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We extend our earlier study of the influence of hyperons and pions on the equation of state of neutron star matter and on neutron star structure in the framework of a relativistic nuclear field theory [1]. There are two motivations for this. First, in the early work on the subject [2,3] nuclear matter properties were not under control, in particular the compression modulus and symmetry energy coefficient, even though neutron stars are very dense and are the most isospin asymmetric objects known to exist. In addition to these particular problems with the early work is the more general one. We now know that the early many-body calculations were not carried out to convergance. When the theory is more accurately calculated, both the Bethe-Breuckner and the variational approaches are in agreement and saturate at a density more than a factor *two* larger than the empirical value, and with too much binding [4]. We have also learned over the last several years that relativity is very important even at nuclear density and therefor especially at higher density.

The second motivation arises from the problem surrounding the origin of neutron stars. Although for many years, supernova erruptions have been thought to be the birthplace of neutron stars, numerical simulations had not produced a successful scenario in which most of the imploding material from the collapse of a massive star is ejected as a result of the bounce and the subsequent shock wave when matter compresses to supernuclear density. Failure to eject means that the stellar material will once more be accreted by gravity, and the massive remnant will subside into a black hole rather than a neutron star, as must be the case whenever the mass of the accreted material exceeds a critical value of several solar masses. There has been a recent development in this field, namely that the long anticipated scenario of ejection by the bounce *can* succeed. The *crucial* element is that the equation of state at high density is sufficiently soft [5]. In this work we advance an hypothesis concerning the physical origin of the softening at high density that is found to be crucial to the bounce scenario. We show that the equation of state of the high density neutron star matter involved in the collapse is substantially softened by the decay or scattering of energetic nucleons at the top of the Fermi sea into hyperons, and at lower density, but less dramatically, by the condensation of negative pions. We show that gravity exploits this softness very effectively in neutron stars, by reducing the limiting mass predicted by theory by an amount equal to one half or more of the range in which theories that neglect these effects predict it to fall. The natural inference is that pions and hyperons are the agents that underlie the parameterized softness of the equation of state that is required by the stellar collapse simulations to achieve a successful ejection of the mantle.

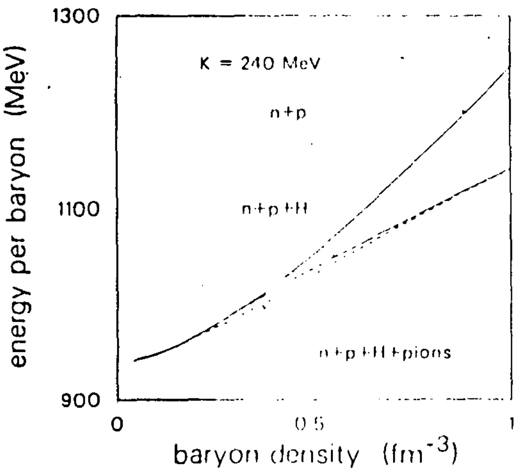

Fig. 1 Equation of state for the three cases, 1) neutron and proton, 2) hyperons in addition, 3) pions in addition. In all cases leptons are present to complete beta equilibrium.

The Lagrangian for the theory is that of the scalar-vector-isovector (σ, ω, ρ) theory [6], suitably generalized for dense asymmetric matter [1]. This generalization must include a consideration of phase transitions corresponding to the condensation of mesons additional to the ones above. It has been shown that in neutron star matter, the only possible additional condensate is the pion. It and the hyperons preclude the condensation of additional mesons [1].

The five coupling constants in the theory, g_σ/m_σ, g_ρ/m_ρ, g_ω/m_ω, b, c, are chosen so that the theory possesses the bulk properties of uniform symmetric matter, $B/A = 15.95$ MeV, saturation density $\rho = 0.145 fm^{-3}$, symmetry energy coefficient $a_{sym} = 36.8$ MeV, the compression modulus $K = 240$ MeV, and the nucleon effective mass at saturation, which we assume to be 0.8.

The couplings $g_{\sigma B}$, $g_{\omega B}$ and $g_{\rho B}$ of the hyperons to the mesons cannot be inferred from the saturation and ground state properties, and are chosen in accord with a suggestion of Moszkowski [3], depending on quark counting in the meson exchange, namely, $g_H/g_N = 2/3$.

For neutron star matter (matter that is charge neutral and in chemical equilibrium), we compare in Fig. 1 the equations of state of matter in three cases, (1) only neutrons, protons and leptons are allowed to participate, (2) all baryons and leptons required by chemical equilibrium are allowed to participate, and (3) in addition pions condense at their vacuum mass. The softening effect of the pions can be seen above their threshold density. They condense at a rather low density in neutron star matter when the constraint of charge neutrality makes them more energetically favorable than leptons. Further softening occurs at higher threshold densities, as the hyperons become successively populated. They quench the pion population at high density because there charge neutrality is achieved mainly among the baryons.

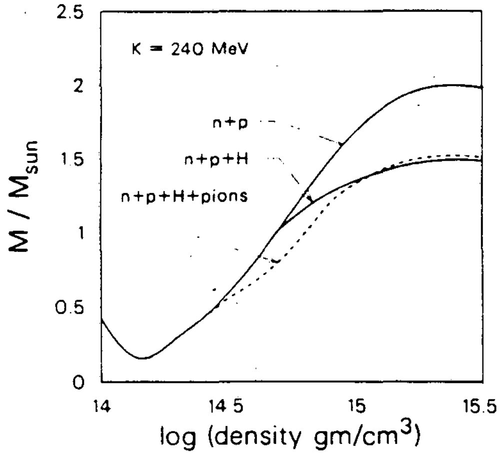

Fig. 2 Neutron star masses as a function of central energy density for the three cases, 1) neutron and proton, 2) hyperons in addition, 3) pions in addition. In all cases leptons are present to complete beta equilibrium. The compression modulus of the corresponding nuclear matter is $K = 240$ MeV.

The same comparisons as above are made in Fig. 2 for neutron star masses as a function of their central densities. Although on the scale shown for the equations of state, the differences between the three cases does not appear to be large, here we see that gravity is quite sensitive to the differences. In particular the limiting mass (maximum neutron star mass for given equation of state), is reduced by about one half solar mass which is a very significant amount considering that all theoretical predictions fall in a narrow range of about one solar mass. The effect is even larger, 3/4 solar masses, if the nuclear compression modulus is 200 MeV.

Our main conclusions are the following:

1) Pions and hyperons substantially soften the equation of state of neutron star matter. The pion threshold occurs at the lowest density. They are quenched at higher density by hyperons, which introduce an even greater softening. Gravity integrates these effects over the range of densities found in neutron stars, with the consequence that star masses are reduced throughout the range in which these particles form a component of charge neutral stable dense matter, the effect being especially large for the star at the limiting mass. The predicted effect of these particles on the limiting mass is large, amounting to one half or more of the range in which this limit falls for theories that ignore the hyperons and pions.

2) The large effects that pions and hyperons have on the mass curve and limiting mass of neutron stars suggests that these may be the physical agents that cause the softening at high density that is found to be "crucial" [5] for obtaining a strong enough bounce during the collapse of a massive star to sustain the ejection of mass into a supernova event.

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