Properties of axisymmetric neutron stars with quark cores

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Introduction

Observations of massive pulsars such as J1614-2230 suggest mass of (1.97±0.04) $M_\odot$. Most equations of state (EoS) involving exotic matter, such as kaon condensates or hyperons, tend to predict maximum masses well below 2.0 $M_\odot$ and are therefore ruled out. Recently, measured mass of PSR J1748-2021B, a millisecond pulsar in the Globular Cluster NGC 6440, is claimed to be as high as $2.74^{+0.41}_{-0.51} M_\odot$ (2σ) [1]. The EoS for β-equilibrated charge neutral neutron star (NS) matter is determined using density dependent M3Y effective nucleon-nucleon (NN) interaction. This EoS is found to satisfy both the constraints from the observed mass-radius relationship of neutron stars and flow data from heavy-ion collisions [2]. The energy density of quark matter is lower than that of this nuclear EoS at higher densities implying the possibility of transition to quark matter inside core. We solve the Einstein's equations using pure nuclear matter and quark core. We are able to reproduce the measured mass-radius relationship for NS.

β-equilibrated nuclear & quark matter EoS

The nuclear matter EoS is calculated using the isoscalar and the isovector components of the M3Y interaction along with the density dependence (DDM3Y). This EoS evaluated at the isospin asymmetry determined from the β-equilibrium proton fraction provides EoS for the β-equilibrated NS matter [2]. For cold and dense quark (QCD) matter the perturbative EoS [3] with two massless and one massive quark flavors and a running coupling constant, is used.

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Calculations and Results

In order to explore the various properties of static and rotating NS using the proposed EoS, the stellar matter is treated as perfect fluid with energy-momentum tensor $T^{\mu\nu}$ given by

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - g^{\mu\nu} P \qquad (1)$$

where ε, P, u^μ and $g^{\mu\nu}$ are the enregy density, pressure, four velocity and the metric tensor, respectively. To study the rotating stars the following metric is used

$$ds^2 = -e^{(\gamma+\rho)}dt^2 + e^{2\alpha}(dr^2 + r^2 d\theta^2) + e^{(\gamma-\rho)} r^2 \sin^2\theta (d\phi - \omega dt)^2 \qquad (2)$$

where the gravitational potentials γ, ρ, α and ω are functions of polar coordinates r and θ only. The Einstein's field equations for the three potentials γ, ρ and α have been solved using the Green's-function technique [4] and the fourth potential ω has been determined from other potentials. All the physical quantities may then be determined from these potentials. We use the 'rns' code [5] for calculating the NS properties. For β-equilibrated NS matter with thin crust (crustal EoS: Feynman-Metropolis-Teller +Bethe-Pethick-Sutherland + Baym-Bethe-Pethick upto 0.0458 fm^{-3}), the maximum mass for the static case is 1.92 $M_\odot$ with radius ∼9.7 km and for the rotating case it is 2.27 $M_\odot$ with equatorial radius ∼13.1 km [2]. The energy density of quark matter is lower than that of the present EoS for β-equilibrated charge neutral NS matter at densities higher than 0.405 fm^{-3} for bag constant $B^{\frac{1}{4}}$=110 MeV [3] implying presence of quark core. When quark core is considered, the maximum mass for the static case is 1.68 $M_\odot$ with radius ∼10.4 km and for the rotating case it is 2.02 $M_\odot$ with equatorial radius ∼14.2 km.

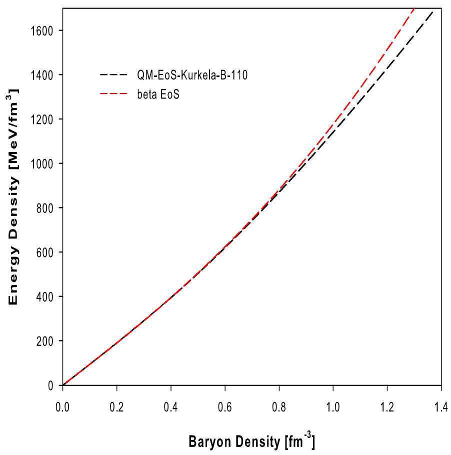

FIG. 1: The EoSs of β-equilibrated charge-neutral neutron star matter and quark matter.

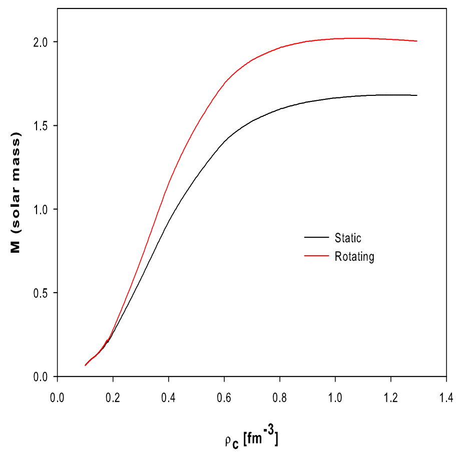

FIG. 2: Variation of mass with central density for static and rotating neutron star with quark core.

Summary and Conclusion

In summary, we have constructed an EoS for β-equilibrated charge neutral NS matter using DDM3Y effective NN interaction whose energy density turns out to be higher than

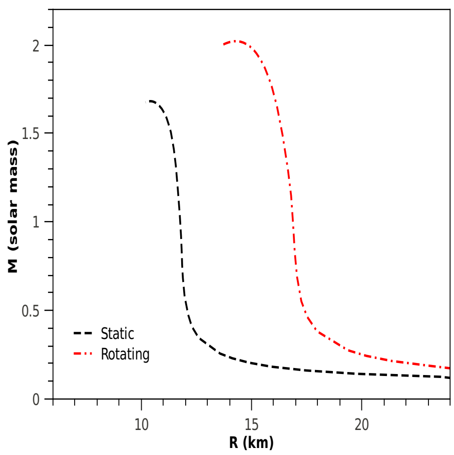

FIG. 3: Mass-radius relationship for static and rotating neutron star with quark core.

that of quark matter at densities above 0.405 fm^{-3} implying possibility of quark core. We have applied our nucleonic EoS with a thin crust to solve the Einstein's field equations to determine the mass-radius relationship of neutron stars with and without quark cores. We have obtained the rotating star masses around (2.02-2.27) $M_\odot$ with equatorial radii around 13-14 kilometres. These results are in excellent agreement with recent astrophysical observations.

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