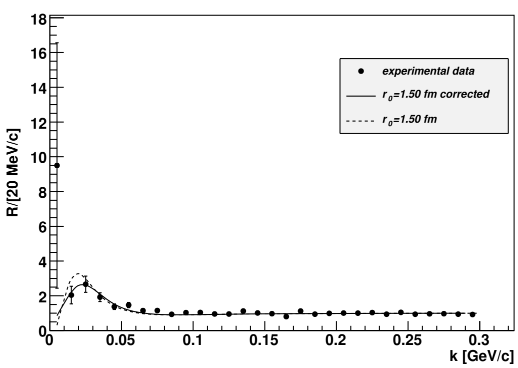

Figure 5. Two-proton correlation function for ^{16}Op reaction, full dots represent experimental values, curves are model calculations [3] - dashed line; model results smeared with experimental resolution - solid line.

The background distribution has been created by mixing protons randomly chosen from different events with the same number of protons and was normalized to the experimental one in the interval of $k \in (200, 300$ MeV/c). The number of background proton pairs is the same as that of experimental ones. Only events with the same number of protons (the same topology) were mixed. To produce one background event with N_p protons, N_e events $(N_e = N_p)$ are selected randomly, where N_p is the number of protons. The protons in each of the selected events have been sorted in descending order of their momenta. From each selected event only one proton entered the final background event according to the following key: the fastest proton of the firstly selected event becomes the fastest one of the background event and so on till the slowest proton of the lastly selected event becomes the slowest proton of the background event.
A clear correlation maximum is observed in the region of small relative momenta around $k = 20$ MeV/c. The hight of the peak of the correlation function can be related to the space-time parameters of the emmiting source. To determine the space size of the two-proton emission region the experimental data have been compared to model curves (dashed line in Fig. 5) and smeared with the experimental resolution (solid line in Fig. 5) [3], curves are plotted for $r_0 = 1.5$ fm. The resolution function of the variable k has been parametrized as a linear function. Its coefficients have been determined by fitting the experimental errors $\sigma(k)$ versus k dependence. The linear parametrization for $k \in (0, 0.3)$ GeV/c gives the following form:

$$\sigma(k) = 0.008 + 0.010k. \tag{3}$$

Then the resolution corrected model values $R'(k)$ can be obtained as follows:

$$R'(k) = \frac{1}{\sqrt{2\pi}} \int \frac{R(k')}{\sigma(k')} \exp\left(-\frac{(k-k')^2}{2\sigma^2(k')}\right) dk'. \tag{4}$$

This expression is fitted to the experimental correlation function and the best agreement between the values, predicted by [3] and the data is obtained for $r_0 = (1.54^{+0.31}_{-0.22})$ fm $(\chi^2/ndf = 0.93)$. The first interval in $k \in (0, 0.01)$ has not been included into the fit procedure. Converting the obtained value of r_0 to root mean square radius one obtains $(2.67^{+0.54}_{-0.38})$ fm. The quoted errors are only statistical, the estimated systematical errors are +1% and −4%. The obtained values agree within errors with the known root mean square radii of oxygen which is (2.7 ± 0.01) fm [15] (see Tab. 2).
One of the challenges in the correlation studies is to understand and estimate the contributions from global conservation laws, resonance decays or by other unexpected

sources. In [5] it was shown that the kinematical background contribution in the case of ^{4}Hep interaction at ^{4}He momenta 5 GeV/c is negligible.

3.2. Two-proton correlations in the dp → pp + X reaction at 3.3 GeV/c

The correlation function for this reaction was defined similary as for the previous reaction. In Fig. 6 the pp correlation function for two protons from charge-exchange dp → (pp)n reaction can be seen. The space size of the two-proton emission zone has been extracted from the comparison of the experimental data (full dots) to the model curve smeared with the experimental resolution (solid line in Fig. 6) [3], curves are plotted for $r_0 = 1.2$ fm.

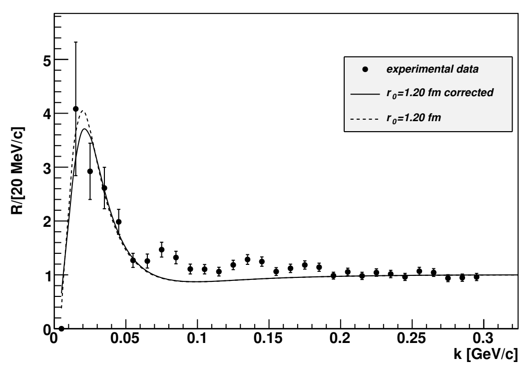

Figure 6. Two-proton correlation function for dp → (pp)n charge exchange reaction, full dots represent experimental values, curves are model calculations [3] - dashed line; model results smeared with experimental resolution - solid line.

The background distribution has been obtained by combining protons from different events of charge-exchange reaction. The number of background proton pairs is the same as that of the experimental ones. The correction for experimental resolution is made in the same way as in the case of ^{16}Op collisions but now with a second order polynomial:

$$\sigma(k) = 0.0049 - 0.024k + 0.08k^2. \quad (5)$$

This parametrization is connected with the fact that the ^{16}Op exposition have been processed with a shifted fiducial volume towards the beginning of the chamber, so greater track lengths became available for the momentum reconstruction than in the case of the dp expositions. This led to different distributions of the measured momentum errors.

The best agreement between the data and the theoretical prediction [3] was achieved for $r_0 = (1.21^{+0.25}_{-0.20})$ fm ($\chi^2/ndf = 0.61$) what leads to a value of $(2.10^{+0.43}_{-0.35})$ fm for root mean square radius of the emission source. The systematical errors for r_0 are estimated $+1\%$ and -7%. Our result within the errors agree with the known root mean square radii of deuteron which is (2.13 ± 0.01) fm [15] (see Tab. 2).
The Tab. 2 [15] summarizes the root mean square radii of the proton-proton and proton-neutron emission regions in the light nuclei interaction with proton (d, ^{3}He, ^{4}He, ^{16}O) at the $(1.25 - 4.4)$ AGeV/c momenta obtained by the correlation method. It includes our previously published results [4], pn and pp emission radii [5, 6] and present results. For comparison data from "Table of Nuclear root mean square charge radii" [15] are also shown for the studied nuclei. We can see that the proton source root mean square radii determined from the correlation functions agree with those of the studied nuclei and no unexpected sources have been obtained at this energies.

4. Conclusion

First results on two protons correlation functions for dp and ^{16}Op reactions have been presented together with the theoretical predictions. Good agreement has been obtained with theoretical calculations based on assumption of independent emission of protons. Final state interaction in $^1S_0$ state, Coulomb interaction and antisymmetry of the two proton wave function have been taken into account. The dimension of the emission region r_0 is a free parameter in this theory. The best value of the r_0 parameter, that characterises the spatial dimension of the Gaussian source is about $(1.54^{+0.31}_{-0.22})$ fm and $(1.21^{+0.25}_{-0.20})$ fm for oxygen and deuteron, respectively. The root mean square radii, which can be compared with other results, have been calculated. From this comparison it can be seen that present results are close to values of nuclear radii. Our data show that the size of the interaction region is determined by the magnitude of projectile nucleus.

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We would like to thank Dr. R. Lednicky for discussion, helpful suggestions and for making available the computer code to evaluate the theoretical correlation functions.

Table 2. Root mean square radius of the proton-proton and neutron-proton emission on light nuclei.

Reactions	rms [fm]	p [GeV/c]	Ref.	rms [fm] [15]
^{4}Hep → pp + X	$1.7^{+0.3}$	8.6	[4]	1.67 ± 0.0026
^{3}Hep → pp + X	$2.6^{+0.3}$	13.6, 13.5	[4]	1.94 ± 0.0300
^{4}Hep → pp + X	$1.6^{+0.3}$	5.0	[5]	1.67 ± 0.0026
^{4}Hep → pn + X	$2.1^{+0.3}$	5.0	[6]	1.67 ± 0.0026
dp → pp + n	$2.10^{+0.43}_{-0.35}$	3.3	this work	2.13 ± 0.0120
^{16}Op → pp + X	$2.67^{+0.54}_{-0.38}$	52.6	this work	2.70 ± 0.0084

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