An Introduction to Chiral Magnetic Effect

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ICTS-seminar, March 7, 2013
A game of collective rotation

Magnetic field

Rotation of many charged particles

Hydrodynamics, Kinetic Theory

Orbital angular momentum
Outline

• A little (pre-)history
• Chiral Magnetic Effect: an introduction
• Approaches to CME/CVE: Field theory, Hydrodynamics, Quantum kinetic theory
• Other related and new phenomena
A little (pre-)history

- Transition between different configuration state → changes in the topological charge → anomalous processes (processes forbidden by the classical process are allowed in quantum theory) [Adler, Phys. Rev. 177 (1969) 2246; Bell, Jackiw, Nuovo Cimento A 60 (1969) 47]
A little (pre-)history

- Quantum tunneling between topologically different configurations as non-perturbative phenomena is suppressed by $e^{-2\pi/\alpha}$ where $\alpha$ is the interaction strength of the gauge theory.

High temperature $\rightarrow$ disappearance of exponential suppression (there is sufficient energy to pass classically over the barrier)

A little (pre-)history


A little (pre-)history

- Topological charge changing process involves P-odd and CP-odd field configurations →


- It is thus possible that an excited vacuum domain which may be produced in heavy ion collisions can break P and CP spontaneously [T.D. Lee, Phys. Rev. D 8 (1973) 1226]

Qun Wang (USTC), An Introduction to Chiral Magnetic Effect
A little (pre-)history

• In deconfinement phase transition, QCD vacuum can possess metastable domains or P-odd bubbles (space–time domains with non-trivial winding number). [Kharzeev, Pisarski, M.H.G. Tytgat, Phys. Rev. Lett. 81 (1998) 512]

• P-odd bubbles does not contradict the Vafa–Witten theorem (P and CP cannot be broken in the true ground state of QCD for $\theta=0$), which does not apply to QCD dense and hot matter where Lorentz-non-invariant P-odd operators have non-zero expectation values. [Vafa, Witten, Phys. Rev. Lett. 53 (1984) 535; Vafa, Witten, Nucl. Phys. B 234 (1984) 173; Son, Stephanov, Phys. Rev. Lett. 86 (2001) 592]
A little (pre-)history


Chirality and Helicity

- **Chirality**
  \[ \psi_L = \frac{1}{2}(1 - \gamma^5)\psi, \quad \psi_R = \frac{1}{2}(1 + \gamma^5)\psi \]

- **Helicity**
  \[ h = \sigma \cdot \frac{p}{|p|} \]

- **In the chiral limit (massless quark) with** \( m_f = 0 \)

<table>
<thead>
<tr>
<th>Helicity</th>
<th>RH chirality</th>
<th>LH chirality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>Anti-particle</td>
<td>-1</td>
<td>+1</td>
</tr>
</tbody>
</table>
Axial Anomaly and Winding number

- All gauge field configurations are classified by the topological winding numbers \( \tilde{F}^{a}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu}^{\rho\sigma} F^{a}_{\rho\sigma} \)

\[
Q_{w} = \frac{g^{2}}{32\pi^{2}} \int d^{4}x F_{\alpha\beta} \tilde{F}^{\alpha\beta} \\
= N_{CS}(t = \infty) - N_{CS}(t = -\infty)
\]

- Axial anomaly

\[
j_{\mu}^{5} = \sum_{f} \langle \bar{\psi}_{f} \gamma_{\mu} \gamma_{5} \psi_{f} \rangle_{A} \\
\partial^{\mu} j_{\mu}^{5} = 2 \sum_{f} m_{f} \langle \bar{\psi}_{f} i \gamma_{5} \psi_{f} \rangle_{A} - \frac{N_{f} g^{2}}{16\pi^{2}} F^{a}_{\mu\nu} \tilde{F}^{a}_{\mu\nu}
\]

Average over gluon field configuration
Axial Anomaly

• Chiral charge number at chiral limit:

\[ N_5 = N_R - N_L = (n_R - \bar{n}_R) - (n_L - \bar{n}_L) \]
\[ = (n_R + \bar{n}_L) - (n_L + \bar{n}_R) \]
\[ = n(h = +1) - n(h = -1) \]

- Momentum [Diagram]
- Spin [Diagram]

\[ N_5 = \# q_R + \# \bar{q}_R - \# q_L - \# \bar{q}_L \]

R,L denote chirality

• Assuming \( N_R(t = 0) = N_L(t = 0) \), then we have

\[ N_5(t = \infty) = -2N_f Q_w = -2N_f \Delta N_{CS} \]
Chern-Simons number and instanton/sphaleron transition

The nontrivial vacuum structure of a SU(N) gauge theory

\[ \langle Q_w^2 \rangle \sim m^2(\eta') + m^2(\eta) - 2m^2(K) \neq 0 \] \[ \langle Q_w \rangle = 0, \text{ neutron dipole moment, [Baker et al, PRL97,131801(2006)]} \]

\[ |\theta| < 10^{-10} \rightarrow \text{ no P and CP violation, but } Q_w \text{ can induce P- and CP-odd effect} \]
Chiral Magnetic Effect

- Magnetic field aligns spin depending on electric charge; The momenta of quarks and antiquarks align along the magnetic field.
- Quarks with RH-helicity move opposite to those with LH-helicity
  - **Momentum**-down:
    \[ d_R + \bar{u}_R \ (Q_e = -) \]
    \[ u_L + \bar{d}_L \ (Q_e = +) \]
  - **Momentum**-up:
    \[ u_R + \bar{d}_R \ (Q_e = +) \]
    \[ d_L + \bar{u}_L \ (Q_e = -) \]
Chiral Magnetic Effect

- Meganetic field locks
  \[
  \text{charge} \leftrightarrow \text{helicity} \leftrightarrow \text{momentum}
  \]
- The asymmetry between RH- and LH-helicity from anomaly will lead to charge asymmetry (charge separation) along magnetic field
- This is called Chiral Magnetic Effect
Charge Separation

- Topological charge + Magnetic field
  \[ Q_w = -1 \]
  \[ \Delta N_5 = 2 \]
  Excess in RH

Chirality + Polarization

Sphaleron transition

Electric charge current induced by magnetic field
Separation of charge along $L_z$ or $B_z$ means P-violation ($\vec{L}$ and $\vec{B}$ are axial vector)

$Q_e = -$ and $\vec{x} \rightarrow -\vec{x}$

$Q_e = -$ and $\vec{j}$

$Q_e = +$ and $\vec{x} \rightarrow -\vec{x}$
Charge Separation means P-violation

\[ L = r \times p \rightarrow L \]
\[ B \rightarrow B \]
\[ E \rightarrow -E \]
\[ j^\mu \rightarrow -j^\mu \]

\[ j \rightarrow -j, \psi_L \leftrightarrow \psi_R \]
\[ j^5_5 = j^5_R - j^5_L \rightarrow j^5_5 \]

\[ \partial_\mu j^5_5 = C E \cdot B \rightarrow \partial_\mu j^5_5 = -C E \cdot B \]
\[ N_R - N_L = Q_W \rightarrow N_R - N_L = -Q_W \]
Induced current by magnetic field

- Chiral chemical potential $\mu_5 = \frac{1}{2}(\mu_R - \mu_L)$

- Induced current
  \[ j = \frac{N_c \sum q f^2}{2\pi^2} \mu_5 B \]

- Derivation:
  Thermodynamic potential
  Linear response theory
  Propagator in magnetic field
  Kubo-Formula
  Chern-Simons term
Chiral Magnetic Effect and Charge Separation

- Average over charge and charge squared:
  \[ \langle Q_e \rangle = 0, \langle Q_e^2 \rangle \neq 0 \]

\[ \langle Q \rangle = 0 \]
\[ \langle Q^2 \rangle \neq 0 \]

Fluctuating EDM of QGP
P- and CP-odd effect
Kharzeev ('06),
Kharzeev and Zhitnitsky ('07)
Kharzeev, McLerran and Warringa ('08)
About unit for magnetic field: from cgs to natural unit

1 $c = 3 \times 10^{10}$ cm $\cdot$ s$^{-1}$
1 $\hbar = 1.05 \times 10^{-27}$ g $\cdot$ cm$^2$ $\cdot$ s$^{-1}$
1 eV $= 1.6 \times 10^{-12} g \cdot cm^2 \cdot s^{-2}$

$$E = \frac{1}{8\pi} \int d^3 x B^2$$

1 s $= 1.52 \times 10^{15} \hbar \cdot eV^{-1}$
1 cm $= 5.06 \times 10^4 \hbar \cdot eV^{-1} \cdot c$
1 g $= 5.6 \times 10^{32} eV \cdot c^{-2}$

1 Gauss $= 10^{-4}$ T
$= 1 g^{1/2} cm^{-1/2} s^{-1}$
$= 6.92 \times 10^{-2} (\hbar c)^{-3/2} \cdot eV^2$

1 MeV$^2 = 1.44 \times 10^{13}$ Gauss
$m_{\pi}^2 \sim 2.8 \times 10^{17}$ Gauss
Ultra-high Magnetic field

Pancake approximation
Kharzeev, McLerran & HJW ('08)
See also Minakata and Müller ('96)

\[ eB\left(\tau = 0.2 \text{ fm}/c\right) \approx 10^3 \sim 10^4 \text{ MeV}^2 \approx 10^{18} \text{ G} \]
The spatial distribution of magnetic fields for b=10 fm at 200 GeV.
Unit: pion mass squared. ---- W. Deng, X. Huang, PRC85, 044907(2012)
Charge correlation at RHIC

STAR Collab., PRL 103, 251601(2009); PRC 81, 054908 (2010)

Au+Au, Cu+Cu at 200 GeV/A
Minimum bias, $|\eta| < 1$, $p_t \in [0.15,2]$ GeV

Sign of local parity violation?
Approaches to CME/CVE

• **Gauge/Gravity correspondence**
  
  Erdmenger, et. al., JHEP 0901, 055(2009);  
  Banerjee, et. al., JHEP 1101, 094 (2011);  
  Torabian and Yee, JHEP 0908, 020(2009);  
  Rebhan, Schmitt and Stricker, JHEP 1001, 026 (2010);  
  Kalaydzhyan and Kirsch, PRL 106, 211601 (2011);  
  ……

• **Hydrodynamics with Entropy/T-invariance Principle**
  
  Son and Surowka, PRL 103, 191601(2009);  
  Kharzeev and Yee, PRD 84, 045025(2011);  
  Pu, Gao and Q.W., PRD 83, 094017(2011);  
  ……

• **Field Theory**
  
  Metlitski and Zhitnitsky, PRD 72, 045011(2005);  
  Newman and Son, PRD 73, 045006(2006);  
  Lublinsky and Zahed, PLB 684, 119(2010);  
  Asakawa, Majumder and Muller, PRC 81, 064912(2010);  
  Landsteiner, Megias and Pena-Benitez, PRL 107, 021601(2011);  
  Hou, Liu and Ren, JHEP 1105, 046(2011);  
  ……

• **Quantum Kinetic Approach**
  
  Gao, Liang, Pu, Q. Wang and X.-N. Wang, PRL 109, 232301(2012);  
  Son, Yamamoto, arXiv:1210.8158;
Approaches to CME/CVE

- Field theory
- Hydrodynamics with entropy principle
- Quantum kinetic theory with Wigner function
Although the chiral magnetic conductivity is given from one loop diagram, the CME is related to the chiral anomaly, which is guaranteed no more high order contributions by the Ward identity. Therefore, at least now, there is no more correlation found from the high orders. [For higher order correction of CVE, see Golkar, Son 2012, Hou, Ren, 2012]
Lattice calculation

• The chiral chemical potential has no sign problem, so the lattice simulations are available [Fukushima, Kharzeev, Warringa, 2008]

\[ \det \mathcal{M}(\mu_5) \equiv \det(\hat{D} + \mu_5 \gamma^0_E \gamma^5 + m) \]

– a direction study of chiral magnetic current as a function of chiral chemical potential [Yamamoto, 2011]
– Abramczy, Blum, Petropoulos, Zhou, 2009
Anomaly in Hydrodynamics with Entropy Principle

- Hydrodynamic equation with anomaly

\[ \partial_\mu T^{\mu\nu} = F^{\nu\lambda} j_\lambda, \quad \partial_\mu j^\mu = C E \cdot B \]

- Entropy production satisfies

\[ s^\mu = s u^\mu - \frac{\mu}{T} \nu^\mu \]

\[ \partial_\mu s^\mu = -\frac{1}{T} \partial_\mu u_\nu \tau^{\mu\nu} - \nu^\mu \left( \partial_\mu \frac{\mu}{T} - \frac{E_\mu}{T} \right) - C \frac{\mu}{T} E \cdot B \]

\[ \tau^{\mu\nu} = -\eta \Delta^{\mu\alpha} \Delta^{\nu\beta} \left( \partial_\alpha u_\beta + \partial_\beta u_\alpha \right) - \left( \zeta - \frac{2}{3} \right) \Delta^{\mu\nu} \partial \cdot u \]

\[ \nu^\mu = -\sigma T \left( \Delta^{\mu\nu} \partial_\nu \frac{\mu}{T} - \frac{E_\mu}{T} \right), \]

- The new (E.B) term violates the positive entropy production

[Son and Surowka, PRL 103, 191601(2009)]
Anomaly in Hydrodynamics with Entropy Principle

• Requiring positive entropy production, new terms are needed

\[
\nu^\mu = -\sigma T \Delta^{\mu \nu} \partial_\nu \left( \frac{\mu}{T} \right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu
\]

\[
s^\mu = su^\mu - \frac{\mu}{T} \nu^\mu + D \omega^\mu + DB B^\mu
\]

• The new coefficients can be fixed

\[
D = \frac{1}{3} C \frac{\mu^3}{T}, \quad DB = \frac{1}{2} C \frac{\mu^2}{T},
\]

\[
\xi = C \left( \mu^2 - \frac{2}{3} \frac{n \mu^3}{\epsilon + P} \right), \quad \xi_B = C \left( \mu - \frac{1}{2} \frac{n \mu^2}{2\epsilon + P} \right)
\]

[Son and Surowka, PRL 103, 191601(2009)]
With two currents

\[ \partial_\mu T^{\mu\nu} = F^{\nu\lambda} j_\lambda \]

\[ \partial_\mu j^\mu = CE \cdot B \]

\[ j^\sigma = nu^\sigma + \nu^\sigma, \quad j_5^\sigma = n_5 u^\sigma + \nu_5^\sigma \]

\[ \nu^\sigma = -\sigma T (\Delta^\sigma \rho \partial_\rho \frac{\mu}{T} - \frac{E^\sigma}{T}) + \xi_5 \omega^\sigma + \xi_B B^\sigma \]

\[ \nu_5^\sigma = -\sigma_5 T \Delta^\sigma \rho \partial_\rho \frac{\mu_5}{T} + \xi_5 \omega^\sigma + \xi_{5B} B^\sigma \]

\[ s^\sigma = su^\sigma - \nu^\sigma \frac{\mu}{T} - \nu_5^\sigma \frac{\mu_5}{T} + D\omega^\sigma + D_B B^\sigma \]

\[ \xi = 2 \mu \mu_5 C, \quad \xi_5 = \mu^2 C \]

\[ \xi_B = \mu_5 C, \quad \xi_{5B} = \mu C \]

\[ D = -\frac{\mu^2 \mu_5}{T}, \quad D_B = -\frac{\mu \mu_5}{T} \]

Pu, Gao, Q.Wang,
PRD83, 094017(2011)
Quantum Kinetic Theory: an approach to CME/CVE

- How to describe CME/CVE as quantum effects in microscopic theory?
- Quantum kinetic theory is quite a natural choice. It can bridge between the microscopic and macroscopic approach.
- We will show that CME/CVE are natural consequences of the quantum kinetic equations. Chiral anomaly appears naturally in a remarkable way and all the other conservation laws are also automatically satisfied.
Gauge invariant Wigner operator/function

\[ W(x, p) = \langle : \tilde{W}(x, p) : \rangle \]

\[ \tilde{W}_{\alpha\beta}(x, p) = \int \frac{d^4y}{(2\pi)^4} e^{-ip\cdot y} \bar{\psi}_\beta \left( x + \frac{1}{2}y \right) \mathcal{P}U \left( A, x + \frac{1}{2}y, x - \frac{1}{2}y \right) \psi_\alpha \left( x - \frac{1}{2}y \right) \]

Gauge link

\[ \mathcal{P}U \left( A, x + \frac{1}{2}y, x - \frac{1}{2}y \right) \equiv \mathcal{P}\text{Exp} \left( -iey^\mu \int_0^1 ds A_\mu \left( x - \frac{1}{2}y + sy \right) \right) \]

Dirac equation

\[ [i\gamma^\mu D_\mu(x) - m] \psi(x) = 0, \quad \bar{\psi}(x) \left[ i\gamma^\mu D_\mu^\dagger(x) + m \right] = 0 \]

Quantum Kinetic Equation for Wigner function for massless fermion in homogeneous magnetic field

\[ \gamma_\mu \left( p^\mu + \frac{1}{2}i \nabla^\mu \right) W(x, p) = 0 \]

\[ \nabla^\mu \equiv \partial_\mu - QF_{\mu\nu} \partial^\nu \]
Wigner function

Decomposition of Wigner function:

\[ W = \frac{1}{4} \left[ \mathcal{T} + i \gamma^5 \mathcal{P} + \gamma^\mu \gamma^\nu \mathcal{A}_\mu + \frac{1}{2} \sigma^{\mu\nu} \mathcal{I}_{\mu\nu} \right] \]

scalar  p-scalar  vector  axial-vector  tensor

Coupled equations for vector and axial-vector

\[
\begin{align*}
p^\mu \gamma^\mu &= 0, \quad p^\mu \mathcal{A}_\mu = 0, \\
\nabla^\mu \gamma^\mu &= 0, \quad \nabla^\mu \mathcal{A}_\mu = 0, \\
\epsilon_{\mu\nu\rho\sigma} \nabla^\rho \mathcal{V}^\sigma &= -2 (p_\mu \gamma^\nu - p^\nu \gamma^\mu), \\
\epsilon_{\mu\nu\rho\sigma} \nabla^\rho \gamma^\sigma &= -2 (p_\mu \mathcal{A}_\nu - p^\nu \mathcal{A}_\mu).
\end{align*}
\]

Vasak, Gyulassy and Elze, Annals Phys. 173, 462 (1987);

16 equations for 8 components of \( \gamma^\mu \) and \( \mathcal{A}_\mu \) these equations must be highly consistent with each other. At this point, \( \gamma^\mu \) and \( \mathcal{A}_\mu \) can be any functions of x and p that satisfy the above equations.
Expand vector and axial vector in powers of $\partial_x^\mu$ and $F^{\mu\nu}$

$$\mathcal{V}_\mu = \mathcal{V}_\mu^0 + \mathcal{V}_\mu^1 + \ldots, \quad \mathcal{A}_\mu = \mathcal{A}_\mu^0 + \mathcal{A}_\mu^1 + \ldots$$

0-th order

$$\mathcal{V}_\mu^0, \quad \mathcal{A}_\mu^0 : (\partial_x^\mu)^0, \quad (F^{\mu\nu})^0$$

1-st order

$$\mathcal{V}_\mu^1, \quad \mathcal{A}_\mu^1 : (\partial_x^\mu)^1, \quad (F^{\mu\nu})^1$$

Iterative equations:

$$\epsilon_{\mu\nu}^{\rho\sigma} \nabla_\rho \mathcal{A}_\sigma^n = -2 \left( p_\mu \mathcal{V}_\nu^{n+1} - p_\nu \mathcal{V}_\mu^{n+1} \right),$$

$$\epsilon_{\mu\nu}^{\rho\sigma} \nabla_\rho \mathcal{V}_\sigma^n = -2 \left( p_\mu \mathcal{A}_\nu^{n+1} - p_\nu \mathcal{A}_\mu^{n+1} \right).$$

Gao, Liang, Pu, Q.Wang, X.N.Wang, PRL 109, 232301(2012)
CME/CVE as Result of Solution to Coupled Quantum Kinetic Equations

\[ j^\mu = \int d^4p \mathcal{V}^\mu = nu^\mu + \xi \omega^\mu + \xi_B B^\mu, \]
\[ j_5^\mu = \int d^4p \mathcal{A}^\mu = n_5 u^\mu + \xi_5 \omega^\mu + \xi_{B5} B^\mu, \]
\[ T^{\mu\nu} = \frac{1}{2} \int d^4p (p^\mu \mathcal{V}^\nu + p^\nu \mathcal{V}^\mu) \]
\[ = (\epsilon + P) u^\mu u^\nu - P g^{\mu\nu} + n_5 (u^\mu \omega^\nu + u^\nu \omega^\mu) \]
\[ + \frac{1}{2} Q\xi (u^\mu B^\nu + u^\nu B^\mu) \]
Transport coefficients

\[ \xi = \frac{1}{\pi^2} \mu \mu_5, \]
\[ \xi_B = \frac{Q}{2\pi^2} \mu_5, \]
\[ \xi_5 = \frac{1}{6} T^2 + \frac{1}{2\pi^2} (\mu^2 + \mu_5^2), \]
\[ \xi_{B5} = \frac{Q}{2\pi^2} \mu. \]

\[ n = \frac{1}{3\pi^2} \mu \left( \pi^2 T^2 + \mu^2 + 3\mu_5^2 \right) \]
\[ n_5 = \frac{1}{3\pi^2} \mu_5 \left( \pi^2 T^2 + \mu_5^2 + 3\mu^2 \right) \]
\[ \epsilon = \frac{1}{2\pi^2} \left[ \frac{7\pi^4}{30} T^4 + \pi^2 T^2 (\mu^2 + \mu_5^2) + \frac{1}{2} (\mu^4 + \mu_5^4) + 3\mu^2 \mu_5^2 \right] \]

All the conservation laws and anomaly can be derived naturally

\[ \partial_\sigma j_5^\sigma = -\frac{Q^2}{2\pi^2} E \cdot B \quad \partial_\sigma j^\sigma = 0 \quad \partial_\sigma T^{\sigma \nu} = Q F^{\nu \rho} j_\rho \]

An Independent derivation of chiral anomaly from quantum kinetic theory!
With more flavors

Consider 3-flavor quark matter \((u,d,s)\), the vector current can be electromagnetic or baryonic

\[
\begin{align*}
\xi^{\text{baryon}} &= \frac{N_c}{\pi^2} \mu \mu_5, & \xi^{\text{baryon}} &= \frac{N_c}{6\pi^2} \mu_5 \sum_f Q_f, \\
\xi^{\text{EM}} &= \frac{N_c}{\pi^2} \mu \mu_5 \sum_f Q_f, & \xi^{\text{EM}} &= \frac{N_c}{2\pi^2} \mu_5 \sum_f Q_f^2.
\end{align*}
\]

Since \(\sum_f Q_f = 0\) for the three-flavor quark matter, we have

\[
\xi_B^{\text{baryon}} = \xi^{\text{EM}} = 0
\]

[Kharzeev and Son, PRL 106, 062301(2011); Gao, Liang, Pu, Q.Wang, X.N.Wang, PRL 109, 232301(2012)]
Local Polarization Effect

Consider 3-flavor quark matter (u,d,s), the axial baryonic current

\[ j_5^\sigma = n_5 w^\sigma + \xi_5 \omega^\sigma + \xi_5 B^\sigma \]

\[ \xi_5 = N_c \left[ \frac{1}{6} T^2 + \frac{1}{2\pi^2} (\mu^2 + \mu_5^2) \right], \]

\[ \xi_{B5} = \frac{N_c}{6\pi^2} \mu \sum_f Q_f = 0. \]

Leading to Local Polarization Effects! (either for high or low energy HIC)

The LPE can be measured in heavy ion collisions by the hadron (e.g. hyperon) polarization along the vorticity direction once it is fixed in the event.

Quadratic in temperature, chemical potential, chiral chemical potential → No cancellation!
Related and new phenomena

• Recently, there are a lot of phenomena related to CME, e.g. chiral magnetic spirals [Basar, Dunne, Kharzeev, 2010, chiral shear wave, Sahoo, Yee, 2009, etc]

• Chiral magnetic wave (CMW) [Burnier, Kharzeev, Liao, and Yee, 2011,2012].

• Berry phase and chiral kinetic equation can be given within quantum kinetic approach [Chen, Pu, Q.Wang, X.N.Wang, 2012; Yamamoto, Son, 2012; Stenphanov, Yin, 2012].

• Other related phenomena are discussed in the physics of neutrinos [Vilenkin, 1979, 1980], primordial electroweak plasma [Giovannini, Shaposhnikov 1998], quantum wires [Alekseev, Cheianov, Frolich, 1998].
• If spontaneous breaking of Parity in QCD-vacuum under magnetic field is confirmed, it would be a big event in fundamental physics!
A poem for beauty and loneliness

Loneliness seems to be luxury in turbulent China now ......