Vorticity and Particle Polarization in Relativistic Heavy-Ion Collisions

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"Finite and infinite Fermi systems", 20-22 March 2019, JINR BLTP

Vorticitical motion of nuclear matter

Large angular momentum

Relativistic nuclear collision

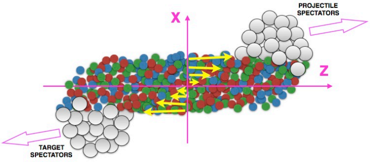
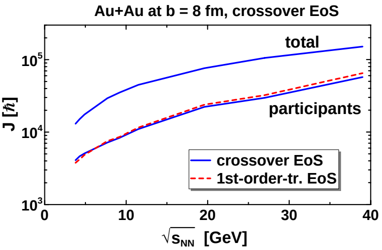


Fig. from Becattini, et al., PRC **95**, 54902 (2017)



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

Relativistic Kinematic Vorticity

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

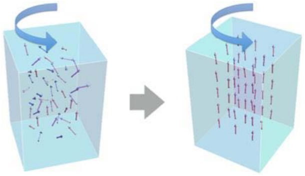
where u_μ = collective local 4-velocity of the matter

Observation of vorticitical motion

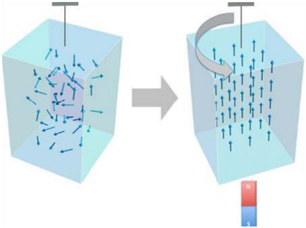
- **Vorticity induces alignment of particle spin along its direction**

- This global polarization is analog of 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



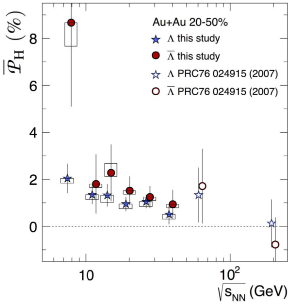
Global Λ and $\bar{\Lambda}$ polarization

- 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

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

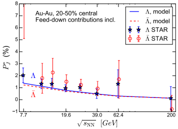
where $\hat{\beta}_\mu = \hbar\beta_\mu$ and $\beta_\mu = u_\nu / T$ with $T =$ the local temperature.
ϖ is dimensionless.

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)]

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

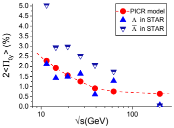
where n_F is the Fermi-Dirac-Juttner distribution function,
the integration runs over the freeze-out hypersurface Σ.

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



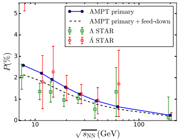
UrQMD+vHLLE model

I. Karpenko and F. Becattini, Eur. Phys. J. C **77**, no. 4, 213 (2017)



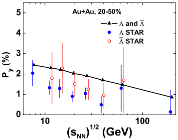
PICR hydrodynamics

Y. Xie, D. Wang and L. P. Csernai, Phys. Rev. C **95**, no. 3, 031901 (2017)



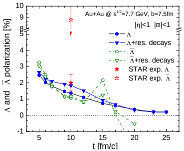
AMPT model

H. Li, L. G. Pang, Q. Wang and X. L. Xia, Phys. Rev. C **96**, no. 5, 054908 (2017)



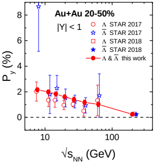
AMPT model

Y. Sun and C. M. Ko, Phys. Rev. C **96**, no. 2, 024906 (2017)



PHSD Model

E. E. Kolomeitsev, V. D. Toneev and V. Voronyuk, Phys. Rev. C **97**, no. 6, 064902 (2018)



AMPT model

D. X. Wei, W. T. Deng and X. G. Huang, Phys. Rev. C **99**, no. 1, 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

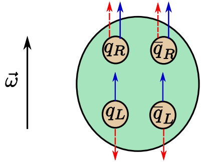
Relativistic Kinematic Vorticity = $\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$

u_μ = collective local 4-velocity of the matter,

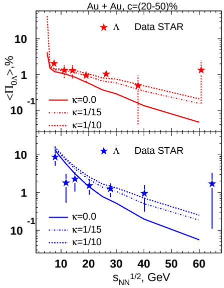
is relevant to the **axial vortical effect**

[O. Rogachevsky, A. Sorin and O. Teryaev, Phys. Rev. C **82**, 054910 (2010)]

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



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



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

κ = a variable parameter,

p_y = Λ's momentum transverse to reaction plane

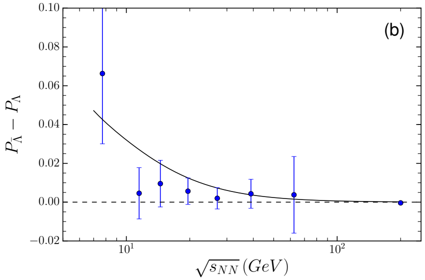
M. Baznat, K. Gudima, A. Sorin and O. Teryaev,

Phys. Rev. C 97, no. 4, 041902 (2018)

Walecka-like spin-orbital interaction

L. P. Csernai, J. I. Kapusta and T. Welle, Phys. Rev. C **99**, no. 2, 021901 (2019)

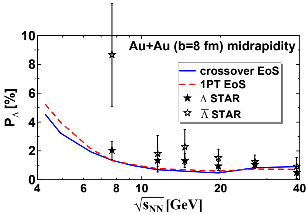
- Nuclear spin-orbit interaction as it is in Walecka model
- No real simulations – just an idea
- Applied to explain the difference in polarizations of Λ's and $\bar{\Lambda}$'s measured by STAR



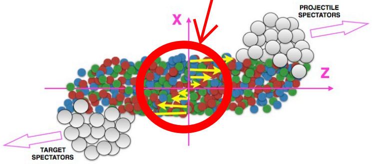
just an estimate

Three-Fluid Dynamics (3FD)

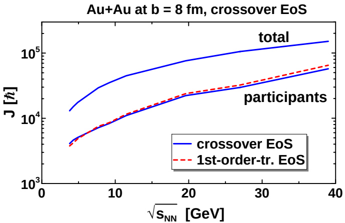
3FD model based on
the thermodynamic approach
also reproduces Λ polarization



STAR polarization was
measured in **midrapidity region**



Prediction:
Polarization is even higher
at NICA/FAIR energies



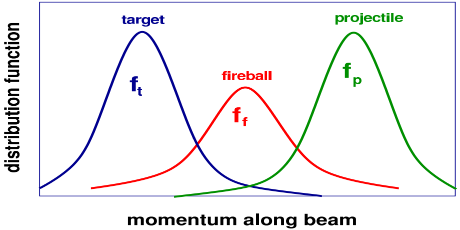
Why polarization decreases with $\sqrt{s_{NN}}$
while angular momentum increases?

Further discussion is within the 3FD model

Y. B. Ivanov, V. N. Russkikh and V. D. Toneev, Phys. Rev. C **73**, 044904 (2006)

3FD Equations of Motion

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



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

Leading particles carry bar. charge — exchange/emission

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

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

Baryon-free fluid — Source term — 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:

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

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)]

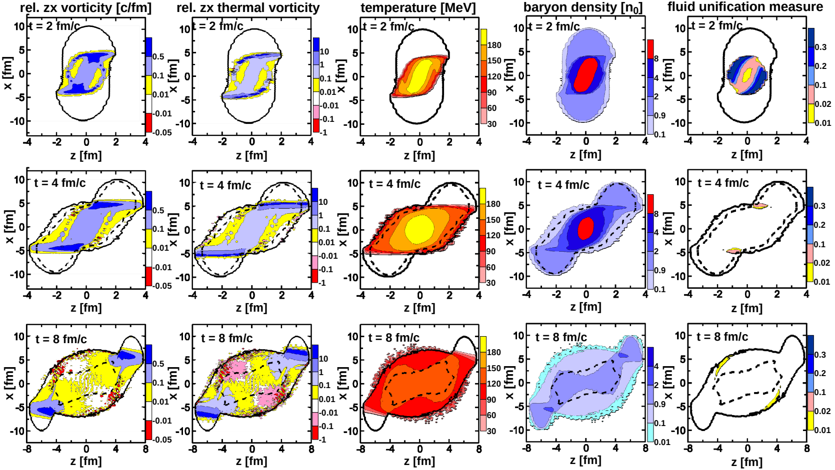
- **Friction**
  calculated in hadronic phase (Satarov, SJNP 1990)
  fitted to reproduce the baryon stopping in QGP phase

- **Freeze-out**
  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

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

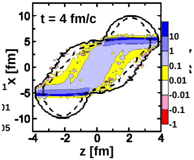
Reaction plane in Au+Au ($b = 6$ fm) at $\sqrt{s_{NN}} = 7.7$ GeV



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

observations

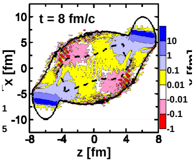
- Vorticity reaches peak values at the participant-spectator border

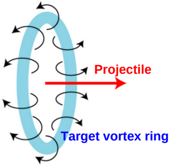


- the vorticity in the participant bulk gradually dissolves in the course of time

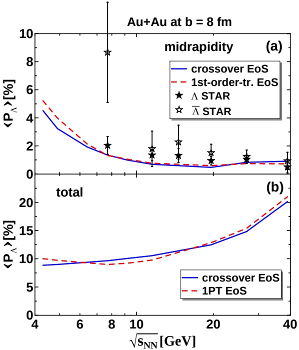
- **Conclusion:** relative polarization of Λ hyperons should be higher in the fragmentation regions than in the midrapidity region

- Ring-like structure in fragmentation regions





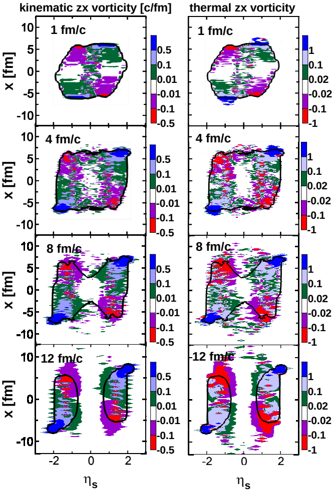
Midrapidity and Total Polarization



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

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

Votex rings



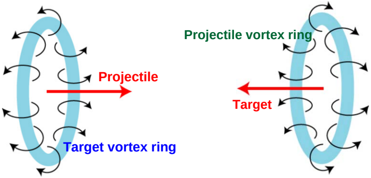
$$\eta_s = \frac{1}{2} \ln \left(\frac{t+z}{t-z} \right)$$

longitudinal space-time rapidity

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

at high energies

strong votex rings are formed

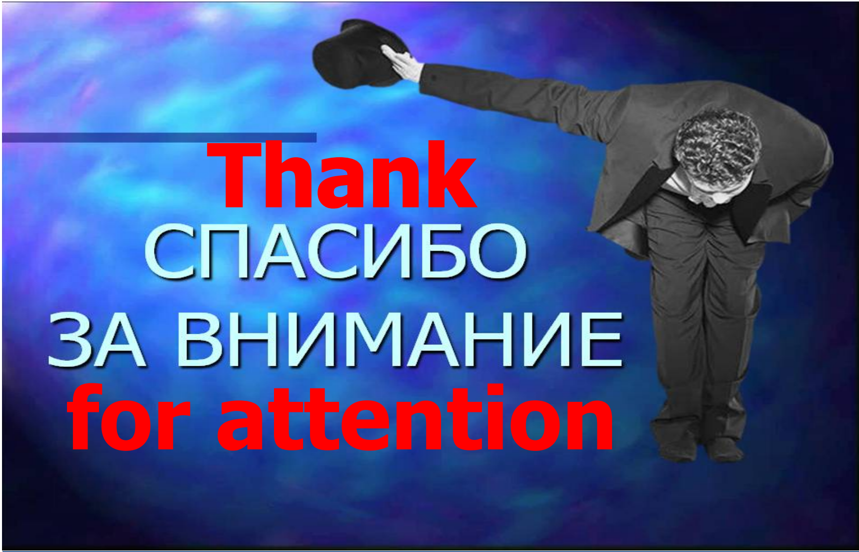


even in central collisions

because of transparency
of colliding nuclei

Summary

- **Particle polarization gives us access to new degrees of freedom in heavy-ion collisions**
- **Global Λ polarization is consistent with our understanding of collision dynamics**
- **Prediction: the Λ polarization should be stronger at peripheral rapidities** corresponding to the participant-spectator border, than that in the midrapidity region
- **Prediction: at high collision energies, strong votex rings are formed in fragmentation regions**


Thank
СПАСИБО
ЗА ВНИМАНИЕ
for attention