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The implications of the two solar mass neutron star for the strong interactions *

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Abstract. The existence of a star with such a large mass means that the equation of state is stiff enough to provide a high enough pressure up to a fairly large density , about four times the nuclear density.

1 Introduction

Equations of state (EOS) that involve nonrelativistic constituents counteract gravitational infall of matter through a fermi pressure that is proportional to the density to the (5/3) power, unlike fermi pressures of relativistic constituents that go as density to the (4/3) power. Clearly the nonrelativistic nucleons are favoured over quarks for stiffer EOS's that can lead to larger mass for the stars.

However, a pure nonrelativistic fermi gas of neutrons is not sufficient to give large masses for neutron stars. Such a non interacting gas can give stars of maximum mass 0.7 solar mass - this a general relativistic effect coming from the Oppenheimer – Volkoff equation where the pressure needs to be proportional to density to a power greater than (5/3) . On the other hand, for white dwarfs fermi pressure of a nonrelativistic electron gas is all that is needed to counteract gravity and have stable stars. This enhanced pressure is provided by nuclear interactions like the hard core.

It is known that stars with soft, relativistic quark matter cores surrounded by a nonrelativistic n+p+e plasma in beta equilibrium can give maximum mass for neutron stars ~ 1.6 solar mass [1,2].

It is also known that there are many nucleon based neutron stars models that have neutron stars with maximum mass above 2 solar masses, eg. the APR 98 EOS of Akmal, Pandharipande and Ravenhall [3].

If we can show that matter in neutron stars is entirely composed of nucleon degrees of freedom then we can have a simple resolution of this problem. *Can we?*

* Talk delivered by V. Soni

2 The Maxwell construction between nuclear matter and quark matter

A simple way to look at whether nucleons can dissolve into quark matter is to plot E_B, the energy per baryon in the ground state of both phases versus $1/n_B$, where n_B is the baryon density. The slope of the common tangent between the two phases then gives the pressure and the intercept the common baryon chemical potential. For the quark matter equation of state see Fig.1.

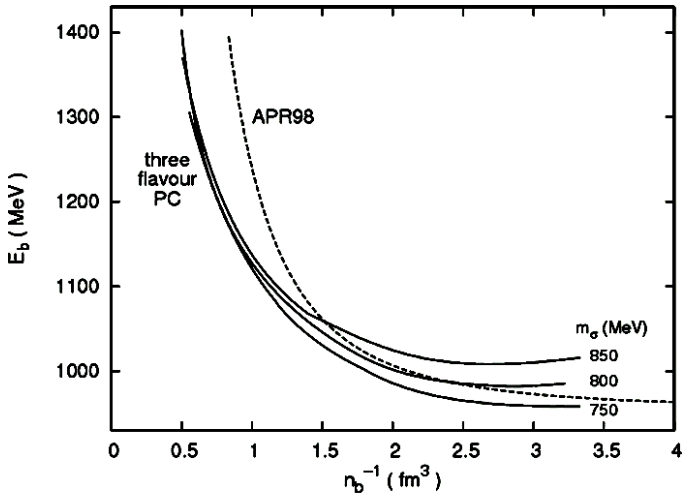

Fig. 1. The Maxwell construction: Energy per baryon plotted against the reciprocal of the baryon number density for APR98 equation of state (dashed line) and the 3-flavour pion-condensed phase (PC) for three different values of m_σ (solid lines). A common tangent between the PC phase and the APR98 phase in this diagram gives the phase transition between them. The slope of a tangent gives the negative of the pressure at that point, and its intercept gives the chemical potential. As this figure indicates, the transition pressure moves up with increasing m_σ, and at m_σ below ~750 MeV a common tangent between these two phases cannot be obtained. (From Fig. 2 of Soni and Bhattacharya [2] or Fig. 3 of the preprint [4])

This is based on an effective chiral symmetric theory that is QCD coupled to a chiral sigma model. The theory thus preserves the symmetries of QCD. In this effective theory chiral symmetry is spontaneously broken and the degrees of freedom are constituent quarks which couple to colour singlet, sigma and pion fields as well as gluons. The nucleon in such a theory is a colour singlet quark soliton with three valence quark bound states [5]. The quark meson couplings are set by matching mass of the nucleon to its experimental value and the meson self coupling which sets the tree level sigma particle mass is set from pi-pi scattering to be of order 800 MeV. Such an effective theory has a range of validity up to centre of mass energies (or quark chemical potentials) of ~ 800 MeV. For details we refer the reader to ref. [2].

This is the simplest effective chiral symmetric theory for the strong interactions at intermediate scale and we use this consistently to describe, both, the composite nucleon of quark boundstates and quark matter. We expect it to be valid till the intermediate scales quoted above. Of course inclusion of the higher mesonic degrees of freedom like the rho and A1 would make for a more complete description. We work at the mean field level the gluon interactions are subsumed in the colour singlet sigma and pion fields they generate. We could further add perturbative gluon mediated corrections but they do not make an appreciable difference.

As can be seen from Fig.1, it is the tree level value of the sigma mass that determines the intersection of the two phases; the higher the mass the higher the density at which the transition to quark matter will take place. In [2] it was found that above, $m_\sigma \sim 850$ MeV, stars with quark matter cores become unstable as their mass goes up beyond the allowed maximum mass. So, if we want purely nuclear stars we should, in this model, work at, $m_\sigma \geq 850$ MeV [2].

From Fig. 1, for the tree level value of the sigma mass ~850 MeV, the common tangent in the two phases starts at $1/n_B \sim 1.75$ fm^3 ($n_B \sim 0,57/\text{fm}^3$) in the nuclear phase of APR [A18 + dv +UIX] and ends up at $1/n_B \sim 1.25$ fm^3 ($n_B \sim 0.8/$ fm^3) in the quark matter phase.

At the above densities between the two phases there is a mixed phase at the pressure given by the slope of the common tangent and the at a baryon chemical potential given by the intercept of the common tangent on the vertical axis. If we are to stay in the nuclear phase the best way is to look at the central density of the nuclear (APR) stars and if it so happens that they are at lower density than that at which the above phase transition begins the we can safely say that the star remains in the nuclear phase.

Going Back to the APR phase in in fig 11 of APR [3] we find that for the APR [A18 + dv +UIX] the central density of a star of 1.8 solar mass is $n_B \sim 0.62$ /fm^3, very close to the initial density at which the phase transition begins.

The reason we are taking a static star mass of 1.8 solar mass from APR [3] is that for PSR-1614, the star is rotating fast at a period of 3 millisec and we expect a ~ 15% diminution of the central density from the rotation [6]. Equivalently, since the above paper reports results for static stars, the central density of a fast rotating 1.97 solar mass star ~ the central density of a static 1.8 solar mass star.

Now we have found that in above scenario the central density is of the same order as the density at which the above phase transition begins in the nuclear phase. Ideally we would like the central density to be a little less than the initial density at which the above phase transition begins in the nuclear phase.

3 Beyond the Maxwell tangent construction for the phase transition

How do we change the crossover and Maxwell tangent construction for the phase transition? There are 2 ways of moving the crossover between the 2 phases and also the initial density at which the above phase transition begins in the nuclear phase to higher density.

(i) By increasing the tree level mass of the sigma we can move the quark matter curve up (Fig. 1), thus moving the initial density at which the above phase transition begins in the nuclear phase to higher density. However we have to be careful. There is not much freedom here, as this is what also determines the $\pi - \pi$ scattering.

(ii) By softening the nuclear EOS at high density, e.g. by including hyperons or pi condensates. But this will increase the central density of the star and also reduce its maximum mass.

Of these the option (i) is a safer option as it does not disturb the central density or maximum mass of the nuclear star. However, the Maxwell construction is not the final word on the phase transition. The exact nature of the transition is not just given by the energy /baryon in the quark matter phase (which depends mainly on m_σ) but will depend on the quark binding inside the nucleon (which depends mainly o the quark meson coupling) and the nucleon nucleon repulsion as we squeeze them. This is not captured by the Maxwell construction.

The nucleon binding in this model is very high (Fig. 2) [5]

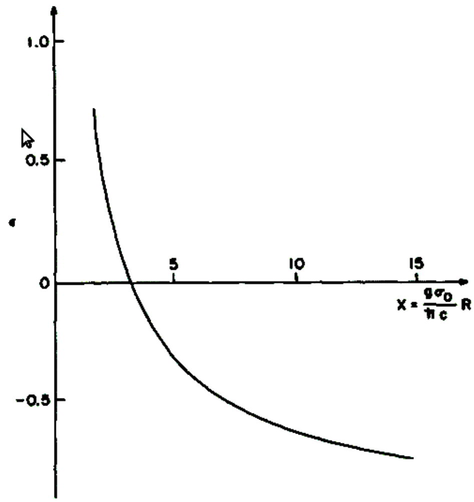

Fig. 2. Dependence of the quark energy on the soliton size X in the quark soliton model (From Fig. 2 of Kahana, Ripka and Soni [5])

The quark eigenfunctions are smaller than the radius of the nucleon; they spread over about 0.5 fermi. This yields a quark wave function size of ~1 fermi or kinetic energy of about 200 MeV. The unbound mass of the quark is given by gf_π ~ 500 MeV and effectively they must contribute 313 MeV to the mass of the nucleon , giving the quark binding energy of ~ 400 MeV.

We can see that the quarks will become unbound (go to the continuum) when the energy eigenvalue is larger than the unbound mass of the quark which is given by $m_{free} = gf_{\pi} \sim 500$ MeV. This happens when in the dimensionless units used in Fig. 2 $\epsilon \geq 1$ at X= 3.12/1.94 = 1.6. This translates into R =(1.6/2.5) fm^{-1} ~ 0.6 fm^{-1} .This is the effective radius of the squeezed nucleon at which the bound state quarks are liberated to the continuum. By inverting the volume occupied by the nucleon and assuming hexagonal close packing, this translates to nucleon density of $1/(6R^3) \sim 0.77$ fm^{-3}.

Thus the quark bound states in nucleon persist untill a much higher density ~ 0.8/fm^3. In other words, nucleons can survive well above the density at which the Maxwell phase transition begins and appreciably above the central density of the APR 2-solar-mass star.

Another feature is the the nucleon nucleon potential. It has been found for skyrmions and such quark-quark solitons with skyrmion configurations that there is a strong N-N repulsion that forces the lowest baryon number $N_B = 2$ configuration to become toroidal [7]. This is an indication that nucleon nucleon potential becomes strongly repulsive.

It thus follows that the phase transition from nuclear to quark matter will encounter a potential barrier before the quarks can go free. This effect cannot be seen by the coarse Maxwell construction which does not track their transition. This will modify the simple minded Maxwell construction which assumes only the energy and pressure that exist independently in the 2 phases. Here is where the internal structure of the nucleon will delay the transition.

All in all this produces a very plausible scenario of how the ~2 solar mass star can be achieved in a purely nuclear phase.

4 Consequences and discussion

A simple consequence of this unexpected scenario at high density is that the the phase diagram of QCD which plots temperature versus baryon chemical potential, the quark matter transition for finite density (in the range above) will be lifted up along the temperature axis.

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