Particle Polarization and Structure of Vortical Field in Relativistic Heavy-Ion Collisions

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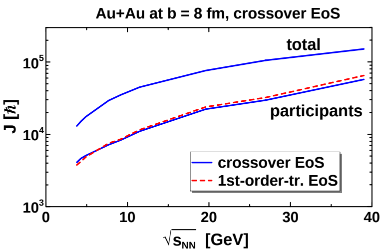
Vorticitical motion of nuclear matter

Large angular momentum



Relativistic nuclear collision

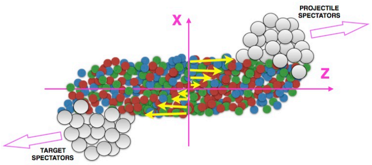


Fig. from Becattini, et al., PRC **95**, 54902 (2017)

Vortical motion: $\vec{\omega} = (1/2)\vec{\nabla} \times \vec{v}$ **= Vorticity**

Relativistic Kinematic Vorticity

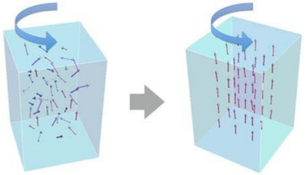
$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

u_μ = collective local 4-velocity of the matter

Observation of vorticitical motion

- **Vorticity induces alignment of particle spin along its direction**

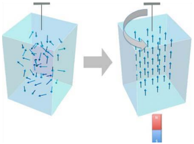
  analogy wiht Barnett effect (1915):
  magnetization by rotation



- **a fraction of orbital momentum of body rotation is transformed into spin angular momentum**

  Reverse effect:
  Einstein-de Haas effect (1915):

- rotation by magnetization



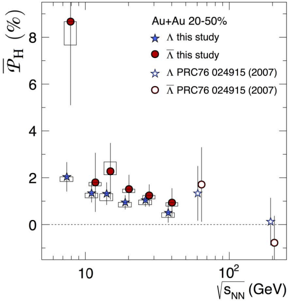
Global Λ and $\bar{\Lambda}$ polarization

- Due to parity violating weak decays
  $\Lambda \longrightarrow p + \pi^-$ **and** $\bar{\Lambda} \longrightarrow \bar{p} + \pi^+$**,**
  Λ and $\bar{\Lambda}$ hyperons are self-analyzing
  p ($\bar{p}$) direction is associated with Λ ($\bar{\Lambda}$) spin in its rest frame

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_\Lambda \mathbf{P}^*_\Lambda \cos\theta^*)$$

$*$ means Λ's rest frame, $\alpha_\Lambda = 0.642$ is Λ's decay constant

- Global Λ and $\bar{\Lambda}$ polarization was measured by STAR collaboration [Nature **548**, 62 (2017)]



Thermodynamic approach to Λ polarization

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

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

n_F = Fermi-Dirac distribution function,
integration over the freeze-out hypersurface Σ.

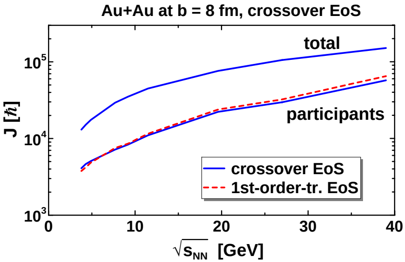
"'**an educated ansatz for the Wigner function** of the Dirac field"'

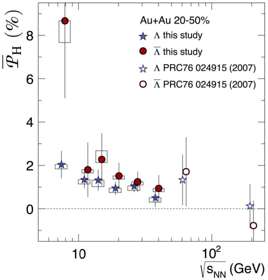
Three-Fluid Dynamics (3FD)

- Is the **3FD*** **model** with the thermodynamic approach for polarization consistent with observed Λ polarization?

  [*] Ivanov, Russkikh and Toneev, PRC **73**, 044904 (2006)

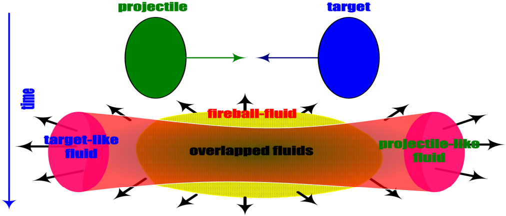
- **Why does the polarization decrease with $\sqrt{s_{NN}}$ while J increases?**





3FD Equations of Motion

Produced particles populate mid-rapidity $\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad\partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

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

Projectile-like fluid: $\partial_\mu J_p^\mu = 0$, $\quad\partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0$, $\quad\partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

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

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

Hydrodymanic densities

Baryon current:

$J^{\mu}_{\alpha} = n_{\alpha} u^{\mu}_{\alpha}$

n_{α} = baryon density of α-fluid

u^{μ}_{α} = 4-velocity of α-fluid

Energy-momentum tensor:

$T^{\mu\nu}_{\alpha} = (\varepsilon_{\alpha} + P_{\alpha}) u^{\mu}_{\alpha} u^{\nu}_{\alpha} - g_{\mu\nu} P_{\alpha}$

ε_{α} = energy density

P_{α} = pressure

+ Equation of state:

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

Physical Input

- **Equation of State**
  crossover EoS and 1st-order-phase-transition (1PT) EoS
  [Khvorostukhin, Skokov, Redlich, Toneev, (2006)]

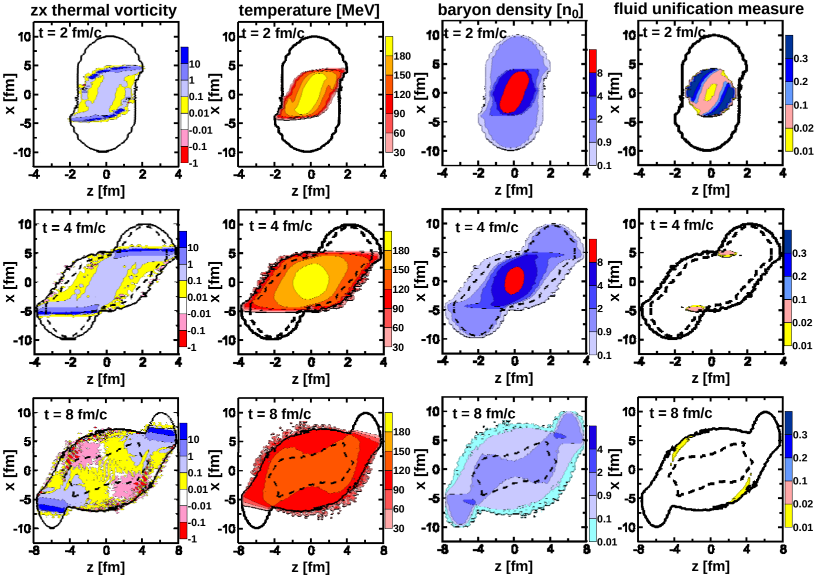
- **Friction**
  calculated in hadronic phase (Satarov, SJNP 1990)
  fitted to reproduce the baryon stopping in QGP phase

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

All parameters of the 3FD model are exactly the same as in calculations of other (bulk and flow) observables

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

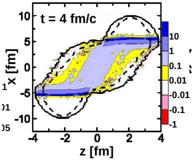
Au+Au ($b = 6$ fm)



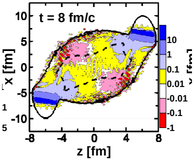
fluid unification measure $= 1 - (n_p + n_p)/n_B$ [$= 0$ if p and t fluids are unified]

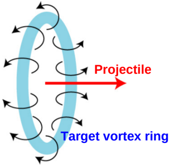
observations

- Vorticity reaches peak values at the participant-spectator border

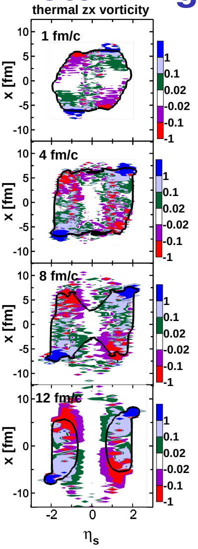


- the vorticity in the participant bulk gradually dissolves in the course of time
- **Conclusion:** relative polarization of Λ hyperons should be higher in the fragmentation regions than in the midrapidity region
- Ring-like structure in fragmentation regions





Votex rings

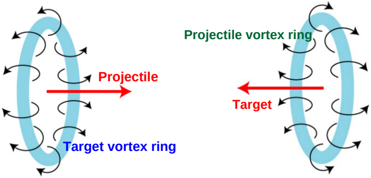


$$\eta_s = \frac{1}{2} \ln \left(\frac{t+z}{t-z} \right)$$

longitudinal space-time rapidity

Central ($b = 2$ fm) Au+Au
at $\sqrt{s_{NN}} = 39$ GeV

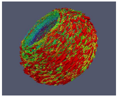
at high energies strong votex rings



[Ivanov, Soldatov, PRC **97**, 044915 (2018)]

are formed even in central collisions

because of transparency of colliding nuclei

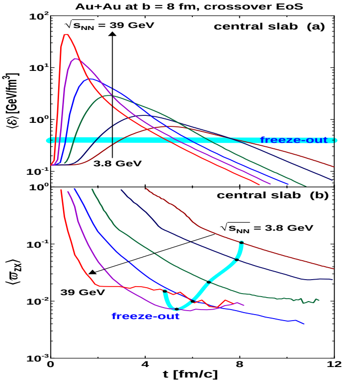
Femto-vortex sheets  at lower energies [Baznat, Gudima, Sorin, Teryaev, PRC 93 (2016) 031902]

Estimation of Polarization

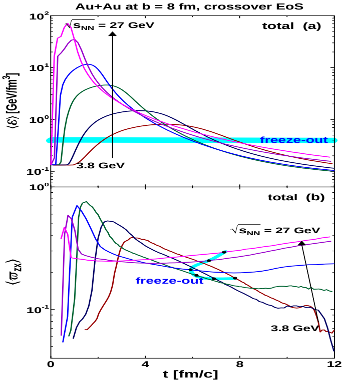
based on mean vorticity $\langle\varpi_{\mu\nu}\rangle$ and isochronous freeze-out.
$\langle\varpi_{\mu\nu}\rangle$ averaged over

"midrapidity", i.e. central slab:

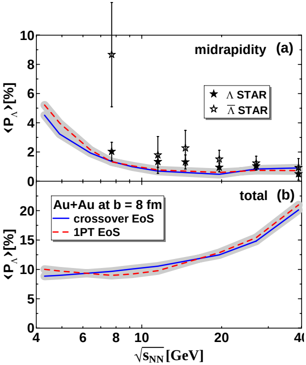
$|x| < R - b/2$, $|y| < R - b/2$, $|z| < R/\gamma_{cm}$



total participant region



Midrapidity and Total Polarization



with the energy, $\sqrt{s_{NN}}$, rise

- the vorticity is stronger pushed out to the fragmentation regions
- **(a)** therefore, the **midrapidity polarization decreases**
- **(b)** while the **total polarization increases**
- votex rings in fragmentation regions become more pronounced

Estimation of uncertainty:

$\sim$ 20% (for midrapidity)

$\sim$ 30% (for total)

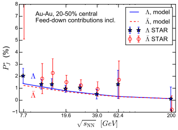
Ivanov, Toneev, Soldatov, PRC **100** (2019)

Summary

- **Global Λ polarization is consistent with our understanding of collision dynamics within 3FD**
- **vorticity is pushed out to fragmentation regions, therefore**
  - **the midrapidity polarization decreases**
  - **while the total polarization increases with energy rise**
- **Prediction:** **the Λ polarization should be stronger at peripheral rapidities** than that in the midrapidity region
- **Prediction:** at high collision energies, **strong vortex rings are formed in fragmentation regions**
- **Prediction:** Midrapidity polarization at NICA/FAIR energies is higher than at BES RHIC

THANK YOU
for your
ATTENTION!

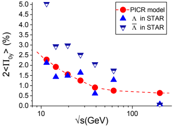
Results of thermodynamic $\Lambda(\bar{\Lambda})$ polarization



UrQMD+vHLLE model

Karpenko, Becattini,

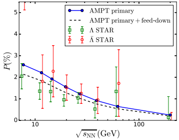
EPJC **77**, 213 (2017)



PICR hydrodynamics

Xie, Wang, Csernai

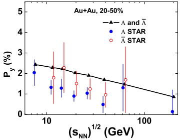
PRC **95**,031901 (2017)



AMPT model

Li, Pang, Wang, Xia

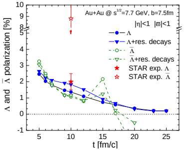
PRC **96**, 054908 (2017)



AMPT model

Sun and Ko,

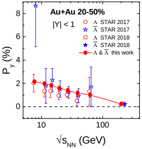
PRC **96**, 024906 (2017)



PHSD Model

Kolomeitsev,Toneev,Voronyuk

PRC **97**, 064902 (2018)



AMPT model

Wei, Deng, Huang,

PRC**99**,014905(2019)

- Global Λ polarization is consistent with our understanding of collision dynamics

  However
- Problem with $\bar{\Lambda}$ polarization at 7.7 GeV, if any
- There are other approaches

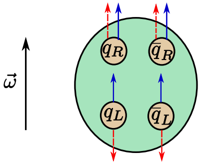
Polarization due to axial vortical effect

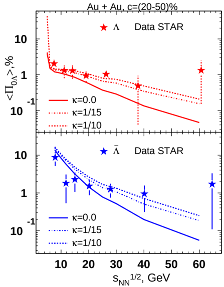
Relativistic Kinematic Vorticity = $\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$

u_μ = collective local 4-velocity of the matter,

is relevant to the **axial vortical effect**
[Rogachevsky, Sorin, Teryaev, PRC **82**, 054910 (2010)
Gao, Liang, Pu, Wang and Wang, PRL 109, 232301 (2012)]

$$\text{strange axial current} = J^\nu_{5s} = N_c \int d^3x \left(\frac{\mu_s^2}{2\pi^2} + \kappa\frac{T^2}{6}\right) \epsilon^{\nu\alpha\beta\gamma} u_\alpha \partial_\beta u_\gamma$$





$$\text{polarization} = \langle \Pi^\Lambda \rangle = \left\langle \frac{m_\Lambda}{N_\Lambda\, p_y} J^0_{5s} \right\rangle$$

μ_s = chemical potential of s-quark, T = temperature,

κ = a variable parameter,

p_y = Λ's momentum transverse to reaction plane

Baznat, Gudima, Sorin, Teryaev

PRC 97, 041902 (2018)