Color Superconductivity and Compact Stars

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Abstract

Background : Color superconductivity is a predicted phase of nuclear matter that occurs at sufficiently high density and low temperatures. **Purpose** : Investigate the feasibility of color superconductivity in compact stars. **Methods** : Study the critical frequency of r-modes for CFL phase compact stars. **Results** : The critical frequency is dramatically low in the considered model. **Conclusions** : Although these considerations rule out a certain color superconducting star, there is much to be considered before reaching a conclusion regarding all compact stars. Color superconductivity in stars is still feasible.

The phase diagram of nuclear matter [Figure 1] is a highly disputed topic in nuclear physics today. It is known that at low baryon chemical potential ($\leq\sim$1000MeV), or baryon density, and low temperature ($\leq\sim$170MeV), normal hadronic matter exists. Hadronic matter is a state of confined quarks, further divided into baryons containing 3 quarks and mesons containing 2 quarks. At high temperatures ($>\sim$170MeV), a deconfined state of quarks exists, quark gluon plasma. When baryonic chemical potential is sufficiently high($>\sim$1000MeV) and temperature is sufficently low, color superconductivity is predicted to occur.

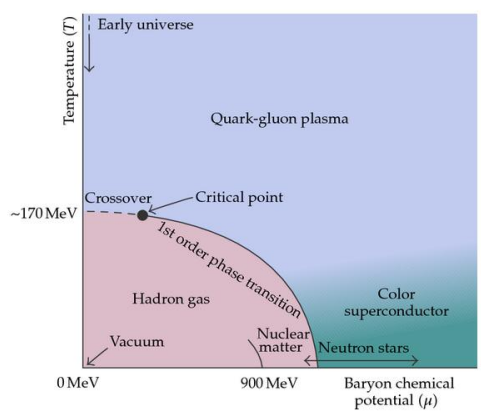

Figure 1: Conjectured phase diagram of nuclear matter which includes color superconductivity. https://www.hindawi.com/journals/ahep/2011/259025/fig4/

Color superconductors are analogous to the ground state electron system described in Bardeen-Cooper-Schrieffer theory of low-temperature superconductivity. Near the Fermi surface, where the quarks have energy close to the Fermi energy, there exist weak attraction channels. The interaction is weak here since QCD is asymptotically free. If two quarks, having the correct quantum numbers, enter this channel they will form Cooper pairs. Cooper pairs are bosonic and will thus form a condensate. This ground state of quark matter at high baryon density breaks the symmetry of fermion number. Color superconductors have similar consequences to superconducting metals including producing an infinite conductivity and exhibiting a color Meissner effect.

Quarks, as opposed to electrons, come in various flavors (up, down and strange), carry color charges as well as spin degrees of freedom. In the Cooper pair condensate, local color symmetry is broken in some phases of color superconductivity as color singlets cannot be made. With so many varieties of quarks, many phases of color superconductivity can be theorized. In particular, I will mention the 2SC and the CFL phases.

The two-flavor color superconductor (2SC) is a phase with spin-0 Cooper pairing. This phase is made up of pairs of up and down quarks holding green and red color charges. The unpaired blue up and down quarks give rise to gapless quasiparticles. At low temperatures, the quasiparticles are the main contributors to the specific heat and the electrical and heat conductivity of the matter. The unpaired blue up and down quarks also participate in β processes, leading to large neutrino emissivity.

The pairing of 3 quarks of each flavor and color is the color-flavor locking (CFL) phase of color superconductors. This phase is favored as more symmetries can be satisfied.

As previously stated, color superconductivity is only allowed at very high densities. These densities can only naturally be found inside of compact stars. So long as the star is a few seconds old, it is also a temperature below the critical temperature for color superconductivity. The make-up of these stars is currently unknown, but measuring observables affected by the phase of the nuclear matter inside of the stars as well as performing rigorous theoretical simulations can provide us with better insight.

Rotation modes, or r-modes, refer to a bulk flow in a rotating star that radiates energy and angular momentum away from the star in the form of gravitational waves. There is a critical frequency of rotation that if surpassed, the star will be unstable to r-modes and spin down until its frequency is less

than the critical frequency. At this frequency, the r-modes are damped out. The critical frequency is determined through consideration of sources that suppress r-modes. These sources of damping include shear and bulk viscosity as well as "surface rubbing", a friction at the surface of the r-mode region and the rigid crust of the star. The viscosities are dependent on temperature, thus a maximum frequency can be based on the current temperature of the compact star.

If a star exhibits color superconductivity, there is an energy gap in the quark excitation spectrum for that star. This suppresses the viscosity by a factor of exp(-Δ/T) where Δ is the energy gap and T is the temperature of the star. Using the assumption that the compact star is made completely of CFL phase quark matter, Madsen [1] found that even for a low energy gap of $\Delta = 1MeV$, the critical frequency is reduced dramatically to $\mathcal{O}$(100Hz) for temperatures below 100keV. Figure 3 shows critical frequency of strange stars as a function of temperature whereas Figure 3 shows the same plot assuming quark matter in the CFL phase. The crosses and box show frequencies of actual stars, and in the second diagram these frequencies are above the critical frequency. This results in an instability, thus for this model these stars are not possibly CFL phase stars. This draws into question if any stars can be made of this phase of nuclear matter.

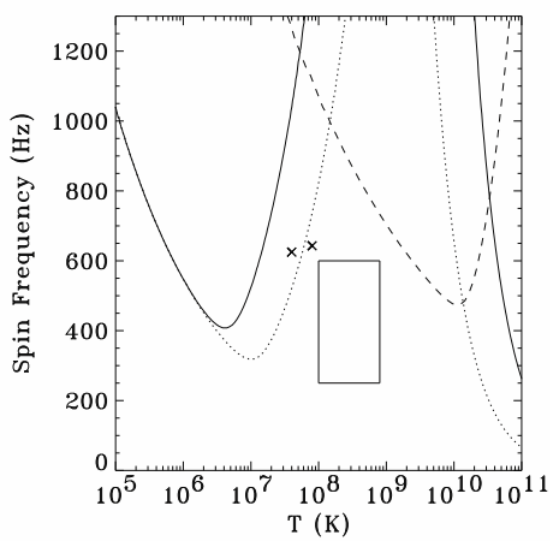

Figure 2: Critical frequencies in Hz for strange stars as a function of temperature. Solid and dotted lines assume strange quark mass of 200 and 100 MeV respectively. The boxed region shows possible locations of LMXB stars and the crosses are upper bounds on core temperatures of the two fastest pulsars. Dashed lines show r-mode instability regions for neutron stars.[1]

Madsen, however, did not rule out the existence of color superconducting stars as many things are left to consider.

The temperatures of the core of stars is not well known, only sophisticated models of heat flow exist, thus the temperature considerations could be wrong. If the core of a star is quark matter, but the mantle is made of nuclear matter, a substantial amount of friction is expected at the interface. This friction could alter the viscosity suppression.

In summary, color superconductivity is predicted to occur at sufficiently low temperatures and very high baryon chemical potentials. Quarks exist in many varieties due to their color, flavor and spin degrees of freedom and thus could form many phases of color superconductors. To our knowledge, the only possibility for the natural occurrence of color superconductivity is inside of compact stars. In work by Madsen, a study of r-modes in a completely CFL phase star has ruled out color superconductivity for stars following his precursors. However, with many details left to consider, color superconducting stars are still very reasonable to consider.

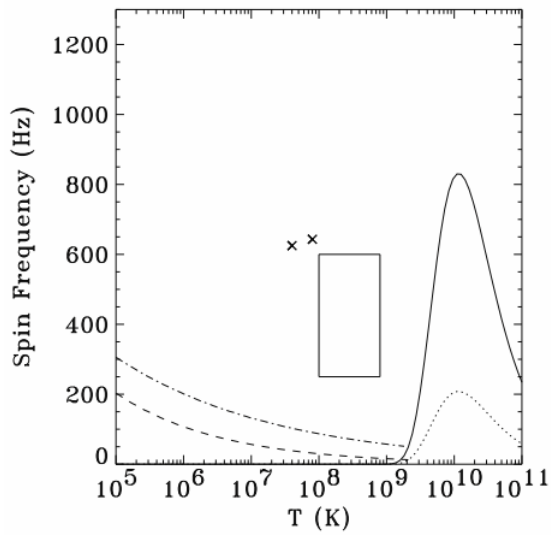

Figure 3: Critical frequencies as a function of temperature as in Figure 2, but assuming quark matter in a CFL phase and $\Delta = 1$MeV. Quark stars above the curves are r-mode unstable.[1]

References

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[2] Mark Alford. Color-superconducting quark matter. *Ann. Rev. of Nuclear and Particle Science*, 51, 2001.

[3] Igor A. Shovkovy. *Two Lectures on Color Superconductivity.* Springer, 2005.