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High Density Matter

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Abstract. The microscopic composition and properties of matter at super-saturation densities have been the subject of intense investigation for decades. The scarcity of experimental and observational data has led to the necessary reliance on theoretical models. There remains great uncertainty in these models which, of necessity, have to go beyond the over-simple assumption that high density matter consists only of nucleons and leptons. Heavy strange baryons, mesons and quark matter in different forms and phases have to be included to fulfil basic requirements of fundamental laws of physics. In this contribution latest developments in construction of the Equation of State (EoS) of high-density matter at zero and finite temperature assuming different composition of matter will be discussed. Critical comparison of model EoS with available experimental data from heavy ion collisions and observations on neutron stars, including gravitational mass, radii and cooling patterns and data on X-ray burst sources and low mass X-ray binaries are made. Fundamental differences between the EoS of low-density, high temperature matter, such as is created in heavy ion collisions and of high-density, low temperature compact objects is discussed.

1. Introduction

One of the central questions of current theoretical physics is what constitutes the structure of matter at high densities and temperatures. This research requires not only a joint effort of nuclear, particle and astrophysics theories, but also the use of the most advanced astrophysical observation data and terrestrial experiments to test the theories.

The key property of high density matter is the Equation of State (EoS). Starting from the Boltzmann theory of ideal gases, the relation between the pressure P, energy density ε and temperature T of matter, can be derived. We have

$$P=\rho^2\left(\frac{\partial(\varepsilon/\rho)}{\partial\rho}\right)_{s/\rho} \quad \varepsilon(\rho,T)=\sum_f\left(\frac{E}{A}(\rho,T)\right)_f \rho_f \quad \mu_B=(\varepsilon+P)/\rho$$

where ρ is particle number density, *E/A* is the energy per particle and the summation carries over all *f* constituents present in the matter. *E/A* is unknown and has to be determined from nuclear and/or particle physics models.

There exist many variants of microscopic and phenomenological models of hadronic matter with different levels of complexity. To name a few, mean-field non-relativistic and relativistic models, *ab initio* models with two- and three-body nucleon-nucleon interactions and Quark-Meson-Coupling (QMC) models are frequently used [1-5].

There is also a wide choice of composition of hadronic matter, from nucleons only to matter including the full baryon octet and baryon resonances (p, n, Λ, Σ, Ξ, Δ), and mesons (π, K, H-dibaryon condensates). At densities around and below nuclear saturation density a possibility of clustering [6, 7] and of formation of exotic phases ("nuclear pasta") have been investigated (see e.g. [8] and ref. therein).

Deconfined (u, d, s) matter at highest densities has been proposed, which ought to be in a color superconducting state [1,2,9]. Descriptions of quark matter range from different forms of the MIT bag, the Nambu-Jona-Lasinio, Chromo-Dielectric, Dyson-Schwinger models, as well as perturbative approach to QCD and implementation of the Polyakov-loop technique at non-zero temperature [9-13]. The EoS obviously varies in different temperature/energy density regimes which in turn dictate the most likely composition of the matter. Some other considerations, such as stability (equilibrum) of the matter must have to be taken into account.

In this contribution we will discuss three major manifestations of high density matter - matter created in heavy-ion collisions (Sec. 2), matter created in core-collapse supernovae (Sec. 3), proto-neutron stars (Sec. 4 and the cores of cold neutron stars (Sec. 5). Discussion and conclusions are presented in Sec. 6.

2. Heavy-Ion Collisions

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Heavy-ion collisions (HI) are the only terrestial events in which hot high density matter is created. The beam energies range from ~ 35 MeV/A to 5 TeV/A at different facilities, NSCL, Texas A&M, GSI, RHIC and LHC (existing), and FAIR and NICA (future). Au and Sn projectiles are frequently used and elliptical and transverse particle flow are usually detected.

The properties of high density matter created in heavy-ion collisions changes significantly with beam energy as schematically illustrated in Fig. 1 At highest energies in the TeV/A region, achievable today at LHC (ALICE) and RHIC, the main objective is to study bulk properties of quark-gluon plasma created in HI-HI collisions under conditions which existed several microseconds after Big Bang. Systematic lowering of the beam energy to the region of ~200 - 10 GeV/A allows search for the transition between quark and hadronic matter and for the still illusive critical point [1].

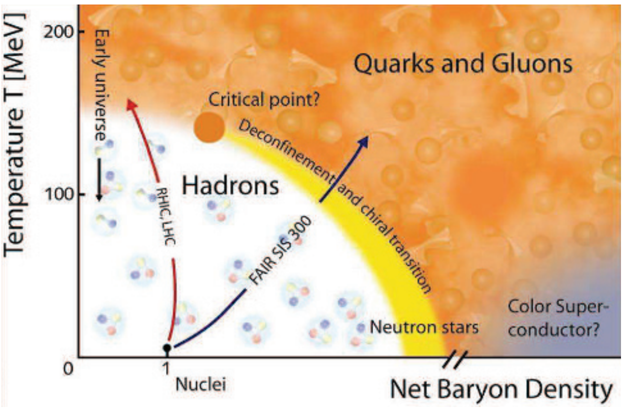

Figure 1. Schematic QCD phase diagram. For explanation, see text.

Beam energy dependence of particle yields, strange particle/antiparticle ratios and energy spectra of emitted particles are measured at higher energies (above ~10 GeV/A) to study matter in the vicinity of the hadron-quark phase transition.

At beam energies (~35 MeV/A - 2 GeV/A), the region below nuclear density and temperatures up to several tens of MeV (the bottom left corner of the QCD diagram in Figure 1) neutron/proton spectral ratios and neutron, hydrogen and light fragment flows can been studied [14]. One of the important results of such experiments is information on the nuclear symmetry energy and its density dependence. The data are used to fit parameters of transport models, which provide energy density and pressure in the matter, i.e. the EoS [15-18]. The much discussed question arises whether such EoS can be meaningfully used to constrain the EoS of high density matter in neutron stars and supernovae.

Matter created at high beam energies has typically very low particle number density (significantly lower than the saturation density of the symmetric nuclear matter, 0.16 fm^{-3} - corresponding to 1 in Figure 1), relatively high energy density 1 - 6 GeV/fm^3 (in dependence on beam energy), close to zero baryon chemical potential and is heated up to several hundred of MeV. The time-scale between the collision and the chemical and thermal freeze out is of order $10^{-23 \text{ to } -24}$ s which implies that the creation of particles during the collision is governed only by the strong interaction, which conserves strangeness and the baryon and lepton number. Analysis of particle spectra and ratios indicate that quark-gluon plasma (QGP) may be reached and quark-antiquark pairs, strange baryons and mesons and pions and a significant number of their antiparticles are subsequently created. The matter is lepton poor, in particular containing very few neutrinos.

At medium beam energies used in experiments with Au or Sn projectiles inelastic nucleon-nucleon (NN) scattering becomes significant and matter consists mostly of N, N*, Δ, light nuclear fragments such as ^{3}H, ^{3}He, ^{7}Li, ^{7}Be, and pions. Strangeness becomes less important, but kaons may be expected [19]. It is claimed that, for a fraction of the time, number densities as high as 5 x nuclear saturation density [14,16,17] can be achieved in ^{197}Au+^{197}Au collisions at beam energies ~50 - 100 MeV/A, due to inertial confinement. The matter cools fast from about an initial about T = 50 MeV and dilutes to subnuclear densities.

Theoretical approaches to the dynamics of HI collisions at medium energies are either algebraic, based on self-consistent solution of the Boltzmann equations (see e.g. [15-18), or geometric, using Molecular Dynamics simulation (MD) in which particles are treated as Gaussian wave packets in a unit cell [20-22]. Both classes of theories yield predictions on trajectories of particle emitted from the collision area. In addition, the MD models provide information on emission of clusters. In the following paragraph we concentrate on the algebraic approach.

Experimental observables sensitive to the EoS are mostly related to the transverse flow of particles from the high density region in the collision. The flow grows with increasing density and density gradient in the transverse direction to the beam axis and can be related, in the equilibrium limit, to the second derivative of energy density with respect to number density [15-17]. Different theoretical models for the density dependence on the energy density will obviously lead to different predictions for the equilibrium pressure and hence the tranverse particle flow. In a real collision, which is not necessarily in equilibrium, the pressure-stress tensor is used. Danielewicz et al. argued (see Supplementary Material in [15]) that, in their model, the ‘ calculated transverse pressure reaches about ~80% of its equilibrium value after about ~3x10^{-23} s and becomes essentially equilibrated after ~4x10^{-23} s. Equilibrium is lost at later times but only after the flow dynamics are essentially complete ‘. The hydrodynamics of the process, based on solution of the Boltzmann equations, depends on the choice of the average mean field potential (with three variable parameters), an empirical term describing momentum dependence of the potential and a ‘collision ‘ term, which absorbs scattering effects by a non-specified residual interaction. Without going into details of application of this model of the collision to actual data [17], there are three questions to be asked :

(i) Are the assumptions on reaching equilibrium during the short time of the collision physically realistic ?

(ii) Is the mean-field potential constrained enough by physical arguments ? Otherwise the results of fits of its parameters to the data may be correlated so that no uniques answer can be achieved.
(iii) Is it justifiable to assume that the EoS for a symmetric and pure neutron matter at zero temperature, extrapolated from the transport theory fitted to the HI collision process, can be applied to matter in cold neutron stars and core-collapse supernova with very different nature (as discussed below).

3. Core-collapse supernovae

A core-collapse supernova (CCS) event provides three unambiguous signals open to direct observation : the explosion, the emission of neutrinos and the creation of a remnant in the form of either a neutron star or a black hole in dependence on the mass of the progenitor star. The simulation of the explosion still poses a challenge to theory despite enormous efforts. The EoS is one of the essential inputs to the simulation (see e.g. [23]) but due to complexity and demand on computer time, effects of choice of the EoS are still waiting to be studied in more detail. There are still open questions concerning the make-up, density and pressure of the collapsing core at bounce and their influnce on the occurrence and properties of the explosion. The neutrino emission is sensitive to the microscopic make-up of the supernova matter and thus provide a fingerprint of the composition of the core [24]. But perhaps most interesting and relevant for this work is the evolution of the CCS core into a hot proto-neutron star and the eventual cooling to a stable cold neutron star. Following this process may provide important clues about the composition of the cold neutron star core and significantly constrain its EoS.

4. Proto-neutron stars

In the first several seconds after the bounce of the collapsing core a neutrino rich proto-neutron star (PNS) begins to form (see Figure 2). Within 0.1 - ~0.3 s it shrinks from over 100 km in radius to about 15 km and keeps accreting mass from the surrounding material. At the moment of explosion this material is blown away and the PNS enters the Kelvin-Helmholz phase which lasts for several seconds. The PNS first goes through de-leptonization when excess trapped electron neutrinos diffuse from the central regions outward through the star. The temperature is still rising as the diffusing neutrinos heat the stellar core while decreasing the net lepton and proton fractions. This stage is followed by an overall cooling stage [25]. The process is illustrated in Figure 2. The most interesting region is for times between the bounce (t = 0) and the explosion (t ~ 300 ms) when the proto-neutron star is isolated from the CCS material.
During the time period between bounce and the start of cooling the microscopic composition of the PNS is formed. It does not significantly change during the cooling period and through the life of the cold neutron star, unless the star is involved in further accretion from a companion and changes its temperature and rotational speed. Currently no established theory exists to relate the composition of the PNS to the conditions in the CCS process.
It is interesting to explore the circumstances of matter in PNS to matter created in HI collisions. The fundamental difference is the life-time of the proto-neutron star, 1-10 s, as compared to that of the HI collision.

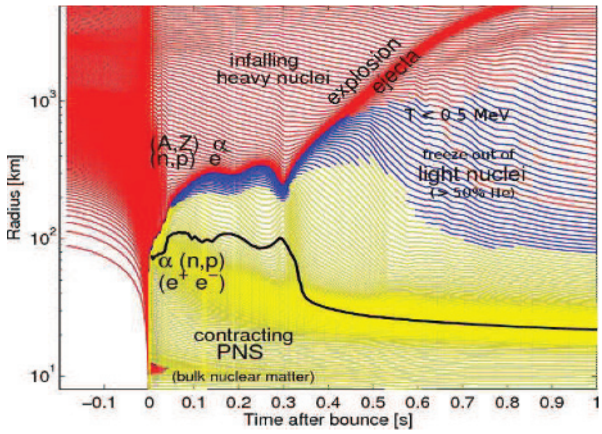

Figure 2. Evolution of CCS matter after bounce. Taken from T. Fischer, Talk at CSQCDII, May 2009.

This time is much longer than the time scale of weak interactions ~10^{-10-13} s. It follows that both the strong and weak interaction are effective in PNS matter which allows development of a richer spectrum of constituents. Baryon and lepton numbers are conserved, but strangeness is not. The matter is neutrino rich (trapped neutrinos) and the models suggest that the particle number density exceeds the nuclear saturation density several times although the energy density is lower than that in the HI matter by a factor ~3, dependent on the beam energy.

Investigation of the pressure, temperature, energy density and chemical potential profiles during the time between bounce and point when the proto-neutron star starts to cool, as provided by core-collapse simulations may reveal information on the possible composition of neutron stars. For example, is generation of hyperonic and/or quark matter energetically possible ? Futher change in composition, caused by increasing density in the shrinking proto-neutron star during the cooling process will have to be taken into account together with the cross section changes with falling temperature.

5. Cold non-rotating neutron stars

Cold neutron stars are the most dense objects bound by gravity in the Universe. It is expected that the matter in their cores exceeds nuclear saturation density by more than a factor of 5 which allows wide speculation on its microscopic structure, as illustrated in Figure 3. The matter is expected to be in a grand equilibrium with respect to weak interaction. It is locally charge neutral and only baryon and lepton numbers are conserved. The EoS of neutron stars core is still a matter of debate, mainly because of uncertainty in its composition.

Hydrostatic equilibrium of a non-rotating (spherical) neutron star is well described by the general relativistic

Tolman-Oppenheimer-Volkoff (TOV) equations. The input to the calculations is the EoS and the output yields the masses of the neutron star models *as a function of their radius*, for a given central energy density.

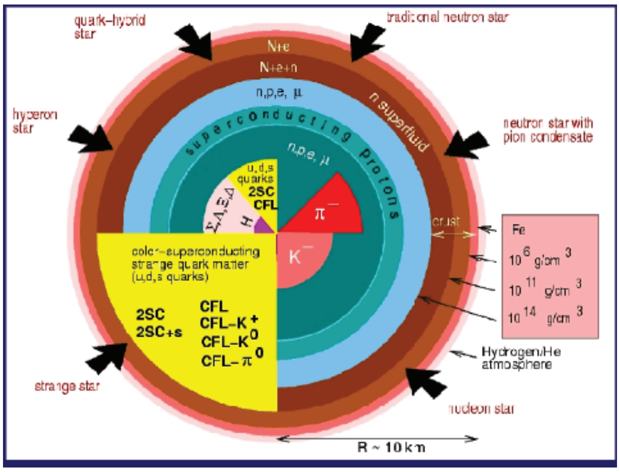

Figure 3. Competing structures in the neutron star cores as predicted by theoretical models. Taken from ref. [2].

To form a true test of theory, accurate knowledge of both the gravitational mass and radius of the same neutron star is needed. The impossibility of separately obtaining mass and radius from the TOV equation is the main obstacle in relating observation to theory; a very difficult task which has not been satisfactorily solved.

The most reliable observational data on neutron stars provide their gravitational mass. Determination of the radius is much more difficult and often is only available on objects of unknown mass. The most precise limits on neutron star masses come from radio pulsars in binary systems with another neutron star but binaries with a white dwarf, a main sequence star and a double pulsar binary are also used for mass determination. Only very recently, neutron stars in X-ray binaries, which accrete material from a companion star and flare to life with a burst of X-rays, have provided data on simultaneous determination of mass and radius of the same object. The analysis of the data is very complex [26-30] and we are left with the situation that adequate mass/radius pairs, which potentially provide a powerful constraint on the neutron star core EoS, are not yet available.

6. Summary and conclusions

We have discussed several examples of high density matter in terrestrial experiments and astrophysical objects. Extensive experimental, observational and theoretical research continues to understand basic properties of the matter in these situations. Differences between the fundamental forces and conservation laws relevant to HI collisions, core-collapse supernovae and neutron stars make it unlikely that these forms of high density matter have the same EoS and can be used to provide constraints on each other, although this idea is commonly argued (e.g. [14,17,31]).

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