Simulating heavy-ion collisions at BES energies

Aritra De, Joe Kapusta, Mayank Singh, Tom Welle

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Standard model of HIC needs to be extended to finite baryon densities. In this work we

- Present a new LEXUS based initial state model
- Use a new crossover equation of state
- Calculate departure functions using a quasiparticle model at finite baryon densities
- Use these new developments to do a baseline calculation for observables at RHIC BES energies
LEXUS based initial conditions

- Original LEXUS (Linear EXtrapolation of Ultrarelativistic Scattering) had no free parameters S. Jeon and J. Kapusta, Phys. Rev. C. 56 (1997)
- LEXUS linearly extrapolated nucleon-nucleon scattering data to nucleus nucleus collisions. Goal was to provide a baseline which would work if there was no new physics beyond nucleon scattering
- Colliding nucleons are assumed to propagate in straight lines colliding with nuclei that cross its path
- Inelastic collisions produced mesons which were assumed to not further interact
Probability of momentum loss in a collision is parametrized as

\[ P(y_{\text{loss}}) = \lambda \frac{\cosh(2y_0 - y_{\text{loss}})}{\sinh(2y_0) - \sinh(y_0)} \]

Rapidity width of produced mesons is given by the Landau model

\[ \sigma_L = \frac{8}{3} \frac{c_s^2}{1 - c_s^4} \log \left( \frac{\sqrt{s}}{2m_N} \right) \approx \log \left( \frac{\sqrt{s}}{2m_N} \right) \]
LEXUS inspired 3D initial state

- Nucleon sampling → Lorentz contraction → Binary collisions
- Nucleons are sampled from a Woods-Saxon distribution and Lorentz contracted in the beam direction
- Nucleons propagate in straight lines in beam direction
- Two nucleons from opposing nuclei collide with probability $\lambda$ when their cylindrical trajectories overlap. Area of the cylinder is given by the total collision cross-section
- Hydrodynamic solver
LEXUS inspired 3D initial state
Equation of State

- Perturbative QCD EOS in QGP phase is matched to a hadron resonance gas EOS at low temperatures M. Albright, J. Kapusta and C. Young, Phys. Rev. C 90 (2014)

\[ P(t, \mu) = S(T, \mu)P_{QGP}(T, \mu) + [1 - S(T, \mu)]P_{HRG}(T, \mu) \]

with

\[ S(T, \mu) = \exp \left( -\frac{1}{\left( \frac{T}{T_0} \right)^r + \left( \frac{\mu}{\mu_0} \right)^r} \right) \]

where \( r \) is an integer.
Equation of State

It shows good match with Lattice EOS at $\mu = 0$...
Equation of State

... and with Lattice EOS calculated at non-zero $\mu$ using Taylor expansion...
Equation of State

... and could be extended beyond.

\[ \mu = 600 \text{ MeV} \]
Departure Functions

• Departure functions account for non-equilibrium corrections at freezeout

\[ f_a = f^{eq}_a (1 + \phi_a) \]

\[ \phi_a = -A_a \partial_\rho u^\rho - B_a p^\nu_a D_\nu \left( \frac{\mu_B}{T} \right) + C_a p^\mu_a p^\nu_a \left( D_\mu u_\nu + D_\nu u_\mu + \frac{2}{3} \Delta_{\mu\nu} \partial_\rho u^\rho \right) \]

• Numerical studies using linear sigma model suggests that the relaxation time

\[ \tau(E_a) \propto E_a \equiv \tau' E_a \] P. Chakraborty and J. Kapusta, Phys. Rev. C 95 (2017)

• For shear correction, we get \( C_a = \frac{\tau'}{2T} \) with \( \tau' = \frac{\eta}{2T\omega} \)
Thermal conductivity

- Unlike shear viscosity, the expression for thermal conductivity associated with baryon current is not so simple

\[ B_a = \tau' \left( b_a - \frac{n_B}{w} E_a \right) - b(T, \mu_B) \]

where

\[ b = \frac{\tau' T}{w^2} \left[ T \chi_{T \mu} + \mu_B \chi_{\mu \mu} \right] - T n_B \left[ T \chi_{TT} + \mu_B \chi_{T \mu} \right] - n_B w \]

and we have susceptibilities

\[ \chi_{xy} = \frac{\partial^2 P(T, \mu)}{\partial x \partial y} \]
pT Spectra

- No overall normalization used
- No initial flow. Initial flow will necessitate use of higher $\eta/s$ which will lead to more entropy production
- No bulk used here. That will also contribute to multiplicity
- No hadronic cascade. Pion winds shift proton spectra to higher $p_T$
Rapidity spectra

Pions

Protons

With departure functions
Without departure functions
$V_2$

$\pi^{-}$ Au+Au 14.5 GeV for 0-10% for $\eta/s = 0.08$

$V_2$

$\pi^{-}$ Au+Au 200 GeV for 0-10% for $\eta/s = 0.08$
Summary

• We present our results for simulations of HICs at non-zero baryon densities. A new baseline calculation for RHIC-BES energies using a LEXUS based initial state, a crossover EOS without critical point and departure functions at finite baryon densities

• A LEXUS inspired 3D initial state model was used

• A crossover EOS from matching HRG and pQCD results was used at finite baryon densities

• Departure functions are calculated at finite baryon densities

• Get reasonable matching to data without an overall normalization

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