Progress Report for the A08 Project

Magnetized and isospin-asymmetric QCD matter

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CRC-TR 211


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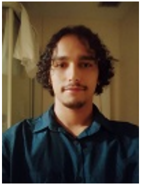
Adeilton Dean Marques Valois

- Equation of state for non-zero isospin and beyond
- Novel features of the phase diagram at non-zero isospin asymmetry
- Heavy-ion-collision-related phenomena at non-zero magnetic fields

Equation of state: Goals and Timeline

Goals:

- EOS at non-zero isospin chemical potential from direct simulations
- Baryonic effects at non-zero isospin
- Electromagnetic effects at non-zero isospin

Timeline:

2021
- Generate new ensembles at $N_t = 16$;
- Finalize EoS measurements at $N_t = 10, 12$;
- Implement Taylor-expansion coefficients;
- Implement current-current correlators

2022
- Perform measurements and λ-extrapolation on $N_t = 16$ ensembles;
- Perform first measurements of Taylor-expansion coefficients;
- Test current-current correlators

Equation of state: Goals and Timeline

Timeline (continued):

2023
- Perform continuum limit of direct EoS measurements at $\mu_I \neq 0$;
- Compute Taylor-expansion coefficients on finer ensembles;
- Perform first measurements of current-current correlators on two coarser lattices

2024
- Compute Taylor-expansion coefficients on finest ensemble;
- Compute EoS at non-zero μ_L and μ_s up to $N_t = 12$;
- Measure current-current correlators on two finer lattices

2025
- Perform continuum limit of EoS at non-zero μ_L and μ_s;
- Finalize current-current correlator measurements and EoS at $eB \neq 0$

Equation of state: Where Are We?

- EoS at non-zero μ_I is fully done on several lattice spacings [Brandt et al., 2023b].
- Baryonic and magnetic effects are treated in a Taylor-expansion around finite μ_I.
- Taylor-coefficients are very sensitive to λ, improvements have poor S/N ratio [Brandt et al., 2022].
- Work-around for μ_B Taylor-coefficients has been found, and first results are available.
- Similar work-around for current-current correlators is more costly and first tests are on the way.

Status: compared to planned timeline, we are moderately delayed due to unforeseen technical issues.

Phase diagram at $\mu_I \neq 0$: Goals and Timelines

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Goals:

- Baryonic effects
- Superconducting BCS phase at large isospin chemical potential
- Role of pion condensation for the chiral limit

Timeline:

2021 • Determine BEC boundary on coarsest lattice at first smaller-than-physical quark mass (including λ extrapolation) and assess cost in view of smaller masses;

• Compute Dirac spectrum on newly generated ensembles of progressively finer lattices at large μ_I;

2022 • Test Lee-Yang zero method;

• Perform continuum extrapolation of BEC boundary at first smaller than physical mass;

• Perform continuum limit of Dirac spectrum at large μ_I and assess T and μ_I dependence of BCS gap;

• Implement correlation function with extended sources;

Phase diagram at $\mu_I \neq 0$: Goals and Timelines

Timeline (continued):

2023 • Optimize eigenvalue measurements of reduced matrix for large lattices;
• Determine BEC boundary at a second smaller-than-physical mass;
• Perform first measurements of correlation functions with extended sources on coarse lattices and test efficacy of method

2024 • Apply Lee-Yang zero method to larger lattices if possible;
• Determine BEC boundary at an even smaller mass, as far as affordable, or perform continuum limit of smallest available mass;
• Comparison and matching of two complementary approaches for location of BEC-BCS phase boundary

2025 • Assess behavior of BEC boundary towards chiral limit;
• Extend BEC-BCS crossover measurements to finer lattice

Phase diagram at $\mu_I \neq 0$: Where Are We?

- First tests to reproduce the BEC phase boundary using Lee-Yang zeros method were unsuccessful, so due to its numerical cost it has not been prioritized.
- BEC line obtained for $m_{ud} = \frac{1}{2} m_{ud,phys}$ at $N_t = 8$.
- Limited checks for $N_t = 10, 12$ (due to large simulation costs).
- Simulations at $m_{ud} = \frac{1}{4} m_{ud,phys}$ are being performed.
- Exact lowest mode deflation for measurements, and λ reweighting implemented to reduce numeric costs.
- BEC-BCS transition related research was severely hindered by Francesca Cuteri leaving the CRC.

Status: compared to planned timeline, we are behind schedule.

Phenomena at $B \neq 0$: Goals and Timelines

Goals:

- Localized magnetic fields
- Chiral magnetic conductivity

Timeline:

2021 • Implement localized external field in simulation code;
• Implement chiral chemical potential and observable C (chiral magnetic conductivity);

2022 • Generate ensembles at finite ζ;
• Implement inhomogeneous observables and ζ-derivatives;
• Measure C on existing $B > 0$ ensembles.

Phenomena at $B \neq 0$: Goals and Timelines

Timeline (continued):

2023
- Determine B–ζ–T phase diagram on coarse lattices and measure inhomogeneous observables;
- Perform first simulations with Wilson fermions at $\mu_5 \neq 0$;
- Perform continuum extrapolations for C obtained with staggered fermions

2024
- EoS at finite ζ;
- Continuum extrapolation of B–ζ–T phase diagram;
- Topology-electric dipole correlations at finite isospin.

2025
- Results for EoS at finite ζ;
- Compare to analytical approaches.

Phenomena at $B \neq 0$: Where are we?

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Localized magnetic fields

- Implemented localized B in code. However, instead of simulating finite μ_5, we focused on the leading-order coefficient of the chiral magnetic current.
- Generated configurations for many B and T on 4 lattices.
- Extrapolated our results to the continuum limit. Instead of drawing the B-ζ-T phase diagram, we kept $\zeta \sim 0.6$ fm fixed to be consistent with the spatial scale of the magnetic field found in HIC simulations [Brandt et al., 2023a].
- We developed a new way to compute the leading-order coefficient of the EoS in a B-expansion, namely, the magnetic susceptibility, from the electric current operator.

Status: we are ahead of schedule. Alternative ways were taken compared to original plan.

Chiral magnetic conductivity

- Characterization of Chiral Magnetic Effect (CME) as an out-of-equilibrium effect.
- Vanishing result for conductivity C in every setup with appropriate choice of currents.
- Clarification of non-zero CME results with Wilson fermions due to the use of non-conserved vector current $\rightarrow$ simulations at $\mu_5 \neq 0$ not required

Status: on schedule

Additional Opportunities and Directions

Chiral magnetic conductivity

- Complete study of the Chiral Separation Effect (CSE) [Brandt et al., 2024].
- Spectral reconstruction to access the out-of-equilibrium conductivity of CME.

Localized magnetic fields

- Computation of the CME and CSE currents on configurations with non-uniform magnetic field with staggered fermions.

A08: Outlook

- **Equation of state for non-zero isospin and beyond**

  • We are moderately delayed due to heavy λ dependence of the Taylor expansion coefficients.
  • A modified approach is implemented, with first results already available.
  • Depending on the success of this approach the project or a larger part of it will be completed on time.

- **Novel features of the phase diagram at non-zero isospin asymmetry**

  • We are behind schedule due in part to unforeseen high numerical costs of simulations and in part to Francesca Cuteri leaving the CRC.
  • The scope of the study had to be reduced.
  • Improved simulation strategy will be used to partially mitigate high numerical costs.

A08: Outlook

- **Phenomena at non-zero magnetic fields**
  • We are on schedule
  • We were able to combine two projects and study the CME and CSE in the presence of non-uniform magnetic fields.
  • Project will most likely be finished on time, with bonus results on the spectral reconstruction of the CME conductivity.

Brandt, B. B., Cuteri, F., Endrődi, G., Markó, G., Sandbote, L., and Valois, A. D. M. (2023a).
Thermal QCD in a non-uniform magnetic background.
JHEP, 11:229.

Brandt, B. B., Cuteri, F., and Endrödi, G. (2022).
Equation of state and taylor expansions at nonzero isospin chemical potential.

Brandt, B. B., Cuteri, F., and Endrődi, G. (2023b).
Equation of state and speed of sound of isospin-asymmetric qcd on the lattice.
Journal of High Energy Physics, 2023(7).

Brandt, B. B., Endrődi, G., Garnacho-Velasco, E., and Markó, G. (2024).
The chiral separation effect from lattice QCD at the physical point.
JHEP, 02:142.