Quarkyonic phase induced by Rotation

The 7th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

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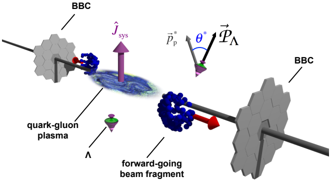
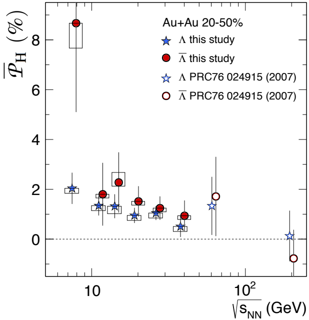
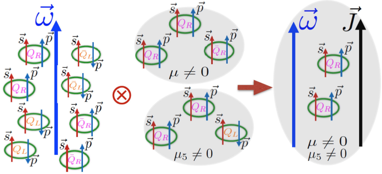
- The Most Vortical Fluid (Nature 548, 62 (2017)).

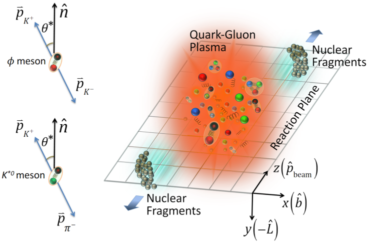




Angular momentum at the order of $10^4 \sim 10^5 \hbar$!

- Rotation gives rise to lots of interesting phenomena...





The rotation effect suppresses the chiral condensate!

A (very incomplete) list of references on chiral condensate
Y. Jiang, J. Liao, Phys. Rev. Lett. 117(19) (2016).
H.-L. Chen, K. Fukushima, X.-G. Huang, K. Mameda, Phys. Rev. D 93(10) (2016).
S. Ebihara, K. Fukushima, K. Mameda, Phys. Lett. B 764 (2017) 94-99.
M. Chernodub, S. Gongyo, J. High Energy Phys. 01 (2017) 136, Phys. Rev. D 95(9) (2017) 096006.
X. Wang, M. Wei, Z. Li, M. Huang, Phys. Rev. D 99(1) (2019) 016018.
H. Zhang, D. Hou, J. Liao, Chin. Phys. C 44(11) (2020) 111001.

How the rotation affects the deconfinement phase transition is still highly debated . . .

X. Chen, L. Zhang, D. Li, D. Hou, and M. Huang, JHEP 07, 132 (2021).
Y. Fujimoto, K. Fukushima, and Y. Hidaka, Phys. Lett. B 816, 136184 (2021).
M. Chernodub, Phys. Rev. D 103, 054027 (2021).
V. V. Braguta, A. Y. Kotov, D. D. Kuznedelev, and A. A. Roenko, Phys. Rev. D 103, 094515 (2021).

PNJL model incorporates confinement effects in the NJL...

What are the influences of rotation on the QCD phase structure?

How does the interplay between chiral and deconfinement phase transitions?

The Lagrangian in the two-flavor NJL model under rotation:

$$\mathcal{L}_{NJL} = \sum \bar{\psi}_f \left\{ i\bar{\gamma}^\mu(\partial_\mu + \Gamma_\mu) - m + \gamma^0 \mu \right\} \psi_f + G(\bar{\psi}\psi)^2, \quad (2.1)$$

The Lagrangian of Polyakov-loop extended NJL model under rotation

$$\mathcal{L}_{PNJL} = \mathcal{L}_{NJL} + \bar{\psi}\gamma^\mu A_\mu \psi - \mathcal{U}(\Phi, \bar{\Phi}, T), \quad (2.2)$$

$$\Phi = \frac{1}{N_c} \langle \mathrm{tr} L \rangle , \bar{\Phi} = \frac{1}{N_c} \left\langle \mathrm{tr} L^\dagger \right\rangle , L(\bar{x}) = \mathcal{P}\exp[i \int_0^\beta d\tau A_4(\bar{x}, \tau)] \quad (2.3)$$

Expanding the Lagrangian up to the first order of angular velocity, the PNJL model under rotation has the form:

$$\mathcal{L}_{PNJL} = \bar{\psi}\left[i\gamma^{\mu}D_{\mu} - m + \gamma^{0}\mu + \left(\gamma^{0}\right)^{-1}\left(\left(\vec{\omega}\times\vec{x}\right)\cdot\left(-i\vec{\partial}\right) + \vec{\omega}\cdot\vec{S}_{4\times4}\right)\right]\psi + G\left(\bar{\psi}\psi\right)^{2} - \mathcal{U}(\Phi[A],\bar{\Phi}[A],T),$$

Carrying out the mean field approximation and the path integral formulation

$$\log Z = -\frac{1}{T}\int d^{3}x\left(\frac{(M-m)^{2}}{4G}\right) + 2\log\det\frac{D^{-1}}{T}$$

$$D^{-1} = \begin{pmatrix} \left(-i\omega_l + \left(n+\frac{1}{2}\right)\omega + \mu - iA_4\right) - M & -\vec{\sigma}.\vec{p} \\ \vec{\sigma}.\vec{p} & -\left(-i\omega_l + \left(n+\frac{1}{2}\right)\omega + \mu - iA_4\right) - M \end{pmatrix}$$

$$\log \det \frac{\hat{D}^{-1}}{T} = tr \log \frac{\hat{D}^{-1}}{T} = \int d^3x \int \frac{d^3p}{(2\pi)^3} \left\langle \psi_p(x) \left| \log \frac{\hat{D}^{-1}}{T} \right| \psi_p(x) \right\rangle .$$

Considering the eigenstate of the complete set of commutating operators $\{\hat{H}, \hat{p}_z, \hat{p}_t^2, \hat{J}_z, \hat{h}_t\}$

$$u = \frac{1}{2}\sqrt{\frac{E+m}{E}} \begin{pmatrix} e^{ip_z z} e^{in\theta} J_n(p_t r) \\ s e^{ip_z z} e^{i(n+1)\theta} J_{n+1}(p_t r) \\ \frac{p_z - isp_t}{E+m} e^{ip_z z} e^{in\theta} J_n(p_t r) \\ \frac{-sp_z + ip_t}{E+m} e^{ip_z z} e^{i(n+1)\theta} J_{n+1}(p_t r) \end{pmatrix},$$

$$v = \frac{1}{2}\sqrt{\frac{E+m}{E}} \begin{pmatrix} \frac{p_z - isp_t}{E+m} e^{-ip_z z} e^{in\theta} J_n(p_t r) \\ \frac{-sp_z + ip_t}{E+m} e^{-ip_z z} e^{i(n+1)\theta} J_{n+1}(p_t r) \\ e^{-ip_z z} e^{in\theta} J_n(p_t r) \\ -s e^{-ip_z z} e^{i(n+1)\theta} J_{n+1}(p_t r) \end{pmatrix}.$$

Taking trace over color space and using $\Omega = -\frac{T}{V}\log\mathcal{Z}$ we obtain

$$
\begin{aligned}
&\Omega_{PNJL} = \\
&G\langle\bar{q}q\rangle^2 - \frac{1}{4\pi^2}\sum_{n=-\infty}^{\infty}\int_0^{\Lambda} \mathrm{p}_t d\mathrm{p}_t \int_{-\sqrt{\Lambda^2-p_t^2}}^{\sqrt{\Lambda^2-p_t^2}} dp_z \left(\left(J_{n+1}(\mathrm{p}_t r)^2 + J_n(\mathrm{p}_t r)^2\right) T \times\right. \\
&\left\{\log\left[1 + 3\Phi e^{-\frac{\varepsilon_n-\mu}{T}} + 3\bar{\Phi}e^{-2\frac{\varepsilon_n-\mu}{T}} + e^{-3\frac{\varepsilon_n-\mu}{T}}\right] + \log\left[1 + 3\bar{\Phi}e^{\frac{\varepsilon_n-\mu}{T}} + 3\Phi e^{2\frac{\varepsilon_n-\mu}{T}} + e^{3\frac{\varepsilon_n-\mu}{T}}\right]\right. \\
&\left.+\log\left[1 + 3\bar{\Phi}e^{-\frac{\varepsilon_n+\mu}{T}} + 3\Phi e^{-2\frac{\varepsilon_n+\mu}{T}} + e^{-3\frac{\varepsilon_n+\mu}{T}}\right] + \log\left[1 + 3\Phi e^{\frac{\varepsilon_n+\mu}{T}} + 3\bar{\Phi}e^{2\frac{\varepsilon_n+\mu}{T}} + e^{3\frac{\varepsilon_n+\mu}{T}}\right]\right\} \\
&+\mathcal{U}(\Phi, \bar{\Phi}, T).
\end{aligned}
$$

here, $\varepsilon_n = \sqrt{(m - 2G\langle\bar{q}q\rangle)^2 + p_t^2 + p_z^2} - \left(\frac{1}{2} + n\right)\omega$ with the dynamic quark mass $M = m - 2G\langle\bar{q}q\rangle$

$$\frac{\mathcal{U}}{T^4} = -\frac{1}{2}b_2(T)\Phi\bar{\Phi} - \frac{b_3}{6}\left(\Phi^3 + \bar{\Phi}^3\right) + \frac{b_4}{4}\left(\Phi\bar{\Phi}\right)^2.$$

$$b_2(T) = a_0 + a_1\frac{T_0}{T} + a_2\left(\frac{T_0}{T}\right)^2 + a_3\left(\frac{T_0}{T}\right)^3.$$

Stationary condition

$$\frac{\partial\Omega}{\partial\langle\bar{q}q\rangle} = 0, \quad \frac{\partial\Omega}{\partial\Phi} = 0, \quad \frac{\partial\Omega}{\partial\bar{\Phi}} = 0.$$

Causality condition

$\omega r < 1$

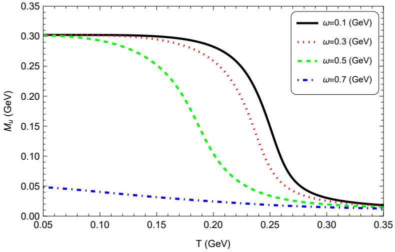
Input parameters

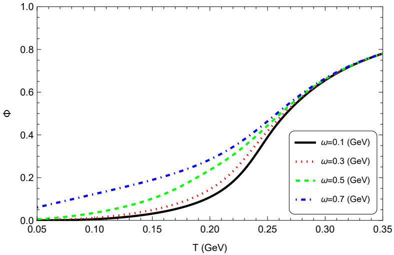
$m = 0.005$ GeV, $\Lambda = 0.65$ GeV, $G = 4.93\,\text{GeV}^{-1}$, $n = 0, \pm1, \pm2\ldots$, $r = 0.1\,\text{GeV}^{-1}$.

a_0	a_1	a_2	a_3	b_3	b_4	T_0
6.75	-1.95	2.625	-7.44	0.75	7.5	0.27 GeV

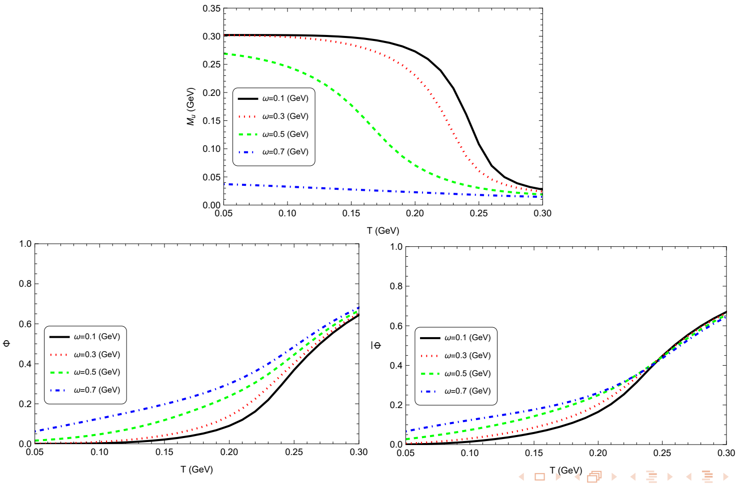
Table: Parameters of the Polyakov sector of the model.

- The light quark effective mass and Polyakov loop as functions of temperature T at $\mu = 0$ GeV for different angular velocities.

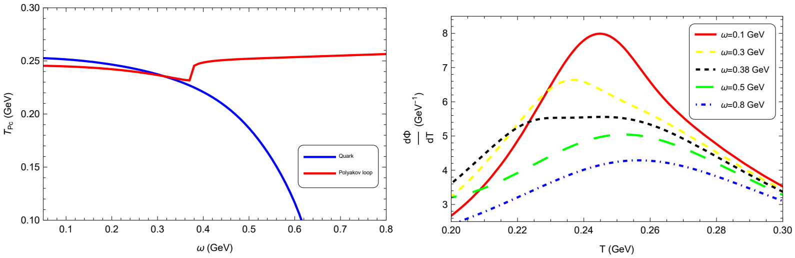




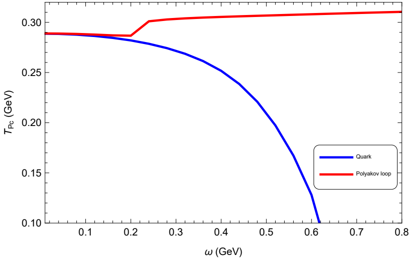
- The light quark mass and the Polyakov loops as functions of temperature at $\mu = 0.1$ GeV for different angular velocities.



- Pseudocritical temperatures of the quark and Polyakov loop according angular velocity at zero chemical potential (left panel). Susceptibilities $d\Phi/dT$ as function of temperature at zero chemical potential for different angular velocities (right panel).



- Pseudocritical temperatures of the quark and Polyakov loop according angular velocity at zero chemical potential with $T_0 = 0.32$ GeV.



We focus on the rotational effect of the coupling between the quark and gauge field on the chiral transition and deconfinement transition…

Conlusion 1

The effect of the rotation plays an important role in the chiral transition.

Conlusion 2

The deconfinement transition is not so sensitive (compared to the chiral transition) to the presence of the rotating effect.

Conlusion 3

The chiral dynamics and gluon dynamics can be splitted by rotation, which means a quarkyonic phase can be induced by rotation.

Thank you for your attention ! !