CHIRAL EFFECTS: NEW TRENDS

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Outline of the talk

Introduction (Quantum anomalies and hydrodynamics)

Part I Gauge anomaly ($\partial_\alpha J_5^\alpha = e^2 C_5^{el}\ \vec{E}\cdot\vec{B}$)
a) Changing the symmetry behind
b) Anomalies as infrared effects

Part II Gravitational anomaly ($\partial_\alpha J_5^\alpha = C_5^{grav} R\tilde{R}$)

a) Basic chiral eddect (kinematical chiral effect)
b) Applications

Part II: collaboration with G. Yu. Prokhorov, O.V. Teryaev (talk here by G. Prokhorov)
Part I: more of review-type + earlier papers of ITEP group

Chiral magnetic effect: a reminder

The best known effect is Chiral Magnetic (CME) Effect:

$$\vec{J}^{el} = e^2 \cdot C_5^{el} \ \mu_5 \vec{B}$$

where μ_5 is axial chemical potential $\vec{B}$ is magnetic field,
As indicated by the e^2 factor, it is a Hall-type current.

The guess turns true if one keeps in mind
specific hydrodynamic interaction

$$\hat{H}_{effective} = \hat{H}_{field\ \ theory} - \mu_{el}\ \hat{Q}_{el} - \mu_5\ \hat{Q}_5$$

Chiral vortical effect

using analogy between $\vec{H}$ and $\vec{\Omega}$
brings in chiral vortical effect (CVE)

$$\vec{J}_5 \;=\; \mu_{el}^2 C_5^{el} \vec{\Omega}$$

which is most interesting
since it survives in absence of $\vec{E}, \vec{B}$ and is to be conserved

No place for a new Noether current (no free symmetry).
The way out: conservation is specific
for absence of dissipation or for ideal fluid

as observed in 2016 but consequences emerge only recently

Upgrading symmetry of the problem

For ideal fluid there is, indeed,
another conserved axial charge (not chiral!):

$$Q_{helicity} \;=\; (const) \int d^3x \; \vec{v} \cdot (\vec{\nabla} \times \vec{v}) \quad ,$$

$$(or \; J^{\alpha}_{helicity} \;\sim\; \epsilon^{\alpha\beta\gamma\delta} u_{\beta} \partial_{\gamma} u_{\delta} \; where \; u_{\alpha} \; is \; fluid \; 4 - velocity)$$

as conserquence of diffeomorphism symmetry of ideal fluid

Thus chiral symmetry is embedded into diffeomorphism, –
fundamental change of symmetry

Regenerating e-m interactions

To get CME back from CVE replace $\partial_\alpha \rightarrow \nabla_\alpha$

Amusing non-relativistic analogs to chiral anomalies

$$\partial_\alpha J_5^\alpha \sim \vec{E} \cdot \vec{B} \quad (as\text{``}usual'')$$

$$\partial_\alpha J_{el}^\alpha \sim \vec{E}_5 \cdot \vec{B} \equiv \vec{\nabla}\mu_{5,non-rel} \cdot \vec{B}$$

where $\vec{E} \equiv \vec{\nabla}\mu$, $\vec{E}_5 \equiv \vec{\nabla}\mu_5$

- no ultraviolet divergences
- non-relativistic anomalies match UV anomalies only up to a factor
- non-conservation of electric charge is declared

A few references on ideal fluid and "anomalies"

"On consistency of hydrodynamic approximation for chiral media", A. Avdoshkin , V.P. Kirilin , A.V. Sadofyev , V.I. Zakharov, e-Print: 1402.3587 [hep-th].
A. G. Abanov and P. B. Wiegmann, "Anomalies in fluid dynamics: flows in a chiral background via variational principle," [arXiv:2207.10195 [hep-th]] + 3 other papers (2021)
"Divergence anomaly and Schwinger terms: Towards a consistent theory of anomalous classical fluids", Arpan Krishna Mitra and Subir Ghosh, 2111.00473 [hep-th].

Conclusions (preliminary) on Part I

What is chiral fluid of massless quarks at short distances

might look as ideal non-relativistic fluid at large distances

since anomalies are similar
(variation of' 't Hooft consistency condition)

Gravitational anomaly and hydrodynamics

General Relativity is built on non-trivial metric tensor

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

Gauge transformation, analog of

$$\delta A_\mu = \partial_\mu \Lambda$$

is

$$\delta h_{\mu\nu} = \partial_\mu \epsilon_\nu + \partial_\nu \epsilon_\mu$$

Gauge invariant field, analog of $\vec{E}, \vec{B}$, is Riemann tensor $R_{\alpha\beta\gamma\delta}$ which involves $(\partial_\alpha \partial_\beta h_{\mu\nu})$ *and* $(\partial_\alpha h_{\mu\nu})^2$
Gravitational anomaly is built on the curvature $R_{\alpha\beta\gamma\delta}$

In absence of sizable curvature we are interested in
what is left of anomaly in absence of curvature

What is left of GR in absence of curvature

Equivalence principle: physics in non-inertial frame is imitated by a nontrivial gravitational field
Two basic non-inertial frames, considered by Einstein:
accelerated and rotated frames
(corresponding $h_{\mu\nu}$ are easy to identify)

In applications to quark-gluon plasma acceleration and rotation 4-vectors are given by:

$$a_\mu = u^\alpha \partial_\alpha u_\mu, \quad \omega_\mu = \epsilon_{\mu\nu\rho\sigma} u^\nu \partial^\rho u^\sigma \quad (u^\nu \text{ is } 4-\text{velocity})$$

Plasma produced in heavy-ion collisions
both accelerated and rotated

Chiral Kinematical Effect (2022)

In presence of gravitational field the axial current J_5^α defined as

$$\nabla_\alpha J_5^\alpha \;=\; C_5^{grav} R\tilde{R}$$

where C_5^{grav} depends on spin of fermions and are known
In absence of curvature $R_{\alpha\beta\gamma\delta}$ the current is still not vanishing and fixed uniquely in terms of kinematical quantities a_μ, w_μ.
In case of spin $1/2$

$$J_5^{\alpha,kinematic} \;=\; -\frac{1}{24\pi^2}\left(3a_\mu^2 + w_\mu^2\right) w^\alpha$$

Idea and details of derivation in George's Prokhorov talk
We add interpretation of the effect

Unruh effect (a reminder)

Observer moving with acceleration a with respect to Minkowskian vacuum sees thermal distribution of particles with temperature

$$T_{Unruh} = \frac{a}{2\pi} \qquad (\textit{quantum effect})$$

while an observer at rest sees no particles

For many, it sounds disappointing that the Unruh effect is observer-dependent. However, it is dynamical: By virtue of the equivalence principle, accelerated frame equivalent to vacuum in strong gravitational field resulting in the same acceleration a. Naturally, such a field produces particles

Kinematical effects refer to noninertial frames describing results of measurements on the Unruh sample of particles

Statistical vs gravitational approaches

Properties of fluids in equilibrium are evaluated statistically in terms of density operator, or effective interaction

$$\hat{H}_{eff} = \vec{\Omega} \cdot \hat{\vec{M}} + \vec{a} \cdot \hat{\vec{K}}$$

where $\vec{M}$ is angular momentum and $\vec{K}$ is the boost (for details see papers of F. Becattini)

In field theory, gravitational interaction is descibed by

$$\hat{H}_{fund} = \frac{1}{2} \hat{\Theta}^{\alpha\beta} h_{\alpha\beta}$$

where $\Theta^{\alpha\beta}$ is the energy momentum tensor, $h_{\alpha\beta}$ is the grav. potentials accommodating the same $\vec{\Omega}$, $\vec{a}$

Evaluate "external probes", $< \Theta^{\alpha\beta} >, < J_5^{\alpha} >$ Expect results to be the same (duality)

More on duality

We have classical set up for duality:

- Two theories with same symmetry pattern: both ideal fluid and gravity are diffeomorphic invariant
- Infrared vs ultraviolet sensitive. Statistics not valid at short distances Field theory needs UV regularization
- Both theories are valid to evaluate a common set of quantuties

As a result, evaluation of the kinematical effect can be rewritten as regularization, via acceleration, of gravitational chiral anomaly

Conclusions on part II

- Working in non-inertial frames, like hydrodynamic gradient expansion valid in non-inertial frames, becomes a trend. Non-inertial frames is a part of gravity and in this sense universal. Specific feature: nonconservation of Noether currents. The new universaity is not fully explored yet.