Evolution of electro-magnetic field in relativistic heavy-ion collisions from the HSD transport approach

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Parity violation in strong interactions

In QCD, chiral symmetry breaks due to a non-trivial topological effect; among the best evidence of this physics would be event-by-event strong parity violation.

The volume of the box is 2.4 by 2.4 by 3.6 fm.

The topological charge density of 4D gluon field configurations.
(Lattice-based animation by Derek Leinweber)

Energy of gluonic field is periodic in $N_{cs}$ direction (~ a generalized coordinate)

Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or crossing the barrier.

Dynamics is a random walk between states with different topological charges.
Dynamics is a random walk between states with different topological charges. In this states a balance between left-handed and right-handed quarks is destroyed, \( N_R - N_L = Q_T \rightarrow \text{violation} \) of P-, CP- symmetry.

Average total topological charge vanishes \( <n_w> = 0 \) but its variance is equal to the total number of transitions \( <n_{w^2}> = N_t \).

Fluctuation of topological charges in the presence of magnetic field induces electric current which will separate different charges.

**Lattice gauge theory**

\[
q \, B = 0.7 \, \text{GeV}^2 \quad \text{and} \quad q \, B = 1.8 \, \text{GeV}^2
\]

The excess of electric charge density due to the applied magnetic field. Red — positive charges, blue — negative charges.

P.V. Buividovich et al., PRD80 (2009) 054503
Charge separation in HIC

Non-zero angular momentum (or equivalently magnetic field) in heavy-ion collisions make it possible for P- and CP-odd domains to induce charge separation.


Electric dipole moment of QCD matter!

$<\cos(\phi_a + \phi_b - 2\psi_{RP})>$

Measuring the charge separation with respect to the reaction plane was proposed by S. Voloshin, Phys. Rev. C 70 (2004) 057901.
Charge separation in RHIC experiments

STAR Collaboration, PRL 103 (2009) 251601

\[ \langle \cos(\varphi_a + \varphi_b - 2\psi_{RP}) \rangle \]

Combination of intense B and deconfinement is needed for a spontaneous parity violation signal
Basic Concept of HSD Transport Approaches

HSD – Hadron-String-Dynamics transport approach


• the phase-space density \( f_i \) follows the transport equations

\[
\left( \frac{\partial}{\partial t} + (\nabla \vec{p} H) \nabla \vec{r} - (\nabla \vec{r} H) \nabla \vec{p} \right) f_i (\vec{r}, \vec{p}, t) = I_{\text{coll}} (f_1, f_2, \ldots, f_M)
\]

with collision terms \( I_{\text{coll}} \) describing:

- elastic and inelastic hadronic reactions:
  - baryon-baryon, meson-baryon, meson-meson
- formation and decay of baryonic and mesonic resonances
- string formation and decay

  (for inclusive particle production: \( \text{BB} \rightarrow X \), \( \text{mB} \rightarrow X \), \( X = \text{many particles} \))

• implementation of detailed balance on the level of 1\( \leftrightarrow \)2
  and 2\( \leftrightarrow \)2 reactions (+ 2\( \leftrightarrow \)n multi-particle reactions in HSD !)

• no explicit phase transition from hadronic to partonic degrees of freedom
Hadron-String-Dynamics
HSD

Retarded electromagnetic field
Transport model with electromagnetic field

The Boltzmann equation is the basis of QMD like models:

\[
\left\{ \frac{\partial}{\partial t} + \vec{r} \cdot \nabla_r + \vec{p} \cdot \nabla_p \right\} f(\vec{r}, \vec{p}, t) = I_{\text{coll}}(f, f_1, \ldots f_N)
\]

Generalized on-shell transport equations in the presence of electromagnetic fields can be obtained formally by the substitution:

\[
\begin{align*}
\vec{r} &\rightarrow \frac{\vec{p}}{p_0} + \nabla_p U , \\
\vec{p} &\rightarrow -\nabla_r U + e\vec{E} + e\vec{v} \times \vec{B} \\
U &\sim \text{Re}(\Sigma^{\text{ret}})/2p_0
\end{align*}
\]

A general solution of the wave equations is as follows:

\[
\begin{align*}
\vec{A}(\vec{r}, t) &= \frac{1}{4\pi} \int \frac{\vec{j}(\vec{r}', t') \delta(t - t' - |\vec{r} - \vec{r}'|/c)}{|\vec{r} - \vec{r}'|} d^3r' dt' \\
\Phi(\vec{r}, t) &= \frac{1}{4\pi} \int \frac{\rho(\vec{r}', t') \delta(t - t' - |\vec{r} - \vec{r}'|/c)}{|\vec{r} - \vec{r}'|} d^3r' dt'
\end{align*}
\]

For point-like particles

\[
\rho(\vec{r}, t) = e \delta(\vec{r} - \vec{r}(t)); \quad \vec{j}(\vec{r}, t) = e \vec{v}(t) \delta(\vec{r} - \vec{r}(t)) \quad \vec{\nabla} \times \vec{A} \rightarrow LW \text{eq.}
\]
Magnetic field for a single moving charge

\[ B_y (x,y=0,z) \]
Magnetic field evolution

Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $b=10$ fm, $t=0.01$ fm/c

Magnetic field and energy density correlation

\[ \text{Au+Au (200)} \]
\[ b = 10 \text{ fm} \]

\[ \text{Au+Au, } \sqrt{s_{NN}} = 200 \text{ GeV, } b=10 \text{ fm, } t=0.01 \text{ fm/c} \]

\[ \text{Au+Au, } \sqrt{s_{NN}} = 200 \text{ GeV, } b=10 \text{ fm, } t=0.05 \text{ fm/c} \]

\[ \text{Au+Au, } \sqrt{s_{NN}} = 200 \text{ GeV, } b=10 \text{ fm, } t=0.2 \text{ fm/c} \]

\[ \text{Au+Au, } \sqrt{s_{NN}} = 200 \text{ GeV, } b=10 \text{ fm, } t=0.5 \text{ fm/c} \]

Time dependence of $eB_y$

- Until $t \sim 1$ fm/c the induced magnetic field is defined by spectators only.
- Maximal magnetic field is reached during nuclear overlapping time $\Delta t \sim 0.2$ fm/c, then the field goes down exponentially.

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Collision of two infinitely thin layers (pancake-like)

V. Voronyuk, et al., PRC83 (2011) 054911
Electric field evolution

Electric field of a single moving charge has a “hedgehog” shape

AuAu, $\sqrt{s_{NN}} = 200$ GeV, $b=10$ fm, $t=0.01$ fm/c

No electromagnetic field effects on observables!
Average momentum increment

Transverse momentum increments $\Delta p$ due to electric and magnetic fields compensate each other!

$$\dot{\vec{p}} = e\vec{E} + e\vec{v} \times \vec{B}$$

$$\Delta \vec{p} = \sum_i \langle \delta \vec{p} \rangle_i \quad \text{for} \quad p_z > 0$$
Transport description of the partonic and hadronic phase

Parton-Hadron-String-Dynamics PHSD
**PHSD - basic concepts**

- **Initial A+A collisions – HSD:** string formation and decay to pre-hadrons

- **Fragmentation of pre-hadrons into quarks:**
  using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) approximation to QCD

- **Partonic phase:** quarks and gluons (= 'dynamical quasiparticles') with off-shell spectral functions (width, mass) defined by the DQPM

- **Elastic and inelastic parton-parton interactions:**
  using the effective cross sections from the DQPM
  ✓ $q + \bar{q}$ (flavor neutral) $\leftrightarrow$ gluon (colored)
  ✓ gluon + gluon $\leftrightarrow$ gluon (possible due to large spectral width)
  ✓ $q + \bar{q}$ (color neutral) $\leftrightarrow$ hadron resonances

- **Hadronization:** based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
  ✓ gluons $\Rightarrow q + \bar{q}$
  ✓ $q + \bar{q}$ $\Rightarrow$ meson (or string)
  ✓ $q + q + q$ $\Rightarrow$ baryon (or string)

- **Hadronic phase:** hadron-string interactions – off-shell HSD

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DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365;
NPA 795 (2007) 70.

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
Summary

- The **HSD transport model with retarded electromagnetic fields** has been developed. Actual calculations show no noticeable influence of the created electromagnetic fields on observables. This happens due to a compensating effect between electric and magnetic fields.

- Direct inclusion of quarks and gluons in evolution is needed => **PHSD model**, which provides a consistent description of off-shell parton dynamics in line with a lattice QCD equation of state.

- Experiments on the CME planned at RHIC by the low-energy scan program are of great interest since they hopefully will allow to infer the critical magnetic field $eB_{\text{crit}}$ governing the spontaneous local CP violation.
ありがとうございます

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PHSD gives harder spectra and works better than HSD at SPS (and top FAIR) energies

At low SPS (and low FAIR) energies the effect of the partonic phase is less pronounced in rapidity distributions and $m_T$ spectra

Cassing & Bratkovskaya, NPA 831 (2009) 215
Transverse mass spectra at RHIC energies

**PHSD improves significantly with respect to HSD (and the data) !**
Rapidity distributions at RHIC energies

Look quite reasonable in comparison to data from STAR, PHENIX and BRAHMS
Elliptic flow vs. centrality

Au + Au collisions at $\sqrt{s} = 200$ GeV

PHSD improves relative to HSD (in line with the data from PHOBOS)
Elliptic flow vs. collision energy

Elliptic flow $v_2$

at midrapidity

Parton energy fraction

at midrapidity

Increase of parton fraction with energy leads to increasing $v_2$