Vorticity and hyperon polarization in PHSD – details of algorithm.

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PHSD

- **QGP** $\varepsilon > \varepsilon_{cr} = 0.5GeV/fm^3$
- **Parallel ensemble method**

W. Cassing, E.L. Bratkovskaya PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3

Definition

Classical vorticity

$$\omega = \frac{1}{2}\,\mathrm{rot}\,\mathbf{v}$$

Relativistic kinematic vorticity

$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

where u_ν is a collective local four-velocity of the matter.

$$u_\nu(x) = \gamma(1, \mathbf{v}(x))\,, \quad \gamma(x) = \frac{1}{\sqrt{1-\mathbf{v}^2(x)}}$$

Definition

Relativistic thermal vorticity

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu) \qquad \beta_\nu = \frac{u_\nu}{T}$$

Polarization due to spin-orbital interaction

F. Becattini et al. Eur. Phys. J. C75, no. 9, 406 (2015)

Spin vector:

$$S^\mu(x,p) = -\frac{s(s+1)}{6m}(1 \pm n(x,p))\varepsilon^{\mu\nu\lambda\delta}\varpi_{\nu\lambda}p_\delta$$

s – spin, p_δ – 4 momentum of particle

- Thermodynamic equilibrium.
- The mechanism is not strictly defined.

Polarization of particle with spin

$$\mathbf{P} = \frac{\mathbf{S}^*}{s}$$

$\mathbf{S}^*$ spin vector in rest frame

Transformation to rest frame ($S_0^* = 0$)

$$\mathbf{S}^* = \mathbf{S} + \mathbf{S}\cdot\mathbf{p}\frac{\mathbf{p}}{m\,(E+m)} - S_0\,\frac{\mathbf{p}}{m} = \mathbf{S} - \mathbf{S}\cdot\mathbf{p}\frac{\mathbf{p}}{E\,(E+m)}$$

Final expression in rest frame

$$S_x^* = \frac{s\,(s+1)}{3\,m}\Big(E\varpi_{yz} + p_y\varpi_{0z} - p_z\varpi_{0y} + (p_x\varpi_{yz} + p_y\varpi_{zx} + p_z\varpi_{xy})\frac{p_x}{(E+m)}\Big)$$

$$S_y^* = \frac{s\,(s+1)}{3\,m}\Big(E\varpi_{zx} + p_z\varpi_{0x} - p_x\varpi_{0z} + (p_x\varpi_{yz} + p_y\varpi_{zx} + p_z\varpi_{xy})\frac{p_y}{(E+m)}\Big)$$

$$S_z^* = \frac{s\,(s+1)}{3\,m}\Big(E\varpi_{xy} + p_x\varpi_{0y} - p_y\varpi_{0x} + (p_x\varpi_{yz} + p_y\varpi_{zx} + p_z\varpi_{xy})\frac{p_z}{(E+m)}\Big)$$

Velocity field. Particles $\to$ continuous medium.

Numerically, velocity field can be defined by introducing a smearing function $\Phi(x, x_i)$, where x is the field point and x_i is the coordinate of the ith particle.

Wei-Tian Deng and Xu-Guang Huang, Phys. Rev. **C 93**, 064907 (2016)

- **Velocity of the particles flow**

$$\mathbf{v}(x) = \frac{1}{\sum_i \Phi(x, x_i)} \sum_i \frac{\mathbf{p}_i}{p_i^0} \Phi(x, x_i),$$

- **Velocity of the energy flow**

$$\mathbf{v}(x) = \frac{\sum_i \mathbf{p}_i \Phi(x, x_i)}{\sum_i [p_i^0 + (\mathbf{p}_i)^2 / p_i^0] \Phi(x, x_i)},$$

- **Velocity of cell (relativistic physical meaning?)**

$$\mathbf{v}(x) = \frac{\sum_i \mathbf{p}_i \Phi(x, x_i)}{\sum_i p_i^0 \Phi(x, x_i)},$$

Particles → continuous medium.

If you know 4-flow

$$J^{\mu}(x) = \left(\sum_i \Phi(x, x_i), \sum_i \frac{\mathbf{p}_i}{p_i^0} \Phi(x, x_i) \right)$$

then it is easy to find velocity of fluid:

$$\mathbf{v} = \frac{\mathbf{J}}{J_0} \qquad u^{\mu} = \frac{J^{\mu}}{\sqrt{J_{\nu} J^{\nu}}}$$

"Particle in Cell" method.

Plasma physics.

Grid density

$$J_a = \sum_i J(\mathbf{r}_i)\, W(\mathbf{r}_i - \mathbf{R}_a),$$

for grid point a at position $\mathbf{R}_a$, sum is over all particles i, W – weighting function

Interpolation

$$J(\mathbf{r}) = \sum_a J_a\, W(\mathbf{r} - \mathbf{R}_a),$$

where sum is over all grid knots.

Square-law spline function W is chosen. 3x3x3 grid knots is always used.

“Particle in Cell” method.

Plasma physics.

Advantages

- Single weighting function for grid densities and for interpolation.
- Particles can have some finite size.
- Continuous interpolation of densities at any point inside a grid (with linear or square-law spline function).
- Continuous derivatives (with square-law spline function).

Claud In Cell: 1D $W(x/\Delta x - nint[x/\Delta x])$

$W(x) = 3./4. - x^2$ – near the nearest grid point a
$W(x) = 0.5 * (0.5 \pm x)^2$ – near two neighbors $a \pm 1$
$W(x) = 0$ – for other

Temperature

Relativistic ideal hadron gas (A.S.Khvorostukhin & V.D.Toneev)

Local energy and baryon densities $\rightarrow$ temperature.

Hadron EOS

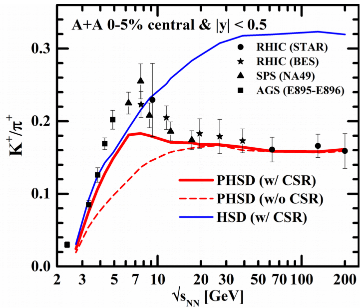
RMF NL Walechka model

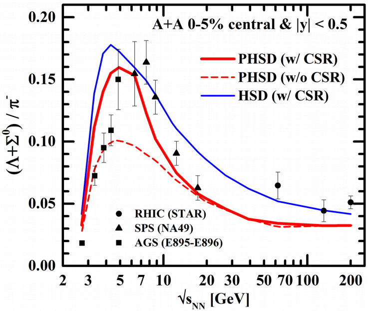
Adopted for scheme above. $\Lambda/\bar{\Lambda}$ is included.

Chiral symmetry restoration in the hadronic phase

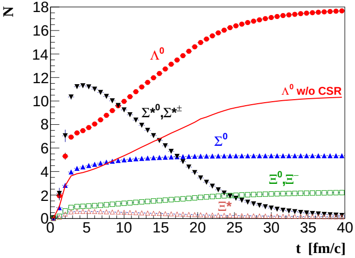
The strangeness enhancement seen experimentally at FAIR/NICA energies probably involves the approximate restoration of chiral symmetry in the hadronic phase.

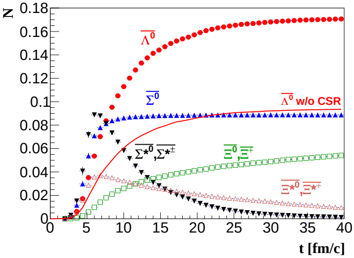
W.Cassing, A.Palmese, P.Moreau, E.L.Bratkovskaya – arXiv:1510.04120 [PRC]



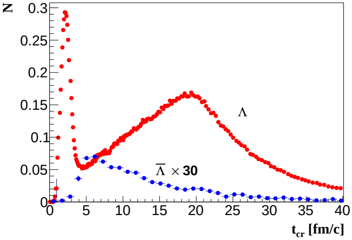


Hyperons production in AuAu@7.7GeV b=7.5fm





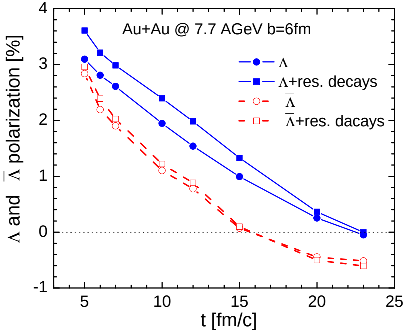
Numbers of strange particle/anti-particles as functions of collision time



Number (rate) of Λs as function of creation time.

Isochronous freeze-out

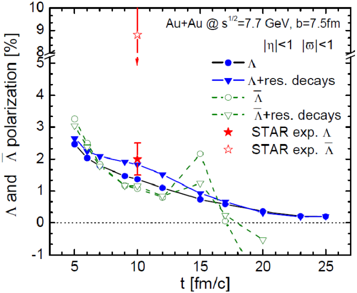
- The vorticity mainly takes place at the border between participant and spectator matter.
- Preliminary results for particles polarization

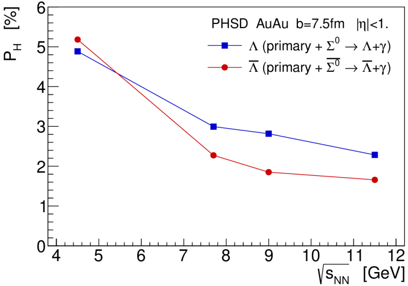


- We can not explain small $\bar{\Lambda}$ polarization (magnetic field??)
- After t>15fm/c thermal vorticity is bad defined.

arXiv:1801.07610, Phys.Rev. C97 (2018) no.6, 064902

Isochronous (left) vs Chemical (right) freeze-out



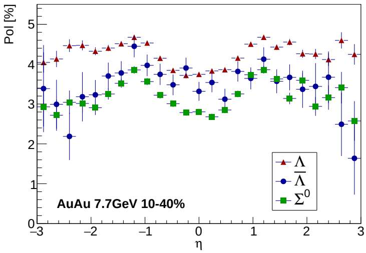


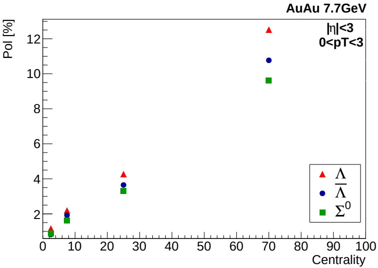
Hadronic EoS (for chemical freeze-out): NL Walechka: $\rho_0 = 0.15 fm^{-3}$,
$Ebind = -16.0 MeV \;\; m^*/m = 0.85 \;\; K = 210 MeV \;\; Asym = 32.50 MeV$

For decays: $C_{\Sigma^* \to \Lambda} = 1/3, \quad C_{\Sigma^* \to \Sigma} = 1/3, \quad C_{\Xi^* \to \Xi} = 1/3$

Elastic do not change polarization.

Polarization of Λ-hyperons





EoS: NL Walechka: $\rho_0 = 0.15 fm^{-3}$, $Ebind = -16.0MeV$ $m^*/m = 0.85$
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Conclusion/TODO

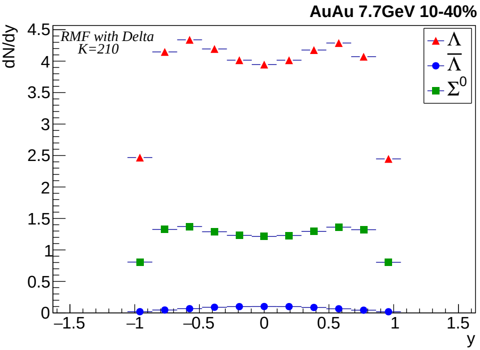
✓ Polarization on chemical freeze-out

✓ Hadronic EOS can not explain difference particle-atiparticle.

- *Combine hadronic and partonic temperature.*
- *Take into account magnetic field.*

Thank you!

Hyperon production



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