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February 1987

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Role of Hyperons and Pions in Neutron Stars and Supernovae [1] [2]

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February 25, 1987

Submitted to Zeitschrift fur Physik A.

[1] *Dedicated to Dr. Earl K. Hyde on the Occasion of his Retirement from the Lawrence Berkeley Laboratory.*

[2] Work supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

Role of Hyperons and Pions in Neutron Stars and Supernova [‡§]

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Abstract

Neutron stars are studied in the framework of nuclear relativistic field theory. Hyperons and pions significantly soften the equation of state of neutron star matter at moderate and high density. We conjecture that they are responsible for the softening that is found to be crucial to the bounce scenario in supernova calculations. Hyperons reduce the limiting mass of neutron stars predicted by theory by one half solar mass or more, which is a large effect compared to the range in which theories of matter predict this limit to fall.

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1 Introduction

In this paper we extend our study of the influence of hyperons and pions on the equation of state of neutron star matter, and on neutron star structure [1,2,3]. There are two motivations for this. The first has to do with the theory of nuclear matter, and the second with developments in the understanding of supernova. We discuss these in turn.

Much has been learned in nuclear theory since the pioneering work of Bethe and Johnson [4] and of Pandharipande [5] on neutron stars. Those calculations were done at a time when it was considered an achievement to obtain the binding and saturation density of nuclear matter correctly. Among the seven criteria that Bethe and Johnson list as being important constraints on a theory of matter, the only properties of matter mentioned are the binding and saturation density. Pandharipande was content with a minimal constraint, that liquid He^3 and He^4 should come out about right. No mention is made of the compression modulus of nuclear matter, nor the symmetry energy, 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 as they relate to neutron star structure, is the more general one. We now know that the early many-body calculations were not carried out to convergence. 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 [6]. We have also learned over the last several years that relativity is very important even at nuclear density and therefore especially at higher density. For example, the relativistic corrections calculated by Ainsworth et. al. [7] amount to 100 percent in both the saturation density and the binding energy of symmetric nuclear matter. Finally, theories of matter based on the Schroedinger theory violate causality at high density. Even if they do so above densities of interest for neutron stars, the fact that they do so means that the equation of states calculated in the non-relativistic approximation are too stiff even below the point where they actually cross the $p = \epsilon$ causality limit, since this should be their asymptote.

The approach used in this work is quite different than that in the early work on neutron star structure, and is one for which the list of successes in describing nuclear properties and scattering of nucleons from nuclei is growing. It is an effective relativistic nuclear field theory, that makes contact with data, not at the level of two-body scattering, but with the bulk properties of nuclear matter. When the coupling constants are determined by the bulk nuclear properties, it is then found that a large number of properties of finite nuclei are well accounted for [8], or conversely [9]. With the theory thus constrained by the important bulk properties, it can be appropriately generalized [1,2,3] and extrapolated to higher density. Of course the finite size of the nucleon and its internal structure places an upper limit on the domain of validity of an effective theory that employs hadrons as the degrees of freedom. The upper limit is so far not known.

The second motivation arises from the problems surrounding supernova and the origin of neutron stars. Although for many years, supernova eruptions have been thought to be the birthplace of heavy elements in the universe and 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 that are produced 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 have been two recent developments. Wilson [10] discovered that by continuing his simulation for more than ten times longer (several hundred milliseconds) after the bounce than had been done previously, the stalled shock was revived by reheating due to absorption of a neutrino shower emitted by the cooling core. This scenario, if confirmed, *requires* the failure of the bounce to promptly eject most of the stellar material. The second development is that in a particular circumstance, the long anticipated scenario of prompt ejection by the bounce *can* succeed [11]. One crucial element is that the equation of state must be soft at high density [12]. The other element is a technical one, namely that the hydrodynamics of the collapse are treated in the frame of general relativity. 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.

The presence of hyperons in neutron stars, although not observable, is hard to refute. A simple Fermi gas model predicts their presence [13], and studies with nuclear forces, support this finding [1,2,3,4,5,14,15]. The presence of pions is less certain, and ultimately depends on the magnitude of their effective mass in neutron star matter as compared to the electron chemical potential. Therefor, as regards pions, we shall consider two extreme cases, one for which pions do not condense because of an assumed effective mass which is too large, and one for which they condense at the vacuum mass.

Star collapse is a dynamic process, but we note that the time scale is long in comparison with the hadronic interaction scale, so that the processes studied here can take place during the collapse phase of the evolution.

2 Theory

Matter at the density of neutron star cores is relativistic and we therefore employ a relativistically covariant field theory of hadrons based on the exchange of scalar, vector, and vector-isovector mesons (σ, ω, ρ). Such a theory [16], augmented with scalar self-interactions [17], can describe very well both the bulk and single-particle properties of finite nuclei [8,9].

We must generalize the theory for neutron stars. Stars are essentially charge neutral because the repulsive Coulomb force is so much stronger than the gravitational one. A star composed solely of neutrons satisfies this condition but is unstable against beta decay. The neutron at the top of the Fermi sea has enough energy to decay into a proton and electron. So pure neutron stars cannot exist. As the density further increases, other baryon thresholds will be reached and neutrons and protons with high kinetic energy will interact or decay to form hyperons, deltas, and excited nucleons. Therefor we should allow for a generalized beta equilibrium in dense neutron star matter, allowing whatever baryons to participate as dictated by the equations of chemical equilibrium, which depend on the chemical potentials of the conserved baryon and electric charges, and on the baryon masses and interactions. This generalization was carried out previously, and we do not recount the details [1,2,3]. Concerning mesons, of all those that are known to exist, only the ones with quantum numbers of the three mentioned above, together possibly with the pion, can have finite mean values in the normal ground state of neutron star matter. We have given the full reason for this previously [2,3], but briefly mention here that the quantum numbers of other mesons, including the pion, are such that a phase transition is required to endow the meson with a finite amplitude. In the absence of such a phase change, the meson satisfies the free Klein-Gordan equation and is free to decay, thus lowering the star's energy. This is the normal fate of the strange mesons produced in association with the hyperons. Concerning the possibility of phase transitions, only negatively charged mesons are energetically favored, because they can then replace relativistic electrons when the electron chemical potential attains the value of the meson effective mass. Being bosons they can all condense in the lowest energy state. This means that the electron chemical potential will saturate when such a meson of lowest mass, namely the pion, condenses. If this happens, all such phase transitions corresponding to higher mass mesons are foreclosed. Even if the pion does not condense, which would be the case if the net interaction (polarization operator) were repulsive in the relevant density range, the condensation of higher mass mesons is foreclosed by the hyperons. The reason is that the rate of increase of the electron chemical potential with density is lowered as it reaches a value near the mass difference between the N and Λ. At that point it is more favorable for a neutron to be transformed into Λ than into proton and electron. Other thresholds are reached with increasing density, and again the electron chemical potential saturates, on a scale typical of the hyperon-nucleon mass difference. This is so much smaller than the mass of the other charged mesons, that again their condensation is foreclosed. Since, with increasing density, charge neutrality can be achieved mainly among baryons, eventually the pion condensate is quenched, if it has occurred at lower density.

Following from the above discussion, we can write the Lagrangian including all baryons and mesons that are relevant to neutron stars as,

$$\begin{aligned}
\mathcal{L} &= \sum_B \overline{\psi}_B(i\gamma_\mu\partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu - \frac{1}{2}g_{\rho B}\gamma_\mu\tau_3\rho_3^\mu)\psi_B \\
&+\mathcal{L}_\sigma^0 + \mathcal{L}_\omega^0 + \mathcal{L}_\rho^0 + \mathcal{L}_\pi^0 - \tfrac{1}{3}bm_n(g_\sigma\sigma)^3 - \tfrac{1}{4}c(g_\sigma\sigma)^4 \\
&+\sum_\lambda \overline{\psi}_\lambda(i\gamma_\mu\partial^\mu - m_\lambda)\psi_\lambda \qquad (1)
\end{aligned}$$

Here ψ_B denotes a baryon spinor and the sum is over all charge states of N, $\Delta, \Lambda, \Sigma, \Xi\ldots$ until the solution converges over the range of densities relevant to the star. The σ- and ω-mesons are Yukawa coupled to the baryons and the ρ-meson is coupled to the isospin current. The $\mathcal{L}^0$ are the free Lagrangians of the mesons. The last term is the lepton Lagrangian, with ψ_λ being the lepton spinor, and the sum is over the electron and muon.

Negative pions will condense when the electron chemical potential attains the value of the pion effective mass in the medium. Under that circumstance they are energetically favored over leptons. When or if this happens, the equation of state will be softened, in general. We will consider two limiting cases, one for which the pions do not condense, because of an assumed too large effective mass. The other limiting case will allow free pions to condense with their vacuum mass. This case will be the opposite extreme, as concerns the effect of pions on the equation of state, and on neutron star masses [18].

When the field equations following from eq. 1 are solved with the subsidiary condition of charge neutrality and chemical equilibrium, we obtain a solution corresponding to neutron star matter. When they are solved with the subsidiary condition of isospin symmetry, we obtain the solution for symmetric nuclear matter. The five coupling constants in the theory, g_σ/m_σ, g_ρ/m_ρ, g_ω/m_ω, b, c are chosen to reproduce the bulk properties of uniform symmetric matter, and a nucleon effective mass of 0.8 at saturation.

For N baryon species, the field equations and conditions of charge neutrality and chemical equilibrium at a chosen baryon density comprise a system of $8+N$ non-linear equations in the unknown meson field amplitudes, chemical potentials, and Fermi momenta,

$$\sigma, \omega_0, \rho_{03}, \mu_n, \mu_e, k_\pi, k_e, k_\mu, k_n, k_p, k_\Lambda, \ldots, k_\Xi, \ldots . \tag{2}$$

If the electron chemical potential attains the value of the pion effective mass, it saturates at that value, and the pion number density replaces it as an unknown which is to be determined by the condition of charge neutrality. When the solution is obtained, the pressure and energy density can be calculated. They are given in this theory by the expressions [2,3],

$$\begin{aligned} p \; = \; & -\tfrac{1}{3}bm_n(g_\sigma\sigma)^3 - \tfrac{1}{4}c(g_\sigma\sigma)^4 - \tfrac{1}{2}m_\sigma^2\sigma^2 + \tfrac{1}{2}m_\omega^2\omega^2 + \tfrac{1}{2}m_\rho^2\rho^2 \\ & + \frac{1}{3}\sum_B \frac{2J_B+1}{2\pi^2}\int_0^{k_B} \frac{p^4}{\sqrt{p^2+(m_B-g_{\sigma B}\sigma)^2}}\, dp \\ & + \frac{1}{3}\sum_\lambda \frac{1}{\pi^2}\int_0^{k_\lambda} \frac{p^4}{\sqrt{p^2+m_\lambda^2}}\, dp \end{aligned} \tag{3}$$

$$\begin{aligned} \epsilon \; = \; & \tfrac{1}{3}bm_n(g_\sigma\sigma)^3 + \tfrac{1}{4}c(g_\sigma\sigma)^4 + \tfrac{1}{2}m_\sigma^2\sigma^2 + \tfrac{1}{2}m_\omega^2\omega^2 + \tfrac{1}{2}m_\rho^2\rho^2 + n_\pi m_\pi \\ & + \sum_B \frac{2J_B+1}{2\pi^2}\int_0^{k_B} \sqrt{p^2+(m_B-g_{\sigma B}\sigma)^2}\, p^2 dp \end{aligned}$$

$$+\sum_{\lambda} \frac{1}{\pi^2} \int_0^{k_\lambda} \sqrt{p^2 + m_\lambda^2}\, p^2 dp \tag{4}$$

In these equations, σ, $\rho(\equiv \rho_{03})$ and $\omega(\equiv \omega_0)$ denote the mean values of the scalar meson, and the time-like components of the neutral ρ- and ω-mesons. The space-like components vanish in isotropic matter. The number density of pions is denoted by n_π, and becomes finite when the electron chemical potential attains the value m_π. The last term of eq. 3 and 4 are the lepton contributions to the pressure and energy density. The hadron contributions are given by the other terms.

The star structure is determined by the solution of the Oppenheimer-Volkoff equations, to which the Einstein equations of general relativity reduce in the special case of static spherical bodies,

$$4\pi r^2 dp(r) =$$

$$-\frac{GM(r)dM(r)}{r^2}\left(1 + \frac{p(r)}{\epsilon(r)}\right)\left(1 + \frac{4\pi r^3 p(r)}{M(r)}\right)\left(1 - \frac{2GM(r)}{r}\right)^{-1} \tag{5}$$

$$dM(r) = 4\pi r^2 \epsilon(r)\, dr \tag{6}$$

The equation of state $p = p(\epsilon)$ from above appears in them, and they express the condition of balance between pressure and gravitational force. They can be integrated from the origin with the initial conditions that $M(0) = 0$ and an arbitrary value for the central density $\epsilon(0)$, until the pressure, $p(r)$, becomes zero. That point, R, defines the radius of the star, and $M(R)$ its mass. For the given equation of state, there is a unique relationship between the mass and central density, $\epsilon(0)$. For each central density the integration also provides the density profile and composition of the star, through the connection between $\epsilon(r)$ and the composition, as provided by the solution, eq. 2, to the theory of matter.

3 Results

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 [19], 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 value of the compression modulus is consistent with the analysis of the giant monopole resonance [20], with the droplet model of atomic masses [19], with the charge-distribution differences in heavy isotopes [21] and it is also consistent with known neutron star masses [18]. The corresponding coupling constants are $(g_\sigma/m_\sigma)^2 = 9.637 fm^2$, $(g_\omega/m_\omega)^2 = 4.5316 fm^2$, $(g_\rho/m_\rho)^2 = 6.4792 fm^2$, $b = 0.00895$, $c = 0.003689$.

The couplings $g_{\sigma H}$, $g_{\omega H}$ and $g_{\rho H}$ 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 [14], 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. This comparison is made again in Fig. 2 for the energy per baryon as a function of the baryon density. In all cases, the compression modulus of the corresponding symmetric nuclear matter is $K = 240$ MeV. Note that neutron star matter is not bound. The softening effect of the pions can be seen in these figures 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.

The same comparisons as above are made in Fig. 3 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 or about 25 percent. We show below that this is even more significant than first appears. Pions effect the intermediate mass stars, because the pion threshold is at lower density, and they are quenched by hyperons at higher density [2,3]. For the latter reason, they have little effect on the limiting mass, though they effect the mass of intermediate stars, and by inference will play a role in stellar collapse.

The evidence on the compression modulus from nuclear structure [19,20] suggests that the above chosen value is optimum. Elsewhere, we have shown that neutron star masses place a lower limit of $K \approx 200$ MeV [18]. Keeping the other nuclear matter properties fixed, the corresponding coupling constants are $(g_\sigma/m_\sigma)^2 = 10.2811 fm^2$, $(g_\omega/m_\omega)^2 = 4.5316 fm^2$, $(g_\rho/m_\rho)^2 = 6.4792 fm^2$, $b = 0.013265$, $c = -0.010695$. Fig. 4 shows that the role of hyperons in this case is even stronger, reducing the limiting mass by 3/4 of a solar mass.

The scale on which the effects of hyperons should be judged is now discussed. We know from Oppenheimer's classic work that the limiting mass of a neutron star corresponding to an ideal gas equation of state is 0.7 solar masses. As a lower theoretical bound this is unrealistic however, since the short range repulsion of the nuclear force will increase it. In fact the results for a large number of calculations fall in a range between about 1.5 and 2.5 solar masses corresponding to various assumptions about the nuclear forces and constituents of matter [22,23]. So the relevant scale is one solar mass. We here find that hyperons can reduce the limiting mass by 1/2 to 3/4 of a solar mass, depending on whether the nuclear compression modulus is assumed to be 240 or 200 MeV respectively.

The effect of hyperons on the limiting neutron star mass found in this work is much larger than was found in the early work, and is typical of or larger than the effect of widely varying assumptions concerning the nuclear force. For example, Pandharipande finds a reduction due to hyperons of only a quarter of a solar mass [23]. From an examination of the baryon thresholds in his calculation, we believe that the main source of the disagreement between our result and his is the absence of a control in his work, on the symmetry energy, which we believe is too small.

Bethe and Johnson [4] did not calculate star structures. This was done in another work [23] which compared models I and V. However the principle difference between these two cases are the nuclear forces, as is clear from an examination of table 7 in ref. [4]. The limiting masses are 1.85 and 1.65 solar masses respectively [23]. It is not possible to isolate the effect of hyperons on star structure from published work on Bethe and Johnson's calculation of the equation of state.

4 Summary

We have calculated the equation of state of neutron stars in a relativistically covariant field theory of interacting hadrons. The coupling constants of the theory are determined by the bulk properties of nuclear matter, including very importantly the compression modulus and the symmetry energy. In particular we studied the role of hyperons and pions. 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. This has an implication for theories of star structure that neglect hyperons. Since neutron stars of mass as large as 1.4 solar masses are known [24], the limiting mass of a theory of matter must exceed this, and by a large margin if the hyperon presence is not accounted for.

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" [12] for obtaining a strong enough bounce during the collapse of a massive star to sustain the prompt ejection of mass into a supernova event.

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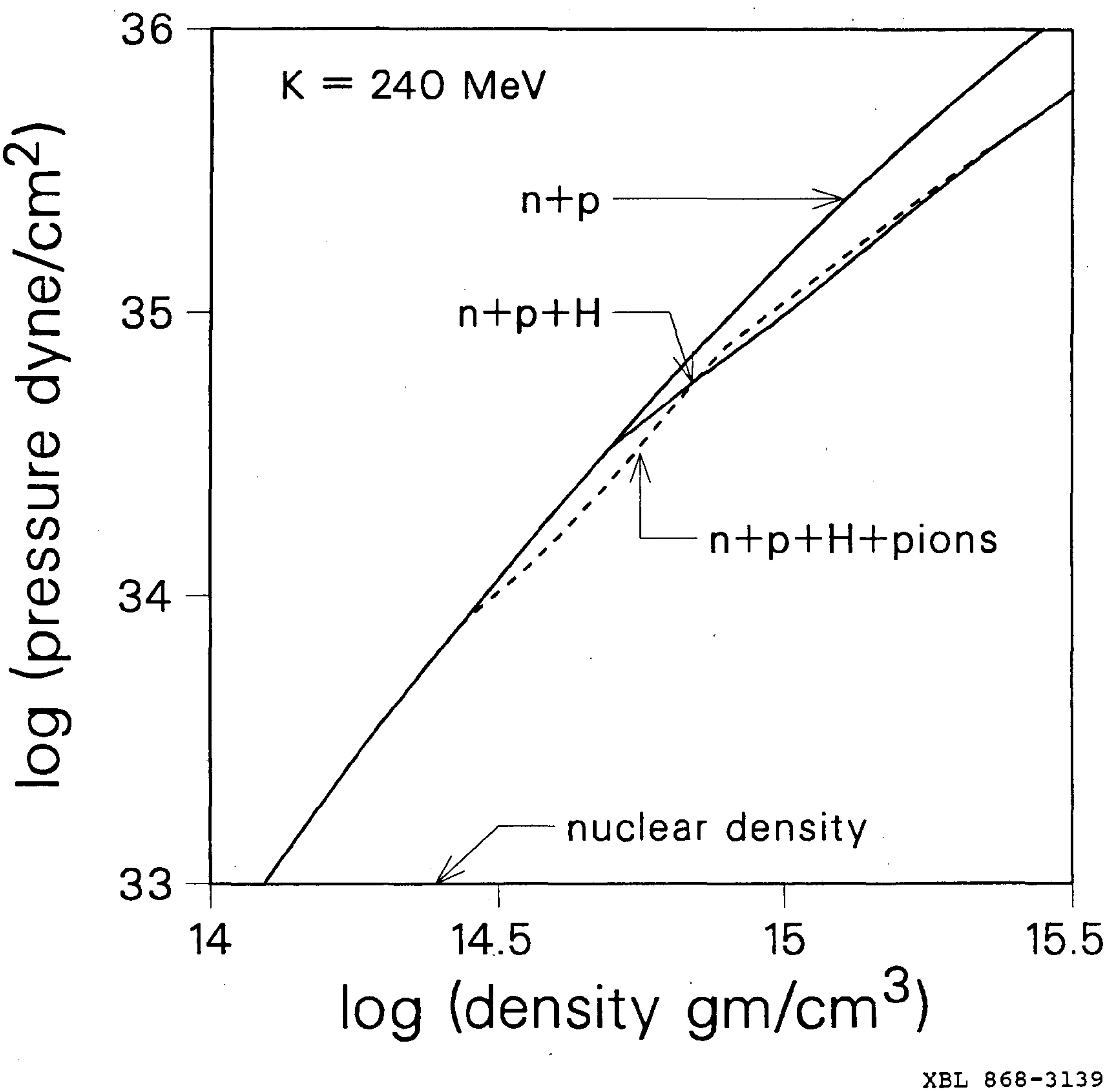

Fig. 1 Equation of state, pressure as a function of energy density, ϵ, for three cases, 1) neutron and proton, 2) hyperons in addition, 3) pions in addition. In all cases leptons are present to complete the beta equilibrium. The compression modulus of the corresponding symmetric nuclear matter is $K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

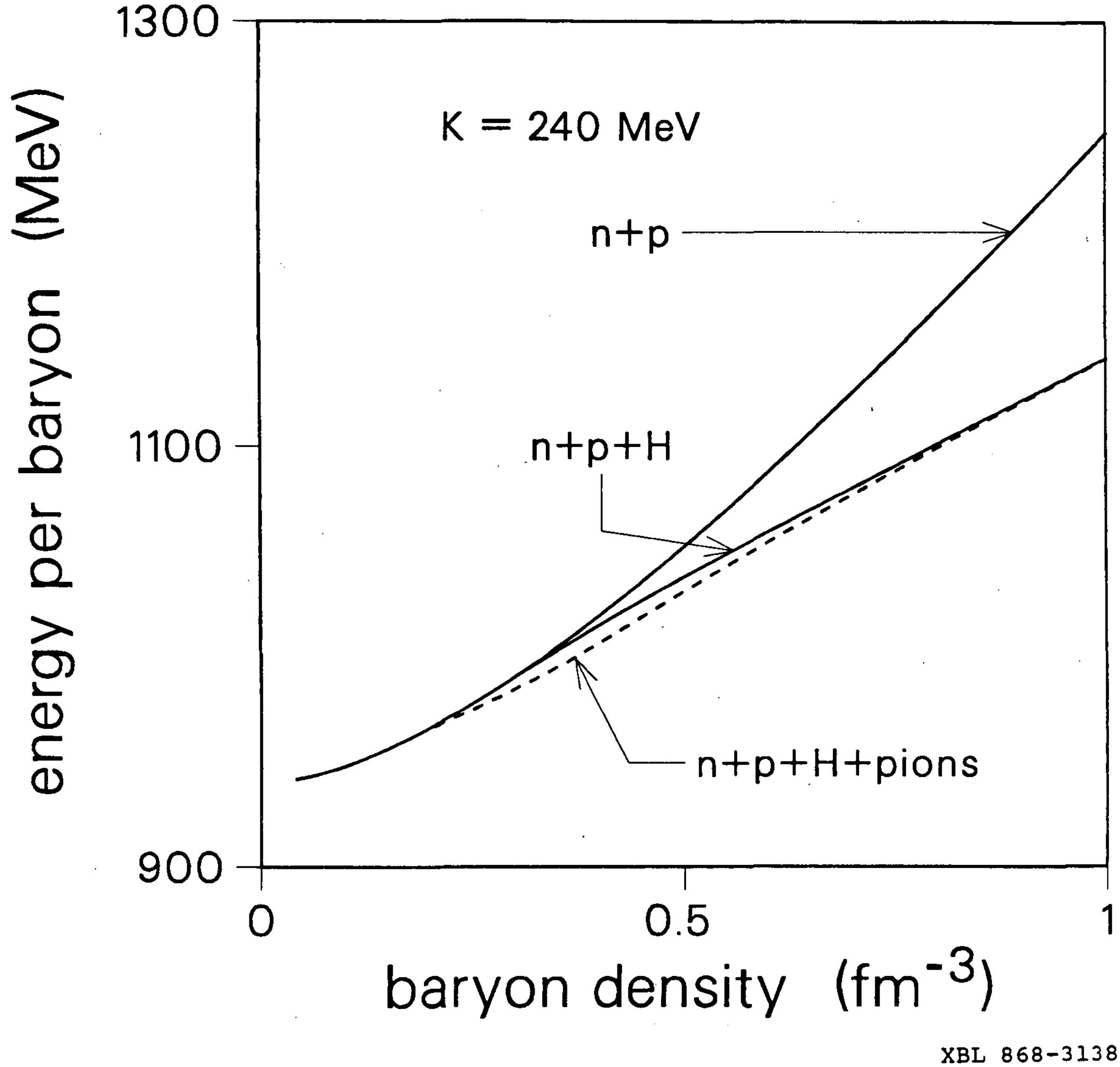

Fig. 2 Equation of state, energy per baryon as a function of baryon number density for the three cases, 1) neutron and proton, 2) hyperons in addition, 3) pions in addition. In all cases leptons are present to complete beta equilibrium. The compression modulus of the corresponding nuclear matter is $K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

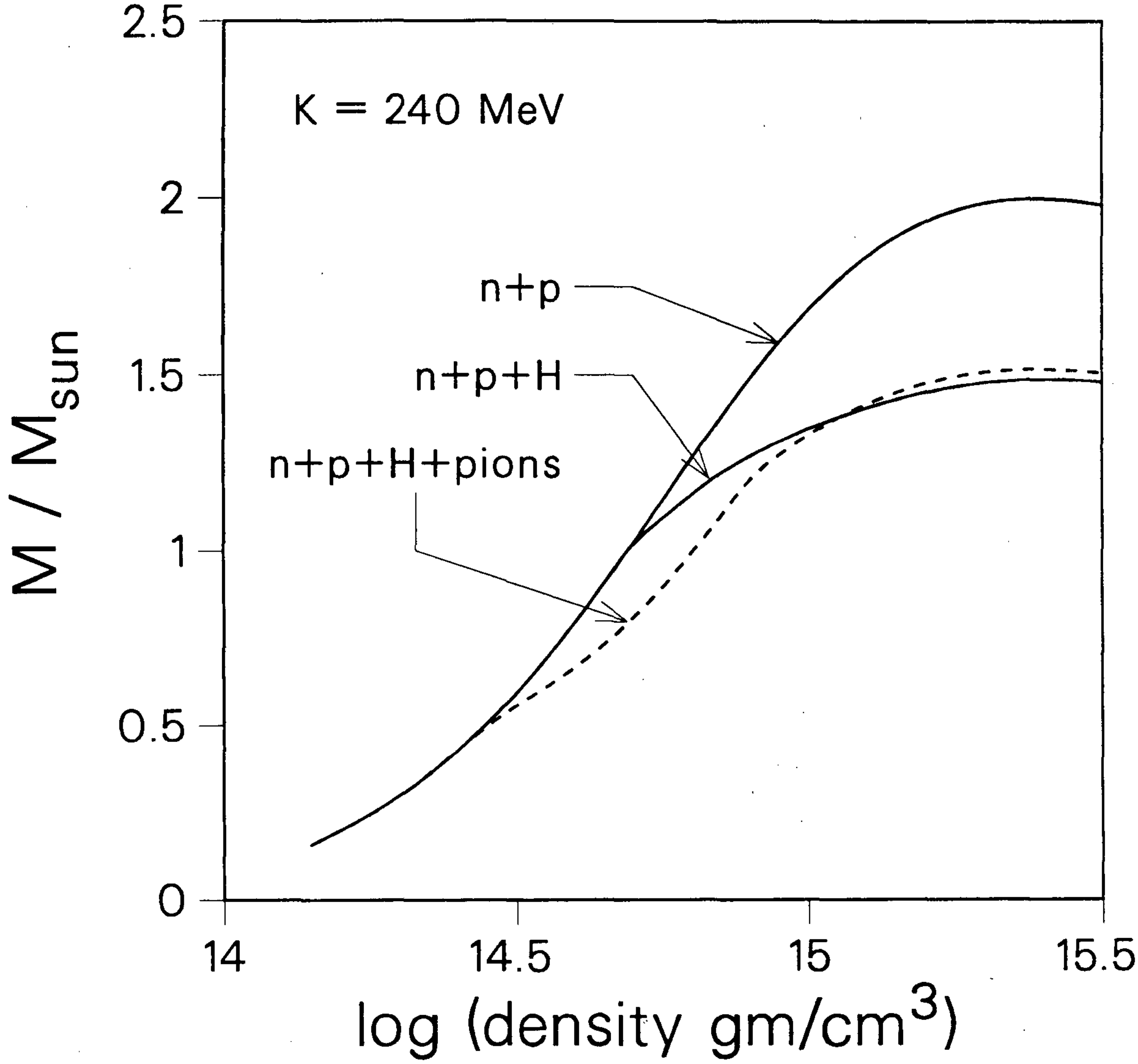

Fig. 3 Neutron star masses as a function of central energy density for the three cases, 1) neutron and proton, 2) hyperons in addition, 3) pions in addition. In all cases leptons are present to complete beta equilibrium. The compression modulus of the corresponding nuclear matter is $K = 240$ MeV.

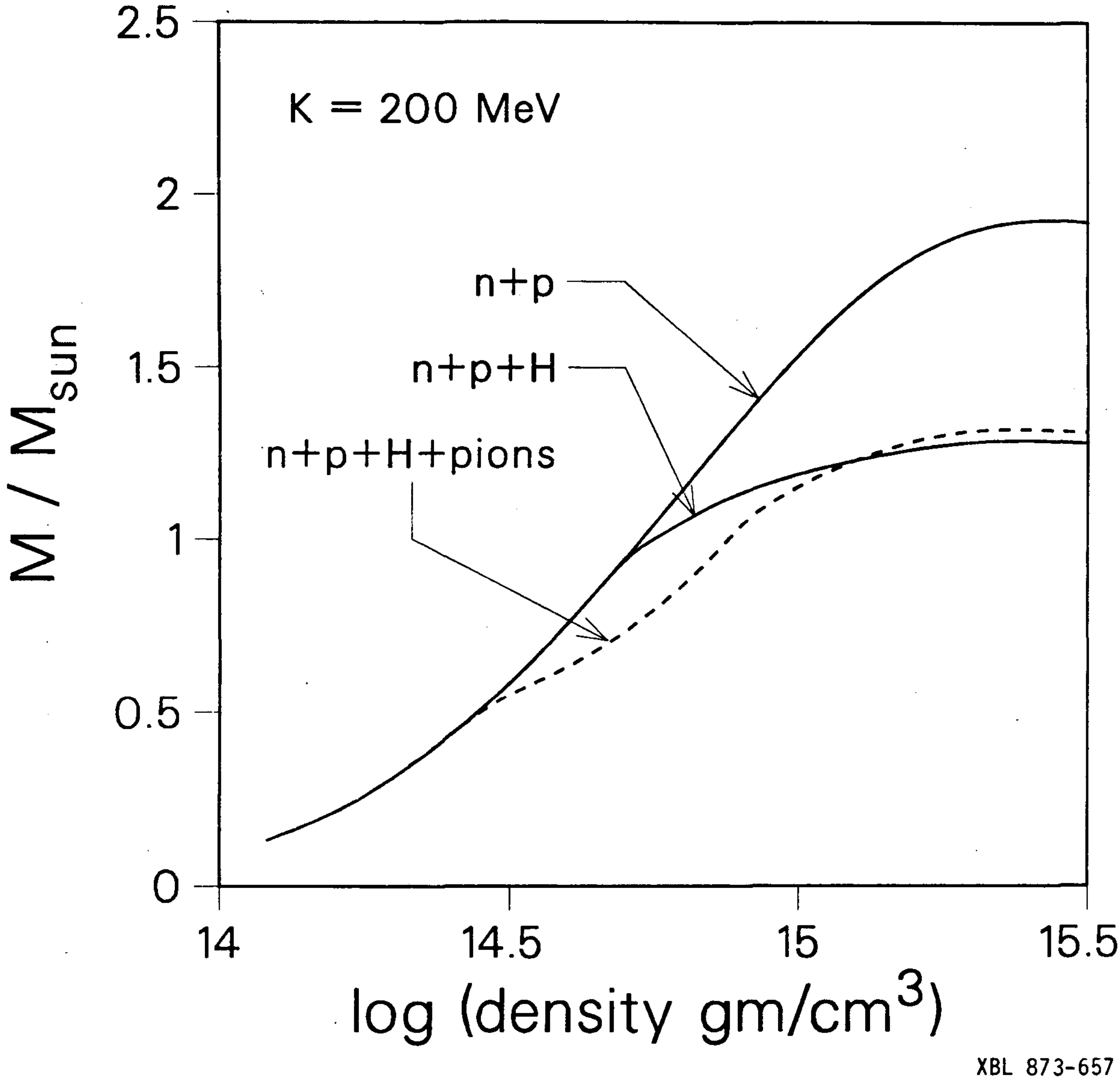

Fig. 4 Neutron star masses as a function of central energy density for the three cases, 1) neutron and proton, 2) hyperons in addition, 3) pions in addition. In all cases leptons are present to complete beta equilibrium. The compression modulus of the corresponding nuclear matter is $K = 200$ MeV.

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