Role of Hyperons in Neutron stars

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Introduction

Neutron stars are the densest manifestations of massive objects in the observable universe. They are the remnants of the gravitational collapse of massive stars (8-20 $M_\odot$) during a Type II, Ib or Ic supernova event. A collapsed core with a mass of the order of 1-2 $M_\odot$ and radius about 10-12 km is what is called a neutron star. The central densities are about 5-10 times the normal nuclear saturation density ($\rho_0 = 0.16\ fm^{-3}$) and hence the conditions of matter inside the neutron stars are very different from normal nuclear matter [1]. A good knowledge of Equation of State (EoS) of the dense matter is thus required to understand the properties of neutron stars.

At high density, new hadronic degrees of freedom like Hyperons (Baryons with strangeness) are expected to appear other than nucleons. These hyperons appear at a density of about 2-3 normal nuclear density (ρ_0) in the inner core of neutron star. The hyperonization of matter leads to the softening of EoS which results in the reduction of maximum mass of neutron star.

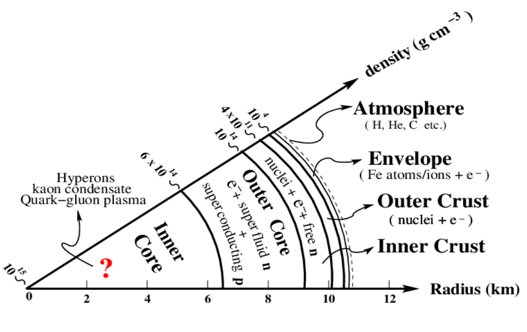

FIG. 1: Internal structure of a neutron star [2].

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In the following, We briefly review the hyperon puzzle and the role of hyperons on the properties of neutron stars.

The Hyperon Puzzle

The reason for hyperons formation in neutron star is mainly due to the fermionic nature of nucleons. At densities 2-3ρ_o, the chemical potential of neutrons becomes sufficiently large enough to allow the most energetic neutrons decay via weak interaction into Λ hyperons. Such conversions relieve the Fermi pressure exerted by the baryons and hence make the EoS softer i.e, the mass of the star is reduced substantially as shown in Fig. 2.

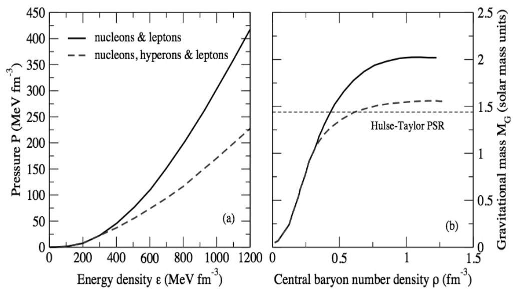

FIG. 2: Effect of presence of hyperons on EoS and mass of a neutron star [3].

The presence of hyperons in neutron stars seems energetically unavoidable but their strong softening of EoS leads to maximum masses that are not compatible with the observation. This is "**Hyperon puzzle**". The measurements of high masses of the millisecond pulsars like PSR J0348+0432 (2.01 $\pm$ 0.04 $M_\odot$) [4] and PSR J1614-2230 (1.97 $\pm$ 0.04 $M_\odot$) [5] rule out all proposed EoS with hyperons. The mechanisms like hyperon-hyperon repulsion [6] and hyperon three-body forces [7] could solve this problem. However, it seems that such mechanisms do not provide the complete solution to the hyperon puzzle and that we should look for other mechanisms. Deconfined quark matter [8] could be one of the possible solutions.

Neutron star cooling

The cooling of newly born neutron stars is first driven by the emission of neutrino from the stars interior and then by photon emission at the surface. The neutrino emission can be slow or fast depending on whether one baryon participates or two. Direct Urca process($n \to p + l + \bar{\nu_l}, p + l \to n + \nu_l$) is the simplest but fast neutrino emission process. Slow processes include modified Urca process ($N + n \to N + p + l + \bar{\nu_l}$), the bremsstrahlung ($N + N \to N + N + \nu + \bar{\nu_l}$), or the Cooper pair formation ($n + n \to [nn] + \nu + \bar{\nu_l}$). With hyperons present in the neutron star, new neutrino emission processes like $Y \to B + l + \bar{\nu_l}$ may occur thus providing fast cooling mechanisms, which in turn reduce the surface temperature than that observed. The study of hyperons thus play an important role in the thermal history of neutron stars.

r-mode instability

The upper limit on the rotational frequency of a neutron star is set by Kepler frequency Ω_k above which the matter is ejected from the star's surface. However, some perturbations/instabilities prevent a neutron star from reaching such high rotational frequencies and thus setting a limit on its rotation [9]. A toroidal mode of oscillation whose restoring force is equivalent to the Coriolis force, called r-mode instability [10], is of particular interest. Such oscillating mode leads to the emission of gravitational waves in rotating neutron stars. These gravitational radiations make an r-mode grow.

Bulk viscosity ζ is considered to be the main dissipation mechanism of r-mode in neutron stars. Without hyperons, the bulk viscosity is mainly determined by direct and modified Urca processes. When the hyperons appear, new mechanisms like non-leptonic hyperon reactions ($N + N \to N + Y, N + Y \to Y + Y$), direct ($Y \to B + l + \bar{\nu_l}$) and modified hyperonic Urca ($B' + Y \to B' + B + l + \bar{\nu_l}$), or strong interactions ($Y + Y \to N + Y$) contribute to the bulk viscosity [11].

Summary

We briefly reviewed the role of hyperons on the neutron star properties. We reviewed the softening of the EoS and the consequent reduction in the maximum mass of neutron stars. The effect of hyperons on the cooling properties of newly born neutron stars and the r-mode instability have also been discussed.

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