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**WHERE TO LOOK FOR PION CONDENSATION
IN HEAVY ION COLLISIONS**

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Where to Look for Pion Condensation in Heavy Ion Collisions

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Abstract

The possibility to observe a pion condensate in peripheral nucleus - nucleus collisions at GSI energies is discussed. A condensate may be observed via pronounced peaks in pion production in a narrow region of momenta $k_{\perp} \simeq (2-3)m_{\pi}$ corresponding to rather large rapidity values.

Very precise measurements of particle production in heavy ion collisions make it worthwhile to think again about signatures of pion condensation. Pion condensation has been widely discussed in the seventies (see e.g. [1,2,3] and refs. therein) and can be described in the following way: When the nuclear matter density ρ becomes large enough ($\rho > \rho_c$), the attractive P -wave πN -interaction triggers a classical pion condensate field characterized by a non-vanishing momentum k_0 . For isospin symmetric nuclear matter with a Fermi-momentum $p_F = \left(\frac{3\pi^2\rho}{2}\right)^{1/3}$ the pion momentum k_0 is of the order of p_F . The critical density depends on phenomenological parameters, which are extracted from nuclear data and vary only slightly with density. Estimates (see [4] and refs. therein) then give a critical density ρ_c in the range $(2-4)\rho_0$, where $\rho_0 \simeq 0.17 fm^{-3}$ is the nuclear saturation density.

The pion condensate is destroyed, when the temperature increases. A typical critical temperature, T_c , is of the order of $\epsilon_F \simeq p_F^2/2m_N^*$, where $m_N^*(\rho)$ is the effective nucleon mass [5,4]. In central nucleus-nucleus collisions, e.g. at GSI-energy ($0.4 GeV/A \leq E \leq 1 GeV/A$) the maximum compression is $\rho_m \simeq 3\rho_0$ which is of the order of the critical density $\rho_c(T=0)$. But the temperatures reached in central heavy ion collisions are so high ($\epsilon_F \leq T_m \leq 3\epsilon_F$) that there is little chance to produce a pion condensate. This is the reason why recently not so much attention has been

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paid to the possible appearance of a pion condensate. Theoretical research, however, has continued to identify signatures of a substantially modified pion-nucleon interaction in hot nuclear matter (see [4,6] and refs. therein).

In this note we want to explore the possibility to observe a pion condensate in peripheral nucleus - nucleus collisions. To be specific we consider 1 GeV/A $Au + Au$ collisions, typical for GSI at the moment. Our main point is that in peripheral collisions one deals with rather cold ($T \leq \epsilon_F/2 \simeq 20 MeV$), dilute ($\rho < \rho_0$) and – especially important – transparent nuclear matter. To reliably estimate observable consequences we start from the extreme case of two freely penetrating nuclei with vanishing spin and isospin. This model has been discussed in ref. [7] with respect to possible pion instabilities in the center of mass frame. We argue here that the instability may occur in the nuclear matter, which is at rest in the laboratory or projectile frame.

Firstly, we point out that in order to deal with transparent nuclear matter one needs a not too small collision energy and also not too small impact parameters. The nuclear system can be considered as transparent if the nucleon mean free path λ is larger than a typical radius of the system ($d/2$). The nucleon mean free path can be estimated as

$$\lambda \simeq 2.4(\rho_0/\rho)fm, \quad (1)$$

since for a 1 GeV proton traversing the nucleus $\lambda \simeq 2.4$ fm according to experiment [8].

The typical collision geometry as well as the density profiles of projectile and target are shown in Fig.1 at the moment corresponding to maximum overlap. With the density profiles of gold nuclei as in Fig.1, an impact parameter $b \simeq 1.5R_{Au}$, and a characteristic size $d \simeq 0.7R_{Au} \simeq 4fm$ the total density amounts to $\rho \simeq (0.7 - 1)\rho_0$ in the overlap region. Then from Eq.(1) we have $\lambda/(d/2) \simeq (1.2 - 1.5)$ which means that we deal with rather transparent nuclear matter. The value of the opaque density ρ_{opaq} at which $\lambda \simeq d/2$ is $\rho_{opaq} \simeq 1.2\rho_0$ (for $d \simeq 4$ fm).

Due to the long mean free path of nucleons we consider the sum of the momentum

distributions of the two colliding nuclei at the total local density $\rho(r_\perp, z)$ as the relevant nuclear momentum distribution $n^*(p)$ in the overlap region. According to Fig.1 we have $\rho(r_\perp \simeq b/2, z \simeq 0) \simeq 0.7\rho_0$.

For simplicity we use the nonrelativistic approximation. Then applying a Galileo transformation to the nucleon distributions we get

$$n^*(p) = n(p) + n(\vec{p} + \vec{p}_{lab}) \quad (2)$$

with

$$n(p) = \Theta(p_F(\rho/2) - |\vec{p}|), \quad (3)$$

where $\Theta(x)$ is the step function and $\vec{p}_{lab}$ is the momentum of the laboratory frame. For the pion momentum $\vec{k}$ in the laboratory frame there exists a minimum value of $\vec{p}_{lab}$ above which the factor

$$n(\vec{p})n(\vec{p} + \vec{p}_{lab} + \vec{k}) = 0. \quad (4)$$

Excitations from one Fermi sphere are not allowed to overlap with the ground state distribution in the other Fermi sphere. This condition is safely satisfied for 1 GeV/A incident energy and for interesting values of the pion momentum $k \leq m_N/2$. For nuclear systems with $N \simeq Z$ the pion condensate arises at $\omega \simeq 0$. The most essential contribution to the pion polarization operator comes from the nucleon particle-hole diagram

(5)

The diagram shows a horizontal oval loop representing a nucleon particle-hole excitation. Two wavy lines enter from the left and exit to the right. Inside the loop, two diagonal lines cross each other, forming an 'X' shape, which represents nucleon-nucleon correlations. The right half of the loop is filled with vertical hatching.

where the crossed vertex symbolizes nucleon-nucleon correlations.

With the momentum distributions of Eqs. (2), (3) satisfying the condition (4) the polarization operator has two terms. The first part of the polarization operator Π_P

from the distribution $n(\vec{p} + \vec{p}_{lab})$ can be simply obtained by replacing the equilibrium Lindhard-Migdal function

$$\Phi_1(\omega, k, \rho/2) \rightarrow \Phi_1(\omega - \vec{k}\vec{v}, k, \rho/2), \quad (6)$$

where $\vec{v} = \vec{p}_{lab}/m_N^*(\rho/2)$. The second part of Π_P relating to the distribution $n(\vec{p})$ is the same as for an equilibrium system but taken at density $= \rho/2$.

In the limit of small values $\omega \ll kv_F(\rho/2)$, where $v_F(\rho/2) = p_F(\rho/2)/m_N^*(\rho/2)$ and with the assumption $k \ll 2p_F(\rho/2)$, one obtains for the π^- -polarization operator (see refs. [4,5,6]) the following expression

$$\begin{aligned} \Pi_P \simeq & -\frac{2f_{\pi N}^2 \Gamma_{\pi NN}^2 (k^2 - \omega^2) m_N^*(\rho/2) \Gamma(g', \rho/2)}{\pi^2} 2p_F(\rho/2) \quad (7) \\ & \times \left\{ [\Phi(\omega, k, \rho/2) + \Phi(\omega - \vec{k}\vec{v}, k, \rho/2)]/2 \right\}, \\ & [\Phi(\omega, k, \rho/2) + \Phi(\omega - \vec{k}\vec{v}, k, \rho/2)]/2 \simeq 1 - \frac{\omega^2}{[kv_F(\rho/2)]^2} + \frac{\omega \vec{k}\vec{v}}{[kv_F(\rho/2)]^2} \\ & - \frac{[\vec{k}\vec{v}]^2}{2[kv_F(\rho/2)]^2} - \frac{1}{12} \frac{k^2}{[p_F(\rho/2)]^2} - \frac{\pi i [|\vec{k}\vec{v} - \omega| + |\omega|]}{4kv_F(\rho/2)}, \end{aligned}$$

where $f_{\pi N} \simeq 1/m_\pi$ is the pion-nucleon coupling constant, $\Gamma_{\pi NN}^2 \simeq \exp(-2k^2/\Lambda^2)$ is the form-factor in the πNN -vertex, $\Lambda \simeq 5m_\pi$, and

$$\Gamma(g', \rho/2) \simeq \frac{1}{1 + 2[g'p_F(\rho/2)/p_F(\rho_0)][\Phi(\omega, k, \rho/2) + \Phi(\omega - \vec{k}\vec{v}, k, \rho/2)]} \quad (8)$$

is the nucleon-nucleon correlation factor parametrized according to ref. [4]. The Landau-Migdal parameter $g'(\rho)$ decreases slightly with decreasing density, $g'(\rho_0) \simeq 1.0$, whereas $g'(0) \simeq 0.5$. In obtaining Eq. (8) we also assume that

$$|\vec{k}\vec{v}/kv_F| \ll 1 \quad (9)$$

The occurrence of the prefactor $2p_F(\rho/2)$ in Eq. (7) instead of the factor $p_F(\rho)$ for the system of one Fermi sphere shows that in colliding nuclear matter the perpendicular pion modes, $\vec{k}\vec{v} = 0$, feel the same strength of interaction as if the system consists of only one Fermi sphere of radius $2p_F(\rho/2)$. This means that the peripheral

collision produces an equivalent total nuclear matter density 4ρ , if we do not take into account the small difference in the nucleon-nucleon correlation factors for both mentioned systems. Peripheral collisions present two advantages. Firstly, because of transparency the two pieces of nuclear matter have a large chance to survive the collision unchanged. Secondly, the pion polarizations due to the Fermi spheres can be summed. This effect largely compensates the reduced local density in peripheral collisions by producing a pion polarization operator of the same size as stationary nuclear matter at four times normal nuclear matter density $\rho = 4\rho_0$ would generate.

In the realistic case one should take into account the Δ -isobar-nucleon hole diagram for the pion polarization operator

(10)

as well as some contact term, the so called regular part of the self-energy

(11)

The latter is necessary in order to satisfy current algebra and PCAC [4].

The Δ -isobar particle-nucleon hole part of the pion polarization operator only shows the specific situation of two colliding Fermi spheres by the presence of a recoil term $\vec{p}\vec{k}/m_N^* \neq 0$ in the denominator of the corresponding Lindhard-Migdal function [5]. As result one has (see ref. [6])

$$\begin{aligned}
 \Pi_{\Delta} \simeq & - \frac{4m_{\Delta}^*(\rho/2)f_{\pi N\Delta}^2\Gamma_{\pi N\Delta}^2\Gamma(g'_{N\Delta},\rho/2)k^2}{9m_N^*(\rho/2)\tilde{\omega}_{\Delta}(t)} \\
 & \times \frac{\rho}{2}[\tilde{\Phi}_{\Delta}(\omega,k,\rho/2) + \tilde{\Phi}_{\Delta}(-\omega,k,\rho/2) \\
 & + \tilde{\Phi}_{\Delta}(\omega - \vec{k}\vec{v},k,\rho/2) + \tilde{\Phi}_{\Delta}(-\omega + \vec{k}\vec{v},k,\rho/2)],
 \end{aligned}
 \tag{12}$$

where

$$\tilde{\Phi}_{\Delta}(\omega, k, \rho/2) = \frac{\tilde{\omega}_{\Delta}}{v_F^3(\rho/2)k^3} \left[\frac{a_{\Delta}^2 - b^2}{2} \ln \frac{a_{\Delta} + b}{a_{\Delta} - b} - a_{\Delta}b \right], \quad (13)$$

$$a_{\Delta} = \omega - \tilde{\omega}_{\Delta}(t), \quad b = kv_F(\rho/2),$$

$$\tilde{\omega}_{\Delta}(t) = \tilde{\omega}_{\Delta} + t/2m_N^*(\rho/2), \quad t = k^2 - \omega^2, \quad \tilde{\omega}_{\Delta} \simeq 2.4m_{\pi},$$

$$f_{\pi N\Delta} \simeq 2.1f_{\pi NN},$$

$$\Gamma_{\pi N\Delta}^2 \simeq \Gamma_{\pi NN}^2/(1 + 0.23k^2/m_{\pi}^2),$$

$\Gamma(g'_{N\Delta}, \rho_0)$ - is the $N\Delta$ - correlation factor, $g'_{N\Delta} \simeq g'/2$, $0.7 \leq \Gamma(g'_{N\Delta}, \rho_0) \leq 1$ at $\omega \simeq 0$.

From Eqs. (12), (13) one easily sees that in the relevant region $\omega \ll m_{\pi}, k < 2p_F, |\vec{k}\vec{v}/kv_F| \ll 1$ the resulting change of Π_{Δ} in comparison with the equilibrium case is smaller than that for the Π_P . In this region one can take the limit $|a_{\Delta}| \gg b$ whereby

$$\tilde{\Phi}_{\Delta}(\omega, k) \simeq -\frac{4\tilde{\omega}_{\Delta}}{3a_{\Delta}}. \quad (14)$$

This function $\tilde{\Phi}_{\Delta}$ does not depend on the $p_F(\rho/2)$ value. The p_F dependence of $\tilde{\Phi}_{\Delta}$ would only arise in next order in the b/a_{Δ} expansion (due to the recoil contribution). Therefore, in approximation (14) the value Π_{Δ} depends only on the total density.

The regular parts Π_{reg} of the polarization operator in the case of one or two Fermi spheres are also essentially the same since Π_{reg} depends only on the total density. According to refs. [4,6] one has

$$\Pi_{reg}(\omega, k) \simeq -0.25\omega^2(\rho/\rho_0) + 0.25m_{\pi}^2(\rho/\rho_0) + 0.5(\rho/\rho_0)k^2. \quad (15)$$

Besides the above mentioned contributions to the pion polarization operator, an extra contribution Π_{rel} due to the relative motion of the projectile and the spectator nucleonic matter arises in the laboratory frame. Due to the kinetic energy transformation from a frame moving with $\vec{v} \simeq \vec{p}_{lab}/m_N^*(\rho/2)$ velocity to the rest frame follows

$$E = E' + \vec{P}\vec{v}. \quad (16)$$

where

$$\vec{P} = (2\omega - \frac{\partial \text{Re}\Pi}{\partial \omega}) \vec{k} \frac{1}{2} \vec{\varphi}^2 V, \quad (17)$$

is the pion field momentum, and V is the volume of the system. This change of energy corresponds to an additional contribution to the pion polarization operator (see ref. [9])

$$\Pi_{rel} \simeq -(2\omega - \frac{\partial \text{Re}\Pi}{\partial \omega}) \vec{k}\vec{v}. \quad (18)$$

At $N = Z$, neglecting Coulomb effects on the critical value of the condensate frequency one has $\omega \simeq 0$. For the perpendicular modes ($\vec{k}\vec{v} = 0$) the sum of the Δ isobar part of the self-energy and the regular part Π_{reg} is approximately the same as for the equilibrium system and $\Pi_{rel} = 0$. On the other hand the particle-hole contribution Π_P to the pion polarization operator in the case of two interpenetrating beams is substantially more attractive than for the case of the equilibrium system.

We estimate the critical density for pion condensation in two interpenetrating beams as $\rho_c \simeq (0.3 - 0.5)\rho_0$ instead of $\rho_c^{eq} \simeq (2 - 4)\rho_0$ for the equilibrium system of the same total density ρ . Thus at $\rho_{opaq} > \rho > \rho_c$ a pion condensate with $\vec{k}_0 \perp \vec{p}_{lab}$, $k_0 \simeq (2 - 3)m_\pi$, $\omega \simeq 0$ may develop.

In a slightly isospin asymmetric system ($(N - Z)/A \ll 1$) as gold the pion polarization operator acquires an additional correction which is mainly due to the S -wave part of the polarization operator. One approximately has (for π^-) [5,4]

$$\delta\Pi(\omega, k) \simeq 0.7\omega(\rho_n - \rho_p)m_\pi/\rho_0. \quad (19)$$

As a result the value $2\omega - \partial\Pi/\partial\omega$ becomes finite at $\omega = 0$ and from Eqs. (8) and (18) one has $\cos\theta \sim +10^{-2}$ for the angle between $\vec{k}_0$ and $\vec{p}_{lab}$. Oppositely for π^+ one obtains $\cos\theta \sim -10^{-2}$. This would indicate slightly different rapidity distributions

for π^+ and π^- . Otherwise the pion condensate peaks correspond approximately to target and projectile rapidities. For $p_{lab} \simeq 1.7m_N, k_\perp \simeq 3m_\pi$ we estimate

$$y_{lab} \simeq \frac{1}{2} \ln \frac{E + p_\parallel}{E - p_\parallel} \simeq \frac{1}{2} \ln \frac{4p_\parallel^2}{k_\perp^2} \simeq 2. \quad (20)$$

In order to be sure that the condensate indeed arises in heavy ion collisions we estimate a typical time necessary for a virtual pion to be driven to the condensate. In accordance with Eq. (7) one has $\tau_{cond} \leq 1fm/c$. This value is still smaller than a typical life-time of the composite system estimated as follows

$$\tau_{life} \sim l_\parallel/v \sim 6fm/c \quad (21)$$

How can a condensate pion having zero energy radiate into the vacuum? For this we need to estimate the desintegration time of the composite system. Let the maximum value of the composite system volume V_m be achieved at time $t \simeq t_0$. At this moment the condensate has its maximum value $|\varphi_{cond}|^2 V_m$, where φ_{cond} is the classical pion condensate field. At $t > t_0$ the condensate volume diminishes. Then the density jumps from ρ inside the overlap region to $\rho/2 < \rho_c$ in the respective spectator nucleus. A typical time for nucleons to pass this density jump region can be roughly estimated as follows

$$\tau_b \sim v^{-1} |\rho^{-1/3} - 2^{1/3}\rho^{-1/3}|, \quad (22)$$

where $\rho^{-1/3}$ is a typical interparticle distance in the composite system and $2^{1/3}/\rho^{1/3}$ is the same value outside the composite system. Estimate of (22) for 1 GeV/A energy gives $\tau_b \sim (0.4 - 0.5)fm/c$. On the other hand the typical time necessary for a condensate pion with energy $\omega \simeq 0$ to reach the free pion branch $\omega \simeq \sqrt{m_\pi^2 + k^2}$ is as follows

$$\tau_{med}^{vac} \simeq \frac{1}{(m_\pi^2 + k_0^2)^{1/2}} \sim (0.4 - 0.7)fm/c. \quad (23)$$

Thus one has $\tau_b \leq \tau_{med}^{vac}$. Let us assume $\tau_b < \tau_{med}^{vac}$, then the breakup of the condensate system can be considered as sudden and the pionic state does not change (see ref. [6])

and refs. therein).

$$\langle t_0 + \tau_b || |\varphi|^2 | t_0 + \tau_b \rangle \simeq \langle t_0 - \tau_b || |\varphi|^2 | t_0 - \tau_b \rangle \simeq |\varphi_{cond}|^2, \quad (24)$$

where φ_{cond} is the classical condensate field. The pion distribution after the collision is given by

$$d^3 N_{\pi-} / d^3 k / (2\pi)^3 = 2V_m (m_\pi^2 + k_0^2)^{1/2} |\varphi_{cond}|^2 \delta(\vec{k} - \vec{k}_0). \quad (25)$$

So, we expect a pronounced peak in the pion distributions at $k_\perp \simeq (2 - 3)m_\pi$ for rather peripheral collisions.

For the running wave $\pi^{+,-}$ condensate field one has

$$\varphi_{cond}^+ \simeq f_\pi \sin \theta_c(\vec{r}) \exp(i\vec{k}_0 \vec{r}), \quad (26)$$

here $f_\pi \simeq 93$ MeV is the pion decay constant and $\theta_c(\vec{r})$ is the chiral angle. The number of condensed π^+ with $k \simeq k_0$ is equal to the number of π^- whereas the number of π^0 is zero. More complicated solutions are also possible. E.g. one also may consider the isotopically symmetric form of the condensate field

$$\vec{\varphi}_{cond} = f_\pi \sin \theta_c(\vec{r}) \left(\frac{\cos \vec{k}_0 \vec{r}}{2^{1/2}}, \frac{\cos \vec{k}_0 \vec{r}}{2^{1/2}}, \sin \vec{k}_0 \vec{r} \right) \quad (27)$$

with equal strength of π^0 field and of π^+ and π^- . Which form of the condensate field is realized depends on the specificity of the system dynamics. For a system of finite size we estimate

$$\sin \theta_c(\vec{r}) \sim \sin \theta_c(\rho) / l_{cond} \rho^{1/3} \sim 1/3, \quad (28)$$

where $\sin \theta_c(\rho) \simeq 1/2$ is the condensate field in infinite nuclear matter at density $\rho \simeq 0.7\rho_0$ and the condensate field decreases on a length scale $l_{cond} \simeq (2 - 3)fm$. The latter value is still larger than the internuclear distance from which nucleons decouple, as mentioned above. Then applying (25) with φ_{cond} from (26) one has

$$N_{\pi-} / N_p \simeq 0.5, \quad (29)$$

where N_p is the number of protons in the small overlap volume V_m .

In the presence of the condensate the fermion quasiparticle states [3] become mixtures of nucleons, deltas and condensate pions. For a condensate field of the form (26) one has a π^- wave in $\vec{k}_0$ direction and a π^+ one in $-\vec{k}_0$ direction. The nucleon momentum is changed in the two Fermi spheres

$$\vec{p} \rightarrow \vec{p} - (\vec{k}\tau_3/2)\cos\theta_c, \quad \vec{p} \rightarrow \vec{p} - (\vec{k}\tau_3/2)\cos\theta_c + \vec{p}_{lab}, \quad (30)$$

τ_3 is the corresponding isotopic Pauli matrix. This is in accordance to the reactions $p \rightarrow n + \pi^+$ and $n \rightarrow p + \pi^-$. So, one can expect a peak not only in the pion distribution at $k_\perp \sim k_0 \sim (2-3)m_\pi$ but also in proton (at $\vec{k}_0/2$) and neutron ($-\vec{k}_0/2$) distributions. The anticorrelation between the $\pi^+(\vec{k}_0)$ and $\pi^-(-\vec{k}_0)$ directions would be an additional signature of the running wave condensate field. Some momentum correlation also exists between the pion $\pi^+(\vec{k}_0)$ and the proton ($\vec{k}_0/2$) or between $\pi^-(-\vec{k}_0)$ and neutron ($-\vec{k}_0/2$). All these correlations have to be established for each individual collision since both the direction of $\vec{k}_0$ and the nucleus, i.e. target or projectile-nucleus in which the condensation occurs vary from collision to collision.

For the charge density in the condensate we estimate (at $N \simeq Z$)

$$\rho_\pi \simeq 2V_{Coul} |\varphi|^2 \left(1 - \frac{\partial^2 \Pi}{2\partial\omega^2} \Big|_0\right) > 0, \quad (31)$$

where V_{Coul} is the Coulomb field of the nucleus. As a result due to the reaction channel $p \rightarrow n + \pi^+$ an excess of π^+ in the condensate may arise.

To conclude: We propose the observation of a pion condensate via pronounced peaks for π^+ and (or π^- and π^0) mesons with $k_\perp \sim k_0 \simeq (2-3)m_\pi$ in rather peripheral nuclear collisions ($b \simeq (1-1.7)R$). The condensate arises in the nuclear matter corresponding to rather large rapidities ($y_{lab} \sim 2$).

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Figure Caption

A typical overlap region and density profiles. Atomic weight $A \simeq 200$, $b \simeq 1.5R$. Lorentz contraction is taken into account for $1\text{ GeV}/A$ collision energy. Hatched area is composite system under consideration.