Massive Neutron Stars with Hadron-Quark Transient Core
—phenomenological approach by "3-window model"—

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Recent observations of a two-solar-mass neutron star ($2M_{\odot}$-NS) present a challenging problem how to accomodate a very stiff equation of state (EOS) responsible for such massive NSs. This problem is serious since every new exotic phase (e.g., meson condensation, hyperon (Y) mixing, quark (Q) matter) leads to a softening of EOS against the requirement from observations. For example, the Y-mixing softens the EOS dramatically and thereby the NS maximum mass (M_{max}) goes down to (1.1-1.2)$M_{\odot}$, clearly contradicting even the "minimal mass"$1.44M_{\odot}$ observed for PSR1913+16.

The aim of this paper is to discuss how NSs could be massive, by introducing a quark degrees of freedom. Our strategy for the approach is to divide the EOS into three density (ρ) regime i.e., pure hadronic matter EOS (H-EOS, $\rho \leq \rho_H$), hadron-quark transient matter EOS (HQ-EOS, $\rho_H \leq \rho \leq \rho_Q$) and pure quark matter EOS (Q-EOS, $\rho \geq \rho_Q$), which we call "3-window model"[1]. This is motivated by the following consideration: Pure H-EOS calculated from point-like hadrons plus their interactions looses the validity with increasing ρ, primarily because baryons have a finite size composed of quarks (and gluons)and deconfinement effects come into play. Also pure Q-matter EOS gets uncertain with decreasing ρ because strong correlations among quarks would develop and confinement effects would participate.

Our basic idea is to supplement the very poorly known HQ-EOS relevant to a confinement-deconfinement transition, by sandwitching it in between the relatively certain H-EOS at lower density side and Q-EOS at higher density side. We use the H-EOS from a G-matrix-based effective interactions which satisfies the ground state prperties of nuclear matter, and the Q-EOS from the (2+1)-flavor NJL-model including a repulsive vector interaction term. We obtain the HQ-EOS by a phenomenological interpolation under the 6 conditions that the energy density (ϵ), pressure (P) and sound velocity (v_s) match at the phase boundaries, ρ_H and ρ_Q. We adopt the interpolation function to satisfy the thermodynamic stability conditions, $P > 0$ and $\partial P/\partial \rho > 0$, and causality, $v_s \leq c$.

We stress that our new approach to the H-Q transition is not restricted by a conventional Gibbs or Maxwell condition which necessarily leads to a softening of EOS. It is found that NSs with H-Q transient core have $M_{max} \sim (2.2-2.4)M_{\odot}$ resolving the conflict between theory and observation, as far as quark degrees of freedom sets in at rather low density (1.5-2.0)ρ_0 (ρ_0=0.17/fm^3 being nuclear density) and the Q-EOS is stiff. The present results confirm those of our preceding works performed from a H-Q crossover picture [2].

[1] T. Takatsuka, T. Hatsuda and K. Masuda, arXiv: 1402.4677v1 [nucl-th] 19 Feb 2014.
[2] K. Masuda, T. Hatsuda and T. Takatsuka, Astrophys. J.794, 12 (2013); Prog. Theor. Exp. Phys. 073 Do1 (2013).