Can a supernova bang twice?

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The implications of a QCD phase transition at high temperatures and densities for core-collapse supernovae are discussed. For a strong first order phase transition to quark matter, various scenarios have been put forward in the literature. Here, detailed numerical simulations including neutrino transport are presented, where it is found that a second shock wave due to the QCD phase transition emerges shortly after bounce. It is demonstrated that such a supernova banging twice results in a second peak in the antineutrino spectrum. This second peak is clearly detectable in present neutrino detectors for a galactic supernova.

§1. Introduction

Core-collapse supernova are enigmatic astrophysical cataclysmic events. The observation of supernova SN1987A and the measurements of its emitted neutrinos inspired to put forward unconventional explosion mechanisms. The detection of neutrinos was puzzling as there was a discrepancy in the timing of the events from various neutrino detectors. However, De Rujula pointed out that the measurements are consistent with the emission of two separate neutrino bursts delayed by about five hours.\textsuperscript{1} He concluded that a supernova may bang twice and suggested that a collapse to a black hole triggered by accretion can explain the second neutrino peak. Hatsuda argued that a hypothetical strange star, a quark star bound by interactions only, could have formed within a second.\textsuperscript{2} He pointed out that the released energy from the transition to a strange star is comparable to the energy emitted in supernovae. The phase transition to quark matter was studied for an adiabatic collapse by Takahara and Sato\textsuperscript{3} They argued that the released latent heat increases the core temperature drastically thereby generating a prolonged emission of neutrinos. In a full hydro simulation with a phase transition a second shock wave emerged\textsuperscript{4} but neutrinos were not considered in the simulation. Drago and Tambini introduced another intriguing scenario where the formation of strange quark matter leads to a prompt bounce.\textsuperscript{5} The mixed phase forms during the supernova collapse, causes a softening of the equation of state. At higher densities the equation of state stiffens again.
for being compatible with the observed pulsar masses. Nakazato, Sumiyoshi, and Yamada performed a full supernova simulation including neutrinos and the quark-hadron mixed phase.\textsuperscript{5}–\textsuperscript{7} They started with a rather high initial mass of 100\( M_\odot \) finding no second shock wave but only that the softening of the equation of state just shortened the timescale for the collapse to a black hole. Here, we report on the implementation of the QCD phase transition for core-collapse supernova simulations with neutrinos included for lower initial progenitor masses.\textsuperscript{8}–\textsuperscript{10} A second shock wave is generated by the appearance of the quark-hadron mixed phase leading to an explosion. When the heated shock material is running over the neutrino sphere, a second burst of neutrinos is released in antineutrinos. This second peak can be observed with the present neutrino detectors Super-K and IceCube for a galactic supernova as shown by Dasgupta et al.\textsuperscript{11}

\section{2. QCD Phase Transition in Neutron Stars}

The QCD phase diagram is largely unknown at high densities and temperatures. The asymptotic freedom of QCD ensures that at large enough energy scales matter should be described in terms of free quarks and gluons and not by hadronic degrees of freedom. At high densities, quark matter could be in a chirally restored but not deconfined phase which is dubbed the quarkyonic phase.\textsuperscript{12} Compact stars consisting of pure quark matter, so called strange stars, could be bound just by interactions with quite exotic properties as shown within the MIT bag model\textsuperscript{13}–\textsuperscript{15} (see also Ref. \textsuperscript{16}). In perturbative QCD calculations to \( O(\alpha_s^2) \) the properties of these strange stars were found to be surprisingly similar to the results of the MIT bag model. Strange stars have quite similar maximum masses and radii compared to ordinary neutron stars. However, a strange star is hypothetical as one has to assume that strange quark matter is more stable than ordinary nuclear matter.

Hence, one has to match to hadronic matter at low densities. The onset of the mixed phase could be as low as \((1 - 2)n_0\) for a large range of values for the MIT bag constants, see e.g. Ref. \textsuperscript{22}. Sufficiently high densities are reached in the core for a 1.3\( M_\odot \) neutron star to have quark matter present. For a strong first order phase transition a third family of compact stars appears in the mass-radius diagram besides white dwarfs and neutron stars.\textsuperscript{22}–\textsuperscript{23} Signals for such a phase transition and the appearance of a third family have been discussed intensively in the literature, as e.g. the spontaneous spin-up of pulsar\textsuperscript{23} and an exotic mass-radius relation with the so called rising twins.\textsuperscript{22} Also the collapse of a neutron star to the third family can release gravitational waves, \( \gamma \)-rays, and neutrinos. The signal of the QCD phase transition for core-collapse supernovae will be the subject of the next section.

\section{3. QCD phase transition in core-collapse supernovae}

The conditions for phase equilibrium in supernova matter have been devised in detail in Ref. \textsuperscript{24}. Several different cases have been considered depending on the locally and globally conserved charges in the thermodynamic system at hand which for supernovae matter would be the proton or lepton fraction in addition to the
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Coulomb charge. An interesting case concerns the one, where the charge is assumed to be locally conserved not globally. Then chargeless bubbles appear in leptonized matter at the early stage of the proto-neutron star’s life which form a mixed phase due to a nonvanishing locally conserved lepton number. The mixed phase disappears when the neutrinos leave the star which can cause a delayed collapse with a pronounced emission of neutrinos. Proto-neutron star evolution with quarks has been simulated in the work of Pons et al. They find that the onset of the quark phase in core-collapse supernovae occurs during the late time evolution of the proto-neutron star. The timescale for quark matter to appear was found to be typically $(5 - 20)$s which is well after the bounce. The late onset of the quark phase is due to a large bag constant, $B^{1/4} > 180$ MeV which was chosen to get a large neutron star mass.

There are several arguments for quark matter to appear at rather low densities in astrophysical systems. First in $\beta$-equilibrium, strange quark matter is favored in comparison to ordinary nuclear matter due to the additional strangeness degree of freedom. Secondly, low values of the proton fraction are also an advantage for quark matter due to the large asymmetry energy of nuclear matter (the situation gets more subtle when effects of color-superconductivity are considered, see Ref. [28] for more details). Thirdly, the phase transition line is located at lower densities at higher temperatures. The total effect is that the production of quark matter in supernovae material can occur at quite low densities so that its production at bounce is possible. For a temperature of $T = 20$ MeV the phase transition to the mixed phase can be located just slightly above normal nuclear matter density for $Y_p = 0.3$. It is important to note that for matter in heavy-ion collisions the phase boundary is shifted to much larger values. It is also crucial to realize that the phase transition is not necessarily related to deconfinement, so the naive picture of overlapping hadrons making the transition can be misleading. In principle, any strong first-order phase transition can be envisioned in dense matter for our purpose here, as one related to chiral symmetry restoration.

There are only two supernova equations of state commonly used for the nuclear phase, the one of Lattimer and Swesty and the one of Shen et al. Advanced modern equations of state are presently being developed. Medium effects for nuclei have been studied in Ref. [31] and applied for supernova conditions by Typel et al. The statistical approach of Botvina and Mishustin for supernova matter utilizes methods from nuclear multifragmentation. A complete supernova equation of state has been developed with an excluded volume which takes into account the whole set of nuclei of the nuclear chart in Ref. [34]. In the following we will use the equation of state from Shen et al. where the phase transition is added by using the MIT bag model.

It turned out that a particular critical point to check the equation of state is the maximum mass for cold neutron stars. Recent mass measurements of the pulsar PSR 1903+0327 indicate a quite high mass of $M = (1.67 \pm 0.01)M_\odot$. A detailed discussion on mass and radius constraints for cold neutron stars can be found in Refs. [37]–[39]. The mass-radius curve for the equation of state used in the supernova simulation is depicted in Fig. 1 for different values of the MIT bag constant.
lower value results in a higher maximum mass. Here we find maximum masses of $M_{\text{max}} = 1.56M_{\odot}$ for $B^{1/4} = 162$ MeV and $M_{\text{max}} = 1.5M_{\odot}$ for $B^{1/4} = 165$ MeV. If one includes corrections from one-gluon exchange, the maximum mass increases to $M_{\text{max}} = 1.67M_{\odot}$ (for $\alpha_s = 0.3$) while the critical density for the onset of the mixed phase is tuned to be similar by lowering the bag constant to $B^{1/4} = 155$ MeV.

The strong first order QCD phase transition has a significant impact on the dynamical evolution of core-collapse supernovae. Full hydrodynamical simulations including neutrinos have been performed for progenitor masses of $M = 10M_{\odot}$ and $M = 15M_{\odot}$ in Ref. [8]. A few hundred milliseconds after the bounce, a second shock wave develops due to the formation of the new high-density phase. The mixed phase has a lower adiabatic index, collapses and hits the high-density core which has a much larger adiabatic index. A shock front forms, travels outwards and accelerates at the steep density gradient on the surface of the proto-neutron stars. When the heated material passes the neutrinosphere, antineutrinos are released in a burst. The antineutrino spectrum will be markedly different from the conventional picture as a pronounced second peak appears shortly after the time of collapse. In the simulations runs the quark core appears between $t_{\text{ph}} = 200$ to 500 ms depending on the progenitor mass and the chosen bag constant. The transition to strange quark matter involves the production of strangeness during the conversion process. In hadronic matter, hyperons can appear to some extent in supernova material due to $\beta$-equilibrium and thermal production, see Refs. [40], [41] who find a hyperon fraction at bounce (assuming $T \sim 20$ MeV) of about 0.1%. This small amount of hyperons already present enables the nucleation of strange quark matter via fluctuations of strangeness.

The results are highly sensitive to the surface tension between the old and the new phase, which is a basically unknown quantity. The nucleation timescales computed are below the timescale of a supernova for critical surface tensions of $\sigma < 20$ MeV fm$^{-2}$, which are usually considered to be small but which are not unreasonable.

The antineutrino peak from the QCD phase transition can be detected with the
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Fig. 2. The expected signal of antineutrinos for a supernova banging twice at a galactic distance of 10 kpc as seen in the Super-Kamiokande detector (left plot) and in IceCube (right plot). A spectacular pronounced second peak is clearly seen in the simulated data, here at a time of around 260 ms (figures taken from Dasgupta et al\textsuperscript{11}).

The present neutrino detectors Super-K and IceCube, see Dasgupta et al\textsuperscript{11}. These detectors are mostly sensitive to antineutrinos by inverse $\beta$-decay reactions ($\bar{\nu}_e p \rightarrow n e^+$). Adopting the antineutrino spectrum from the supernova simulation, the observed antineutrino signal from a supernova would clearly reveal a second peak. Fig. 2 shows the expected signal for Super-K and IceCube assuming a galactic supernova at a distance of 10 kpc. The second peak in the antineutrino spectra sticks out quite strikingly showing the high sensitivity of the present neutrino detectors. Unfortunately, the sensitivity of the neutrino detectors at the time of SN1987A were orders of magnitude lower, otherwise one might have already seen that a supernova can indeed bang twice.

Acknowledgements

This work is supported by BMBF under grant FKZ 06HD9127, by DFG under grant PA1780/2-1 and within the framework of the excellence initiative through the Heidelberg Graduate School of Fundamental Physics, the Gesellschaft für Schwerionenforschung GSI Darmstadt, the Helmholtz Research School for Quark Matter Studies, the Helmholtz Graduate School for Heavy-Ion Research (HGS-HIRe), the Graduate Program for Hadron and Ion Research (GP-HIR), the Helmholtz Alliance Program of the Helmholtz Association, contract HA-216 ”Extremes of Density and Temperature: Cosmic Matter in the Laboratory”, the Swiss National Science Foundation, grant no. PP00P2-124879/1 and 200020-122287, and CompStar, a research networking program of the European Science Foundation.

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