

New aspects of the QCD phase transition in proto-neutron stars and core-collapse supernovae

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Abstract. The QCD phase transition from hadronic to deconfined quark matter is found to be a so-called “entropic” phase transition, characterized, e.g., by a negative slope of the phase transition line in the pressure-temperature phase diagram. In a first part of the present proceedings it is discussed that entropic phase transitions lead to unusual thermal properties of the equation of state (EoS). For example one finds a loss of pressure (a “softening”) of the proto-neutron star EoS with increasing entropy. This can lead to a novel, hot third family of compact stars, which exists only in the early proto-neutron star phase. Such a hot third family can trigger explosions of core-collapse supernovae. However, so far this special explosion mechanism was found to be working only for EoSs which are not compatible with the $2 M_{\odot}$ constraint for the neutron star maximum mass. In a second part of the proceeding it is discussed which quark matter parameters could be favorable for this explosion mechanism, and have sufficiently high maximum masses at the same time.

1. Introduction

Even after decades of intensive research, it is still not completely understood how massive stars explode. On the one hand, the so-called neutrino-driven mechanism has been shown to be working in multi-dimensional simulations [1, 2], in which hydrodynamic instabilities and non-radial fluid motions increase the neutrino heating efficiency to a sufficient level to lead to shock revival. On the other hand, even the most sophisticated multi-dimensional core-collapse supernova simulations result in rather low explosion energies, which could not explain all of the observations. Furthermore, there is not yet a consensus among different groups about the outcome of simulations and the strength of multi-dimensional effects.

As a consequence, it is not yet known which progenitor stars will end as black holes and which as neutron stars, and also their contributions to nucleosynthesis and galactic chemical evolution are uncertain. Regarding these remaining uncertainties, numerical aspects of both the neutrino transport and the hydrodynamics are of crucial importance. All of the present-day simulations are limited by insufficient computing power, even by using the largest available supercomputers.

However, the supernova dynamics also depend on the employed neutrino-matter interaction rates, and the equation of state (EoS) of hot and dense nuclear matter. At present, these two aspects also carry large uncertainties. For example, we do not know yet the state of matter at the highest densities in the interior of neutron stars. Even if accurate radius measurements of



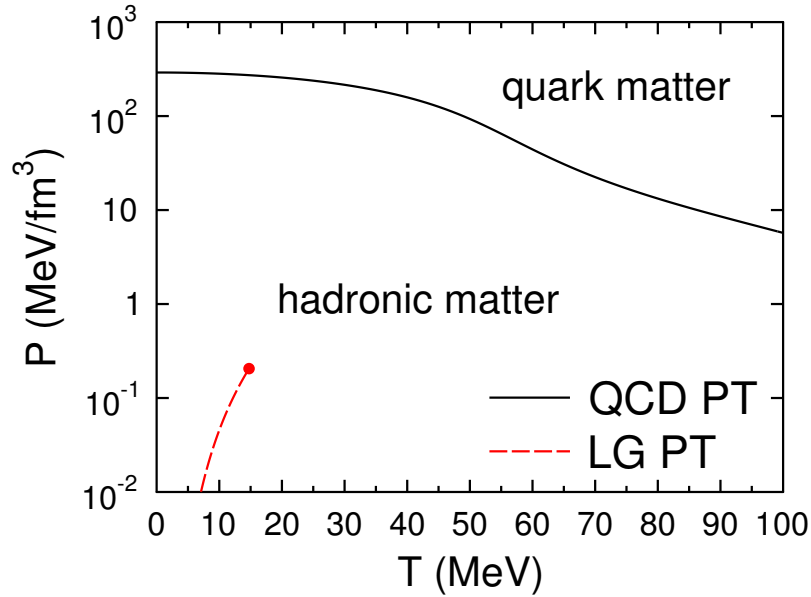


Figure 1. Illustrative phase diagram of isospin-symmetric matter in the temperature-pressure plane. The black solid line shows the QCD phase transition calculated with a simple bag model for up- and down quark matter. The red dashed line shows the nuclear liquid-gas phase transition calculated with the relativistic mean-field model FSUgold [4].

neutron stars will become available in the future, this will not necessarily constrain the interior particle composition, nor the question if a phase transition from hadronic to quark matter takes place in neutron stars. This is known as the so-called masquerade problem [3].

In the present proceeding we investigate the possible role of quark degrees of freedom at high densities and/or temperatures in the context of the explosion mechanism of core-collapse supernovae. In particular, we are interested in the questions how quark matter can influence the dynamics of supernovae, which properties of quark matter are most interesting in this environment, and if there might even be observable signatures of the presence of quark matter in supernovae and proto-neutron stars.

2. The entropic QCD phase transition

In this and the following section we summarize the most important arguments and conclusions of Ref. [5]. When one discusses the state of matter, this is typically done by means of phase diagrams. For the QCD phase diagram usually temperature T and baryon chemical potential μ_B are chosen as state variables. Sometimes instead of μ_B also the baryon number density n_B is used. If one then compares the nuclear liquid-gas phase transition with the QCD phase transition, these two first-order phase transitions have the same qualitative appearance, just the scales are different. Naively one could thus think that they are of the same type.

However, if one compares them in the plane of pressure P and temperature T , as is done in Fig. 1, one sees an obvious qualitative difference: the liquid-gas phase transition line has a positive slope dP/dT , whereas the slope of the QCD phase transition is negative. To distinguish these two types of first-order phase transitions, the terms “enthalpic” ($dP/dT > 0$) and “entropic” ($dP/dT < 0$) were introduced in Refs. [6, 7] and, e.g., used in Ref. [5]. Qualitative differences of the two phase transitions were also noted in Refs. [8, 9, 10, 11]. For a discussion of other interesting aspects of the pressure-temperature phase diagram, see Ref. [12].

As is known from standard textbooks of thermodynamics, the slope of the phase transition line in T - P can be related to the properties of the two coexisting phases by the Clausius-Clapeyron equation:

$$\frac{dP}{dT} = \frac{S^H - S^Q}{1/n_B^H - 1/n_B^Q}, \quad (1)$$

where S^H (S^Q) denotes the entropy per baryon of the hadronic (quark) phase, and n_B^H and n_B^Q the corresponding baryon number densities, where $n_B^H < n_B^Q$. The entropic property therefore results from the unusual situation that the more dense phase (in this case the quark phase) has a higher entropy per baryon than the more dilute phase (the hadronic phase). A larger entropy per baryon can in turn be related to a larger specific heat capacity.

It was stressed in Refs. [6, 7] that most of the entropic phase transitions of fluid-fluid type are driven by the same physical mechanism: forced decomposition (delocalization) of some kind of bound complexes under compression (pressure ionization, pressure dissociation, pressure quark deconfinement, etc.). For a phase transition in which “composite” particles are decomposed into their elementary building blocks (such as the QCD phase transition, where hadrons are decomposed into quarks), resulting in a larger number of degrees of freedom, it seems to be a natural consequence that the specific entropy is increased. Indeed, the entropic property has been identified for several different models for the QCD phase transition: in Ref. [10] for the Chiral SU(3) model of Ref. [13], in Fig. 1 for a simple quark bag model, and in Ref. [14] also for the very different “vBag” model. However, it is also known that the heat capacity of quark matter is reduced in color-superconducting or crystalline phases [15]. Therefore it would be quite interesting to see the P - T phase diagrams of such models, to identify whether they also result in entropic phase transitions.

Entropic phase transitions lead to a number of unusual thermodynamical properties, which is connected to negative signs of second-order mixed partial derivatives of the thermodynamic potential that are usually positive [6, 7]. Some of these unusual thermal properties of the EoS are discussed in the following. In case of a simple Maxwellian phase transition, the pressure is independent of density and therefore one has

$$\left. \frac{dP}{dT} \right|_{PT} = \left. \frac{\partial P}{\partial T} \right|_{n_B}, \quad (2)$$

where the expression on the left hand side is the derivative along the phase transition line. The EoS of an entropic phase transition therefore has the unusual thermal behavior that $\left. \frac{\partial P}{\partial T} \right|_{n_B} < 0$. This is, for example, opposite to the behavior of all ideal gases. Using standard thermodynamic relationships, one furthermore can show that

$$\left. \frac{\partial P}{\partial T} \right|_{n_B} < 0 \Leftrightarrow \left. \frac{\partial T}{\partial n_B} \right|_S < 0. \quad (3)$$

This means that an entropic phase transition gives a decreasing temperature for an adiabatic compression. What is behind Eq. (3) is somewhat more general: in Refs. [6, 7] it was pointed out that an unusual sign of a second-order mixed partial derivative of the thermodynamic potential never occurs isolatedly, but is accompanied by a change of the sign of many other second-order mixed partial derivatives.

These unusual thermal properties are relevant for proto-neutron stars. To describe the hydrostatic structure of relativistic stars, one needs the pressure–energy density relation, $P = P(\epsilon)$. If one considers stars at finite entropy, a useful quantity to characterize thermal effects is therefore the derivative $\partial P / \partial S|_\epsilon$. For $\partial P / \partial S|_\epsilon > 0$ one has an increase of pressure

Table 1. Selected properties of the currently existing general-purpose quark-hadron hybrid EoSs. Listed are the included particle degrees of freedom, the maximum mass M_{\max} of cold, spherical (non-rotating) neutron stars and their radii at a fiducial gravitational mass M_G of $1.4 M_\odot$. Note that for STOSQ184n M_{\max} is below $1.4 M_\odot$ and therefore the value of $R_{1.4M_\odot}$ does not exist. For STOSQ162n the value of $R_{1.4M_\odot}$ could not be found in the literature. This table represents an excerpt from Table III of Ref. [17].

Model Name	Degrees of Freedom	M_{\max} (M_\odot)	$R_{1.4M_\odot}$ (km)	References
STOSQ209n π	$n, p, \alpha, (A, Z), \pi, q$	1.85	13.6	[18]
STOSQ162n	$n, p, \alpha, (A, Z), q$	1.54	—	[19]
STOSQ184n	$n, p, \alpha, (A, Z), q$	1.36	—	[19]
STOSQ209n	$n, p, \alpha, (A, Z), q$	1.81	14.4	[18, 19]
STOSQ139s	$n, p, \alpha, (A, Z), q$	2.08	12.6	[20, 21, 22]
STOSQ145s	$n, p, \alpha, (A, Z), q$	2.01	13.0	[20]
STOSQ155s	$n, p, \alpha, (A, Z), q$	1.70	9.93	[23]
STOSQ162s	$n, p, \alpha, (A, Z), q$	1.57	8.94	[24]
STOSQ165s	$n, p, \alpha, (A, Z), q$	1.51	8.86	[24]

with heating, which can be called “thermal stiffening”, and for the opposite sign one has a loss of pressure, which can be called “thermal softening”. This derivative can be transformed to

$$\left. \frac{\partial P}{\partial S} \right|_\epsilon = -T n_B c_s^2 + \frac{T}{C_V} \left. \frac{\partial P}{\partial T} \right|_{n_B}, \quad (4)$$

where c_s is the speed of sound and C_V is the heat capacity per baryon [16, 5]. The first term in this equation is a relativistic correction and generally smaller than the second term. This implies that an entropic phase transition always has $\left. \frac{\partial P}{\partial S} \right|_\epsilon < 0$, corresponding to a softening of the EoS for increasing entropy. In the following section, we discuss the consequences of this softening on the proto-neutron star stability and on the core-collapse supernova dynamics.

3. Consequences for proto-compact stars and core-collapse supernovae

If one wants to explore EoS effects for a realistic setup of proto-neutron stars, core-collapse supernovae, or neutron star mergers, one needs an EoS with full density-, temperature-, and isospin-asymmetry- (or, equivalently, electron fraction Y_e) dependence, covering a wide range of conditions, see Ref. [17]. Usually such “general purpose” EoSs are provided in tabular form. At present just very few general purpose EoSs exist, and even less which consider deconfined quark matter at high densities and/or temperatures. In Table 1 we give an overview about the currently existing general-purpose hybrid EoSs.

All of these EoSs use STOS [25, 26] for the hadronic phase, and a simple bag model of u,d,s-quarks for the quark phase, sometimes including α_S -corrections for strong interactions. All of them assume global charge neutrality during phase coexistence. This assumption, and the choice of T , n_B , and Y_e as state variables, requires to make a Gibbs construction for the phase transition. It results in a so-called non-congruent phase transition, in contrast to a congruent phase transition which one gets for a simple Maxwell construction [27, 10].

From the existing EoSs, only STOSQ139s and STOSQ145s have a sufficiently high maximum mass above $2 M_\odot$ to be compatible with the pulsar mass measurements of Refs. [28, 29]. They employ bag constants B of $B^{1/4} = 139$ MeV, respectively 145 MeV. However, also these two EoSs

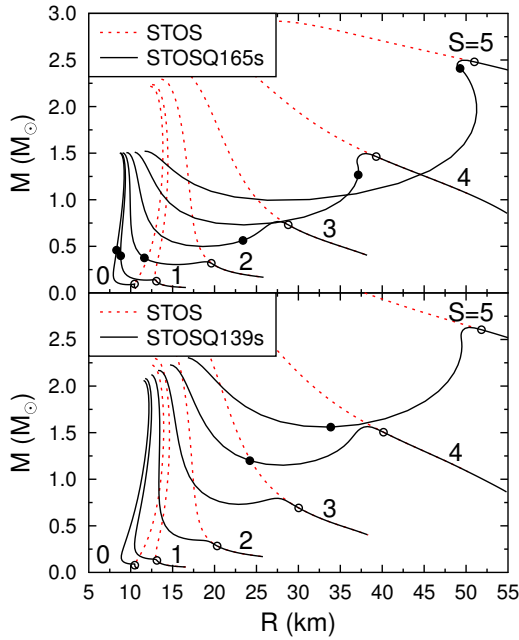


Figure 2. M - R -relations for different entropies per baryon S (indicated by the numbers in the figure) and in beta-equilibrium without neutrinos. Red dotted lines: STOS hadronic EoS. Black solid lines: STOSQ165s hybrid EoS (top panel) and STOSQ139s (bottom panel). Open (full) circles indicate that phase coexistence (pure quark matter) has been reached. Figure adapted from Ref. [5], where further details can be found.

are problematic, as the values of the nuclear symmetry energy and the so-called slope parameter of STOS are in clear contradiction with various experimental constraints [30, 17]. This means there is not a single general-purpose hybrid EoS with good nuclear matter properties and a sufficiently high maximum mass. Nevertheless we use some of the models of Table 1 in the following for further investigation, simply because nothing else is available.

The effects of entropic phase transitions pointed out in Sec. 2 assumed a simple Maxwellian (congruent) phase transition. For the existing general-purpose EoSs one always has a Gibbs (non-congruent) phase transition instead. To investigate whether or not one still has the same effects in this more complicated situation, in Ref. [5] the $P(\epsilon)$ -relations of STOS and STOSQ165s were compared with each other. It was found that hadronic matter stiffens when it is heated, i.e., $\left. \frac{\partial P}{\partial S} \right|_{\epsilon} > 0$. In the quark phase, the pressure increases only slightly with entropy, which can be easily understood because the $P(\epsilon)$ -relation of ultra-relativistic Fermi gases is independent of the entropy per baryon. For parts of the phase-coexistence regions it was found that $\left. \frac{\partial P}{\partial S} \right|_{\epsilon} < 0$, i.e., matter softens when it is heated. This is the behavior which one expects for an entropic phase transition. However, the unusual thermal properties show up only in parts of the phase-coexistence region.

To investigate the stability of proto-neutron stars, one has to solve the Tolman-Oppenheimer-Volkoff (TOV) equations. Figure 3 shows the resulting mass-radius curves without trapped neutrinos (i.e., in weak equilibrium) for several values of the entropy per baryon, for the hadronic STOS and the hybrid STOSQ165s and STOSQ139s EoSs. One sees that at high enough entropy per baryon a strong third family arises¹. After the onset of the phase transition, there is a loss of stability which is only regained for much higher central densities, for neutron stars with a sufficiently large quark matter core.

A third family of cold compact stars is already extensively discussed in the literature. The novel aspect which is visible in Fig. 3, and which was first pointed out in Ref. [5], is that this third family exists only in the proto-neutron star stage for high enough entropies. Therefore it is also called the *hot* third family. At zero temperature the third family is only marginal

¹ Different compact star configurations at the same mass but different radii are also called twins.

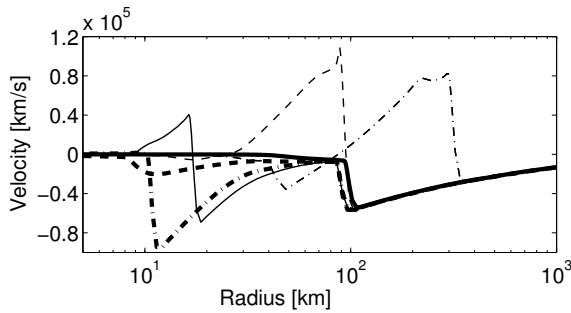


Figure 3. Velocity profiles at different times during the post-bounce evolution of a $10 M_{\odot}$ progenitor model based on the STOSQ165s EoS, illustrating the development of the explosion through different stages; thick solid line at 240.5 ms, dashed at 255.2 ms, dash-dotted at 255.5 ms and thin solid line at 255.6 ms, dashed at 256.4 ms, dash-dotted at 258.3 ms. Figure taken from Ref. [24]

or completely absent. The formation of the hot third family is a consequence of the unusual thermal properties of the EoS discussed above. By comparing panel b) with a) of Fig. 3, one sees that for STOSQ139s, which has a high maximum mass, the third family is less pronounced than for STOSQ165s, and occurs only for higher entropies per baryon.

This third family feature is highly relevant for the explosion mechanism of core-collapse supernovae, as explained in the following. During the post-bounce evolution, matter is accreted onto the newly formed proto-neutron star, increasing its mass continuously. In case a local maximum of the mass-radius curve is reached during this accretion, the star will collapse to the more compact configuration and thereby release a significant amount of gravitational binding energy. Exactly this behavior of a collapsing proto-neutron star was observed in the detailed, spherical core-collapse supernova simulations of Refs. [24, 23]. After the collapse of the proto-neutron star, an outgoing shock wave was formed, which merged with the standing accretion shock and eventually resulted in an energetic and robust explosion. Fig. 3 shows the velocity profiles of a simulation using the STOSQ165s EoS.

Interestingly, this explosion mechanism has a clear observational signature. Once the shock runs over the neutrino spheres, a burst of anti-electron neutrinos is released [24, 23, 31]. The time-delay between the first neutrino burst corresponding to bounce and the second neutrino burst induced by the phase transition represents a measure of the phase transition density. Regarding the nucleosynthesis contribution of this special kind of core-collapse supernovae, a weak r-process was found to take place in the ejecta after the onset of the explosion [32].

However, for the very limited set of general purpose hybrid EoSs presently available, explosions could only be obtained for models which have a too low maximum mass. For example the STOSQ139s EoS did not lead to explosions [22]. This is fully consistent with the results presented above that the third family feature is much weaker for STOSQ139s than for STOSQ165s. If the maximum mass is high, the effects of the phase transition are generally weaker, and quark matter behaves similarly as hadronic matter. This can be seen as a dynamic variant of the masquerade problem [3].

As a different consequence of entropic phase transitions in proto-neutron stars, in Ref. [16] it was pointed out that they can lead to a special form of “inverted” convection. In this case the condition for convective stability is opposite as for normal convection, and if convection occurs cold bubbles of matter are transported outwards.

The question whether or not the explosion mechanism of core-collapse supernovae triggered by the QCD phase transition is still possible, can only be answered by developing new quark-hadron general purpose hybrid EoS and testing them in detailed core-collapse supernova simulations. On the one hand, there is the obvious tension between a high maximum mass and a sufficiently strong phase transition. On the other hand, only very few models have been tested so far, regarding both the EoS and the progenitor model. The new insight from Ref. [5], summarized

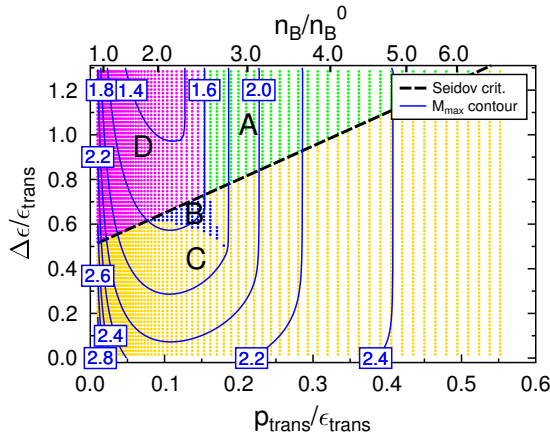


Figure 4. Contour lines for the maximum mass (blue solid lines), for a systematic variation of the phase transition properties $\Delta\epsilon$ and P_{trans} , using HS(DD2) for the hadronic phase, and an EoS with a constant speed-of-sound ($c_s^2 = 1/3$) for the quark phase. The color coding distinguishes the four different types of hybrid stars: “A (absent)”, “B (both)”, “C (connected)” and “D (disconnected)”. Figure taken from Ref. [33].

in the present proceeding, is that the unusual thermal properties of the phase transition and the novel hot third family stand behind this explosion mechanism. This new understanding will help to finally answer the aforementioned question. One direct conclusion is that a third family which is already present in cold neutron stars is helpful, but not strictly required to get a pronounced third family at the proto-neutron star stage. Due to the strong entropy dependence of the third family, one can conclude that the entropy profile of the progenitor star plays an important role.

4. A systematic analysis of cold hybrid stars

With these new conclusions at hand, in Ref. [33] we performed a systematic analysis of the quark matter parameter space, to identify interesting regions favorable for this explosion mechanism. The aim was to fix the quark matter parameters by looking for third-family solutions in cold neutron stars, taking into account the $2 M_\odot$ constraint. To do so, we employed the method of Ref. [34], where the constant speed-of sound EoS is used for quark matter, so that the phase transition depends only on two parameters, the energy-density discontinuity $\Delta\epsilon$ and the transition pressure P_{trans} . These two parameters are then systematically varied, and for each parameter combination the TOV equations are solved to obtain the mass-radius curve and the maximum mass.

In addition, Ref. [34] introduced four types of hybrid stars for further classification of the solutions. In case a) hybrid stars are absent; all neutron star configurations with quark matter in their interior are unstable. In case c) one has a hybrid star branch which is connected to the branch of hadronic stars. In case d) there is no connected hybrid star branch, but only a disconnected third family. In case b) one has both, i.e., the connected hybrid star branch as in case c), but in addition also the disconnected third family branch as in case d).

For our parameter scan in Ref. [33], we chose the general purpose EoS HS(DD2) [35, 21] for the hadronic phase. This EoS is available in tabular form and can be directly used in simulations of core-collapse supernovae and neutron star mergers, see, e.g., Refs. [36, 37]. HS(DD2) has good nuclear matter properties, in agreement with many experimental constraints, see, e.g., Refs. [21, 38, 17]. Furthermore, its maximum mass of cold neutron stars of $2.42 M_\odot$ is sufficiently high to allow for additional degrees of freedom at high densities. For example in Ref. [39] the lambda hyperon was added, leading to a still sufficiently high maximum mass of $2.10 M_\odot$.

Figure 4 shows the results of the parameter scan using a squared speed-of-sound of quark matter of $c_s^2 = 1/3$. As a first result it can be seen in the lower left corner that the phase transition can increase the maximum mass of the hybrid EoS above the value of the purely hadronic EoS. Even values above $2.8 M_\odot$ are possible. As explained in detail above, it is favorable for the

explosion mechanism if one has a third family already for cold neutron stars, which is then enhanced when considering the proto-neutron star stage with finite entropies. Cases b) and d), which both have a third family, are therefore particularly interesting for this scenario. In Fig. 4, case b) occurs only in a very limited parameter region and leads to maximum masses even below $1.8 M_{\odot}$. However, there are cases d) with a maximum mass above $2.0 M_{\odot}$. These promising configurations require a low phase transition density around saturation density n_B^0 and values of $\Delta\epsilon/\epsilon^{\text{trans}} > 0.5$. We found that if a larger value of the speed of sound is considered, the favorable region of cases d) can be significantly extended, but first concentrated on the canonical value of $1/3$.

Relatively low phase transition densities are also required for this explosion mechanism for a different reason, namely, because the densities reached in a core-collapse supernova stay below approximately $2n_B^0$ in the early post-bounce phase of an intermediate mass progenitor. If the phase transition density was significantly higher, effects of quark matter could only be expected for very massive progenitors, or at a later stage of the evolution. This would be a different scenario than the one considered in Refs. [24, 23].

Previous parameter scans which used the framework of Ref. [34] did not consider chemical equilibrium in the phase coexistence region explicitly. Pressure equilibrium is automatically achieved, and thermal equilibrium, too, as only zero temperature is used. It is easy to derive the $P(\mu_B)$ relation (with μ_B denoting the baryon chemical potential) of the constant-speed-of-sound EoS formulated as $P(\epsilon)$, where a new free parameter is appearing in form of an integration constant. If one imposes chemical equilibrium at the transition point, this parameter is fixed by the baryon chemical potential of the hadronic phase.

Using this procedure, we found for some parameter combinations that not only one, but several phase transitions occur. For example one possibility is that after a first deconfinement transition a reconfinement from quark to hadronic matter takes place [33]. Such spurious multiple phase transitions were not identified in previous versions of the parameter scan, instead only one deconfinement transition was enforced. This means thermodynamic stability was not taken into account. However, this can also be physically motivated. There is no reason why to expect reconfinement and multiple phase transitions, and they can occur in regimes where either the hadronic or the quark EoS is not reliable any more. On the other hand, they could also point to unphysical parameter combinations of the quark EoS. For some further discussion see Ref. [33] and references therein.

If one takes into account thermodynamic stability and allows for multiple phase transitions in the parameter scan, the maximum masses in the lower left corner of Fig. 4 stay below the value of HS(DD2) [33], which is quite interesting. However, maximum masses above the one of HS(DD2) are still possible, namely for special cases which correspond to absolutely stable quark matter which occur in a different region of the quark matter parameter space [33].

Parts of the small favorable region for the supernova explosion mechanism (case d) with $M_{\text{max}} > 2 M_{\odot}$ would also be affected from the reconfinement problem. Nevertheless, a slightly reduced region with a third family and a sufficiently high maximum mass is remaining, which does not have this problem.

The constant-speed-of sound EoS of quark matter is not suitable for core-collapse supernova simulations, as it does not provide information about the particle composition or the temperature dependency. However, in Ref. [33] it was shown that the parameters $\Delta\epsilon$ and P_{trans} can be mapped onto a bag model description with strong interaction corrections. In Ref. [33], a particular parameter set from the favorable region was chosen (not affected from the reconfinement problem), and also its bag model parameters were presented. At present, we are working on the generation of a new quark-hadron general-purpose hybrid EoS, employing this parameter set.

5. Summary and Conclusions

An entropic phase transition is defined by having a negative slope of the phase transition line in the temperature-pressure plane. Using the Clausius-Clapeyron equation, the negative slope can be related to a higher entropy per baryon of the more dense phase during phase coexistence. In the QCD phase transition hadrons are decomposed into their elementary particles, the quarks, and therefore it seems to be a natural consequence that the QCD phase transition is entropic. So far the authors are not aware of models for the QCD phase transition which predict the opposite (i.e., enthalpic) behavior which one has, e.g., for the nuclear liquid-gas phase transition.

Entropic phase transitions result in unusual thermal properties of the EoS. For example, one has a decrease of temperature for an adiabatic compression, or a decrease of pressure with increasing temperature. They also result in a softening of the $P(\epsilon)$ EoS (i.e., a decrease of pressure) for increasing entropy. This softening can affect the stability of proto-neutron stars. It can lead to a novel, hot third family of compact stars, which exists only at the proto-neutron star stage, if one has high enough entropies. Such a third family is highly relevant for the dynamics of core-collapse supernova, as the collapse from the second to the third family has been shown to be able to trigger explosions. However, so far this mechanism was only achieved for EoSs with too low maximum masses.

To answer the question whether this explosion mechanism is still possible despite the $2 M_{\odot}$ constraint, one has to develop new general-purpose hybrid EoSs and test them in numerical simulations. As a first step towards the creation of a new general-purpose hybrid EoS, we performed a systematic parameter scan for the quark matter EoS parameters. For $c_s^2 = 1/3$, there is a small parameter region which leads to sufficiently high maximum masses above $2 M_{\odot}$, and has a weak third family feature already for cold neutron stars. This is the parameter region which we consider most promising for the phase-transition induced explosion mechanism of core-collapse supernovae. Besides testing new EoSs, one should also investigate different progenitor stars, because stars with high entropy cores could be particularly favorable for explosions.

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