Axial Vortical Effect and polarization of resonances in heavy-ion collisions

1805.12029, 1911.04545, 2109.06048

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24th International Spin Symposium (SPIN2021), Matsue, Shimane Prefecture, Japan
18 to 22 October 2021

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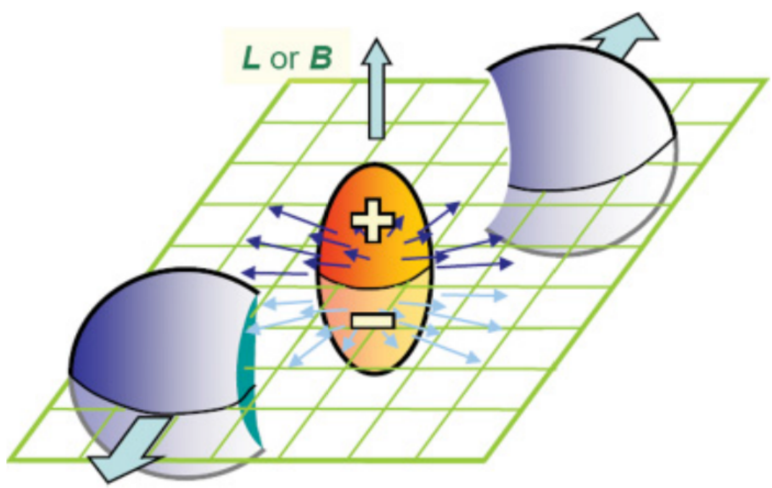
Introduction

Introduction and motivation

In noncentral collisions of heavy ions, **huge magnetic fields** and a **huge angular momentum** arise. *Differential* rotation - different at different points: **vorticity** and vortices.

– Rotation 25 orders of magnitude *faster* than the rotation of the Earth:

the vorticity is about 10^{22} sec^{-1}



- **Acceleration** is of the **same order** of magnitude as vorticity (as the components of the same tensor).

[I. Karpenko and F. Becattini, Nucl. Phys., A982:519–522, 2019]

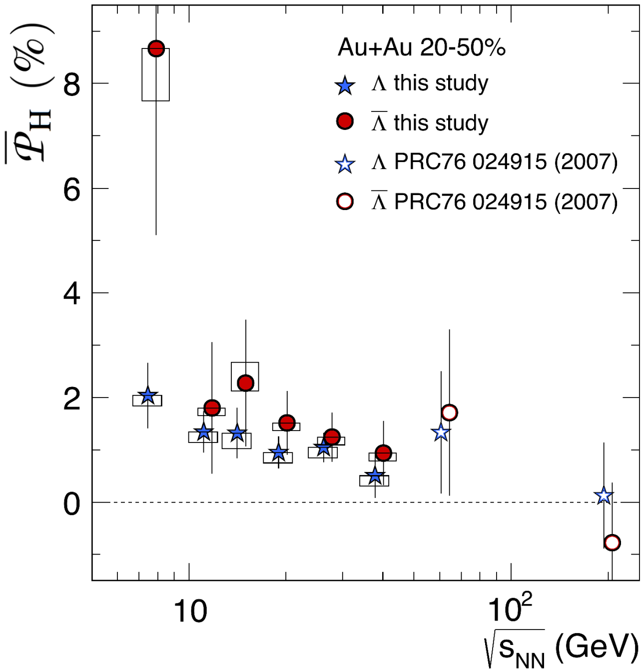
- *Another mechanism*: accelerations due to the tension of the hadron string (acceleration is much higher – of the order of Λ_{QCD})

$$e^+e^- \to \gamma^* \to q\bar{q} \to \text{ hadrons}$$

[P. Castorina, D. Kharzeev, H. Satz, Eur. Phys. J., C52:187–201, 2007]

Introduction and motivation

The orbital angular momentum transforms into polarization - an analogue of the Barnett effect.



[Nature 548 (2017) 62-65 arXiv:1701.06657 [nucl-ex]]

Look Zuo-tang Liang talk.

- Generation of **hyperon polarization**.
- Both **vorticity** and **acceleration** are essential for polarization.
- Also described based on **Chiral Vortical Effect (CVE)** [Rogachevsky, Sorin, Teryaev, Phys.Rev.C82(2010) 054910], [Baznat, Gudima, Sorin, Teryaev, Phys.Rev.C93, no.3,031902 (2016)]

$$\textbf{CVE:} \quad \langle j_\mu^5 \rangle = \left(\frac{T^2}{6} + \frac{\mu^2}{2\pi^2} \right) \omega_\mu$$

– **Qualitative and quantitative correspondence!**

- – Polarization from quantum anomaly ~ *spin crisis* and *gluon anomaly*: [Efremov, Soffer, Teryaev, Nucl.Phys.B 346 (1990) 97-114]

  proton spin → hyperon polarization,
  gluon field → chemical potential*4-velocity

- Also described on the basis of a thermodynamic approach (Wigner function): [I. Karpenko, F. Becattini, Nucl.Phys.A 982 (2019) 519-522]

Introduction and motivation

Chiral anomaly

gauge part

gravitational part

$$\nabla_\mu j_5^\mu = -\frac{Q^2 e^2}{16\pi^2\sqrt{-g}}\varepsilon^{\mu\mu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} + \frac{1}{384\pi^2\sqrt{-g}}\varepsilon^{\mu\mu\rho\sigma}R_{\mu\nu\kappa\lambda}R_{\rho\sigma}{}^{\kappa\lambda}$$

Holography

- *[K. Landsteiner, E. Megias, F. Pena-Benitez. Phys. Rev. Lett. 107, 021601 (2011).]*
- *[M. Stone and J. Kim, Phys. Rev. D98, no. 2, 025012 (2018).]*
- *[S. P. Robinson, F. Wilczek Phys.Rev.Lett. 95 (2005) 011303 MIT-CTP-3561 gr-qc/0502074.]*

Although the gravitational chiral anomaly **is not important** in **volume**, it is significant at the **boundary** or at the **horizon**.

Gauge chiral anomaly and CVE

$$j_5^\mu = n_5 u^\mu + \frac{\mu^2+\mu_5^2}{2\pi^2}\omega^\mu + \frac{\mu}{2\pi^2}B^\mu$$

[D. T. Son and P. Surowka, Phys. Rev. Lett. 103 (2009) 191601.]

[A. V. Sadofyev, V. I. Shevchenko and V. I. Zakharov, Phys. Rev. D 83 (2011) 105025.]

Gravitational part

$$j_5^\lambda = (\frac{T^2}{6} + \frac{\mu^2+\mu_5^2}{2\pi^2})\omega^\lambda$$

Vorticity and acceleration in hydrodynamics

CVE: Wigner function vs Zubarev operator

Calculation based on the **Zubarev density operator** [F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys., 338:32-49, 2013] :

$$\langle j^5_\mu \rangle_\rho (m=0) = \left(\frac{1}{6}\left[T^2 + \frac{|\omega|^2}{4\pi^2}\right] + \frac{\mu^2}{2\pi^2} + \frac{|a|^2}{8\pi^2} \right)\omega_\mu$$

Calculation based on the **Wigner function** [M. Buzzegoli, E. Grossi, and F. Becattini, JHEP, 10:091, 2017] :

$$\langle j^5_\mu \rangle_W (m=0) = \left(\frac{1}{6}\left[T^2 + \frac{|\omega|^2 - |a|^2}{4\pi^2}\right] + \frac{\mu^2}{2\pi^2} \right)\omega_\mu + \frac{1}{12\pi^2}(\omega a)\, a_\mu$$

- The CVE and corrections to it were calculated in both approaches (the emergent anomaly in thermodynamics).
- Nonconservation of current from the Wigner function → solved in Zubarev approach.
- Higher order terms → to be related to other types of quantum anomalies.

Vorticity as a real chemical potential and acceleration as an imaginary potential

The **vorticity** enters the formulas as a **real chemical potential**:

$$\mu \to \mu \pm \frac{\Omega}{2}$$

If we consider also the **acceleration**, then:

$$\boxed{\mu \to \mu \pm \frac{\Omega}{2} \pm \frac{i|\boldsymbol{a}|}{2}}$$

Acceleration appears as **imaginary chemical potential!**

[G. Prokhorov, O. Teryaev and V. Zakharov, Phys. Rev. D 98, no. 7, 071901 (2018).]

Consequence: *instability* below the Unruh temperature

[G. P., O. V. Teryaev, V. I. Zakharov, Phys. Rev., D100(12):125009, 2019]

Chiral vortical effect for spin 3/2: result

After summation of all the contributions, the next formula for CVE for **spin 3/2** is obtained from *Zubarev operator* **[2109.06048]**:

$$\boxed{\langle \hat{j}_A^{\nu} \rangle^{(1)} = \left(\frac{5T^2}{6} + \frac{5\mu^2}{2\pi^2} \right) \omega^{\nu}}$$

Chiral anomaly for **spin 3/2** was *[Stephen L. Adler. Phys. Rev. D, 97(4):045014, 2018]*:

$$\langle \partial_\mu \hat{j}_A^{\mu} \rangle = -\frac{5}{16\pi^2} \varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}$$

The relationship with anomaly is checked for higher spins!!!

Duality

Main idea

It will be shown that the **statistical** approaches used to describe **heavy ion collisions** lead to the same results as field theory in **curved space-time**.

This will allow us to conclude that the **duality exists**.

Thus, one can either use physics in *curved* space to describe effects in the *microworld of particle interactions*, or make a prediction for *curved space* based on *statistics*.

Density operator

Zubarev density operator

[D. N. Zubarev, A. V. Prozorkevich, S. A. Smolyanskii, TMF, 40:3:394–407, 1979],
[M. Buzzegoli, E. Grossi, and F. Becattini, JHEP, 10:091, 2017]

$$\hat{\rho} = \frac{1}{Z} \exp\left\{ - \int_{\Sigma} d\Sigma_\mu [\hat{T}^{\mu\nu}(x)\beta_\nu(x) - \xi(x)\hat{j}^\mu(x)] \right\}$$

- A technique for calculating the effects of medium motion (*vorticity* and *acceleration*) has been developed.
- **CVE** and *corrections* to it were obtained [G.Y., O.V. Teryaev, V.I. Zakharov, JHEP, 02:146, 2019].
- Close statistical methods have been used to describe processes in **heavy-ion collisions** [I. Karpenko and F. Becattini, Nucl. Phys., A982:519–522, 2019].
- Explanation of **hadron polarization** due to vorticity.

Effects of acceleration from Zubarev operator: results

$$\langle \hat{T}^{\mu\nu} \rangle^0_{\text{fermi}} = \Big(\frac{7\pi^2 T^4}{60} + \frac{T^2|a|^2}{24} - \frac{17|a|^4}{960\pi^2}\Big) u^\mu u^\nu - \Big(\frac{7\pi^2 T^4}{180} + \frac{T^2|a|^2}{72} - \frac{17|a|^4}{2880\pi^2}\Big) \Delta^{\mu\nu} + \mathcal{O}(a^6)$$

$$\langle \hat{T}^{\mu\nu} \rangle^0_{\text{real}} = \Big(\frac{\pi^2 T^4}{30} + \frac{T^2|a|^2}{12} - \frac{11|a|^4}{480\pi^2}\Big) u^\mu u^\nu - \Big(\frac{\pi^2 T^4}{90} - \frac{T^2|a|^2}{18} + \frac{19|a|^4}{1440\pi^2}\Big) \Delta^{\mu\nu} + \Big(\frac{T^2}{12} - \frac{|a|^2}{48\pi^2}\Big) a^\mu a^\nu + \mathcal{O}(a^6)\,.$$

The energy-momentum tensor **vanishes** at the **Unruh temperature**

$$\boxed{\langle \hat{T}^{\mu\nu} \rangle = 0 \qquad (T = T_U)}$$

Thus, a consequence of the **Unruh effect** is **justified** .

[F. Becattini, Phys.Rev.D 97 (2018)]

[G. Y., O. V. Teryaev, and V. I. Zakharov. JHEP, 03:137, 2020]

Space-time with conical singularity

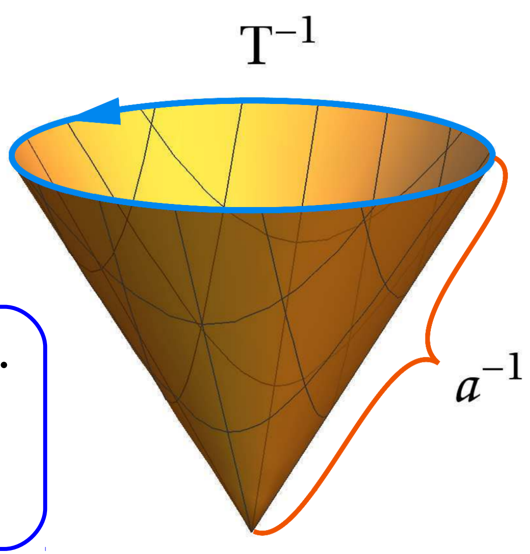
The effects of acceleration can also be investigated from the point of view of an **accelerated observer**. In this case, the **Rindler coordinates** are to be used:

$$ds^2 = -r^2 d\eta^2 + dr^2 + d\mathbf{x}_\perp^2$$

Passing to imaginary time:

$$ds^2 = \boxed{r^2 d\eta^2 + dr^2} + d\mathbf{x}_\perp^2$$

It describes a flat two-dimensional cone with an angular deficit $2\pi - a/T$.
This metric contains a **conical singularity** at $r = 0$.



Dictionary for translation
Thermodynamic characteristics in *Geometrical*:

Inverse **acceleration** $\Longleftrightarrow$ **distance** from the **vertex**.

Inverse proper **temperature** $\Longleftrightarrow$ **circumference**.

[G. Y., O. V. Teryaev, and V. I. Zakharov. JHEP, 03:137, 2020]

The duality of statistical and geometric approaches

The following expressions were obtained for the vacuum value of T_2^2 in spacetime with a cosmic string [V. P. Frolov and E. M. Serebryanyi, Phys. Rev. D 35, 3779 (1987)]

String:

$$\langle T_2^2 \rangle_{s=0} = \frac{\nu^4}{480\pi^2 r^4} + \frac{\nu^2}{48\pi^2 r^4} - \frac{11}{480\pi^2 r^4}$$

$$\langle T_2^2 \rangle_{s=1/2} = \frac{7\nu^4}{960\pi^2 r^4} + \frac{\nu^2}{96\pi^2 r^4} - \frac{17}{960\pi^2 r^4}$$

The coincidence will be for **massive** fields as well

Passing to the Euclidean Rindler spacetime, we obtain

Rindler:

$$\rho_{s=0} = \frac{\pi^2 T^4}{30} + \frac{T^2|a|^2}{12} - \frac{11|a|^4}{480\pi^2},$$

$$\rho_{s=1/2} = \frac{7\pi^2 T^4}{60} + \frac{T^2|a|^2}{24} - \frac{17|a|^4}{960\pi^2}$$

= Zubarev

The obtained expressions **correspond** to the energy calculated using the **Zubarev density operator** in inertial frame.

[G. Y., O. V. Teryaev, and V. I. Zakharov. JHEP, 03:137, 2020]

Conclusions

Conclusions

1. The Chiral vortical effect (CVE) and corrections to it in various thermodynamic approaches (Wigner function and Zubarev operator) were obtained → indirect connection of these appraches with chiral anomalies.

2. The role of vorticity and acceleration as real and imaginary chemical potentials is shown.

3. The relationship between CVE and chiral anomaly in the case of higher spins (spin 3/2) is checked.

4. The duality of hydrodynamics and gravity is shown: the approach with the Zubarev density operator ↔ space with a conical singularity (black hole, cosmic strings...).

Conclusions

There is an intriguing possibility of extracting information about the fundamental properties of matter - quantum anomalies and the physics of curved space-time (black holes and cosmic strings) - from hydrodynamics in heavy ion collisions.

Thank you for attention!