Spin 1 resonances as probes of spin-vorticity dynamics



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Based on 2410.16448,2305.02985 (PRD),2104.12941 (PRC) , ongoing work



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The theoretical necessity of spin-vorticity non-equilibrium

**The experimental necessity** of spin 1 and higher (qubits vs qutrits)

**From qutrits** to non-equilibrium to data

**Coalescence** of light vector mesons

**Blast wave** estimates. What to look for?

Quarkonia mass shifts

**Melting** a new mechanism for alignment Correlate abundance and vorticity?

What to measure to get non-equilibrium

#### Hydrodynamics with spin





A remarkable experimental discovery, which opened a fascinating field of theoretical investigation.



What does a relativistic system look like where

- Close to local equilibrium (strongly coupled, many DoFs)
- Dofs have spin (not "colliding balls" but "shapes")



Unresolved very non-trivial statistical mechanics problem. Spin not the same as "small vortex".

**Spin** quantum microstate, determines macroscopic entropy

**Vorticity** A <u>classical</u> collective excitation carrying angular momentum

So spin hydrodynamics means <u>backreaction</u> of microscopic DoFs on macroscopic perturbations! EFT in development, conceptual issues (minimal dissipation, pseudogauges,non-locality...) not understood

#### Phenomenology so far:Becattini et al, 1303.3431

GC ensemble with angular momentum as a conserved quantity, fermions (1 species)

$$\exp\left(-\frac{p_{\alpha}u^{\alpha}}{T}\right) \to \exp\left(-\frac{p_{\alpha}u^{\alpha}}{T}\right)(\bar{u},\bar{v})\exp\left[\frac{\Sigma_{\mu\nu}\omega^{\mu\nu}}{T}\right]\left(\begin{array}{c}u\\v\end{array}\right)$$

And Fermi-Dirac statistics. Here

- $\omega^{\mu\nu}$  vorticity tensor
- $\Sigma^{\mu\nu}$  spin projection tensor  $\sim \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix}$

local equilibrium isentropic particle production with spin

#### **Fits** $\Lambda$ global polarization

**Doesen't fit** local polarization (wrong phase).

- use T-vorticity but
- Symmetric shear and isothermal freeze-out but

equilibrium, local or global,about conserved charges!. Only circulation conserved is enthalpic ( $\nabla \times [(e+p)\vec{u}]$  associated to angular momentum) not T-circulation or symmetric shear) so on a theory level there is something to understand

**Underestimates** and wrong sign for some spin-1 particles,  $\phi, J/\Psi$ 

**Investigation ongoing** Toroidal vortex rings, jet-induced polarization,...

But... and this is the main point! Theoretically This can not be the whole story! Perfect equilibrium between vorticity and spin <u>acausal!</u>

GT+Montenegro, 1807.02796, GT, Montenegro, Tinti, 1701.08263



The reason: vortical susceptibility means vortices and sound waves <u>Mix</u>, affecting dispersion relation Vorticity+spin must be aligned at equilibrium for entropy to have a well-defined minimum, <u>But</u> this cannot occur instantaneusly in a dynamical system

 $\tau_Y u_\alpha \partial^\alpha s_{\beta\gamma} + s_{\beta\gamma} = \omega_{\beta\gamma}$ 

**GT, Tinti, Montenegro** dispersion relation quartic, non-causal (Ostrogradski's thm). **GT, Montenegro** :  $\tau_Y$  Kramers-Konig dual to vortical susceptibility

N. Weickgenannt et al transport with spin  $\rightarrow$  non-local collision term

**E.Speranza et al** non-linear stability analysis

Ryblewski, Florkowski,... effective spin hydro

Qualitative picture :GT,D Montenegro, 1807.02796 lower limit to  $\eta/s$  in polarizeable fluids (anti-"ferrovortetic" or phase transition)

$$\tau_Y^2 \ge \frac{8c\chi^2(b_o, 0)}{(1 - c_s^2)b_o F'(b_o)} \quad , \quad \frac{\eta}{s} \ge \underbrace{\#}_{\ll 1?} \mathcal{O}(T\tau_Y)$$



Many attemps at quantitative picture Stephanov, Hongo, Florkowski, Ryblewski, Torrier spin/vorticity nonequilibrium theoretically inevitable, Phenomenology needed!

Spin and vorticity: classical-quantum interaction

$$\rho_{spin} = \text{Tr}_{bath} \left[ \rho_{spin} \times \underbrace{\rho_{bath}}_{vorticity} \right]$$

- $\rho_{spin}$  Mixed, evolves under Lindblad equation
- $\rho_{bath}$  Maximally mixed, evolves under classical equation of motion
- $H_{int}$  spin-orbit coupling
- **Cooper-Frye** limit of maximal mixing
- Need model-building for this



Global vorticity formed <u>earlier</u>, local vorticity <u>later</u>. Thus the former should be more equilibrated with vorticity than the latter! important consequences for  $\Lambda$ , vector meson. But we need more quantitative observables!

Why spin 1 resonances can help: spin 1/2 is a qbit of information

$$\rho = \begin{pmatrix} \rho_{1,1} & \rho_{1,-1} \\ \rho_{1,-1}^* & 1 - \rho_{1,1} \end{pmatrix} , \qquad \underbrace{U^{-1}\rho U = \text{Diag}(\alpha, 1 - \alpha)}_{dU = \hat{I} - \delta\theta \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} - i\delta\phi \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}}$$

1 parameter,2 angles Whatever mechanism combines spin ( $\equiv \phi$ ) and angular momentum ( $\equiv \theta$ ) will result in some supportion of +1,-1

$$\frac{dN_{decay}}{d\theta} = 1 + \alpha \cos \theta \quad , \quad \alpha \sim \rho_{1,1}$$

Thus in practice any state indistinguishable from equilibrium  $\rho_{equilibrium} \propto \begin{pmatrix} e^{w/T} & 0\\ 0 & e^{-w/T} \end{pmatrix}$  Can study Dependence of  $\alpha$  on  $y, p_T$  but need to fit many parameters. Need qualitative signature!

Spin1 <u>has more</u> information! (Liang, Wang, nucl-th/0410079)

$$\frac{dN_{decay}}{d\theta d\phi} \propto \cos^2 \theta \rho_{00} + \sin^2 \theta \left(\frac{1-\rho_{00}}{2} + r_{1,-1}\cos(2\phi) + \alpha_{1,-1}\sin(2\phi)\right) +$$

 $+\sin(2\theta)\left(r_{10}\cos\phi + \alpha_{10}\sin\phi\right)$ 



**Small system** Beam direction, momentum three parameters

$$\rho_{00} \equiv \frac{1+\lambda_{\theta}}{3+\lambda_{\theta}} \quad , \quad Re[\rho_{1,-1}] \equiv \frac{\lambda_{\phi}}{3+\lambda_{\theta}} \quad , \quad Re[\rho_{-10}-\rho_{10}] \equiv \frac{\lambda_{\theta\phi}}{3+\lambda_{\theta}}$$

**Large system** Beam direction, momentum and impact parameter 2 additional parameters,  $Im[\rho_{1,-1}], Im[\rho_{-10} - \rho_{10}]$  Crucial information about phases

(Wild idea : Perhaps can get new axis from cumulants in small systems?)

Spin-1 is a qutrit! Two vectors! Can be mixed  $\rho^2 \neq \rho$  in all frames!



$$\rho_8(n_3, n_8) = \frac{1}{3} U^{-1}(\theta, \phi) \begin{pmatrix} 1 + \sqrt{3} n_3 + n_8 & 0 & 0\\ 0 & 1 - \sqrt{3} n_3 + n_8 & 0\\ 0 & 0 & 1 - 2n_8 \end{pmatrix} U(\theta, \phi)$$

Two parameters, two angles so generic state neither pure nor thermal! But what is angle  $\phi$ ? Need "objective" ebye definition! beam axis

From angular distributions to purity

$$\frac{dN_{decay}}{d\theta d\phi} \propto \cos^2 \theta \rho_{00} + \sin^2 \theta \left(\frac{1-\rho_{00}}{2} + r_{1,-1}\cos(2\phi) + \alpha_{1,-1}\sin(2\phi)\right) +$$

 $+\sin(2\theta)\left(r_{10}\cos\phi + \alpha_{10}\sin\phi\right)$ 

Matrix elements and purity directly related

$$\frac{1}{12} \left( 3 \left( n_8 - \sqrt{3} \, n_3 \right) \cos \left( 2\theta_r \right) - \sqrt{3} \, n_3 + n_8 + 4 \right) = \rho_{00}$$
$$\frac{\left( n_8 - \sqrt{3} \, n_3 \right) \sin \left( \theta_r \right) \cos \left( \theta_r \right) \cos \left( \phi_r \right)}{\sqrt{2}} = r_{10}$$
$$\frac{\left( \sqrt{3} \, n_3 + 3n_8 \right) \sin \left( \theta_r \right) \sin \left( \phi_r \right)}{3\sqrt{2}} = \alpha_{10} \quad , \quad \phi_r = -\frac{1}{2} \tan^{-1} \left( \frac{\alpha_{1,-1}}{r_{1,-1}} \right)$$

A concrete example: Coalescence  $K^*,\phi$ 



**Cooper-Frye limit** for some  $\theta$ 

$$\hat{\rho} = \frac{1}{N} U(\theta)^+ \begin{pmatrix} e^{-w/T} & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & e^{w/T} \end{pmatrix} U(\theta)$$

So all quantities related to  $\phi_r$  compatible with zero

**Non-equilibrium** Non-trivial  $\rho_{i\neq j}$  with two well-defined axes,  $\theta_r, \phi_r$ , whose exact nature depends on mechanism combining spin and vorticity

#### Coalescence in a rotating medium

THe expression of the vector meson density matrix in terms of the quark density matrices and the vorticity is straight-forwardly

$$\left(\hat{\rho}^{M}\right)_{mn} = \sum_{ijkl} \left(P_{12}^{L}\right)_{ijklmn} U_{S}(\phi_{r},\theta_{r}) \left(U_{\omega}(\mu_{1},\nu_{1})\rho^{1}(\Omega)U_{\omega}^{-1}(\mu_{1},\nu_{1})\right)_{ij} \times$$

### $\times \left( U_{\omega}(\mu_{2},\nu_{2})\rho^{2}(\Omega)U_{\omega}^{-1}(\mu_{2},\nu_{2}) \right)_{kl} U_{S}^{-1}(\phi_{r},\theta_{r})$

Where  $P_L(w)$  is the (unknown) probability to aquire a spin quantum number from vorticity and the rest are 6-j and C-G coefficients!

Big approximation : non-relativistic. But with constituent quarks and moderate  $p_T, y$  not bad

#### Golden signature:off-diagonal elements



If ebye  $\phi$  coefficients  $\simeq 0$ , Cooper-Frye, otherwise coalescence

Towards more quantitative phenomenology: Blast wave model+coalescence

Use blast-wave model with vorticity, Florkowski et. al., 1904.00002



The idea: longitudinal polarization due to non-equilibrium between spin and vorticity Early polarization due to enthalpy gradients, "out of phase" late vorticity due to flow gradients "spin chemical potential" following initial circulation, fitted final vorticity, T, flow, coalesce using previous prescription spin 1 mesons and baryons? Transverse and longitudinal?



Non-zero meson spin alignment and small baryon polarization follow somewhat naturally



Adjusting parameters allows you to change phase of local polarization. NB: Symmetric shear <u>also</u> manifestation of spin-vorticity non equilibrium



but Not predictive (lots of parameters), in particular Wigner function: if prefers  $\uparrow\uparrow$ , baryon polarization <u>negative</u>, if  $\uparrow\downarrow$  positive P(L): transfer of angular momentum from spin to voricity, decoherence problem, can in principle be calculated from linear response Modulation generally big ( $\gg \langle P \rangle$ ), so is preliminary STAR data!



But if  $\rho_{00}$  and baryon polarization depend strongly on  $\phi$ , it will become a viable explanation, partial-wave like analysis



But the "golden" signature (absent from Cooper-frye: non-diagonal coefficients for spin 1 mesons too, and are non-zero for coalescence!

 $\rho_{00} \equiv \left\langle \cos^2 \theta_D \right\rangle , \quad r_{1,-1} \equiv \left\langle \sin^2 \theta_D \cos(2\phi_D) \right\rangle \equiv \operatorname{Re}\rho_{1,-1}$ 

And then we discovered some of it was measured... for quarkonium!

$$\rho_{00} = \frac{1 + \lambda_{\theta}}{3 + \lambda_{\theta}} \quad , \quad r_{1,-1} = \frac{\lambda_{\phi}}{3 + \lambda_{\theta}} \quad , \quad r_{10} = \frac{\lambda_{\theta\phi}}{3 + \lambda_{\theta}}$$

(NB fewer coefficients as  $J/\psi 
ightarrow \mu\mu, \phi 
ightarrow KK$  )



Solving for  $n_{1,8}$  gives close to maximally mixed state



Off-diagonal elements compatible with zero, Cooper-Frye! but...



Remember spin-orbit non-equilibrium is all about interplay between eaaly (global) and <u>late</u> (local) axes. Need modulation in angle from reaction plane of  $\lambda$ s!

Qualitatively one expects of diagonal elements to be "local", and ny harmonic function averages to zero. Is it zero in every azimuthal bin?

Getting more quantitative for Quarkonium Rotating Cornell potential with spin orbit interaction



Rotating Cornell potential with spin orbit interaction

$$\begin{cases} \mathbf{P} = \mathbf{p_1} + \mathbf{p_2}, & \mathbf{p} = \mu \left(\frac{\mathbf{p_1}}{m_1} - \frac{\mathbf{p_2}}{m_2}\right) \\ \mu = \frac{m_1 m_2}{m_1 + m_2}, & \mathbf{r_1} = \mathbf{R} + \frac{m_2}{m_1 + m_2} \mathbf{r}, & \mathbf{r_2} = \mathbf{R} - \frac{m_1}{m_1 + m_2} \mathbf{r} \end{cases}$$

$$\mathcal{H} = \frac{P^2}{2M} + \frac{p^2}{2\mu} - \mathbf{P} \cdot (\omega \times \mathbf{R}) - \mathbf{p} \cdot (\omega \times \mathbf{r}) - \omega \cdot (\mathbf{S}_1 + \mathbf{S}_2) + V(\mathbf{r})$$

With a Cornell-type potential. This way vorticity and spin interactions accounted for. Mass correction  $\Delta E_{i,j}$  and Melting temperature from Debye formula. More realistic QFT/Open QM models?

#### Mass becomes sensitive to relative direction of spin and vorticity



This is experimentally undetectable (widening), but...

#### One can get melting temperature from Debye formula!



Melting temperature depends non-monotonically on rotation and (anti)polarization. Could such "distillation" explain  $\phi$  spin alignment?  $\phi$  is quarkonium and only polarized survive! If confirmed by more realistic models (QFT,openQM) need abundance vs alignment scans with rapidity.

Can also have to do with quarkonium being more suppressed at higher rapidity (Which is also higher vorticity)



"Distillation" is an important effect qualitatively different from Cooper-Frye Need: SUppression vs alignment in rapidity!

#### Correlation between invariant mass and off-equilibrium $\rho!$



Short term prospects:  $\Omega, \Delta$ 

 $\Omega \to \Lambda K \to p\pi K$ 

**Spin 3/2** ,  $5 \times 5$  density matrix

**Double weak decay**, all 24 elements in principle measureable

So far within error bar w.r.t.  $\Lambda$  but could be hiding a treasure trove of non-equilibrium infromation!

#### Prospect for theory: hadron spin structure Ongoing work with So-Houng Lee, Hyunjoo Kim, Kayman Jhosef : OPE of

$$\underbrace{\langle 0 | T [J^{\mu}, J^{\nu}] | 0 \rangle}_{\phi, J/\psi, \Upsilon} \equiv \underbrace{S_q}_{quark \ spin} + \underbrace{L_q}_{Non-local \ W} + L_g$$

In rotating frame. passive vs active

- Use sum rules for decomposition
- Distinguish between <u>passive</u> and <u>active</u> rotation Naively hydrodynamic vortex ≡ passive, mean field ≡ active Most lattice calculations passive
- Make link between realistic spin structure of meson and hydrodynamics

#### Far away experimenta possibility:Vortex states



$$\phi\left(\vec{x}\right) = \int d^{3}k \exp\left[i\vec{k}.\vec{x}\right] \Phi\left(\vec{k}\right) \hat{a}_{\vec{k}} \left|0\right\rangle$$

If one can produce  $\Phi(\vec{k}) \sim \vec{\nabla} \times \vec{k}$ , wavepacket can contain arbitrary amount of angular momentum, even for scalar targets A variety of applications in QED and QCD thought of for vortex beams



So far done for  $e, \gamma$  but why not A ? https://indico.ihep.ac.cn/event/24375/ In development, Zhuhai (Ivanov) and HIAF Maintaining coherence hard, especially at high energy we need "target" of such states, heavy ion at high l to collide projectiles on! If one could make such an ion with  $l = 10^{3-4}$ 



Put One nucleon in an initial vortical quantum state, collide with projectile that does not need to be in such a state, measure global and local polarization! Why worth doing? "tune" initial state contribution to local (longitudinal) spin by hand, sensitive probe to spin-vorticity non-equilibrium and interplay of global (transverse) and local vorticity.

#### Conclusions

**Non-equilibrium** between spin and vorticity theoretically well-established, need phenomenology

Spin and vorticity different objects

**Cooper-Frye** could be misleading

Spin1 vector mesons can serve as such a link because of a rich structure in their density matrix. Coalescence in vector mesons, potential models in quarkonia

**To do** 3/2 states, realistic hadronic spin structure and perhaps collisions with vortex states

# SPARE SLIDES