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Subatomic particle processes within neutron stars: from ordinary to exotic

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Abstract.

We generally agree nowadays that the extreme densities reached in the centers of neutron stars provide a high-pressure environment in which numerous new particle processes are likely to compete with each other. These processes range from the almost traditional (but certainly far from old-fashioned) generation of hyperons or formation of kaon condensates and H-matter to the newly non-conformist idea of the formation of a so-called absolutely stable strange quark matter, a configuration of matter more stable than the most stable atomic nucleus even. *[1], [7]* Whether the new ideas are purely speculative or not, we cannot pronounce ourselves with a scientific weight; what is sure is that empirical data acknowledges for “strange” possibilities within neutron stars. Starting from the assumption that we do not reject propositions unless we are offered irrefutable counter-proofs, we find of high interest the new dimensions that the analysis of the neutron stars as stable strange quark matter opens and consider this opportunity in order to expose and qualitatively examine such a proposition. The present paper aims at presenting concise and up to date qualitative information concerning super dense “exotic” neutron star matter by referring to and commenting upon some of the existing accredited works in this domain.

1. Introduction – discovery of neutron stars, characteristics, pulsars

Only two years after the discovery of the neutron by James Chadwick in 1932, Walter Baade and Fritz Zwicky, the same two astronomers that first coined the term ‘supernova’, already proposed the existence of the neutron stars. The supernovae were described immediately thereafter, in relation to the latest discovery of the neutron stars, as “ the transitions from ordinary stars into neutron stars, which in their final stages consist of extremely closely packed neutrons” *[2]* Theoretically, however, neutron stars were predicted earlier by L.D. Landau who had shown independently of Chandrasskhar that the mass of a white dwarf could not be indefinitely large. Consequently Landau was the first scientist to raise the question of what will happen to a star that does not have an internal source of energy and whose mass exceeds the Chandrasekhar limit. The American physicists Oppenheimer and Volkoff carried out the first calculations of the structure of neutron stars in 1939, based on the pioneering work of Landau.*[4]*

We will briefly consider in the following lines some of the striking features of the neutron stars to later introduce the even more striking consequences of these properties. As mentioned above, in a very concise phrase, neutron stars are the extremely dense neutron-packed remnants of massive stars that blew apart in supernova explosions. Together with the white dwarfs and the blackholes, the neutron stars are stellar corps representing the latest phases in the stellar evolution. In a rough characterization, and as most important property for further notice, the masses of these three distinct categories of stellar corps are different; hence, if a white dwarf will have a mass of maximum 1.4 $M_{\odot}$ (the Chandrasekkar limit), a neutron star will vary in mass between 1.4 and 2.4 $M_{\odot}$, while a blackhole will have a mass above 2.4, some astronomers stipulating a limit even higher than 3 $M_{\odot}$. For a typical 1.4 $M_{\odot}$ we would approximately have a number of 10^{57} neutrons and therefore we would in fact deal with a huge nucleus having a mass number of $A\sim10^{57}$ that is held together by gravity and supported by neutron degeneracy pressure. It is estimated that the radius of such a star would lie somewhere between the incredibly small margins of 10 and 15 km, whereas the average density would be $6.65 * 10^{14}$ gcm^{-3}, which is higher than the typical density of an atomic nucleus. In an attempt to trivially exemplify this tremendous density, subjected to its value all the 5.5 billion inhabitants of the Earth could be crowded into a cube of 1 cm side length. *[2]* The gravity compressing the matter in the inner core is fierce: the gravity acceleration for a neutron star with 10 km radius is 190 times bigger than g at Earth’s surface.

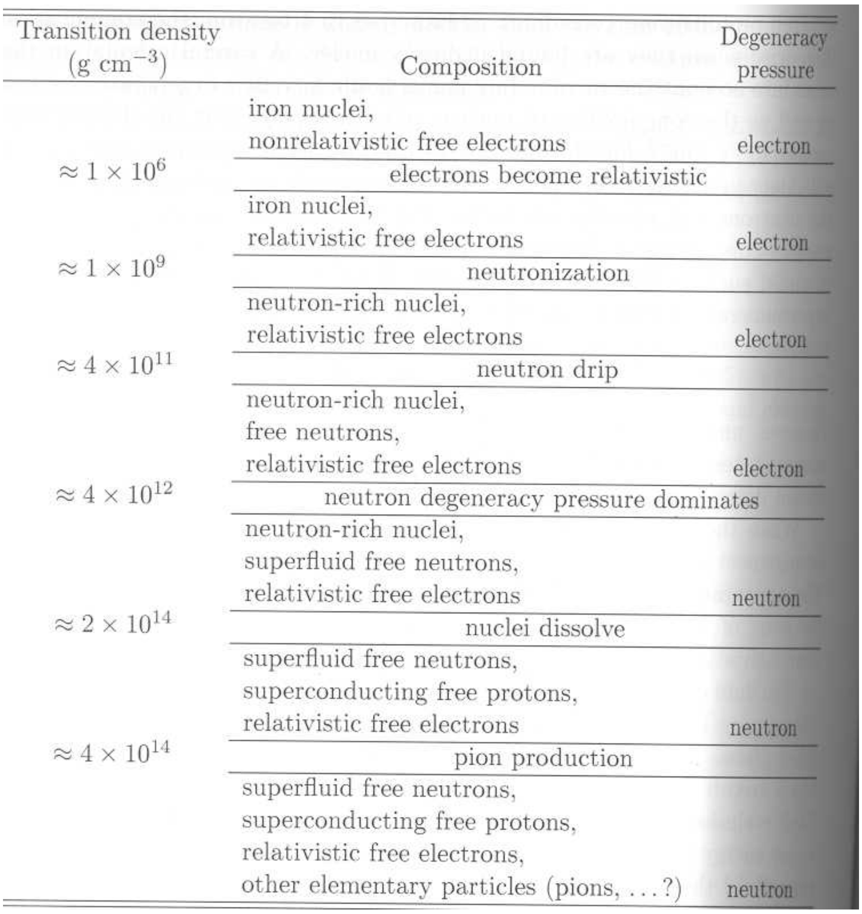
Apart from the properties described before and partially as a consequence of these basic properties, the neutron stars carry enormous magnetic fields and angular momenta. These fields exceed the Earth' s by a factor of around 10^{12}, and they rotate about once per second despite having masses exceeding that of the Sun. Such powerful electrodynamics produces beams of radio waves, which sweep across earth' s observatories once per pulsar rotation.*[6], [5]* This produces a fascinating periodic signal that can be observed and studied. Presently there are about 1400 pulsars known, but there is no reason to think that not all neutron stars are pulsars (most of them are being incapable of being spotted as pulsars). Without denying the merits and the fascination of the pulsars as stellar corps, we will not insist more on pulsars properties hereinafter but rather concentrate on the characteristics of the neutron stars as such.

Ineluctably within the high-pressure environment described above numerous subatomic particle processes will compete with each other. These processes range from ordinary ones (by ordinary we do not want to mitigate their scientific value) to very spectacular phenomena that stretch from the generation of new baryonic particles (Δ, Σ, Λ, Ξ) to quark (u, d, s) deconfinement and to the formation of Boson condensates (Π^-, K^-, H-matter). *[7]* We will deal with these latter processes as the subject of the present paper.

2. High density structure of neutron stars- traditional approach

A few years ago the investigation of the neutron stars and their properties was based entirely on the idea that astrophysical properties of neutron stars are mainly determined by the nature of their interaction with the surroundings. Even if this approach proved very efficient in predicting new types of neutron stars, it could help explaining the interior of neutron stars up to accurate details. In fact we cannot affirm that the interior of neutron stars is known to an acceptable extent even nowadays. Things are known up to a certain depth within the neutron star (where the densities are still “reasonable”), while theories about the inner core are more of the speculative domain. Nonetheless progress in the domain was enormous and future seems also promising in this field. Among the most valuable sources of information leading to results in the super dense structure of neutron stars, we have the calculations concerning the cooling of neutron stars. Thus, knowing the thermal evolution of a neutron star also yields information about such temperature-sensitive properties as transport coefficients, transition to superfluid states, but especially crust solidification and crust-superfluid interfaces, which is of interest for our purpose *[1]*

In order to appreciate the very exotic nature of the material comprising a neutron star we basically need to think of the equilibrium configuration of 10^{57} nucleons together with enough neutrons to provide zero net charge. Obviously this equilibrium arrangement is one involving the least energy. If we were to resume the composition in function of the transition density, we would obtain the following very concise table (Table 15.1, page 602 in *[2]*).



Transition density ($g\ cm^{-3}$)	Composition	Degeneracy pressure
	iron nuclei, nonrelativistic free electrons	electron
$\approx 1 \times 10^{6}$	electrons become relativistic	
	iron nuclei, relativistic free electrons	electron
$\approx 1 \times 10^{9}$	neutronization	
	neutron-rich nuclei, relativistic free electrons	electron
$\approx 4 \times 10^{11}$	neutron drip	
	neutron-rich nuclei, free neutrons, relativistic free electrons	electron
$\approx 4 \times 10^{12}$	neutron degeneracy pressure dominates	
	neutron-rich nuclei, superfluid free neutrons, relativistic free electrons	neutron
$\approx 2 \times 10^{14}$	nuclei dissolve	
	superfluid free neutrons, superconducting free protons, relativistic free electrons	neutron
$\approx 4 \times 10^{14}$	pion production	
	superfluid free neutrons, superconducting free protons, relativistic free electrons, other elementary particles (pions, …?)	neutron

We can notice that at relatively low densities (for our purpose this would mean densities inferior to 10^{6} g cm^{-3}) the nucleons are found in iron nuclei. This is nothing but the so-called “minimum energy compromise” between the repulsive Coulomb force between the protons and the attractive nuclear force between all of the nucleons *[2]*. Soon thereafter the electrons become relativistic and the minimum arrangement of protons and neutrons changes as now the electrons can convert protons in neutrons within the iron nuclei through

$p^+ + e^- \rightarrow n + \nu_e$ *[2]*

As the density raises above 10^9 g cm^{-3} "neutranization" takes place. The supernumerary neutrons generated would ordinarily revert to protons via the β- decay. Nonetheless, given the state of complete electron degeneracy, the neutrons cannot decay back into protons, as there are no vacant states available for an electron to occupy (Pauli exclusion principle).

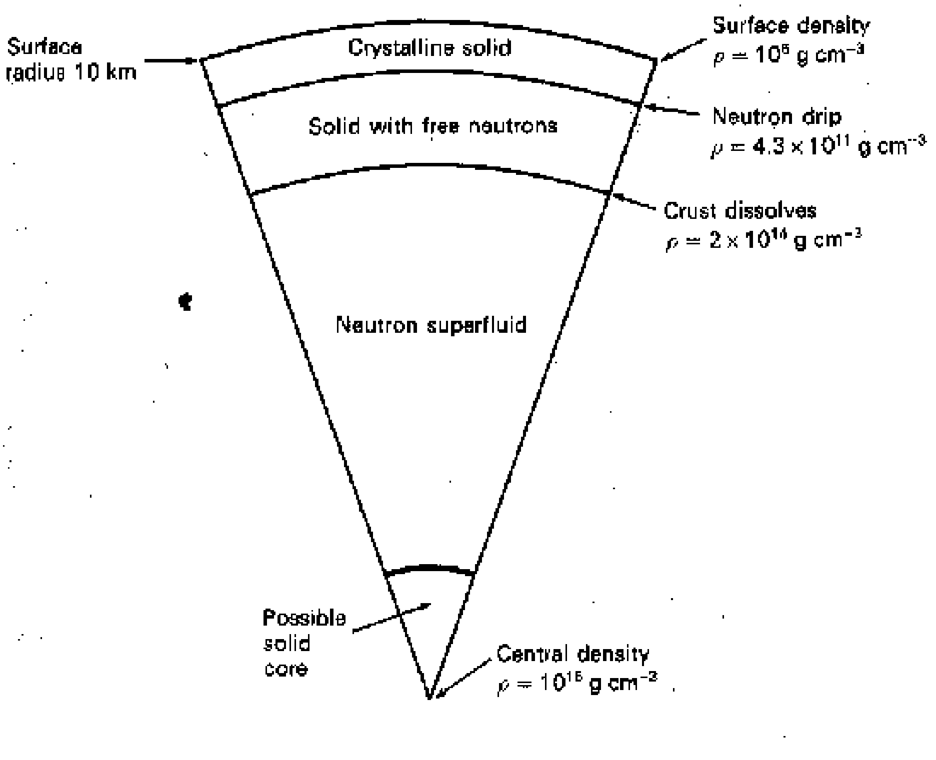
Extremely interesting, when the density reaches about 4* 10^{11} g cm^{-3}, the minimum level energy will be one with the neutrons found outside the nuclei. This phenomenon is called “neutron drip” and marks the appearance of the non-relativistic degenerate free neutrons and relativistic degenerate electrons. The consequence is that the obtained fluid of free neutrons has no viscosity as degenerate bosons (combination of two neutrons) can all crowd into the lowest energy state; hence, no loss of energy. We have a superfluid that flows without resistance.

We see that when the density reaches approximately 4* 10^{12} g cm^{-3} the neutron degeneracy pressure exceeds the electron degeneracy pressure. The nuclei will “dissolve”, as the distinction between the neutrons outside and inside the electrons will become meaningless. We obtain a superconducting fluid due to the pair of protons next to the superfluid neutrons.

So far the properties of the neutron star material are understood. But hereinafter the traditional approach does not have any answers. For higher densities, the pions are supposed to appear as result of the decay of a neutron into a proton:

$n \rightarrow p^+ + \Pi^-$ *[2]*

A relatively substantive representation of the structure of a neutron star is the following *[6]*

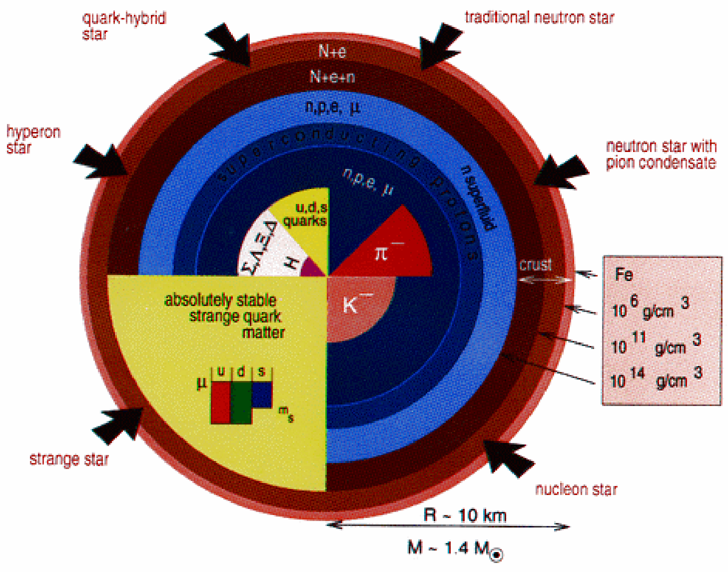


The outer crust is the crystalline crust, consisting of heavy nuclei. Nearest the surface the nuclei are probably ^{56}Fe. The inner crust consists of a superfluid of free neutrons and relativistic degenerate electrons. The interior of the neutron stars consists of superfluid neutrons with a smaller number of superfluid superconducting protons and relativistic degenerate electrons. There is supposed to be a solid core consisting of pions or other elementary particle. At this point the exotic part in the neutron stars begins.

3. **Exotic particles. Exotic processes within neutron stars. Strange matter.**

Many physicists adopted a relatively strong position in relation to the existence of the solid core. While the number of the skeptics seem to have declined, the proofs for the existence of this solid core are still lacking the clarity that could rend them effective. Nonetheless, having that lately we are able to observe the neutron stars with the "state-of-the-art" radio telescopes *[1]* Arecibo, Jodrell Bank, Parkes, VLA and so on or with the x-ray satellites Chandra, HST, RXTE, XMM *[5]*, for the first time we can attempt to seriously constrain the properties of dense matter from astrophysical observations.

The following figure represents an adequate summary of the possible (speculative) scenarios accounting for the structure and processes within the neutron star *[7]*.



We will further investigate these exotic scenarios from a didactical point of view, leaving to the researcher what belongs to the researcher.

Trying to debunk the widely held theory that the neutron star is constituted from neutrons, the most modern and progressive researcher will notice that a typical neutron star will contain neutrons and a small number of protons whose charge is balanced by leptons (e^-, μ^-). Theoretically there should not be any impediment for the neutrons to transform into Λ hyperons. Mathematically, the associated chemical potentials should be subjected to $\mu^n = \mu^{\Lambda.}$ At the existing densities the neutron Fermi momenta are considerable great so that the hyperons make their appearance. It is therefore expected that in addition to nucleons and electrons, neutron stars consist of a substantial (estimated at about 20%) population of hyperons, which are the first incursion of the strangeness within neutron stars.

Not only hyperons, but also kaons might appear, once the reaction of converting electrons to K^- mesons becomes possible:

$$e^- \rightarrow K^- + \nu \qquad [1]$$

Nevertheless we cannot be sure whether the chemical potentials obey the relation in this case ($\mu^e = \mu^K$) as that depends on the mass of the K^- in dense matter. Similar to the pion condensate, which does not belong here, the kaon condensate would also soften the equation of state and enhance the star neutrino luminosity.

Going further in describing strangeness, another boson that could appear in the center of the neutron is the so-called H-dibaryon. This is a strange six-quark composite with both spin and isospin zero and with baryon number 2. Because, as just said, the neutron stars might contain a substantial amount of Λ hyperons, these could combine with the H-dibaryon leading to the formation of the H-matter. Specialists affirm that H-matter could exist in the cores of moderately dense neutron stars. Nevertheless, going further with the speculations, H-matter could not remain dormant in the neutron stars but because of their instability against compression could trigger the conversion of neutron stars into the hypothetical strange stars. And “strangeness” in the context of processes within neutron stars really begins with quark deconfinement. *[1]*

The idea of “strangeness” of matter is older than someone might think. It has been suggested already back in 1970 by a number of researchers that neutrons, protons plus the heavier constitutes (Δ, Σ, Λ, Ξ) can melt, creating the quark-gluon plasma state. Evidence of the creation of such matter in the framework of CERN’s Lead Beam Program has been claimed very recently (actually this very year)[1]. Presently the density at which the expected phase transition to quark matter really occurs is not known. It is nevertheless expected that at densities similar to those in neutron stars the nuclear boundaries of hadrons would dissolve and the formerly confined quarks would populate free states outside the hadrons. This idea sounds unbelievable and very high-reaching but surprisingly enough observational astrophysicists may be able to spot evidence for this phase of matter *[1]*. We keep our reservation and consider that such hopes might be a bit too optimistic. Nonetheless we should acknowledge that the theories advanced are not that implausible.

Together with quark deconfinement, some other very interesting phenomena are sought to appear, amongst the most fascinating ones being the color superconductivity. It has been recently discovered that instantons may cause strong correlations between up and down quarks, which could further give way to the existence of colored diquark pairs in superdense matter. These pairs would form a Bose condensate in cold and dense quark matter. *[1], [3]* Carrying color charges the condensate should exhibit color superconductivity. It is not known yet the magnitude of the critical temperature associated with the color superconductive phase

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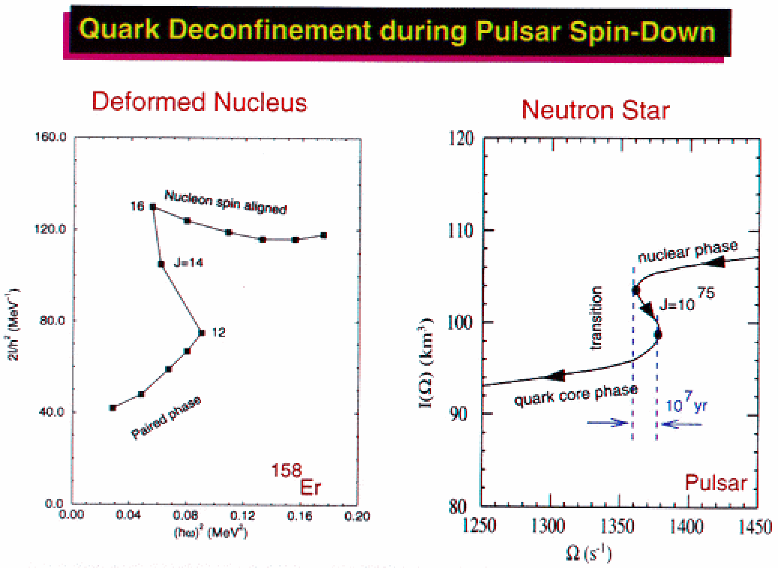
[1] See the communication of the CERN Press Office in the summer of 2000, Evidence for a New State of Matter: An Assessment of the Result from the CERN Lead Beam Programme

even if some researchers argue that it might be calculated (and that it is acknowledged) *[4], [1]*

If quark deconfinement is sought to be the harbinger of the strangeness, absolutely stable quark matter is definitely describing its core. It is known that for a few hundred u, d, s quarks the energy per baryon of quark matter can be just as well below the energy of the most stable atomic nucleus, ^{56}Fe , therefore the assumption made so far that quark matter forms a state of matter higher in energy than atomic nuclei is not necessarily so strong. Consequently the quark matter would be absolutely bound with respect to the iron nuclei. In this event the ground state of the strong interaction would be strange quark matter made up of u, d, s, quarks, instead of nuclear matter. Naturally, the absolute stability of this “ strange matter” gives way to a variety of new types of objects from “strangelets” *[1]* at small baryon number end, $A \sim 10^2$ to the compact stars where strange matter becomes unstable against gravitational collapse (with $A \sim 10^{57}$)

4. **Possible empirical support for the ‘strangeness’**

First of all we can discuss the spotted anomalies in the spin-down behavior of isolated neutron stars. What actually happens is that for rotating neutron stars (that is, pulsars) quark matter is detected. In the course of spin-down, because of the emission of magnetic dipole radiation and pairs electron-positron, the neutron stars become more and more compressed. For some of the pulsars the mass and the initial rotational frequency may be exactly so that the central density rises from below to above the critical density for dissolution of baryons into their quark constituents. This is accompanied by a de facto sudden shrinkage of the neutron star, affecting the star’s moment of inertia dramatically. The following figure exemplifies what has been stated above *[1], [7]*.



Backbending predicted in 1960 by Mottelson and Valatin (phase transition from spin aligned state at high Ω to pair-correlated superfluid at low Ω).

Backbending in pulsar may result if phase transition occurs.

Depending on the ratio at which quark and normal matter change with frequency, the moment of inertia can decrease in a completely arbitrary manner. The changes in the moment of inertia reflect themselves in the breaking index, n (which can be calculated from the associated equation, depending on the moment of inertia). The future astrophysical observation of such anomalies in the breaking behavior of pulsars may be interpreted as a clear signal for quark deconfinement in neutron stars (we might even go so far and name this branch as quark astronomy).

Another important empirical evidence resides in the anomaly in the frequency distribution of neutron stars in low-mass x-ray binaries. The x-ray neutron stars are being spun up by the accretion of matter from a lower mass, less dense companion within the binary. Angular momentum added to a neutron star in this way is consumed by inhibiting a further spin-up until the quark-matter has been converted into a mixed phase of matter made up of hadrons and quarks *[1]*. There will be an anomalous number of accreters that appear at or near this frequency. Quark deconfinement might be an explanation for this phenomenon, although it is not the only one to be brought up.

The empirical data is definitely not important in a quantitative but rather qualitative manner in our case. There are not many processes to account or to suggest quark deconfinement but those that might be actually put in application, i.e. the anomalies discussed above would represent almost irrefutable prove.

5. **Conclusions?**

The idea of quark deconfinement leading to the formation of absolutely stable quark matter is tried to be made popular (and reasonable, we would add). It seems from the empirical data and consequentially applied theory that such explanations are plausible, therefore a harsh renouncement to these ideas would not be justified. It is maybe also interesting to think ahead about the consequences, the implications of this current of opinion. In the event that this idea is correct, many far-reaching implications for neutron starts are immediate, among them being that *all* neutron stars are entirely "strange stars" being made of 3-flavor strange quark matter and in sharp contrast with the other stars made up of hadronic matter. It seems that the eventual outcome has the potential ability to trigger more research (implicitly more funds for research) and more anxiety to positively assess the existence of the exotic and strangeness within neutron stars.

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