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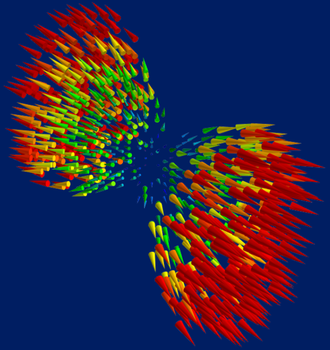
27–31 Oct 2025
Europe/Moscow timezone

The acceleration and the Unruh temperature in the heavy-ion collisions at the NICA complex energies

Phys.Rev.C 107 (2023) 3 & *Particles* 6 (2023) 1 &
Particles 7 (2024) 4 & *Phys.Rev.C* 111 (2025) 3 &

arXiv:2502.10146



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28 Oct 2025

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† *The research supported by the grants of JINR №25-301-06 and BASIS #25-1-5-80-1*

The introduction and motivation

The Most Intriguing Fluid in Nature

The strongly interacting nearly ideal fluid

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NUCLEAR PHYSICS A
Nuclear Physics A 757 (2005) 1–27

Quark–gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment

Abstract

We review the main results obtained by the BRAHMS Collaboration on the properties of hot and dense hadronic and partonic matter produced in ultrarelativistic heavy ion collisions at RHIC. A particular focus of this paper is to discuss to what extent the results collected so far by BRAHMS, and by the other three experiments at RHIC, can be taken as evidence for the formation of a state of deconfined partonic matter, the so-called quark–gluon plasma (QGP). We also discuss evidence for a possible precursor state to the QGP, i.e., the proposed color glass condensate.

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Nuclear Physics A 757 (2005) 28–101

The PHOBOS perspective on discoveries at RHIC

PHOBOS Collaboration

Abstract

This paper describes the conclusions that can be drawn from the data taken thus far with the PHOBOS detector at RHIC. In the most central Au + Au collisions at the highest beam energy, evidence is found for the formation of a very high energy density system whose description in terms of simple hadronic degrees of freedom is inappropriate. Furthermore, the constituents of this novel system are found to undergo a significant level of interaction. The properties of particle production at RHIC energies are shown to follow a number of simple scaling behaviors, some of which continue trends found at lower energies or in simpler systems. As a function of centrality, the total number

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Nuclear Physics A 757 (2005) 102–183

Experimental and theoretical challenges in the search for the quark–gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions

STAR Collaboration

Abstract

We review the most important experimental results from the first three years of nucleus–nucleus collision studies at RHIC, with emphasis on results from the STAR experiment, and we assess their interpretation and comparison to theory. The theory-experiment comparison suggests that central Au + Au collisions at RHIC produce dense, rapidly thermalizing matter characterized by: (1) initial energy densities above the critical values predicted by lattice QCD for establishment of a quark–gluon plasma (QGP); (2) nearly ideal fluid flow, marked by constituent interactions of very short mean free path, established most probably at a stage preceding hadron formation; and (3) opacity to jets. Many of the observations are consistent with models incorporating QGP formation in the early collision stages, and have not found ready explanation in a hadronic framework. However, the

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Nuclear Physics A 757 (2005) 184–283

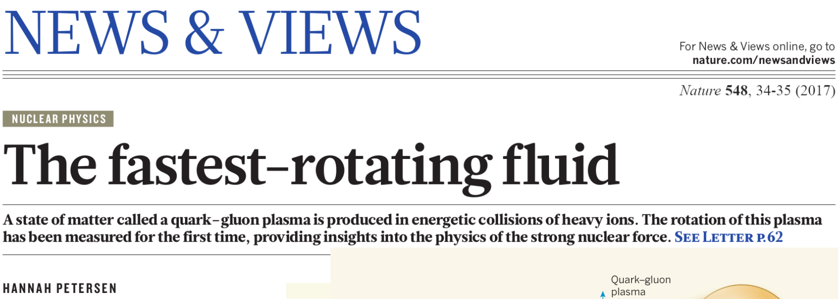
Formation of dense partonic matter in relativistic nucleus–nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration

PHENIX Collaboration

Abstract

Extensive experimental data from high-energy nucleus-nucleus collisions were recorded using the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC). The comprehensive set of measurements from the first three years of RHIC operation includes charged particle multiplicities, transverse energy, yield ratios and spectra of identified hadrons in a wide range of transverse momenta (p_T), elliptic flow, two-particle correlations, nonstatistical fluctuations, and suppression of particle production at high p_T. The results are examined with an emphasis on implications for the formation of a new state of dense matter. We find that the state of matter created at RHIC cannot be described in terms of ordinary color neutral hadrons.

The fastest rotating fluid



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Nature **548**, 34-35 (2017)

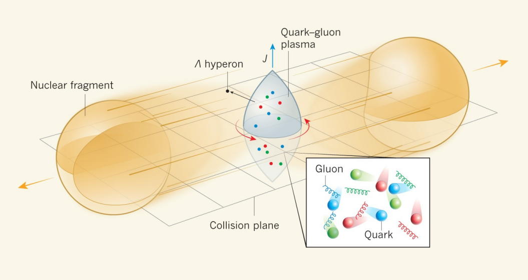
NUCLEAR PHYSICS

The fastest-rotating fluid

A state of matter called a quark–gluon plasma is produced in energetic collisions of heavy ions. The rotation of this plasma has been measured for the first time, providing insights into the physics of the strong nuclear force. SEE LETTER P.62

HANNAH PETERSEN

- The collective dynamics of heavy-ion collisions can produce emergent phenomena, like *spin polarization*.
- The observed global polarization of Λ and $\overline{\Lambda}$ in heavy-ion collisions suggests that *a quark-gluon plasma may be the fastest-rotating fluid in nature*.



More about the motivation

- Rotating gluons *increase* the phase transition temperature, while the rotating fermions *decrease* it [*V. V. Braguta et al.'20'21*]
- The rotation and acceleration influence on the phase transition [*M. N. Chernodub et al.'17'24'25*]
- **The Unruh effect** in the heavy-ion collisions [*D. Kharzeev'06*, *F. Becattini'18*, *G. Yu. Prokhorov, O. V. Teryaev, and V. I. Zakharov'19'23*]
- The predictions of the large *magnetic* [*V. Skokov, A. Y. Illarionov, and V. Toneev'09*] and *electric* [*H. Taya, T. Nishimura, and A. Ohnishi'24*] fields $\Longrightarrow$ *large vorticity and acceleration?*
- *Negative moment of inertia* of the QGP [*V. V. Braguta et al.'23'24*]
- Pion vortices in rotating systems [*D. N. Voskresensky'24'25*]
- A lot of results within the framework of the holographic models, effective approaches, (in-)direct QFT calculations...

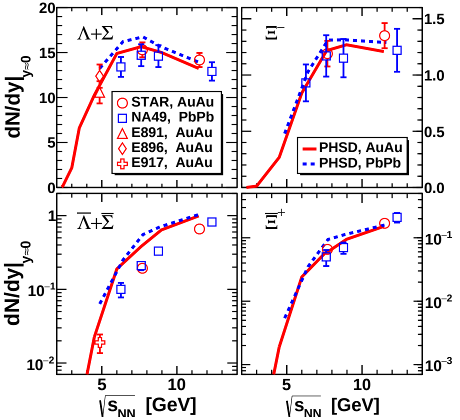
The setup

The PHSD transport model and the particles-to-medium transition

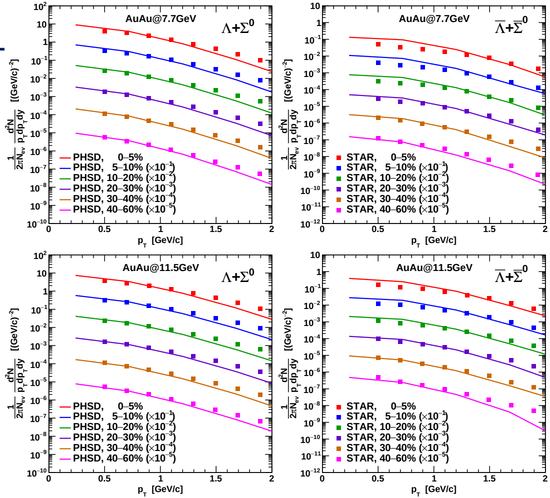
The PHSD transport model

The **PHSD transport model**† as a heavy-ion collisions framework: based on **the Kadanoff-Baym equations** (on-shell and off-shell dynamics, first gradient expansion, test particles ansatz), **DQPM** (parton phase), **FRITIOF Lund** (hard scattering), **Chiral Symmetry Restoration** (strangeness production), ...

† *W. Cassing, E.L. Bratkovskaya*, *Phys. Rev. C* **78** (2008); *Nucl. Phys. A* **831** (2009); ...



V. Voronyuk, N.S. Tsegelnk, E.E. Kolomeitsev, *Phys.Rev.C* **111** (2025) 3



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The particles-to-medium transition

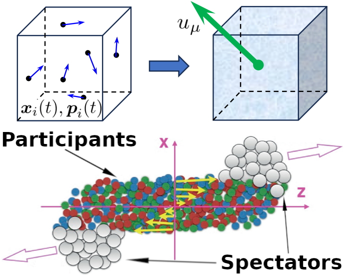
particles–to–medium transition ⟷ fluidization ⟷ continuization ⟷ collectivization

- *At each time step* we perform **the effective fluidization** procedure:

$$T^{\mu\nu}(\mathbf{x},t) = \frac{1}{\mathcal{N}} \sum_{a,i_a} \frac{p^{\mu}_{i_a}(t)\, p^{\nu}_{i_a}(t)}{p^{0}_{i_a}(t)} \Phi\left(\mathbf{x}, \mathbf{x}_{i_a}(t)\right), \qquad \mathcal{N} = \int \Phi\left(\mathbf{x}, \mathbf{x}_i(t)\right)\, d^3x \;-\; \text{norming factor},$$

$$J^{\mu}_{B}(\mathbf{x},t) = \frac{1}{\mathcal{N}} \sum_{a,i_a} B_{i_a} \frac{p^{\mu}_{i_a}(t)}{p^{0}_{i_a}(t)} \Phi\left(\mathbf{x}, \mathbf{x}_{i_a}(t)\right), \qquad \Phi\left(\mathbf{x}, \mathbf{x}_i(t)\right) \;-\; \text{smearing function},$$

$$u_\mu T^{\mu\nu} = \varepsilon\, u^\nu, \qquad n_B = u_\mu J^{\mu}_{B}, \qquad \longrightarrow \qquad \text{EoS}^{a} \qquad \longrightarrow \qquad \text{Temperature}(\varepsilon, n_B)$$



- **The fireball criterion**:
  only cells with $\varepsilon \geq \varepsilon_f \approx 0.05\,\text{GeV/fm}^3$!

- **Spectators separation**:
  spectators *do not interact* and *do not form fluids* but have *an indirect impact* via transport equations!

- See for details [*N.S. Tsegelnk, E.E. Kolomeitsev, V. Voronyuk*, *Phys.Rev.C* **107** (2023) 3]

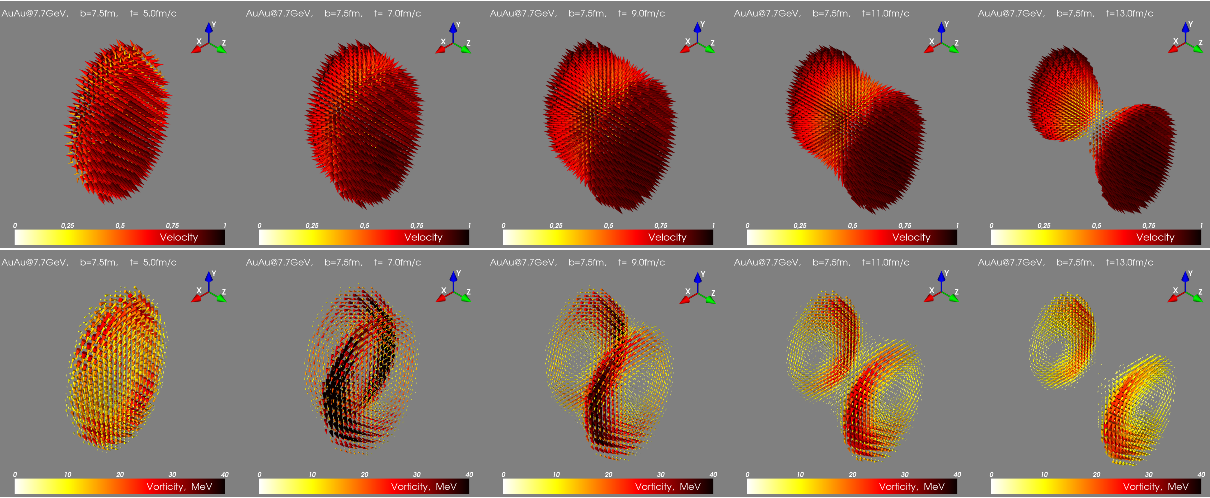
[a] **Hadron resonance gas**: *L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin*, Phys. Atom. Nucl. **72** (2009)

The medium dynamics

The velocity, vorticity, acceleration and the Unruh temperature

The velocity and vorticity of the fireball

AuAu@7.7GeV, b=7.5fm



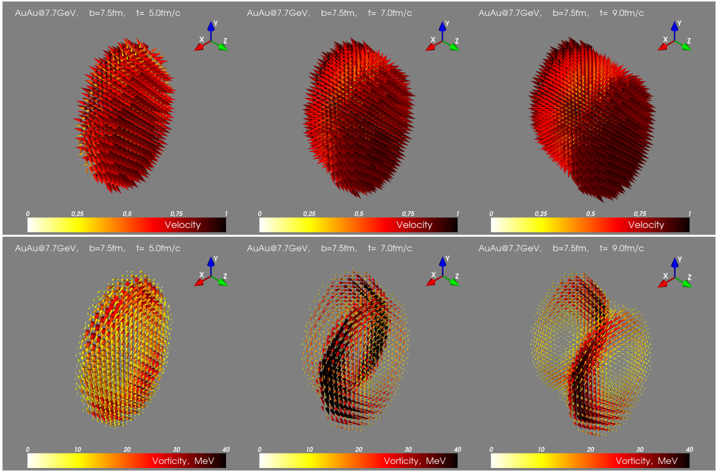
N. Tsegelnk, E. Kolomeitsev, V. Voronyuk, Particles **6** (2023) 1

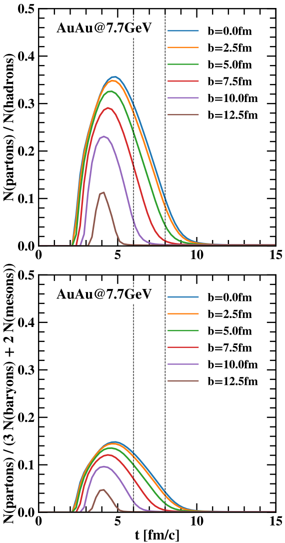
vorticity: $\omega = \nabla \times \mathbf{v}$

"QGP, or not QGP, that is the question"

Is a QGP the fastest-rotating fluid?

AuAu@7.7GeV, b=7.5fm





The largest vorticity for the system occurs at times $t \approx 6 - 8\,\mathrm{fm}/c$, but already at $t \approx 7\,\mathrm{fm}/c$ *the QGP phase is almost absent!*

~~QGP~~ *Nuclear medium* has significant vorticity!

The vortex rings in nature

RESEARCH ARTICLE | MAY 22 2025

Hydrodynamics of suckermouth catfish: The role of wake forces during the fast start

Jinhao Wang (王锦昊); Ge Shi (史歌); Long Zheng (郑龙); Luquan Ren (任露泉)

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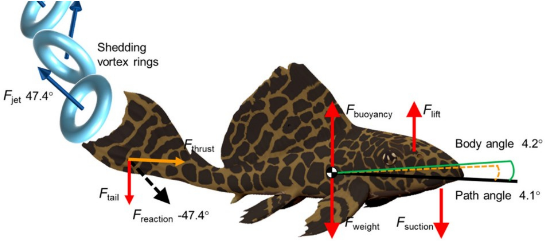
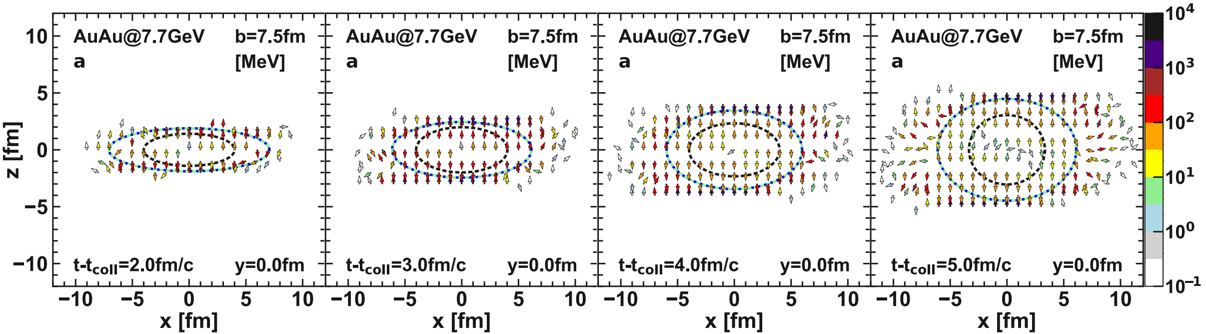
Physics of Fluids 37, 051912 (2025)

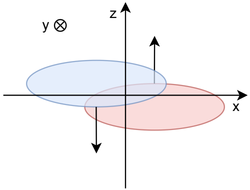


What about **the acceleration** and **the Unruh temperature**?

The acceleration $a_\mu = u^\nu \partial_\nu u_\mu = (a^0, \mathbf{a})$

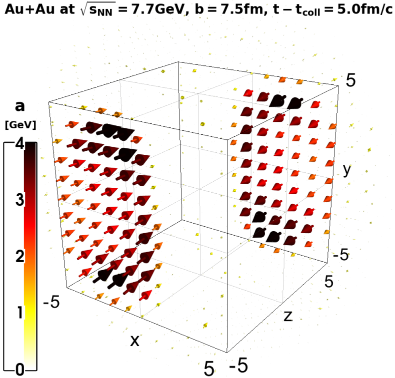


- Here we show a *vector part* $\mathbf{a}$ of the 4-vector a_μ (*not 3-acceleration!*).
- *Inner* black-and-white contour for the QGP phase ($\varepsilon_{\rm QGP} > 0.5$ GeV/fm^3).
- *Outer* blue-and-green contour for the fireball ($\varepsilon_f > 50$ MeV/fm^3).
- The maximum magnitude ($|\mathbf{a}| \sim 1 - 10$ GeV) is located at the system edge at $|z| = |z_{\max}|$. These zones are characterized by an *extremely high deceleration* due to *the relativistic stopping*.
- For the fireball and QGP the acceleration is *smaller* and *co-directed within expansion*. The maximum magnitude ($|\mathbf{a}| \sim 0.1 - 1$ GeV) is located near the edges of the fireball and QGP.



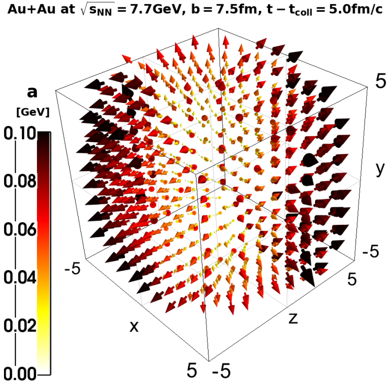
The acceleration $a_\mu = u^\nu \partial_\nu u_\mu = (a^0, \mathbf{a})$

full system



- The maximum magnitude ($|\mathbf{a}| \sim 1 - 10$ GeV) is located at the system edge at $|z| = |z_{\max}|$.
- These zones are characterized by an *extremely high deceleration* due to *the relativistic stopping*.
- *G.Yu. Prokhorov, D.A. Shohonov, O.V. Teryaev, N.S. Tsegelnik, V.I. Zakharov*, arXiv:2502.10146; *will be in the published version*

fireball $\varepsilon_f > 0.05$ GeV/fm^3

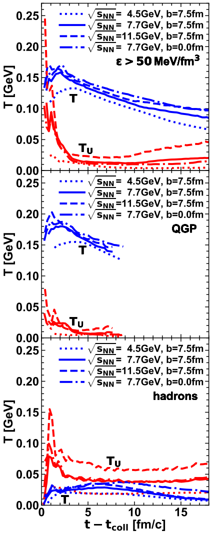


- The maximum magnitude ($|\mathbf{a}| \sim 0.1$ GeV) is located near the edge at $|z| = |z_{\max}| - \delta z$.
- These zones are characterized by a *smaller acceleration co-directed within expansion*.
- *unpublished; in preparation...*

The Unruh temperature

$$T_U = \sqrt{-a^\mu a_\mu}/2\pi$$

$$T - \text{fluid temperature}$$



◀ *For QGP and fireball*, except the first moments, where $\langle T_U \rangle_{vol}$ may be close to $\langle T \rangle_{vol}$:

$$\langle T_U \rangle_{vol} < \langle T \rangle_{vol}.$$

◀ *For hadrons*, except $t - t_{coll} = 5 - 10$ fm/c at $\sqrt{s_{NN}} < 11.5$GeV, where $\langle T_U \rangle_{vol} \approx \langle T \rangle_{vol}$:

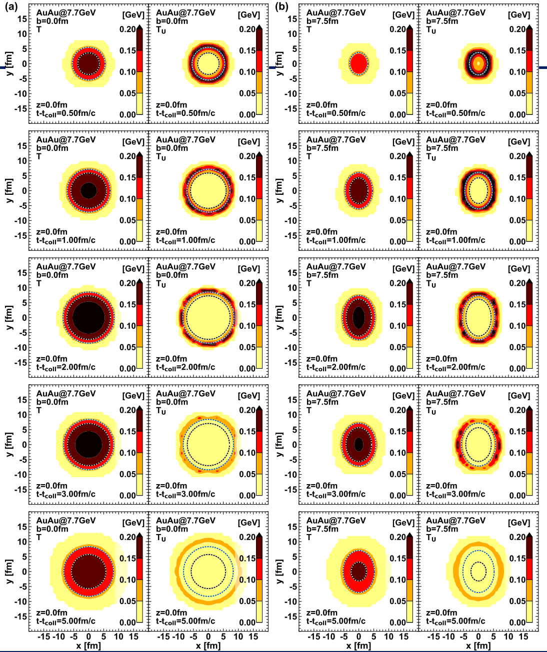
$$\langle T_U \rangle_{vol} > \langle T \rangle_{vol}.$$

◀ Qualitatively, the picture is independent of the parameters of the colliding system.

Inner black-and-white contour for the QGP phase ($\varepsilon_{QGP} > 0.5$ GeV/fm^3). ▶

Outer blue-and-green contour for the fireball ($\varepsilon_f > 50$ MeV/fm^3). ▶

$T_U \geq T$ only for the boundary layer *around the fireball*. ▶



• *G.Yu. Prokhorov, D.A. Shohonov, O.V. Teryaev, N.S. Tsegelnik, V.I. Zakharov*, arXiv:2502.10146

QGP and fireball: small acceleration and

$$\langle T_U \rangle_{vol} < \langle T \rangle_{vol}$$

Hadrons: large acceleration and

$$\langle T_U \rangle_{vol} > \langle T \rangle_{vol}$$

Conclusions and prospects

Let's summurize our results

Conclusions and prospects

The simultations of the heavy-ion collisions at the NICA energies show:

- The vorticity of the nuclear medium (*not only QGP* or not at all) is the largest predicted ($\omega \sim 80\,\mathrm{MeV}/\hbar \sim 10^{23}\,\mathrm{s}^{-1}$), but *the flow is mostly shear!*
- The acceleration for hadron matter *is extremely high* $a \sim 1\,\mathrm{GeV}$ (similar to the values near the horizon of a black hole), leading to $\langle \mathrm{T_U} \rangle_{\mathrm{vol}} > \langle \mathrm{T} \rangle_{\mathrm{vol}}$.
- The acceleration for the QGP and firebal is smaller but may be also high $a \sim 0.1\mathrm{GeV}$, but $\langle \mathrm{T_U} \rangle_{\mathrm{vol}} < \langle \mathrm{T} \rangle_{\mathrm{vol}}$.
- The vorticity and acceleration of the nuclear medium lead to *the global polarization* and its values in a good correspondence with the experimentall data.

The research supported by the grants of **JINR №25-301-06** and **BASIS #25-1-5-80-1**.

The grant **BASIS #25-1-5-80-1** *"Non-inertial effects, electromagnetic fields and phase transitions within the holographic approach, QFT methods and the PHSD transport model"*:

- Using the holographic model of $\mathcal{N} = 4$ SYM plasma, calculate the quark-antiquark potential and the energy losses of high-energy quarks passing through the plasma in the presence of 1) *electromagnetic fields* and 2) *acceleration*.
- Compare the holographic calculations within the results from the PHSD model and QFT calculations.

The predictions of the vortex structures

PHYSICAL REVIEW C **93**, 031902(R) (2016)

Femto-vortex sheets and hyperon polarization in heavy-ion collisions

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(Received 7 October 2015; revised manuscript received 20 January 2016; published 4 March 2016)

We study the structure of vorticity and hydrodynamic helicity fields in peripheral heavy-ion collisions using the kinetic quark-gluon string model. The angular momentum conservation within this model holds with a good accuracy. We observe the formation of specific toroidal structures of vorticity field (vortex sheets). Their existence is mirrored in the polarization of hyperons of the percent order.

DOI: 10.1103/PhysRevC.93.031902

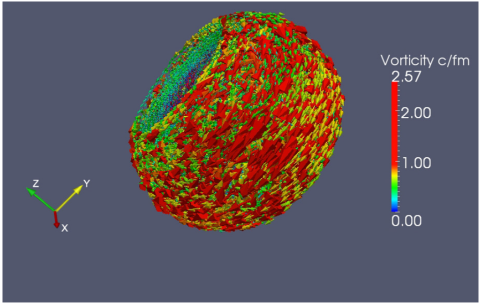

FIG. 3. The vortex sheet.

Vortex rings in heavy-ion collisions at energies $\sqrt{s_{NN}} = 3$–30 GeV and possibility of their observation

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The ring structures that appear in Au+Au collisions at collision energies $\sqrt{s_{NN}} = 3 - 30$ GeV are studied. The calculations are performed within the model of three-fluid dynamics. It is demonstrated that a pare of vortex rings are formed, one at forward and another at backward rapidities, in ultra-central Au+Au collisions at $\sqrt{s_{NN}} > 4$ GeV. The vortex rings carry information about early stage of the collision, in particular about the stopping of baryons. It is shown that these rings can be detected by measuring the ring observable R_Λ even in rapidity range $0 < y < 0.5$ (or $-0.5 < y < 0$) on the level of 0.5–1.5% at $\sqrt{s_{NN}} = 5 - 20$ GeV. At forward/backward rapidities, the R_Λ signal is expected to be stronger. Possibility of observation of the vortex-ring signal against background of non-collective transverse polarization is discussed.

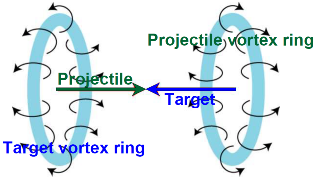
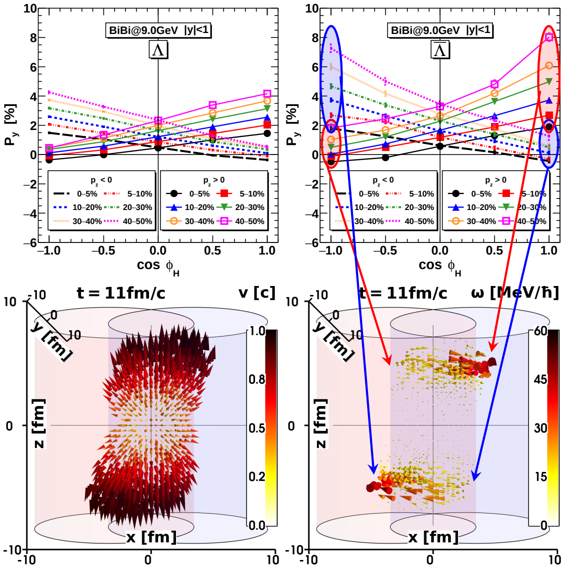


FIG. 1: Schematic picture of the vortex rings at forward/backward rapidities. Curled arrows indicate direction of circulation of the matter.

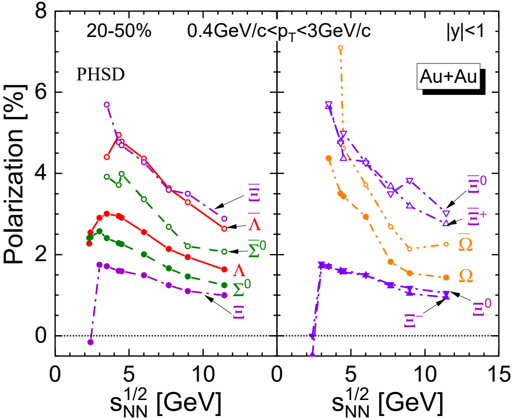
The vorticity imprint

$$\phi_{\mathrm{H}} = \mathrm{atan}(p_y/p_x)$$
$$\cos\phi_{\mathrm{H}} = p_x/p_T$$

- The highest polarization corresponds to the particles *moving in the same direction as the projectile* (*target*), which *are mostly born from the matter of the projectile* (*target*)!
- *We can increase the polarization signal by selecting particles by angle and momentum.*
- ***The imprint of the vorticity mechanism is the angular dependence of the polarization!***
- *N. Tsegelnk, V. Voronyuk, E. Kolomeitsev*, *Particles* **7** (2024) 4



Polarization vs. collision energy



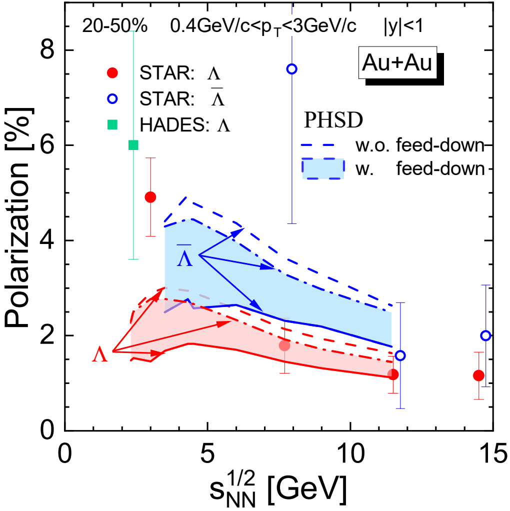
- There is a *different polarization* for particles and antiparticles for all the hyperon species.
- The polarization of all the hyperon kinds *decreases with an energy increase* for $\sqrt{s_{NN}} > 3 - 4$ GeV.
- The *strongest decrease* and *smallest difference* are for Ω and $\overline{\Omega}$.
- The *biggest difference* is for Ξ and $\overline{\Xi}$.
- The maximum of Λ and $\overline{\Lambda}$ polarization occurs at $\sqrt{s_{NN}} \approx 4$ GeV.

- The following polarization hierarchy holds for the energy range $\sqrt{s_{NN}} = 3.5 - 11.5$ GeV:

$$P_{\overline{\Xi}} \approx P_{\overline{\Lambda}} > P_{\overline{\Sigma}^0} > P_{\Lambda} > P_{\Sigma^0} > P_{\Xi}.$$

- *V. Voronyuk, N.S. Tsegelnk, E.E. Kolomeitsev*, *Phys.Rev.C* **111** (2025) 3

The feed-down and $\Lambda - \Sigma$ ambiguity



- The polarization of Λ hyperons *agrees* with experimental data, *except low energies.* The polarization of $\bar{\Lambda}$ is *larger in $1.5-2$ times* than Λ.
- The filled area reflects uncertainty between ratio of Λs and Σs. The limiting case when all Σs are actually Λs is depicted via dash-dotted line.
- *It looks more attractive to consider the global polarization of Ξ hyperons*, which experimentally could be *clearly identified* and would carry *direct information about the spin polarization of the fireball*.
- Moreover, a part of Ξ comes from Ξ^* decays and *carries by factor 5/3 stronger polarization than primary Ξs.*
- *V. Voronyuk, N.S. Tsegelnk, E.E. Kolomeitsev*, *Phys.Rev.C* **111** (2025) 3