Letter of Intent

Acronym and title: EOS, Constraining Neutron Star Matter with Heavy Ion Collisions

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1. Research objectives

The objective of EOS is to advance our understanding of QCD matter and the nuclear equation-of-state in the high baryon density regime. Various questions arise in this region of the phase diagram, ranging from the isospin asymmetry of the nuclear Equation-of-State (EOS) via the interaction of hyperons to chiral symmetry restoration and deconfinement. The planned studies will combine theoretical and experimental information from Heavy Ion Collisions at moderate energies (GSI, FAIR and RHIC-BESII), neutron-rich nuclear/hypernuclear spectroscopy (CERN, MAMI, JLab, J-PARC) as well as hyperon-nucleon correlation studies (LHC and RHIC) to construct a realistic EOS for dense systems. The results of the project will be relevant for the understanding of QCD matter at high baryon densities, and consequently related to the emission of gravitational waves in supernovae and neutron star mergers.

Advancements in the overall description of the QCD phase diagram are planned using lattice QCD methods, as well as FRG and Dyson Schwinger approaches. These will be complemented by effective field theory models (e.g. chiral EFTs) that allow to connect the calculated thermodynamic properties to transport simulations of heavy ion reactions. Then relativistic transport and hydrodynamic simulations connect the properties of dense QCD matter to experimentally accessible observables (particle spectra, dileptons, fluctuations, clusters, polarization). In parallel, different interactions of hyperons and nucleons will be validated by femtoscopic correlations and hypernuclear data.

The project builds on substantial progress achieved by the Chart_QGP and THEIA networking activities within STRONG-2020, which established close scientific collaborations between the theoretical and experimental communities across Europe and partner countries. EOS contributes and accelerates progress in these fields.

This will be achieved by coordinating activities, with special focus on theoretical ab-initio approaches, phenomenological model building and theoretical interpretations, relevant for the Transnational Access infrastructure GSI/FAIR, by sharing models, analysis tools and data repositories, and harmonizing theoretical interpretation frameworks. A major goal is the training of the next generation of scientists in joint workshops for the community and especially for the ECRs of the networks.

2. Connection to Transnational Access infrastructures (TAs)

The main part of the project is centered around the GSI/FAIR facility, with special emphasis on predictions and interpretations for the HADES and CBM physics programs. It will further include and contribute to the analysis of hyperon-nucleon interactions which are important at high baryon densities using ALICE@LHC, STAR@BNL and experimental programs planned at MAMI, JLab and J-PARC. It will intertwine ab-initio methods with state-of-the-art simulation tools to pin down the properties of dense baryonic matter. The activities are structured around the scientific focus areas, each linked to specific science questions addressed by the programs at the mentioned TAs:

1.) Structure of the QCD phase diagram, EOS and the CEP: The work program aims to advance the understanding of the QCD phase diagram by integrating lattice QCD, functional methods, and effective chiral models. Lattice QCD results at low baryon chemical potential will be used to extract Taylor coefficients and susceptibilities, providing key constraints for effective models and functional approaches. Functional Renormalization Group and Dyson-Schwinger methods will explore the QCD phase structure at higher densities, yielding predictions for order parameters, phase boundaries, and critical behavior. These results will be used for the development of chiral mean-field models that incorporate both hadronic and quark degrees of freedom in a thermodynamically consistent framework. The final goal is to produce unified EOS, with and without critical phenomena, for use in heavy-ion collision simulations, and to identify observables sensitive to the critical point for guiding CBM@FAIR data analysis especially in the direction of fluctuation studies.

2.) Development and unification of transport and hydrodynamic simulations: To connect the theoretical developments to experimental observables at CBM@FAIR, the results from lattice QCD, functional methods, and effective chiral models will be systematically implemented into state-of-the-art transport and (hybrid-)hydrodynamic models such as UrQMD, SMASH, and PHSD/PHQMD. These models serve as essential tools for simulating the dynamical evolution of heavy-ion collisions and translating theoretical input into experimentally measurable quantities. The unified EOS, including versions with and without a critical point, will be incorporated into hydrodynamic and hybrid frameworks to study their impact on flow observables, particle yields, and fluctuation signatures. Critical-point sensitive inputs, such as susceptibilities and cumulants, will be used to model event-by-event fluctuations and non-equilibrium effects near the phase transition. In transport approaches like PHSD, modifications of the partonic and hadronic interactions informed by the QCD-EOS will allow for a more realistic modeling of the system evolution under FAIR conditions. This integration ensures a consistent link between theory and experiment, enabling the identification of robust signals of the QCD phase structure and guiding the interpretation of CBM data, especially on flow observables and dileptons.

3.) Link to measurements: Finally, such frameworks provide a connection between the QCD-EOS and critical phenomena to a broad range of observables specifically relevant to the HADES@GSI and CBM@FAIR, and STAR-BES@BNL experiments. a) Particle spectra and dilepton yields are directly sensitive to the temperature, collective flow, and medium properties governed by the EoS; thus, incorporating state-of-the-art theoretical inputs allows for a more accurate reproduction and interpretation of these observables. Specifically, cluster formation, particularly light nuclei and hypernuclei, is sensitive to the density and isospin dependence of the EOS. b) Complementary, the fundamental hadronic interactions, derived from the theoretical inputs, can be constrained and validated by using novel two- and three-body correlation function measurements by ALICE@LHC and STAR@RHIC (involving Λ, Σ and Ξ hyperons), nuclear/hypernuclear spectra at MAMI, JLab, J-PARC, and kaonic atom and bound state measurements at LNF and J-PARC. The combined study of such measurements will constrain the spin/isospin dependence of the hadronic interactions in the strangeness sector as well as to investigate the charge symmetry breaking of hyperon-nucleon interactions in neutron-rich environments. c) Hyperon polarization, which is driven by the gradients of the hydrodynamic fields, provides unique insight into the evolution of the QCD medium and on quantities influenced by the EOS and the presence of phase transitions. Connections to neutron star physics emerge naturally through the high-density EOS by extrapolating the combined knowledge to calculate neutron star matter, where they impact predictions for maximum mass, radius, and tidal deformability, quantities directly measurable via gravitational wave observations. This multi-disciplinary consistency strengthens the broader relevance of the work, linking HADES@GSI, CBM@FAIR physics, STAR@BNL and ALICE@LHC results as well as MAMI, JLab, J-PARC programs with astrophysical observations enhancing the synergy between nuclear theory, heavy-ion phenomenology, and astrophysics.

3. Estimated budget request

- Organization of three workshops for the project's scientists with focus on ECRs, incl. support for travel and accommodation – 3 x 40.000 € per workshop
- Indirect costs - 30.000 €
- Workshop at GSI (via additional support from the budget of GSI TA) - 30.000 €

Thus, the total budget estimate is 150.000 € (+30k€ from GSI TA) for the full period of 4 years.

4. Participating and partner institutions

Goethe-Universität, Germany, CTU, Czech Republic, U Banska Bystrica, Slovakia, GSI Helmholtz Center, Germany, Justus-Liebig University, Germany, U. Heidelberg, Germany, TU Munich, Germany, Berg. Univ. Wuppertal, Germany, INFN (Catania, LNF, Pisa, Torino, Trieste, Florence), Italy, Wroclaw University, Poland, University Claude Bernard, France, ICE, Barcelona, Spain, Wigner Research Center, Hungary, SUBATECH, France, Nucl. Phys. Institute Rez/Prague, Czech Republic, Hebrew U. Jerusalem, Israel, FZ Jülich, Germany, Instituto de Estructura de la Materia Madrid, Spain, TU Darmstadt, Germany, U. Barcelona, Spain, U. Bochum, Germany, U. Bonn, Germany, Chalmers U. of Technology, Sweden, U. Mainz, Germany, U. Valencia, Spain