Snowmass2021 - Letter of Interest

Cold QCD Matter at High Densities

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) *EF06, EF05, TF02*

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Abstract: The cores of neutron stars constitute the densest form of visible matter in the universe. Despite its widespread importance for understanding the formation of visible matter and evolution of structure in our universe, very little is known about the microscopic structure and macroscopic properties (e.g. equation of state) of neutron stars cores. Recent advances in the study of temporal hadronic fluctuations, known as short-range correlations, were shown to provide access to properties of cold hardonic matter at several times nuclear saturation density. The combination of precision experimental data from a range of facilities, and developments in ab-initio and EFT calculations of many-body hadronic systems allow using such data to constrain the microscopic (i.e. quark-gluon) structure and properties of of cold dense matter. We propose for the community to support such studies and develop the relevant theoretical framework for incorporating their findings into studies of cold QCD Matter at high densities.

Understanding the inner working of neutron stars – the densest form of matter in the universe – is a long-standing challenge. Neutron stars are born in the gravitational collapse of massive stars, leaving extremely compact remnants behind. The density of matter inside the core of neutron stars ranges from about 2 to 5 times that of atomic nuclei, which is why they are often referred to as the most extreme form of matter in the universe.

While the formation of neutrons in the gravitational collapse process that forms neutron stars is overall understood, we do not know what forms of matter these high-density neutrons take. Observations indicate that about 10% of the matter in the core of neutron stars manage to stay in the form of protons and electrons, but not much is know about how they interact with the neutrons and what impact said interaction has on the energy balance in the star and thereby on its cooling rates and equation of state.

As experimental data on the microscopical properties of QCD matter at such high-densities is very sparse, the range of theories describing high-density QCD matter range from pure hadronic matter governed by short-distance effective nuclear interactions, through the formation of strangeness, and to complete deconfinement of hardonic states and the formation of quark matter. The recent observation of two solar mass neutron starts, combined with the detection of gravitational waves emitted in the process of neutron star collisions, provide first insight into many of the macroscopic properties of these enigmatic objects which raises renewed interest in their microscopical inner workings. For example, we now understand that a large fraction of the heavy elements in our universe were formed when neutrons stars collide with each other. However, it is challenging to directly relate such observations to the detailed microscopic structure of the core of the star, allowing many different models to explain the measured data.

Terrestrial studies of the microscopic structure of neutron stars matter are highly challenging. To reach the relevant density regime, atomic nuclei must be compressed to twice to five-times their densities. Traditionally, this is done using heavy ion collisions that form high-temperature high-density matter that is both very complex to study and does not clearly extrapolate to cold matter.

An alternative approach developed in the past decade is to reach the relevant conditions by detecting quantum-fluctuations of short-range correlated hadronic pairs inside atomic nuclei[1]. In these fluctuated states nucleons correlate with each other and, for a brief time, form high-density droplets of nuclear matter. We refer to these states as Short- Ranged Correlations (SRC).

The study of SRC pairs and triplets allows understanding the properties of dense nuclear matter starting directly from the underlying short-distance few-body interactions. Combined with novel tagged DIS measurements, a new generation of experiments sets to map the density dependence of partonic structure functions - providing first experimental constraints to the limits of confinement in high-density matter.

Recent results from such studies allowed studying the dynamics of protons in high-density neutron rich systems such as neutron-stars, which impacts their cooling rates and equation of states[2;3]; Map the underlying haronic interactions at very short distances[4–7]; Validate the retainence of hadronic bound states at high density states[4]; and probe the impact of the strong interaction and large spatial overlap between hadrons on their quark-gluon sub-structure[1;8–10].

This LOI sets to form a bridge between the medium-energy community that is leading these studies and the cosmic and high-energy frontier communities that can benefit from their results and help shape the next generation of experimental studies, along side the development of theoretical frameworks for the proper interpretation of their data.

References

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