Femtoscopic scales of particle-emitting source in small and large systems

V K Semenova, E V Khyzhniak and G A Nigmatkulov
National Research Nuclear University MEPhI 115409, Kashirskoe shosse 31, Moscow, Russia
E-mail: varvara.k.semenova@gmail.com

Abstract. The femtoscopy technique allows one to measure the spatial and temporal scales of the particle-emitting source produced in high-energy collisions. In non-central ultra-relativistic heavy-ion collisions, emitting source may be tilted in the reaction plane. The orientation of freeze-out distributions is interesting because it provides complementary information about quark-gluon matter properties. In the experiment, the tilt can be extracted by measuring femtoscopic radii as a function of the pair angle with respect to the first-order event plane.

In this talk, we will present results of azimuthally sensitive femtoscopic analysis of Au+Au and Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We will also present the transverse momentum and multiplicity dependence of identical pion femtoscopic radii from d+Au, $^3$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. All data was obtained from the UrQMD model.

1. Introduction
In high-energy nuclear collisions a process of particle production is not fully understood. Measuring a geometry of emitting source relative to different event parameters such as multiplicity, pair transverse momentum and type of collision system is one of the first steps.

In order to study the dynamics of pion and kaon production the Ultrarelativistic Quantum Molecular Dynamics (UrQMD 3.4) model was used. UrQMD is a transport model for simulating heavy-ion collisions designed as multipurpose tool for studying a wide variety of heavy ion related effects ranging from multifragmentation and collective flow to particle production and correlations [1, 2].

The femtoscopy is a method based on the correlations caused by quantum statistics, Coulomb and strong final-state interactions which allows one to measure the spatial and temporal scales of the particle-emitting source [3]. For measuring those correlations one uses a correlation function, $C(q)$:

$$C(q) = \frac{A(q)}{B(q)},$$

where $q$ is a relative four-momentum, $A(q)$ is a distribution constructed from particles from the same event (contains BE correlations), and $B(q)$ is reference distribution that is identical to $A(q)$, but does not contain BE correlations. Since UrQMD does not contain them, each pair from $A(q)$ was weighted with: $w = 1 + \cos(\Delta x q)$, where $\Delta x$ is a relative four-coordinate of produced particles. The spatial and temporal structure of the particle-emitting source is mostly defined by the dynamics of the collision processes [4, 5]. In non-central collisions created medium between
two colliding systems can be tilted in the reaction plane. According to Ref. [6, 7] azimuthally sensitive femtoscopic measurements allow one to probe shape and orientation of the emission source.

According to Ref. [8] dependence of the radii on charged particle multiplicity changes with increasing size of the initial system. The femtoscopy can measure radii of the particle-emitting source as a function of multiplicity ($N_{ch}$) and pair transverse momentum ($k_T$).

In order to extract radii from the small systems and azimuthally sensitive femtoscopy the one-dimensional and three-dimensional fit functions were used, respectively.

In case of one-dimensional analysis, the correlation functions were fitted using:

$$C(q_{inv}) = 1 + \lambda e^{-q_{inv}^2 R_{inv}^2} \quad (2)$$

and

$$C(q_{inv}) = 1 + \lambda e^{-q_{inv} R_{inv}} \quad (3)$$

where $q_{inv} = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2}$ is a relative four-momentum of the pair, $\lambda$ is the chaocity parameter. This functions were used for measuring radius of particle-emitting source under assumption that particle-emitting source is a sphere. This simplification allows one to study dynamics of particle emission process in terms of particle-emitting source size.

For three-dimensional analysis we decompose the relative momentum of the pairs into the three projections, namely $out$, $side$ and $long$, according to the Bertsch-Pratt parameterization [9, 10]. Correlation functions were constructed in longitudinally co-moving system (LCMS), where $p_{z,1} + p_{z,2} = 0$, and fitted with function:

$$C(q) = 1 + \lambda e^{\exp \left[-\sum_{i,j=\text{out},\text{side},\text{long}} q_i q_j R_{ij}^2 \right]} \quad (4)$$

where $q_i$ is the relative momentum of the pair in the $i$ direction. According to Ref. [11], $R_{side}$ contains information about geometry, $R_{out}$ convolutes the information about geometry and emission duration and $R_{long}$ contains information about system lifetime. The $k_T$ dependence of the femtoscopic radii shows the dynamics of the system and allows one to probe the different regions of the homogeneity [12].

2. Azimuthally sensitive femtoscopy

In heavy-ion collisions spatial anisotropy leads to momentum anisotropy. In non-central collisions created medium can be tilted in reaction plane from beam direction. Azimuthally sensitive femtoscopy allows one to measure shape and size of emitting source in order to measure the tilt of that area in reaction plane. Basics of methods is in measuring radii for different azimuthal angles of the pair with respect to the reaction plane angle. The azimuthally sensitive femtoscopic analysis was performed in a symmetric (Au+Au) and asymmetric (Cu+Au) collision system at $\sqrt{s_{NN}} = 200$ GeV to investigate the orientation of the emission source.

For both systems three-dimensional distribution of relative momentum projections were built for different ranges of centrality, $k_T$ and azimuthal angle of the pair with respect to the reaction plane ($\phi - \Psi_1$). Correlation functions were fitted using Eq. (2).

Figure 1 shows the dependence of the squares of the radii of pion-emitting source on azimuthal angle of the pair relative to the first-order event plane for collision systems Au+Au and Cu+Au. As one can see femtoscopic radii measured for Au+Au collisions are systematically larger than those for Cu+Au at the same centrality and pair transverse momentum.
Figure 1. The dependence of the squares of three-dimensional femtoscopy radii and cross components of the fit on $\phi - \Psi_1$ in $k_T$ range from 0.15 GeV/c to 0.65 GeV/c and centrality range 20-40% in Cu+Au (solid markers) and Au+Au (empty markers) system $\sqrt{s_{NN}} = 200$ GeV.

3. Femtoscopy in small systems

According to recent research the emitting source radius dependence on event multiplicity changes with initial size of the colliding system\cite{8}. For checking its behavior on small changed system, 82M d+Au and 51M $^{3}$He+Au collisions with energy $\sqrt{s_{NN}} = 200$ GeV has been analyzed. Only particles within $|\eta| < 1$ and momentum range from 0.15 to 1.45 GeV/c were selected for research.

Figure 2 shows correlation functions for like-sign pions and kaons fitted with Gaussian fit function from Eq. (3) and exponential fit function from Eq. (4). Correlation function for identical kaons was built for furthermore comparison of pions and kaons behavior which can be different because of different contribution from resonance decays. For like-sign pions exponential fits have a better description of the data as compared to the Gaussian ones.

Radii and chaocity parameter were extracted from fits and presented as dependence on $k_T$ on Fig. 3. As we can see femtoscopic radii extracted for d+Au and $^{3}$He+Au collisions are similar for multiplicities below 20 (for the given $k_T$ range). For higher multiplicities femtoscopic radii measured for $^{3}$He+Au collisions are systematically larger than those for d+Au.

4. Conclusions

One-dimensional correlation functions of like-sign pions and kaons have been studied for the d+Au and $^{3}$He+Au collision systems at $\sqrt{s_{NN}} = 200$ GeV. The pion correlation functions have been analyzed for several multiplicity and pair transverse momentum regions. The radii were
Figure 2. Correlation function of identical pions (a,b,e,f) and kaons (c,d,g,h) with different $k_T$ range for d+Au (a,b,c,d) and $^3$He+Au (e,f,g,h) systems at $\sqrt{s_{NN}} = 200$ GeV with multiplicity in range from 5 to 9, fitted with Gaussian distribution (solid line) and exponential distribution (dashed line).

Figure 3. $R_{inv}$ and $\lambda$ for like-sign pions distributions in different ranges of $k_T$ and multiplicity for d+Au (solid markers) and $^3$He+Au (empty markers) systems at $\sqrt{s_{NN}} = 200$ GeV.

extracted using Gaussian and exponential fits. The exponential fits describe pion correlation functions better than Gaussian ones. The parameters extracted under the assumption that the pion-emitting source was exponential are larger than under the assumption that the source was Gaussian. Femtoscopic radii extracted for d+Au and $^3$He+Au collisions are similar within
uncertainties for multiplicities below 20 (for the given $k_T$ range). For higher multiplicities femtoscopy radii measured for $^3$He+Au collisions are systematically larger than those for d+Au.

An azimuthally sensitive femtoscopy was performed in a symmetric (Au+Au) and asymmetric (Cu+Au) collision system at $\sqrt{s_{NN}} = 200$ GeV to investigate the orientation of the emission source. The dependences of the squares of the three-dimensional radii of pion-emitting source on the difference between the azimuthal angle of the pair and the angle of the reaction plane for different collision centralities in Au+Au and Cu+Au systems at $\sqrt{s_{NN}} = 200$ GeV were constructed. The extracted radii for Au+Au collisions are systematically larger than those for Cu+Au at the same centrality and pair transverse momentum.

Acknowledgements

The reported study was funded by RFBR according to the research project No. 16-02-01119 a, supported by program of increasing the competitive ability of NRNU MEPhI (agreement with RMHES of August 27, 2013, project no. 02.a03.21.0005), and was partially supported by the Ministry of Science and Higher Education of the Russian Federation, grant N 3.3380.2017/4.6.

References

[1] Bass S A et al 1998 Prog. Part. Nucl. Phys. 41 225
[2] Bleicher M et al 1999 G25 1859
[3] Podgoretsky M I 1989 Particles & Nuclei 20 630
[4] Kopylov G I and Podgoretsky M I 1972 Sov. J. Nucl. Phys. 15 219
[5] Kopylov G I, Lyuboshits V L and Podgoretsky M I 1974 JINR-P2-8069
[6] Lisa M A et al 2000 Phys. Lett. B 496 8
[7] Lisa M A, Heinz U and Wiedemann U A 2000 Phys. Lett. B 489 4
[8] Abelev B et al 2014 Phys. Lett. B 739 139
[9] Pratt S 1984 Phys. Rev. Lett. 53 3
[10] Bretsch G 1989 Nucl. Phys. A 489 6
[11] Makhlin A N and Sinyukov Y M 1988 Z. Phys. C 39 13
[12] Akkelin S V and Sinyukov Y M 1995 Phys. Lett. B 382 7