Neutron stars from an effective quark theory of QCD†

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The study of neutron star matter has attracted increased attention recently because of the observation of massive neutron stars exceeding two solar masses[1] and gravitational wave measurements of a binary neutron star merger event.[2] In this work, we investigate whether a single effective quark theory of QCD which can describe both the structure of free and in-medium hadrons as well as nuclear systems,[3] can also produce properties for neutron stars which agree with data. For this purpose, we use the two-flavor Nambu-Jona-Lasinio (NJL) model[4] with the proper-time regularization scheme, which incorporates important aspects of confinement.[3]

We calculate the effective potentials of nuclear matter (NM) and quark matter (QM) in the mean field approximation as functions of two independent chemical potentials for baryon number and isospin. The Fermi gas of electrons is also included so as to achieve β equilibrium and charge neutrality. Besides the vacuum (Mexican hat shaped) part, the effective potentials contain pieces which describe the Fermi motion of composite nucleons (case of NM) or constituent quarks (case of QM) in scalar and vector mean fields. The description of the nucleon is based on the Faddeev method in the quark-diquark approximation, taking into account both the scalar and axial vector diquark channels. In the QM sector we also take into account the pairing of quarks in the scalar diquark channel, which gives rise to a gap (color superconductivity). We use the Gibbs equilibrium conditions to describe the phase transition from NM to QM with an intermediate mixed phase. The constituent quark mass (scalar mean field), the gap, and the isoscalar- and isovector-vector mean fields are determined self consistently by minimization of the effective potential for fixed chemical potentials.

The model parameters in the single nucleon and NM sector are the same as in Ref. 3). In order to realize a phase transition to QM at reasonable transition densities (between $2\rho_0$ and $4\rho_0$, where $\rho_0 = 0.16$ fm^{-3}) with a stable QM component, we found that it is possible to use the same value for the pairing strength in QM as for the scalar diquark interaction in the single nucleon sector, but the vector couplings must be smaller than in NM by a factor of 0.5–0.68.In the results below we use a reduction factor of 0.68 for both isoscalar- and isovector vector couplings in QM.

By using our equation of state as an input to solve the Tolman-Oppenheimer-Volkoff equations, we can calculate the properties of neutron stars. From our results, shown in Figs. 1 and 2, we can conclude that our NJL model description, which has been very successful for single hadrons and nuclear systems, leads to a satisfying scenario also for the phase transition to QM and the resulting properties of neutron stars.

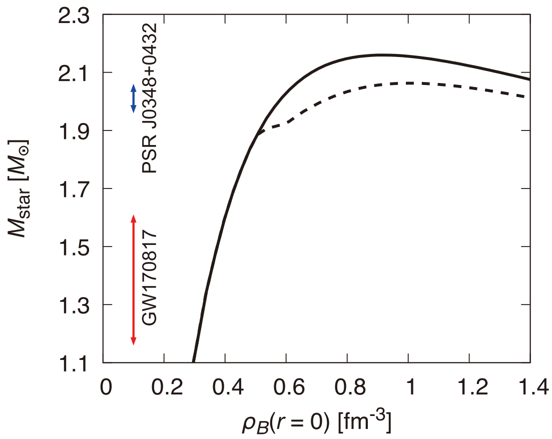

Fig. 1. Neutron star mass vs. central baryon density. The solid line shows the pure NM case, and the dashed line shows a phase transition to QM at about $3\rho_0$. PSR J0348 + 0432 and GW170817 indicate the observed values of star masses of Refs. 1–2), respectively.

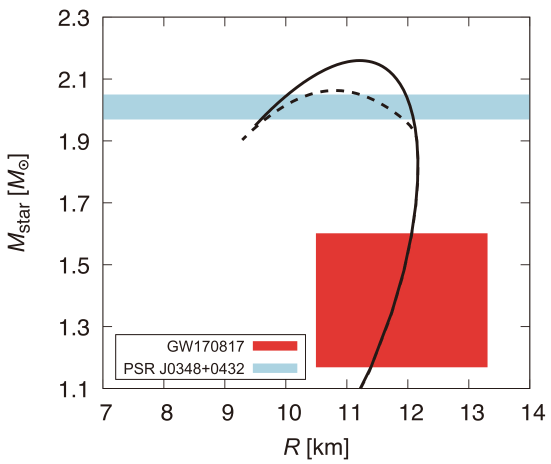

Fig. 2. Mass-radius relation for neutron stars. For explanation of lines and symbols, see the caption to Fig. 1.

References
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† Condensed from an article by T. Tanimoto *et al.*, to be published in Phys. Rev. C (2019).
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