Physics of Hadronic Matter — Fragment Formation, Strangeness, and Equation of State

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Hierarchies in Nuclear Physics

Nuclear physics aims at elucidating properties and dynamics of quantum many-body system composed of particles interacting via strong interaction, i.e., hadrons, quarks and gluons. Although the elementary theory for this field is Quantum Chromodynamics (QCD), it is not possible at present to apply QCD directly to actual problems in nuclear physics, which is mainly in non-perturbative regime of QCD. It is not possible at present to solve varous nuclear physics problems starting from bare realistic nucleon-nucleon interaction, too. Instead, basic laws and rules in specified degrees of freedom have been found and successfully applied to various problems. It means that there are several hierarchies in nuclear physics; quarks and gluons, hadrons, nuclei, and nuclear matter. Correspondingly, there are several types of research in each hierarchy or connecting hierarchies:

(1) Quark-gluon dynamics from QCD itself or from effective Lagrangian,
(2) Making hadrons and obtaining hadron-hadron interaction from quarks and gluons,
(3) Obtaining baryon-baryon interaction from hadronic (meson-baryon) Lagrangian,
(4) Quantum mechanical problem of few-hadron systems starting from bare realistic hadron-hadron interactions,
(5) Obtaining effective nucleon-nucleon and nucleon-cluster interactions starting from bare realistic hadron-hadron interactions,
(6) Quantum mechanical problem of few-cluster systems starting from effective nucleon-nucleon or nucleon-cluster interaction within a limited model space corresponding to the effective interaction,
(7) Solving complex hadron many-body dynamics by using mean field, semi-classical or statistical models,
(8) Obtaining nuclear and hadronic matter properties based on the knowledge of nuclear structure and reaction studies,
and
(9) Applying the knowledge of nuclear structure, reaction, and nuclear matter to related fields such as astrophysical problems.

In the Nuclear Theory Group in the Division of Physics, Graduate School of Science, Hokkaido University, we are making research at present for the subjects of (1)-(2) and (6)-

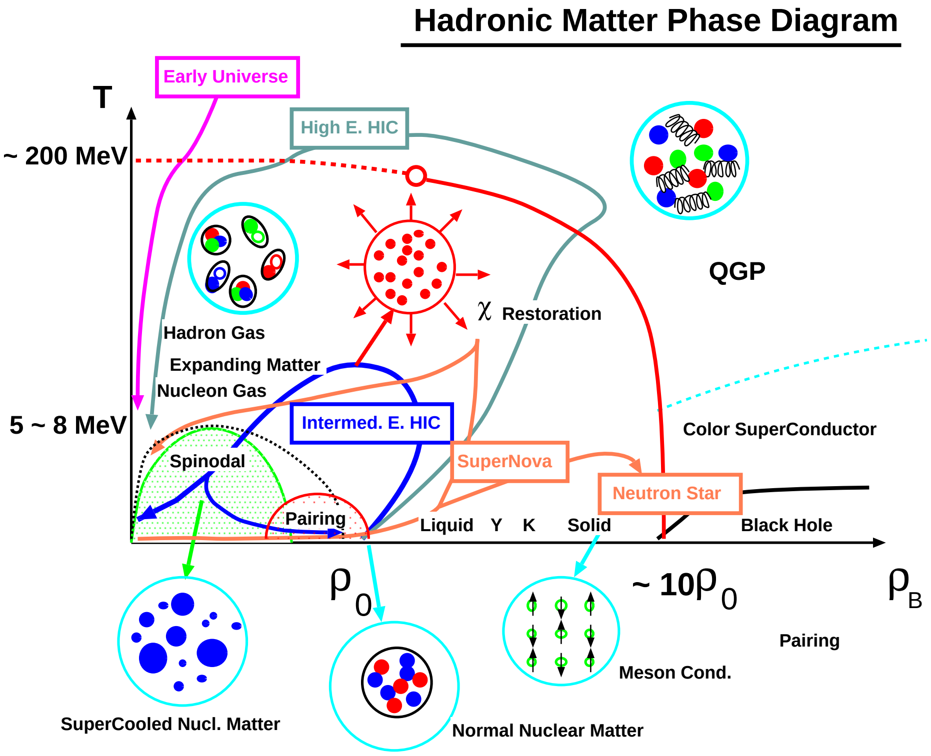

Figure 1: Hadronic matter phase diagram.

(9). In the history, our group and members gratuated our group have made superior research works also in the subjects (3)-(5). It is important to note that these studies are closely related to each other. In this symposium, we have tried to cover as many subjects in the above list, as organizers.

Physics of Hadronic Matter

Nuclear matter is idealized bulk material which is approximately realized around the centeral region of heavy-nuclei. As shown in Fig. 1, as the temperature and density varies, various degrees of freedom appears. At low temperature and around the normal nuclear matter density (ρ_0), nucleons form nuclei, but as the temperature increases or the baryon density decreases, nucleons start to move freely. This behavior is similar to the phase transition from liquid (nuclei) to gas (nucleon gas). For high baryon densities ($\rho_B = (2-4)\rho_0$) in charge neutral matter, the Fermi energies of nucleons as well as electrons increase, then hyperons are expected to admix to nucleon and lepton matter. Since there are neutral (Λ, Σ^0, Ξ^0) and negatively charged (Σ^-, Ξ^-) hyperons, they help to suppress electron Fermi energy and to symmetrize nuclear matter at high density. This "hyperon rich" nuclear matter is now widely believed to appear in the central region of neutron star. When the temperature goes over the pion mass, huge amount of pions are created thermally and hadrons start to overlap frequently exchanging quarks and anti-quarks among multi-hadrons (Hagedorn regime). At the end, quarks and gluons can move freely, and form the Quark-Gluon Plasma (QGP). The deconfinement phase is also expected to emerge at very high baryon density. At around the density $\rho_B = (5-10)\rho_0$, baryon start to overlap, and it becomes preferable for quarks to be freed. Recent theoretical studies suggest that the deconfined quarks at high baryon density form pairs, and the color superconductor would be realized.

Physics of hadronic matter is interesting and important from several aspects. First, the equation of state and particle composition determines the evolution of early universe and compact steller objects. Second, the QCD phase transition is the transition from a complex nonperturbative vacuum to a simple perturbative vacuum of QCD, which would tell us that our physical vacuum is a *condensed matter* of $q\bar{q}$. Thirdly, the similarity of the hadronic matter diagram and superconductor [1] — AF, SC, normal/LG, Pairing, Uniform/Hadron, CSC, QGP — may suggest a general feature of phases in quantum many-body systems.

Since the active degrees of freedom changes drastically in the temperature and density region in the phase diagram, the physics of nuclear or hadronic matter requires integrated knowlegdes of nuclear physics in the above list of subjects, if we aim to clarify its properties from more elementary degrees of freedom in a constructive manner. On the other hand, we can probe nuclear or hadronic matter under extreme conditions far from normal nuclear matter ($\rho_B \sim \rho_0, T \sim 0$) through the study of various nuclear reactions, supernova explosions, and neutron stars. Therefore, one way to study hadronic phase diagram is to apply effective or phenomenological models to nuclear reactions and compact astrophysical objects, then to compare the model results with real data. This is the way we are making in our group.

Contents of Talk

In this talk, I try to review the physics of hadronic matter in relation to the recent works of our group [2, 3, 4, 5, 6] on fragment formation in normal and sub-saturation densities, strangeness nuclear physics, and the equation of state of hot and dense hadronic matter.

References

[1] For example, phase diagram of superconductor (CeRhIn$_5$ and CeIn$_3$) shown in S. Kawasaki et al., cond-mat/0110620, gives similar structure as in Fig. 1.

[2] P.K. Sahu, in this extended abstract book; P.K. Sahu, W. Cassing, U. Mosel, A. Ohnishi, Nucl. Phys. **A672** (2000), 376. nucl-th/0206010; P.K. Sahu, N. Otuka, A. Ohnishi, nucl-th/0206010; N. Otuka, P.K. Sahu, M. Isse, Y. Nara, A. Ohnishi, nucl-th/0102051.

[3] P.K. Sahu and A. Ohnishi, Nucl. Phys. **A691** (2001), 439.

[4] A. Ohnishi, Y. Hirata, Y. Nara, S. Shinmura and Y. Akaishi, Nucl. Phys. **A691** (2001), 242.

[5] C. Ishizuka, A. Ohnishi, K. Sumiyoshi, in this extended abstract book; nucl-th/0208020.

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State-of-the-art kaonic hydrogen atom. The quest for K-d. Hadron physics with strangeness. Spectroscopy of n' mesic nuclei. B-Factory at KEK and PANDA at FAIR.Â Strangeness hadron physics tries to reveal the complex dynamics and phenomena of quarks and gluons, e.g., hadron properties in nuclear medium, symmetry breaking pattern and hadron mass generation, new forms of hadrons, which are described by the Quantum Chromo Dynamics (QCD).Â The AMADEUS project. The strangeness sector of the non-perturbative regime of the low energy region of QCD is of main importance for the understanding of the hadron interactions and structure, and its in-medium modifications. Presentation on theme: "Generalized Entropy and Transport Coefficients of Hadronic Matter Azwinndini Muronga 1,2 1 Centre for Theoretical Physics & Astrophysics Department of."â€" Presentation transcript: 1 Generalized Entropy and Transport Coefficients of Hadronic Matter Azwinndini Muronga 1,2 1 Centre for Theoretical Physics & Astrophysics Department of Physics, University of Cape Town 2 UCT-CERN Research Centre Department of Physics, University of Cape Town Zimanyi 75 Memorial Workshop 02-04 July 2007, Budapest, Hungary.Â 11 Transport Coefficients and Equation of State From Maxwell-Cattaneo-type equations Thermodynamics from transport models Thermodynamics from hadronic gas model (e.g. mesons). 12 Relaxation Coefficients.