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**Physics of Dense Matter, Neutron Stars,
and Supernova**

N.K. Glendenning

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Norman K. Glendenning

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Physics of Dense Matter, Neutron Stars and Supernova

Norman K. Glendenning

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

Nuclear and astrophysical evidence on the equation of state of dense matter is axamined. The role of hyperonization of matter in the development of proto-neutron stars is briefly discussed.

NUCLEAR EVIDENCE. It has been claimed that supernovae, by their occurance tell us that the nuclear equation of state must be soft [1,2]. In Fig. 1 we review a large body of data from nuclear evidence and neutron stars, which disagrees with this [3]. We examine below the particular path that led to the claim, show how the same equation of state employed in the supernova simulations is incompatible with neutron star masses, and conclude that there is an opportunity for discovering new physics possibly in the presupernova simulations or in the late stages of the collapse that will reconcile supernova with the existing knowledge of the equation of state

PROMPT SUPERNOVA EXPLOSIONS. Type II supernovae are those whose progenitor masses are greater than about 10 $M_\odot$. After evolving for about 10^7 years during which a core of neutron rich iron of mass of the order of the Chandrasekhar mass is built, stability against gravitational collapse is lost. The mass of the iron core is is crucial to the success or failure of the prompt bounce scenario. As the star collapses the core attains supernuclear densities, and a shock wave is formed which moves outward through the core toward the infalling mantle. For each 1/10 $M_\odot$ of iron core that the shock wave traverses, it dissipates about 2×10^{51} ergs due to the dissociation of the iron nuclei in its path. This is comparable to the entire energy output of a supernova. It is generally accepted that the shock cannot promptly eject matter if the iron core is more massive than about 1.35 $M_\odot$. Otherwise it stalls at about 100 km and becomes an accretion shock. So there is a very narrow window of iron cores in which the prompt scenario has a chance of working. Within this narrow window the Brookhaven-Stony Brook group found that *if* they chose a sufficiently soft equation of state, they could simulate a prompt bounce scenario for a supernova explosion, with a resultant neutron star residue[1,2]. If this were the whole story, then a tentative conclusion could be reached that the equation of state must be sufficiently soft at high density

because of the occurrence of type II supernovae. This is indeed the conclusion that the authors drew, and which has been much advertised.

However there are many uncertainties in the physics of the simulation besides the equation of state. One of these has been mentioned, the iron core mass. Another is the specific entropy of the core just prior to collapse following an evolution of $\sim 10^7$ years! Both can easily change the amount of iron that the shock must dissociate before reaching the mantle by the crucial 1/10 $M_\odot$, less than a ten percent effect. Can such an evolution be modeled with such certainty?

Nevertheless taking all such effects in their favor, the soft equation of state is still found necessary to achieve the prompt ejection *with* the desired explosion energy[2] for SN1987A, the supernova event of early 1987. Using precisely their equation of state described in ref.[1], and the neutron fraction ($x \equiv Z/A = 1/3$) employed by those authors we have solved the Oppenheimer-Volkoff equations of star structure. The maximum mass for their equation of state is too small compared to the masses of two known neutron stars as shown in Fig. 2. One is the very accurately measured mass of PSR1913+16, and the other is the less well known mass of 4U0900-40.
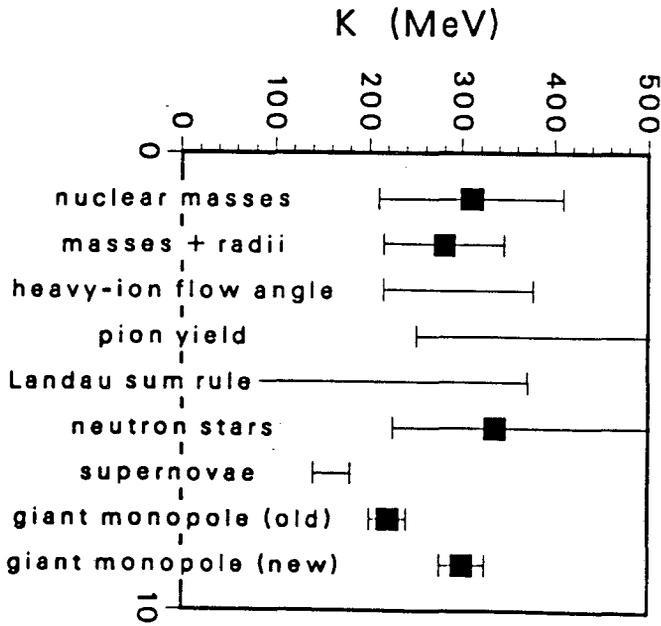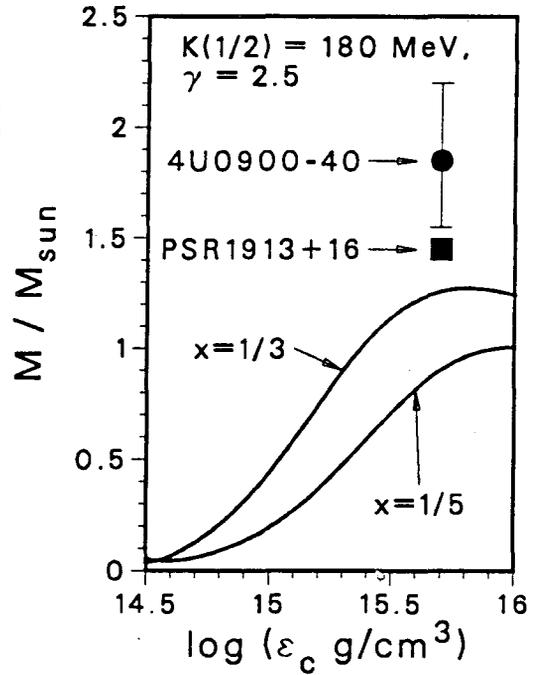

Fig. 1.

Fig. 2

One may be tempted to argue that the supernova matter is less dense than that of a neutron star, and that it is less neutron rich. However there are numerous physical effects at higher density that soften the equation of state. Neutronization is but one of them. If it were not energetically favorable it wouldn't happen, so it

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does soften the equation of state and its effect (the curve labeled $x = 1/5$) for the BCK equation of state is also shown.

Therefore it is unproven that the prompt-bounce mechanism can be made to work in supernova simulations, *given the present estimates of the iron core masses*, with equations of state that are soft enough to release enough energy for prompt ejection of the mantle, and stiff enough to be compatible with certain measured neutron star masses and with the preponderance of evidence from nuclear physics[3] shown in Fig. 1. Consequently it is premature to conclude as has been done, that supernovae, by their occurrence, imply a soft equation of state. This is all the more reinforced by the observation that there exists an alternative mechanism that does not impose this restriction on the equation of state, discovered by Wilson[4].

NEUTRON STARS. We have seen that with the present knowledge of supernova physics, the prompt bounce mechanism requires an equation of state that is too soft to support measured neutron star masses. How stiff do neutron stars require it to be? First we must realize that neutron stars are not pure in neutron. As the density of neutron matter is increased, the Fermi energy soon surpasses the threshold for decay first to proton and lepton and then to hyperons[5]. We have emphasized[6] how this hyperonization can soften the equation of state at the *higher* densities at which it occurs ($\approx 2\rho_0$) and *reduce the limiting neutron star mass* by as much as $3/4 M_\odot$ for soft equations of state . The net effect therefore is that the equation of state must be rather stiff near saturation, so that with this softening at higher density, observed neutron star masses can be accounted for.

We analyse neutron stars in the framework of relativistic nuclear field theory, taking into account all higher baryon states to convergence. The full Lagrangian including leptons is given in ref. [5] together with the equation of state. When the field equations are solved subject to the subsidiary condition of isospin symmetry, the solution corresponds to symmetric nuclear matter. When this same theory is solved with subsidiary conditions of charge neutrality and beta equilibrium, we get the solution for neutron star matter. These solutions, by convention, will be denoted always by the properties of the corresponding solutions of symmetric matter. We vary the stiffness of the equation of state of neutron star matter at high density. This is accomplished through a variation of the coupling constants of the theory which leaves the bulk properties of cold symmetric matter fixed at saturation, with the exception of K. In this way we are able to place a lower bound on K.

The largest measured mass is is $1.85^{+0.35}_{-0.30} M_\odot$ for 4U0900-40. The most probable value of the mass of the above star is found to place a lower bound of $K \geq 335 MeV$. If the lower bound on the mass measurement of 4U0900-40 is used, then the lower bound on K becomes about 225 MeV.
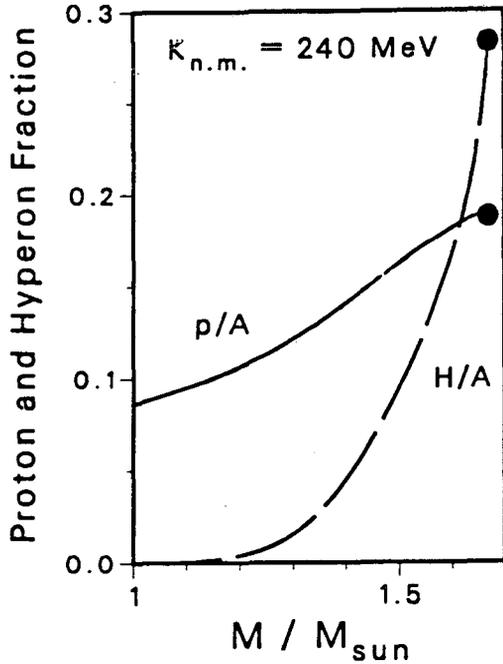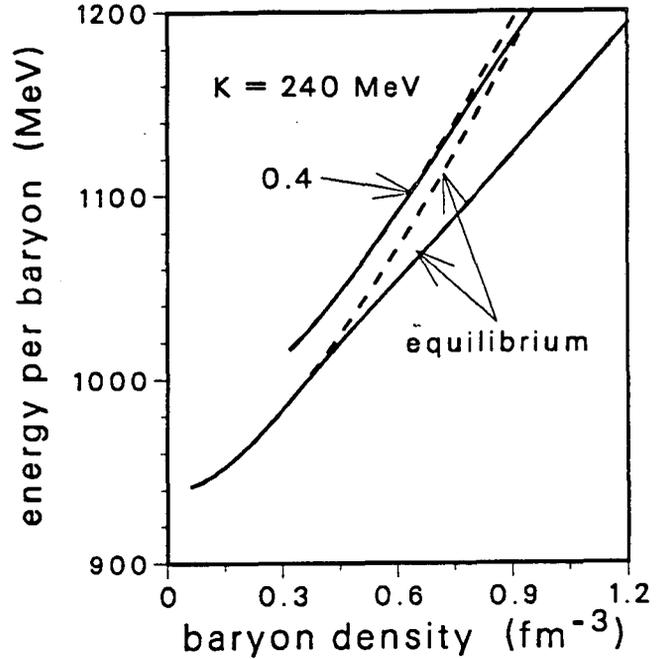
Fig. 3. Fig. 4

Fig. 3.

Fig. 4

HYPERONIZATION AND LATE STAGE COLLAPSE. We have seen that taking into account the hyperonization of the neutron star core the equation of state is softened at high density, and that this softening is exploited by gravity very effectively as registered in the reduction of neutron star masses in comparison with calculations where hyperonization is neglected. *The time scale of star collapse (∼ 100 milliseconds), is long compared to the weak interaction lifetime, so that the hyperonization of supernovae matter can occur during the collapse.* Whether it does so before the ejection of the mantel or afterwards will depend on the time scale on which the trapped neutrinos leak out of the core. The energetically favored transformation of nucleons to hyperons in matter near its ground state is not through the strong interaction, which involves the associated production of kaons, but through the week interactions, such as $n + e^- \rightarrow \Sigma^- + \nu$. In any case hyperonization is accompanied by the production of neutrinos, and will be inhibited as long as the neutrinos are blocked. In Fig.3 we show the fraction of baryons that are protons and that are hyperonized. It is evident that as a very sharp function of star mass, deleptonization is more complete for the stars near the mass limit, and that correspondingly a greater number of neutrinos are produced. However since the hyperonization is partially blocked by neutrino trapping, it occurs on the neutrino transport time scale. We show a sequence of equations of state in Fig.4 for which the lepton fraction is held fixed. (We do not include the neutrino energy.) The early proto-neutron star will be built from an equation of

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state of $Y = 0.4$ say. Only as the neutrinos diffuse out of the star will it relax into its ground state, the equation of state for which is labeled as equilibrium. The solid curves refer to models in which hyperonization is included, and the dashed to models in which it is neglected. It is apparent that a massive proto-neutron star above the mass limit of the equilibrium equation of state , could be stabilized during the neutrino trappig era, only to subside into a black hole as the neutrinos leak out. Signatures of such a fate, and its effect if any on the outcome of say the late-time supernova mechanism, and on the supernova remnant would be an interesting subject of investigation [7].

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LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720