Neutrons are forming an external skin in Nuclei and Neutron Stars

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Abstract

This paper provides some pointers that are relevant to a few select topics about neutrons structures, neutron stars, and relationship to QCD, in particular with respect to confinement, and stangelets.

Neutron stars observations seem to confirm the apparition of deconfined quark gluon plasma at the core of neutron stars, and the presence of a superconducting layer above, so that the crust and the superconducting/superfluid region can also explain neutron stars glitches.

Aspects covered in the paper are related to the multi-fold analysis of QCD and QED, including confinement, asymptotic freedom and the mass gap, for which we provided new intuitive analyses and interpretations. It confirms the ability to deconfine, à la percolation, under high density and pressure, while still hiding colors, and the existence of superconducting phases.

A consequence of the short analysis is that we can support a neutron star core that is an hybrid of deconfined quarks and nuclei, plus possibly hyperons, while proposing that strangelets are likely not produced by neutron stars: a good news for the future of normal matter, that otherwise could have been infected by any minuscule strangelets contribution, spelling (locally) the end of matter as we know it, even if it is a slow process.

1. Introduction

This paper republishes v1 and v2 of [1], and expands on some results reported on observations related to the core of neutron stars, based on results about neutrons, and more recent observations and simulations of neutron stars.

Based on our analysis of quark gluon plasmas and deconfinement [12], we add our support for hybrid nuclei/deconfined quark model (with possibly hyperons), and predict no strangelets neutron stars.

2. Neutrons are forming an external skin in Nuclei and Neutron Stars

It has been reported that neutrons are forming an external skin in Nuclei and Neutron Stars [2,3]. This recent result was in fact expected.

Indeed, neutrons and protons are internally a sea of quarks, with just at best some preferences for the valence quarks. One can expect that they have roughly the same density. The mass of the proton is smaller than the mass of the neutron. With the same density [4], it is implied that the volume of the proton has to be smaller than the volume of the neutron. Hence the result, where the radius size difference accounts for the neutron skin, as a bump vs. protons. One can therefore expect that an external skin will also appear in nuclei with, by definition, the

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external layer being dominantly visited by neutrons: neutrons are located more are the surface of nuclei than protons, to accommodate the extra volume requirements when they are packed together. Measurements show that as a result nuclei are stiffer (in collisions) than expected.

As explained in [2], the case for neutron stars is "same same, but different".

And so, neutron stars have structures, and they differ from just nuclei. Per the reasoning above, one is tempted to expect a skin / external region of neutrons. It is roughly the case, except for the ions and electrons to roughly neutralize it, and an atmosphere around [5]: we have a neutron crust that maybe super material.

Yet from [5,6], it seems clear that, indeed, the density argument does not hold for neuron stars: the sea of quarks and gluons is not sufficient and must contains other particles. The main next candidate being the s quark (as the next one in the mass progression). It is analogous to, for example, Hyperons, as discussed in those papers, at the nuclei level. We also need protons, and not just quarks, to address the lack of squeezability and larger than expected size of the neutron star discussed in [6]: proton repulse themselves giving the structure that would not exist if we just had quarks.

Continuing on the analysis of the composition of neutron stars, one may want to wonder why protons are still believed to be part of the neutron stars, or even appear as shown in [5], where the neutron stars also include a protons core inside. It results from the observation that in neutron rich nuclei material, protons have an increasing probability to pair with neutrons into high energy pairs, while the probability of neutron pairing seems constant. It denotes that in such neutron rich nuclei, protons carry a significant amount of energy [7,8]. It is expected that the same behavior extends to neutron stars. The probability is estimated to be ~ 95% neutrons, 5% protons. This result would be for the core where hyperons may also appear.

For the rest, the superfluid neutrons and the superconductor protons are discussed in [9] and references therein: they result from simulations that show that such a model explains the thermal evolution observed with neutron stars.

So we have:

- Cooper pairs of neutron giving neutron super fluid BEC (external because easiest to form per above + no electromagnetic repulsion).
- Cooper pairs of protons (BEC) at stronger pressure because they are harder to form due to the electromagnetic repulsion (also in smaller number due to above)
- Protons + Neutrons / along with Hyperons / Soup of quarks including strange quarks / pions but formed into particles (or pairs of particles) at even larger density (See also [10]).

Note: Text added on January 1, 2024:

As a confirmation of the superconducting/superfluid (super solids as crystals (crust) + superfluid (below)) phases, and the presence of the crust is provided in [24-26]. Glitches due to vortex escaping the superfluid and reaching the crust to modify its acceleration, leading to glitches where it spins suddenly changes. This behavior has been observed with neutron stars.

3. Deconfined Quark Gluon Matter

As conjectured above, recent observations show that the neutron star core is expected to contain quarks and gluons (and maybe more), that are deconfined [23]. This can be easily justified at the light of multi-fold QCD analysis in [12] end references therein, where we explain why phase diagrams published in the literature for Quark gluon matter can support deconfined and superconducting/superfluid/supersolid phases at high densities and pressures. More details on the multi-fold theory can be found at [13-18].

Accordingly, when there is enough overlap between the quarks, e.g., due to immense pressures and densities, we expect a change of phase where quarks and gluons can percolate across the soup and therefore deconfine, still not allowing any color to exist on its own, yet with some bound situation also involved. Papers in the literature also call this quark matter [23].

Unfortunately, one would expect that in such a scenario, as the deconfined plasma forms, the size of ethe neutron stars would decrease as the mass increase, at least for a while. It is not what is reported in [5], with a core probably being a mixture of quarks, nuclei and possibly hyperons. As pressure would further increase, more massive neutrons stars, we would predict that more deconfined plasma appears, possibly still in an hybrid mode, until everything becomes plasma but for larger masses than initially thought. The last 2 figures in [5] also indicate such an evolution. So we see that the results of [5] do not invalidate a quark gluon deconfined plasma but instead show a mix of it with other nuclei and possible hyperons, as deconfinement progressively takes place, aligned with the percolation model as in [12.

Note: Text added on August 7, 2023:

4. No Strangelets or Stange Stars

The presence of a crust of neutrons, even if internal, also indicates that strangelets, i.e., bound condensed states of many strange, up and down quarks [11], may not exist, at least not in neutron stars, and if they did they will not touch normal matter anytime soon: they would be limited to the inner core, indeed, superconducting protons are probably stabler than strangelets that are a more complex condensate requiring stronger pressures. It would be hard for them to transform the proton pair (their energy is lower than the individual nuclei), and cross that region. And so strange stars would also not exist, at least not resulting from the evolution of neutron stars.

Strangelets are bound states, not referring to just strange quarks [11]. All known strange particles are unstable, decaying into up quarks via the weak interaction, but it has been proposed that when we have many up, downs and strange quarks, they may slowly form energy state(s) lower than up and down quark combinations, because more quarks can be in their lowest states, per the Pauli exclusions principle (the problem does not repeat with other quark flavors because of the mass differences). Therefore, it has been conjectured than any contact between strangelets and normal (only based on up and down quarks) would result into everything converting to strangelets. [11] provides a description of the conversion scenario.

The notion of bound state is important. With deconfinement, as pressure and density (and temperature) increase, we just argued that deconfinement increases, as it can provide alternate low energy evolution again bypassing the strangelet as lowest energy level: it is no more conversion of nuclei to strangelets but dissociation of everything, and no return (no path to reduce pressure) to states where nuclei or strangelets would recombine, so formation of only strangelets is not an option. Even dissociation of nuclei to form strangelets is probably disrupted first by the surrounding deconfinement. Note that hyperons and Lambdas, if present along other nuclei, are still unstable, *albeit possibly with a longer lifetime inside neutron stars. Strangelets themselves within a deconfined environment may not be such a stabler alternative to nuclei in the same environment.*

So it seems that we can breathe easier, as this means that slow conversion, on contact, of normal matter into strange matter may not be something that happens in our universe, at least with neutron stars

Until other sources of strangelets are proposed, the risk is significantly reduced.

5. Conclusions

The paper provides an overview of some of the latest results and views in terms of neutron stars, vs. observations of protons and neutrons in nuclei. It complements some discussion in papers and web page discussion for [12,19,20,21]. We argue for hybrid nuclei / quark deconfinements (+ possibly hyperons), with color still hidden, at high pressure and densities. The hybrid is a normal smooth evolution form confined to deconfined states are told in [12].

We also argue about the absence/non-existence of strangelets, at least sourced by neutron stars, both because of deconfinement that offers stabler alternatives ,and the challenge for any strangelets to transform and cross the proton superconducting core, which is not a case of nuclei to strangelets transformation either.

Note that an attentive reader may argue that section 3 glosses over quark mater versus deconfined quark gluon plasma. Somehow, it is not that clear cut if we have quarks or deconfined quarks

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