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Test of Nonstatic Spherical Quark-Gluon Plasma by Two-Pion Interferometry

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Abstract A model of expanding pion sources in relativistic heavy ion collisions, when only hadronic matter is generated, is proposed. The two-pion correlation function at small relative momentum for such a model is obtained with two-pion interferometry at small relative momentum, and the relation between the real spatial parameter $R_{\rm e}$ and the apparent spatial parameter $R_{\rm a}$ of the pion sources is given. The relation is different from the one when QGP is created. The difference can be used to test nonstatic, spherical quark-gluon plasma produced in relativistic heavy ion collisions. The relation also showes a scaling behavior.

Key words quark-gluon plasma, two-pion interferometry, relativistic heavy ion collisions

The physics of relativistic heavy ion collisions is an interdiscipline between particle physics and nuclear physics. Intensity interferometry and collective flow analysis are two powerful tools to probe the properties and dynamical evolution of the matter produced in partcle-particle, particle-nucleus and nucleus-nucleus collisions in the region of relativistic collision energies[1—7]. Correlation functions in intensity interferometry can be derived from quantum field theory or quantum mechanics. Emission functions of particle sources produced in relativistic heavy ion collisions reflect dynamics in relativistic heavy ion collisions. When emission functions of particle sources are known, the correlation functions can be determined. The phase transition of quark-gluon plasma to hadronic matter is a major concern in physics of relativistic heavy ion collisions because it provides study of quamtum chromodynamics(QCD) and cosmology with earth-based experiments. Some experimental data (such as enhancement of strange hadrons, low-mass dilepton yields and J/ψ suppression) show that quark-gluon plasma (QGP) may be created, and several theoretical models predict that QGP can be created at a time of about 1fm/c and disappear at a time of about 6fm/c after the collisions. When QGP is generated, its temperature drops as time elapses. As the temperature of QGP reaches a critical value $T_{\rm c}$ of about 170MeV, the phase transition of QGP to hadronic matter (including pion mesons) happens at constant pressure and temperature, and QGP emits hadrons on its surface.

Intensity interferometry at small relative momentum for static particle-emitting sources in relativistic heavy ion collisions is investigated thoroughly in our papers[7—14]. For expanding pion sources, Pratt proposed a model[6]. In his model, pions are emitted from a radially-expanding spherical shell with a constant expanding velocity v, and the relation between the real spatial parameter $R_{\rm e}$ and the apparent spatial parameter $R_{\rm ap}$ of the pion sources is

$$R_{\rm ap}=R_{\rm e}f_{\rm p}\ , \tag{1}$$

$$f_{\rm p}=\sqrt{\frac{3}{2}}\left[\frac{(\sinh(2a)/2)-a}{a\sinh^2 a}\right]^{1/2}. \tag{2}$$

If v is negative, the pion sources contract. In such a case, Pratt's model can be used to describe the pion

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sources produced by QGP generated in relativistic heavy ion collisions.

In this paper, we consider a model for expanding pion sources when only hadronic matter is produced. In our model, the pion sources expand througout the dense and hot region produced in relativistic heavy ion collisions with a constant radially-expanding velocity v. For such a model, two-pion interferometry at small relative momentum is presented and the relation between the real spatial parameter R_{e} and the apparent spatial parameter R_{a} of the pion sources is given. The relation is different from the one when QGP is created. The difference can be used to test nonstatic spherical quark-gluon plasma produced in relativistic heavy ion collisions.

In relativistic heavy ion collisions, the two-pion correlation function is defined as

$$C_2(\boldsymbol{p}_1,\boldsymbol{p}_2)=\frac{P_2(\boldsymbol{p}_1,\boldsymbol{p}_2)}{P_1(\boldsymbol{p}_1)P_1(\boldsymbol{p}_2)}\ , \tag{3}$$

where $P_2(\boldsymbol{p}_1,\boldsymbol{p}_2)$ is the probability of pion-pairs appearing in relativistic heavy ion collisions, and $P_1(\boldsymbol{p})$ is the probability of a single pion meson created in relativistic heavy ion collisions. In the Pratt's formulation of two-pion interferometry[6], the two-pion correlation function at small relative momentum is expressed as

$$C_{2\mathrm{p}}(\boldsymbol{p}_1,\boldsymbol{p}_2)=1+\lambda\frac{\left|\iint\mathrm{d}x\cdot\exp(\mathrm{i}x\cdot q)g(x,p)\right|^2}{\left|\iint\mathrm{d}x\cdot g(x,p)\right|^2}\ , \tag{4}$$

where $g(x,p)$ is the emission function for pion sources, x the four-dimensional coordinate of a pion meson, p the four-dimensional momentum of the pion meson, $q=p_2-p_1$ the four-dimensional momentum difference of a pion-pair, and λ the two-pion correlation factor. For our model of pion sources, when only hadron matter is produced, the emission function $g(x,p)$ is

$$g(x,p)\ =\ B\cdot\exp\left(-\frac{r^2}{R_{\mathrm{e}}^2}\right)\cdot\exp\left(-\frac{t^2}{\tau^2}\right)\cdot \exp\left(-\frac{E_{\mathrm{p}}-\boldsymbol{v}\cdot\boldsymbol{p}}{T\sqrt{1-v^2}}\right)\ , \tag{5}$$

where $\boldsymbol{v}$ is the constant radial expansion velocity of a pion source, T the temperature of the source, R_{e} the real spatial parameter of the source, τ the temporal parameter of that source, $E_{\mathrm{p}}=\sqrt{p^2+m^2}$ the energy of the pion meson, and B the normalization factor. For such a pion source, the pion momentum distribution is

$$P_1(\boldsymbol{p})=A\exp\left(-\frac{E}{T\sqrt{1-v^2}}\right)\sinh(a)/a\ , \tag{6}$$

where A is a normalization factor, and

$$a=\frac{vp}{T\sqrt{1-v^2}}\ . \tag{7}$$

In experiments, the radial expansion velocity v and the temperature T of the source can be obtained by fitting the pion momentum distribution $P_1(\boldsymbol{p})$. According Eq. (6), the pion momentum distribution $P_1(\boldsymbol{p})$ doesn't change whether QGP is produced or not. At small relative momentum, the two-pion correlation function for pion sources, when only hadron matter is produced, is

$$C_{2\mathrm{e}}(\boldsymbol{p}_1,\boldsymbol{p}_2)\ =\ 1+\lambda_{\mathrm{e}}-\lambda_{\mathrm{e}}q^2\left[\frac{1}{2}b\tau^2+ \frac{1}{2}R_{\mathrm{e}}^2\left(1-\frac{4}{3\pi}\left(\frac{\mathrm{actha}-1}{a}\right)^2\right)\right], \tag{8}$$

where

$$b=\frac{mT}{3mT+m^2}\ , \tag{9}$$

For experiments, the two-pion correlation function at small relative momentum is[7—14]

$$C_{2\mathrm{a}}(\boldsymbol{p}_1,\boldsymbol{p}_2)=1+\lambda_{\mathrm{a}}-\frac{1}{2}\lambda_{\mathrm{a}}q^2\left(R_{\mathrm{a}}^2+\frac{1}{2}b\tau^2\right), \tag{10}$$

where R_{a} is called the apparent spatial parameter of a pion source, a quantity measured directly from experiments. For the same pion source, setting Eq. (10) equal to Eq. (8) gives

$$\lambda_{\mathrm{a}}=\lambda_{\mathrm{e}}\ , \tag{11}$$

$$R_{\mathrm{a}}=R_{\mathrm{e}}f\ , \tag{12}$$

where

$$f=\left[\frac{1}{2\pi^{1/2}}-\frac{4}{3\pi}\left(\frac{\mathrm{actha}-1}{a}\right)^2\right]^{1/2}. \tag{13}$$

Eq. (1) and Eq. (12) suggest that the relation between the real spatial parameter R_{e} and the apparent spatial parameter R_{a} of the pion sources doesn't change no matter whether pion sources expand or contract. Define $D=R_{\mathrm{ap}}-R_{\mathrm{a}}$. Fig. 1 shows R_{ap}, R_{a} and D as a function of momentum of the pion meson when T=150MeV, v=0.5c and R_{e}=4.1fm. The figure indicates that the bigger the momentum, the smaller the apparent spatial parameters, a phenomenon found in the experiment[15]. The figure also shows that D decreases as momentum increases. Such difference between $R_{\rm ap}$ and $R_{\rm a}$ can be used to test nonstatic spherical quark-gluon plasma produced in relativistic heavy ion collisions.

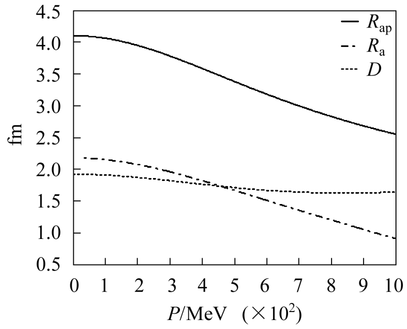

Fig. 1. $R_{\rm ap}$, $R_{\rm a}$ and D as a function of momentum of the pion meson when T=150MeV, v=0.5c and $R_{\rm e}$=4.1fm.

In conclusion, the expression for the two-pion correlation function at small relative momentum for expanding pion sources, when only hadronic matter is produced in relativistic heavy ion collisions, is Eq. (8), and the relation between the real spatial parameter $R_{\rm e}$ and the apparent spatial parameter $R_{\rm a}$ of the pion sources is Eq. (12). The relation is different from the one when QGP is created. The difference can be used to test nonstatic spherical quark-gluon plasma produced in relativistic heavy ion collisions. Moreover, both Eq. (1) and Eq. (12) show a scaling behavior, which, in our case, means that the ratio of the real spatial parameter to the apparent spatial parameter of the pion sources doesn't not change when a is a constant , although the radial expansion velocity v, the pion meson momentum and the temperature T of pion sources may be different .

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非静态球形夸克–胶子等离子体的2π干涉学的检测

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摘要　提出了一种相对论重离子碰撞中强子物质生成时的π膨胀源模型. 得到了该模型中的小相对论动量区域的2π关联函数及表观π源参数 R_{a} 与实际π源参数 R_{e} 的关系. 这一关系与QGP生成时的关系有所区别. 这一区别可以用来检测相对论重离子碰撞中产生的非静态球形夸克–胶子等离子体的存在性. 两个关系也显示了一种标度行为.

关键词　夸克–胶子等离子体　2π干涉学　相对论重离子碰撞

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