Relativistic Dissipative Spin Hydrodynamics from Kinetic Theory

Based on : PLB 814 (2021) 136096, PRD 103 (2021) 1, 014030, S. Bhadury*, W. Florkowski, A. Jaiswal, A. Kumar and, R. Ryblewski

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Introduction :

- Theoretical prediction of spin-polarization due to spin-orbit interaction was verified from experiments at RHIC and LHC.

  [Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94, 102301 (2005); Phys. Lett. B 629, 20 (2005)]

  [STAR Collaboration, Nature 548, 62 (2017), Phys. Rev. Lett. 123, 132301 (2019), Phys. Rev. Lett. 126, 162301 (2021)]

- Apart from the Global Spin-Polarization (GSP), a Longitudinal Spin-Polarization (LSP) has also been reported.

  [STAR Collaboration, Nature 548, 62 (2017), Phys. Rev. Lett. 123, 132301 (2019)]

- Theoretical models assuming equilibration of spin degrees of freedom, have provided explanation of the GSP, but quantitative and qualitative mismatch between theory and experiments exist for LSP.

  [I. Karpenko and F. Becattini, EPJC 77 (2017) 4, 213, PRL 120, 012302 (2018)]

- The solution may be to go beyond the assumption of equilibration.

Relativistic Hydrodynamics :

- Inspired by the success of Relativistic Hydrodynamics (RH) in explaining the multitude of properties of QGP evolution, development of a framework of RH that incorporates spin was started.

  [P. Romatschke, IJMPE 19 (2010) 1-53, J. Y. Ollitrault EJP 29 (2008) 275-302, Jaiswal and Roy AHEP 2016 (2016) 9623034]

  [F. Becattini et al, Annals Phys. 338 (2013) 32-49, PRC 95 (2017) 5, 054902, EPJC 77 (2017) 4, 213]

  [W. Florkowski et al. PRC 97 (2018) 4, 041901, PRD 97 (2018) 11, 116017]

  [D. Montenegro et al. PRD 96 (2017) 5, 056012, PRD 96 (2017) 7, 076016]

- Noting that, spin-polarization originates from rotation of fluid, we need to allow conservation of angular momentum in description of hydrodynamics. Thus the conservation laws are :

$$\partial_\mu N^\mu = 0, \qquad \partial_\mu T^{\mu\nu} = 0, \qquad \partial_\lambda J^{\lambda,\mu\nu} = 0 \implies \partial_\lambda S^{\lambda,\mu\nu} = 2\, T^{[\nu\mu]} \tag{1}$$

- Equations of dissipative RH are not closed and require a microscopic theory.

Kinetic Theory :

- To import spin in kinetic theory (KT), we start from the Wigner function ($\mathcal{W}_{\alpha\beta}$), that bridges the gap between QFT and KT.
- For spin-1/2 particles we set up kinetic equation of $\mathcal{W}_{\alpha\beta}$ using Dirac equation.
  [Xin-Li Sheng, PhD Thesis (2019)]
- The Wigner function can be decomposed as,

$$\mathcal{W}_{\alpha\beta} = \frac{1}{4}\left(\mathcal{F} + i\gamma^5\mathcal{P} + \gamma^\mu\mathcal{V}_\mu + \gamma^5\gamma^\mu\mathcal{A}_\mu + \frac{1}{2}\Sigma^{\mu\nu}\mathcal{S}_{\mu\nu}\right)_{\alpha\beta} \tag{2}$$

	Scalar Component	***Axial Component***
Kin. Eq.	$k^\mu\partial_\mu\mathcal{F}(x,k) = \mathcal{C}_\mathcal{F}$	$k^\mu\partial_\mu\mathcal{A}^\nu(x,k) = \mathcal{C}^\nu_\mathcal{A}$
RTA	$C_\mathcal{F} = \frac{(k\cdot u)}{\tau_{\rm eq}}\Big[\mathcal{F}_{\rm eq}(x,k) - \mathcal{F}(x,k)\Big]$	$C^\nu_\mathcal{A} = \frac{(k\cdot u)}{\tau_{\rm eq}}\Big[\mathcal{A}^\nu_{\rm eq}(x,k) - \mathcal{A}^\nu(x,k)\Big]$
Dist. fn.	$\mathcal{F}^\pm(x,k) = 2m\int_{p,s} f^\pm(x,p,s)\ \delta^{(4)}(k\mp p)$	$\mathcal{A}^\mu_\pm(x,k) = 2m\int_{p,s} s^\mu f^\pm(x,p,s)\ \delta^{(4)}(k\mp p)$

[S.B., W. Florkowski, A. Jaiswal, A. Kumar and, R. Ryblewski, PLB 814 (2021) 136096, PRD 103 (2021) 1, 014030]

Kinetic Theory and Transport Coefficients :

- We take the equilibrium phase-space distribution function to be :

$$f^{\pm}_{\mathrm{eq},s}(x,p,s) = e^{-\beta(u\cdot p)\pm\xi}\left(1+\frac{1}{2}\omega_{\mu\nu}s^{\mu\nu}\right)+\mathcal{O}(\omega^2) \tag{3}$$

[F. Becatinni et al., Annals Phys. 338 (2013) 32-49, W. Florkowski et al., PRD 97 (2018) 11, 116017]

- Near local equilibrium $f_{\mathrm{s}}(x,p,s)$ can be expanded in Chapman-Enskog like expansion as,

$$f^{\pm}_{s}(x,p,s) = f^{\pm}_{\mathrm{eq},\,s}(x,p,s) + \delta f^{\pm}_{s}(x,p,s). \tag{4}$$

- Evaluating δf, we can determine the transport coefficients.

$$\delta N^{\mu} = \tau_{\mathrm{eq}}\beta_n(\nabla^{\mu}\xi), \tag{5}$$

$$\delta T^{\mu\nu} = \tau_{\mathrm{eq}}\big[-\beta_{\Pi}\,\Delta^{\mu\nu}\,\theta+2\,\beta_{\pi}\,\sigma^{\mu\nu}\big], \tag{6}$$

$$\delta S^{\lambda,\mu\nu} = \tau_{\mathrm{eq}}\Big[B^{\lambda,\mu\nu}_{\Pi}\theta+B^{\phi\lambda,\mu\nu}_{n}(\nabla_{\phi}\xi)+B^{\alpha\beta\lambda,\mu\nu}_{\pi}\sigma_{\alpha\beta}+B^{\rho\gamma\phi\lambda,\mu\nu}_{\Sigma}(\nabla_{\rho}\omega_{\gamma\phi})\Big] \tag{7}$$

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Thank you.