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J.Pluta

SPACE-TIME CHARACTERISTICS OF SECONDARY PROTON SOURCES IN RELATIVISTIC NUCLEAR COLLISIONS FROM TWO-PARTICLE CORRELATIONS*

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INTRODUCTION

Investigation of two-particle correlations at small relative momenta gives one the possibility of obtaining information on the space-time characteristics of the particle emission process. In the case of protons the correlations arise mainly due to the final state interaction, Coulomb repulsion and quantum statistical effects[1–3]. The resulting correlations appear in the form of a broad peak approaching maximum for about 20 MeV/c if the correlation function is plotted versus half difference of the proton momenta. A stronger effect corresponds to smaller space-time parameters of emitting sources.

The first experimental evidence of two-proton correlations at small relative momenta was found by Siemiarczuk and Zielinski more than twenty years ago[4]. Distinct enhancement at the lower end of the two-proton effective mass distribution has been observed by the authors when comparing it with the background distribution. This effect was confirmed later[5]. At present, intensive investigations are being carried on and a large amount of data has been collected[6–23].

The two-particle correlations and space-time characterictics of particle emission process were investigated during many years at JINR, Dubna. The theoretical approach was developed by Kopylov and Podgoretsky for bosons[2], and by Lednicky and Lyuboshitz for fermions[3]. Experimental investigations were performed using two bubble chambers: the 2-meter propane chamber with tantalum plates in it[6–9], and the 180-litre xenon chamber[10]. Some recent results will be discussed in this paper.

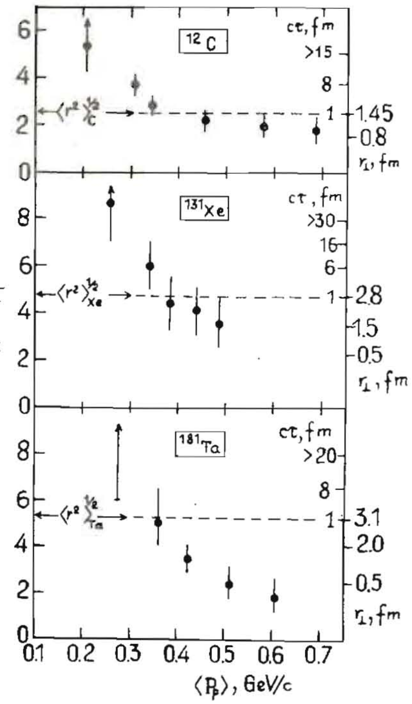
PAIR MOMENTUM DEPENDENCE OF TWO PROTON CORRELATIONS

Experimental investigations of the two-proton correlations have revealed some interesting regularities. One of the widely discussed effects is the dependence of the measured size of proton emission volume on the momenta of emitted protons. Generally speaking, faster protons appear to be emitted from smaller sources[6–17]. This effect was first observed at Dubna in 1980[6]. As different measurents were performed under different experimental conditions, it is difficult to find a simple rule for all the obtained results. We have investigated this dependence for various reactions and in the secondary proton momentum region from 150 MeV/c up to 1 GeV/c /8-10/. The results of these measurements will be discussed below after presenting them in the unified form as a dependence of the RMS radius of the proton emission volume on the mean proton momenta:

$$< r^2 >^{1/2} = f(< p_p >),$$

where: $p_p = (|\vec{p}_1 + \vec{p}_2|)/2$; $\vec{p}_1, \vec{p}_2$ are the momenta of correlated protons. Fig. 1 shows this dependence for three different reactions. A similar behaviour is seen for each set of data.

In the momentum range (0.3-0.4) GeV/c the size of the proton emission volume appears to be close to that of the target nucleus in all considered reactions. For lower proton momenta the RMS radii are systematically larger; for higher momenta smaller radii have been obtained. These effects were suggested to occur due to increasing lifetime of the sources (in the case of smallest nucleon momenta) /16, 24/, or due to non-spherical shape of the proton emission volume (for higher momenta of emitted protons) /17, 18/. The questions: whether it is possible to explain similarly the correlations observed in Fig. 1 and how strong the influence of these effects on the two-proton correlations function is, will be discussed below.



Let us consider the scales in Fig. 1. The scale on the left-hand side shows the RMS radii of the proton emission volumes extracted from the data. In order to determine these values, the experimental correlation functions have been compared with the theoretical ones containing the radius r_0 of the emission volume and the lifetime τ_0 of the sources as free parameters /3, 27/. In the theoretical description the emission points were assumed to be independent and distributed in the space and time according to the four-dimensional Gaussian law. The RMS radius is then equal to $\sqrt{3}\,r_0$. The theoretical correlation functions were computer assuming $r_0 = 1$ fm. The correlation functions were plotted againts k* variable, where k* is the half difference of the proton momenta in the rest frame of the pair. The details of our experimental procedure are given in Refs. /8-10/.

Fig. 1. Space-time parameters of the proton emission volume for different mean values of the proton momenta. The reactions for target indicated are: C − (p, d, α, C)-C, 4.2 GeV/c per nucleon /8/, [Xe] −π^-− Xe, 3.5 GeV/c /10/, [Ta] − p-Ta, 10 GeV/c /9/.

Let us assume now that the changes of the two-proton correlations, giving growth to the proton emission volume above the RMS radius of the target nucleus, are due to the increase of the emission time intervals, without changing the size of the emission volume. The changes in the opposite directions are supposed to be caused by decreasing the perpendicular source size with respect to the incoming particle direction, without changing the longitudinal one. The following figures illustrate the influence of these effects on the height of correlation maximum for the nuclei discussed here.

Figure 2 shows the time dependence of the height of the two-proton correlation function (k* = 20 MeV/c) for different space sizes of the emitting sources. The chosen values of r_0 and v correspond to our experimental conditions: r_0 values are simply $\sqrt{3}$ times less than the RMS radii of given target nuclei and v corresponds roughly to the mean velocity of registered protons. Considerable changes of the correlation function are seen, up to ct values of several tens of fm.

A similar type of dependence presents Fig. 3 where the height of the two-proton correlation function is plotted versus the values of the transver-

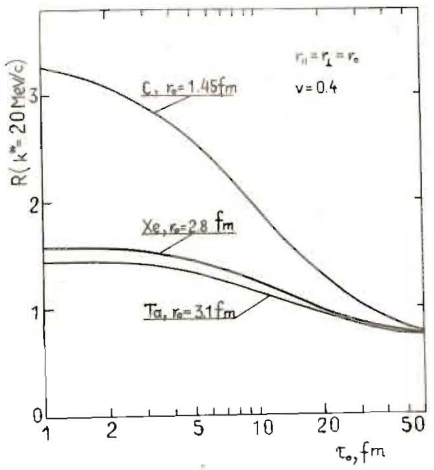


Fig. 2. Time dependence of the height of the two-proton correlation function for different source sizes of the emission volumes.

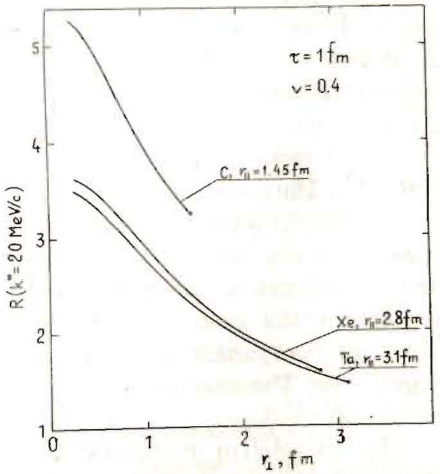


Fig. 3. Perpendicular size dependence of the height of the two-proton correlation function for different longitudinal sizes r of the emission volume.

sal size $r_\perp$ of the proton sources. All the curves are drawn up to the values corresponding to spherical shapes of emitting volumes. For heavy nuclei the correlation effect changes considerably and for perpendicular dimensions less than 1 fm the maximum of the correlation function is more than two times higher than in the case of spherical shapes of the emitting volumes.

Let us return now to the scales in Fig. 1. The right hand side scales (non linear) indicate the values of time intervals and perpendicular dimensions which should be used to obtain the correlation effect corresponding to the RMS radius on the left-hand side scale. The obtained values are in agreement with the experimental results in Refs. /16–18/. They correspond to the results of theoretical computations performed in Ref. /24/ as well.

COMPARISON WITH OTHER DATA

The dependences presented separately for different targets in Fig.1 can be simply compared by changing the RMS radius of the proton emission volume with the ratio:

$$r_{rel} = \langle r^2 \rangle^{1/2} / \langle r^2 \rangle^{1/2}_T ,$$

where $\langle r^2 \rangle^{1/2}_T$ is the RMS radius of the target nucleus. Fig. 4 combines in this way three parts of Fig. 1.

It is interesting to compare these results with the others obtained elsewhere. There are a few works where two-proton correlations were investigated in a relatively narrow momentum or energy intervals /13–15, 18/. The corresponding results are shown in Fig. 4, as well. All the quoted data are converted to the RMS radii, if necessary, prior to present them in Fig. 4 /25/. The RMS radii of the nuclei were obtained from the experimental data of Ref. /26/. Thus, some common features can be seen.

1. The observed momentum dependence divides emitted protons into three different classes corresponding to different space dimensions of the emitting suorces, as compared to the dimensions of the target nuclei.

2. For the mean proton momenta about 0.4 GeV/c, the source dimensions are comparable to those of the target nucleus independently of the target mass. The only exception are data for very low incident energy ($E/A = 35$ MeV /13/).

3. The relative decreasing of source radii in a higher momentum region seems to be stronger in the case of heavy targets.

Similar dependences have also been observed qualitatively in several other works /7, 11, 12/. On the other hand, there are indications that this general dependence is affected by some additional effects. In the low incident nucleus energy region ($E/A \lessdot 60$ MeV) the influence of the projectile mass and energy has been observed /15/. An angular dependence seems also to be imposed on the momentum one /18/. The form of the momentum dependence, presented in Fig. 4, may be treated therefore as a reference function to look for other effects depending on particular experimental conditions.

Fig. 5 presents a direct comparison of the RMS radii obtained for "fast" protons ($\langle p_p \rangle \geq 0.3$ GeV/c) in different experiments with the correspon-

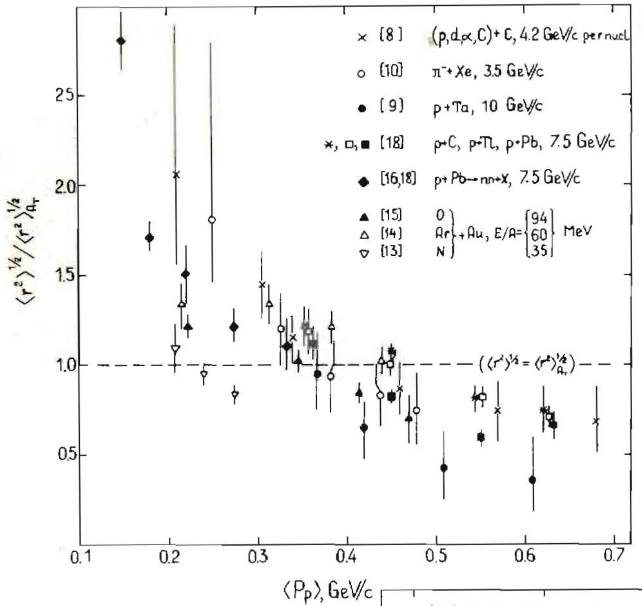


Fig. 4. Dependence of the source sizes on the mean proton momenta expressed in units of the RMS radius of the target nucleus. To unify the scales, the kinetic energy scale in Refs. /13–15/ was directly changed to the momentum one.

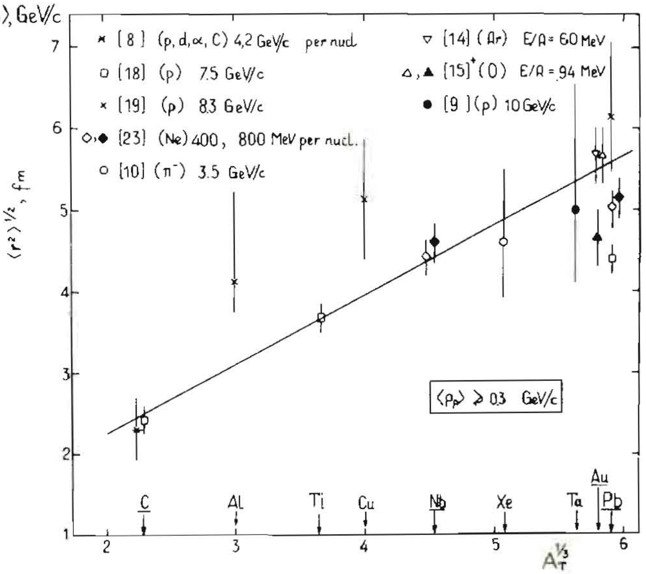


Fig. 5. Dependence of the RMS radius of the fast proton emission volume on the mass number of the target nucleus. The line represents the RMS radii of the target nuclei as obtained from Ref. /26/ + – the data taken from Fig. 6 of Ref. /15/ for two values of proton kinetic energies. The symbols in brackets indicate the type of the projectile.

ding RMS radii of the target nuclei. The reactions, where the mass of the target nucleus is much greater than that of the projectile, were selected. The straight line presents the approximation of experimental data obtained for the RMS radii of different nuclei /26/. One can see that for fast protons the RMS radii of the emission volume are compatible with the RMS radii of the target itslf. Some dispersion, seen for heaviest nuclei, reflects the momentum and angular dependences due to different experimental conditions. Three points are located relatively high , though their positions follow the overall dependence. These data correspond to backward emitted protons /18, 19/ and will be commented on later.

The relationship, shown in Fig. 5, is similar as observed by J.Bartke for pions /28/, but for protons the projectile mass has been replaced by the mass of the target nucleus.

CONCLUSIONS AND COMMENTS

We have discussed the dependence of the size of the proton emission volume on the momenta of emitted protons. The common experimental rule is that faster protons are emitted from smaller sources. Two factors have been tested to explain this dependence: large emission time intervals and a small perpendicular size of the emission volume. Each of these factors was supposed to dominate in different proton momentum intervals.

In principle, the factors considered can explain the experimental results although some comments are needed here.

1. The correlation function is less sensitive to the changes of the time parameter than to the space ones. To explain our experimental results, time intervals should be as large as several tens of fm/c.

2. A stronger momentum dependence observed for heavy targets at higher proton momenta seems to be compatible with the assumption that it is caused by systematic decreasing of the perpendicular sourse size. To explain our results, the shape of the fast proton source should be in the form of a thin tube corresponding to the path of the projectile throughout the target.

3. Sharp limits assumed, when considering separately the two different effects, should be taken as a crude approximation. Even, if only these two factors are responsible for the observed momentum dependence — smooth transition is much more reliable.

4. Taking target mass as a reference variable, the tacit assumption has been made that registered protons are mainly target fragments, what is not a case when a massive projectile with not too high energy per nucleon is used. As mentioned above, the influence of the projectile mass and energy on the overall pair energy dependence was observed for the reactions in a relatively low energy region /15/. Since for a higher incident energy the projectile mass dependence has not been observed (see Ref. /8/), it seems natural to suppose that, if the incident energy is insufficient for colliding nuclei to penetrate each other, the measured sizes reflect the limits of the reaction zone.

5. Correlations between the space and time characteristics are possible in the process of particle emission. A sequential ejecting of nucleons during the passage of an incident particle through the target nucleus leads to the strong angular dependence of the two-proton correlations /17/. This effect is consistent with the assumption on a small parpendicular size, fast protons are ejected from. Similar result can be expected if secondary protons are emitted from a moving sources. Angular dependence of the two-proton correlations has been observed experimentally, indeed /18, 29/ .

6. Different emission angles can reflect different mechanisms of the particle emission, conseqently, different space-time characteristics of the emission process. Protons emitted into the backward hemishere represent, for example, a special class of the so-called, cumulative particles emitted into the kinematical region forbidden for one-nucleon collisions /30/. Backward emitted protons are often considered as "essentially emitted from a thermalized system" /29/

7. Analysis of final-state interaction effects points out also to the dependence of the correlation function on the pair velocity with respect to the emitting sources /3, 17/. This effect, important for relativistic protons, may slightly affects the momentum dependence of the two-proton correlations discussed here.

The following picture seems to emerge from the data analysis performed above. Fast protons are emitted successively in the first stage of the collisions. Their space-time characteristics reflect the collision geometry. Decreasing of the proton momenta is related with the expansion of the emission zone to spread eventually over the whole target nucleus. Corresponding time intervals increase as well. Slow protons are emitted according to the typical thermalized process.

In reality, several interrelated factors contribute to the correlations observed. Some of them were listed above. A detailed analysis is still necessary for separated momentum and angular intervals of registered protons to disentangle various effects involved here.

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Плюта Я. E1-88-754

Пространственно-временные характеристики источников вторичных протонов в релятивистских ядерных столкновениях, получаемые по методу двухчастичных корреляций

Обсуждаются последние результаты по двухчастичным корреляциям в области малых относительных импульсов. Зависимость размеров области испускания вторичных протонов от их импульсов, анализируется с целью выявления приемлемого объяснения наблюдаемых эффектов. Рассматриваются два фактора: большие временные интервалы испускания протонов и малые поперечные размеры источников. Предполагается, что каждый из этих факторов доминирует в разных интервалах импульсов протонов. Анализ экспериментальных данных показывает, что наблюдаемые эффекты включают в себя несколько взаимосвязанных факторов.

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Space-Time Characteristics of Secondary Proton
Sources in Relativistic Nuclear Collisions
from Two-Particle Correlations

Recent experimental results on two-proton correlations at small relative momenta are discussed. Dependence of the size of the proton emission volume on the momenta of emitted protons has been analysed to find a plausible description of the observed effects. Two factors were tested: large emission time intervals and small perpendicular source sizes. Each of these factors is supposed to dominate in different proton momentum intervals. Analysis of the experimental data shows that there are several interrelated contributions to the observed effects.

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

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