Novel Quantum Phenomena in the Subatomic Swirls

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The Subatomic Swirls

An exciting discovery from STAR Collaboration at RHIC: The most vortical fluid!

GLOBAL $\Lambda$ HYPERON POLARIZATION IN NUCLEAR COLLISIONS

The STAR Collaboration*
Introduction
Nuclear Physics: Exploring the Heart of Matter

The physical world has a hierarchy of structures.

- **matter**
- **molecule**
- **atoms**

Most basic entities: quarks and gluons.

- **atomic nucleus**
- **proton**
- **neutron**

Quantum Chromodynamics (QCD)

[21x495]Nuclear force

[a millionth of a mm]

[a trillionth of a mm]
Quantum Chromodynamics (QCD)

The fundamental theory of strong nuclear force: QCD, a non-Abelian gauge theory of quarks and gluons

\[ \mathcal{L} = \bar{\psi} (i \slashed{\partial} - M - g A_a G^a) \psi - \frac{1}{4} F_{\mu \nu}^a F^{a \mu \nu} \]

\[ F_{\mu \nu}^a = \partial^\mu A_\mu^a - \partial^\nu A_\nu^a - g f_{abc} A_\mu^b A_\nu^c \]

Asymptotic Freedom: coupling becomes large at low energy or long distance scale.

\[ \Lambda_{QCD} \sim 200 \text{MeV} \quad R \sim 1 \text{fm} \]

Nobel Prize 2004
QCD Confinement: “The Missing Particles"

Free Quark Searches

All searches since 1977 have had negative results.

This null result is by itself a remarkable FACT of Nature.

Confinement problem: Biggest challenge within Standard Model!

Mathematics: one of the seven Millennium Problems!

QCD vacuum as “dual superconductor” with dual Meissner effect? Color-magnetic topological condensate?
Chiral Symmetry: Spontaneous Breaking

Dirac Sea

$\begin{align*}
m_{\pi} & \approx 140 \text{MeV}, \\
m_{n} & \approx 940 \text{MeV}
\end{align*}$

Vacuum condensate

It accounts for 99% of the mass of our visible matter in universe.
QCD as Topological Material

**Instantons**

\[ Q_w = \frac{1}{32\pi^2} \int d^4x (gG_{\mu\nu}^a) \cdot (g\tilde{G}_{\mu\nu}^a) \]
Emergent Phenomena in QCD

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and “applications”.

It embodies many deep aspects of relativistic quantum field theory (confinement, asymptotic freedom, anomalies/instantons, spontaneous symmetry breaking ... )
This talk will focus on the “hot frontier”.
Quark-Gluon Plasma (QGP): A Subatomic Quantum Fluid
QCD in Hot Environment

The “super” side is hard, and let’s attack the lambda point from the “right side”, when the system is just about to condense!

Why don’t we do the same for QCD?!

QCD at extreme temperatures:
At high enough $T \gg \Lambda_{\text{QCD}}$
A transition to a quark-gluon plasma (QGP)!
[mid ~ late 1970’s]
QGP: A New Phase of Matter

from Lattice QCD

RHIC  LHC

free QGP

A relativistic pion gas

\[ \epsilon = 3 \times \frac{\pi^2}{30} T^4 \]

More precisely, Hadron Resonance Gas

* Two benchmarks at low/high T
* A transition regime in the middle
* Crossover (instead of a phase transition)
QGP: A New Phase of Matter

The liberated quarks & gluons

The restored chiral symmetry

The high T phase of QCD matter (a few hundred MeV & up) is a distinctive new phase, the quark-gluon plasma (QGP).
Little Bangs in Heavy Ion Collisions (HIC)

An artistic presentation: “nuclei as heavy as bulls, colliding into new phase of matter”
The Setup of Heavy Ion Collision

A typical off-central collision.

Quark-gluon plasma is created in such collisions!
QGP Shining Brightly!

QGP is hot stuff: about trillion degrees!

Official Guinness World Record: the highest man-made temperature!
QGP: An Old Phase of Matter

The highest ever temperature was in the beginning of universe. The QGP temperature was available back then.

The quark-gluon plasm is an old phase of matter!
Anisotropic Explosion: Elliptic Flow

\[ \frac{dN}{dP_t \, d\phi} = \frac{dN}{dP_t} \left[ 1 + 2v_2(P_t) \cos(2\phi) + \ldots \right] \]

Coordinate-space-anisotropy \( \Rightarrow \) momentum-space-anisotropy

**Relativistic Hydrodynamics**

@ 1~10 fm scale.

This response is very sensitive to fluid dissipation from STAR

\[ 1 \leq 4\pi(\eta/s)_{QGP} \leq 2.5 \]

from STAR
QGP: Nearly Perfect Quantum Liquid

\[ \eta \sim \rho v_T \lambda \sim n p_T \lambda \]

\[ s \sim \eta \]

\[ \eta/s \sim p_T \lambda \sim \lambda/\lambda_{dB} \]

QGP is a quantum fluid:

\[ \lambda_{M.F.P.} \sim \lambda_{de Broglie} \]

[A recent ravel: cold atomic gas with infinite scattering length]

It has nearly perfect fluidity: less dissipative than known substance; very close to conjectured lower bound.
Vorticity & Magnetic Field
Fascinating New Frontiers

"Hot Frontier"

"Force Frontier"

"Dense Frontier"

QGP fluid in extremely strong vorticity and magnetic fields
Rotating Quark-Gluon Plasma

\[ L_y = \frac{Ab \sqrt{s}}{2} \sim 10^{4\sim5} \hbar \]

QGP’s way of accommodating this angular momentum
Quantifying Fluid Rotation

\[ \vec{\omega} = \frac{1}{2} \nabla \times \vec{V} \]

\[ \Omega_{\mu \nu} = \frac{1}{2} (\partial_\nu u_\mu - \partial_\mu u_\nu) \]

Heavy ion collisions:

\[ v \sim 0.1 \, c \]

\[ \partial \sim fm^{-1} \]

\[ \omega \sim 10^{22} \, s^{-1} \]
The averaged vorticity strongly increases toward low beam energy!

Jiang, Lin, JL, PRC2016; Deng & Huang, PRC2016; Xia, Li, Wang, et al, PRC; Shi, Li, JL, PLB2018; …
The angular momentum together with large (+Ze) nuclear charge —> strong magnetic field!
Strong Electromagnetic Fields

- Strongest B field (and strong E field as well) naturally arises!
  [Kharzeev, McLerran, Warringa; Skokov, et al; Bzdak-Skokov; Deng-Huang; Skokov-McLerran; Tuchin; ...]
- “Out-of-plane” orientation (approximately)
  [Bloczynski-Huang-Zhang-Liao]

\[ E, B \sim \gamma \frac{Z \alpha_{EM}}{R_A^2} \sim 3m_\pi^2 \]
Strong Electromagnetic Fields

Quantitative simulations confirm the existence of such extreme fields!

[STAR measurements of dielectron directly from such fields, PRL2018]
Spin & Rotational Polarization
Spin-Fluid Coupling

How does a many-body system cope with a sizable angular momentum?

Orbital motion (vorticity); Spin alignment (polarization).

Fluid vorticity
Macroscopic

Individual spin
Microscopic, quantum
Spin & Rotational Polarization

**Dirac Lagrangian in rotating frame:**

\[
g_{\mu\nu} = \begin{pmatrix}
1 - \vec{v}^2 & -v_1 & -v_2 & -v_3 \\
-v_1 & -1 & 0 & 0 \\
-v_2 & 0 & -1 & 0 \\
-v_3 & 0 & 0 & -1 \\
\end{pmatrix}
\]

\[
\vec{\gamma}^\mu = e_a^\mu \gamma^a
\]

\[
\Gamma_\mu = \frac{1}{4} \times \frac{1}{2} [\gamma^a, \gamma^b] \Gamma_{ab\mu}
\]

\[
\vec{v} = \vec{\omega} \times \vec{x}.
\]

\[
\mathcal{L} = \bar{\psi} \left[ i \vec{\gamma}^\mu (\partial_\mu + \Gamma_\mu) - m \right] \psi
\]

**Under slow rotation:**

\[
\mathcal{L} = \psi^\dagger \left[ i \partial_0 + i \gamma^0 \vec{\gamma} \cdot \vec{\partial} + (\vec{\omega} \times \vec{x}) \cdot (-i \vec{\partial}) + \vec{\omega} \cdot \vec{S}_{4\times4} \right] \psi
\]

\[
\hat{H} = \gamma^0 (\vec{\gamma} \cdot \vec{p} + m) - \vec{\omega} \cdot (\vec{x} \times \vec{p} + \vec{S}_{4\times4}) = \hat{H}_0 - \vec{\omega} \cdot \hat{\mathcal{J}}
\]

Rotational polarization effect!
Rotational Polarization

$$\hat{H} = \gamma^0(\vec{\gamma} \cdot \vec{p} + m) - \vec{\omega} \cdot (\vec{x} \times \vec{p} + \vec{S}_{4\times4}) = \hat{H}_0 - \vec{\omega} \cdot \hat{J}$$

Rotational polarization effect!

For thermally produced particles: “equal-partition” of angular momentum

$$dN \propto e^{\frac{\vec{\omega} \cdot \hat{J}}{T}}$$
From Vorticity to Spin Polarization

“Spin hydrodynamic generation”

Viscous fluid flow
→ vorticity
→ spin polarization

“Fluid Spintronics”
Fluid Spintronics in the Subatomic Swirls

STAR Collaboration, Nature 2017
Fluid Spintronics in the Subatomic Swirls

\[ \omega \approx (9 \pm 1) \times 10^{21} \text{s}^{-1} \]

The most vortical fluid!

Jiang, Lin, JL, PRC2016

STAR Collaboration, Nature 2017
Rotational Suppression of Fermion Pairing

Let us consider pairing phenomenon in fermion systems. There are many examples: superconductivity, superfluidity, chiral condensate, diquark, …

We consider scalar pairing state, with $J=0$.

$$\vec{S} = \vec{s}_1 + \vec{s}_2 \quad \vec{J} = \vec{L} + \vec{S}$$

Rotation tends to polarize ALL angular momentum, both $L$ and $S$, thus suppressing scalar pairing.

[Yin Jiang, JL, PRL2016]
[Rotational Inhabitation: Chen, Fukushima, Huang, Mameda, PRD2016]
Chiral Magnetic Effect in the Subatomic Chiral Matter
Exciting Progress: See Recent Reviews


Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

**Classical symmetry:**

\[ \mathcal{L} = i \bar{\Psi} \gamma^\mu \partial_\mu \Psi \]

\[ \mathcal{L} \rightarrow i \bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + i \bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R \]

\[ \Lambda_A : \Psi \rightarrow e^{i \gamma_5 \theta} \Psi \]

\[ \partial_\mu J_5^\mu = 0 \]

---

**Broken at QM level:**

\[ \partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B} \]

\[ dQ_5/dt = \int_x C_A \vec{E} \cdot \vec{B} \]

* \( C_A \) is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect

[e.g. \( \pi^0 \rightarrow 2 \gamma \)]
* Spontaneously broken chiral symmetry in the vacuum is a fundamental property of QCD.

* A chirally symmetric quark-gluon plasma at high temperature is also a fundamental property of QCD!

Can we see direct experimental evidence for that?
Chiral Restoration via Chiral Anomaly

\[ J_5^\mu = J_R^\mu - J_L^\mu \]

Low T
Strong spon. breaking

High T
Quantum Anomaly

Look for pure quantum anomaly effect in hot QGP with chiral symmetry restoration!
The Chiral Magnetic Effect (CME)

\[ \vec{J} = \frac{Q^2}{2\pi^2} \mu_5 \vec{B} \]

Chirality & Anomaly & Topology
Electric Current
Q.M. Transport
Magnetic Field
Intuitive Picture of CME

Intuitive understanding of CME:

Magnetic polarization $\Rightarrow$ correlation between micro. SPIN & EXTERNAL FORCE

$\otimes$

Chiral imbalance $\Rightarrow$ correlation between directions of SPIN & MOMENTUM

Transport current along magnetic field

$$\vec{J} = \frac{Q^2}{2\pi^2} \mu_5 \vec{B}$$
From Micro. Laws To Macro. Phenomena

Micro. Laws:
- Symmetry;
- Lagrangian;
- Conservation laws;
- …...

Macro. Phenomena:
- Thermodynamics;
- Transport;
- Fluid Dynamics;
- …...

Quantum Field Theory \rightarrow\text{Weakly Interacting} \rightarrow\text{Kinetic Theory} \rightarrow\text{Strongly Interacting} \rightarrow\text{Fluid Dynamics}

WHAT ABOU the “SEMI”-SYMMETRY???
i.e ANOMALY?!
— classical symmetry that is broken in quantum theory
CME = Macroscopic Chiral Anomaly

\[ \partial^\mu j^5_\mu = \frac{q^2}{2\pi^2} E \cdot B \]

\[ \frac{dN_5}{dt d^3x} = \frac{q^2}{2\pi^2} E \cdot B \]

Chirality -->

\[ \int d^3x j_{el} \cdot E = \mu_5 \frac{dN_5}{dt} = \frac{q^2 \mu_5}{2\pi^2} \int d^3xB \cdot E \]

\[ E \to 0 \]

\[ j_{el} = \left( \frac{q^2 \mu_5}{2\pi^2} \right) B \]

* This is a non-dissipative current!
* Indeed the chiral magnetic conductivity is P-odd but T-even!
  (In contrast the Ohmic conductivity is T-odd and dissipative.)

CME is a quantum/anomalous transport current as macroscopic manifestation of microscopic quantum anomaly.
Fluid Dynamics That Knows Left & Right

conservation law:
\[ \partial_\mu J^\mu = 0 \quad \Rightarrow \quad \partial_\mu J^\mu = C E^\mu B_\mu \]

constituent relation:
\[ J^\mu = n u^\mu + \nu^\mu \]

Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

It would be remarkable to actually “see” this new hydrodynamics at work in real world materials!

[Son, Surowka, 2009;…] CVE CME
Looking for CME in Heavy Ion Collisions

The quark-gluon plasma is a subatomic CHIRAL MATTER.

Can we observe CME in heavy ion collisions??

\[ \mathbf{J} = \sigma_5 \mu_5 \mathbf{B} \]

1) (nearly) chiral quarks
2) chirality imbalance
3) strong magnetic field
From Gluon Topology to Quark Chirality

QCD anomaly: gluon topology $\rightarrow$ chirality imbalance

$$Q_w = \frac{1}{32\pi^2} \int d^4x \ (gG_{\mu\nu}^a) \cdot (g\tilde{G}_{\mu\nu}^a)$$

$$N_5(t \rightarrow +\infty) - N_5(t \rightarrow -\infty) = \frac{g^2}{16\pi^2} \int dt d^3r \ G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a$$

**QCD anomaly: gluon topology $\rightarrow$ chirality imbalance**

$$N_R - N_L = N_5 = 2Q_w$$
From CME Current to Charge Separation

\[ \mathbf{J} = \sigma_5 \mu_5 \mathbf{B} \]

**strong radial blast:** position $\rightarrow$ momentum

Very difficult measurement:
* Zero average, only nonzero variance;
* Correlation measurement with significant backgrounds;
* Signal likely small

\[ \langle a_\pm \rangle \sim \pm \langle \mu_5 \rangle \mathbf{B} \]
Latest Exp. Search Status

[From Z. Ye, STAR Summary Talk @ QM2018]

ALICE @ LHC 2.76TeV: signal level possibly about 8~10% (upper limit ~30%)

CMS @ LHC 5.02TeV: signal level no more than 7%

The trend with beam energy seems in line with expectation!
Badly needed: Quantitative predictions for CME signal in heavy ion collisions!
Anomalous Viscous Fluid Dynamics (AVFD)

AVFD:
Anomalous-Viscous Fluid Dynamics
We now have a versatile tool to quantitatively understand and answer many important questions about CME in heavy ion collisions!

The AVFD Framework

Anomalous-Viscous Fluid Dynamics

\[ D_\mu J_R^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B_\mu \quad D_\mu J_L^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B_\mu \]

\[ J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{N_c q}{4\pi^2} \mu_R B_\mu \]

\[ J_L^\mu = n_L u^\mu + \nu_L^\mu - \frac{N_c q}{4\pi^2} \mu_L B_\mu \]

CME

Viscous Effect

\[ \Delta^\mu_\nu d \nu_{R,L}^\nu = - \frac{1}{\tau_{rlx}} (\nu_{R,L}^\mu - \nu_{NS}^\mu) \]

\[ \nu_{NS}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu} \partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q E_\mu \]

on top of VISH2+1D — OSU Group

[We now also have MUSIC-AVFD!]
The AVFD At Work

[arXiv:1611.04586; arXiv:1711.02496]

Zero B Field

Nonzero B Field

\( \tau = 0.60 \text{ fm/c} \)

\( n_{R/L}^u \)  \hspace{1cm} B = 0  \hspace{1cm} n_R^u \)  \hspace{1cm} B \neq 0
The AVFD At Work

[arXiv:1611.04586; arXiv:1711.02496]

Left-handed

Right-handed

$\tau = 0.60 \text{ fm/c}$

$x (\text{fm})$

$y (\text{fm})$

$n_L^u$

$n_R^u$

$x (\text{fm})$

$y (\text{fm})$
The Charge Separation from AVFD

$B \text{ field } \otimes \mu_5 \Rightarrow \text{ current} \Rightarrow \text{ dipole (charge separation)}$

$$dN_\pm/d\phi \propto 1 + 2 a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$$
AVFD Predictions v.s Experimental Data

Excellent agreement!

Chiral Magnetic Wave (CMW)

CMW: gapless collective excitation in chiral fluid
—> charge quadrupole of QGP —> elliptic flow splitting


[STAR, PRL2015]

[STAR@RHIC]

[Also seen by ALICE@LHC]
There Are Electric Fields Too!

*Chiral matter in strong electric field:*
  Chiral Electric Separation Effect (CESE)

[Huang, JL, PRL2013; Jiang, Huang, Liao, PRD2014]

\[ \dot{j}_A = \chi_e \mu_V \mu_A E, \]

\[ \sigma_e = \chi_e \mu_V \mu_A \]

**QED plasma**

\[ \sigma_e \approx \frac{T}{e^4 \ln(1/e)} \left( 20.5 \frac{\mu_V \mu_A}{T^2} \right) \]

**QCD plasma**

\[ \sigma_e \approx \frac{N_c N_f T}{g^4 \ln(1/g)} \left( 4.83 \frac{\mu_V \mu_A}{T^2} \right) \]
Summary & Outlook
Summary: the Subatomic Swirls

Quark-Gluon Plasma: A Subatomic Chiral Fluid

The new, 5th state of matter

The hottest material

The oldest state of matter: early cosmos

The most perfect fluid

Subatomic swirls as the most vortical fluid with the strongest B field

Spin Polarization

CME