Vorticity in heavy-ion collisions at NICA

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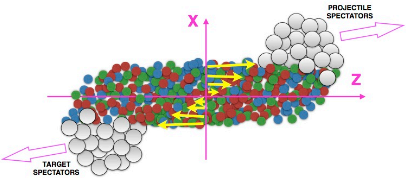
Relativistic Kinematic Vorticity



Large angular momentum

$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

where $u_\mu =$ collective local four-velocity of the matter,
is relevant to the **chiral vortical effect**

that leads to contribution to the electromagnetic current

$$J^\kappa_{\mathrm{e}} = \frac{N_c}{4\pi^2 N_f} \varepsilon^{\kappa\lambda\mu\nu} \partial_\mu \mathbf{u}_\nu \, \partial_\lambda \left(\theta \sum_j e_j \mu_j \right)$$

N_c and N_f are the number of colors and flavors respectively,
e_j and μ_j are the electric charge and chemical potential of a particle of j flavor
and θ **is the topological QCD field**.

Relativistic Thermal Vorticity

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \hat{\beta}_\mu - \partial_\mu \hat{\beta}_\nu),$$

where $\hat{\beta}_\mu = \hbar\beta_\mu$ and $\beta_\mu = u_\nu / T$ with $T =$ the local temperature.

ϖ is dimensionless.

ϖ is related to **the polarization vector,** $\Pi^\mu(p)$**, of a spin 1/2 particle** in a relativistic fluid [F. Becattini, et al., Annals Phys. **338**, 32 (2013)]

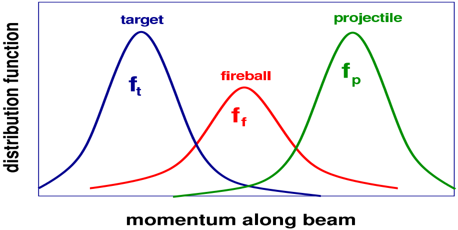
$$\Pi^\mu(p) = \frac{1}{8m} \frac{\int_\Sigma \mathrm{d}\Sigma_\lambda p^\lambda n_F (1 - n_F)\, p_\sigma \epsilon^{\mu\nu\rho\sigma} \partial_\nu \beta_\rho}{\int_\Sigma \Sigma_\lambda p^\lambda \, n_F},$$

where n_F is the Fermi-Dirac-Juttner distribution function,
the integration runs over the freeze-out hypersurface Σ.

3FD Equations of Motion

Produced particles populate mid-rapidity

$\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J^\mu_t = 0$ $\qquad$ $\partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}$

Leading particles carry bar. charge $\qquad$ exchange/emission

Projectile-like fluid: $\partial_\mu J^\mu_p = 0,$ $\qquad$ $\partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}$

Fireball fluid: $J^\mu_f = 0,$ $\qquad$ $\partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}$

Baryon-free fluid $\qquad$ Source term $\qquad$ Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0$$

Hydrodymanic densities

Baryon current:

$J_\alpha^\mu = n_\alpha u_\alpha^\mu$

n_α = baryon density of α-fluid

u_α^μ = 4-velocity of α-fluid

Energy-momentum tensor:

$T_\alpha^{\mu\nu} = (\varepsilon_\alpha + P_\alpha) u_\alpha^\mu u_\alpha^\nu - g_{\mu\nu} P_\alpha$

ε_α = energy density

P_α = pressure

+ Equation of state:

$$P = P(n, \varepsilon)$$

Physical Input

- **Equation of State**

  crossover EoS [Khvorostukhin, Skokov, Redlich, Toneev, (2006)]

- **Friction**

  calculated in hadronic phase (Satarov, SJNP 1990)

  fitted to reproduce the baryon stopping in QGP phase

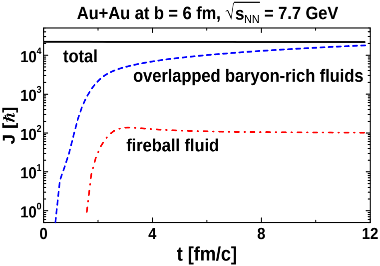
- **Freeze-out**

  When system becomes dilute, hydro has to be stopped

  Freeze-out energy density ε_{frz} = 0.4 GeV/fm^3

Below we consider Au+Au collisions at $b = 6$ fm

3FD vorticity at NICA energies



angular momentum *J* vs time

J of the f-fluid is $\sim$ 100 lower than that of the overlapped baryon-rich fluids.

The energy in the fireball fluid is $\sim$ 10 lower than that in the baryon-rich fluids.

Therefore, the baryon-rich fluids dominate.

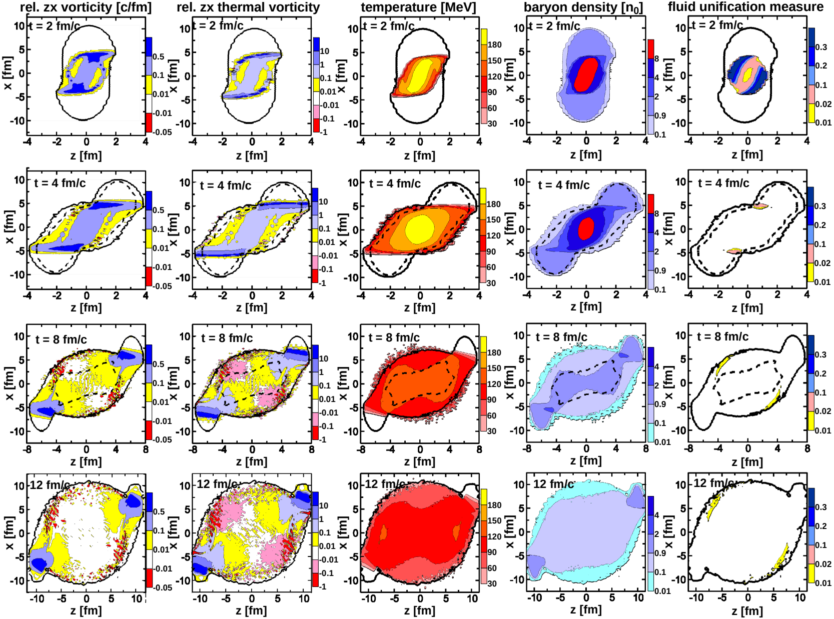
4-velocity of the baryon-rich matter $= u_B^\mu = J_B^\mu/|J_B|$,
where $J_B^\mu = n_p u_p^\mu + n_t u_t^\mu$ is the total baryon current.

The temperature [required by the thermal vorticity]

$$T_B = \sum_{\alpha=p,t} T_\alpha \varepsilon_\alpha \Big/ \sum_{\alpha=p,t} \varepsilon_\alpha$$

(proper-energy-density-weighted temperature)

vorticity in reaction plane at $\sqrt{s_{NN}} = 7.7$ GeV

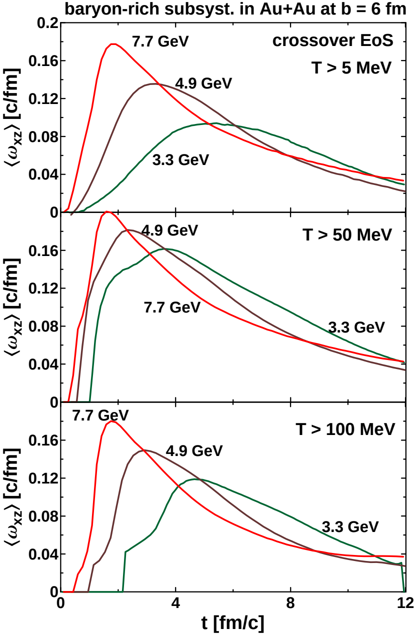


fluid unification measure $= 1 - (n_p + n_p)/n_B$ [$= 0$ if p and t fluids are unified]

observations

- kinematic and thermal vorticity reaches peak values at the participant-spectator border
- thermal vorticity reaches extremely high peak values also because of strong gradients of the temperature at the border.
- the vorticity in the participant bulk gradually dissolves in the course of time and practically disappears to the end of the collision
- **Conclusion:** relative polarization of Λ hyperons should be higher in the fragmentation regions than in the midrapidity region

Kin. vorticity averaged with energy density



biased averaged quantities

- $T > 5$ MeV
- $T > 50$ MeV
- $T > 100$ MeV

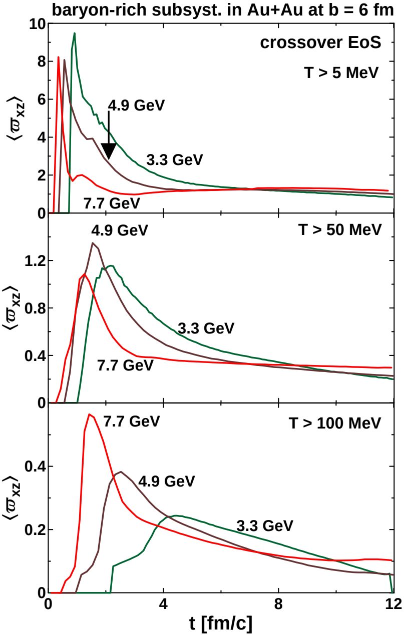
to test the effect of the participant-spectator border.

$\langle \omega_{zx} \rangle$ **weakly depends on** T **constraint.**

$\langle \omega_{zx} \rangle$ **is almost independent of** $\sqrt{s_{NN}}$ **at "freeze-out" stage.**

Final-stage values are compatible with those at $\sqrt{s_{NN}} = 5$ GeV [O. Teryaev and R. Usubov, Phys. Rev. C **92**, 014906 (2015)] within the HSD and at $\sqrt{s_{NN}} = 8$ GeV [L. P. Csernai, et al., Phys. Rev. C **90** 021904 (2014)] in the rel. PICR hydro.

T-vorticity averaged with energy density



biased averaged quantities

- $T > 5$ MeV
- $T > 50$ MeV
- $T > 100$ MeV

to test the effect of the participant-spectator border.

$\langle\varpi_{zx}\rangle$ strongly depends on T cutoff because of strong T gradients at the border.

$\langle\varpi_{zx}\rangle$ is almost independent of $\sqrt{s_{NN}}$ at "freeze-out" stage.

Even at $T_0 = 100$ MeV cut-off, $\langle\varpi_{zx}\rangle$ at $\sqrt{s_{NN}} = 7.7$ GeV essentially exceeds those of [L. P. Csernai, et al., Phys. Rev. C 90 021904 (2014)] for $\sqrt{s_{NN}} = 8$ GeV.

Only 150 MeV cutoff makes these values compatible.

Summary

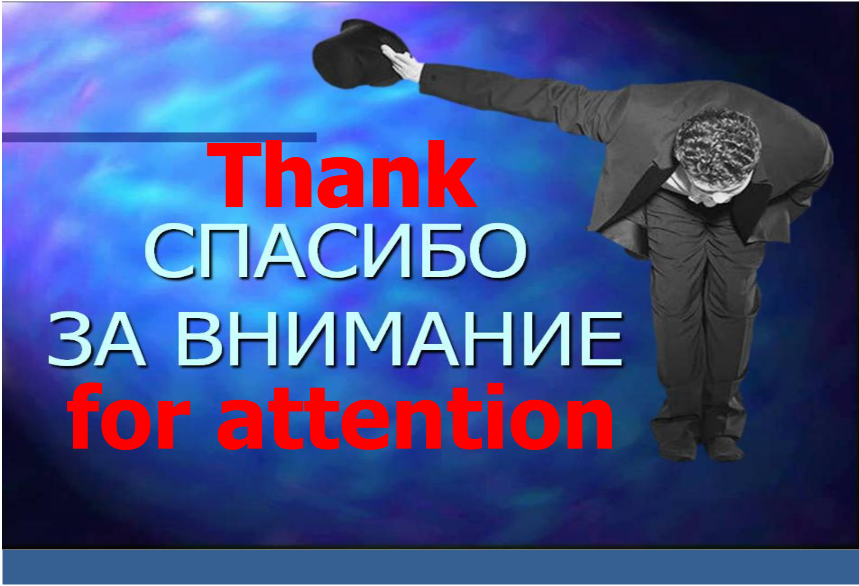
- **the vorticity mainly takes place at the border between participant and spectator matter**

  This effect was noticed in

  [M. I. Baznat, K. K. Gudima, A. S. Sorin and O. V. Teryaev, Phys. Rev. C **93**, 031902 (2016); **88**, 061901 (2013)] in the QGSM.

- **this effect is essentially enhanced for the thermal vorticity** because of strong temperature gradients at the participant-spectator border.

- **the Λ-hyperon polarization should be stronger at peripheral rapidities,** corresponding to the participant-spectator border, than that in the midrapidity region.


Thank
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ЗА ВНИМАНИЕ
for attention