Equation of State for Neutron Stars: a Status Report

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The equation of state (EOS) of neutron star (NS) matter is necessary for constructing NS models. The $T = 0$ approximation is assumed. The baryon number density $n_{\rm b}$ is conveniently measured in the standard nuclear density $n_0 = 0.16\ {\rm fm}^{-3}$, corresponding to the matter density $\rho_0 = 2.7 \times 10^{14}\ {\rm g\ cm}^{-3}$. The density of matter is expected to reach up to $10\rho_0$ at the center of the most massive NS (those with the maximum allowable mass $M_{\rm max}$). The corresponding maximum baryon density can be as large as $8n_0$, because the kinetic energy and the interaction energy bring a contribution to ρ. Basically, the EOS $P = P(\rho)$ consists of a crust segment with $\rho \lesssim 0.5\rho_0$ and a liquid core segment with $0.5\rho_0 \lesssim \rho \lesssim 10\rho_0$. Within the core, containing more than 95% of the NS mass, the pressure is dominated by the strong (nuclear) interactions between nucleons (baryons). Pulsar observations show that the strong repulsion due to nuclear forces can support against gravity $2M_\odot$ NS, a mass which is nearly triple of $M_{\rm max} = 0.7M_\odot$ that can be supported by the pressure of a non-interacting Fermi gas of nucleons.

More than forty unified EOS are now available, derived using the same nuclear interaction model for the crust and the core. Experimental constraints, as well as recent precise ab initio many-body calculations for neutron matter and nuclear matter, put strong constraints on the EOS at $n_{\rm b} \leq n_0$ ($\rho \leq \rho_0$). However, then, from n_0 up to $8n_0$ at the center of NS with the maximum allowable mass $M_{\rm max}$, the uncertainty in the EOS grows rapidly with the density, being nevertheless constrained in the $P-\rho$ plane by the conditions of causality (on the high P side) and $M_{\rm max} > 2M_\odot$ (on the low P side). We briefly review unified EOS for NS starting from realistic two-nucleon ($N = 2$) and three-nucleon $N = 3$ nuclear forces. Uncertainty resulting from the poor control over the $N > 2$ contribution to the EOS, relevant not only for $M_{\rm max}$, but present alas already at n_0, is stressed. Recent versions of the relativistic mean-field theory of dense hadronic matter, where the basic lagrangian involves baryon fields coupled to meson fields and the EOS is obtained in the mean-field approximation are reviewed. These extensions involve a density-dependence for the meson masses and the nucleon-meson coupling constants, and some effects of the finite size of nucleons. Problems resulting from the finite size of nucleons and its treatment via the excluded-volume approximation are briefly discussed. In this context, the non-linearity of the high density $\rho - n_{\rm b}$ relation is stressed and its physical importance illustrated. The uncertainty in the theoretical prediction of EOS for densities $\rho_0 < \rho < 10\rho_0$ grows so rapidly with increasing ρ, that an extrapolation procedure to the high-density regime should actually be considered. The uncertainty strip narrows only after reaching $\rho > 100\rho_0$, where quarks are certainly deconfined and perturbative QCD can be used. Perspectives for getting the true EOS for NS from the simultaneous precise measurements of mass and radius of NS are outlined.

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