

## ABSTRACT

This thesis presents a comprehensive study of the non-equilibrium dynamics of (quantum) many-body systems within the framework of relativistic hydrodynamics. As an effective field theory, relativistic hydrodynamics describes the macroscopic evolution of a system using coarse-grained variables, systematically organized through a gradient expansion. The time evolution of such systems is governed by equations of motion derived from conservation laws associated with the symmetries of the underlying microscopic theory. The broad applicability of hydrodynamics stems from a fundamental scale separation: when the system size is much larger than the microscopic correlation length, hydrodynamic behavior emerges universally—regardless of the underlying microscopic details. While the formalism is applicable to a wide class of quantum systems, the primary emphasis of this thesis is on understanding the qualitative and quantitative properties of the quark-gluon plasma (QGP).

Recent advances in spin hydrodynamics have been driven by the need to interpret global and local spin polarization measurements of hadrons produced in heavy-ion collisions. At the theoretical level, this framework allows for a degeneracy in the definition of hydrodynamic variables, giving rise to ambiguities in their formulation. These ambiguities can be systematically understood through the Belinfante–Rosenfeld pseudogauge transformation. Consequently, the local equilibrium expectation values of generic operators become pseudogauge dependent, due to the corresponding freedom in the definition of the local density operator. This thesis explores how the construction of spin observables is influenced by such pseudogauge choices and demonstrates that only the canonical spin operator satisfies the standard  $SO(3)$  algebra. Additionally, it is shown that the pseudogauge dependence becomes particularly relevant when the system size is comparable to the thermal correlation length, as revealed by analyzing equal-time correlation functions of the pseudogauge-transformed energy-momentum tensor. This implies that while pseudogauge effects may influence microscopic or intermediate scales, the macroscopic, long-wavelength behavior governed by hydrodynamics remains pseudogauge-independent. Furthermore, this work includes a systematic study of off-equilibrium contributions to the spin current, along with a complete characterization of associated transport coefficients via Green-Kubo relations.

In contrast, the global equilibrium state is free from such ambiguities, and the expectation values of observables are uniquely defined. In this context, the thesis introduces an alternative field-theoretical approach that leads to a general virial theorem applicable to systems with mechanical (e.g., energy, angular momentum, boost) and chemical (e.g., U(1), SU(N)) global charges. This formulation is valid for any quantum field theories (except gauge theories) with spin less than or equal to one.

The second part of the thesis investigates the behavior of a heavy probe—specifically, heavy quarks—interacting with a thermal background. Heavy quarks are predominantly produced in the early stages of heavy-ion collisions via hard scattering processes and, thus, serve as sensitive probes of the initial state of the system. In such collisions, ultra-strong magnetic fields (up to  $\sim 10^{14}$  T) generated by spectator nucleons can polarize these heavy quarks. However, once the QGP medium is formed, the magnetic field decays rapidly and becomes insufficient to sustain the polarization. Concurrently, heavy quarks undergo energy loss and momentum diffusion through stochastic interactions with the medium, resulting in translational Brownian motion. Similarly, their spin polarization is gradually diminished due to random collisions with medium constituents—a process described by rotational Brownian motion. This thesis develops a model for rotational Brownian motion of heavy quarks in the QCD medium and shows that it provides a quantitative explanation of the ALICE measurements of the spin alignment parameter for the  $D^{*+}$  meson as a function of transverse momentum.

The final part of the thesis constructs a general framework for charge transport in media with multiple conserved charges, using the non-equilibrium statistical operator method. The hot and dense matter produced in relativistic heavy-ion collisions possesses several conserved quantum numbers—such as baryon number, strangeness, and electric charge. The coupled diffusion of these charges is described by a diffusion matrix that encodes the cross-influences among various charge species. A derivation of the Kubo relations is presented to evaluate the elements of this diffusion matrix, and it is demonstrated that in the weak-coupling regime, the resulting diffusion coefficients agree with those obtained from kinetic theory under appropriate relaxation time approximations. To illustrate this formalism, a toy model involving two interacting scalar fields with two conserved charges is analyzed. Additionally, the thesis investigates the universal scaling behavior—analogueous to

the Wiedemann–Franz law—of the ratio between thermal conductivity and shear viscosity for a conformal fermionic system across regimes of both small and large chemical potential.

Altogether, this thesis explores the collective dynamics of the thermal QGP medium through spin and multicomponent charge transport, and investigates heavy-quark polarization as a non-equilibrium probe of its properties.